DEVELOPING AN INTEGRATED CATCHMENT-SCALE MODELLING APPROACH FOR SUPPORTING THE SUSTAINABLE MANAGEMENT OF WATER NUTRIENT POLLUTION FROM DIFFUSE AGRICULTURAL SOURCES

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Abstract

Water is one of our most vital natural resources for life sustaining and human's economic development and social well-being. Agricultural diffuse water pollution (ADWP), the biggest remaining problem of water pollution in the world, has been realised as a major threat for water quality and the implementation of the EU Water Framework Directive (WFD). Indicative estimates of the costs of water pollution from ADWP are about £225 M per year in the UK, whilst failure to meet the requirements of the EU WFD by 2015 may incur heavy fines. From the technical and scientific points of view, there are three major gaps, namely, "method and tool", "research scale" and "fundamental knowledge" gaps between current ADWP research and the successful implementation of the EU WFD. It is timely to develop integrated catchment-scale numerical modelling tools or methods to handle the ADWP problem at the catchment scale.

This thesis describes the development of an integrated catchment-scale modelling approach, ICEMAN, for supporting the effective decision-making of the ADWP sustainable management at the catchment scale, thus helping the implementation of the EU WFD in handling ADWP.

In order to quantitatively describe the nutrient process in the complete hydrological cycle, it is necessary to integrate numerical water models into ICEMAN to calculate or simulate the groundwater pollution pathway vulnerability, groundwater pollution risk, water balance in soil, nutrients biochemical cycling in soil, and surface water quality and quantity processes.

This study showed that GIS and the Arc Hydro model consisting of the modules of data mining, hydrological analysis, and visualisation can facilitate the developing and applying the ICEMAN by providing data support and powerful functions of spatial analysis.

The DRASTIC model was applied in the case study area – Upper Bann Catchment, Northern Ireland for assessing the groundwater pollution pathway vulnerability of general pollutants and pesticide. The results showed that DRASTIC is suitable to be introduced into the ICEMAN for catchment-scale groundwater pollution vulnerability assessment. However, DRASTIC has drawbacks in the groundwater pollution risk assessment, namely, having no risk concept and considering no pollutant dynamic nature with runoff.

A D-DRASTIC approach was developed in this study for reliable groundwater pollution risk assessment from diffuse agricultural sources based on DRASTIC within an ArcGIS environment. D-DRASTIC overcomes the pitfalls of applying DRASTIC in groundwater risk assessment. The results of applying D-DRASTIC in the case study showed that D-DRASTIC is helpful in guiding the activities of groundwater pollution prevention at the catchment scale; and can be used in the development of ICEMAN.

A numerical catchment-scale surface water model capable of the simulation of ADWP is necessary in developing the ICEMAN method. A HSPF model was selected based on the review of popular surface water models; and tested in the study area. The calibrated and validated HSPF model can well represent the characteristics of surface water quantity and quality in the study area. Climate change scenario evaluation results in five years showed that when the annual mean temperature increase 3°Celsius the mean yearly total runoff volume will decrease by 11% and the mean daily river flow of five years will decrease by 11%. The results showed that HSPF is a suitable model in simulating the diffuse source surface water pollution; and can be integrated into the ICEMAN.

ICEMAN was developed by integrating the models of Arc Hydro, DRASTIC, D-DRASTIC, HSPF into an ArcGIS environment. ICEMAN can describe the nutrient biochemical cycles in soil, whole hydrological quantity and quality processes, and groundwater pollution vulnerability and risk, by considering factors in the catchment ADWP process, namely, meteorology, nutrient loading from different land uses, nutrient biochemical cycling in soil, nutrient dynamic nature with runoff and interflow, topography, depth to water, net recharge, aquifer media, soil media, impact of the vadose zone media, hydraulic conductivity of the aquifer, and the relationships between soil water and groundwater. The results of applying ICEMAN in the study area showed that ICEMAN can well support the decision-making of the catchment ADWP sustainable management. In the study area, ICEMAN provides satisfied simulation of river flow and quality, groundwater pollution vulnerability and risk zones, and quantitative descriptions of ADWP process including nutrient biochemical cycle in soil; and can help better understand the ADWP characteristics in a specific catchment. In addition, ICEMAN can evaluate the impacts of water management plans on water processes under the climate change. For example, when changing 20% farming land into forest land in the Gamble's Bridge watershed of the study area, the mean concentrations of nitrate, nitrite, NH4, and PO4 in river will decrease by 19%, 33%, 31%, and 31% respectively.

ICEMAN, transferable to other areas, can bridge gaps of "method and tool" and "research scale" in the implementation the EU WFD in handling ADWP; and can act as an important complement of the River Basin Management Plans. This multi-disciplinary study may provide a good starting point for tackling ADWP at the catchment scale in an integrated, quantitative, and sustainable manner. Therefore, the results in this multi-disciplinary study are not only useful for better implementation of the EU WFD, but also helpful for tackling the ADWP problem outside the EU.

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About the author

The author, Lei Wang, have undertaken a second PhD here in the UK as a foundation to a career in the area of water environment, after two-year experience in industry following author's original PhD studies in China.

So far, the author has participated in 11 projects covering geo-environment, geo-information integration theory and applications, GIS theory and applications, applied geophysics, and software engineering. The author has published 21 journal papers and 2 books.

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Chapter 1

Introduction

This chapter 1) explains project background, aim, and objectives; 2) introduces and justifies the research scheme, process, and key methodologies employed or developed in this study; 3) discusses the significance of this study; and 4) describes the structure of this thesis by providing the overall thread of this systematic study.

1. The background of this study

Fresh water is one of the precious natural resources, and plays a vital role in the subsistence of life on earth. Controlling water pollution is critical in sustainable development. In the year 2000, the European Union Water Framework Directive (WFD) set a framework for comprehensive management of water resources in the European Community, within a common approach and with common objectives, principles and basic measures. The fundamental objective of the EU WFD aims at maintaining "high status" of waters where it exists, preventing any deterioration in the existing status of waters and achieving at least "good status" in relation to all waters by 2015.

Diffuse pollution, also called non-point source pollution, is from no discrete point of discharge that can be readily identified and controlled; is often episodic and pollution can enter the environment by a number of pathways. The amount and timing of any pollution event is governed by climatic conditions, the physical and geological nature of the land, and on-going land management practices (Defra, 2004). D'Arcy et al. (2000) defined diffuse pollution as follows:

"Pollution arising from land-use activities (both urban and rural) that are dispersed across a catchment, or subcatchment and do not arise as a process effluent, municipal sewage effluent, or an effluent discharge from farm buildings."

The largest source of diffuse water pollution is agriculture. In England, it is estimated that over 70% of nitrates in natural waters are derived from agricultural land (Defra, 2002a). In agriculture, the main pathways of pollutants reach water are runoff from land or through land drains to surface water, and leaching of subsurface flow to either groundwater or surface water. Fig. 1.1 shows main sources and pathways of the agricultural diffuse water pollution (ADWP). The diffuse agricultural pollutants include nutrients (particularly nitrogen and phosphorus), pesticides, faecal material (such as slurry, manure, and other materials of high organic content such as dirty water), and silt. The arable framing in the UK is now dependent on the application of inorganic fertilisers and pesticides to maintain simplified but more intense cropping patterns. Beef cattle and sheep, occupying areas of unimproved and rough grassland, could cause the water pollution problems of the loss of veterinary medicines (including used sheep dip), soil erosion as a result of over-grazing and poaching of soils, bank side erosion as a result of stream access and microbial pollution of water. The main risks of dairying to water are soil erosion from poaching or as a result of exposure of soils during maize production, bank side erosion as a result of stream access, loss of nutrients, pesticides (used on fodder crops) and veterinary medicines, loss of faecal matter and loss of organic matter, leading to high BOD levels in streams. Pig breeding and rearing have the water pollution risks of soil erosion, and elevated levels of phosphorus in soil beyond crop requirements from manures and slurries. Poultry rearing produce huge amount of manure rich in nitrogen and phosphorus, and could cause nutrients lose to water bodies after being applied to local land with high application rates. Diffuse pollution risks associated with horticultural practices are mainly associated with the loss of nutrients, pesticides and silt (Defra, 2004).

The factors which affect the risk of ADWP are the weather, the soil and sub soil type, the underlying geology conditions, the slope of the land, and the presence of direct connections to a water body (such as water channels and fissures). Within soil, nitrogen fertilisers readily release ammonium and nitrate. Nitrate is highly soluble and so is mainly lost by leaching, which can reach the highest level in winter when there is little or no crop growth to take up the nitrogen made available by mineralisation. High concentrations have been recorded following winter application of manures especially after rainfall events. Nitrogen can also be lost as ammonia following the application of organic nutrient sources such as manures and slurries just prior to rainfall. Phosphorus loss from agricultural land occurs mainly via overland flow and via drain flow; and is predominantly in particulate form with soil erosion. It is estimated that about 60% of phosphorus loss can be accounted for by this mechanism. The intensity and duration of rainfall, the slope of the land, the susceptibility of the soil to erosion, and the presence of subsurface pathways influence the rate and amount of particulate phosphorus lost to water. Phosphate (solubilised phosphorus) is generally lost to surface waters in leachate with subsurface flow and surface runoff following rainfall. Phosphate has been estimated to account for about 20% of phosphorus loss from agriculture but accounts for a greater proportion of the phosphorus lost from grasslands (Defra, 2004).

ADWP, which is not only a serious environmental issue but also a threat to economics and human health (Defra, 2002b), is still the biggest remaining water pollution problem in many countries (Campbell et al., 2004), although many efforts have been made for handling the ADWP problem since the 1970's. The ADWP problem has been identified as a major threat for water quality and the implementation of the EU WFD (EHS, 2000; DoE & DARD UK, 2003; Ferrier et al., 2004; Torrecilla et al., 2005).

Many programmes have been carried out in tackling the ADWP problem for the implementation of the EU WFD, such as River Basin Management Plans (RBMP), the network of Pilot River Basins (PRB) with fifteen PRBs in eighteen countries under the Common Implementation Strategy (CIS), projects for handling the ADWP under the fifth and sixth EC's framework programmes (FP), the water environment research under the EC's LIFE programme, and studies of the ADWP problem in each EU Member State (EUMS). However, water environmental scientists are facing challenges in bridging the gaps of "research scale", "method and tool", and "fundamental knowledge" for the successful implementation of the EU WFD in the field of the ADWP before 2015 (Chapter 2 discusses these gaps between current ADWP research and the successful implementation of the EU WFD).

For the "study scale" gap, the prevention of ADWP at the catchment scale is the key for handling the ADWP problem in a sustainable manner, and it is necessary to develop catchment-scale methods and tools to support the ADWP management. For the "method and tool" gap, more efforts should be made for each EU Member State (EUMS) to develop integrated and pragmatic methods or tools by making best use of or by improving existing knowledge, methods, and tools for tackling the ADWP problem at the catchment scale. For the "fundamental knowledge" gap, more multi-disciplinary or inter-disciplinary fundamental studies should be carried out for better scientific understanding of water cycle within and between atmosphere, geosphere, hydrosphere and biosphere, and of the pollutant biochemical and physical process in the complete hydrological cycle, and then to support the development of innovative measures to effectively handle the ADWP – the old but still remaining problem in the world. Based on this background, this research was launched.

2. The aim, objectives, and research scope of this study

The aim of this study was:

To develop an integrated modelling approach to support the catchment-scale sustainable management of nutrients from diffuse agricultural sources for better implementation of the EU WFD in handling ADWP.

The objectives of this study were:

1. Analyse the gaps between current ADWP research and the successful implementation of the EU WFD in the field of ADWP handling;

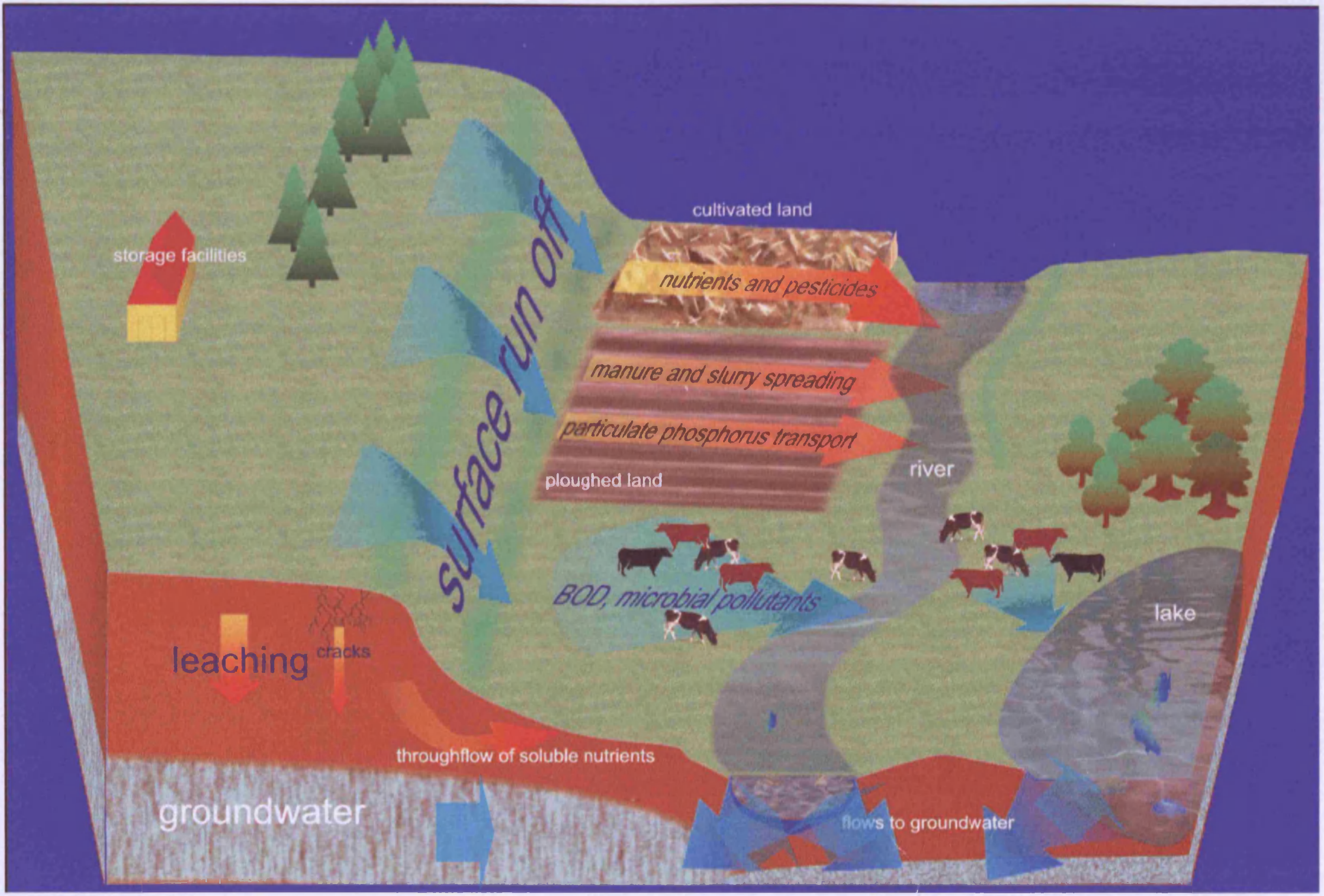

Fig. 1.1. Simplified diagram main sources and pathways of ADWP (adapted from Defra, 2004)

2. Set up a multi-sphere Geographic Information System (GIS) database in the case study area – the Upper Bann Catchment, Northern Ireland;
3. Set up a GIS hydrological model to support further investigations;
4. Groundwater pollution vulnerability assessment in the case study area;
5. Develop an method for reliable groundwater pollution risk assessment by considering the groundwater pollution pathway vulnerability, the risk concept, and nutrient dynamic nature with runoff;
6. Select a suitable catchment-scale surface water model for modelling ADWP;
7. Assess the selected catchment-scale surface water model by applying it in the case study area;
8. Evaluate the impacts of ADWP management plans on catchment water process under the climate change;
9. Develop an integrated modelling approach to support the decision-making of the prevention of surface water and groundwater nutrient pollution from diffuse agricultural sources at the catchment scale.

The research scope of this study:

- Effective management requires collaboration between researchers, policy makers and the community. This study has focused on the catchment-scale numeric modelling which can support the decision-making of the management of the ADWP problem in the context of better implementation of the EU WFD from the scientific aspect;
- This study has focused on nutrients from diffuse agricultural sources including nitrogen and phosphorus;
- This study has focused on the prevention of nutrient water pollution at the catchment scale instead of the remediation of contaminated water;
- This study has considered nutrient biochemical cycles in soil, and hydrology and hydrogeology processes within and between atmosphere, soil, groundwater, and surface water.

3. The roadmap of investigation

As discussed above, it is necessary to develop an integrated modelling approach to support the decision-making of the sustainable catchment-scale nutrient management, in order to effectively and efficiently tackle the ADWP problem for better implementation of the EU WFD. Therefore, this study was designed to investigate the processes of hydrology, hydrogeology, nutrient biochemical cycling in soil, and their relationships in an integrated manner. Fig. 1.2 shows the investigation roadmap of this study.

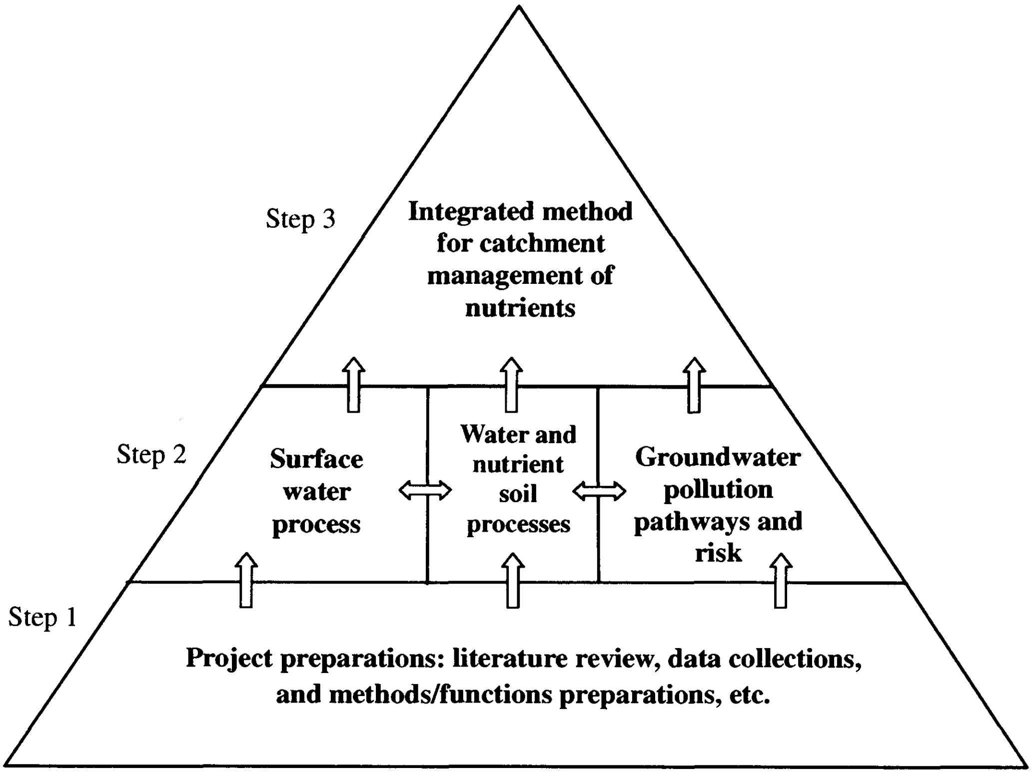

Fig. 1.2. The investigation roadmap of this study

For step 1, the preparations of this study included literature review, choosing methodologies, data acquisition, learning selected models or tools, building up GIS database, and establishing the GIS hydrological model for data and function preparations of further investigation.

The general knowledge of the ADWP mechanism can not to be universally applied because the ADWP processes vary greatly with significant varying situation, i.e. land use, climate, agriculture activity, soil, topography, hydrogeology conditions and the sensitivity of particular water bodies to pollution. Therefore, numerical models were introduced to describe quantitatively special ADWP mechanisms in soil, surface water and groundwater within a specific catchment. In step 2, the groundwater pollution pathway vulnerability, groundwater pollution risk, water balance in soil, nutrient biochemical cycling in soil, and surface water process were studied, in order to analyse quantitatively the nutrient process in the phases of source – pathway – target (the target in the surface water), and to support the development of the integrated modelling approach for supporting the sustainable management of ADWP at the catchment scale.

The work in step 3 was based on the results of step 2. An integrated modelling approach for catchment nutrient management was developed by integrating a GIS hydrological model, a surface water model, a groundwater vulnerability assessment model, and a groundwater risk assessment model into an ArcGIS environment. GIS spatial analysis functions were used to develop data exchange methods that can greatly facilitate the water modelling in different ADWP processes within a catchment, thus greatly improving the efficiency of application of the final modelling approach. A framework was established to make these models describing different catchment ADWP processes to support and complement each other, in order to describe the water cycle in soil, nutrient biochemical cycle in soil, surface water process, groundwater pollution pathway vulnerability, groundwater pollution risk, water and nutrient dynamic nature with surface runoff and interflow, the interaction between soil water and groundwater, and the soil process relationship with stream water process. In addition, studies were carried out to evaluate the impacts of land use change, agricultural activity change, best management practices (BMP), and climate change on water quantity and quality process at the catchment scale, thus proving the final integrated modelling approach useful in supporting the effective and efficient decision-making for catchment ADWP sustainable management.

4. Methods

4.1. The case study area

The Upper Bann Catchment, covering an area of 674 km2, lies in the southeast of Northern Ireland (NI) (Fig. App.A.3). The reasons for selecting the Upper Bann Catchment as a case study area are listed below.

1) The area is one of six priority catchments for water quality management action, namely, Upper Bann, River Bush, River Lagan, Newry River, Strule River, and Tall River Catchments (EHS, 2000).

2) This area contains Upper River Bann, which is the largest river that supplies the Lough Neagh - predominant inland water situated centrally in the NI with total area of 388 km^2.

3) According to Lough Neagh & Lower Bann Advisory Committees (2006), the dramatic nutrient enrichment in Lough Neagh, occurred in the 20th Century, had been the result of increased nutrients coming both from urban and agricultural sources. While the nutrients from urban sources have decreased appreciably since 1986, the diffuse agricultural nutrient inputs to Lough Neagh have continued to increase. Therefore, the ADWP management in the Upper Bann Catchment is significant for water quality control in Lough Neagh.

4) This area is an agricultural land use dominated catchment; and is suitable for the ADWP study.

5) The research group I have been working with has some sets of data for this area.

Methods or tools, which can be used for the implementation of the EU WFD, should be transferable to other areas. Therefore, the transferability is the one of the important characteristics of methods developed in this study. The case study area was used as a test area for methods developed in this study.

The details of the conditions of the Upper Bann Catchment are given in the appendix A, according to the demand of the regulation of thesis with paper format.

4.2. Geographic Information System

GIS is a computer system capable of integrating, storing, editing, analysing, sharing, and displaying spatial data and associated attributes. The development of the integrated modelling method for handling the ADWP problem involves atmosphere, hydrosphere, and geosphere factors; and was an inherent geographical activity requiring the handling of multiple forms of spatial data. With the advantages of spatial data management, analysis, and visualisation, ArcGIS 9.0 platform was employed in this research for processing data, and the development of modelling methods.

4.3. GIS database

A multi-sphere GIS database was set up to support this multi-disciplinary study. This GIS database employed raster, vector, and time series data formats. All raster data have the resolution of 50m×50m. The details of this GIS database in the case study area are given in the Appendix A, according to the demand of the regulation of the thesis format.

4.4. GIS Arc Hydro model

Intensive data and spatial analysis functions were needed to support this multi-disciplinary study in modelling the complex catchment ADWP processes. Therefore, it is necessary to choose a suitable model for this purpose. The Arc Hydro model (Maidment, 2002), developed to support water resources applications and provide a starting point for a water resources database development and its application, was selected for this study. The Arc Hydro model set up in this study consists of data mining, hydrological analysis, and visualisation modules. Because of its simple data input and easy-to-use but powerful functions, the Arc Hydro can facilitate the development of the integrated modelling method for supporting the catchment-scale nutrient management, and make the application of this integrated decision-support method easier in other catchments. The paper in chapter 3 provides the details of the setting up the Arc Hydro model and its significance for this study.

4.5. Curve Number method for runoff calculation

Runoff plays an important role in stream water generation and groundwater net recharge. Both land use and soil type influence the runoff process. The widely used curve number (CN) method (NRCS, 2004), developed by US Natural Resources Conservation Service, was employed in calculating the runoff, runoff accumulation according to topography, and the groundwater net recharge. For details of the application the CN method and its results, please see the paper in chapter 5.

4.6. DRASTIC method for groundwater vulnerability assessment

There are four types of methods for groundwater vulnerability assessment, i.e., process based (modelling), statistical, observation based, and index methods. The process based, and index methods are helpful for groundwater pollution prevention. Index method has the advantages of easy understanding and applying; and disadvantage of subjectivity in the factor weighting and numerical value assignation. The widely used DRASTIC method, one of index methods, developed by the U.S. Environmental Protection Agency (EPA) (Aller et al., 1987), was adopted for the assessment of groundwater pathway vulnerability in this study. In the application of the DRASTIC method, seven factors, i.e. 'depth to water', 'net recharge', 'soil media', 'topography', 'impact of vadose zone', and 'hydraulic conductivity of the aquifer', were calculated or abstracted from the GIS database established in this study. The groundwater vulnerability maps of general pollutants and pesticide in the study area were generated. The spatial distribution of "low", "moderate" and "high" vulnerability zones in general pollutant and pesticide maps can guide people in groundwater pollution prevention in a catchment. The paper in chapter 4 provides the details of groundwater pollution vulnerability assessment in the study area using DRASTIC.

4.7. A D-DRASTIC method for groundwater risk assessment

Groundwater pollution vulnerability and risk are two different concepts. The DRASTIC method is capable of the assessment the pathway possibility that pollutant hazards may be transmitted to groundwater, however it has two pitfalls in the groundwater pollution risk assessment, namely, having no risk concept and ignoring pollutant transport with runoff. A D-DRASTIC method for groundwater risk assessment was developed to overcome these drawbacks. By introducing the risk concept and soluble pollutant dynamic nature with runoff, the results of the D-DRASTIC method can provide more reliable groundwater pollution risk maps, which are useful in guiding the practices of the prevention of groundwater pollution from diffuse soluble pollutants at the catchment scale. The paper in chapter 5 describes the development of the D-DRASTIC method and its application in the study area.

4.8. HSPF model for surface water process modelling

A numeric catchment-scale surface water model for simulating ADWP is necessary in the development of the integrated modelling method in this study. Many factors were considered in selecting a suitable model, such as application scale, contaminant simulation capability, nutrient cycling process in soil, climate change response, both pervious and impervious land use supporting. Hydrological Simulation Program—FORTRAN (HSPF) (Barnwell and Johanson, 1981), developed by United States Environmental Protection Agency (USEPA), was chosen based on the review of most of popular and free surface water models. HSPF can continuously simulate water quantity and quality processes on pervious and impervious land surfaces and in streams. HSPF can be used to simulate river flow, river nutrient concentration, and to evaluate the impacts of climate change, land use change and filter strip method (one of best management practices for reducing the ADWP) on catchment water process. For the details of selecting and assessing the HSPF model for better implementation of the EU WFD, please see the paper in chapter 6. Appendix B describes the major technical details of the HSPF model.

4.9. An ICEMAN approach for catchment ADWP management

In order to handle the ADWP problem, it is necessary to carry out a multi-disciplinary study to develop integrated modelling methods or tools to support the decision-making of the ADWP prevention management at the catchment scale. An integrated approach – ICEMAN (Integrated approach for Catchment water quality Management) was developed in this study. The ICEMAN method considers nutrient biochemical cycles in soil, hydrology and hydrogeology processes within and between soil, groundwater, and surface water by integrating a numerical GIS hydrological model, a surface water diffuse pollution model, a groundwater pollution vulnerability model, and a groundwater risk assessment model into an ArcGIS environment. ICEMAN can provide quantitative descriptions of nutrient process in hydrological cycle within a specific catchment; and can evaluate the impacts of the policies of the ADWP management on water quality and quantity under the climate change, thus facilitating the decision support of the ADWP management at the catchment scale. The details of the ICEMAN method are given in chapter 7.

5. The significance of this study

5.1. For better implementation of the EU WFD

By making good use of the existing knowledge of nutrient cycling in soil, and the processes of hydrology and hydrogeology within and between atmosphere, soil, groundwater, and surface water, this multi-disciplinary study can bridge the gaps between current ADWP research and the implementation of the EU WFD in the field of ADWP handling, namely, "method and tool" and "research scale" gaps. The transferable ICEMAN method developed in this study can be an important complement of the Programme of Measures of RBMPs for the implementation of the EU WFD. The beneficiaries of this study include UK and other EU governments.

5.2. For tackling the ADWP problem

The ICEMAN method is helpful for supporting the effective and efficient catchment-scale sustainable management of the ADWP in a quantitative and transferable manner. This multi-disciplinary study may provide a good starting point for tackling the ADWP problem – a remaining water pollution problem in many countries. Therefore, the results in this study are also helpful for tackling the WADP problem outside the EU, especially for developing agricultural countries. In addition, this study can also provide data, methods and tools that could be useful to organisations, such as Department for Environment Food and Rural Affairs in UK, for following further studies and validations.

5.3. For water environmental science communities

The investigation measures, the data, the scientific knowledge of the catchment ADWP processes, assessing existing models, and the development of the new methods in this study can benefit water environmental science communities.

6. Structure of the thesis

This thesis is in the format of research papers. Chapter 2 to chapter 7 are papers extracted from this systematic study in the order of the investigation process. Fig. 1.3 shows the relationship between the structure of the thesis and the systematic study process.

The paper in chapter 2 discusses the challenges in handling the ADWP for successful implementation of the EU WFD from scientific and technical points of view, and points out that it is timely for scientists to develop more integrated catchment-scale modelling methods or tools to support the effective and efficient management of ADWP, in order to solve the ADWP problem and to bridge the gaps in the implementation of the EU WFD. Chapter 2 explains the background for launching this study.

The paper in Chapter 3 describes the roles of the Arc Hydro model and GIS in the preparations of data and hydrological analysis functions for this systematic study. This chapter shows that the introduction of the Arc Hydro model and GIS can not only facilitate the development of the final integrated modelling approach for supporting decision-making of the ADWP management at the catchment scale, but also make the application of methods developed in this study easier in other catchments.

Chapter 4 describes the assessment of the groundwater pollution vulnerability in the study area using the DRASTIC method. The groundwater pollution vulnerability maps of general pollutants and pesticide generated in this study showed the groundwater pollution pathway vulnerability, thus helping the guidance of the prevention activities of the groundwater pollution from diffuse agricultural sources at the catchment scale. DRASTIC can be used in developing the final method in this study. The work in chapter 4 was trying to consider the actual pollutant input from different land uses by overlaying the land use layer with the map of the groundwater pathway vulnerability. The paper in this chapter points out that the DRASTIC method has drawbacks in the groundwater pollution risk assessment. In order to overcome these pitfalls, the study in chapter 5 was carried out.

Chapter 5 introduces a catchment-scale D-DRASTIC approach for groundwater pollution risk assessment from soluble diffuse agricultural pollutants. The D-DRASTIC method can overcome the drawbacks found in the study of chapter 4, by introducing the risk concept, pollutant hazards and their dynamic nature with runoff according to topography. This method reflects the interaction between surface water and groundwater at the soil interface. The application of the D-DRASTIC method in the case study area showed that this method may provide a good starting point for handling groundwater pollution from diffuse agricultural sources at the catchment scale. The paper of chapter 5 implies that D-DRASTIC is suitable for the groundwater pollution risk assessment; and can be integrated into the final catchment-scale modelling approach in this study.

Based on the review of popular and free surface water models, the paper in chapter 6 selects the HSPF model for catchment-scale surface water ADWP modelling, and then assesses HSPF in the study area. The results showed that HSPF is a suitable model for better implementation of the EU Water Framework Directive in handling the ADWP problem. Chapter 6 implies that HSPF is a suitable model to be integrated into the final catchment-scale modelling approach in this study.

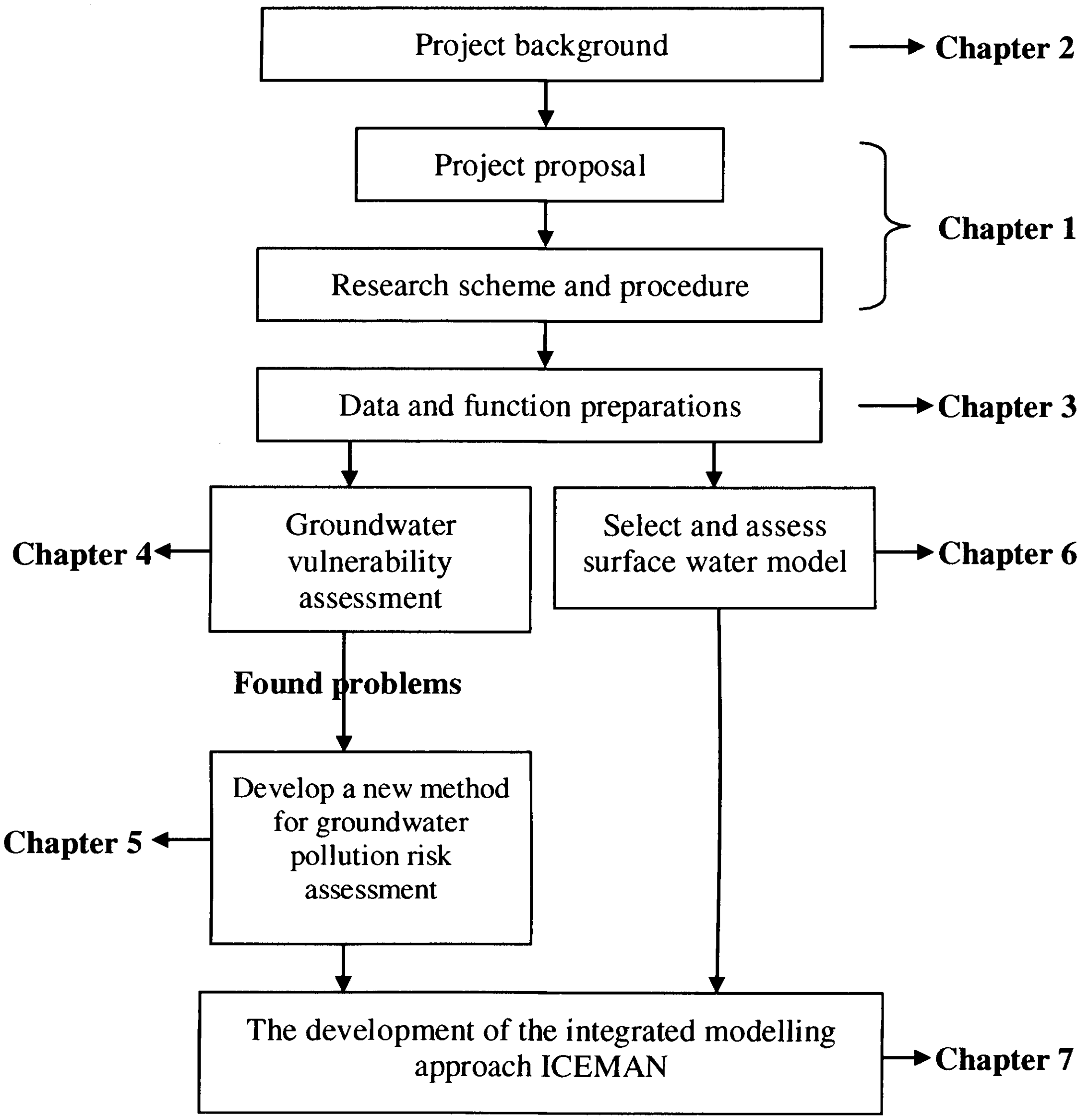

Fig. 1.3. The structure of the thesis and the systematic study process

The paper in chapter 7 introduces the final modelling approach – ICEMAN for supporting the decision-making of the sustainable ADWP management at catchment scale. The results of chapter 3, 4, and 5 were integrated into an ArcGIS environment, in order to develop ICEMAN. The ICEMAN was tested in the case study area.

Chapter 8 summarises the research and draws the main conclusions. Appendix A describes the study area – Upper Bann Catchment based on the multi-sphere GIS database established in this study. Appendix B is the major technical details of HSPF. Appendix C contains four proposals, which are composed and submitted by the author during this PhD study, namely, ERC first grant, NERC, NERC FREE call, and Royal Academy of Engineering & EPSRC Fellowship (2007-2008) proposals.

Chapter 2

Challenges for scientific research in the implementation of the EU Water Framework Directive in handling agricultural diffuse water pollution *

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Abstract

Agricultural diffuse water pollution (ADWP), the biggest remaining water pollution problem in many countries, is a major threat to the implementation of the EU Water Framework Directive. Indicative estimates of the costs of water pollution from agricultural diffuse pollution are about £225 M per year in the UK, whilst failure to meet the requirements of the EU Water Framework Directive by 2015 may incur heavy fines. From the technical and scientific points of view, there are three major gaps, namely, "method and tool", "research scale" and "fundamental knowledge" gaps between current research of agricultural diffuse pollution and the successful implementation of the EU Water Framework Directive. In order to meet challenges in bridging these gaps, it is timely for scientific communities to develop more integrated catchment-scale numeric modelling tools and methods to support effectively and efficiently the management of diffuse pollutants in the complete hydrological catchment cycle. Moreover, it is necessary to develop innovative and practical measures for tackling ADWP by carrying out more multi-disciplinary or inter-disciplinary fundamental studies of the key driving forces in the catchment process of

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ADWP. GIS and WebGIS can play important roles in the ADWP research for the implementation of the EU Water Framework Directive.

Keywords: Agriculture diffuse water pollution (ADWP); EU Water Framework Directive; Catchment scale modelling; Hydrological cycle; Nutrient cycle; GIS

1. Introduction

Water is essentially important in human development but is at risk of pollution. By comparison with point source water pollution, diffuse source water pollution is more complex and difficult to control because of its dispersed and numerous sources; and it is not only a serious environmental issue but also a threat to economics and human health (Defra, 2002b). For example, water with high concentration of nutrients (i.e. nitrogen and phosphorus) can cause eutrophication in rivers, lakes and estuaries by igniting huge algae and phytoplankton blooms, and depleting oxygen in water. In the Mississippi such blooms are now leading to so-called 'dead zones', where the death of the algae means all the oxygen in the water is used up, killing fish and other aquatic life. Meanwhile, nitrogen cycling can produce large amounts of the greenhouse gas 'nitrous oxide'. The removal of diffuse source pollutants represents a significant fraction of the total UK water treatment costs: the approximate annual costs in the UK of treating drinking water for pesticides are about £120 million, for phosphate and soil erosion about £55 million, for microorganisms around £23 million and for nitrate around £16 million (Pretty et al., 2000). Nitrate concentrations in excess of 10 mg dm^{-3} in drinking water may reduce the ability of human blood to carry oxygen and, in the very young, cause 'blue baby syndrome' (USDA, 1991; Matson et al., 1997). In addition, a potential cancer risk from nitrate (and nitrite) in water and food has been reported (Rademaher et al., 1992; Yang et al. 2007).

The importance of water has been reflected in a series of environmental action programs from the early 1970s to the present day. As part of a substantial restructuring of EU water policy and legislation, the EU Water Framework Directive (WFD) agreed by the European Parliament and Council in September 2000, came into force on 22nd

December 2000 (EC, 2000). This directive constitutes the most important EU initiative in the water field for decades aiming at achieving at least "good status" for all the waters in the EU Member States (EUMS) by 2015. The EU WFD sets a framework for comprehensive management of water resources in the European Community, within a common approach and with common objectives, principles and basic measures.

Diffuse water pollution is the biggest remaining problem of water pollution in many countries (Campbell et al., 2004), and the largest source of diffuse water pollution is agriculture. In England, it is estimated that over 70% of nitrates in natural waters are derived from agricultural land (Defra, 2002a). Agricultural diffuse water pollution (ADWP) has been identified as a major threat to water quality and the implementation of the EU WFD (EHS, 2000; DoE & DARD UK, 2003; Ferrier et al., 2004; Torrecilla et al., 2005). Each EUMS faces heavy fines if it fails to meet the requirement of the EU WFD by 2015. The successful implementation of the EU WFD needs the common efforts from scientific and policy-making communities, and other stakeholders. Water environmental scientists are facing challenges in ADWP studies that support the decision-making for water resource management.

Based on a review of the EU WFD and current ADWP research, this paper aims at: 1) discussing the problems of current ADWP studies in the successful implementation of the EU WFD from the technical and scientific points of view, namely, "method and tool", "research scale", and "fundamental knowledge" gaps; and 2) giving suggestions for bridging these gaps of the implementing the EU WFD in the ADWP management field.

2. The EU WFD overview

The EU WFD establishes a strategic framework for the sustainable management of water resources. It addresses inland surface waters, estuarine and coastal waters and groundwater. The fundamental objective of the WFD is to maintain "high status" of waters where it exists, to prevent any deterioration in the existing status of waters and to achieve at least "good status" in relation to all waters by 2015. The objectives of the EU WFD include: 1) to promote sustainable water use based on long-term protection of available water resources; 2) to provide sufficient supply of good quality surface water and groundwater as a need for sustainable and balanced water use; 3) to provide an enhanced protection and improvement of the aquatic environment by phasing out of discharges, emissions and losses of priority substances; 4) to contribute to mitigating the effects of potential floods and droughts; 5) to protect territorial and marine waters; 6) to establish a register of 'protected areas' for protection of habitats or species; 7) to protect and enhance the status of aquatic ecosystems (EUROPA, 2006). EUMS will have to ensure that a co-ordinated approach is adopted for achieving the EU WFD objectives and for implementing the programmes of measures for this purpose. There are main deadlines from the EU WFD: 1) 2003 – identification of river basins, assignment to districts, and the identification of competent authorities; 2) 2004 – characterisation of River Basin Districts (RBD), pressures and review of impacts, economic analysis (update every six yearly from 2013); 3) 2006 – establishment of monitoring network and making work plan for river basin management and public participation (update every six yearly from 2006); 4) 2007 – the overview of main issues (update every six yearly from 2013); 5) 2008 – draft River Basin Management Plans (RBMP) (update every six yearly from 2008); 6) 2009 – RBMP and programme of measures (update every six yearly from 2009); 7) 2010 – implementation of water pricing policies; 8) 2012 – programme of measures operational (update every six yearly from 2012); 9) 2015 – environmental objectives reached (EC, 2000).

The EU WFD is not conflict with, but works together or complements other EU exiting water legislations. For example, the EU WFD incorporates the requirements of current use-related or quality-objective directives and the quality standards laid down in the dangerous substances directive. While the Urban Waste Water Treatment, Nitrates, Bathing Water, and the Integrated Pollution Prevention and Control (IPPC) Directives will remain in force, some of the measures provided in many of the directives will be required for the implementation of the EU WFD in controlling pollution from certain activities. For water functions, there are five directives, namely, Fish Water Directive (78/659/EEC), Surface Water for the Production of Drinking Water Directive (75/440/EEC), Shellfish Water Directive (79/923/EEC), Bathing Water Directive (76/160/EEC) and Drinking Water Directive (98/83/EC). The limits and target values of the water quality in these directives will be used by the EU WFD. For water pollution sources, there are four directives: Nitrates Directive (91/676/EEC), Pesticides Directive (91/414/EEC), Urban Waste Water Treatment Directive (91/271/EEC), and IPPC Directive (96/61/EC). The Nitrates Directive concerns agriculture and demands EUMS to identify vulnerable zones, and to develop action programmes for controlling nitrate drainage into waters from these zones. According to this directive, the maximum 170 kg nitrate is applied on each hectare of the land. The Pesticides Directive also refers mainly to agriculture and contains provisions on the authorisation of pesticides in EUMS. For specific substances, there are two directives, i.e. Dangerous Substances Directive (76/464/EEC) and Groundwater Directive (80/68/EEC). These directives require EUMS to eliminate emissions of black list substances and reduce emissions of grey list substances by taking appropriate steps.

3. The implementation of EU WFD

3.1. River Basin Management Plans

The main activities for the implementation of the EU WFD take place in the context of RBMP led by local authorities. RBMP, the backbone of the EU WFD implementation, aims at: 1) establishing a strategic plan for long-term management of a RBD; 2) setting up an integrated monitoring and management system for all waters within a RBD to develop a programme of measures for delivering environmental improvements; and 3) acting as the main reporting mechanism to the EC. EUMS had identified their river basins and assigned them to RBDs prior to 22 December 2002. For all RBDs, six-yearly RBMPs and programmes of measures have to be developed. The first plans need to be ready by December 2009. However, in December 2007 an interim overview of the significant water management issues was carried out, and in December 2008 the draft river basin management plan should be published (EC, 2000). According to the EU WFD, the characteristics of a RBMP are: 1) mapping and identification of protected areas; 2) setting up monitoring networks and presenting in map form of monitoring results carried out for surface water, groundwater, and protected areas; 3) list of environmental objectives; 4) summary of economic analysis of water use; 5) register of any more detailed programmes and management plans for the RBD dealing with particular sub-basins, sectors, issues or water types, together with a summary of their contents; 6) summary of the public information and consultation measures taken, their results and the changes to the plan made as a consequence; 7) a list of the competent authorities; and 8) contact points and procedures for obtaining background documentation and information.

The process of a RBMP preparation includes establishing a cost effective programme of measures for achieving the environmental objectives of the EU WFD. Programmes of measures in RBMPs are required to be operational by 2012. A programme of measures may include wide-ranging actions:

- measures taken to identify, monitor and protect significant drinking water sources
- measures to manage specific pressures arising from human activities, such as forestry, agriculture and urban development
- measures taken to prevent pollution from priority substances
- measures taken to prevent or reduce impact of accidental pollution incidents
- measures taken in relation to water bodies unlikely to achieve the EU WFD objectives
- supplementary measures identified as necessary to meet environmental objectives
- measures taken to avoid increase in pollution of marine waters
- measures for water demand management
- controls on abstraction and impoundment of water

- controls adopted for point source discharges and other activities with an impact on water status
- an identification of cases where direct discharges to groundwater have been authorised
- practical steps taken to apply the principle of cost recovery of water use
- economic instruments
- river restoration strategies.

3.2. The Common Implementation Strategy

The successful implementation of the EU WFD will be equally as challenging and ambitious for all EUMS, institutions and stakeholders involved. Therefore, a strategic document establishing a Common Implementation Strategy (CIS) for the EU WFD has been developed and finally agreed under the Swedish Presidency in 2001 in order to assist coherent and harmonious implementation of the EU WFD among EUMS (EC, 2003). Although the individual EUMS is responsible for implementing the EU WFD, a broad European joint partnership among the water directors of the EUMS is necessary in order to (Quevauviller et al., 2005):

- develop a common understanding and approaches;
- elaborate informal technical guidance including best practice examples;
- share experiences and resources;
- avoid duplication of efforts; and
- limit the risk of bad application.

This joint process needs the involvement of stakeholders, non-governmental organisations, research community, and EU candidate countries to facilitate the cohesion process of the EU WFD implementation. CIS activities include carrying out the pilot testing exercises, facilitating inter-calibration, developing technical guidance on specific outstanding or new issues, maintaining the network of collaborating institutions, and reviewing the guidance documents. Ten working groups and three expert advisory forum (EAF) groups were completed in the first phase of the CIS at the end of 2003 and led to the availability of 14 guidance documents. The current second phase of CIS involves four working groups, namely on ecological status (WG 2A), economics and pilot river basins (PRB) (WG 2B), groundwater body characterisation and monitoring (WG 2C) and reporting (WG 2D), as well as two EAF groups (Quevauviller et al., 2005).

3.3. The pilot river basin network

The implementation of a CIS for the WFD started with the development of guidance documents. The guidance methodologies will need to be validated to ensure their applicability and practicality across the widest possible range of conditions (climatic, technical and political) found in the EUMS and candidate countries. For this reason, the EC established a network of PRBs with fifteen PRBs in eighteen countries to test and validate the CIS guidance documents. The first phase of PRB was finished and an activity report was available. For example, in the Ribble PRB of the UK, studies have been focused on setting up team building, stakeholder mapping, setting up stakeholder forum, meeting experts to develop solutions to technical problems for the proposed planning process, finding ways for public participation, etc (UK EA, 2004).

3.4. Programmes relating to the implementation of the EU WFD

The EC has been supporting research on water since several years through its successive framework programmes (FP) for Research and Technological Development (RTD). The FP is the EU's main instruments for encouraging collaborative, trans-national research, development and innovations in science, engineering and technology, and for supporting the implementation of related European policies. In the FP5 (1998-2002), more than 150 million euros has been invested in research projects of the action of "Sustainable Management and Quality of Water" relevant to the EU WFD. These projects were divided into several clusters, namely, integrated catchment modelling (CATCHMOD), ecological quality assessment, management of scarce water resources (ARID), integrated urban water management (CITY-NET), drinking water (CLUED'EAU), monitoring of contaminated sites, sediments and dredging materials, soil protection, residues of pharmaceuticals in water and soil (PHARMA), and flood forecasting (ACTIF). CATCHMOD cluster, aiming at developing common harmonised modelling tools for the integrated management of water at river basin or sub-basin scales. Table 2.1 shows the result of each project in the CATCHMOD.

Table 2.1.
The results of projects in the CATCHMOD cluster of FP5

Project name	**Project result**
HarmoniQuA	A computer based Modelling Support Tool (MoST) to provide a user-friendly guidance and quality assurance framework that will contribute towards enhancing the credibility of catchment and river basin modelling.
EUROHARP	Evaluated nine different contemporary methodologies for quantifying diffuse losses of N and P in 17 study catchments across north-south and east-west gradients in European climate, soils, topography, hydrology and land use.
HarmoniRiB	Supported the WFD implementation, by addressing issues of uncertainty in data and modelling, and by developing a virtual laboratory for modelling studies.
BMW	Established a set of socio-economic, bio-geo-chemical and systems analytical criteria to assess the appropriateness of integrated models for the use in the implementation of the EU WFD.
Tisza River Basin	Helped saving the water resources and ecological values with the help of integrated catchment management tools and to secure the sustainable use of the resources of the Tisza River Basin, a trans-boundary basin.
DAUFIN	Developed improved tools for hydrological modelling.
EuroLakes	The qualitative and quantitative identification of conflicting uses of the lakes and the lakes' basins where undoubtedly the drinking water aspect is of primary but not exclusive importance.
FIRMA	The improvement of water resource planning by developing and applying agent-based modelling to integrate physical, hydrological, social and economic aspects of water resource management.
GOUVERNE	Developed and applied user-based and scientifically validated decision support systems for the improved management of groundwater resources at the catchment and sub-catchment levels.
HarmoniCA	Created a forum for unambiguous communication, information exchange and harmonisation of the use and harmonisation of information communication and technology tools for integrated river basin management, and the implementation of the EU WFD.

HarmoniCoP	Increased the understanding of participatory RBMP in Europe; and to generate practical information about participation processes in river basin management to support the implementation of the public participation provisions of the EU WFD.
MULINO	Developed a methodological approach and provide an operational Decision Support System (DSS) for sustainable water use management at the catchment scale to support the implementation of the EU WFD.
TempQSim	Improved the tools for increasing the efficiency of the integrated water management in the Mediterranean and in semiarid river catchments.
TRANSCAT	Created an operative and integrated comprehensive DSS that should provide the basis for water management, possibly close to optimal, in the borderland regions in the context of the EU WFD.
CLIME	develop a suite of methods and models used to manage lakes and catchments under future as well as current climatic conditions.

In the FP6 for RTD (2002–2006), the Priority 6.3 “Global change and ecosystems” (opening the possibility to fund research projects dealing with policy in general) and the Priority 8 “Policy-oriented research” (responding to direct policy needs expressed by various EC General Directorates) were two main priorities that integrate research in support of water policies. Following them, four integrated projects relevant to the implementation of the EU WFD have been funded, namely, Euro-limpacs, AquaTerra, NeWater and AquaStress. Euro-limpacs was to evaluate the impacts of global change on European freshwater ecosystems; AquaTerra focused on integrated modelling of the river-sediment-soil-groundwater system in the context of global change in five contrasting European river basins; NeWater addressed the transformation processes of elements of current water management regimes in the transition to adaptive integrated water resources management; and AquaStress found new tools integrating management, technical economic and institutional instruments for water stress areas. In addition, three specific targeted research projects were funded by the FP6, namely, RIVERTWIN, TWINBAS, and WADE, to improve the effectiveness of the co-operation between European and third countries river basins for the implementation of integrated water resources management principles as stated in the EU WFD and the EU Water Initiative.

LIFE is the EC's financial instrument for co-financing projects, which demonstrate new ways of dealing with a wide range of environmental problems. LIFE, acting as a source of examples of good practice for meeting the demands of the EU WFD, has helped EUMS meet some of their needs regarding the implementation of the WFD, as well as contributing to EU Commission objectives and policy. For the first phase of LIFE (1992-1995), some 400 million euros were allocated; in the second phase (1996-1999) approximately 450 million euros. The third and last phase, LIFE III (2000-2004), had a budget of 640 million euros, which was subsequently extended from 2005 to 2006 with a budget of 317 million euros. LIFE+ is being launched from 2007 to 2013. In LIFE Environment, about 38% of projects have dealt with a range of water-based issues: approximately 43% on management of river basins, 16% on protection of groundwater, 16% on wastewater treatment, 16% on pollution prevention and reduction and 9% on planning and organisation of water management. These projects have certainly provided added know-how and the use of best practices in the water sector, at least in the regions, where the projects were implemented. However, it is difficult to ascertain the extent to which they have actually supported the implementation of the WFD. In comparison with the PRB approach under the CIS, the LIFE projects tend not to be implemented on a river basin scale and LIFE beneficiaries are only occasionally the competent authorities responsible for implementing integrated river basin management (Oliver et al., 2005).

4. Challenges in the implementation of the EU WFD

The EU WFD introduces an innovative, integrated and holistic approach to the protection and management of water resources. Much effort has been made for the EU WFD implementation. However, from the scientific and technical points of view, there are still gaps between current research and the successful implementation of the EU WFD in the field of the ADWP.

4.1. Method and tool gap

The EC's approach of implementing the EU WFD has been to provide examples of good practice for the implementation of the EU WFD rather than to be prescriptive – the EU WFD is a directive after all, and it is up to each EUMS to implement (Oliver et al., 2005). Each EUMS has difficulties in developing numeric models and methods for successful implementation of the EU WFD.

RBMP is a mechanism or system for reporting and administration that insure the successful implementation of the EU WFD. According to the characteristics of RBMP, its intrinsic value is not as the principal mechanism for the obligations of implementing the EU WFD, but as a document for consultations with the public and primary stakeholders on plans for management of the water environment within RBD. RBMPs will also be the main reporting mechanism to the EC and the public, and will include the detailed targets that have to be met and the timescale. Although RBMP sets out the specific programme of measures to achieve improvements to the water environment, the answer of the question of what these measures will actually look like, or specifically what they will include, is still largely unknown (UK EA, 2005). In addition, EUMS do not know how best to deal with the requirements of the EU WFD (Quevauviller et al., 2005). Similarly, CIS and PRB, playing important roles in coping with coordination problems between EUMS for successful implementation of the EU WFD, do not directly contribute to the development of new methods or tools.

Each EUMS has to work on the better definition and guidance on producing measures for effective water resources management. However, many of the research tasks from the EU WFD are new, and often no useable methodologies exist (Mostert, 2003; Giupponi, 2005). Alternatively, if useable methodologies do exist, these methods are not enough for the implement of the EU WFD. For example, in England and Wales there is already wide ranging legislation to protect and manage the water environment, for instance, to control or prevent water pollution and to control water abstraction. The majority of the 'basic' programme of measures, required under Article 11(3) of the EU WFD can be fulfilled through the implementation of this legislation, but these measures are still not enough for the implement of the EU WFD, especially in handling the ADWP (UK EA, 2005).

As mentioned above, ADWP, an old but the biggest remaining water pollution problem in many countries, is threatening the successful implementation of the EU WFD. Nevertheless, there are not enough efforts made in existing programmes relating to the implementation of the EU WFD in the ADWP field. For example, among 15 finished projects of CATCHMOD in the FP5, only EUROHARP was directly dealing with ADWP problems. HSPF (Barnwell and Johanson, 1981; Nasr et al., 2007), one of the longest history, worldwide used, and comprehensive catchment/watershed hydrology and water quality models, was not evaluated in the EUROHARP project. The ADWP cannot easily be regulated because of its numerous and dispersed sources, complicated pathways that are difficult to be traced, and the high costs of monitoring and enforcement. In addition, whilst farming is the main source of diffuse pollution, it also produces goods. In order to balance the competition between socio-economic and environment for effective ADWP management, it is necessary to have a comprehensive understanding of the ADWP catchment process in specific natural and anthropic activity conditions. Therefore, more effort should be made to develop integrated numeric modelling tools or methods for providing scientific and technique support in handling the ADWP problem and hereby a successful implementation of the EU WFD.

4.2. Research scale gap

The prevention at a catchment scale is the key for handling the ADWP problem in a sustainable manner. In principle, there are two types of control measures for ADWP, namely, preventative and remedial measures. Even though remedial measures, which cannot contribute to reducing contaminates in the source water, may be needed to meet the legislative requirements for drinking water, they are not appropriate for long-term solution of the ADWP problem (Koo and O'Connell, 2006). Once water is contaminated, it will be very costly to clean-up and can take a long time to recover, especially for groundwater (EHS, 2001). In addition, spatial variability and data constraints preclude monitoring all waters and make remediation activities expensive and often impractical (Babiker et al., 2005). Therefore, the prevention of water quality deterioration at source prior to contamination is critical for sustainable water quality management. Since it is difficult to determine at the regional scale the contribution of diffuse agricultural sources to water pollution (Defra, 2002c), water protection practices should be carried out at the catchment or watershed scale. For this reason, the EC Nitrate Directive (91/676) insists that nitrate should be controlled by prevention at source level, i.e. at the catchment scale.

RBMP, utilising the river basin as the natural unit, is helpful to decide the priority of water management at the basin scale. However, the practical control of the catchment ADWP in a river basin needs modelling tools for supporting water pollution prevention at the catchment scale in order to complement the RBMP. Many ADWP studies have been carried out at river basin, national, and even European scales. For example, Giupponi and Vladimirova (2006) developed a screening model (Ag-PIE) for the assessment of pressures from agricultural land use and the consequent impacts on water at the European scale. Each EUMS has carried out water quality studies at the national scale. Within the UK context, the Soil Survey and Land Research Centre (SSLRC – now NSRI) and the British Geological Survey (BGS) generated the England and Wales national series of fifty-three 1: 100,000 groundwater vulnerability maps (Palmer and Lewis, 1998). In Scotland, Association of Directors and River Inspectors of Scotland created Scotland 1: 625,000 groundwater vulnerability maps (ADRIS, 1995). Environment and Heritage Service (EHS) and Department of the Environment, Northern Ireland (DENI) made a Northern Ireland 1: 250,000 groundwater vulnerability map (DENI, 1994; EHS, 2001). Department for Environment, Food and Rural Affairs (Defra), Geological Survey of Northern Ireland (GSNI) , BGS and Scottish Executive developed the maps of groundwater Nitrate Vulnerable Zones (NVZs) for England, Wales, Northern Ireland and Scotland (BGS, 2001; Defra, 2002d; GSNI, 2002). UK Technical Advisory Group (UKTAG) carried out studies of assessing agricultural pressures and impacts risk on water quality at the national scale in the UK (UKTAG, 2004; EHS, 2005). These small-scale ADWP studies are helpful in setting the priority for handling the ADWP at the Europe/national/river basin scales, but have limitation in guiding the ADWP catchment-scale prevention practices, which are important in sustainable management of the ADWP. For instance, according to Jordan and Smith (2005), most of Northern Ireland should be designated as NVZs according to the new demand of the EC. This result is, therefore, helpless for guiding the ADWP prevention at the water source catchments. On the other hand, studies and experiments on the nutrient biochemical processes were largely carried out in the laboratory or at plot scale in the field. This data needs to be extrapolated to determine what is relevant at the catchment scale (UK EA, 2006), and to develop better catchment-scale nutrient cycling models.

4.3. Fundamental knowledge gap

Good scientific understanding of the physical and biochemical processes of diffuse pollutants in the water cycle is essential for guiding the prevention of ADWP at the catchment scale. Currently, there is still limited scientific knowledge of the four-dimensional (i.e. three spatial dimensions plus one time dimension) transport and biochemical transformation processes of diffuse pollutants within and between air, plants, soil, rocks, groundwater and surface water under different conditions of natural and agricultural activities. In the finished cluster of the FP5, no one project focused on the fundamental study of the catchment process of diffuse pollution. For example, the MULINO project developed a DSS tool to assist water authorities in the management of water resources using DPSIR conceptual framework (Drivers – Pressures – State – Impacts – Responses) (Giupponi et al., 2004). The DSS in MULINO is a good tool for the process of decision-making. However, the indicator establishment and building the chains of Drivers – Pressures – State (i.e. conceptual phase, design phase, and choice phase) in MULINO were based on the knowledge of the ADWP processes at that time. In other words, MULINO was limited in improving the scientific understanding of the mechanism of the ADWP catchment process, and in developing better measures for ADWP management. Because of the importance of the fundamental catchment research, the UK Environment Agency (2006) began to treat the "improving scientific knowledge of catchment process" as one of major future tasks of the Integrated Catchment Science (ICS) strategy.

5. Implications for future studies of agricultural diffuse water pollution

Scientists are facing challenges in filling these gaps discussed above for successful implementation of the EU WFD in the ADWP field. Here are some suggestions for meeting these challenges.

5.1. Making best use of existing knowledge of the ADWP process

It is necessary to develop integrated and pragmatic catchment-scale modelling methods or tools to support the decision-making of the ADWP management in a sustainable manner, by selecting, evaluating, and integrating the existing methods and tools based on current scientific understanding of the mechanisms of the ADWP catchment process. Recently, more and more attention has been paid to the research of catchment-scale water pollution process. For example, although the CATCHMOD cluster in the FP5 was mainly focusing on the research for the integrated management of water at river or sub-basin scales, there were several projects based on catchment-scale, such as GOUVERNE (GOUVERNE Consortium, 2003), MULINO (MULINO project, 2006) and TempQSim (TempQSim project, 2006). UK EA has been developing the strategy of solving environmental problems using the ICS. The MAGPIE tool was developed to calculate total nitrate leaching losses from all agricultural activities (Lord and Anthony, 2000). Many tools for nutrient process in the water and land phases were developed, such as ANIMO (Groenendijk and Kroes, 1999), INCA (Whitehead et al., 2006), HSPF, SWAT (Arnold et al., 1998), and SHETRAN (Ewen, 1995). The PLANET tool was developed by UK Defra, EA and the Department for Agriculture and Rural Development in Northern Ireland (DARDNI) for farmers to build a nutrient and manure application plan in a group of fields. The ongoing catchment sensitive farming programme is trying to work with stakeholders to develop an effective package of good farming practices to tackle the ADWP. However, separately, these tools or studies can not describe the complicated ADWP catchment process involving many factors in multi-spheres. The sustainable management of the ADWP needs integrated numeric models or methods covering the phases of source – pathways – targets at the catchment scale. The existing ADWP studies provide a good start for developing such kind of numeric tools or methods for modelling the catchment-scale ADWP processes. For example, the HSPF model, capable of investigating the fate and distribution of nitrogen in the aquatic and terrestrial environment, could be a platform for integrated study of the ADWP catchment process by introducing the functions of groundwater pollution risk assessment and groundwater simulation.

Based on the existing scientific knowledge of the ADWP processes, many measures of dealing with the ADWP problem, such as land use change, best management practices (BMP), contaminated water remediation and drinking water treatment, were developed. The effective and efficient application of these measures depends on good understanding of the ADWP processes under specific conditions. Nevertheless, the general knowledge of the ADWP mechanisms can not be universally applied, thus causing problem – each EUMS has difficulties in choosing and applying these measures in different catchments in different countries due to significant varying situation, i.e. land use, climate, agriculture activity, soil, topography, hydrogeology conditions and the sensitivity of particular water bodies to pollution. Therefore, it is necessary to develop the integrated, catchment-scale and modelling-based decision-support tools or methods helping people to choose measures accordingly by providing the scientific evidences of the particular mechanisms of the ADWP processes in specific catchments.

An integrated ADWP modelling method or tool consists of hydrological, hydrogeological, and nutrient biochemical cycle in soil, with impact from and to atmospheric and biological elements. It is fundamental to study the vulnerability of groundwater and its pollution pathway, groundwater risk, water and nutrient dynamic nature with surface runoff and interflow, the interaction between soil water and groundwater, and the soil process in connection to stream water process. It is worth noting that the integrated modelling method or tool should be able to evaluate the impacts of land use change, agricultural activity change, best management practices, and climate change on water quantity and quality, in order to support effectively and efficiently the decision-making of the ADWP management at the catchment scale. In addition, the accuracy, uncertainty, and transferability need to be considered in developing such new numeric modelling tools.

5.2. Developing innovative measures for the ADWP management

As mentioned above, many studies have been carried out in the fields of groundwater risk assessment, groundwater simulation, contaminated groundwater remediation, nutrient biogeochemical cycle, surface water modelling, nutrient control economic analysis, and ADWP handling measures. However, the successful implementation of the EU WFD needs count on not only applying existing methods, but also more importantly on developing methods for tackling ADWP. It was from the 1970's and early 1980's that scientists have been developing and updating methods to solve the ADWP problem. However, ADWP remains an important issue in resolving water pollution problems demanded by the EU WFD. Therefore, it is necessary to carry out comprehensive research in developing and testing innovative numeric modelling methods and engineering measures for pragmatic and sustainable management of the ADWP problem before 2015. This demands better scientific understanding of water cycle within and between atmosphere, geosphere, hydrosphere and biosphere; and of the pollutant process of biochemical transformation and physical transport in the complete hydrological cycle. Thus, more multi-disciplinary or inter-disciplinary fundamental studies of the ADWP catchment-scale processes are needed to find key driving forces controlling the processes. For example, better understanding of the impacts of land use, soil type, agricultural activity, and climate change on water cycle and nutrient processes is indispensable for finding unconventional measures to maximise soil nutrient availability to plants and minimise soil nutrient movement to watercourse without or with fewer side effects to ecosystem.

5.3. Information system

The implementation of the EU WFD is a challenge for the support of a WFD-specific information management. With advantages of spatial data management, analysing and visualisation, Geographic information system (GIS) has been used worldwide and approved to be a powerful tool for water resources management, which is an inherent four-dimensional geographical activity requiring handling of multiple forms of spatial data. WebGIS, developing GIS functionality in the internet to make distributed geographic information available to a very large worldwide audience through web browsers, can greatly contribute to the data and knowledge transfer of handling ADWP, efficient online management for governments and public participation, and the collaboration between researchers, policy makers and the community demanded by the EU WFD. In addition, a central multi-sphere catchment-scale GIS database in a WebGIS based framework of information management in a EUMS can greatly facilitate ADWP studies in this country.

6. Conclusions

The ADWP problem is one of the major threats for the successful implementation of the EU WFD. In handling ADWP, scientists are facing the challenges of bridging the gaps of "method and tool", "research scale", and "fundamental knowledge" to meet the water quality requirements of EU WFD by 2015. By making best use of existing knowledge of the ADWP process, it is timely to develop integrated catchment-scale numeric modelling tools or methods to study the complete hydrological and pollutants cycles within and between atmosphere, hydrosphere, geosphere, and biosphere, thus supporting the sustainable management of ADWP at the catchment scale. To solve the ADWP problem realised several decades ago, it is necessary to carry out more multi-disciplinary or inter-disciplinary fundamental studies of mechanisms of the complex ADWP catchment processes and its controlling factors, thus supporting the development of innovative and pragmatic measures for handling ADWP. GIS and WebGIS can play useful roles in the ADWP research.

Chapter 3

The roles of GIS and Arc Hydro model in developing the integrated modelling method for catchment-scale water quality management [*]

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Abstract

It is necessary to develop an integrated modelling method to support the decision-making of sustainable management of the agricultural diffuse water pollution (ADWP) at the catchment scale. This paper describes the roles of the Arc Hydro model and Geographic Information System (GIS) platform in developing such kind of integrated catchment-scale modelling method, by testing them in the Upper Bann Catchment, Northern Ireland. Results showed that ArcGIS and Arc Hydro model, consisting of data mining, hydrological analysis, and visualisation modules, can provide data support and powerful spatial analysis functions, thus facilitating the development and applying the integrated catchment ADWP modelling approach which can provide quantitative understanding of the mechanism of ADWP for both groundwater and surface water in a specific catchment; and can evaluate the impacts of the policies of the ADWP management on water quality and quantity at the catchment scale.

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[*] J.L. Wang is the senior author
This paper has not been submitted

Keywords: Agriculture diffuse water pollution; Catchment scale; Arc Hydro; GIS; Groundwater vulnerability; EU Water Framework Directive

1. Introduction

Both ground and surface water are indispensable in human's living and social development. Water pollution is not only an environmental issue but also an economic and human health problem. Since diffuse pollution is more complex and more difficult to control compared with point water pollution, so far it is the biggest remaining problem of water pollution in the world (Campbell et al., 2004). Among diffuse water pollution sources, the single and biggest threat is from agriculture. For example, it is estimated that in England over 70% of nitrates in natural waters are derived from agricultural land (Defra, 2002a). Agriculture diffuse water pollution (ADWP) has been realised as a main threat for water quality and the implementation of the EU Water Framework Directive (WFD) (EHS, 2000; DoE & DARD UK, 2003; Ferrier et al., 2004; Torrecilla et al., 2005).

Once water is contaminated, it will be very costly to clean-up and can take a long time to recover, especially for groundwater (EHS, 2001). For instance, the UK approximate annual costs of treating drinking water for pesticides are about £120 million, for phosphate and soil about £55 million, for nitrate around £16 million and for microorganisms around £23 million (Pretty et al., 2000). Therefore, compared with water remediation, the prevention of water quality deterioration at source before it can cause contamination is critical for the handling of the ADWP problem in a sustainable way. Since it is difficult to determine at the regional scale the contribution of diffuse agricultural sources to water pollution (Defra, 2002c), water protection practices should be carried out at catchment or watershed scale. For successful ADWP prevention at the catchment scale, it is necessary to develop methodologies or tools that support the decision making of the ADWP sustainable management at any specific catchment by considering both the risk assessment of the groundwater and surface water pollution. This demands that pragmatic and easily applicable tools and models should be developed or assessed to support the development of such a catchment-scale integrated modelling method. The development of such kind of integrated ADWP modelling method is a multi-disciplinary study that should consider the hydrology, hydrogeology, nutrient biochemical processes, and their mutual complex interactions, thus demanding the intensive support of data and spatial analysis functions. Therefore, it is necessary to select and test suitable powerful models or tools to facilitate the developing and applying of the integrated modelling approach of catchment ADWP processes.

This paper adopts and tests the Arc Hydro model and Geographic Information System (GIS) in the Upper Bann Catchment; and demonstrates their roles of data and spatial analysis function supports in the development of the integrated modelling method for supporting the decision-making of the catchment-scale ADWP sustainable management.

2. Methods

2.1. Study area

The Upper Bann Catchment, covering an area of 674 km^2, lies in the southeast of Northern Ireland (Fig. 3.1). The study area has a mean annual rainfall of 995 mm and a mean annual potential evapotranspiration 516 mm. Average altitude in the study area is 110 m. The steepest area is located in the Mourne Mountains to the southeast; steeper areas are found at the source of the Cusher River to the southwest and Slieve Croob to the east of the study area. The topography gently undulates throughout the

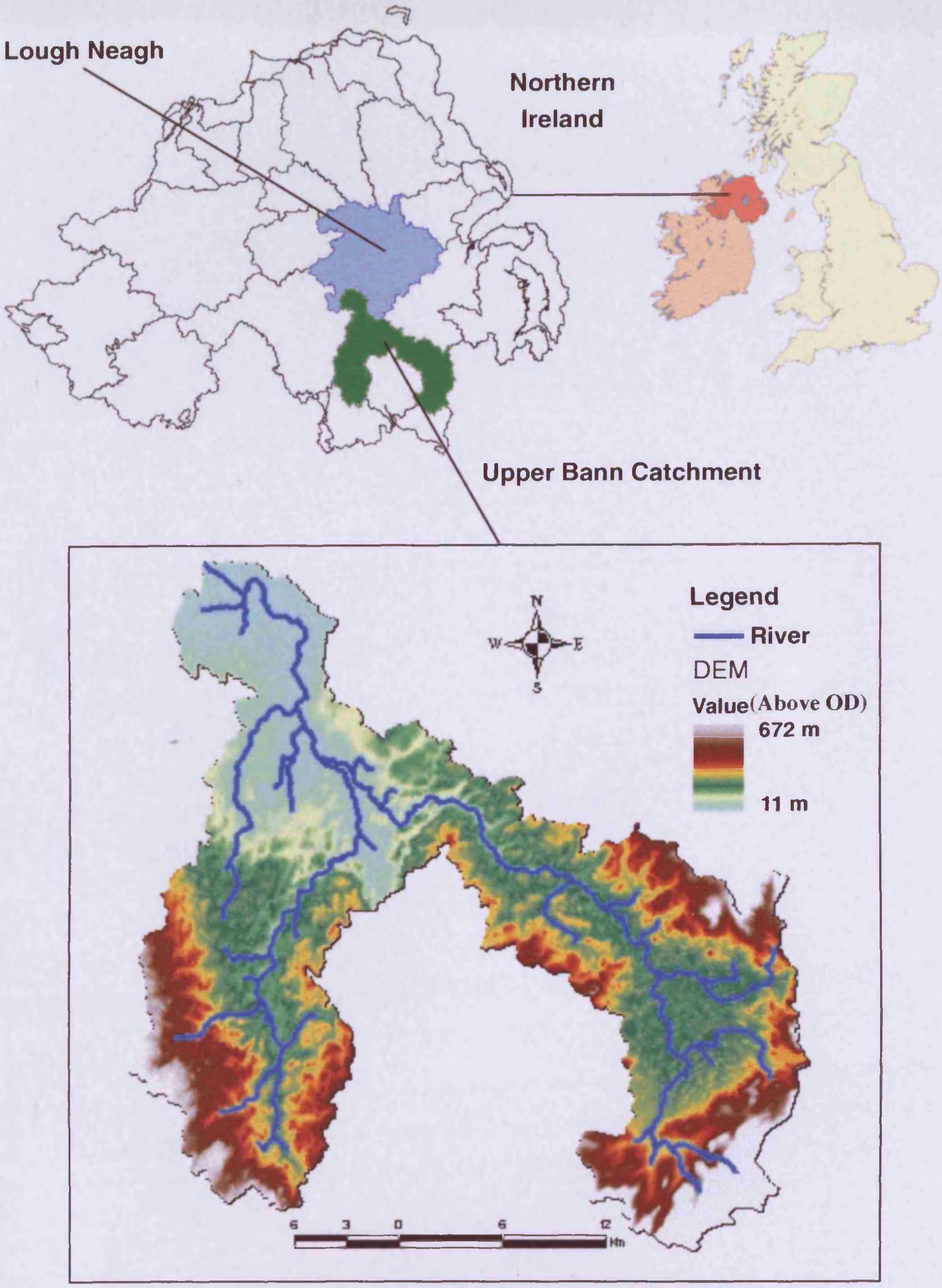


Fig. 3.1. The location of the Upper Bann Catchment in Northern Ireland

rest of the study area, rising from 11 m above OD at Lough Neagh to a maximum of 672 m above OD in the Mourne Mountains. Upper Bann is a complex rural catchment with a wide range of land uses, including fruit growing, livestock farming, arable farming and urbanisation. Agriculture land accounts for 92.9% of the study area, dominated by grassland (76.3%) and arable land (10.2%) with some woodland (6.5%).

In Northern Ireland, surface water is the dominant source of public water supply with groundwater estimated to provide only 8% of the total public water supply. Despite the small direct contribution to public supply, groundwater still has an important role to play because of its contribution to the baseflow of surface water, where most of public supply originates; and is widely used as sources of private supply. Therefore, both surface water and groundwater are vital to social and economic development throughout the rural community. The river quality monitoring data (1991 and 1995) shows the deterioration in River Bann's quality. It has been identified that diffuse contributions from agriculture are the primary cause of the current water quality problem in the study area. The area contains Upper River Bann, which is the largest river that supplies Lough Neagh - predominant inland water situated centrally in the country with total area of 388 km^2. According to Lough Neagh & Lower Bann Advisory Committees, the dramatic nutrient enrichment in Lough Neagh, which occurred in the 20th Century, had been the result of increased nutrients coming both from urban and agricultural sources. While the nutrients from urban sources have decreased appreciably since 1986, the diffuse agricultural nutrient inputs to Lough Neagh have continued to increase. The ADWP management in the Upper Bann Catchment is significant for water quality control in Lough Neagh.

The details of the conditions of the study area are given in appendix A.

2.2. Geography Information System

The modelling of whole catchment ADWP processes, which needs multi-sphere data, i.e., hydrosphere, geosphere, and biosphere data, is an inherent geographical activity requiring handling of multiple forms of spatial, temporal, and attribute data. GIS is an ideal tool for this purpose because of its advantages of spatial data management, analysis, and visualisation. In addition, as a general spatial analysis platform, GIS is extensible for modellers to develop models according to their specific requirements. ArcGIS 9.0 platform was chosen in this study. Arc Hydro dataset is the base of hydrological spatial analysis. The study area DEM data (50m×50m) obtained from Environmental Heritage Service (EHS) was input into the ArcGIS.

2.3. Arc Hydro

The Arc Hydro model, consisting of data model and toolsets, was developed to support water resources applications and provide a starting point for water resources database and application development (Maidment, 2002). The Arc Hydro data model can be defined as a geographic database containing a GIS representation of a hydrological information system. This data model takes advantage of the next generation of spatial data model – geodatabase, a combination of GIS objects enhanced with the capabilities of a relational database to allow for relationships, topologies, and geometric networks. The Arc Hydro toolset is a suite of tools, which facilitate the creation, manipulation, and display of Arc Hydro features and objects within a GIS environment. The tools provide raster, vector, and time series functionality, and many of them populate the attributes of Arc Hydro features. There are four methods for linking water management models with GIS, i.e., loose coupling, tight coupling, embedding GIS functionalities into a hydrological model, and embedding a hydrological model into GIS (He et al., 2001; Shen et al., 2005). The Arc

Hydro model belongs to 'embedding a hydrological model into GIS' using of existing GIS spatial analysis functions.

2.4. Arc Hydro Data Model

The arc Hydro data model, describing spatial and temporal data on surface water resource features of the landscape, addresses three issues, i.e. hydro description, hydro connectivity, and hydro modelling. Hydro description shows what the principal water resource features of the landscape are; Hydro connectivity describes ways water moves from feature to feature; and hydro modelling simulates the time patterns of water flow and water quality associated with these features. The Arc Hydro data model consists of five components, i.e. Network, Drainage, Channels, Hydrography and Time Series. The Network component contains a water resources network of streams, rivers and the centerlines of water bodies to describe the connectivity of water movement through the landscape. The Drainage component defines drainage areas delineated through the analysis of land surface topography. The Channel component describes the three-dimensional shape of river and stream channels. The Hydrography component contains base map information on point, line and area water resource features. The Time Series component describes time varying water property of the features.

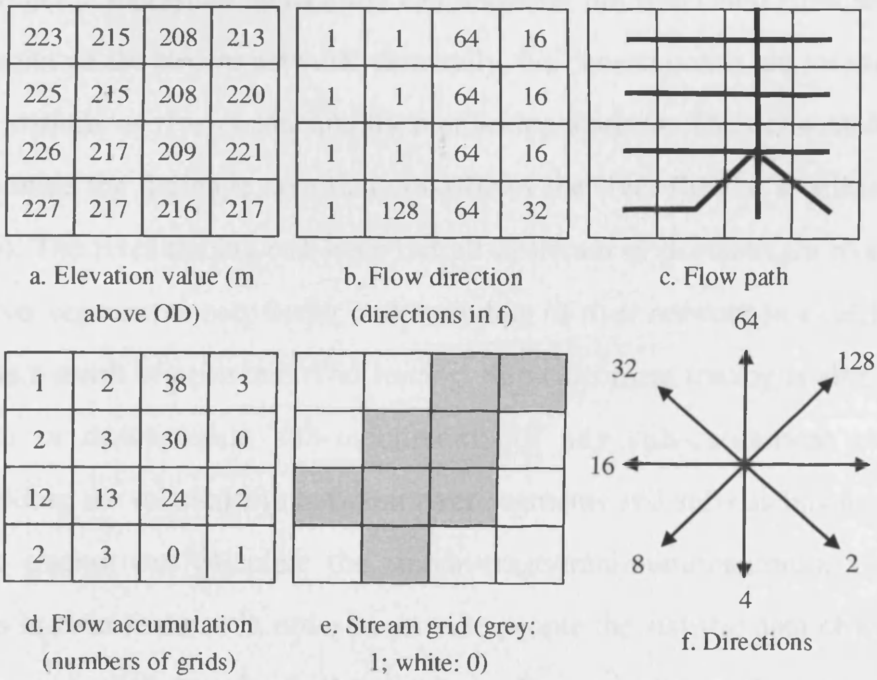
An Arc Hydro geodatabase consists of Hydro Features connected to Time Series. Hydro Features describe the physical environment through which water flows, while the Time Series describe the flow and water quality properties of the water within those features. Within an Arc Hydro geodatabase, Every Hydro Feature is identified using a unique identification - HydroID. The linkage between Hydro Features is formed using topology information stored in their attribute database. These linkages can be used to trace water movement from one feature to the next, and to associate several different spatial representation of the hydrologic entity with one another. Hydro Features are connected to Time Series by storing a HydroID as an attribute of each data value of time series (Maidment, 2002).

2.5. Terrain Pre-processing in GIS

The purpose of terrain pre-processing is to perform an initial analysis of the terrain and to prepare the dataset for further hydrological modelling. A Digital Elevation Model (DEM), a grid in which each cell is assigned the average elevation on the area represented by the cell, is required as input for terrain pre-processing. Terrain Pre-processing contains the following functions: DEM Reconditioning, Fill Sinks, Flow Direction, Flow Accumulation, Stream Definition, Stream Segmentation, Catchment Grid Delineation, Catchment Polygon Processing, Drainage Line Processing, Adjoint Catchment Processing, Drainage Point Processing, Longest Flow Path for Catchments, Longest Flow Path for Adjoint Catchments, Slope, Slope greater than 30 and facing North, and Weighted Flow Accumulation.

Employing the AGREE method, DEM Reconditioning adjusts the surface elevation of the DEM to be consistent with a vector coverage. The vector coverage can be a stream or ridge line coverage. The details of AGREE method are provided at the website http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html. If a cell is surrounded by higher elevation cells, the water is trapped in that cell and cannot flow. These problems can be eliminated using the Fill Sinks function to modify the elevation value. Flow Direction creates flow direction grid from a DEM grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell (Fig. 3.2-b). The flow path (Fig. 3.2-c) can be derived from flow direction. Flow Accumulation computes the associated flow accumulation grid that contains the accumulated number of cells upstream of a cell in a flow direction grid

(Fig. 3.2-d). Stream Definition creates a stream grid with cells from a flow accumulation grid that exceed the user-defined threshold of the number of accumulation grids (Fig. 3.2-e). Stream Segmentation creates a stream link grid from the stream grid. Every link between two stream junctions gets a unique identifier. Catchment Grid Delineation creates a grid in which each cell carries a grid value indicating to which catchment the cell belongs. Drainage Line Processing converts the input Stream Link grid into a Drainage Line feature class. Each line in the feature class carries the identifier of the catchment in which it resides. Adjoint Catchment Processing generates the aggregated upstream catchments from the "Catchment" feature class. For each catchment that is not a head catchment, a polygon representing the whole upstream area draining to its inlet point is constructed and stored in a feature class that has an "Adjoint Catchment" tag. This feature class is used to speed up the point delineation process. Weighted Flow Accumulation creates weighted flow accumulation grid from a flow direction grid and a weight grid.



223	215	208	213
225	215	208	220
226	217	209	221
227	217	216	217

a. Elevation value (m above OD)

1	1	64	16
1	1	64	16
1	1	64	16
1	128	64	32

b. Flow direction (directions in f)

c. Flow path

1	2	38	3
2	3	30	0
12	13	24	2
2	3	0	1

d. Flow accumulation (numbers of grids)

e. Stream grid (grey: 1; white: 0)

f. Directions

Fig. 3.2. The protocol of the flow processing based on DEM

3. Results and discussions

The GIS Arc Hydro model set up for the Upper Bann Catchment consists of three main modules, namely, data mining, hydrological analysis, and visualisation (Fig. 3.3). Data mining module was used in the establishment of the multi-sphere GIS database of the study area. For example, catchment and sub-catchment boundaries, the drainage areas of water quality monitoring points, flow direction, flow accumulation, stream network and topography slope were derived from the DEM data in the study area. Hydrological analysis module includes spatial functions of the point watershed delineation, river tracing, flow path tracing, sub-catchment tracing, and river attribute calculation, etc. Visualisation module is able to visualise two-dimension, two-dimension plus time series, and three-dimension data.

The flow path tracing function traces the flow path from any point in the study area to its outlet, and geographically tells users where water goes in the study catchment (Fig. 3.4). The point watershed delineation can delineate the watershed from an arbitrarily chosen point on the stream network. Generally, the chosen points are locations of river gauging stations or river water quality monitoring stations. The delineated watershed can determine the drainage area that contributes the river flow at a delineation point (Fig. 3.5). The river tracing can trace out all upstream or downstream river segments of any river segment to help better understanding of river network in a catchment. Fig. 3.6 shows a result of upstream river tracing. Sub-catchment tracing is able to trace all upstream or downstream sub-catchments of any sub-catchment to help the understanding the relationship between river segments and sub-catchments (Fig. 3.7). Attribute tracing can calculate the sum/average/minimum/maximum value of the attributes in river features in order to provide people the statistic data of hydrological condition in a catchment for further analysis. For example, total upstream drainage area or stream length can be calculated. The function of "two-dimensional data plus

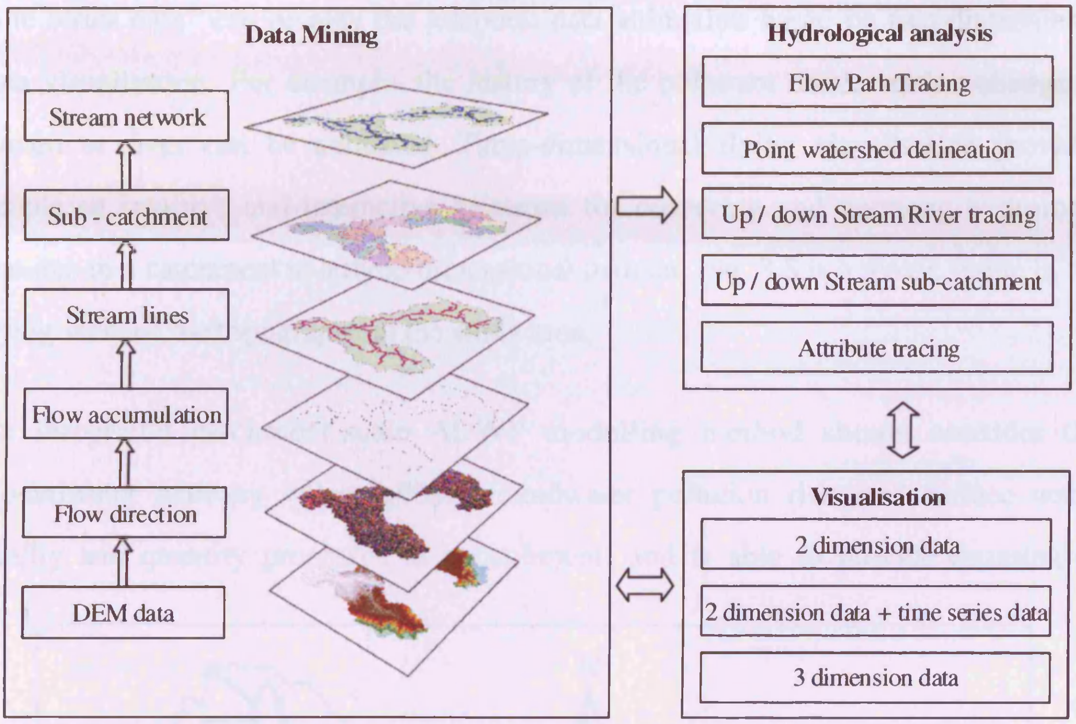


Fig. 3.3. The structure of the GIS Arc Hydro model in the study area

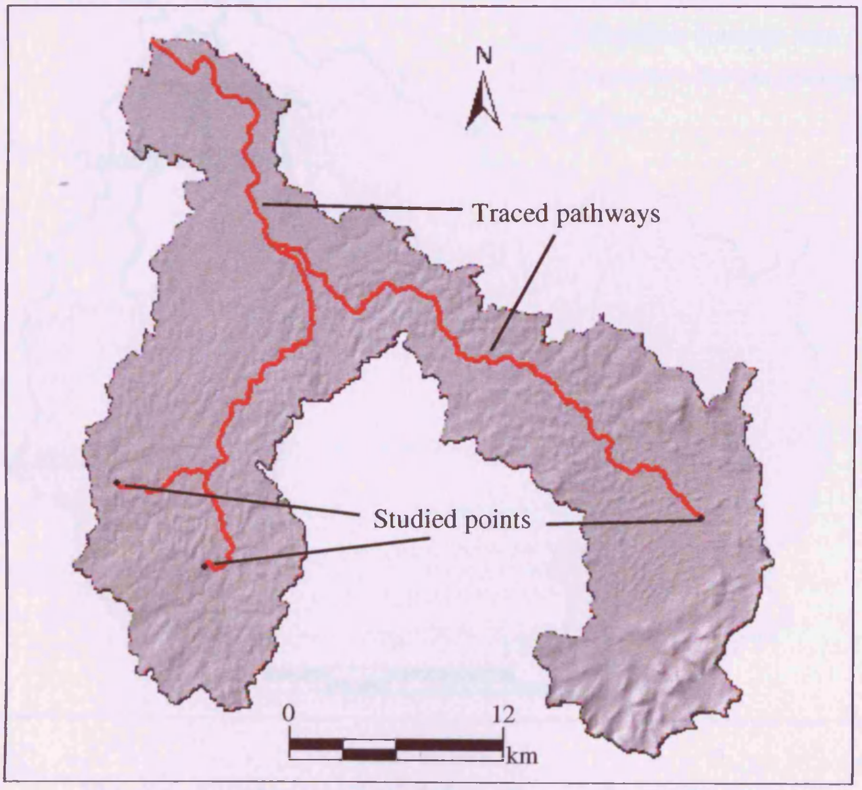


Fig. 3.4. Flow path tracing in the study area

time series data" can display the temporal data animation based on two-dimensional data visualisation. For example, the history of the pollutant concentration change in stream or river can be animated. Three-dimensional flying visualisation provides people an intuitive and interactive measures for observing and querying hydrologic features in a catchment in a three-dimensional manner. Fig. 3.8 is a movie frame in the flying view of the topography in the study area.

An integrated catchment-scale ADWP modelling method should consider the groundwater pathway vulnerability, groundwater pollution risk, and surface water quality and quantity processes in a catchment; and is able to provide quantitative

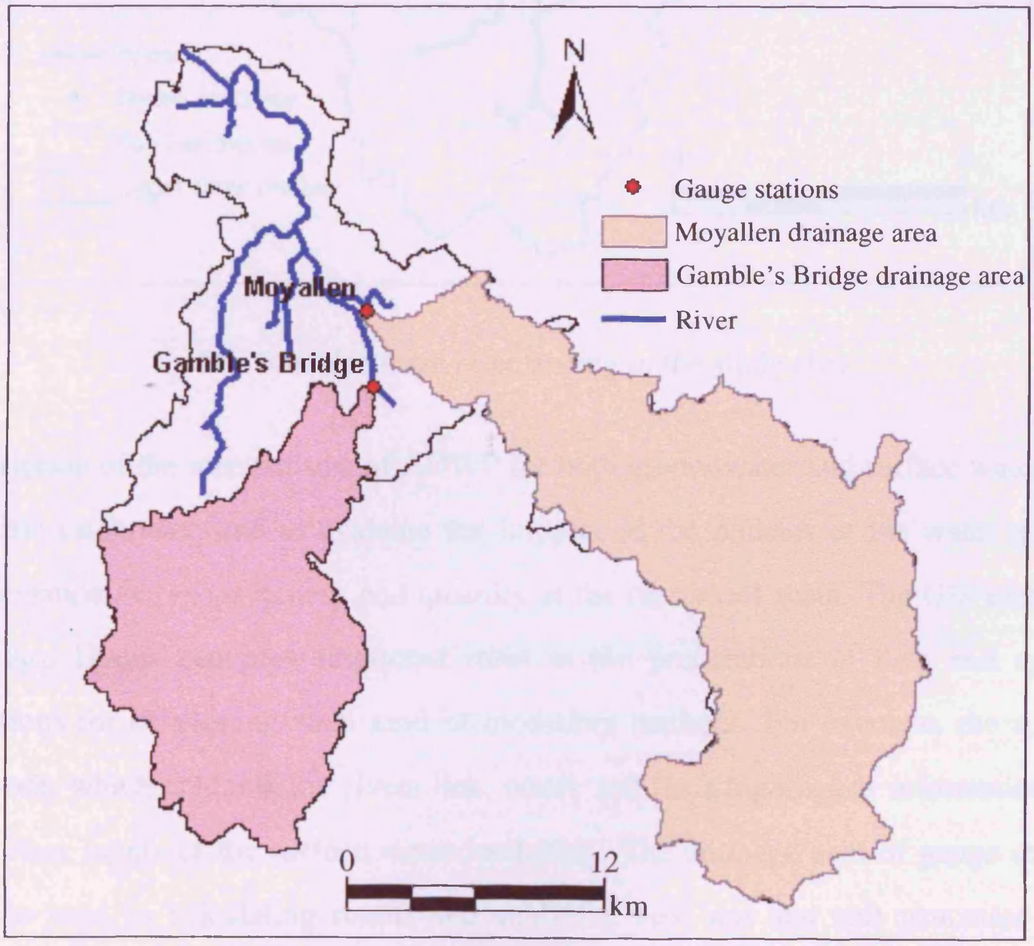


Fig. 3.5. Point watershed delineation in the study area

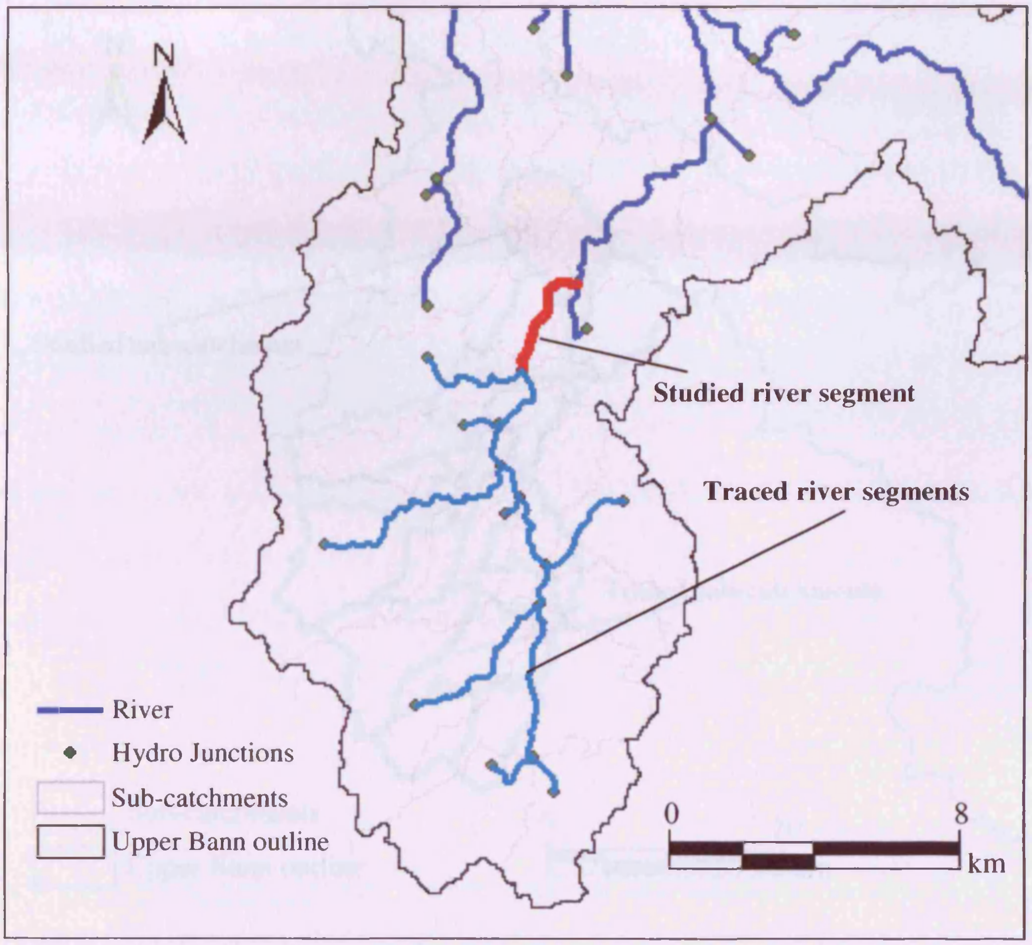


Fig. 3.6. Upstream river tracing in the study area

description of the mechanisms of ADWP for both groundwater and surface water in a specific catchment, and to evaluate the impacts of the policies of the water quality management on water quality and quantity at the catchment scale. The GIS platform and Arc Hydro can play important roles in the preparations of data and spatial functions for developing such kind of modelling methods. For example, the stream network, which contains the rivers link, nodes and their topological information are important inputs of the surface water modelling. The drainage area of gauge station can be used in calculating runoff and analysing land use and soil structures in a drainage area that contribute to the variations of the pollutant concentration at the gauge station. It is worth noting that the function of "weighted flow accumulation" is

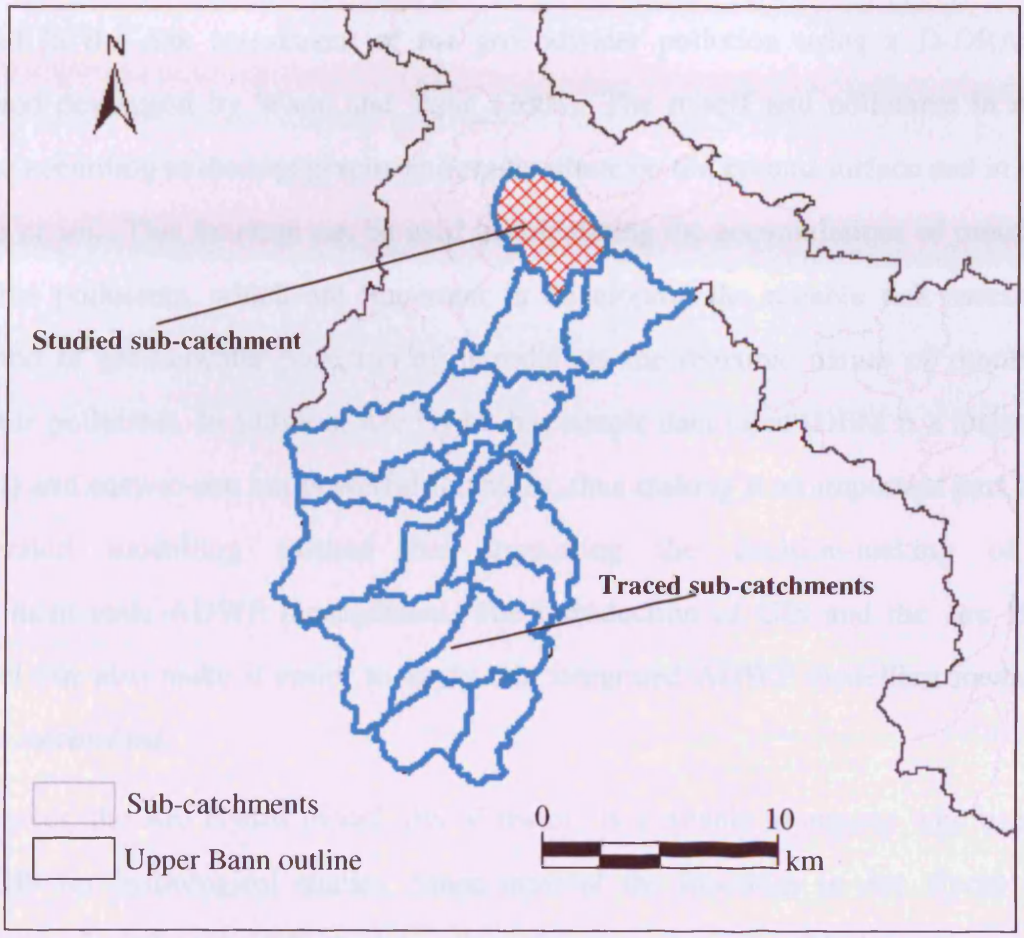


Fig. 3.7. Upstream sub-catchment tracing in the study area

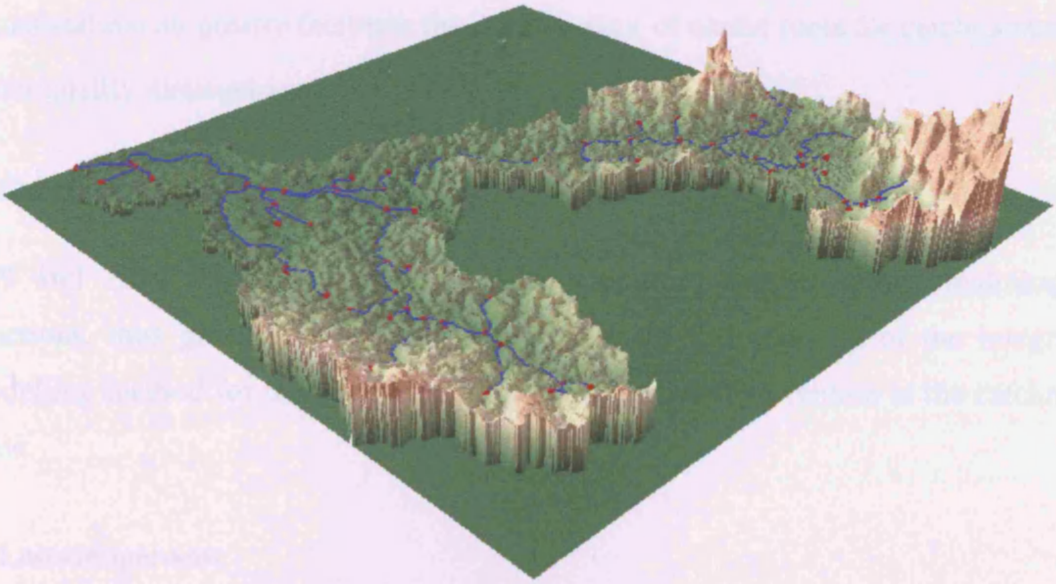


Fig. 3.8. The three-dimensional flying view of the topography in the study area

useful in the risk assessment of the groundwater pollution using a D-DRASTIC method developed by Wang and Yang (2008). The runoff and pollutants in runoff move according to the topography and re-distribute on the ground surface and in upper layer of soil. This function can be used in calculating the accumulations of runoff and soluble pollutants, which are important in developing the reliable risk assessment method of groundwater pollution by introducing the dynamic nature of runoff and soluble pollutants. In addition, Arc Hydro has simple data input (DEM is a major data input) and easy-to-use but powerful functions, thus making it an important part in the integrated modelling method for supporting the decision-making of the catchment-scale ADWP management. The introduction of GIS and the Arc Hydro model can also make it easier to apply this integrated ADWP modelling method in other catchments.

Moreover, the Arc Hydro model, free software, is available to anyone who uses the ArcGIS for hydrological studies. Since most of the functions in Arc Hydro were developed based on ArcGIS modules, these functions are extensible in water resource research. Powerful GIS functions of the spatial data management, analysis and visualisation can greatly facilitate the development of useful tools for catchment-scale water quality management.

4. Conclusion

GIS and ARC Hydro can provide data support, powerful spatial hydrological functions, thus greatly facilitating the development and applying of the integrated modelling method for the decision-support of the ADWP prevention at the catchment scale.

Acknowledgement

The authors wish to acknowledge the assistance of the EHS for providing DEM data.

Chapter 4

Assessing groundwater pollution vulnerability in the Upper Bann Catchment of Northern Ireland *

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Abstract

The catchment-scale groundwater vulnerability assessment that delineates zones representing different levels of groundwater susceptibility to contaminants from diffuse agricultural sources has become an important element in groundwater pollution prevention for the implementation of the EU Water Framework Directive (WFD). This paper aims at assessing groundwater vulnerability in the Upper Bann Catchment, Northern Ireland using the DRASTIC model on an ArcGIS platform. Groundwater vulnerability maps of both general pollutants and pesticide in the study area were generated by using data of depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity. The mountain areas in the study area have 'high' (4.5% of the study area) or 'moderate' (25.5%) vulnerability for general pollutants due to high rainfall, net recharge and soil permeability. However, by considering the diffuse agricultural sources, the mountain areas are actually at low groundwater pollution risk. The results of overlaying the maps of land use and the groundwater vulnerability are closer to the reality. This study shows that the results of DRASTIC are helpful for guiding the prevention practices of groundwater pollution at the catchment scale. However, DRASTIC does not consider the risk concept. GIS can greatly facilitate the application of the DRASTIC model.

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* J.L. Wang is the senior author
This paper has not been submitted

Keywords: DRASTIC; Groundwater vulnerability; Agriculture diffuse groundwater pollution; Catchment scale; Geographic Information Systems; EU Water Framework Directive

1. Introduction

Groundwater, making up almost the entire volume of the earth's usable fresh water apart from the water frozen in ice caps, glaciers and permanent snow, plays an important role in maintaining life and social development. For example, groundwater provides a third of drinking water in England and Wales; 30.3% population in Canada and 50 % population in United States depend on groundwater for domestic use. In comparison with point source groundwater pollution, diffuse agricultural source groundwater pollution is more complex and difficult to control, and is not only a serious environmental issue but also an economic and human health problem. For example, groundwater with high concentration of nutrients (nitrogen and phosphorus) could flow into surface water in the form of baseflow and cause eutrophication in rivers, lakes and estuaries by igniting huge algae and phytoplankton blooms, and depleting oxygen in water. In the Mississippi, such blooms are now leading to so-called "dead zones", where the death of the algae means all the oxygen in the water is used up, killing fish and other aquatic life. Nitrogen cycling can produce large amounts of the powerful greenhouse gas 'nitrous oxide'. The approximate annual costs in the UK of treating drinking water for pesticides are about £120 million, for phosphate and soil about £55 million, for nitrate around £16 million and for microorganisms around £23 million (Pretty et al., 2000). Nitrate concentrations in excess of 10 mg/L in drinking water may reduce the ability of human blood to carry oxygen and, in the very young, cause 'blue baby syndrome' (USDA, 1991; Matson et al., 1997). A potential cancer risk from nitrate (and nitrite) in water and food has been reported (Rademaher et al., 1992; Yang et al. 2007).

Once groundwater is contaminated, it will be very costly to clean-up and may take a long time to recover (EHS, 2001). Moreover, spatial variability and data constraints preclude monitoring all waters and make remediation activities expensive and often impractical (Babiker et al., 2005). Therefore, the measures of the groundwater pollution prevention before the happening of pollution, contributing to reducing contaminates in the source water, are more feasible and effective than water remedial measures (Koo and O'Connell, 2006). In agricultural diffuse groundwater pollution (ADGWP), it is hard to tell where the pollutants exactly come from. Thus, compared with ADGWP, the prevention of groundwater contamination from point sources, such as, storage tanks, septic systems, hazardous waste sites, landfills and factories, will be easier. Because of the fact that it is difficult to determine at the regional scale the contribution of diffuse sources to water pollution (Defra, 2002c), groundwater protection practices should be carried out at the catchment or watershed scale. Groundwater vulnerability assessment, which is capable of delineating zones that are more susceptible to pollutants from diffuse agricultural sources at the catchment scale, is important for guiding the prevention activities of the ADGWP.

This study aims at: 1) assessing groundwater pollution vulnerability in a catchment dominated by agricultural land use – the Upper Bann Catchment of Northern Ireland, using of Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and aquifer hydraulic Conductivity factors using DRASTIC, an index model developed by the U.S. Environmental Protection Agency (EPA) (Aller et al., 1987); and 2) introducing Geographic Information System (GIS) in the application of DRASTIC.

2. Background

The term vulnerability of groundwater, introduced by the end of 1960s, means the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system, and constitutes the susceptibility of groundwater to contamination by surface, or near surface pollutants (Vrba and Zoporozec, 1994; Palmer et al., 1995). Many approaches have been developed for groundwater vulnerability assessment. So far, there are four types of methods for the groundwater vulnerability assessment (Zhang, 1996; Worrall and Besien, 2005; Wang and Yang, 2008): 1) Modelling approaches use the physical process based simulation models to estimate approximately the contaminant transport. However, insufficient data and computational burden generally preclude their application (Barbash and Resek, 1996; Thapinta and Hudak, 2003). 2) Observation based methods generate groundwater vulnerability maps based on the observed contaminations. Due to neglecting complex polluting pathways from the ground surface to groundwater, their results are helpful for contaminated groundwater remediation but can help less in guiding the groundwater pollution prevention activities. 3) Statistical methods use statistics to correlate spatial variables with actual occurrence of pollutants in groundwater. Their limitations include insufficient water quality observations, data accuracy and careful selection of spatial variables (Babiker et al., 2005). 4) Index methods combine the factors controlling the pollutant transport from the ground surface into the saturated zone resulting in spatial distributed vulnerability indices. Their major drawback is the subjectivity in the factor weighting and numerical value assignation. However, the index methods possess below advantages: i) the factors such as rainfall and depth to groundwater can be available over large areas, which makes them suitable for regional scale assessments (Thapinta and Hudak, 2003); ii) it's easy to understand and apply the index methods.

Within the UK context, many groundwater pollution potential studies have been carried out. Fifty-three 1:100,000 scale groundwater vulnerability maps in England and Wales (Palmer and Lewis, 1998), 1:625,000 scale groundwater vulnerability map in Scotland (ADRIS, 1995), and Northern Ireland 1:250,000 scale groundwater vulnerability map (DENI, 1994; EHS, 2001) were produced using index methods; the maps of groundwater Nitrate Vulnerable Zones (NVZs) for England, Wales, Northern Ireland and Scotland (BGS, 2001; Defra, 2002d; GSNI, 2002) were developed; and studies assessing agricultural pressures and impacts risk on water quality at national scale in UK (UKTAG, 2004; EHS, 2005) was carried out. These multi-basin or national scale studies are helpful for setting the priority of groundwater pollution protecting work, but have limitations in guiding the prevention practices of ADGWP at the catchment scale. UK's index methods used for groundwater vulnerability assessment consider only few factors (such as overlying soil cover, the presence and nature of the drift, the nature of strata, and the thickness of the unsaturated zone), leading to high uncertainty in the result (Palmer et al., 1995; Palmer and Lewis, 1998; Giupponi and Vladimirova, 2006).

3. Study area

The Upper Bann Catchment, Northern Ireland is the study area in this study. The details of the conditions of the study area are given in appendix A.

4. Methods

4.1. DRASTIC

The DRASTIC method, one of index methods, is a numerical ranking composite description of all the major geological and hydrological factors that affect and control the groundwater movement into, through, and out across the vertical profiles of an area. With the intrinsic meaning of the groundwater pollution vulnerability, DRASTIC has 7 factors: 1) 'Depth to water', the depth to aquifer from the ground surface, determines the medium depth through which pollutants travel before reaching the aquifer. 2) 'Net recharge', the amount of water that penetrates the ground surface and reaches the water table, acts as a principle vehicle for transporting pollutants to the water table through the leaching process. 3) 'Aquifer' refers to the saturated zone material properties and controls the pollutant permeability and attenuation processes. 4) 'Soil media', the uppermost weathered portion of the unsaturated zone characterised by significant biological activity, controls the amount of recharge that can infiltrate downward. 5) 'Topography', the slope of the land surface, dictates the likelihood that runoff will remain on the surface to allow contaminant percolation to the saturated zone. 6) 'Impact of vadose zone' represents the type of material in the zone above the water table and below the typical soil horizon, which controls the passage and attenuation of the contaminated material to the saturated zone. 7) 'Hydraulic conductivity of the aquifer' indicates the ability of the aquifer to transmit water, hence determines the rate of the flow of contaminant material within the groundwater system. Since the importance of these factors in groundwater pollution process are different, each factor was assigned by a relative weight ranging from 1 to 5 determined using a Delphi (consensus) approach. The detailed weighting process of DRASTIC can be found in Aller et al. (1987). The most significant factor has a weight of 5 and the least significant has a weight of 1.

The involvement of multi-sphere factors, i.e., hydrosphere, atmosphere, and geosphere makes the ADGWP vulnerability assessment an inherent geographical activity requiring handling of multiple forms of spatial data. With the advantages of spatial data management, analysis, and visualisation, ArcGIS 9.0 was adopted for the DRASTIC method in the data preparation, and the mathematic calculation of the raster data layers. The definition of DRASTIC index in GIS was adapted (Eq. 4.1) from the original definition of Aller et al. (1987).

$$DVI_i = D_{iw}D_{ir} + R_{iw}R_{ir} + A_{iw}A_{ir} + S_{iw}S_{ir} + T_{iw}T_{ir} + I_{iw}I_{ir} + C_{iw}C_{ir} \qquad (4.1)$$

where *DVI* represents the DRASTIC vulnerability index; the subscript i is the ith cell in GIS raster data structure; D, R, A, S, T, I and C are the seven factors in DRASTIC; the subscript r and w the numerical ratings (to be calculated) and weightings of seven factors.

Assumptions of DRASTIC include: 1) the contaminant is introduced at the ground surface; 2) the contaminant is flushed into the ground water by precipitation; 3) the contaminant is soluble; 4) the area assessed using DRASTIC is 100 acres or larger (Aller et al., 1987). In ADGWP, the soluble pollutants from the agricultural land use percolate into groundwater with net recharge water.

The weights of D, R, A, S, T, I and C in Eq. IV.1 are 5, 4, 3, 2, 1, 5 and 3 respectively for general pollutant, while 5, 4, 3, 5, 3, 4, and 2 for pesticide groundwater pollution vulnerability calculation. In DRASTIC, each factor has its ranges or significant media types for assigning its rating value that represents its relative significance in the impact on groundwater pollution potential. Higher DRASTIC indices imply greater pollution vulnerability and vice versa. The preparation and analysis of data and the implementation of the DRASTIC were performed using ArcGIS.

4.2. The preparation of parameter maps using GIS

Before the application of the DRASTIC model, a GIS database was set up. Borehole, drift and solid geology data were from the Geological Survey of Northern Ireland (GSNI); meteorological data were from the British Atmospheric Data Centre (BADC); the land cover data were provided by the Centre for Ecology & Hydrology (CEH); the soil data were acquired from the Department of Agriculture and Rural Development (DARD) of Northern Ireland; and the DEM data were obtained from the Environmental Heritage Service (EHS). In order to facilitate the application of DRASTIC, all data of DRASTIC factors were converted into raster data format in the ArcGIS platform with the resolution of 50m×50m. The rating of these 7 factors in DRASTIC was based on the standards set in the DRASTIC manual.

4.2.1. Depth to water

The data for 'depth to water' in the study area were obtained from 660 borehole logs containing the first water strike information. These point data were interpolated to continuous raster layer representing the water table surface. Deeper water table implies less chance for contamination to occur because of long transport time, greater opportunity for chemical reaction and the occurrence of pollutant attenuation (Aller et al., 1987). In the study area, the depth of water table below ground is shallow with the average value of 2.5m, and three rating values were calculated, i.e., 7 (4.6-9.1m), 9 (1.5-4.6m) and 10 (0-1.5m). In DRASTIC, the higher ratings imply greater groundwater pollution potential and vice versa.

4.2.2. Net recharge

Net recharge is the amount of precipitation minus surface runoff and evapotranspiration. The mean precipitation and evapotranspiration of 10 years from 1990 to 2000 were interpolated from the meteorological data. Surface runoff data was calculated adopting the US Natural Resources Conservation Service (NRCS) curve number (CN) method (NRCS, 2004). Both land cover and soil properties influence the process of runoff generation. Land covers in the study area were reclassified into brush, woods, row crop, pasture, fallow, water and urban area, according to NRCS CN method. Since this study was focusing on the soluble pollutants from diffuse agricultural sources, the urban areas were regarded as impervious surface. Based on the soil properties, soil in the study area was classified into four groups (*A, B, C* and *D*) with *A* having low runoff potential and *D* having high runoff potential (SCS, 1972). Curve number in each cell of the area was determined using the land use and soil re-classification data. In this method, the curve number of the impervious land and water body were assigned value 98. The runoff value in each cell of the study area was calculated using Eq. 4.2.

$$\begin{cases} Q = \dfrac{(P - 0.2S)^2}{P + 0.8S} \\ CN = \dfrac{1000}{10 + S \times 0.0394} \end{cases} \qquad P > I_a \qquad (4.2)$$

where Q is the depth of runoff, P the depth of rainfall, and I_a the initial abstraction, all in mm. I_a consists mainly of interception, infiltration during the early parts of storm and surface depression storage. S is the maximum potential retention in mm; relationship between I_a and S is expressed as I_a=0.2S (NRCS, 2004). CN is the curve number showing graphically the relationship between rainfall and runoff.

With the average value of 147.3 mm, the net recharge GIS raster layer in the area were classified into 5 ranges and assigned rating values of 1 (0 - 50.8mm), 3 (50.8 - 101.6 mm), 6 (101.6 - 177.8mm), 8 (177.8 - 254mm) and 9 (more than 254mm). Higher net recharge rating values mean higher recharge rates and higher groundwater pollution potential.

4.2.3. Aquifer media

Consolidated or unconsolidated rock serves as an aquifer. In general, the larger the grain size and the more fractures or openings within the aquifer, the higher permeability and the lower attenuation capacity the aquifer media have. Aquifer media information in the study area was obtained from drift geology map and previous hydrogeology investigations. The study area is covered in a thick layer of glacial drift (between 5-20 m) with very few outcrops of bedrock left exposed. Overlying these are recent peat and alluvial deposits, the latter may vary from gravels to laminated clays (Doherty, 2002). Aquifer media in the study area consist of glacial till, peat, sand and gravel, alluvium (sand and silt) and outcrop rock in exposure. Glacial till is unconsolidated to semi-consolidated mixtures of gravel, sand, silt and clay-size particles that are poorly sorted and stratified. The low permeability glacial till was assigned a rating value 5. Peat, which consists of un-decomposed to partially decomposed plant material that is fresh enough to be identified and is relatively permeable but with high contaminant attenuation, was assigned a rating value 4. Sand and gravel was given a rating value 8 because of high permeability. Alluvium of finer-grained and "dirtier" sands was given a rating value 6. Outcrop rocks information was obtained form solid geology map. In the study area, outcrop rocks include basalt (dolerite), igneous rock (felsite, granite, granodiorite), shale (mudstone) and Sandstone, assigned with rating values of 9, 3, 2 and 6 respectively according to the definition in DRASTIC. Higher aquifer media rating value means higher permeability, lower attenuation capacity of the aquifer media and higher groundwater pollution potential.

4.2.4. Soil media

Soil media information was gathered from the Northern Ireland soils database (DARD, 1997). In general, the less the clay shrinks and swells and the smaller the grain size, the less the pollution potential. Based on the contents of each soil type (sand, silt and clay) quantified by Cruickshank (1997), soils in the study area were re-classified using the British Soil Classification Standard BS3882. The quantity of organic material present in the soil may also be an important factor particularly in the attenuation of pesticides. Table 4.1 shows soil types, components, soil media re-classification and each soil type rating in the study area. Urban areas were regarded as impervious surface by assigning rating value 1. Water bodies, such as lakes, wet land and ponds, were treated as thin or absent soil by assigning rating value 10 – the highest ground water pollution potential.

Table 4.1. Soils properties and their DRASTIC rating values

Soil code in the database	**Soil parent material**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Soil media classification**	**Soil rating**
BRS	Shale gravel	-	-	-	Gravel	10
BRGN	Granite gravel	-	-	-	Gravel	10
GRGN	Granite gravel	-	-	-	Gravel	10
HRGN	Granite gravel	-	-	-	Gravel	10
HRS	Shale gravel	-	-	-	Gravel	10
RRGN	Granite gravel	-	-	-	Gravel	10
BPS	Shale	41.7~47.8	34.6~39.7	15.7~23.6	Loam	5
BPST	Shale Till	46.3~61.65	22.6~38.8	12.6~15.7	Sandy loam	6
PPS	Shale	41.7~47.8	34.6~39.7	15.7~23.6	Loam	5
SBPGN	Granite	63.4~80.9	15.6~25.7	2.8~10.3	Sandy loam	6
SBPS	Shale	49.8~65.8	20.4~26.4	13.8~23.8	Sandy loam	6
BES	Shale	29.7~50.8	38.6~42.4	14.6~27.9	Loam	5
BEST	Shale Till					
SBES	Shale	29.7~50.8	38.6~42.4	14.6~27.9	Loam	5
SBEST	Shale Till					
SWG1BRT	Basalt Red Sandstone Till	45.4~48.9	24.2~26.6	26.9~28.8	Sandy clay loam	4
SWG1BST	Basalt shale Till					
SWG1BT	Basalt Till					
SWG1GNT	Granite	61.5~68.3	18.8~22.5	10.8~15.5	Sandy loam	6
SWG1RST	Red Sandstone Till	34.5~38.9	38.8~42.1	20.5~25.7	Loam	5
SWG1RT	Red Trias Sandstone Till	61.2~67.5	17.4~20.1	12.5~19.6	Sandy loam	6
SWG1S	Shale	38.3~40.5	41.2~44.1	17.6~18.3	Loam	5
SWG1ST	Shale Till					
SWG2BST	Basalt shale Till	27.2~39.2	33.1~35.1	27.5~37.5	Clay loam	3

SWG2BT	Basalt Till					
SWG2LNCT	Lough Neagh Clay Till	34.7~52.7	28.1~30.5	19.2~35.2	Clay loam	3
SWG2ST	Shale Till	35.8~51.5	31.9~43.1	16.2~21.1	Loam	5
G2ALL	Alluvium	41.0~55.7	25.4~36.7	18.9~22.9	Loam	5
G2OA	Organic Alluvium	25.2~32.7	43.4~43.8	23.4~31.4	Clay loam	3
G3ALL	Alluvium	7.5~21.9	70.0~77.6	0.5~22.5	Silt Loam	4
G3OA	Organic Alluvium	25.2~32.8	43.4~43.8	23.4~31.4	Clay loam	3
SWHGGN	Granite	83.3	13	3.8	Loamy sand	9
SWHGS	Shale	52.7~61.5	36.0~36.4	2.5~10.9	Sandy loam	6
SWHGST	Shale Till	52.7~61.5	36.0~36.5	2.5~10.10	Sandy loam	6
PT	Peat	-	-	-	Peat	8
URB	Urban	-	-	-	Impervious	1
WAT	Water	-	-	-	Thin or Absent	10

4.2.5. Topography

Slopes, which provide a greater opportunity for pollutants to infiltrate, will be associated with higher groundwater pollution potential. Topography also controls the gradient and direction of flow. Typically, steeper slopes signify higher groundwater velocity. Slope in the study area was derived from DEM data in ArcGIS, and then was divided into ranges and assigned ratings from 1 to 10 according to the DRASTIC rating standard. It worth noting that the ranges of ‘percent slope’ described in the DRASTIC model are recommended to be converted to degree slope when applying DRASTIC in GIS. Steep areas were assigned low rating values because they increase the runoff washing out contaminants, whilst flat areas, slow down the runoff and allow more time for percolation, were given high rating values.

4.2.6. Impact of vadose zone media

The media type determines the process of biodegradation, neutralisation, mechanical filtration, chemical reaction, volatilisation and dispersion in the vadose zone. Vadose zone media identification and classification were based on the soil map, drift geology map, borehole data and water table depth information. Rocks (shale, basalt, igneous, shale and sandstone) and drifts (glacial till and gravel) were found in the study area.

The rating for the thin gravel was assigned 10 – the highest pollution potential. Glacial till's components and draining properties in the study area vary greatly. With the soil database and the detailed soil properties information, the glacial till was re-grouped according to their sand contents (7~87%). Sandy till is 'sand and gravel with significant silt and clay' (definition in DRASTIC) with rating value 6; whilst a dense, un-fractured, clayey till (silt/clay) was assigned rating value 3. Other types of glacial till were respectively assigned the rating values between 3 and 6 using their sand contents. Vadose zone media ratings reflect their grain size, sorting, homogeneity and amount of fine material. Higher rating value means higher groundwater pollution potential.

4.2.7. Aquifer hydraulic conductivity

The values of aquifer hydraulic conductivity (*K*) were estimated based on the *K* ranges provided in the DRASTIC method and validated using the values from literature and pumping tests in near areas. K values in the area were assigned the rating values of 1 (0.04 - 4.1m/day), 2 (4.1 - 12.2m/day), 6 (28.5 - 41m/day), 8 (41 - 82m/day), and 10 (more than 82m/day). Higher K ratings imply the higher aquifer permeability and higher groundwater pollution potential.

5. Results

5.1. DRASTIC factors

Although the DRASTIC index values represent the overall groundwater vulnerability, the result of each factor is also useful in understanding the pathway of the groundwater pollution in a study area. In 'depth to water' rating layer, comparatively high groundwater pollution potential cells with rating values of 9 and 10 cover 98% of the study catchment. Cells with value 7 are located in the low-lying area to the middle and northwest of the study catchment. High net recharge ratings 8 (13% of the total study area) and 9 (21%) can be found in mountain areas, whereas low net recharge ratings 1 (31%) and 3 (17%) are located in low-lying areas. The undulating drumlin areas have a moderate net recharge rating 6 (18%) (Fig. 4.1 – Net recharge ratings). In the aquifer rating result (Fig. 4.1 – Aquifer media ratings), most parts of the area have a rating value 5 (78%) standing for glacial till media for unconfined aquifer. On the background of rating 5, the strips of alluvium, sand and silt developing along streams/rivers have comparatively higher groundwater pollution potential with the rating 6 (11%). Outcrops at mountain areas with rating 2 (1%) and 3 (3%) have low groundwater pollution potential. With the dominant soil types of 'loam' – rating 5 (52%), 'clay loam' – 3 (16%) and 'sandy loam' – 6 (15%), the soil media rating values gradually decrease from mountain areas to low-lying area, except a small area immediately south of the Lough Neagh covered by peat with higher vulnerability than basalt and till around it (Fig. 4.1 – Soil media ratings). In topography rating layer, the steep slope cells with the rating values of 1 (5%) and 3 (10%) are located in the mountain areas to the southeast, southwest and east of the study area. In contrast, the low-lying area to the northwest of the study area has high ratings of 9 (33%) and 10 (22%). In addition, the undulating area of the rest of the study have the mixture of values of 1, 3, 5 (30%), 9 and 10. The vadose zone media with the rating value 6 (15%) – 'alluvium strata' developing along streams or rivers on the background of rating 4 (72%) – 'till' form distinct strips with comparatively high groundwater pollution potential. High rating values 8 (1%), 9 (1%) and 10 (2%) can be found in mountain areas. In the '*K*' rating layer, most of parts in the area have comparatively low aquifer permeability with rating values of 1 (81%) and 2 (6%), while cells with rating value 8 (8%) form obvious alluvium strips along streams or rivers (Fig. 4.1 – *K* ratings).

5.2. Groundwater pollution vulnerability

The groundwater vulnerability for general pollutants and the groundwater pesticide vulnerability were calculated using Eq. 5.1. Ten vulnerability ranks were identified in the study area. Fig. 4.2 shows 'high' (4.5% of total area) and 'moderate' (25.5%) vulnerability zones in the mountain areas to the southeast (Mourne Mountains), east (Slieve Croob) and southwest (source of River Cusher) due to high rainfall, net recharge and soil permeability. While the 'low' (73.8%) vulnerability zones can be found in the middle and northwest of the study area where the covering soil has low permeability. Because of the high permeability of alluvium, sand and gravel in the riverbeds, strips along streams/rivers have comparatively higher vulnerability ranks than their backgrounds. The groundwater pesticide vulnerability map (Fig. 4.3) has similar ranks distributing trends as Fig. 4.2. However, the 'high' (4.7%) and 'moderate' (50.7%) vulnerability zones in Fig. 4.3 have higher proportions than that of Fig. 4.2.

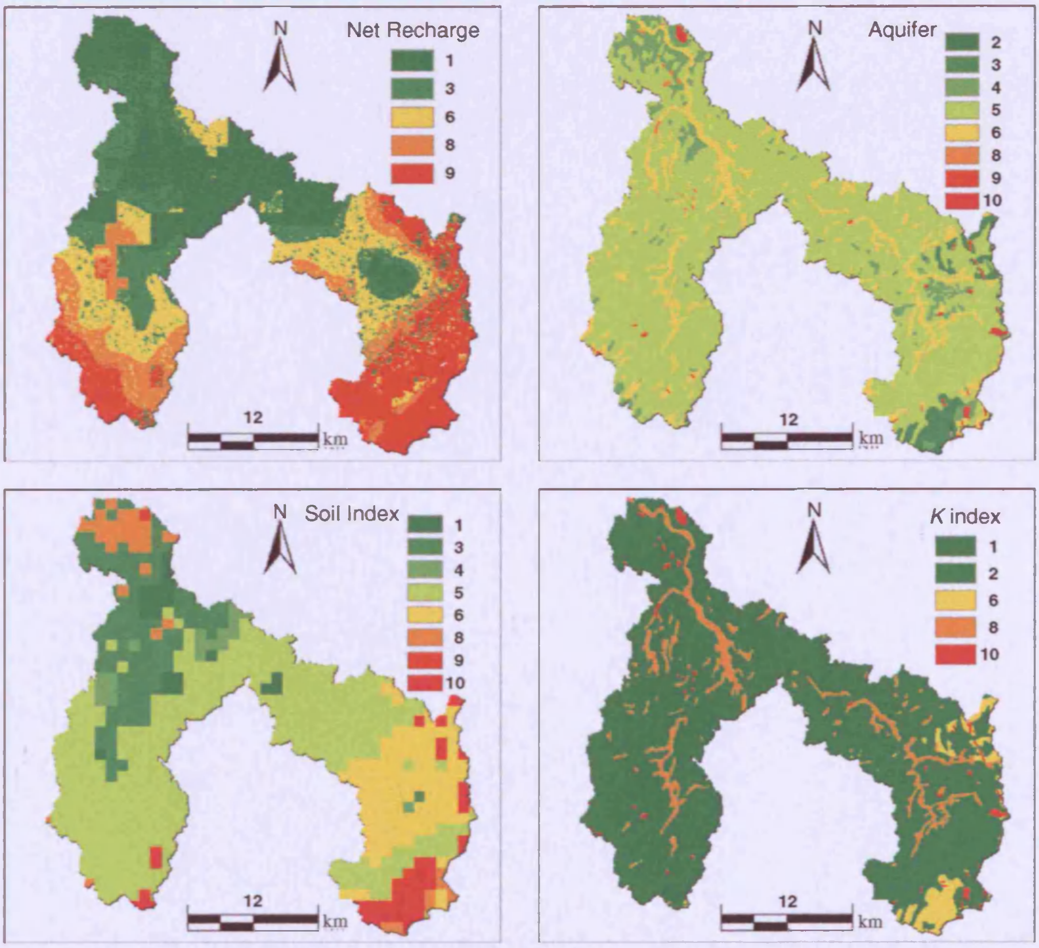

Fig. 4.1. Ratings of four factors in DRASTIC in the Upper Bann Catchment

Generally, the high ADGWP risk is associated with arable land having higher fertiliser or pesticide application rate than other land uses. Thus, the more vulnerable zones in mountain areas with few arable land use areas may have low ADGWP risk. While some of the less vulnerable areas in the low-lying part of the study area could have high ADGWP risk mainly due to higher density of arable land use areas. The land use layer was overlaid on the groundwater water pollution vulnerability map, in order to reflect the ADGWP risk by considering pollution sources. Take nitrate as an example, the result of Fig. 4.4 is in line with the trend of the groundwater nitrate concentration monitoring data in the study area.

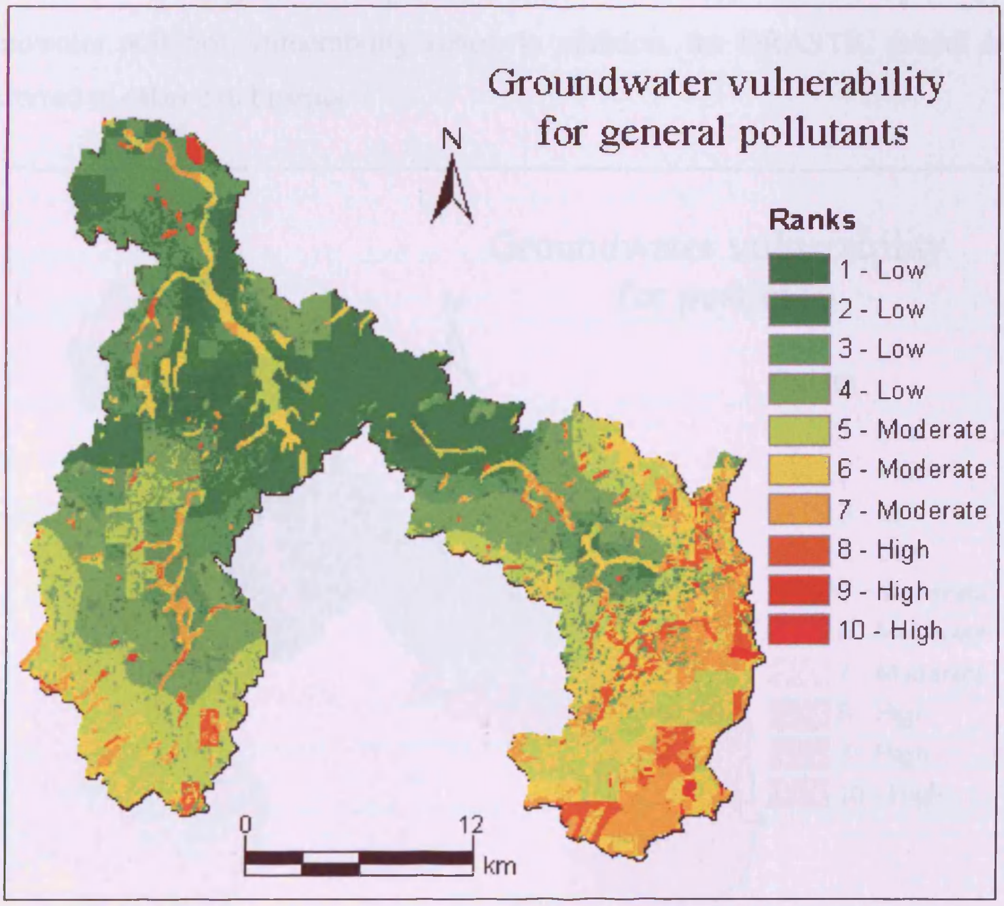

Fig. 4.2. Groundwater vulnerability for general pollutants in the Upper Bann Catchment

6. Discussions

DRASTIC is helpful for tackling ADGWP at the catchment scale in the implementation of the EU Water Framework Directive (WFD). The EU WFD introduces an innovative, integrated and holistic approach to the protection and management of water resources. Agricultural diffuse water pollution has been identified as a major threat for achieving the demands of the EU WFD (Ferrier et al., 2004; Torrecilla et al., 2005). So far, the answer of the question what technical measures will actually be used or developed in the implementation of the EU WFD is still largely unknown (UK EA, 2005). By considering 7 factors in the pathway of soluble pollutants reaching groundwater from the ground surface, the DRASTIC results are useful for guiding the prevention activities of the ADGWP by delineating groundwater pollution vulnerability zones. In addition, the DRASTIC model can be transferred to other catchments.

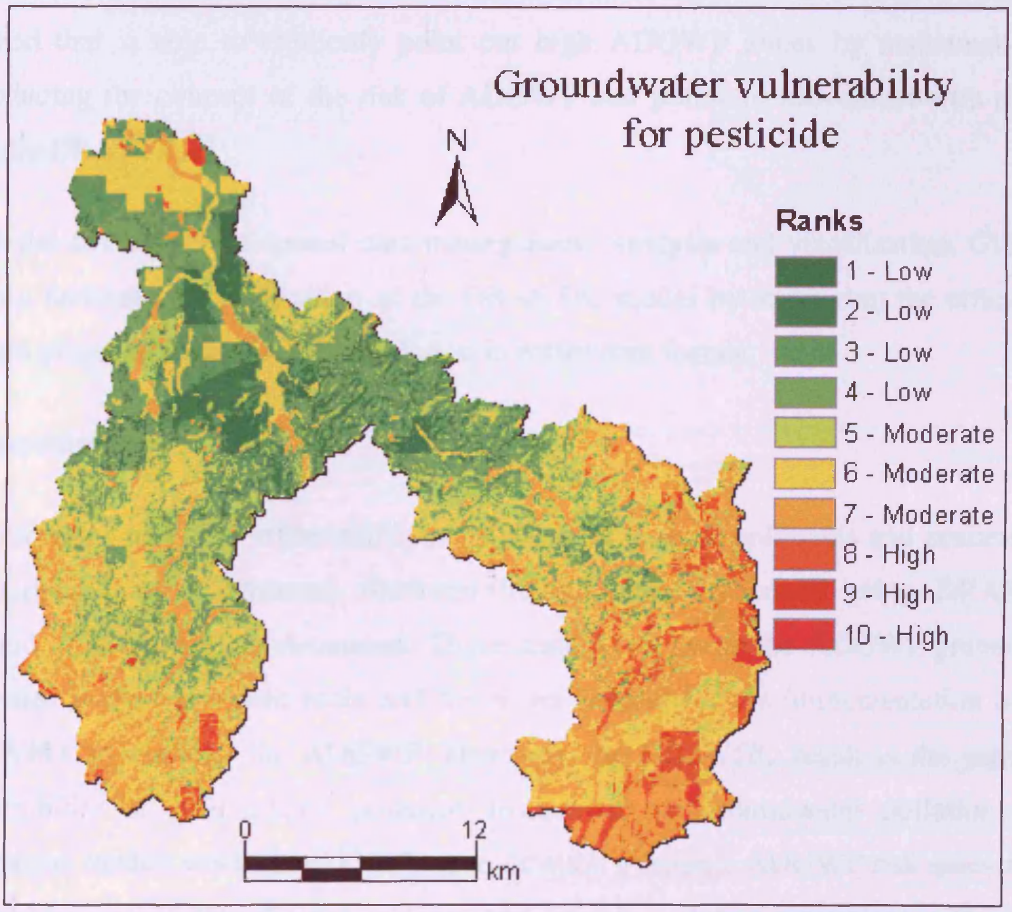

Fig. 4.3. Groundwater pesticide vulnerability in the Upper Bann Catchment

Although DRASTIC is an index method with the subjective weighting and the numerical value assignation of various factors, these selected factors and their subjective weights can well reflect the key mechanism of processes in the groundwater pollution pathway. Thus, DRASTIC is being used worldwide for the groundwater vulnerability assessment at both large and small scales (Worrall and Kolpin, 2004; Babiker et al., 2005; Hamza et al., 2007). Nevertheless, DRASTIC has drawbacks in the prevention of ADGWP at the catchment scale. For example, the DRASTIC reflects pathway vulnerability in ADGWP, but both pathway vulnerability and pollution sources are needed for the actual ADGWP management. Although the overlaying of DRASTIC index and land use maps in Fig. 4.4 makes better result than Fig. 4.2, the judgement of exact target zones for the ADGWP prevention is still not easy. Therefore, it is necessary to develop a more reliable ADGWP risk assessment method that is able to explicitly point out high ADGWP zones by mathematically introducing the concept of the risk of ADGWP and pollutant movement with runoff into the DRASTIC.

With the advantages of spatial data management, analysis and visualisation, GIS can greatly facilitate the application of the DRASTIC model by improving the efficiency of data preparation and index calculation in raster data format.

7. Conclusions

Groundwater pollution vulnerability maps for both general pollutants and pesticide in the Upper Bann Catchment, Northern Ireland, were generated using DRASTIC method in an ArcGIS environment. These results can guide the ADGWP prevention activities at the catchment scale and hence are helpful for the implementation of the EU WFD in handling the ADGWP. However, the DRASTIC result is the pathway vulnerability of groundwater pollution instead of the groundwater pollution risk. Therefore, further work should be done to develop a reliable ADGWP risk assessment method by considering the risk concept and soluble pollutant movement with runoff on the ground surface.

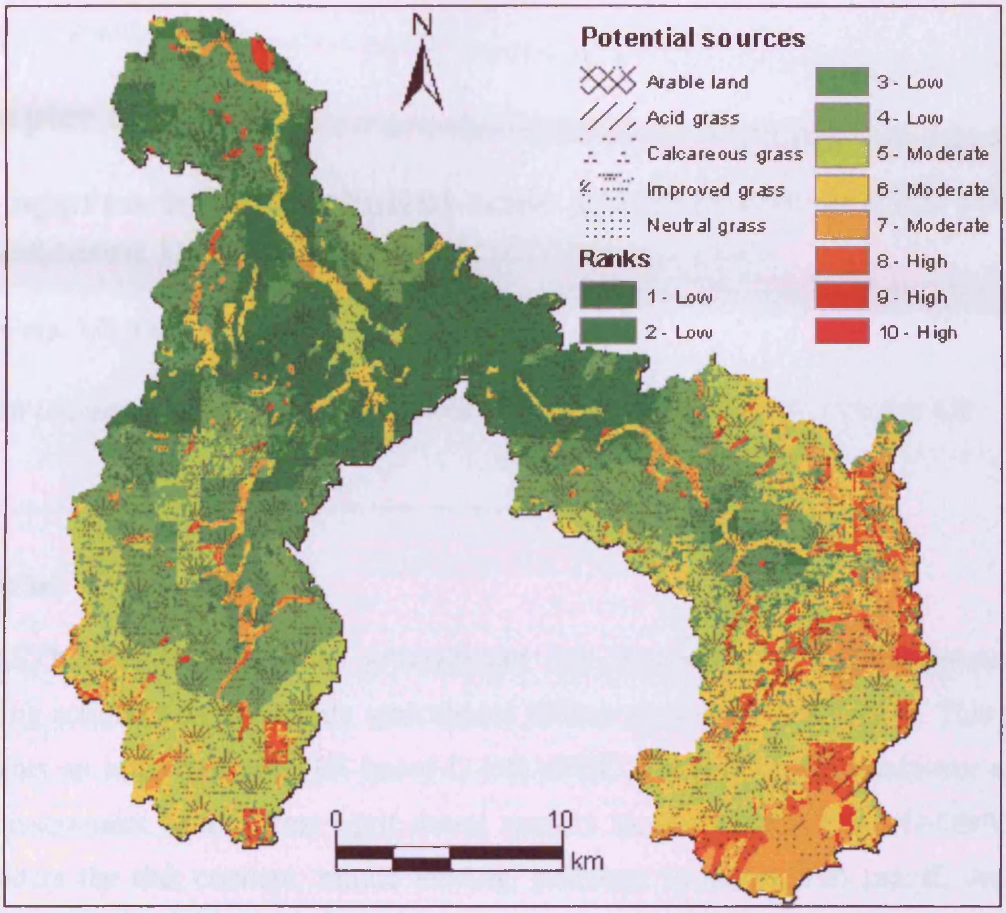

Fig. 4.4. Overlaying the land use map on the groundwater vulnerability map in the Upper Bann Catchment

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Chapter 5

An approach for catchment-scale groundwater nitrate risk assessment from diffuse agricultural sources [*]

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Abstract

DRASTIC has drawbacks in groundwater risk assessment that are important in guiding activities to prevention agricultural diffuse groundwater pollution. This paper presents an improved and GIS-based D-DRASTIC approach for groundwater nitrate risk assessment from diffuse agricultural sources based on DRASTIC. D-DRASTIC considers the risk concept, nitrate loading, pollutant transport with runoff, depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone media, and the hydraulic conductivity of the aquifer. D-DRASTIC was developed within an ArcGIS environment and applied to the Upper Bann Catchment, Northern Ireland as a case study. D-DRASTIC shows that 'very high' and 'high' zones of groundwater nitrate risk occupy 5% and 11% of the case study area, respectively. When considering groundwater pollution sources and pathways, the results using D-DRASTIC are helpful in guiding the activities of groundwater pollution prevention at the catchment scale in the context of better implementation of the EU Water Framework Directive.

Keywords: Risk assessment; Agriculture diffuse groundwater pollution; Catchment scale; Geographic Information Systems

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1. Introduction

Groundwater provides an important component of water resources due to its relatively low susceptibility to pollution in comparison with surface water, and its large storage capacity. Nitrate-N groundwater contamination, a global problem, drives mainly from the threat of diffuse agricultural sources. It is important to note that nitrate pollution is not only an environmental issue but also an economic and human health problem (Defra, 2002b; Defra, 2002e). The approximate annual cost of treating drinking water for nitrate is around £16 million in the UK (Pretty et al., 2000). Nitrate concentrations in excess of 10 mg NO3-N /L in drinking water may pose a risk to young animals and human babies (USDA, 1991; Matson et al., 1997). It could cause the infants to develop a blue colouration and respiratory problems known as blue baby syndrome (methemoglobinemia) by reducing the ability of human blood to carry oxygen to the individual body cells (Magee, 1982; Basso and Ritchie, 2005; Bryan, 2006). A potential cancer risk from nitrate (and nitrite) in water and food has been reported (Rademaher et al., 1992; Hill, 1999).

The diffuse source water pollution, which is more complex and difficult to control in comparison to point source pollution, has been regarded as the biggest remaining problem of water pollution in many countries (Campbell et al., 2004). Within diffuse water pollution sources, the single, biggest threat is from agriculture. The EU Water Framework Directive (WFD) (EC, 2000) introduces an innovative, integrated and holistic approach to the protection and management of water resources. However, so far the answer of the question what technical measures will actually be used or developed in the implementation of the EU WFD is still largely unknown (UK EA, 2005). Agricultural diffuse water pollution has been realised as a major threat for achieving the demands of the EU WFD (Ferrier et al., 2004; Torrecilla et al., 2005).

Once groundwater is contaminated, it will be very costly to clean-up and can take a long time to recover (EHS, 2001). Moreover, spatial variability and data constraints preclude monitoring all groundwater and make the remediation activities expensive and often impractical (Babiker et al., 2005). The prevention of groundwater quality deterioration at source before contamination occurs, therefore, is critical for long-term effective groundwater management (Koo and O'Connell, 2006). Because it is difficult to determine at a regional scale the contribution of diffuse agricultural sources to water pollution (Defra, 2002c), groundwater protection practices should be carried out at catchment or watershed scale. For example, The EC Nitrate Directive (91/676) insists that nitrate should be controlled by prevention at source level, namely diffuse agricultural sources at catchment scale. Groundwater pollution risk assessment, capable of delineating zones where the groundwater is more susceptible to pollutants from diffuse agricultural sources at catchment scale, can act as an efficient decision support tool to explicitly guide the prevention activities of agricultural diffuse groundwater pollution (ADGWP).

At the present stage, there are gaps between current research and the risk assessment of groundwater pollution for the purpose of the ADGWP prevention at catchment scale. To bridge these gaps, a GIS based D-DRASTIC method was developed by introducing pollution loading and transport based on the DRASTIC approach. The objectives of this paper are first to describe the ways in which D-DRASTIC overcomes the pitfalls of applying DRASTIC in groundwater risk assessment by introducing the risk concept and pollutants' dynamic nature with surface water; and second to discuss the implications of the D-DRASTIC approach based on its application in the Upper Bann Catchment, Northern Ireland.

2. Risk assessment background

The concept of groundwater vulnerability was first introduced by the end of the 1960s to create awareness of groundwater contamination (Vrba and Zoporozec, 1994). The vulnerability of groundwater is the possibility of percolation of contaminants from the ground surface into the groundwater system, and constitutes the susceptibility of groundwater to contamination by surface, or near surface pollutants (Robins et al., 1994; Palmer et al., 1995). So far, there are mainly four types of groundwater vulnerability assessment methods:

1) Process based (modelling) approach uses physically based simulation models to make approximate estimates of contaminant transport. This method not only provides detailed estimates of contaminant migration, but also is able to evaluate the impacts of human activities on groundwater quality by covering the complete phases of source – pathway – target in the groundwater pollution process including the movement of groundwater. Therefore, this method is suitable for guiding the prevention and remediation of groundwater pollution. However, insufficient data and computational burden generally preclude their application (Barbash and Resek, 1996; Thapinta and Hudak, 2003).

2) Statistical method uses statistics to correlate spatial variables with actual occurrence of pollutants in groundwater. The results of this method are based on objective observation data; and are directly useful for groundwater remediation. Its limitations include insufficient water quality observations, data accuracy and careful selection of spatial variables (Babiker et al., 2005). In addition, this method only covers the target phase in the groundwater pollution without considering the groundwater movement.

3) Observation based method generates groundwater vulnerability maps based on the observed contaminations. This method provides results based on the observation data at monitoring sites. However, this method, which is purely based on the observations of measured concentrations, is not able to cover the phases of source, pathway, and the movement of groundwater in the groundwater pollution process. For example, Fig. 5.1 shows that the groundwater pollutant of site A is from the diffuse source at site B instead from the site C above the site A. Therefore, the result of this method is more like a groundwater pollution status map. Although some studies tried to militate against this problem by selecting carefully study areas, such as Worrall and Besien (2005). However, when this method is transferred to other catchments with complex land use and hydrogeological situations, its results could have great uncertainty in the guidance of the prevention of groundwater pollution. Moreover, expensive monitoring and observation errors constrain the real application of this method in the

implementation of the EU WFD.

4) Index method combines factors that control the pollutant transport pathways from the ground surface into saturated zone to calculate the spatial distributed vulnerability

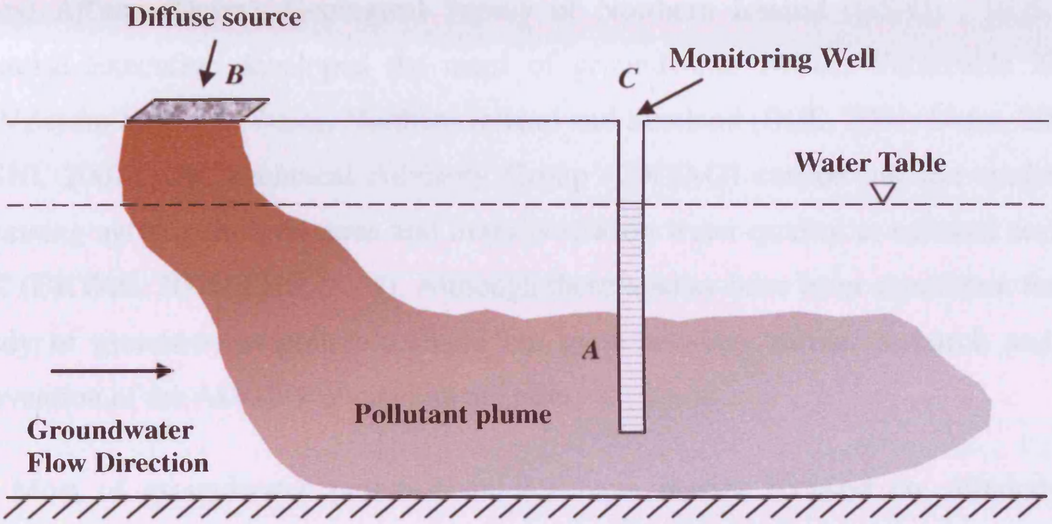


Fig. 5.1. Uncertainty of diffuse pollution sources in the catchment water management

indices of groundwater pollution pathway. The vulnerable maps created by this method could be useful for guiding the prevention of the groundwater pollution by cutting off groundwater pollution pathways. It is easy to obtain the data demanded by this method, such as topography, rainfall, geology (Thapinta and Hudak, 2003). In addition, the index method has the advantages of easy understanding and application. However, one major drawback of this method is the subjectivity in the factor weighting and numerical value assignation. In addition, the index method covers source and (or) pathway phase in the groundwater pollution process without considering the target phase in the groundwater pollution.

Within the UK context, there has been a good amount of work done on groundwater pollution potential. For example, the Soil Survey and Land Research Centre (SSLRC) and the British Geological Survey (BGS) generated the England and Wales national series of fifty-three 1:100,000 scale groundwater vulnerability maps (Palmer and

Lewis, 1998). In Scotland, Association of Directors and River Inspectors of Scotland created Scotland 1:625,000 scale groundwater vulnerability map (ADRIS, 1995). Environment and Heritage Service (EHS) and Department of the Environment, Northern Ireland (DENI) made Northern Ireland 1:250,000 scale groundwater vulnerability map (DENI, 1994; EHS, 2001). Department for Environment, Food and Rural Affairs (Defra), Geological Survey of Northern Ireland (GSNI) , BGS and Scottish Executive developed the maps of groundwater Nitrate Vulnerable Zones (NVZs) for England, Wales, Northern Ireland and Scotland (BGS, 2001; Defra, 2002d; GSNI, 2002). UK Technical Advisory Group (UKTAG) carried out the studies of assessing agricultural pressures and impacts risk on water quality at national scale in UK (UKTAG, 2004; EHS, 2005). Although these studies have been significant for the study of groundwater pollution, there are gaps between current research and the prevention of the ADGWP at catchment scale.

(i) Most of groundwater pollution studies have mainly focused on vulnerability assessment instead of the risk assessment. High groundwater vulnerability does not always mean high groundwater pollution risk. Eq. 5.1 shows the definition of risk (Chabert, 2003).

$$\text{Risk} = f\ (\text{Hazard, Vulnerability}) \qquad (5.1)$$

where "Vulnerability" means the system vulnerability for one specific "Hazard". Different hazards could have different vulnerabilities.

The combination of the occurrence of hazard and the vulnerability of the system results in the risk (Hauger et al., 2003). Groundwater is only at risk if both the hazard and the pathway by which the hazard may be transmitted to groundwater exist. Therefore, the groundwater pollution risk assessment that considers both hazard (such as the nitrate from agricultural activities) and vulnerability (e.g. possibility of pathway for pollutants reaching the groundwater) is needed.

(ii) The studies of groundwater vulnerability assessment in the UK have been based on a multi-basin or national scale. For example, Jordan and Smith (2005) drew a conclusion that most of Northern Ireland should be designated as NVZs according to the new demand of the European Commission. Even though Jordan and Smith's work is helpful for setting the priority of groundwater pollution protecting plan in the UK, it can hardly guide the prevention practices of ADGWP that should be carried out at catchment scale. Therefore, methods capable of the detailed risk assessment of catchment-scale groundwater pollution are needed for actual ADGWP management.

(iii)The fact that only few factors, such as overlying soil cover, the presence and nature of the drift, the nature of strata, and the thickness of the unsaturated zone, have been considered in the UK groundwater vulnerability assessment leads to high uncertainty in the result (Palmer et al., 1995; Palmer and Lewis, 1998; UKTAG, 2004; Giupponi and Vladimirova, 2006).

(iv)Current studies, ignoring the dynamic nature of hazard with surface water, are not enough in making sound plans for the prevention of ADGWP at catchment scale.

The DRASTIC method, an index method, was developed by the U.S. Environmental Protection Agency (EPA) (Aller et al., 1987). DRASTIC has the disadvantages of the index methods. Despite the fact that DRASTIC is a method with the subjective weighting and the numerical value assignation of factors, these factors and their weighting values, which were selected and calculated based on the knowledge and understanding of groundwater pollution from a group of groundwater pollution experts, can well reflect the key mechanisms of the groundwater pollution pathways. Therefore, the DRASTIC method is being widely used for groundwater vulnerability assessment at various scales (Al-Adamat et al., 2003; Worrall and Kolpin, 2004; Babiker et al., 2005). The applications of DRASTIC have been summarised in Table 5.1. The effectiveness of DRASTIC has met with mixed success (Rupert, 2001). DRASTIC focuses only on the pathway phase from the groundwater surface to water table. After entering aquifers, soluble pollutants move with groundwater flow before reaching the target (monitoring wells). Therefore, the groundwater vulnerability result of DRASTIC can be significantly different from the groundwater quality monitoring data without considering the complicated groundwater movement in aquifers of study area. By direct comparisons of the results of DRASTIC with groundwater quality monitoring data in some areas, Rupert (2001) drew the conclusion that DRASTIC is a poor predictor of groundwater pollution. DRASTIC has two pitfalls in groundwater pollution risk assessment:

1) DRASTIC has no the risk concept. The purpose of DRASTIC is to evaluate the groundwater pathway vulnerability of general soluble pollutants (Aller et al., 1987). In this study, the hazard is nitrate from diffuse agricultural sources, whilst the vulnerability is the pathway for nitrate entering groundwater from ground surface. Risk assessment can provide more objective and practicable support for the effective decision making of groundwater quality protection.

2) Since DRASTIC was designed for groundwater vulnerability assessment, it does not consider pollutant movement via runoff on the ground surface. However, the soluble hazard can be carried by surface runoff and interflow from one place to another in the reality; and can consequently be redistributed above the water table

Table 5.1.

A review summary of the DRASTIC applications in groundwater pollution potential evaluation

Applications	**Vulnerability concept**	**Risk concept**	**Modification**	**References**
USA	Yes	No	No	Aller et al., 1987
USA	Yes	Yes	Excluded three factors and considered land use factor	Evans and Myers, 1990
New Zealand	Yes	No	No	Close, 1993
Europe	Yes	No	No	Lobo Ferreira and Oliveira, 1997
South Africa	Yes	No	No	Lynch et al., 1997
Israel	Yes	No	No	Melloul and Collin, 1998
Israel	Yes	Yes	Considered land use factor	Secunda et al., 1998
South Korea	Yes	No	No	Kim and Hamm, 1999
USA	Yes	No	No	Fritch et al., 2000

Latin America	Yes	No	No	Ramos and Rodríguez, 2003
Jordan	Yes	Yes	Excluded hydraulic conductivity of the aquifer and considered land use factor	Al-Adamat, et al., 2003
Japan	Yes	Yes	Considered land use factor	Babiker et al., 2005
North Africa	Yes	No	No	Hamzaa et al., 2006
UK	Yes	No	No	Koo and O'Connell, 2006

according to the topography in a catchment. This phenomenon is termed pollutant dynamic nature, and can strongly affect risk assessment results. For example, Fig. 5.2-a shows the pollutant distribution on the ground surface; Fig. 5.2-b the groundwater vulnerability status, representing the possibility for groundwater pollution through the vertical pathways from ground surface; and Fig. 5.2-c and d are the results of the groundwater pollution risk assessment without and with considering the pollutants horizontal movement. The results for cell *D* in Fig. 5.2-c and d are different. Under the control of topography, pollutant in cell *A* moves to cell *D* with runoff resulting high groundwater contamination risk in cell *D*. The result of Fig. 5.2-d is more reliable for guiding the decision making of the ADGWP prevention. It is thus necessary to introduce the risk concept and pollutant dynamic nature based on groundwater vulnerability method to develop practical groundwater pollution risk assessment method.

3. Methodologies

3.1. DRASTIC

DRASTIC is a numerical ranking composite description of all the major geologic and hydrologic factors that affect and control the groundwater movement into, through and out across the vertical profiles of an area. The acronym DRASTIC stands for seven factors: D – **D**epth to water; R – net **R**echarge; A – **A**quifer media; S – **S**oil media; T – **T**opography (slope); I – **I**mpact of the vadose zone media; and C – hydraulic

Conductivity of the aquifer. Each of the DRASTIC factors is assigned by a relative weight ranging from 1 to 5 determined using a Delphi (consensus) approach. The most significant factor has a weight of 5 and the least significant has a weight of 1. The detailed weighting process of DRASTIC can be found in Aller et al. (1987). The intrinsic meaning of the DRASTIC result is the groundwater pollution vulnerability, as it can be determined by Eq. 5.2.

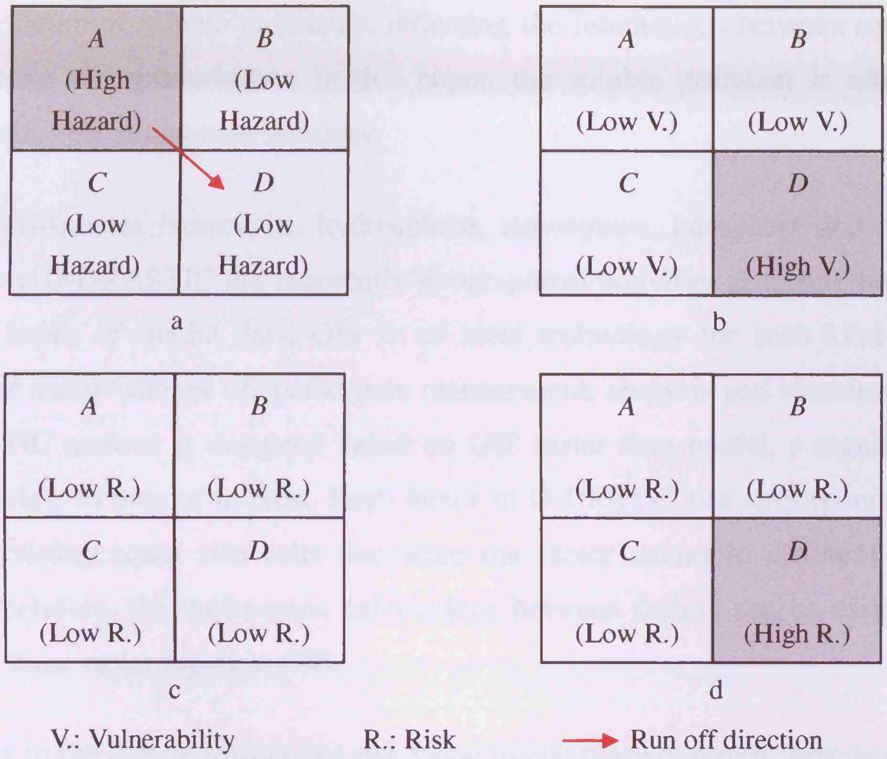


Fig. 5.2. The effect of pollutants movement on risk evaluation result

$$DVI_i = D_{iw}D_{ir} + R_{iw}R_{ir} + A_{iw}A_{ir} + S_{iw}S_{ir} + T_{iw}T_{ir} + I_{iw}I_{ir} + C_{iw}C_{ir} \qquad (5.2)$$

where *DVI* represents the DRASTIC vulnerability index; *D*, *R*, *A*, *S*, *T*, *I* and *C* are seven factors in DRASTIC; the subscript *r* and *w* the numerical ratings (to be calculated) and weightings for general soluble pollutants (5, 4, 3, 2, 1, 5 and 3) respectively; the subscript *i* is the *i*th cell in GIS raster data structure. Higher DRASTIC indices imply greater pollution vulnerability and vice versa.

3.2. D-DRASTIC

D-DRASTIC developed in this study introduces the risk concept and the dynamic nature of pollutants by considering the soluble pollutant loading and transport based on the DRASTIC approach. The first 'D' in D-DRASTIC stands for 'dynamic' – the dynamic nature of soluble pollutants, reflecting the interactions between runoff, soil, vadose zone and groundwater. In this paper, the soluble pollutant is nitrate, as a groundwater risk assessment indicator.

Since multi-spheres factors, i.e. hydrosphere, atmosphere, geosphere and biosphere, involved in D-DRASTIC are inherently geographical activities requiring handling of multiple forms of spatial data, GIS is an ideal technology for such kind of study because of its advantages of spatial data management, analysis and visualisation. The D-DRASTIC method is designed based on GIS raster data model, a regular grid of cells covering an area of interest. Each factor in D-DRSTIC has corresponding raster layer containing equal size cells that store the factor values in different locations (cells). Therefore, the mathematic calculations between factors can be easily carried out using these raster layers in GIS.

According to the risk definition, the risk value in one place is zero if there is no hazard no matter how high the value of vulnerability is at this place and vice versa. Therefore, the risk value of one cell in a study area can be expressed by multiplying the values of hazard and vulnerability at this location. In order to reflect the risk concept, hazard value is normalised by dividing the difference between the hazard value in each cell and the minimum value of the study area by the difference between the maximum and minimum hazard value of the study area, which yields values with a range of [0, 1]. As a result, zones with minimum hazard value in one specific catchment will have zero value of hazard, and no groundwater pollution risk. Because of the normalisation of hazard, the groundwater pathway vulnerability index is also normalised as a range of (0, 1] by dividing the vulnerability index value in a cell with the maximum value in study catchment. After normalisation, the values of D-DRASTIC have a range of [0, 1], thus improving the readability of groundwater risk assessment result. In one area, the highest groundwater risk zone has a value of "1" and the lowest groundwater risk zone has a value of "0".

The D-DRASTIC method can be expressed as:

$$RI_i = \frac{DVI_i}{DVI_{\max}} \times \frac{H_i - H_{\min}}{H_{\max} - H_{\min}} \qquad (5.3)$$

$$H_i = VH_i + HH_i \qquad (5.4)$$

$$VH_i = \frac{LR_i \times K_1}{NR_i \times K_2} = \frac{LR_i}{NR_i} \times K \qquad (5.5)$$

$$HH_i = \frac{EC_i \times K_1}{RO_i \times K_2} = \frac{EC_i}{RO_i} \times K \qquad (5.6)$$

where RI_i is the result of the D-DRASTIC risk assessment in cell i, $RI_i \in [0, 1]$; DVI_i the index of the DRASTIC groundwater pollution vulnerability in cell i, calculated by Eq. 5.2; $DVI_{\max}$ the maximum DRASTIC groundwater pollution vulnerability index in the study area; H_i the soluble pollutant hazard to groundwater, standing for the nitrate hazard to groundwater in cell i, or the nitrate concentration in cell i; $H_{\min}$ and $H_{\max}$ represents the minimum and maximum hazard concentrations (mg N/L) in the study area respectively. VH_i is the vertical nitrate flux reaching groundwater via leaching and percolation in cell i; HH_i the extra nitrate carried by runoff to cell i that can promote further nitrate leaching and percolation through soil and unsaturated vadose zone, then contaminate groundwater. LR_i is the nitrate-leaching rate (Kg N/ha/yr) in cell i; NR_i (mm) net recharge in cell i; EC_i the accumulated nitrate runoff export coefficient (Kg N/ha/yr) in cell i; RO_i the accumulated runoff (mm) in cell i. The process of rainfall producing runoff will be explained in the following section 4.2.1 in detail. $K_1 = 2.5 \times 10^5$ (mg N/yr) is a converter of the nitrate-leaching rate or runoff export coefficient from Kg N/ha/yr to mg N/cell/yr; $K_2 = 2.5 \times 10^3$ another converter of the net recharge in an area of 1 m^2 from $mm/m^2/yr$ to liter/cell/yr; $K=K_1/K_2=100$ (cell size: 50m×50m).

Higher RI_i value means higher groundwater pollution risk. According to Eq. 5.3, when nitrate concentration in a cell has the minimum value in a catchment, the groundwater risk index value in this cell will be zero regardless the DVI_i value. The value of RI_i in cell i will be "1" when both DVI_i and H_i approach their maximum values respectively in this cell.

4. Application

ArcGIS was adopted for the application of D-DRASIC in this study. The study area was divided into regular sized 50×50m grids for the application of the D-DRASTIC method.

4.1. The case study area

The Upper Bann Catchment, Northern Irela3nd is the study area in this study. The details of the conditions of the study area are given in appendix A.

4.2. Calculation of D-DRASTIC factors

The calculations of D-DRASTIC factors were based on a multi-sphere spatial database containing DEM, catchment boundary, stream network, land use, soil, drift and solid geology, meteorological and borehole data. The nitrate accumulation with runoff, depth to water table, net recharge, aquifer media, soil media, topography, vadose zone media and aquifer hydraulic conductivity were derived or calculated accordingly.

4.2.1. Calculating runoff

Both hazard and net charge calculations were based on the surface runoff data that was calculated by adopting the US Natural Resources Conservation Service (NRCS) curve number (CN) method (NRCS, 2004). The curve number runoff equation is:

$$\begin{cases} Q = \dfrac{(P-0.2S)^2}{P+0.8S} \\ CN = \dfrac{1000}{10+S\times 0.0394} \end{cases} \qquad P > I_a \qquad (5.7)$$

where Q is the depth of runoff, P the depth of rainfall, and I_a the initial abstraction, all in mm. I_a consists mainly of interception, infiltration during the early parts of storm and surface depression storage. S is the maximum potential retention in mm; relationship between I_a and S is expressed as I_a=0.2S (NRCS, 2004). *CN* is the curve number showing graphically the relationship between rainfall and runoff.

Both land cover and soil properties influence the process of runoff generation. To calculate S value in Eq. 5.7, the curve number of each combination of land cover and soil was determined beforehand. Land covers in a study area were reclassified into brush, woods, row crop, pasture, fallow, water and urban area, according to the US NRCS CN method (NRCS, 2004). Since this study has focused on the soluble pollutants (e.g. nitrate) from diffuse agricultural sources, the urban areas were regarded as impervious surface. According to soil properties, soil in the study area was classified into four groups (*A, B, C* and *D*) with *A* having low runoff potential and *D* having high runoff potential (SCS, 1972). Table 5.2 shows the details of the reclassification of soils in the study area. Curve number of each cell was determined based on the land use and soil reclassification data in the study area. In this method, impervious and water surfaces were assigned CN=98. The surface runoff was then calculated in each cell using Eq. 5.7. The results of all cells formed the runoff weight layer in the study area.

4.2.2. Calculating the accumulation of nitrate with runoff

In the nitrogen cycle, while nitrate is taken up by plants or converted into nitrogen, nitrate also leaches vertically into groundwater and simultaneously moves horizontally with runoff. Nitrate in runoff may finally enter rivers or leach into groundwater in the process of movement with surface runoff or interflow. On the ground surface, nitrate accumulates with runoff according to topography. In order to calculate nitrate accumulation, a raster digital elevation model (DEM) was introduced. Fig. 5.3-a is a small part of DEM in the study area. The runoff flow direction, streams and the data of the cell accumulation were derived based on the DEM using the ArcGIS hydrology analysis tools. The value of each cell in the raster layer of cell accumulation (Fig. 5.3-d) represents the total number of the upper stream cells whose runoff (with nitrate) moves into or through this cell. Since the nitrate export rates and runoff amount are different in one place to another in the real world, the weights of the nitrate export rate and runoff need to be introduced. The weight layer of the nitrate export represents the spatial distribution of the nitrate export rate in different land uses, whilst the runoff weight layer spatially describes the value of runoff potential in the catchment. The final accumulation grid data of nitrate or flow accumulation in each cell were calculated by multiplying the weight layer and the layer of cell accumulation (Fig. 5.3-d). Extra nitrate carried by surface runoff to cell *i* (HH_i) was calculated using Eq. 5.6. In the D-DRASTIC method, all cells including the cells representing streams are treated equally.

Table 5.2.

The reclassification of soils in the study area according to their texture properties

Soil type code in the database	Soil parent material	Sand (%)	Silt (%)	Clay (%)	Soil media classification	Soil rating
BRS	**Shale gravel**	-	-	-	**Gravel**	**A**
BRGN	**Granite gravel**	-	-	-	**Gravel**	**A**
GRGN	**Granite gravel**	-	-	-	**Gravel**	**A**
HRGN	**Granite gravel**	-	-	-	**Gravel**	**A**
HRS	**Shale gravel**	-	-	-	**Gravel**	**A**

RRGN	Granite gravel	-	-	-	Gravel	A
BPS	Shale	41.7~47.8	34.6~39.7	15.7~23.6	Loam	C
BPST	Shale Till	46.3~61.65	22.6~38.8	12.6~15.7	Sandy loam	B
PPS	Shale	41.7~47.8	34.6~39.7	15.7~23.6	Loam	C
SBPGN	Granite	63.4~80.9	15.6~25.7	2.8~10.3	Sandy loam	B
SBPS	Shale	49.8~65.8	20.4~26.4	13.8~23.8	Sandy loam	B
BES	Shale	29.7~50.8	38.6~42.4	14.6~27.9	Loam	C
BEST	Shale Till					
SBES	Shale	29.7~50.8	38.6~42.4	14.6~27.9	Loam	C
SBEST	Shale Till					
SWG1BRT	Basalt Red Sandstone Till	45.4~48.9	24.2~26.6	26.9~28.8	Sandy clay loam	C
SWG1BST	Basalt shale Till					
SWG1BT	Basalt Till					
SWG1GNT	Granite	61.5~68.3	18.8~22.5	10.8~15.5	Sandy loam	B
SWG1RST	Red Sandstone Till	34.5~38.9	38.8~42.1	20.5~25.7	Loam	C
SWG1RT	Red Trias Sandstone Till	61.2~67.5	17.4~20.1	12.5~19.6	Sandy loam	B
SWG1S	Shale	38.3~40.5	41.2~44.1	17.6~18.3	Loam	C
SWG1ST	Shale Till					
SWG2BST	Basalt shale Till	27.2~39.2	33.1~35.1	27.5~37.5	Clay loam	D
SWG2BT	Basalt Till					
SWG2LNCT	Lough Neagh Clay Till	34.7~52.7	28.1~30.5	19.2~35.2	Clay loam	D
SWG2ST	Shale Till	35.8~51.5	31.9~43.1	16.2~21.1	Loam	C
G2ALL	Alluvium	41.0~55.7	25.4~36.7	18.9~22.9	Loam	C
G2OA	Organic Alluvium	25.2~32.7	43.4~43.8	23.4~31.4	Clay loam	D
G3ALL	Alluvium	7.5~21.9	70.0~77.6	0.5~22.5	Silt Loam	C
G3OA	Organic Alluvium	25.2~32.8	43.4~43.8	23.4~31.4	Clay loam	D
SWHGGN	Granite	83.3	13	3.8	Loamy sand	A
SWHGS	Shale	52.7~61.5	36.0~36.4	2.5~10.9	Sandy loam	B
SWHGST	Shale Till	52.7~61.5	36.0~36.5	2.5~10.10	Sandy loam	B
PT (Peat)		-	-	-	Peat	B
URB (Urban)		-	-	-	Impervious	D
WAT (Water)		-	-	-	Thin or Absent	D

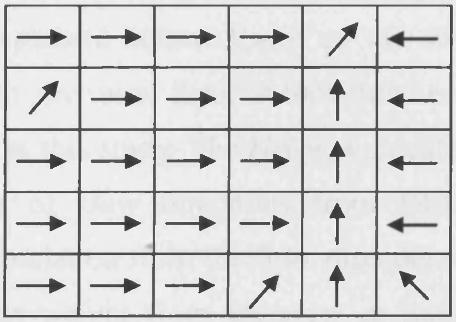
4.2.3. Calculating the nitrate hazard

The nitrate hazard (*H*) includes vertically leaching nitrate (*VH*) and horizontal surface flux (*HH*) in D-DRASTIC. The former is the nitrate part available for leaching process, and the latter is the extra nitrate added by runoff from adjacent areas that may promote the further nitrate leaching and the percolation process into groundwater. In this study, nitrate was regarded as a reactive tracer across the soil-ground profile. The vertical hazard *VH* was calculated using Eq. 5.5. Koo and O'Connell (2005) derived the nitrate-leaching rate with SHETRAN model (Birkinshaw and Ewen, 2000) based on quantified nitrogen mass balance information. The mean nitrate-leaching rate of arable land is 26.4 kg N/ha/yr, grassland 15.5 kg N/ha/yr and woodland 0.4 kg N/ha/yr. These three types of land use cover 92.9% of the study catchment. Since this study has

244	234	222	214	208	209
250	239	223	215	208	213
247	238	225	215	208	220
242	236	226	217	209	221
240	234	227	217	216	217

a. Elevation value

b. Streams derived from cell accumulation



c. Surface water flow direction

1	3	4	5	65	1
0	0	1	2	38	3
0	1	2	3	30	0
10	11	12	13	24	2
0	1	2	3	0	1

d. Cell accumulation

Fig. 5.3. The protocol of the cell accumulation grid calculation based on DEM

focused on the nitrate diffuse water pollution from agriculture sources, the nitrate-leaching rate of other land uses (only 7.1%) were simplified as zero. Net recharge (*NR*), representing the amount of water per unit area of land which penetrates ground surface and reaches water table, is the amount of precipitation minus the surface runoff and evapotranspiration. The mean precipitation and evapotranspiration of 10 years (1990-2000) were interpolated based on the meteorological data from the British Atmospheric Data Centre (BADC).

In the *HH* calculation, the land cover data and soil data were provided by the Centre for Ecology and Hydrology (CEH) and the Department of Agriculture and Rural Development (DARD) of Northern Ireland respectively. Jordan and Smith (2005) calculated the nitrate export coefficient using a backward, stepwise regression of the CORINE land cover (Cruickshank and Tomlinson, 1996). The mean coefficients of the nitrate export for the arable land, the improved grassland and the non-improved grassland are 69.3, 24.4 and 13.3 kg N/ha/yr, respectively. The nitrate export coefficients of other non-agricultural land uses (7.1% of the catchment) were given '0' as explained before. Based on the nitrate export coefficient results from Jordan and Smith, the raster layer of the nitrate export weight was generated using the land cover data in this study. The *HH* was calculated by following process: 1) deriving the raster layer of flow directions from DEM; 2) deriving the raster layer of the cell accumulation from the flow direction data; 3) preparing the raster layer of the nitrate export weight from literature or local studies; 4) deriving the *EC* layer of nitrate export coefficients (Eq. 5.6); 5) preparing the runoff weight layer; 6) deriving the *RO* layer of the surface runoff (Eq. 5.6); and 7) generating the *HH* layer. Fig. 5.4 shows the flow chart of calculating *HH*.

4.2.4. Preparing other factors

Depth to water table, net recharge, aquifer media, soil media, topography, vadose zone media and aquifer hydraulic conductivity were respectively derived and calculated by following DRASTIC standards using GIS database and the data from other investigations or literature in the same area.

5. Results

5.1. D-DRASTIC factors

Fig. 5.5 shows the *VH* result in the study area. *VH* values range from 0 to 24.6 mg N/L. Zones with high *VH* values are located at the lowland area in the middle of the study area where River Bann meets with River Cusher, while low *VH* zones are located at mountain areas to the southeast (Mourne Mountains), east (Slieve Croob) and southwest (source of the Cusher River).

The *HH* result (0~8.9 mg N/L) is shown in Fig. 5.6. The comparison of the calculated *HH* concentration with 29 surface water mean nitrate concentration data of 5 years (1995~2000) was made. These 29 observed data were obtained from different monitoring stations operated by EHS along the rivers/streams in the study area. The linear regression showed a significant correlation between estimated *HH* values and observed nitrate concentrations.

$$HH_{Estimat} = 0.8832 \times HH_{Obs} + 0.3281 \qquad (R^2 = 0.8491) \qquad (5.8)$$

Eq. 5.8 shows that the *HH* result calculated in GIS is reliable to be used as redistributed hazard with runoff for groundwater nitrate risk assessments. The total nitrate hazard to groundwater was calculated using Eq. 5.4 (see Fig. 5.7).

In the study area, the depth to water table were derived from 660 borehole logs that contain the first water strike information. In the layer of ‘depth to water’, comparatively high groundwater pollution potential cells with rating values of 9 and 10 cover 98% of the catchment because of the shallow water table (average value 2.5 m); while cells with value 7 are located in the low-lying area to the middle and northwest of study catchment. In the ‘net recharge’ rating layer, high net recharge ratings 8 (13% of the total study area) and 9 (21%) can be found in mountain areas, whereas low net recharge ratings 1 (31%) and 3 (17%) are located in low-lying area. Moreover, undulating drumlin areas have a moderate net recharge rating 6 (18%) (Fig.

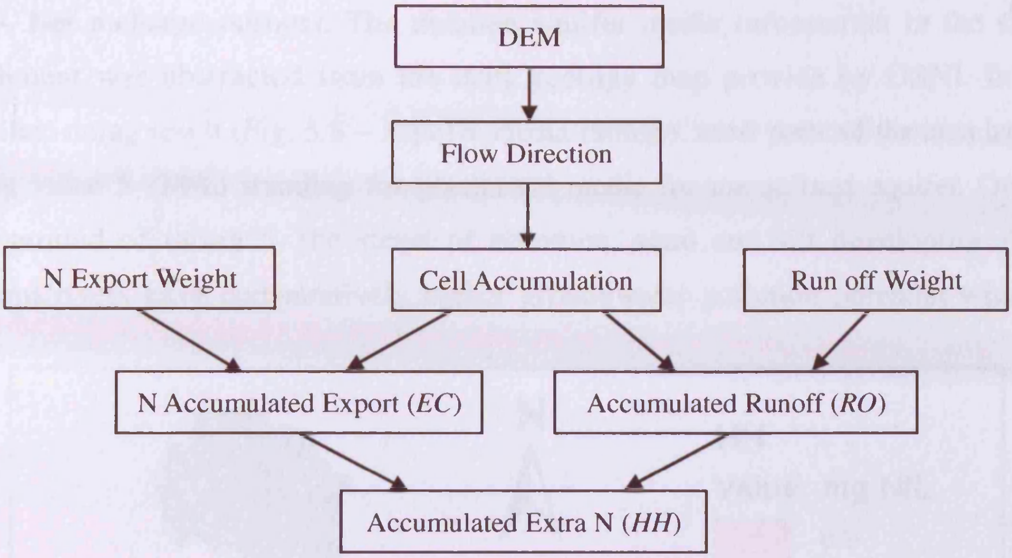


Fig. 5.4. The flow chart of calculating *HH*

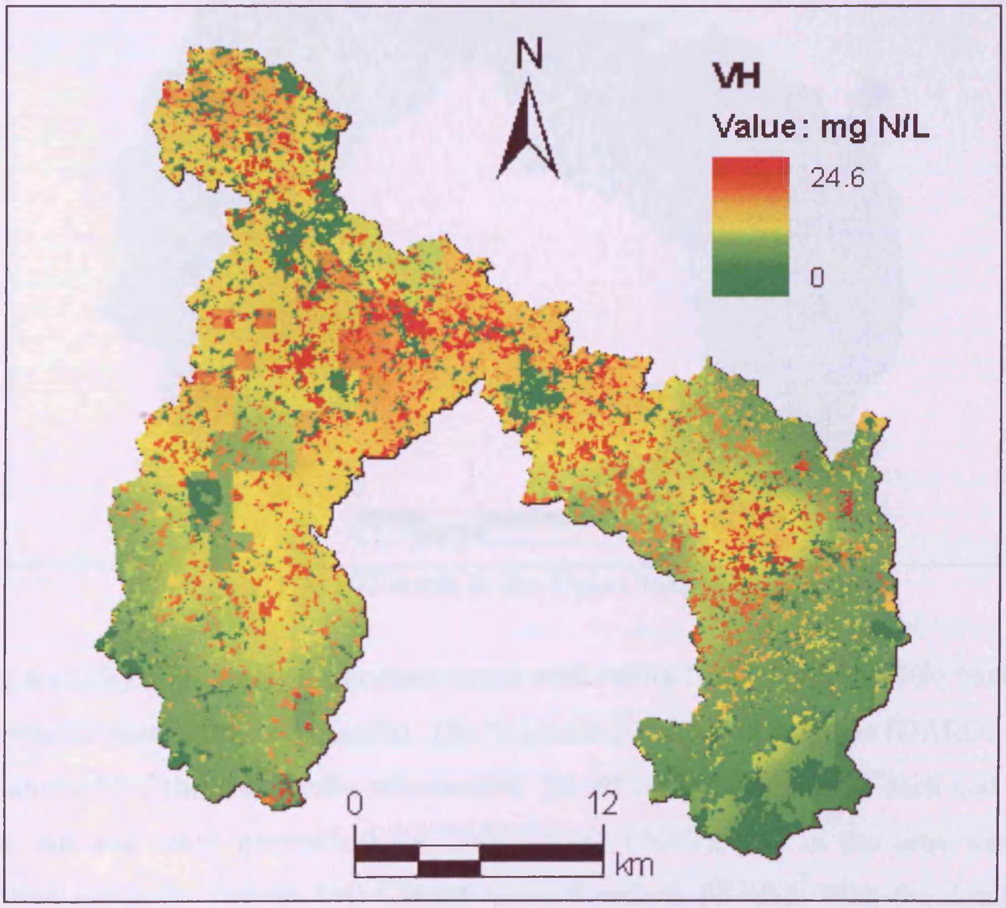


Fig. 5.5. The *VH* result in the Upper Bann Catchment

5.8 – Net recharge ratings). The detailed aquifer media information in the study catchment was abstracted from the drift geology map provide by GSNI. In the 'aquifer' rating result (Fig. 5.8 – Aquifer media ratings), most parts of the area have a rating value 5 (78%) standing for glacial till media for unconfined aquifer. On the background of rating 5, the strips of alluvium, sand and silt developing along streams/rivers have comparatively higher groundwater pollution potential with the rating 6 (11%). Outcrops at mountain areas with rating 2 (1%) and 3 (3%) have the low groundwater pollution potential. The Northern Ireland soil database (DARD, 1997) was adopted for the soil media information. Based on the contents of each soil type (sand, silt and clay) quantified by Cruickshank (1997), soil in the area was re-classified using the British Soil Classification Standard BS3882. With the dominant soil types of 'loam' – rating 5 (52%), 'clay loam' – 3 (16%) and 'sandy loam' – 6

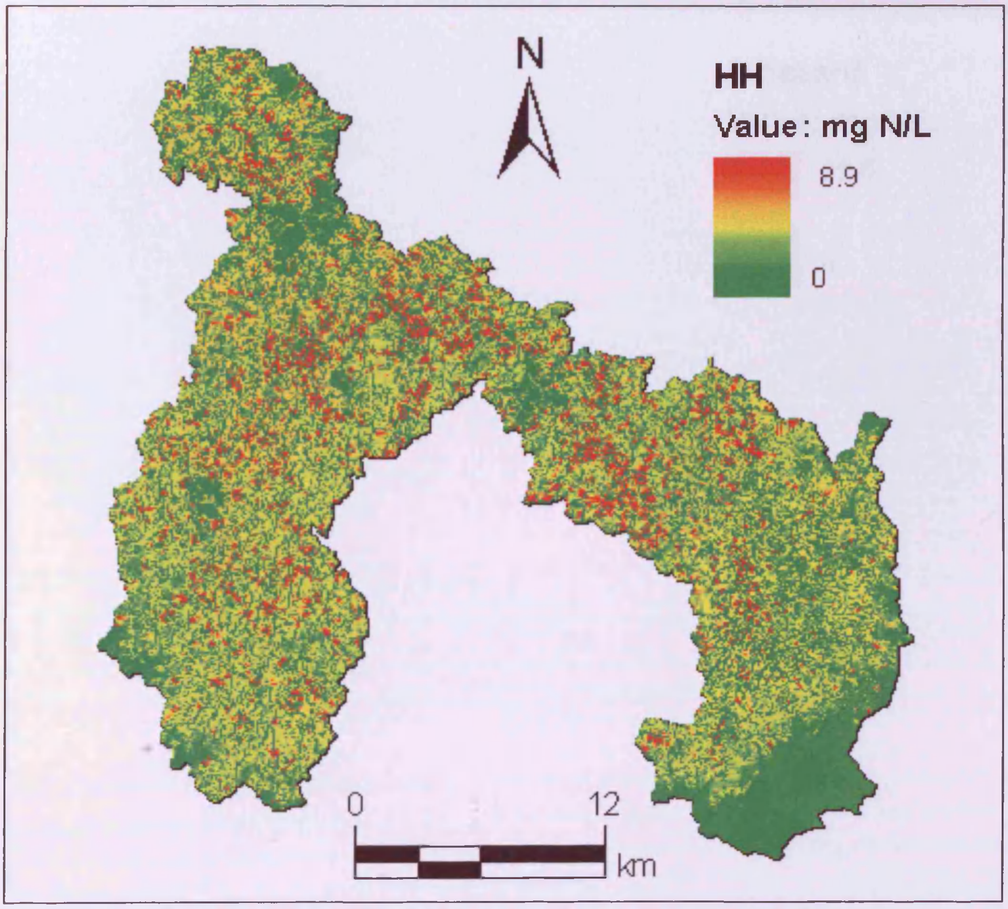


Fig. 5.6. The *HH* result in the Upper Bann Catchment

(15%), the values of soil media rating gradually decrease from mountain areas to low-lying area, except that a small area near the Lough Neagh is covered by peat with higher vulnerability than basalt and till around it (Fig. 5.8 – Soil media ratings). In 'topography' rating layer, steep areas were assigned low rating values because they increase the potential of runoff washing out contaminants, whilst flat areas were given high rating values due to their capability of slowing down runoff and allowing more time for percolation. Steep slope cells with the rating values of 1 (5%) and 3 (10%) are located in the mountain areas to the southeast, southwest and east of the study area, whereas the low-lying area to the northwest of the study area has high ratings of 9 (33%) and 10 (22%). In addition, the undulating area of the rest of the study have the mixture of values of 1, 3, 5 (30%), 9 and 10. In the calculation of 'vadose zone' rating

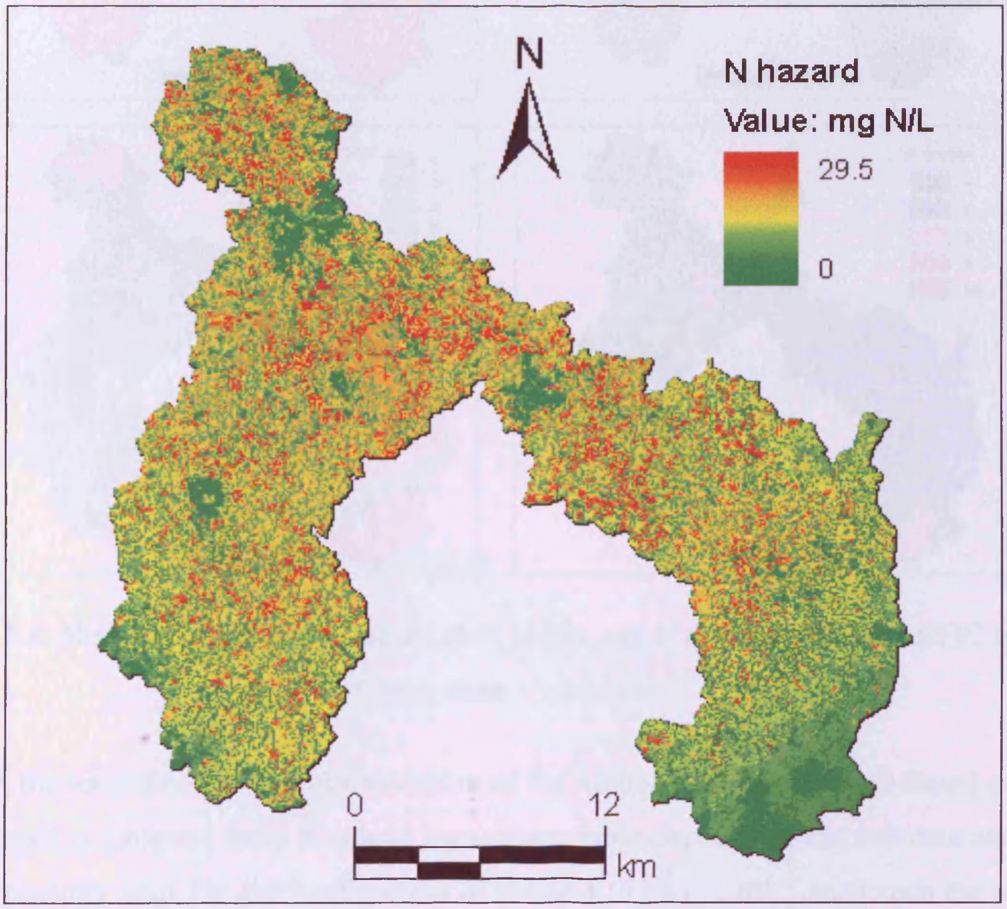


Fig. 5.7. The total nitrate hazard to groundwater in the Upper Bann Catchment

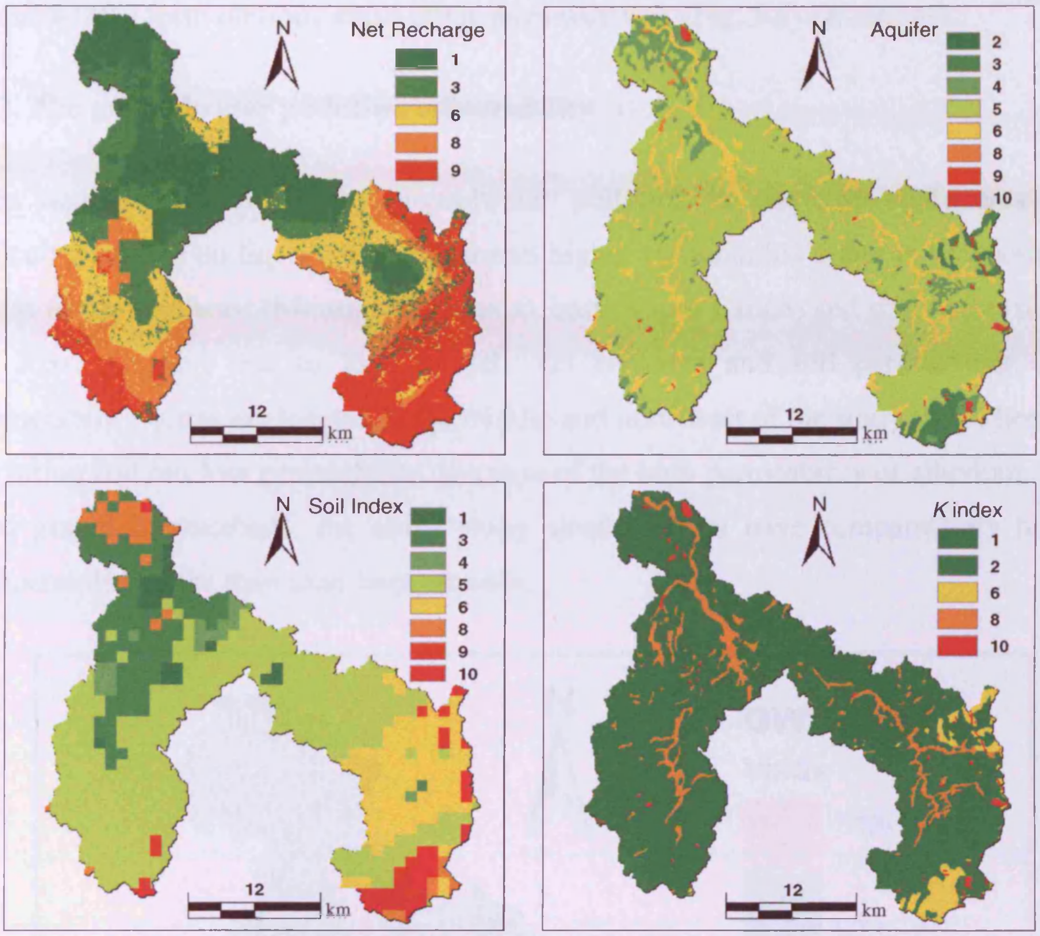


Fig. 5.8. Net recharge, Aquifer media, Soil media and *K* ratings of D-DRASTIC in the Upper Bann Catchment

layer, the identification and classification of the vadose zone media were based on the information gathered from borehole logs, water table depth data, the soil data and the drift geology map. On the background of rating 4 (72%) – 'till ', cells with the rating value 6 (15%), namely, 'alluvium strata', developing along streams/rivers, form distinct strips with comparatively high groundwater pollution potential. High rating values 8 (1%), 9 (1%) and 10 (2%) can be found in mountain areas. The values of aquifer hydraulic conductivity (*K*) were estimated based on the K ranges provided in the DRASTIC method; and validated using values from literature or pumping tests in near areas. In '*K*' rating result, most of parts in the area have comparatively low aquifer permeability with rating values of 1 (81%) and 2 (6%), while cells with rating value 8 (8%) form obvious strips along streams/rivers (Fig. 5.8 – *K* ratings).

5.2. The groundwater pollution vulnerability

The aquifer vulnerability to groundwater pollution in the case study area was calculated based on Eq. 5.2. Fig. 5.9 shows higher vulnerability zones in the mountain areas to the southeast (Mourne Mountains), east (Slieve Croob) and southwest (source of River Cusher) due to high rainfall, net recharge and soil permeability. Low vulnerability zones are located in the middle and northwest of the study area where the covering soil has low permeability. Because of the high permeability of alluvium, sand and gravel in riverbeds, the strips along streams/rivers have comparatively higher vulnerability ranks than their backgrounds.

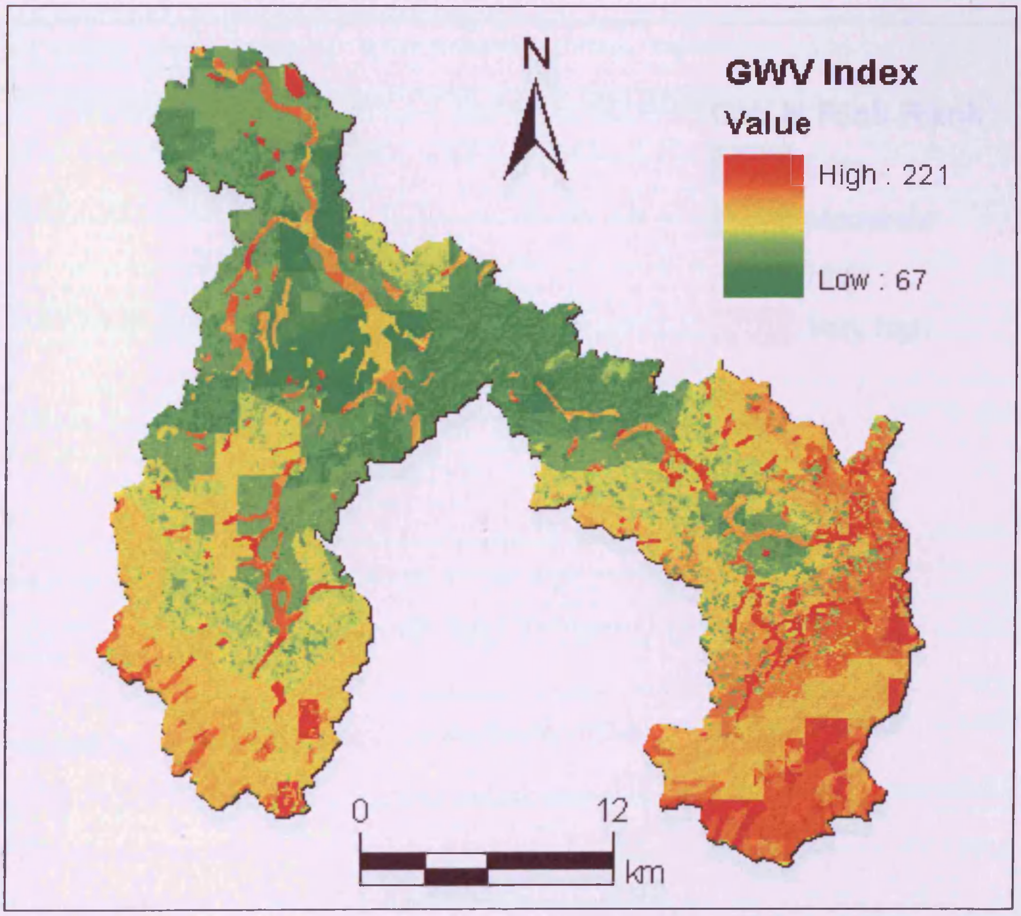


Fig. 5.9. Groundwater vulnerability in the Upper Bann Catchment

5.3. The groundwater nitrate pollution risk

The final nitrate pollution risk of groundwater was calculated using Eq. 5.3. In the study area, the values of DVI_{max}, H_{min} and H_{max} are 221, 0 mg N/l and 29.5 mg N/l respectively. The risk assessment result of groundwater nitrate pollution in the catchment is shown in Fig. 5.10. Four risk ranks were classified using natural breaks method (Jenks, 1967), namely, "low", "moderate", "high" and "very high" groundwater nitrate pollution risk. "Very high" risk zones, 5% of the study area, are located in undulating drumlin and low-lying areas; "high" risk zones, 11% of the area, are found around streams/rivers; "moderate" risk zones occupy 47% of the area; and "low" risk zones, 37% of the area, are found everywhere especially in the Mourne Mountains to the southeast of the study area.

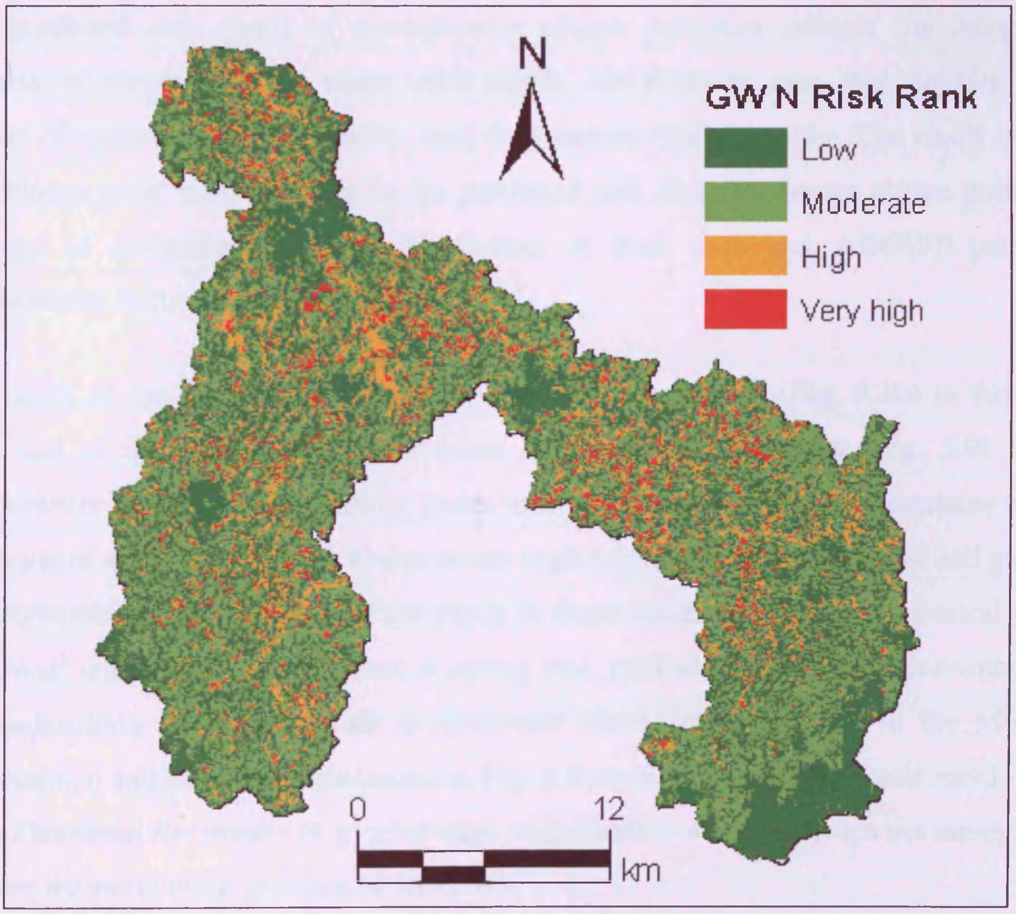


Fig. 5.10. Groundwater nitrate risk assessment in the Upper Bann Catchment

Although there is no high-density groundwater monitoring network in the study area, the observed groundwater nitrate concentration trend, derived from the four groundwater monitoring locations in the study area, is in line with the risk assessment result, tending to validate the model. The groundwater monitoring data show that the nitrate concentrations increase slightly from southeast to northwest in the study area. Within 'very high' risk zones, dominant land cover types are arable horticulture (66%) and improved grassland (24%). Arable horticulture and improved grassland in 'high' risk zones are 22% and 66%, respectively. In 'moderate' and 'low' risk risk zones, the dominant land cover type is improved grassland, while arable land, neutral grass and open dwarf shrub heath occupy relatively small portions of these zones.

6. Discussions

The predicted risk result of groundwater nitrate pollution reflects the integrated impacts of nitrate sources, water table depth, net recharge rate, soil, aquifer type, impact of vadose zone, topography, and the conductivity of aquifer. The result in Fig. 5.10 shows great heterogeneity in the predicted risk of groundwater nitrate pollution because of complicated spatial distributed of land uses and ADGWP pathway vulnerability in the study area.

The result of the D-DRASTIC groundwater risk assessment (Fig. 5.10) is different from that of the DRASTIC groundwater vulnerability assessment (Fig. 5.9). High groundwater pollution vulnerability zones are located in the Mourne Mountains to the southeast of study area (Fig. 5.9) due to the high rainfall, high net recharge and greater soil permeability. However, land use types in these zones are acid grass, neutral grass and dwarf shrub having low nitrate-leaching rate, instead of arable land use with high nitrate-leaching rate. The actual groundwater nitrate pollution risk in the Mourne Mountains is not as high as illustrated in Fig. 5.9 as shown by groundwater monitoring data. Therefore, the results of groundwater vulnerability assessment are not enough for guiding the prevention practice of ADGWP.

In comparison, the result of the D-DRASTIC approach, containing the risk concept and soluble pollutant dynamic nature with runoff, is more helpful in the decision-making of ADGWP management. D-DRASTIC can provide decision maker explicit results, such as “very high” and “high” risk zones, to help them to effectively and efficiently carry out the activities of the groundwater pollution prevention from the diffuse agriculture sources. For example, farmers in “very high” and “high” risk zones may be required to comply with mandatory measures to reduce nitrate-leaching according to the code of good agricultural practice (DARD, 2003), especially for the farmers who are working on the arable land and improved grassland. What the practices of the groundwater pollution prevention really need are both the groundwater pathway vulnerability that spatially indicates the potential zones of groundwater pollution, and the groundwater pollution risk that spatially reflects the actual status of groundwater pollution sources and pathways.

Although this study used nitrate as an indicator, the D-DRASTIC method can be suitable for other soluble pollutants from diffuse agricultural sources with further testing support. In addition, the D-DRASTIC approach is transferable to other areas. Nevertheless, the D-DRASTIC approach should be used in areas greater than 0.405 km^2 due of the DRASTIC assumption.

The D-DRASTIC method may provide a good starting point for better implementation of the EU WFD in the groundwater pollution control at the catchment scale; and could be a complement of coarse screening models in River Basin Management Plans (RBMP) by focusing on the localised catchment scale. The spatial distributed risk zones of groundwater pollution provided by D-DRASTIC can help decision-makers to make plans and carry out ADGWP prevention practices effectively in a specific catchment with high priority of ADGWP management.

When D-DRASTIC is to be applied in other areas, the values of DVI_{max}, H_{min} and H_{max} should be assigned the maximum or minimum value of the study area. If the cell size of raster data is different from 50x50m, the K value in Eq. 5.5 and 5.6 should be recalculated accordingly. Since D-DRASTIC was designed for ADGWP prevention at localised scale, it provides zones with relative high risk of groundwater pollution in a specific catchment, which has high priority of groundwater pollution prevention. The comparison of ADGWP risk levels between catchments is not necessary in the context of localised water prevention.

Denitrification is likely to play a role in reducing the nitrate available for entering into watercourses in Northern Ireland (Jordan and Smith, 2005). However, it was assumed not significant for this study because: (1) denitrification in a catchment can be regarded as spatially homogeneous due to similar soil moisture and temperature conditions within small area; and (2) the denitrification with same value throughout the catchment does not affect the final risk assessment result according to the definition of D-DRASTIC in Eq. 5.3. If D-DRASTIC is to be applied in large areas with heterogeneous conditions of soil moisture and temperature, denitrification process should be considered.

Nitrate loading values used in the D-DRASTIC method in this study were obtained from previous studies. In order to get more accurate result of groundwater risk in a specific area, the nitrate loading values in different land uses could be derived using the process-based water flow and transport simulation models.

7. Conclusions

The GIS-based D-DRASTIC approach developed in this study generates groundwater risk maps by integrating pollutant loading for different land uses and groundwater pollution pathways. By overcoming the drawbacks of DRASTIC in groundwater risk assessment, D-DRASTIC is more helpful in guiding prevention practices for groundwater pollution at the catchment scale. The application of this improved approach in the Upper Bann Catchment showed better presentation of the risk assessment from surface land uses. The D-DRASTIC method can complement the RBMP in the implementation of the EU WFD by acting as a localized tool to guide sustainable groundwater management. In addition, the D-DRASTIC method is transferable other catchments. Further research may be needed to test and improve the suitability of D-DRASTIC for groundwater risk assessment from other soluble pollutants.

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Chapter 6

Selecting and assessing HSPF model for the implementation of the EU Water Framework Directive in handling the diffuse source surface water pollution [*]

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Abstract

A numeric catchment-scale surface water model capable of the simulation of agriculture diffuse water pollution is necessary in sustainable surface water management for better implementation of the EU Water Framework Directive. This paper selects and tests Hydrological Simulation Program – FORTRAN (HSPF) model based on the review of popular surface water models. HSPF was tested in the Upper Bann Catchment, Northern Ireland. The calibrated and validated HSPF model can well represent the characteristics of surface water quantity and quality in the study area. Climate change scenario evaluation results in five years showed that when the annual mean temperature increase 3°Celsius the mean yearly total runoff volume will decrease by 11.1% and the mean daily river flow of five years will decrease by 11.4%. If 20% crop and pasture land is converted into forest land in the study area, the mean river concentration of nitrate, nitrite, NH4 and PO4 in five years will decrease by 19.4%, 33.3%, 31.3% and 31.3% respectively. When applying filter strip method in 80% crop and pasture land in the area, the reduction of the mean concentration of nitrate, nitrite, NH4 and PO4 in five years will be 15.3%, 33.3%, 31.3%, and 5.6% respectively. This study shows that HSPF is a suitable model in handling diffuse source surface water pollution; and can be introduced into the Programme of

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[*] J.L. Wang is the senior author
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Measures in the River Basin Management Plans for better implementation of the EU WFD in the UK.

Keywords: Agricultural diffuse water pollution; Catchment water quality management; Surface water modelling; EU Water Framework Directive; Climate change; Best management practices.

1. Introduction

Water pollution, a global problem, is not only an environmental issue but also an economic and human health problem. As a part of a substantial restructuring of EU water policy and legislation, the EU Water Framework Directive (WFD) was agreed by the European Parliament and Council in September 2000 and came into force on 22nd December 2000 (EC, 2000). The EU WFD sets a framework for comprehensive management of water resources in the European Community, within a common approach and with common objectives, principles and basic measures. The fundamental objective of the Water Framework Directive aims at maintaining "high status" of inland surface waters, estuarine and coastal waters and groundwater where it exists, preventing any deterioration in the existing status of waters and achieving at least "good status" in relation to all waters by 2015. Member States will have to ensure that a co-ordinated approach is adopted for the achievement of the objectives of the WFD and for the implementation of programmes of measures for this purpose.

Agriculture diffuse water pollution (ADWP) has been realised as a major threat for water quality and the biggest remaining problem of water pollution in many countries (Campbell et al., 2004). ADWP is also the main threat for the implementation of the EU WFD (DoE & DARD UK, 2003; Ferrier et al., 2004; Torrecilla et al., 2005). Another serious problem for the implementation of the EU WFD is that all EU member states lack of pragmatic methods and tools to fulfil new tasks from the EU WFD (Mostert, 2003; Giupponi, 2005), and what scientific measures or tools will actually be used or developed for the implementation of the EU WFD, especially in handling the ADWP, is still largely unknown to the EU member states (UK EA, 2005).

Not all water quality problems require a water quality modelling effort. Numeric water modelling, however, is necessary for the catchment ADWP sustainable management. Compared to point pollution, ADWP is more complex and difficult to control due to its numerous and dispersed sources, and the difficulties in tracing its pathways. Suitable numeric ADWP models not only provide the quantitative description of water quantity and quality to temporal and spatial detail, and of the contaminant transformation and transport in the ADWP phases of source – pathway – target, which vary greatly with different natural and farming conditions; but also are capable of evaluating the impacts of management plans on water processes in which the extension and extrapolation of measured data are needed. The quality and complexity of diffuse water pollution model will directly affect the reliability of modelling results. The model of diffuse water pollution should consider these factors: ADWP is a weather-driven process, meteorological conditions (such as, precipitation, air temperature, solar radiation, and wind speed) have obvious influence on the quantity and quality of waters; the effluents from agricultural diffuse source may include pesticides, nutrients, sediments from eroded or overgrazed lands, and microorganisms; soils are the interface between natural and human activity input and the output of water quantity and quality, water and solute processes in soil are necessary in a good ADWP model. Human activities such as farming, urbanisation, and land use make great impact on the status of waters by modifying soil property and structure and changing nutrient chemical process in soil; in reality, a catchment contains not only pervious agricultural land but also impervious urban land; for supporting ADWP management, it is important that a model is capable of evaluating the effectiveness of proposed strategies to reduce the loading of agricultural contaminants into water course under the climate change – an inevitable global problem that we have to face. Therefore, the factors of application scale, contaminant simulation capability, nutrient cycling process in soil, climate change response, both pervious and impervious land use supporting, etc., should be considered in choosing a numeric catchment surface water model for better implementation of the EU WFD in handling the ADWP.

This paper aims to 1) select a proper numeric model for better implementation of the EU WFD in modelling ADWP field based on the review of popular surface water models; 2) assess the selected model - Hydrological Simulation Program – FORTRAN (HSPF) by applying it in water quantity and nutrient quality modelling in the Upper Bann Catchment, Northern Ireland; and evaluating the impact of ADWP management strategies on water quality.

2. Model selection

The choice of the numeric model depends on the objectives of the study. For better implementation of the EU WFD in the ADWP field, water modelling should be able to: 1) get reliable water quantity and quality simulation results; 2) be applied at catchment/watershed scale or larger scale; 3) calculate the complex nutrient bio-chemical process in different soil types; 4) take into account both diffuse and point source pollutions; 5) model the process of the ADWP from both agriculture and urban land uses; and 6) evaluate the impacts of water quality management scenarios on water under climate change.

It was the 1970's and early 1980's when people were realising increasing water pollution problems. In order to deal with diffuse water pollution, scientists have been developing and updating mathematical models to characterise the pollutant loadings and water quality impacts, and more and more water simulation models are available. Models below are the most notable, well known, operational and free models.

Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), a field scale model, was developed by the US Department of Agriculture (USDA) - Agricultural Research Service (ARS) for the analysis of agricultural best management practices (BMP) for pollution control. The model can be get from the website: http://www.wiz.uni-kassel.de/model_db/mdb/creams.html. This model uses separate hydrology, erosion, and chemistry sub-models connected together to calculate runoff volume, peak flow, infiltration, evapotranspiration, soil water content, and percolation on a daily basis; simulate plant nutrients and pesticides; and determine storm load, average concentrations of sediment-associated and dissolved chemicals in the runoff, sediment, and percolation through the root zone (Leonard and Knisel, 1984). User defined management activities, such as aerial spraying, soil incorporation of pesticides, animal waste management, and agricultural best management practices (minimum tillage, terracing, etc.), can be simulated by CREAMS. Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) was developed by the USDA - ARS (Leonard et al., 1987) based on CREAMS. GLEAMS, consisting of three major components namely hydrology, erosion/sediment yield, and pesticides, can be treated as the vadose zone component of the CREAMS model. The soil is divided into various layers, with a minimum of 3 and a maximum of 12 layers of variable thickness are used for water and pesticide routing (Knisel et al., 1989). The limitations of CREAMS/GLEAMS include: 1) the maximum size of the simulated area is limited to a small field plot; 2) they are limited in data management and handling; 3) they can not simulate instream processes; 4) they have limited simulation capability for snow accumulation, melt, and resulting runoff, and hydrologic impacts of frozen ground conditions (Kauppi, 1982; Knisel et al., 1983).

Storm Water Management Model (SWMM) was developed for US EPA as single-event model specifically for the analysis of combined sewer overflows (CSO) (Metcalf & Eddy Inc. et al., 1971; Roesner et al., 1988). The model is available at the website: http://www.epa.gov/ednnrmrl/models/swmm/index.htm. SWMM consists of several modules, namely Runoff, Transport and Extran, designed to simulate both continuous and single event quantity and quality processes in the urban hydrologic cycle. Storm sewers, combined sewers, and natural drainage systems can be simulated. Storage, Treatment, Overflow, Runoff Model (STORM) was developed by the Corps of Engineers Hydrologic Engineering Center of US for the application of the San Francisco master plan for CSO pollution abatement (HEC, 1977). STORM contains simplified hydrologic and water quality routines for continuous simulation in urban areas, and can be used to calculate hourly runoff volumes and depths, snowmelt, dry-weather flows, suspended solids, settleable solids, BOD, total coliforms, ortho-phosphate, and nitrogen. The weaknesses of SWMM and STORM include: They both are urban models; the quality simulation of SWMM is weak in the representation of the true physical, chemical and biological processes that occur in nature; SWMM has weak groundwater simulation capability; STORM uses the quality routines embodied in SWMM with very few modifications; although STORM has less data requirements, its hydrologic routines are too simple for complicated water simulation (Donigan & Huber, 1991; Shoemaker et al., 2005).

Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) was developed by the Agricultural Engineering Department of Purdue University (Beasley and Huggins, 1981). It can be get from the website: http://cobweb.ecn.purdue.edu /~aggrass/models/answers/. The ANSWERS model is capable of predicting the hydrologic and erosion response of agricultural watersheds. Since ANSWERS is a distributed parameter model, its application requires that the watershed to be subdivided into a grid of square elements. The modular program structure of ANSWERS allows easier modification and customising of existing program code. However, there are limitations for ANSWERS: 1) Although ANSWERS has PC version for small watershed application, a mainframe computer is required for a simulation run of ANSWERS on a large watershed; 2)this storm event model requires complex input data preparation; 3) the water quality constituents modelled are limited to nitrogen and phosphorous, and snowmelt processes or pesticides cannot be simulated by the model; 4) nitrogen and phosphorus are simulated using correlation relationships between chemical concentrations, sediment yield and runoff volume, and no transformation of nitrogen and phosphorus is considered (Donigan & Huber, 1991).

Unified Transport Model for Toxic Materials (UTM-TOX) was developed by Oak Ridge National Laboratory for the U.S. EPA Office of Pesticides and Toxic

Substances, Washington, D.C. (Patterson et al., 1983). UTM-TOX includes atmospheric transport, terrestrial ecology and hydrology and Wisconsin hydrologic transport model to establish chemical mass balances, make chemical budgets and to estimate chemical concentrations in the environment. The limitations of this model are: 1) the model ignores the interaction between chemicals and sediment in streams; 2) the model is quite complex and requires significant user expertise; 3) the model concentrates on pesticides and toxic substances.

Pesticide Root Zone Model (PRZM) was developed at the U.S. EPA Environmental Research Laboratory in Athens, Georgia (Carsel et al., 1984). The model's website is: http://www.epa.gov/ceampubl/gwater/przm3/index.htm. PRZM can be used to simulate chemical movement in unsaturated zone within and immediately below the plant root zone using of its hydrology and chemical transport modules. The most recent version of PRZM is included in an integrated root/vadose/groundwater model called RUSTIC (Risk of Unsaturated/Saturated Transport and Transformation of Chemical Concentrations) for the prediction of pesticide fate and transport through the crop root zone, and saturated zone to drinking water wells (Dean et al., 1989). PRZM can not handle lateral flow because of its one-dimensional in the vertical direction; PRZM only simulates downward movement of water and does not account for diffusive movement due to soil water gradients; the model only simulates organic chemicals, for example pesticides.

Agricultural Nonpoint Source Pollution Model (AGNPS) was developed by USDA - ARS (Young et al., 1986). Its homepage is: http://www.wsi.nrcs.usda.gov/products/w2q/h&h/tools_models/agnps/index.html. AGNPS is a distributed parameter model, and can be used to estimate nutrients and sediments in runoff, and to compare the effects of various pollution control practices in watershed management. AGNPS can also handle point source pollutions. The methods used for the prediction of nitrogen and phosphorus yields from the watershed are also used in CREAMS. The methods for nitrogen and phosphorus concentration calculations are similar to ANSWERS. The limitations of AGNPS include: 1) the model does not handle pesticides; 2) the pollutant transport component needs further field testing; 3) nutrient transformation and instream processes are not within model capabilities; 4) it is used only to simulate single event; 5) it is an empirical model; 6) channels are assumed to have a triangular shape (Donigan & Huber, 1991; Shoemaker et al., 2005).

Enhanced Stream Water Quality (QUAL2E) model, a comprehensive and versatile one-dimensional stream water quality steady model, was developed based on Streeter-Phelps model (Streeter and Phelps, 1925) to simulate nutrient dynamics, algal production, and dissolved oxygen with the impact of benthic and carbonaceous demand in streams (Brown and Barnwell, 1987). The model is available at the website: http://www.epa.gov/athens/wwqtsc/html/qual2k.html. Fifteen water quality variables are modelled in QUAL2E. The model is intended as a waste load allocation and water quality planning tool for developing total maximum daily loads (TMDL). It can also be used in conjunction with field sampling for identifying the magnitude and quality characteristics of nonpoint sources. The limitations of QUAL2E include: 1) one-dimensional channel that cannot handle tidal impact; 2) steady flow is not able to model variable flow condition; 3) the model is unsuitable for rivers that experience temporal variations in streamflow or where the major discharges fluctuate significantly over a diurnal or shorter time period (Birgand, 2004).

Simulator for Water Resources in Rural Basins (SWRRB) was developed by modifying CREAMS for evaluating basin scale water quality y by operating on a daily time step and simulates weather, hydrology, crop growth, sedimentation, and nitrogen, phosphorous, and pesticide movement (Williams et al., 1985). Its website is: http://rhino.cee.odu.edu /model/swrrbwq.php. The model considers both soluble pollutants and sediment attached pollutants. The nitrogen and phosphorus calculations are performed using relationships between chemical concentration, sediment yield and runoff volume. However in SWRRB, there is very minimal model documentation; the snow accumulation processes are ignored in the hydrology component; no comprehensive instream simulation is available for pesticides calculation; nutrient transformations along with pesticide daughter products are not accounted for in the model (Arnold et al., 1989).

Soil Water and Analysis Tools (SWAT), a physical-based model, was developed by USDA-ARS in the early 1990s for the prediction of the long-term impact of rural and agricultural management practices (such as detailed agricultural land planting, tillage, irrigation, fertilisation, grazing, and harvesting procedures) on water, sediment and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions (Arnold et al., 1998). It can be downloaded from the webpage: http://www.brc.tamus.edu/swat/. SWAT incorporates features of several ARS models and is a direct outgrowth of the SWRRB and CREAMS model. Since SWAT is a physically based model, watersheds with no monitoring data can be modelled; the relative impact of alternative input data (such as changes in management practices, climate, vegetation) on water quality or other variables of interest can be quantified using readily available inputs. While SWAT can be used to study more specialised processes such as bacteria transport, the minimum data required to make a run are commonly available from government agencies. In addition, the continuous time SWAT model enables users to study long-term impacts. However, SWAT has some limitations: 1) not for simulating sub-daily events such as a single storm event and diurnal changes of dissolved oxygen in a water body; 2) only route one pesticide each time through the stream network; 3) can not specify actual areas to apply fertilisers; 4) a large watershed can be divided into hundreds of hydrologic response units (HRU) resulting in many hundreds of input files, which are difficult to manage and modify without a solid interface; 5) the use of equations that have parameters that are not directly measured by using data. Although efforts have been made to incorporate more process-based equations, some of the basic processes modelled by SWAT still have room for improvement; 6) SWAT has the difficulty in simulating snowmelt; 7) SWAT does not simulate detailed event based flood and sediment routing; 8) SWAT has difficulties in modelling floodplain erosion and snowmelt erosion during the spring and winter months (Peterson and Hamlett 1998; Benaman et al., 2005; Shoemaker et al., 2005).

The SHETRAN system was developed by the Water Resources Systems Research Laboratory (WRSRL) based on the SHE (Système Hydrologique Européen) through the international collaboration between groups in the United Kingdom, Denmark, and France (Ewen, 1995). SHETRAN is a three-dimensional, surface/subsurface, physically-based, spatially-distributed and finite-difference model for water flow, multifraction sediment transport and multiple, reactive solute transport in river basins. It gives a detailed description in time and space of the flow and transport in the basin, which can be visualised using animated graphical computer displays. SHETRAN represents physical processes using physical laws applied on a three-dimensional finite-difference mesh to model hourly flow and transport for periods of up to a few decades. Since SHETRAN is a new model, its limitations need to be discussed in future worldwide applications.

Hydrological Simulation Program – FORTRAN was developed by United States Environmental Protection Agency (USEPA) to represent contributions of sediment, nutrients, pesticides, conservatives and faecal coliforms from agricultural areas; and to continuously simulate water quantity and quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments (Barnwell and Johanson, 1981). HSPF can be downloaded from the website: http://www.epa.gov/ceampubl /swater/hspf/index.htm. By supporting conventional and toxic organic pollutants from both point sources and diffuse sources, HSPF is one of few comprehensive watershed hydrology and water quality models that allow the integrated simulation of land and soil contaminant runoff processes with instream hydraulic, water temperature, sediment transport, nutrients, and sediment-chemical interactions. The runoff flow rate, sediment load (sand, silt, and clay), nutrient and pesticide concentrations, and history time series of water quantity and quality at any point in a watershed can be calculated using this model. The runoff quality capabilities include both simple relationships (namely empirical buildup/washoff and constant concentrations) and detailed soil process options (namely leaching, sorption, soil attenuation, and soil nutrient transformations). HSPF includes the organic chemical transfer and reaction processes of hydrolysis, oxidation, photolysis, biodegradation, a volatilization, and sorption. The instream nutrient processes include DO, BOD, nitrogen and phosphorus reactions, pH, phytoplankton, zooplankton, and benthic algae. Any time step from 1 minute to 1 day can be used, and any period from a few minutes to hundreds of years may be simulated. HSPF is generally used to assess the effects of land-use change, reservoir operations, point or diffuse source treatment alternatives, flow diversions, etc. The limitations of HSPF include: 1) it relies on many empirical relationships to represent physical processes; 2) its lump simulation processes for each land use type at the sub-watershed does not consider the spatial distribution of one land parcel relative to another in the watershed; 3) it approaches a distributed model when smaller sub-watersheds are used, but this may result in increased model complexity and simulation time; 4) it requires extensive calibration; 5) it requires a high level of expertise for application; 6) the model is limited to well-mixed rivers and reservoirs and one-directional flow (Shoemaker et al., 2005).

Among the models reviewed above, HSPF, SWMM, STORM, and CREAMS have persisted for long period of time, while SWAT and SHETRAN are comparatively new and need more reviewing and assessing work. The comparisons of the ADWP models have been carried out. For example, Im et al. (2003) compared HSPF and SWAT and draw conclusion that considering differences in annual loads and the trend of monthly loads, HSPF hydrology and water quality simulation components are more accurate than SWAT. Nasr et al. (2007) compared HSPF, SWAT and SHETRAN and found that HSPF has better river flow simulation and SWAT has better result in total phosphorus simulation. Of all models discussed, HSPF has the most complex mechanisms for the simulation of subsurface water quality processes in both the saturated and unsaturated zones. Although SWMM includes subsurface flow routing, the quality of subsurface water can only be approximated using a constant concentration. HSPF is one of the most detailed, operational models of agricultural runoff and erosion by simulating land surface and soil profile chemical/biological processes that determine the fate and transport of pesticides and nutrients; and by considering of all stream flow components (i.e., surface runoff, interflow and baseflow) and their pollutant contributions. HSPF can model runoff from any land category, including both pervious and impervious urban categories. Since its initial release, HSPF has maintained a reputation as perhaps the most useful watershed-scale hydrology/water quality model that is available within the public domain (Donigian and Imhoff, 2002). As a proven and tested continuous simulation watershed model, HSPF has been widely reviewed and applied throughout its development cycle since 1980 (Ng and Marsalek 1989; Rahman and Salbe, 1995; Ross et al., 1997; Brun and Band, 2000; Albek et al., 2004; Shoemaker et al., 2005; Luo et al., 2006). Although HSPF has its limitations, so far it comparatively well meets the demands of ADWP modelling studies than other models. However, more studies are needed in assessing the suitability of HSPF in the implementation of the EU WFD in the ADWP field.

3. Materials for model assessment

3.1. Study area

The Upper Bann Catchment, Northern Ireland is the study area in this study. The details of the conditions of the study area are given in appendix A.

3.2. Data

Digital Elevation Model (DEM) data, vector river network data and river chemical quality monitoring data were obtained from Environmental Heritage Service (EHS); land cover data was provided by Centre for Ecology & Hydrology (CEH), while soil data was acquired from the Department of Agriculture and Rural Development (DARD) of Northern Ireland; weather data, such as hourly precipitation, air temperature, wind speed, and dewpoint, were provided by British Atmospheric Data Centre (BADC); Catchment and watersheds boundaries were derived from DEM data. A multi-sphere GIS database, which supports both raster and vector data formats, was built for this study. All data mentioned above and data derived, such as catchment outline, river network, topography in Triangle Irregular Network format, flow direction, flow accumulation, stream segmentation, sub-catchment grid data, catchment polygon data, drainage point of each sub-catchment, were input into this GIS database. All raster data in this study have the resolution of 50m×50m.

3.3. HSPF development and interface

With its predecessors dating back to the 1960s, HSPF is the culminating evolution of the Stanford Watershed Model (SWM) (Crawford and Linsley, 1966), watershed-scale Agricultural Runoff Model (ARM) (Donigian et al., 1977), Nonpoint Source Loading Model (NPS) (Donigian & Crawford, 1976) and Sediment and Radionuclides Transport (SERATRA) (Onishi and Wise, 1979). HSPF is currently in version 12.2 (Bicknell et al., 2005). In order to improve the efficiency of using HSPF, WinHSPF was designed as an interactive Windows interface to HSPF, and fully-integrated into a multipurpose environmental analysis system - Better Assessment Science Integrating point and Nonpoint Sources (BASINS) system, developed by United States Environmental Protection Agency (USEPA) based on Geographic Information System (GIS) foundation for performing watershed and water quality-based studies (Lahlou et al., 1998). User control input (UCI) files are used for data exchange among WinHSPF, BASINS and GIS. Within the BASINS system, WinHSPF is intended to be used in conjunction with the interactive program known as "GENeration and analysis of model simulation SCeNarios," (GenScn) to analyse results of model simulation scenarios and compare scenarios. HSPF was applied through BASINS and WinHSPF software packages.

3.4 Theoretical description of HSPF

HSPF uses the concept of HRU to divide the watershed into homogeneous segments. In each HRU, the soil layer is vertically divided into three layers (storages), i.e., upper-zone, lower-zone and active groundwater. The water flux and evapotranspiration in each HRU are calculated respectively according to the moisture conditions in these three storages. Horizontally, three types of flow components, i.e., surface runoff, interflow, and active groundwater, contribute to the streamflow routed by a nonlinear function. As Fig. 6.1 illustrates, HSPF has four application modules, i.e., PERLND for pervious land segments, IMPLND for impervious land segments, RCHRES for river reaches and well-mixed reservoirs, and BMP for simulating constituent removal efficiencies associated with implementing management practices

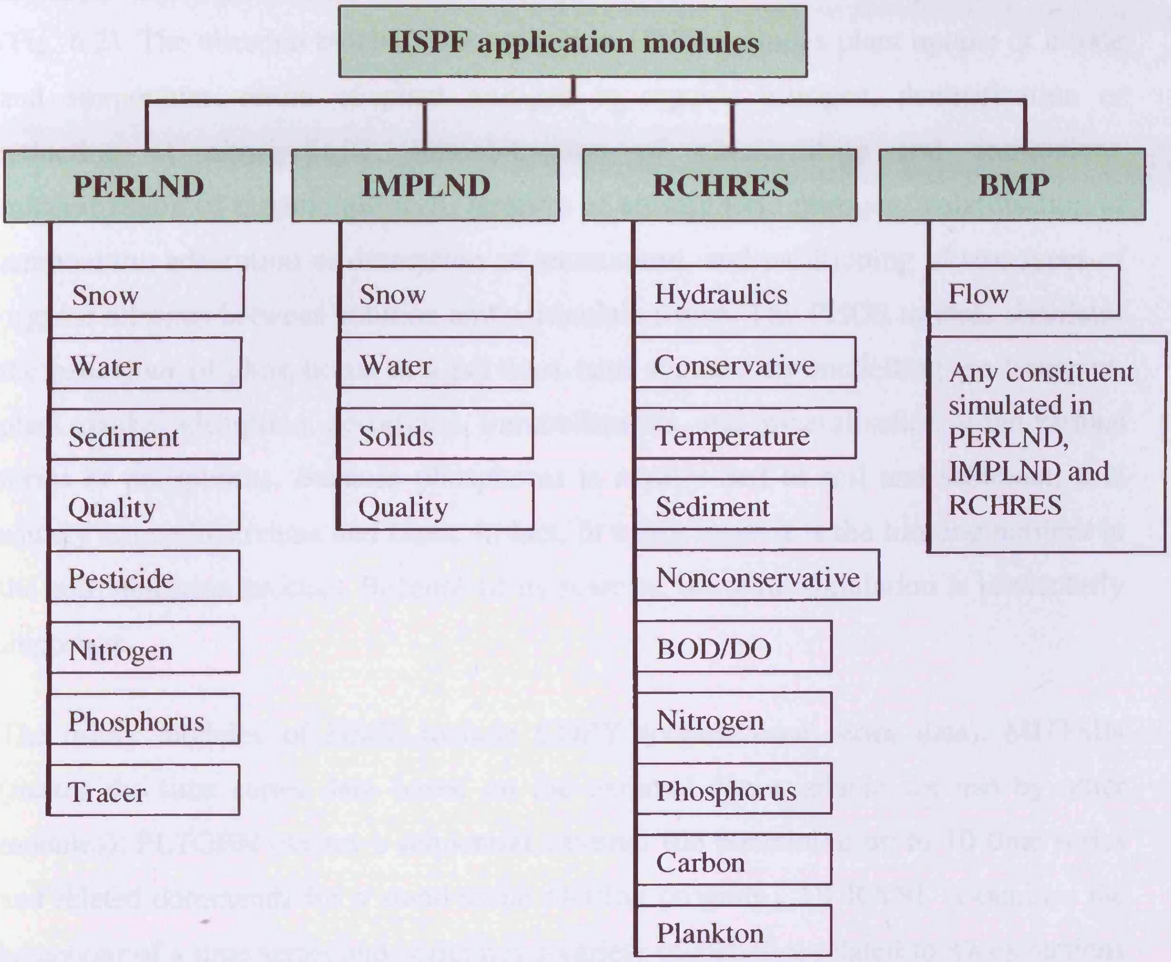

Fig. 6.1. HSPF application modules and their capabilities

(Donigian and Imhoff, 2002; Bicknell et al., 2005). PWATER, key component of module PERLND, was designed to calculate the components of the water budget, and to predict the total runoff from a pervious area. The algorithms used to simulate these land related processes, the product of over 15 years of research and testing, are based on the original research for the LANDS subprogram of the SWM IV (Crawford and Linsley, 1966). PERLND and IMPLND processes are simulated through water budget, and the generation and transport of water quality constituents and sediment. Empirical equations are adopted in HSPF for the calculations of interception, evapotranspiration, overland flow, interflow, infiltration and groundwater loss processes. Sediment production in HSPF is based on detachment and scour from a soil matrix and transport by overland flow in pervious areas, whereas solids buildup and washoff are simulated for impervious areas. HSPF includes modules to simulate nutrients cycling processes (Fig. 6.2). The nitrogen biochemical process in HSPF includes plant uptake of nitrate and ammonium, return of plant nitrogen to organic nitrogen, denitrification or reduction of nitrate-nitrite, immobilisation of nitrate-nitrite and ammonium, mineralization of organic nitrogen, fixation of atmospheric nitrogen, volatilisation of ammonium, adsorption or desorption of ammonium, and partitioning of two types of organic nitrogen between solution and particulate forms. The PHOS module simulates the behaviour of phosphorus in a pervious land segment by modelling the transport, plant uptake, adsorption, desorption, immobilisation, and mineralization of the various forms of phosphorus. Because phosphorus is readily tied to soil and sediment, it is usually scarce in streams and lakes. In fact, in many cases it is the limiting nutrient in the eutrophication process. Because of its scarcity, accurate simulation is particularly important.

The utility modules of HSPF include COPY (copies time series data), MUTSIN (makes the time series data based on the external file available for use by other modules), PLTGEN (writes a sequential external file containing up to 10 time series and related commands for a stand-alone plotting program), DURANL (examines the behaviour of a time series and computes a variety of statistics related to it's excursions above and below certain specified levels), GENER (performs any one of several transformations on one or more input time series), DISPLY (prints time series data in a tabular format and summaries of the data) and REPORT (produces time series output in a very flexible fashion).

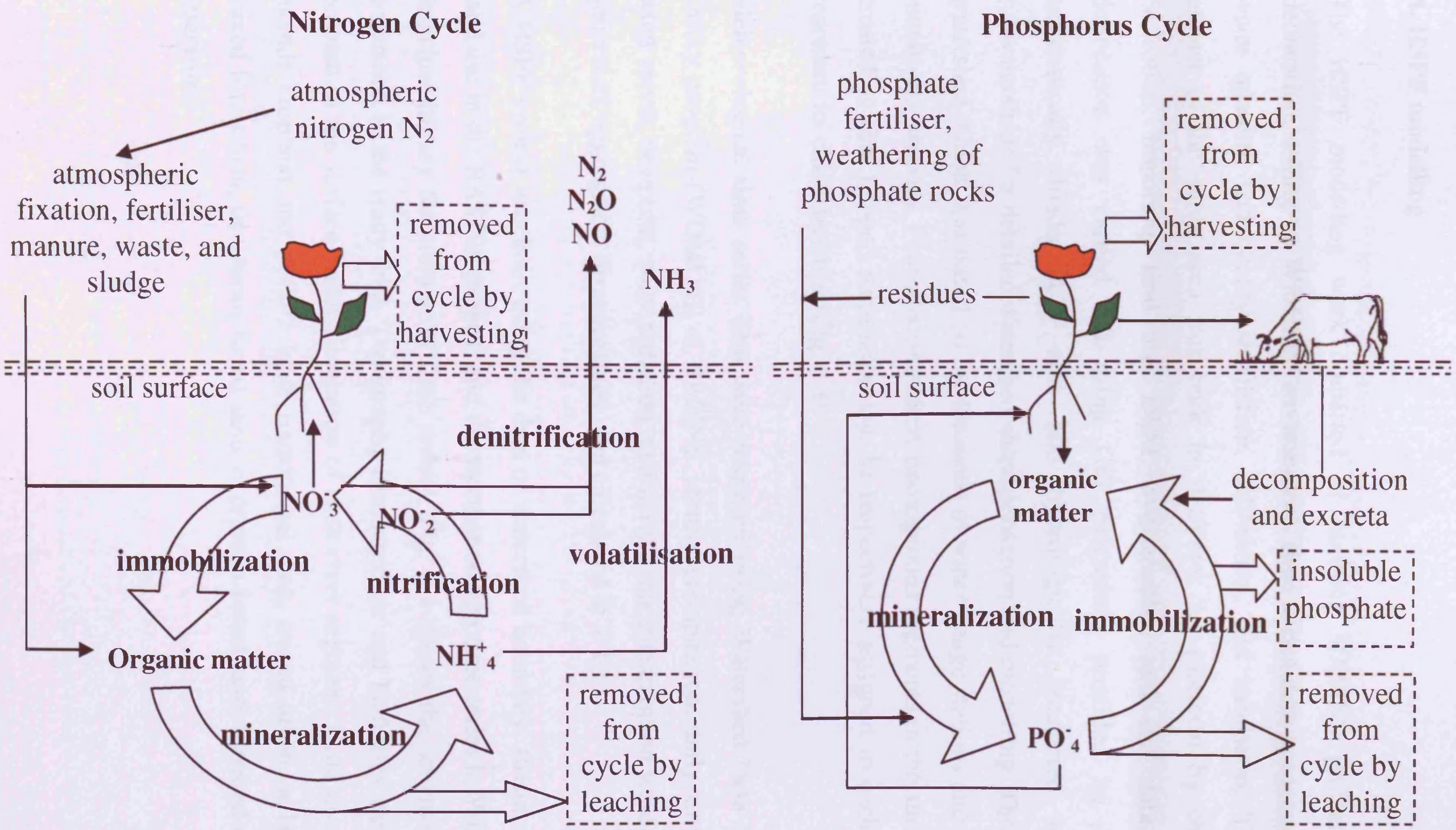

Fig. 6.2. Schematic representation of nitrogen and phosphorus cycles

4. HSPF modelling

The HSPF modelling work consisted of building BASINS project, watershed delineation, setting up WinHSPF environment, time series data preparations, surface water quantity and quality simulation, calibration, and validation. The BASINS project of the study area was built in ArcView 3.1 platform by choosing data projection, importing land use, DEM, hydrography, and soil data. Watershed delineation was carried out using GIS extensions provided by BASINS to automatically divide study area into hydrologically connected segments or subwatersheds for detailed watershed characterisation and modelling. The selection of watershed outlets was based on the locations of water gauge stations and river quality monitoring stations. Four approximately homogenous segments in the study area were created so that lumped parameters can be respectively assigned to each segment to represent its characteristics (Fig. 6.3).

Meteorological time series data were managed using Watershed Data Management Utility program (WDMUtil) of BASINS. Hourly precipitation, daily air temperature, wind speed, dewpoint, solar radiation, and daily evapotranspiration were reformatted, generated, aggregated, disaggregated, and calculated in WDM.

A HSPF project was built using the data of watershed boundary, streams, outlets and land use in the BASINS project, and the weather station time series in WDM files (the principal library for storage of time series). Fig. 6.4 shows the schematic of HSPF watershed in the study area. Topography characteristic and land uses were taken into account in the surface water simulation of each river segment. Land uses in the area include cropland and pasture land, transitional area, mixed urban or built-up land, mixed forest land, deciduous forest land, evergreen forest land, forested wetland, and reservoirs.

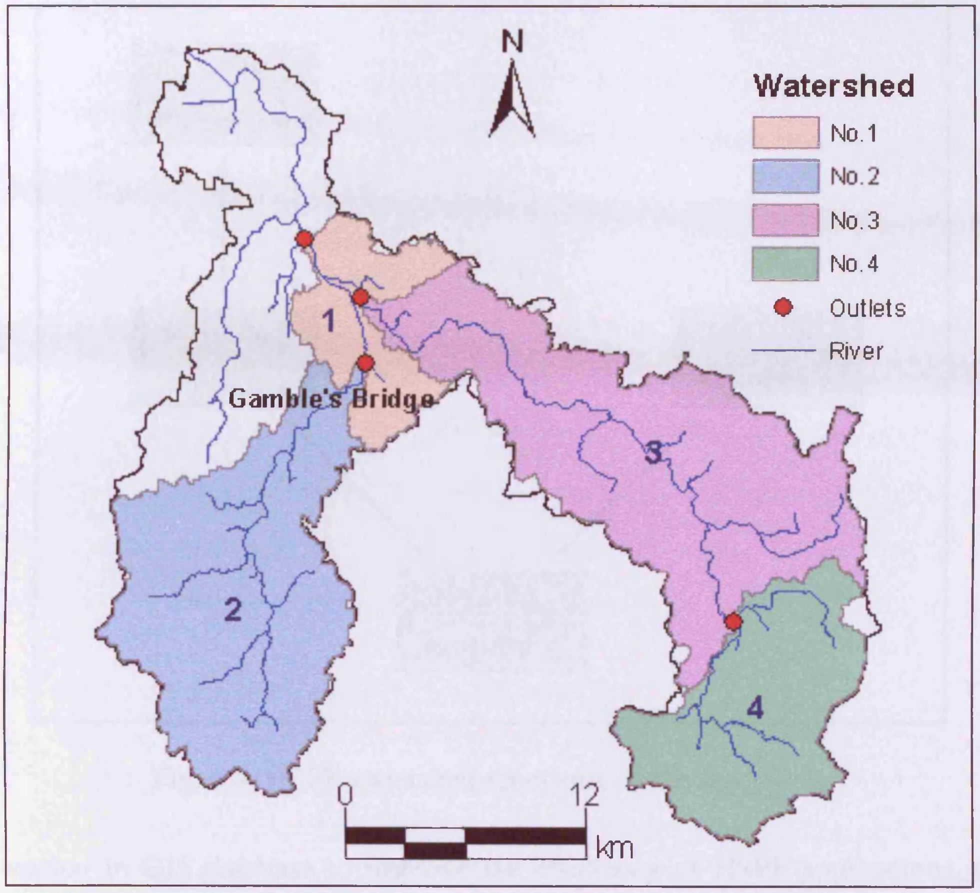

Fig. 6.3. Watershed delineation result in the study area

4.1. Parameter estimation

When a HSPF project was created from BASINS, an UCI file was created to hold and supply parameters to HSPF. The estimation of a large array of parameter values was required to quantitatively represent/depict watershed hydrological cycle and water quality. Although BASINS can estimate many parameter inputs using available

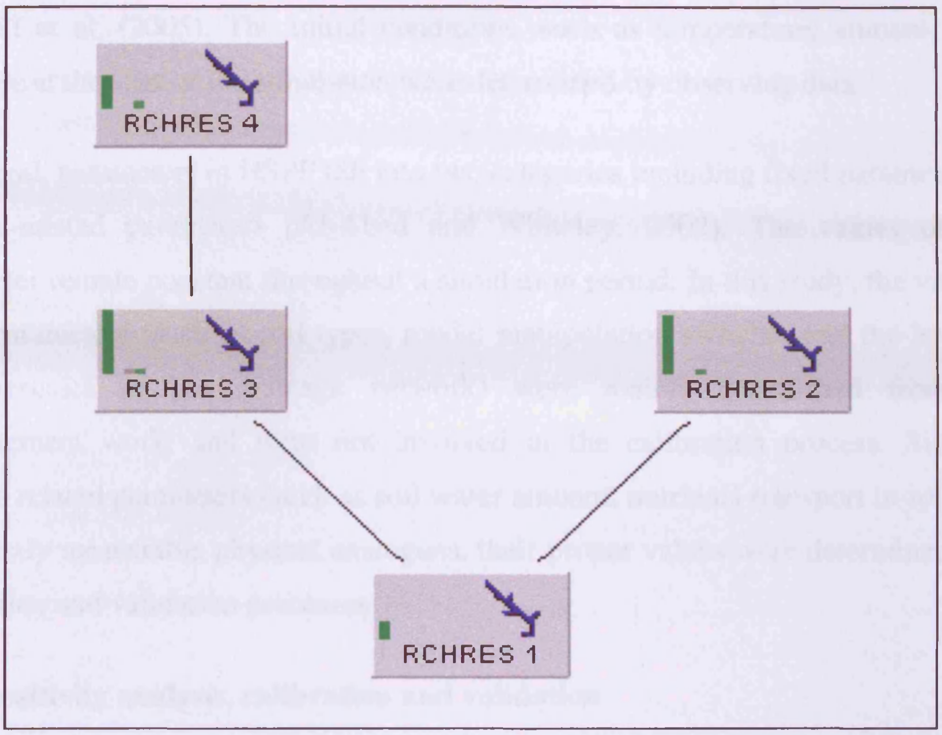

Fig. 6.4. HSPF watershed schematic of the study area

information in GIS database to improve the efficiency of HSPF applications, these values could be highly inaccurate and should be manually modified if more accurate information is available. Based on these initial parameter values, manual parameter estimation work were carried out using monitoring data and the results of previous researches and experiments in the study area. In order to reduce the uncertainty of water modelling, the recommended value ranges of key parameters provided in HSPF manual were referenced. The important parameters of HSPF include AGWRC, INFILD, INFILT, INTFW, INFEXP, IRC, KVARY, LZETP, LZS, LZSN, PETMAX, and UZSN, etc. (hydrologic component); AFFIX, KSER, JSER, KGER, COVER, JGER, KRER, KSER and SMPF, etc. (sediment component); SQO, POTFW, POTFS, ACQOP, SQOLIM, IOQC, KBOD20, TCBOD, KODSET, SUPSAT, BRNIT, VRPO4, KTAM20, KNO220, TCNIT, KNO320, TCDEN, DENOXT, ALR20, ALDH, ALDL, OXALD, NALDH, PALDH, KAM and KMP, etc. (Nutrients, dissolved oxygen and algae components). The detailed description of HSPF parameters can be found in

Bicknell et al. (2005). The initial conditions, such as temperature, amount of soil moisture at the start of the simulation were determined by observing data.

In general, parameters in HSPF fall into two categories including fixed parameters and process-related parameters (Al-Abed and Whiteley, 2002). The values of fixed parameter remain constant throughout a simulation period. In this study, the values of fixed parameters (such as soil types, model manipulation switches and the hydraulic characteristics of the drainage network) were mainly established from field measurement work; and were not involved in the calibration process. Since the process related parameters (such as soil water amount, nutrients transport in soil) have no directly measurable physical analogues, their proper values were determined in the calibration and validation processes.

4.2. Sensitivity analysis, calibration and validation

Sensitivity analysis can test the overall responsiveness of the model to certain input parameters (Oyarzun et al., 2007), thus pointing out the critical parameters that need to be carefully investigated through data gathering and field studies for reliable modelling output. Additionally, sensitivity analysis can be treated as a way of understanding the general behaviour of a model in evaluating its confidence and in interpreting results during the calibration phase (Kleijnen, 2005).

The sensitivity analysis in this study started from carrying out a baseline model run. The value for each parameter in the baseline simulation were worked out by considering the recommended value ranges given in the HSPF manual, available field and laboratory data, and averaged literature values in past modeling studies. Then, important parameters in the hydrologic, sediment, nutrient and biochemical processes involved in the HSPF were selected. These parameters include CEPSC, interception storage capacity; INFILT, infiltration parameter; IRC, interflow recession parameter; INTFW, interflow parameter; UZSN, upper zone nominal storage; LZSN, lower zone nominal storage; LZETP, lower zone evapotranspiration parameter; AGWRC, groundwater recession rate; DEEPFR, fraction of groundwater inflow to deep recharge;

BASETP, fraction of remaining ET from baseflow; AGWETP, fraction of remaining ET from active groundwater; KVARY, groundwater recession flow; INFEXP, exponent of infiltration; INFILD, ratio between maximum and mean infiltration capacities; SLSUR, slope of the assumed overland flow plane; KBOD20, BOD decay rate; KNO320, denitrification rate of nitrate; TCNIT, temperature coefficient for the nitrogen oxidation rate; KTAM20, oxidation rate of total ammonia; KNO220, oxidation rate of nitrites; TCDEN, temperature coefficient for the denitrification rate; DENOXT, oxygen concentration threshold above which denitrification ceases; and MALGR, maximal algal growth rate for phytoplankton. All of these are process-related parameters.

Two sensitivity analysis runs were carried out by using a high (200% of the upper range of the parameter) and a low (50% of the value of the lower range of the parameter) value. Results of 46 model runs in this study were compared to the result of the baseline model run to determine the relative sensitivity of model results to specific model parameters. The sensitivity analysis highlighted the 10 most important parameters in surface water quality and quantity simulation in this study, namely, INFILT, UZSN, IRC, LZSN, AGWRC, DEEPFR, BASETP, AGWETP, KBOD20, KNO320, KNO220, TCNIT, TCDEN, and DENOXT. The calibration of this study was carried out based on these important parameters.

Calibration is an iterative process used in establishing the most suitable values for process related parameters. The important water flow and quality parameters found in the sensitivity analysis were calibrated and validated in the watershed 2 (Fig. 6.3) for Gamble's Bridge station having monitoring data. Hourly precipitation, hourly air temperature, daily maximum and minimum temperature, solar radiation, evapotranspiration were from weather station "Glenanne_Saws" in the watershed 2. Weather data between 2000 and 2005 were used for river flow quantity and quality simulations. River flow data from 2000 to 2003 were used for river flow calibration. In calibration process, parameters in HSPF were adjusted by comparing the difference between the simulated and observed river flow data using the GenScn module in the

BASINS. Flow duration curve and scatter plot methods were used in this process. In order to reduce the parameter uncertainty, only one parameter was adjusted each time. More than 30 runs were carried out before reaching the satisfied simulation results. Below are calibrated values of important parameters of HSPF. INFILT: 8.15 – 19.05 (mm/h) for different land uses; UZSN: 28.8 (mm); IRC: 0.65 l/day; LZSN: 72 mm; AGWRC: 0.992 1/day; DEEPFR: 0.25; BASETP: 0.12; AGWETP: 0.1; KBOD20: 0.1 1/h; KNO320: 0.05 1/h; KNO220: 0.05 1/h; TCNIT: 1.01 1/h TCDEN: 1.02 1/h; and DENOXT: 1.6 1/h.

The calibrated hydrological parameters in HSPF were then validated using river flow data between 2004 and 2005. Then, nutrients, i.e., NO3, NO2, NH4 and PO4 were simulated, calibrated and validated respectively. River chemical quality monitoring data between year 2000 and 2003 were used for model calibration, while the data from year 2003 to 2005 were used for model validation. The HSPF model well calibrated and validated using monitoring water data in one area can properly describe the characteristics of water quantity and quality processes in this area.

4.3. Scenarios evaluation

4.3.1. Climate change scenario

Climate change is one of the most important global environmental problems due to the global warming caused by the increasing concentration of greenhouse gases. Most of studies predict increasing future temperature. For example, Yanshin (1991) predicted that annual mean temperatures will rise about 2°Celsius by 2025 and 3°Celsius by 2050. In this study, it was assumed that the mean annual temperature will increase 3°Celsius during next 50 years, and other weather features such as solar radiation, wind pattern, and precipitation, will not to change. To simulate the river flow based on calibrated and validated model for this scenario, the monitored hourly temperature data in five years were manually modified by adding 3°Celsius. Since temperature has great impact on evaporation, potential evapotranspiration and pan evaporation were re-calculated using Jensen and Haise (1963) formula and Penman (1948) formula respectively.

4.3.2. Land use change scenario

Generally the crop and pasture land uses have higher nutrient loading rates than other land uses in the diffuse water pollution. The water quality and quantity will be affected by the change of land use in the watershed. In this scenario, it was supposed that decision makers are going to convert 20% crop and pasture land (3104 ha) into forest land; other conditions such as climate, agricultural activities, soil and topography will not to change. The areas of land uses in the watershed 2 were manually modified in the calibrated and validated HSPF model. The change of land uses had no spatial distribution concept in this study because of the lumped parameter characteristic of the HSPF model.

4.3.3. BMP scenario

In the ADWP management, BMP are effective, practical, structural or non-structural methods which prevent or reduce the movement of sediment, nutrients, pesticides and other pollutants from the land to the water course. In this study, it was assumed that the filter strip method, one of BMP, is to be implemented in 80% crop and pasture land in the study watershed and all other conditions will keep unchanged. The BMP scenario was set in the "BMP" module of HSPF.

5. Results

5.1. River flow simulation

Flow duration curve is a plot that shows the percentage of chance that flow in a stream is likely to equal or exceed some specified value of interest. For each frequency in the range from 0 to 100 percent in X-axis, the flow that will be exceeded is plotted on the Y-axis. Ideally, simulated and observed flow duration curves should be very similar.

Fig. 6.5 shows that simulated and observed river flow from 2000 to 2003 correlated well in frequency. Fig. 6.6 is the scatter plot of the simulated flow against the observed flow. The closer the data comes to falling on a 45° angle line, the better the two data sets match. The result of Fig. 6.6 also shows that the model was well calibrated in study area. The calibrated hydrological parameters of the HSPF model in the study area were then validated using data from 2004 to 2005 (Fig. 6.7). All results show that HSPF hydrological component was well calibrated. The mean value of runoff components (including surface runoff, interflow, and baseflow) and evaporation for each land use (2000-2005) were calculated from the calibrated HSPF model (Fig. 6.8). Crop and pasture land has highest interflow whilst mixed urban land has highest surface runoff.

5.2. River quality simulation

Compared with the nutrient simulation results having daily interval time series data, the river quality monitoring data were limited in number with monthly interval.

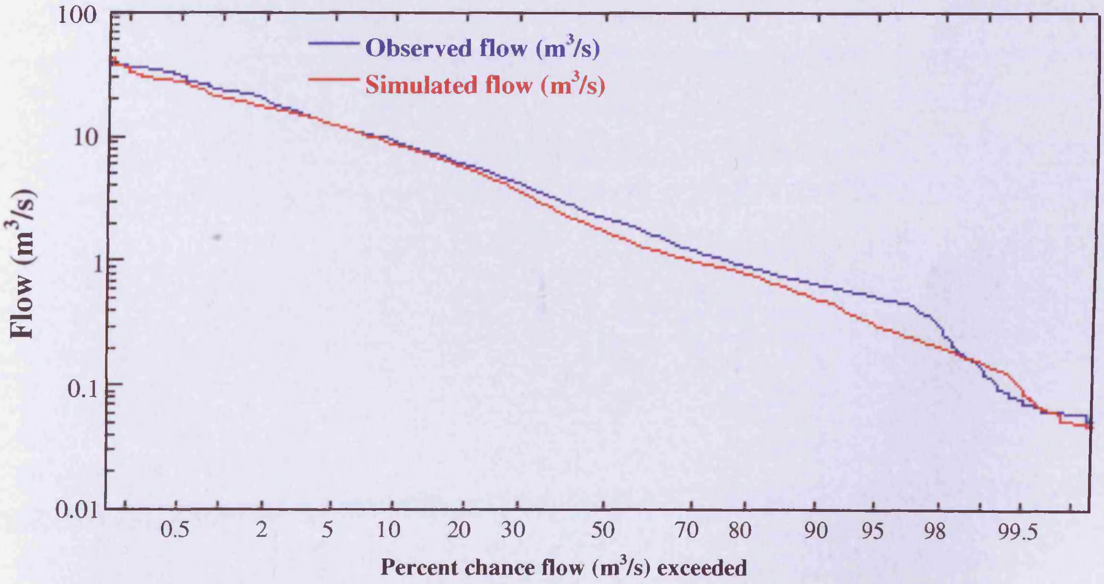

Fig. 6.5. Flow duration curves of simulated and observed river flow (2000-2003)

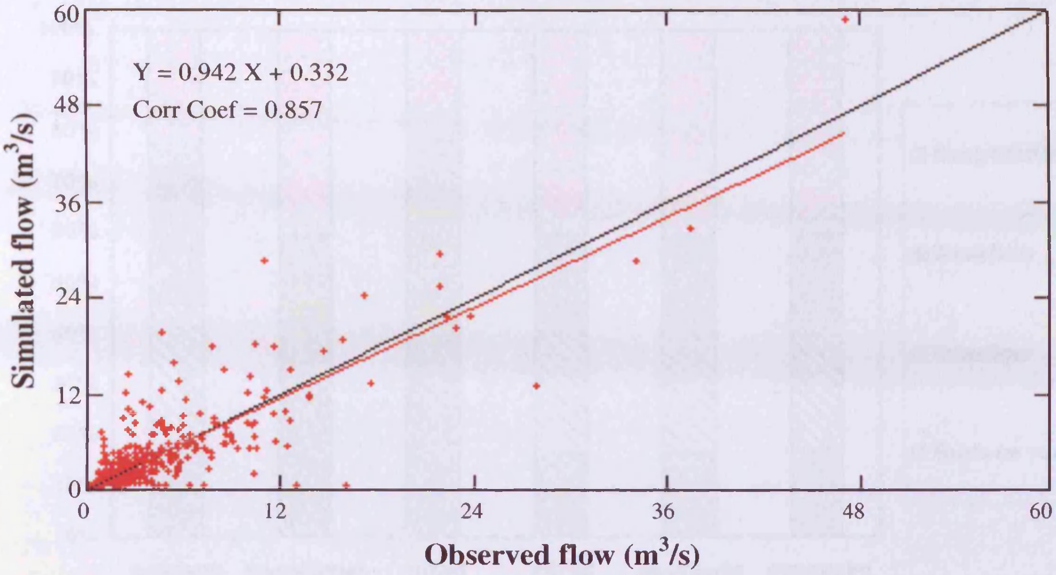

Fig. 6.6. Scatter plot of simulated and observed river flow (2000-2003)

Therefore simple statistic methods (such as count, percent, mean and standard deviation) instead of complex statistic methods (such as correlation coefficient and coefficient of determination) were used for model calibration and validation. The

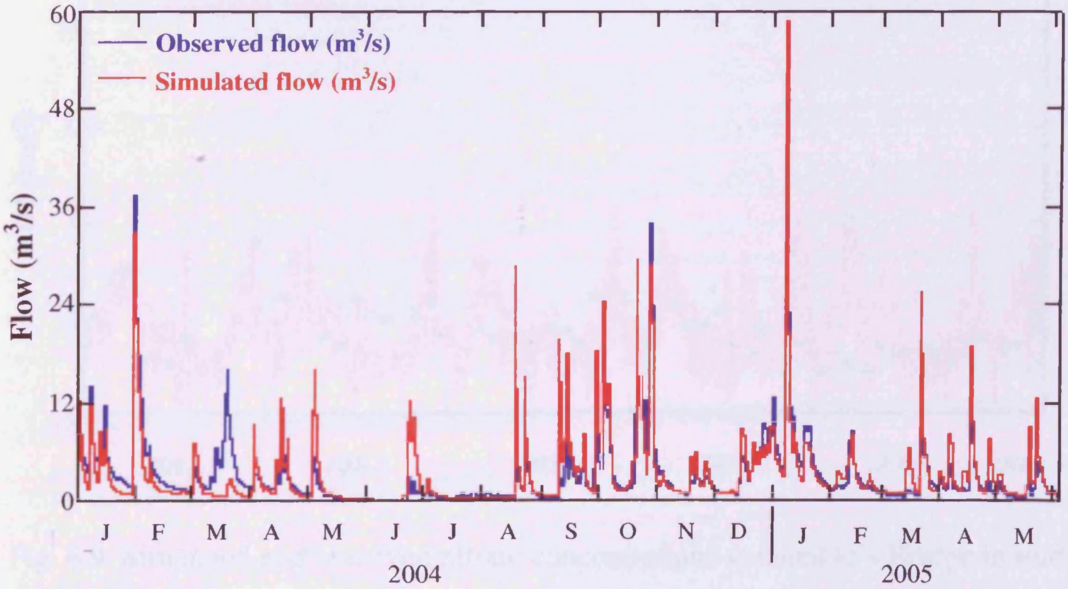

Fig. 6.7. Model validation using simulated and observed river flow data (2004-2005)

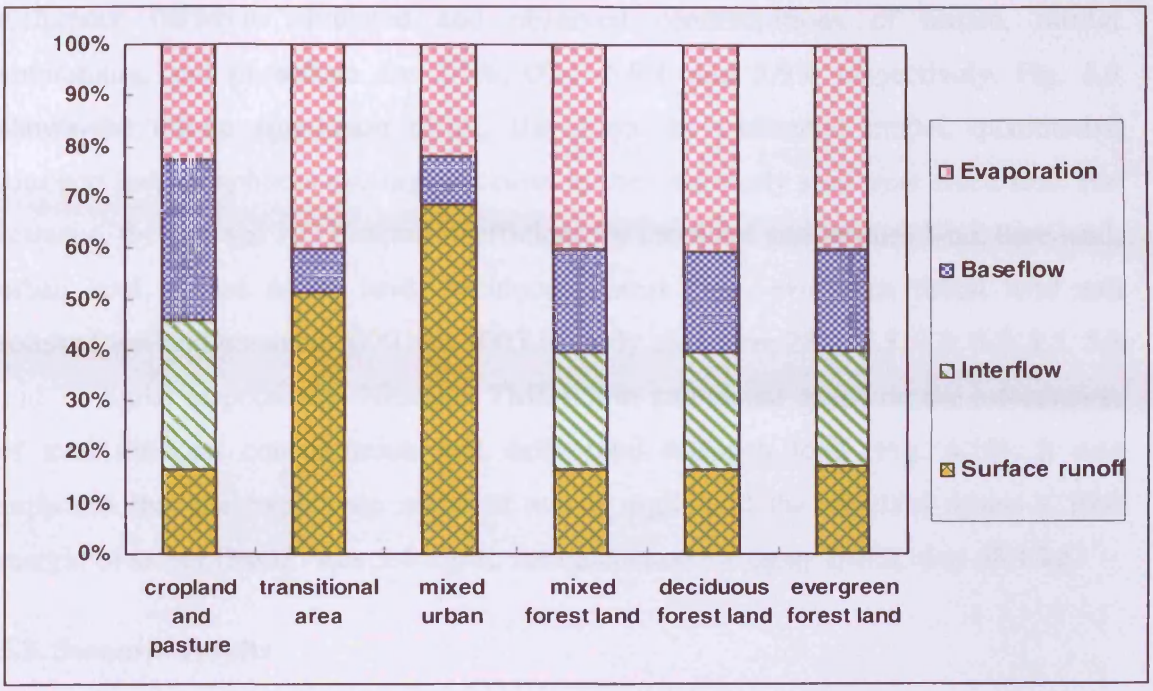

Fig. 6.8. The average value of runoff components and evaporation for each land use (2004-2005)

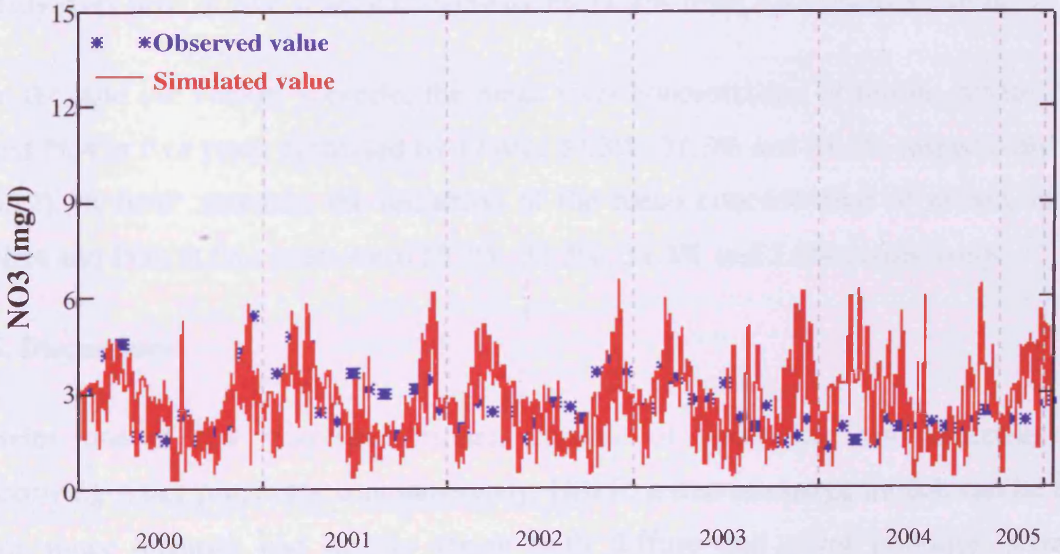

Fig. 6.9. Simulated and observed nitrate concentrations at Gamble's Bridge in study area

difference between simulated and observed concentrations of nitrate, nitrite, ammonium, and phosphate are 3.8%, 0%, -5.9% and 5.9% respectively. Fig. 6.9 shows the nitrate simulation result. Based on the calibrated model, quantitative nitrogen and phosphorus cycling processes in the case study area were calculated. For instance, the average NO3 export coefficient for cropland and pasture land, bare land, urban land, mixed forest land, deciduous forest land, evergreen forest land and forested wetland between 2000 and 2005 in study area were 28.7, 7.5, 3.0, 5.7, 5.5, 5.3, and 7.6 kg/ha respectively. Nitrogen TMDL was calculated based on the information of total nitrogen concentration and daily total nitrogen load (Fig. 6.10). It was supposed that the hypothetic standard was 6 mg/L and the standard minus a 10% margin of safety (MOS) was 5.4 mg/L, the calculated nitrogen TMDL was 68.1 kg.

5.3. Scenario results

The evaluation result of climate change scenario shows that when the annual mean temperature increase 3°Celsius the yearly total runoff volume of five years will decrease by 8%, 12.9%, 10.2%, 13%, 11.2% respectively (Fig. 6.11), and the mean daily river flow of five years will decrease by 11.4% from 3.5 m^3/s to 3.1 m^3/s.

In the land use change scenario, the mean river concentration of nitrate, nitrite, NH4 and PO4 in five years decreased by 19.4%, 33.3%, 31.3% and 31.3% respectively (Fig. 6.12). In BMP scenario, the reduction of the mean concentration of nitrate, nitrite, NH4 and PO4 in five years were 15.3%, 33.3%, 31.3% and 5.6% respectively.

6. Discussions

Being one of few watershed models capable of simulating land processes and receiving water processes simultaneously, HSPF, a free of charge model, can be used for water quantity and quality (from both diffuse and point pollution sources) simulation at catchment/watershed that contains both agricultural and urban land use. The results of HSPF evaluation in this study shows that the calibrated HSPF can derive the quantitative nutrient cycling in each type of land use and soil to help people better understand the ADWP mechanism before making water quality management policies in a specific catchment/watershed. HSPF can also be applied for evaluating the impacts of management policies on catchment water processes in the combined conditions of climate change, land use change and BMP. In addition, there is a sound data management component in HSPF that helps users easily manipulate a huge amount of time series data and allows automatic data exchange between data management module and other modules in the HSPF, hence improves the efficiency of modelling. In conclusion, HSPF is a suitable surface water model for supporting the ADWP management at the catchment scale.

In comparison of two types ADWP controlling measures, i.e. remedial and preventative measures, the prevention of ADWP at source level – catchment-scale is vital for both sustainable water quality management and the implementation of the EU WFD (EHS, 2001; Defra, 2002c; Koo and O'Connell, 2006). Once water is contaminated, it will be very costly to clean-up and can take a long time to recover, especially for groundwater. Moreover, it is difficult to determine at the regional scale

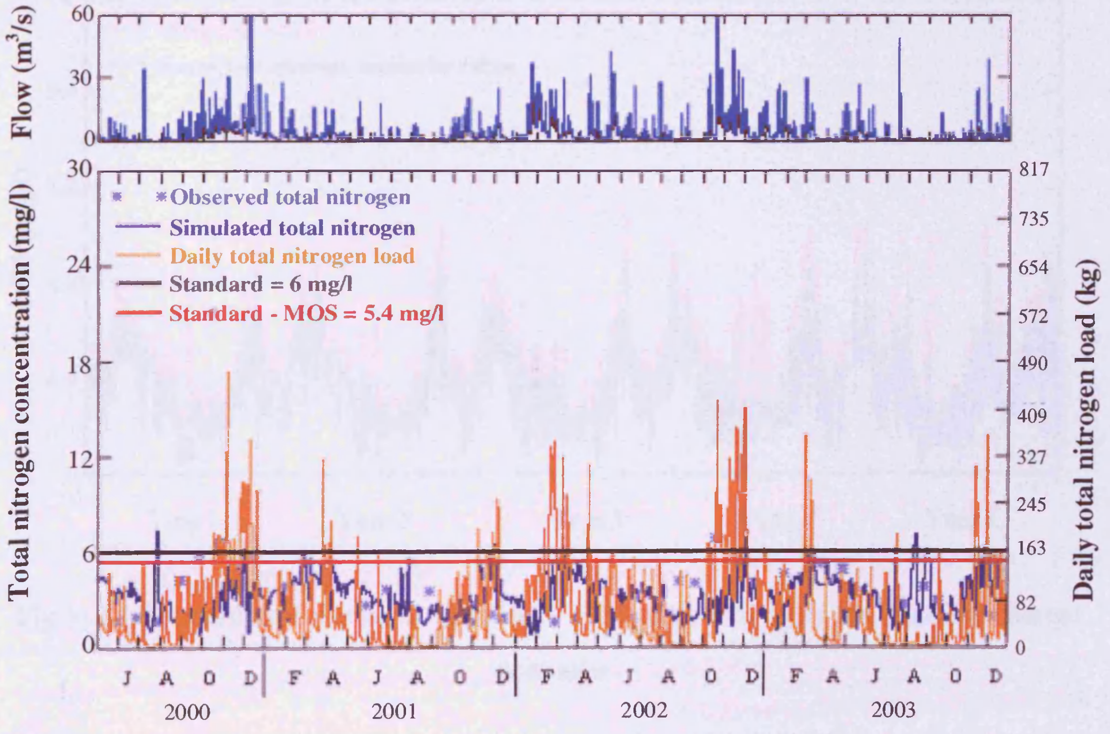

Fig. 6.10. A simplified nitrogen TMDL calculation

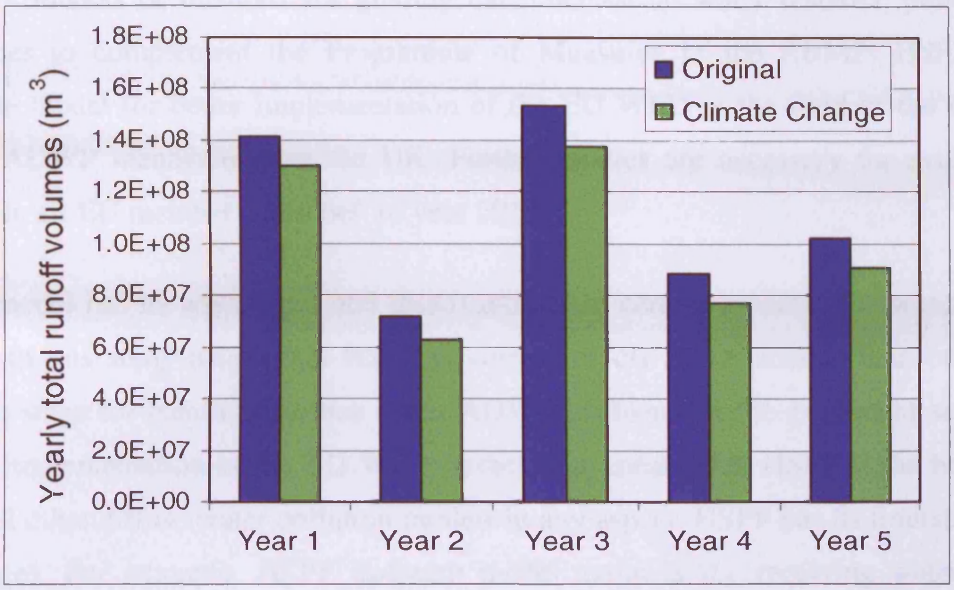

Fig. 6.11. The impact of climate change on yearly total runoff volumes

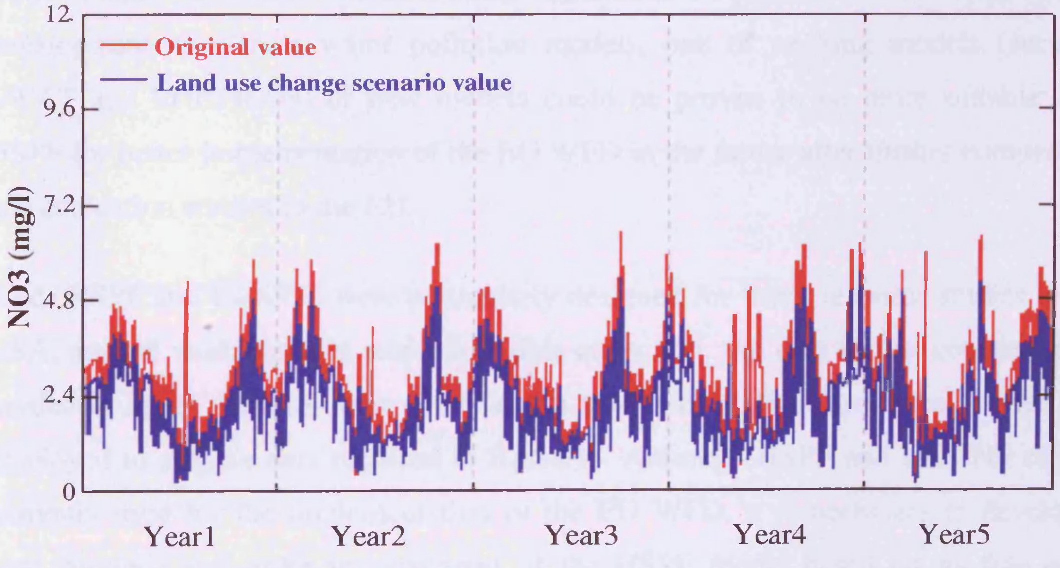

Fig. 6.12. Variation of nitrate at Gamble's Bridge over 5 years for land use change scenario

the contribution of diffuse agricultural sources to water pollution. River Basin Management Plan (RBMP), utilising the river basin as the natural unit, is the backbone of the implementation of the EU WFD. It is timely to develop and evaluate suitable models or methods for guiding catchment-scale water resource prevention activities to complement the Programme of Measures in the RBMP. HSPF is a suitable model for better implementation of the EU WFD in the field of the surface water ADWP management in the UK. Further studies are necessary for evaluating HSPF in all EU member states before year 2015.

Each model has its advantages and disadvantages in certain aspects. The selection of HSPF in this study means that HSPF is comparatively more suitable than others at current stage for handling surface water ADWP problems at the catchment scale for better implementation of the EU WFD, rather than means that HSPF is the best one over all other diffuse water pollution models in any aspect. HSPF has its limitations or shortages. For example, HSPF instream model assumes the receiving water body model is well-mixed with width and depth; application of this methodology generally requires a team effort because of its comprehensive but complex nature; for overland flow, model assumes one-directional kinematic-wave flow, etc. With quick development of diffuse water pollution models, one of existing models (such as SWAT and SHETRAN) or new models could be proven to be more suitable than HSPF for better implementation of the EU WFD in the future after further comparison and evaluation studies in the EU.

Since HSPF and BASINS were particularly designed for water resource studies in the USA, manual work (such as projection, data collection, and data format converting) is needed to apply them in other countries. In this study, GIS hydrological model was employed to prepare data required in BASINS. Although HSPF and BASINS can be currently used for the implementation of the EU WFD, it is necessary to develop a new interface and make improvement of the HSPF model based on its free open source code to facilitate its application in European countries in the long run.

7. Conclusion

Based on the review of popular surface water models, HSPF was selected for catchment-scale modelling of surface water pollution from agricultural diffuse sources. The assessment of HSPF in the Upper Bann Catchment showed that HSPF can well guide the catchment-scale management of surface water pollution from agricultural diffuse sources, by quantifying nutrient biochemical cycling in different types of soil, and evaluating the impacts of water management plans on surface water under the climate change. HSPF is suitable to be introduced into the Programme of Measures in the RBMPs for better implementation of the EU WFD in the UK. However, further studies are needed to assess the suitability of applying HSFP in all EU member states. In addition, it is necessary to develop a new software interface for HSPF based on its open source code, for its easy applications in the EU member states for the long run.

Acknowledgements

The authors wish to acknowledge the assistance of the EHS for providing DEM and river chemical monitoring data. We acknowledge River Agency for providing daily river flow data. We also wish to thank CEH UK in providing land covers data, BADC for providing meteorological data and DARD for providing soil data. Although there is no high-density groundwater monitoring network in the study area, the observed groundwater nitrate concentration trend, derived from the four groundwater monitoring locations in the study area, is in line with the risk assessment result, tending to validate the model. The groundwater monitoring data show that the nitrate concentrations increase slightly from southeast to northwest in the study area. Within 'very high' risk zones, dominant land cover types are arable horticulture (66%) and improved grassland (24%). Arable horticulture and improved grassland in 'high' risk zones are 22% and 66%, respectively. In 'moderate' and 'low' risk zones, the dominant land cover type is improved grassland, while arable land, neutral grass and open dwarf shrub heath occupy relatively small portions of these zones.

Chapter 7

An integrated modelling approach for catchment sustainable management of water nutrient pollution from diffuse agricultural sources [*]

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Abstract

Agricultural diffuse water pollution (ADWP), the biggest remaining problem of water pollution in many countries, has been realised as a major threat for the implementation of the EU Water Framework Directive (WFD). This paper presents an integrated modelling method ICEMAN for supporting the decision-making of the prevention of water nutrient pollution from diffuse agricultural sources at the catchment scale. ICEMAN integrates Geographic Information System hydrology, groundwater pollution vulnerability, groundwater risk, and surface water diffuse pollution models into an ArcGIS environment. Therefore, it can describe the nutrient biochemical cycles in soil, whole hydrological quantity and quality processes, and groundwater pollution vulnerability and risk, by considering factors in the catchment ADWP process, namely, meteorology, nutrient loading from different land uses, nutrient biochemical cycling in soil, nutrient dynamic nature with runoff and interflow, topography, depth to water, net recharge, aquifer media, soil media, impact of the vadose zone media, hydraulic conductivity of the aquifer, and the relationships between soil water, groundwater, and surface water. ICEMAN was applied in the Upper Bann Catchment, Northern Ireland. Results show that ICEMAN can well support the decision-making of the catchment ADWP sustainable management. In the study area, ICEMAN provides satisfied simulation of river flow and quality,

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This paper has not been submitted

groundwater pollution vulnerability and risk zones, and quantitative descriptions of ADWP process including nutrient biochemical cycle in soil. In addition, ICEMAN can evaluate the impacts of water management plans on water processes under the climate change. For example, when changing 20% farming land into forest land in the Gamble's Bridge watershed, the mean concentrations of nitrate, nitrite, NH4, and PO4 in river will decrease by 19.4%, 33.3%, 31.3%, and 31.3% respectively. ICEMAN, transferable to other areas, can bridge gaps of "method and tool" and "research scale" in the implementation the EU WFD; and can act as an important complement of the River Basin Management Plans. This multi-disciplinary study may provide a good starting point for tackling ADWP at the catchment scale in an integrated, quantitative, and sustainable manner.

Key words: Agriculture diffuse water pollution; Catchment water management; Surface water model; Groundwater pollution risk assessment; EU Water Framework Directive; GIS

1. Introduction

Fresh water, a precious natural resource, plays an important role in the development of human society. Diffuse water pollution is not only an environmental issue but also a major threat to economics and human health (Defra, 2002b; Defra, 2002e). For example, water with high concentration of nutrients can cause eutrophication in rivers, lakes and estuaries by igniting huge algae and phytoplankton blooms, and depleting oxygen in water. In the Mississippi such blooms are now leading to so-called 'dead zones', where the death of the algae means all the oxygen in the water is used up, killing fish and other aquatic life. Nitrogen cycling can produce large amounts of the powerful greenhouse gas 'nitrous oxide' that is responsible for the depletion of the ozone layer. The approximate annual costs in the UK of treating drinking water for pesticides are about £120 million, for phosphate and soil erosion about £55 million, for nitrate around £16 million and for microorganisms around £23 million (Pretty et al., 2000). Moreover, nitrate concentrations in excess of 10 mg NO3-N/L in drinking water may pose risk to young animals and human babies (USDA, 1991; Matson et al., 1997). The nitrite oxidizes iron could cause the infants to develop a "blue baby syndrome" (methemoglobinemia) by reducing the ability of blood to carry oxygen to the individual body cells (Basso and Ritchie, 2005; Bryan, 2006). A potential cancer risk from nitrate (and nitrite) in water and food has been reported (Rademaher et al., 1992; Hill, 1999; Yang et al. 2007).

In the year 2000, EU Water Framework Directive (WFD) (EC, 2000) set a framework for comprehensive management of water resources in the European Community aiming at achieving at least "good status" for all the waters in the EU member states by 2015. By comparison with point water pollution, diffuse water pollution is more complex and more difficult to control due to its numerous and dispersed sources, and its complex pathways. So far, the diffuse water pollution is the biggest remaining problem of water quality in the world (Campbell et al., 2004). Within the sources of the diffuse water pollution, the single, biggest threat is from agriculture. For example, it is estimated that over 70% of nitrate in natural waters are derived from agricultural land in England (Defra, 2002a). By far the most important sources of nitrogen to agricultural land are chemical fertilisers and animal manure (The Royal Society of London, 1983; Baker, 1992). Agriculture diffuse water pollution (ADWP) has been realised as a major threat for water quality and the implementation of the EU WFD (EHS, 2000; DoE & DARD UK, 2003; Ferrier et al., 2004; Torrecilla et al., 2005).

The EU WFD introduces an innovative, integrated and holistic approach to the protection and management of water resources. However, many of the tasks from the EU WFD are new and often no useable methodologies exist; thus, new methodologies and tools are required to support implementation of the new policy (Mostert, 2003; Giupponi, 2005). Although the strategies of administration and reporting have been made to help all EU member states achieve the demands of the EU WFD, what scientific measures will actually be used or developed for the implementation of the EU WFD is still largely unknown (UK EA, 2005).

The prevention of water quality deterioration at source (at the catchment or watershed scale) before the happening of contamination is critical for sustainable water quality management (Wang and Yang, 2008). Therefore, in order to handle the ADWP problem for successful implementation of the EU WFD, it is necessary to carry out multi-disciplinary study to develop integrated methods and tools that support the decision-making of the ADWP prevention practices at the catchment scale.

This paper aims to: (1) introduce an integrated approach – ICEMAN (Integrated approach for Catchment water quality Management) for supporting the decision-making of sustainable ADWP management at the catchment scale. By integrating Geographic Information Systems (GIS) hydrological model, surface water diffuse pollution model, groundwater vulnerability model, and groundwater risk assessment model, this method can provide quantitative descriptions of the catchment ADWP processes in the phases of source – pathway – target including the nutrient biochemical process in soil, which are important in the decision-making of the sustainable ADWP management in a catchment. In addition, the ICEMAN can evaluate the impacts of ADWP prevention plans on water process before making the final decision; (2) and discuss the implications and limitations of ICEMAN based on its application in the Upper Bann Catchment, Northern Ireland.

2. Methodology

The general knowledge of the ADWP mechanism can not to be universally applied to everywhere because the ADWP processes vary greatly with significant varying situation, i.e. land use, climate, agriculture activities, soil, topography, hydrogeology conditions and the sensitivity of particular water bodies to pollution. Thus, numeric models should be introduced to quantitatively describe special ADWP mechanisms in soil, surface water and groundwater in a specific catchment. In order to support the decision-making of the ADWP management in any catchment, it is necessary to develop an integrated modelling method providing reliable descriptions of surface water processes and detailed spatial distribution of groundwater pollution risk zones. The ICEMAN method, developed in this study, integrates the GIS hydrological model, groundwater vulnerability assessment model, groundwater risk assessment model, and surface water ADWP model.

As illustrated in Fig. 7.1, the ICEMAN method starts with GIS database. Since this study involved the data of meteorology, soil, land use, hydrogeology, hydrology and topography, a multi-sphere GIS database was set up. The GIS hydrological model was introduced to prepare necessary data for ICEMAN using its hydrological analysing functions. For example, the catchment boundary, the watersheds of gauge stations, stream network, river flow direction, river flow accumulation and topography slope data were derived from Digital Elevation Model (DEM) data using GIS hydrological model. In addition, its spatial analysis and visualisation tools are helpful for better understanding hydrological conditions in a catchment. The introduction of this GIS hydrological model can greatly facilitate the data preparation process in the ICEMAN application.

Whilst the result of groundwater vulnerability assessment represents the spatial distribution of the potential pathway for soluble contaminants on the ground surface to reach groundwater, the result of groundwater risk assessment provides the actual possibility of groundwater pollution arose from the occurrence of both hazard and pathway vulnerability by considering pollutants hazard and their dynamic nature with runoff. Although the later one is more useful than the first one in guiding ADWP prevention practises in the reality, the groundwater vulnerability assessment is still necessary because the combination of these two results will help people better understand groundwater pollution pathway and pollutant source situation in a catchment, and guide making sound groundwater protection policies. Therefore, both of them will be included into the ICEMAN.

Calibrated and validated numeric model can quantitatively represent the characteristics of water quantity and quality process including the nutrient biochemical cycling and balance in soil. For example, the calibrated and validated surface water ADWP model in one catchment reflects how weather factors, soil types, land uses, and topography impact water quantity and quality in this area. In addition, the nutrient leaching and loading rates in each land use and the nutrient biochemical process in the soil of certain land use can be derived from the surface water model for

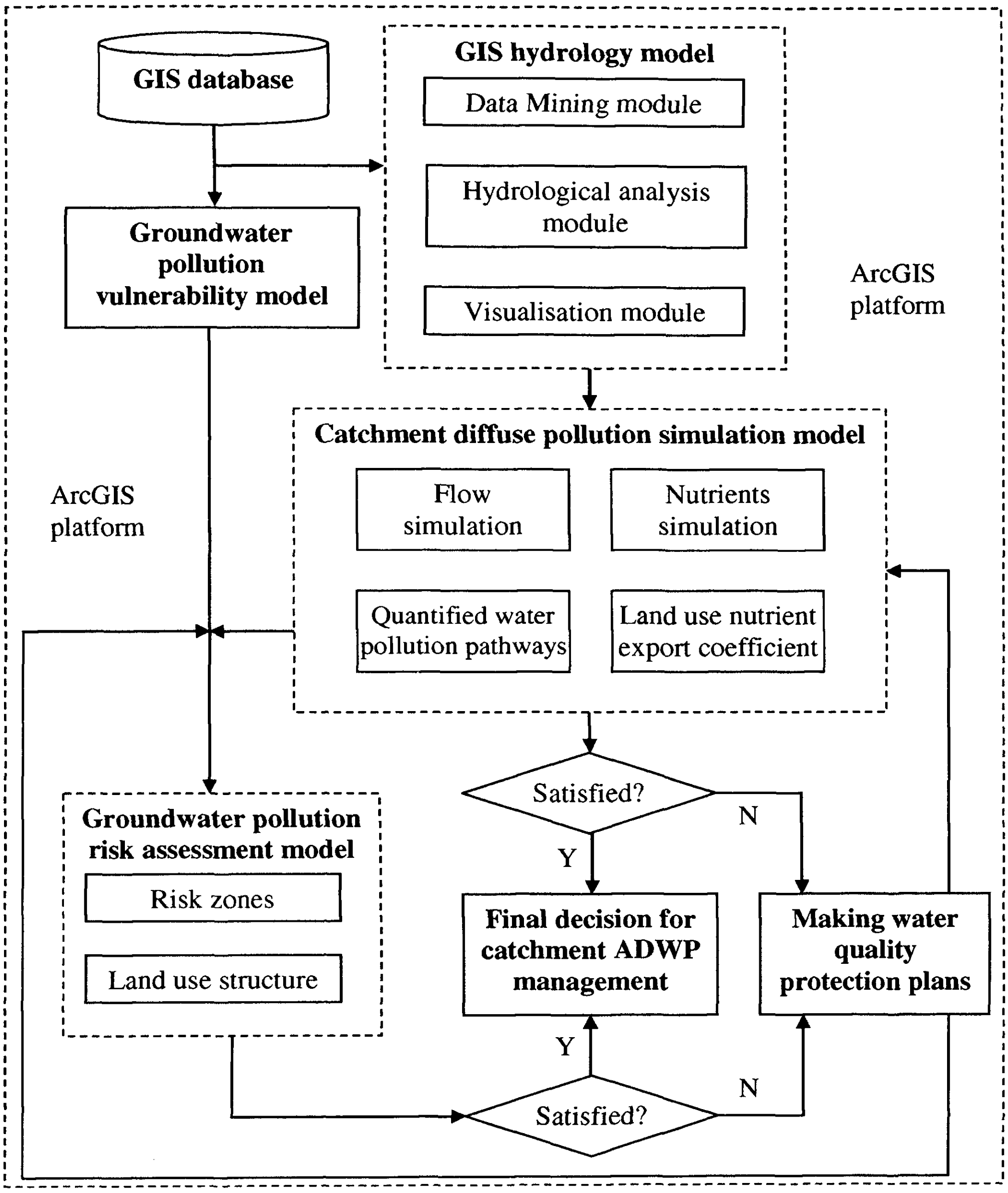

Fig. 7.1. Schematic diagram of the ICEMAN approach

better understanding of the ADWP mechanism in a specific catchment. These results can lead to reliable groundwater nutrient risk assessment by integrating the re-accumulation of nutrients with runoff and their soil process into groundwater vulnerability assessment method.

With the advantages of spatial data management, analysing, and visualisation, GIS is a suitable platform for the development of decision-support tool for catchment water resources management. Thus, this study employed ESRI ArcGIS platform. By using

GIS visualisation modules, the results of groundwater risk assessment and the analysis of surface water ADWP and their diffuse agricultural sources can be explicitly presented to decision makers and stakeholders for making sound decisions of the ADWP prevention at the catchment scale. ICEMAN can evaluate the impacts of the plans of the ADWP prevention on waters process before making the final water management decision in a catchment. The GIS system can also be used to prepare the data of scenarios of climate change and the proposed plans of the ADWP management. Making and evaluating the decisions of water resources management in a specific catchment is an iteration process until the suitable or optimised ADWP management strategy is found.

2.1. GIS hydrological model

Hydrology factor is the driving force behind water physical and chemical processes in a catchment, therefore hydrological modelling plays an important role in better understanding of the catchment-scale ADWP mechanism. Arc Hydro (Maidment, 2002) model was employed in setting up GIS hydrological model on the ArcGIS platform. Arc Hydro is an extension of geodatabase model for the support of water resource applications, and a starting point for water resource database and application development. Arc Hydro is capable of deriving the catchment or watershed boundary, flow direction, flow accumulation, stream network and topography slope from DEM data. These data are useful in calculating the groundwater pollution vulnerability and risk zones, and in the simulation of river flow and quality. In addition, Arc Hydro can provide spatial analysis and visualisation functions, such as point watershed delineation, flow path tracing, up or down stream tracing, streams tracing using attribute data, and 2D&3D visualisation for better understanding of the hydrology conditions in a catchment. It is worth noting that Arc Hydro can also be used to calculate the transport and accumulation of soluble contaminants with runoff according to topography for more reliable groundwater pollution risk assessment (Wang and Yang, 2008).

2.2. Surface water model

The objective understanding of water quantity and quality processes in watersheds is indispensable for catchment water quality sustainable management. Models capable of simulating the response of watersheds to different inputs become available. Hydrological Simulation Program — FORTRAN (HSPF), designed for simulating water quantity and quality, processes on pervious and impervious land surfaces and in streams and well-mixed impoundments (Bicknell et al., 2005), was employed for this study. HSPF is one of few available models that can simulate continuous dynamic events or steady-state behaviour over the required range of both hydrologic and water quality processes through both the surface and groundwater regimes in a catchment. In order to facilitate the application of HSPF, Better Assessment Science Integrating point and Nonpoint Sources (BASINS), developed by United States Environmental Protection Agency (USEPA), was adopted. BASINS system, in which HSPF is a module, is a multipurpose environmental analysis system designed for performing watershed and water quality-based studies. The details of BASINS are given at the website www.epa.gov/waterscience/basins.

2.3. DRASTIC

Among four types of methods for groundwater vulnerability assessment, i.e., process based (modelling), statistical, observation based and index methods, only process based and index methods cover the source and pathway phases of groundwater pollution. Compared with process based method, the index method has the advantages of easy understanding and applying; and the disadvantage of subjectivity in the factor weighting and numerical value assignation of factors. The DRASTIC method, one of index methods, developed by the U.S. Environmental Protection Agency (EPA) (Aller et al., 1987), was chosen in this study. DRASTIC is a numerical ranking composite description of major geological and hydrological factors that affect and control the groundwater movement into, through and out across the vertical profiles of an area. The acronym DRASTIC stands for seven factors: D – Depth to water; R – net Recharge; A – Aquifer media; S – Soil media; T – Topography (slope); I – Impact of the vadose zone media; and C – hydraulic Conductivity of the aquifer. The intrinsic meaning of the DRASTIC result is the pathway vulnerability that allows pollutant to enter the groundwater zone from the ground surface and soil, as it can be determined by Eq. 7.1.

$$DVI_i = D_{iw}D_{ir} + R_{iw}R_{ir} + A_{iw}A_{ir} + S_{iw}S_{ir} + T_{iw}T_{ir} + I_{iw}I_{ir} + C_{iw}C_{ir} \qquad (7.1)$$

where *DVI* represents the DRASTIC vulnerability index; *D*, *R*, *A*, *S*, *T*, *I* and *C* are the seven factors in DRASTIC; the subscript *r* and *w* are numerical ratings (to be calculated) and weightings (5, 4, 3, 2, 1, 5 and 3) of seven factors; the subscript *i* is the *i*th cell in the GIS raster data structure. Higher DRASTIC indices imply greater pollution vulnerability and vice versa. The weight of each DRASTIC factor was determined using a Delphi (consensus) approach (Aller et al., 1987). The most significant factor has a weight of 5 and the least significant has a weight of 1.

Although DRASTIC is a subjective method, its factors and their weighting values, which were selected and calculated based on the knowledge and understanding of groundwater pollution from a group of groundwater pollution experts, can well reflect the key mechanisms of the groundwater pollution pathways.

2.4. D-DRASTIC

Groundwater pollution vulnerability and risk are two different concepts. Groundwater vulnerability represents the pathway possibility that the hazard may be transmitted to groundwater. Risk definition can be expressed by Eq. 7.2. The combination of the occurrence of hazard and vulnerability of the system results in the risk (Hauger et al., 2003). In other words, groundwater is only at risk if both hazard and pathway vulnerability exist (EHS, 2001). For this reason, a D-DRASTIC method was developed for catchment-scale groundwater pollution risk assessment (Wang and Yang, 2008). D-DRASTIC can provide objective evidences for the decision-making of the groundwater ADWP prevention, by introducing the concept of risk, the loadings of pollutants from diffuse agricultural sources, and pollutants dynamic nature with runoff on the ground surface and in upper layer of soil (Eq. 7. 3)

$$\text{Risk} = \text{f (Hazard, Vulnerability)} \tag{7.2}$$

$$RI_i = \frac{DVI_i}{DVI_{\max}} \times \frac{H_i - H_{\min}}{H_{\max} - H_{\min}} \tag{7.3}$$

$$H_i = VH_i + HH_i \tag{7.4}$$

$$VH_i = \frac{LR_i \times K_1}{NR_i \times K_2} = \frac{LR_i}{NR_i} \times K \text{ (mg N/liter)} \tag{7.5}$$

$$HH_i = \frac{EC_i \times K_1}{RO_i \times K_2} = \frac{EC_i}{RO_i} \times K \text{(mg N/liter)} \tag{7.6}$$

where RI_i is the result of the D-DRASTIC risk assessment in cell *i*, $RI_i \in [0, 1]$. Higher RI_i value means higher groundwater pollution risk; DVI_i the index of the DRASTIC groundwater pollution vulnerability in cell *i*, calculated by Eq. 7. 1; $DVI_{\max}$ the maximum DRASTIC groundwater pollution vulnerability index in the study area; H_i the soluble pollutant hazard to groundwater, standing for the nitrate hazard to groundwater in cell *i*, or the nitrate concentration in cell *i*; $H_{\min}$ and $H_{\max}$ represents the minimum and maximum hazard concentrations in the study area respectively. VH_i is the vertical nitrate flux reaching groundwater via leaching and percolation in cell *i*; HH_i the extra nitrate carried by runoff to cell *i* that can promote further nitrate leaching and percolation through soil and unsaturated vadose zone, then contaminate groundwater. LR_i is the nitrate-leaching rate (Kg N/ha/a) in cell *i*; NR_i (mm) net recharge in cell *i*; EC_i the accumulated nitrate runoff export coefficient (Kg N/ha/a) in cell *i*; RO_i the accumulated runoff (mm) in cell *i*. The process of rainfall producing runoff will be explained in the following section 4.2.1 in detail. $K_1=2.5\times10^5$ (mg N/a) is a converter of the nitrate-leaching rate or runoff export coefficient from Kg N/ha/a to mg N/cell/a; $K_2 = 2.5\times10^3$ another converter of the net recharge from mm/m^2/a to liter/cell/a; $K=K_1/K_2=100$ (cell size: 50m×50m).

2.5. The Integration of models in ArcGIS

Not simply putting GIS hydrological model, HSPF, DRASTIC, and D-DRASTIC models together to cover different processes of the ADWP, ICEMAN integrates these models into a GIS framework instead. The integration work was carried out on the ArcGIS 9.0 platform. GIS existing functions were used to generate the data exchange attribute and spatial data between models; and to visualise the results of modelling, thus melting these models into one framework. All the models in the ICEMAN support and complement each other to model the whole catchment ADWP process. In ICEMAN, the GIS database, a key part of the integration of models, can be updated using the results of models in ICEMAN. For example, it can be updated using the derived data from the Arc Hydro model, and then feeds data into HSPF in modelling catchment surface water processes. Plant uptake, mineralisation, immobilisation, nitrification, and denitrification in the surface layer, upper layer, and lower layer of the soil can be derived from calibrated HSPF in a study area. These quantitative results of nitrogen cycling, stored in the GIS database, are useful in studying the interactions between runoff, soil process, and groundwater pollution process, thus making the groundwater risk assessment more reliable. In this study, the more accurate nutrient loading rates and leaching rates of different land uses, derived from the calibrated HSPF, were used in calculating the HH_i and VH_i values in D-DRASTIC. The spatial distributed groundwater risk zones in turn can guide the positioning the land use change during the evaluation of the land use scenario in HSPF before the final decision making of catchment ADWP prevention.

After the integration of models, ICEMAN can describe the water cycle in soil, nutrient biochemical cycle in soil, runoff on pervious and impervious land use, groundwater pollution pathway vulnerability, groundwater pollution risk, water and nutrient dynamic nature with surface runoff and interflow, the interaction between soil water and groundwater, and the relationship between soil water process and stream water at the catchment scale (Fig. 7.2). In addition, ICEMAN can also evaluate the impacts of land use change, farming activity change, Best Management Practices (BMP), and climate change on water quantity and quality processes at the catchment scale.

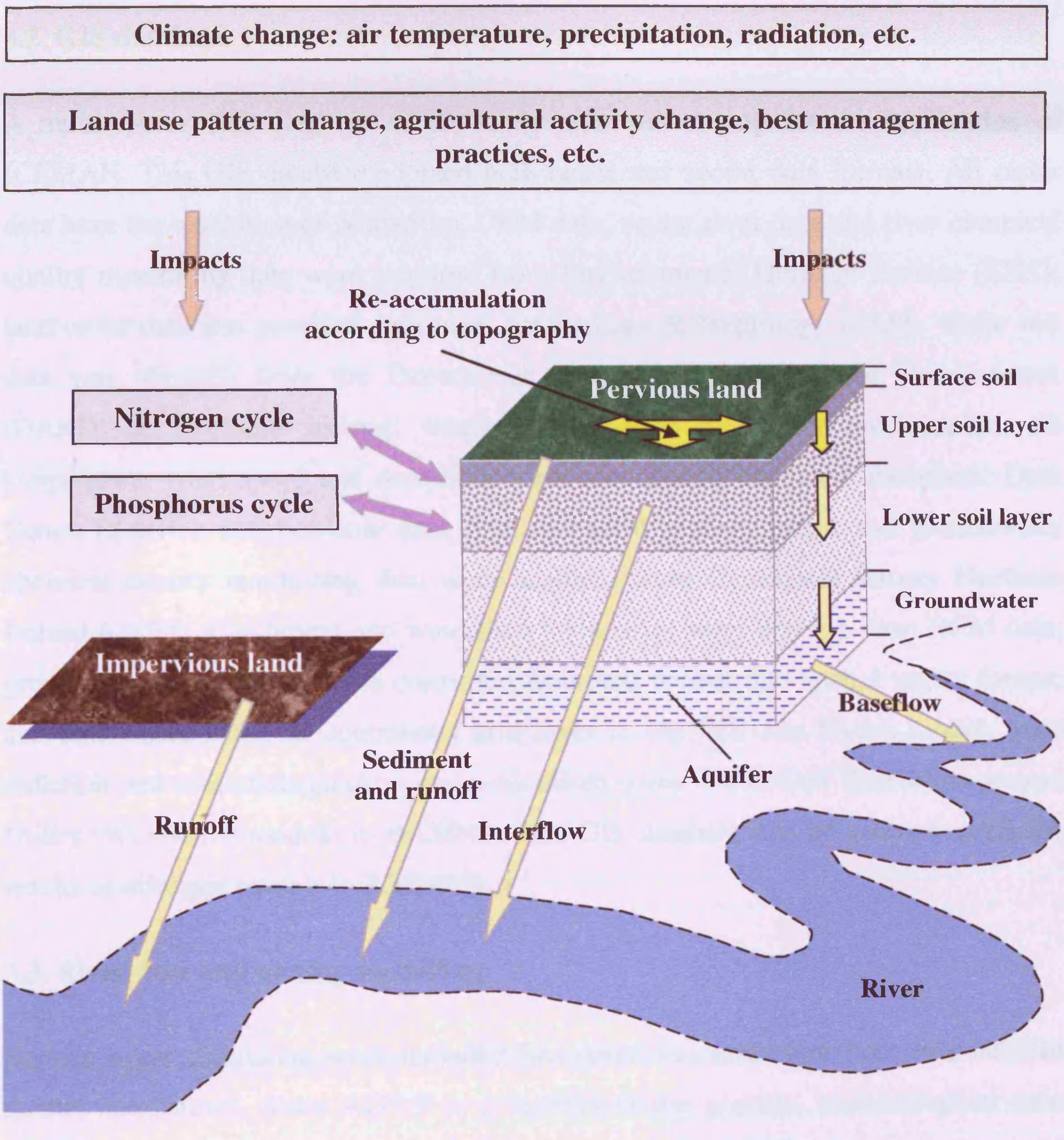

Fig. 7.2. The catchment ADWP processes described in ICEMAN

3. Application

3.1. The case study area

The Upper Bann Catchment, Northern Ireland is the study area in this study. The details of the conditions of the study area are given in appendix A.

3.2. GIS database

A multi-sphere GIS database of the study area was set up for the application of ICEMAN. This GIS database adopted both raster and vector data formats. All raster data have the resolution of 50m×50m. DEM data, vector river data and river chemical quality monitoring data were acquired from Environmental Heritage Service (EHS); land cover data was provided by Centre for Ecology & Hydrology (CEH), while soil data was obtained from the Department of Agriculture and Rural Development (DARD) of Northern Ireland; weather data, such as hourly precipitation, air temperature, wind speed and dewpoint, were provided by British Atmospheric Data Centre (BADC); 660 borehole data, drift and solid geology maps, and groundwater chemical quality monitoring data were acquired from Geological Survey Northern Ireland (GSNI). Catchment and watershed boundaries were derived form DEM data; groundwater quality data were converted from text format into spatial vector format, and then interpolated as continuous grid layer in the GIS Arc Hydro model; solar radiation and evapotranspiration were calculated using Watershed Data Management Utility (WDMUtil) module in BASINS. This GIS database can be updated using the results of different models in ICEMAN.

3.3. River flow and quality modelling

Surface water simulating work included two parts, i.e., river flow and river nutrient quality simulations. Since ADWP is a weather-driven process, meteorological time series data (such as, hourly precipitation, hourly air temperature, wind speed), were used. All weather time series data and other monitoring time series data (such as, river flow, river quality) were prepared and managed in the WDMUtil. The process described above can be illustrated by Fig. 7.3. The knowledge of the mechanisms of the ADWP processes at the catchment scale is the basis of making sound policies of catchment water resources management. After the calibration and validation of HSPF, the derived quantitative descriptions of hydrology and nutrient cycling processes are helpful for better understanding of the ADWP processes, and reliable groundwater pollution risk assessment in the study area. Based on calibrated and validated HSPF in the study area, the evaluations of the impacts of water management policies on water quantity and quality were carried out. Please refer chapter 6 for more details.

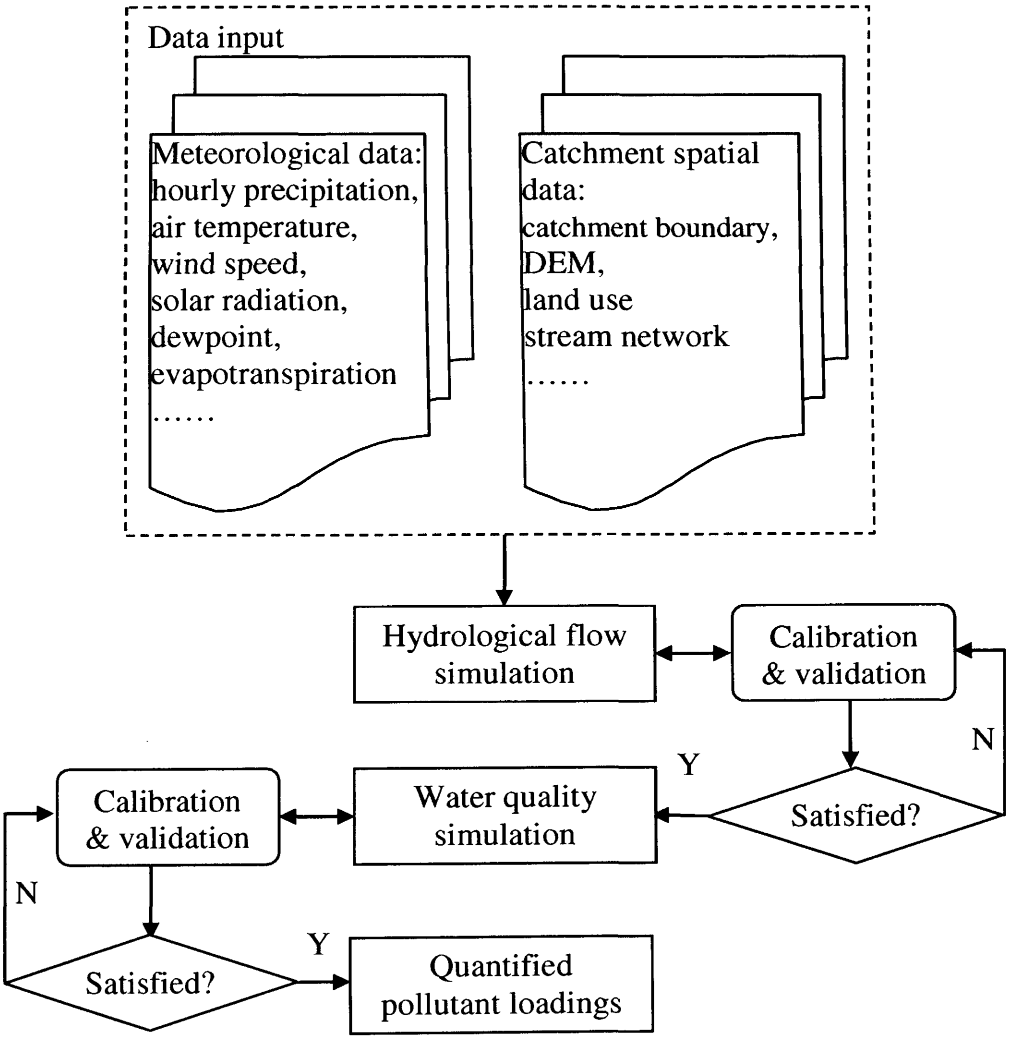

Fig. 7.3. Catchment river flow and quality modelling process

3.4. Groundwater pollution risk assessment

The data of depth to water table, net recharge, aquifer media, soil media, topography, vadose zone media and aquifer hydraulic factors were abstracted from the GIS database of the study area for calculating groundwater pollution vulnerability using DRASTIC. Since the assessments of groundwater vulnerability and risk were carried out using GIS raster data, all factors involved for calculation were converted into GIS raster format. Further details of the groundwater vulnerability assessment in the Upper Bann Catchment are given in Wang and Yang (Chapter 4). The D-DRASTIC method in ICEMAN was employed for the groundwater risk assessment in the study area. The calculation of *HH*, reflecting the interactions between runoff, interflow, soil water and groundwater, was the one of the key processes in groundwater pollution risk assessment. Soluble contaminants could flow and re-accumulate with overland runoff on the ground surface and in soil according to the topography of a catchment, thus the GIS accumulation layers of surface water (including overland runoff and interflow) and soluble pollutants with runoff were calculated. A full description of the groundwater pollution risk assessment in the study area is given in Wang and Yang (2008).

4. Results

4.1. Surface water process

In order to get more accurate water simulation results, the Upper Bann catchment was divided into four watersheds according to the locations of river flow gauge stations in the study area. Hourly precipitation, hourly air temperature, daily maximum and minimum temperature, solar radiation, evapotranspiration from 1/2000-5/2005 were used for surface water quantity and quality simulations. By taking the Gamble's Bridge station (Fig. 7.12) as an example, all simulated and observed data mentioned below were from this station. River flow data (1/2000-12/2003) were used for river flow calibration. In calibration process, parameters in HSPF were adjusted in terms of the difference between the simulated and observed river flow data. Fig. 7.4 shows the comparison between simulated and observed river flow time series data. Flow duration curves (Fig. 7.5) shows that simulated and observed river flow correlated well in frequency. Scatter plot (Fig. 7.6) also shows that the model was well calibrated. The calibrated model was then validated using data between 1/2004 and 5/2005 (Fig. 7.7). After river flow calibration and validation, the parameters value in HSPF can well reflect the hydrological characteristics in the case study area.

In the process of water quality simulation, water chemical quality monitoring data between year 2000 and 2003 were used for the model calibration, while observed

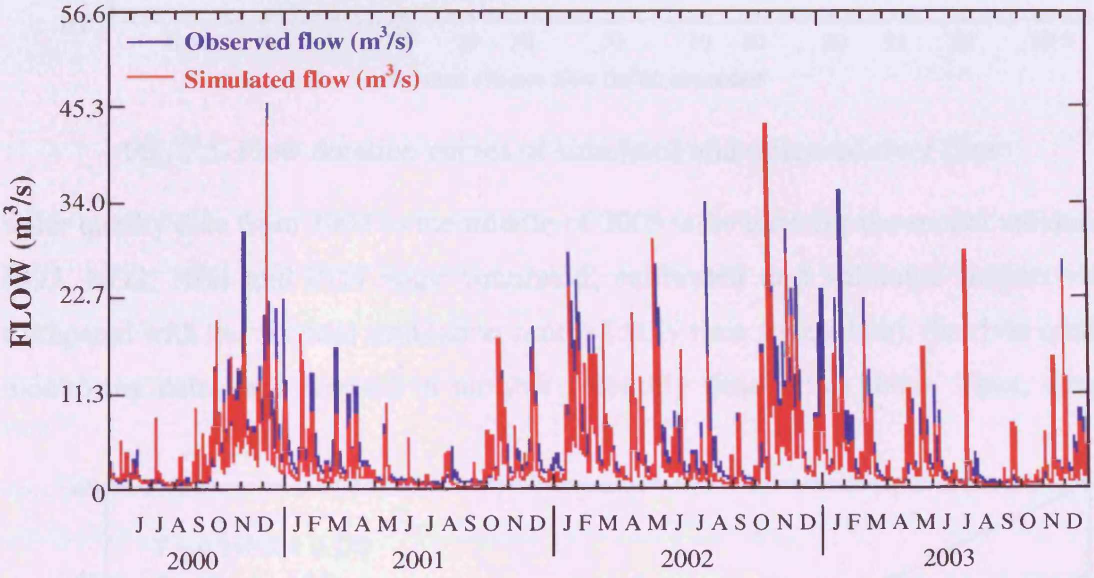

Fig. 7.4. Simulated and observed river flow at Gamble's Bridge in study area

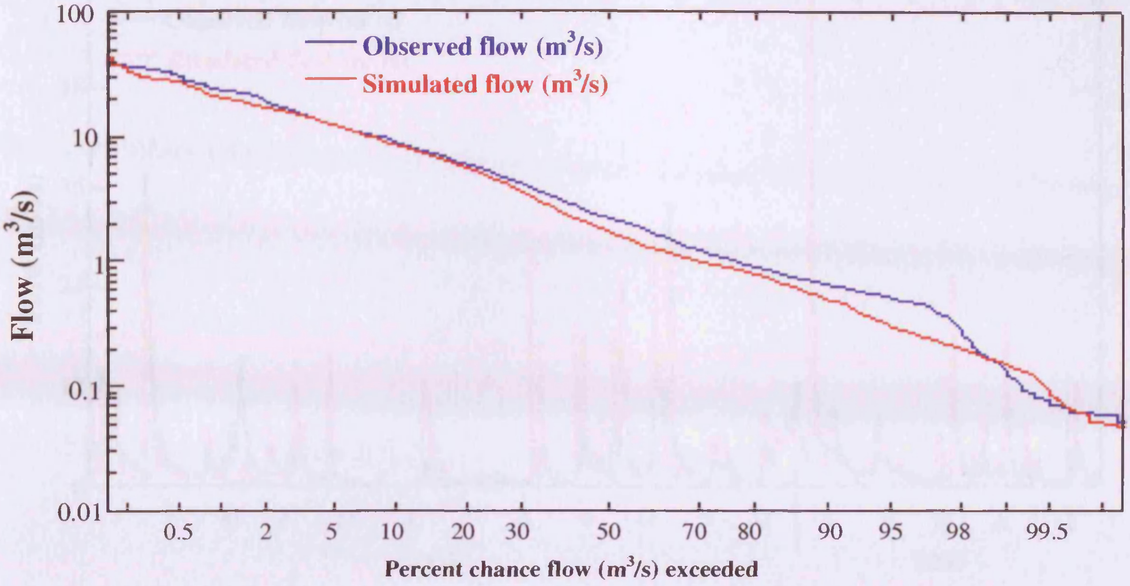

Fig. 7.5. Flow duration curves of simulated and observed river flow

water quality data from 2003 to the middle of 2005 were used for the model validation. NO3, NO2, NH4 and PO4 were simulated, calibrated and validated respectively. Compared with the nutrient simulation results (daily time series data), the river quality monitoring data were limited in number (monthly time series data). Thus, simple

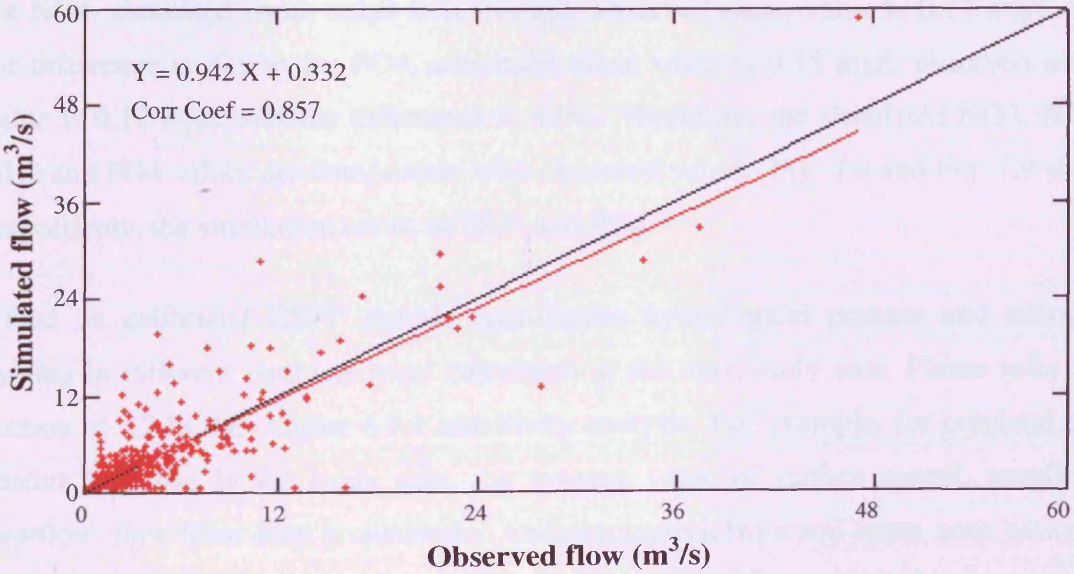

Fig. 7.6. Scatter plot of simulated and observed river flow

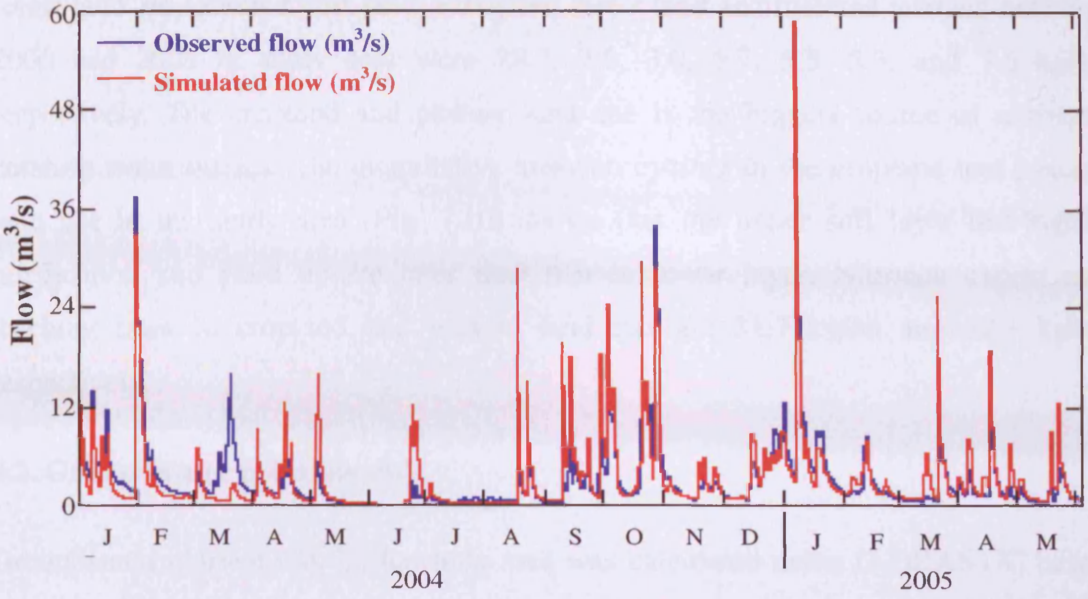

Fig. 7.7. Model validation using simulated and observed river flow data (2004-2005)

statistic methods (such as count, percent, mean, and standard deviation) instead of complex statistic methods (such as correlation coefficient, coefficient of determination) were used for the calibration and validation. After the calibration, for nitrate, simulated mean value is 2.68 mg/l, observed mean value is 2.58 mg/l, and the difference is 3.8%; for nitrite, both simulated and observed mean value are 0.06 mg/l; for NH4, simulated mean value is 0.16 mg/l, observed mean value is 0.17 mg/l, and the difference is -5.9%; for PO4, simulated mean value is 0.18 mg/l, observed mean value is 0.17 mg/l, and the difference is 5.9%. Therefore, the simulated NO3, NO2, NH4 and PO4 values are comparable with observed values. Fig. 7.8 and Fig. 7.9 show, respectively, the simulation result of NO3 and PO4.

Based on calibrated HSPF model, quantitative hydrological process and nitrogen cycling in different land use were calculated in the case study area. Please refer the section of 4.2 in the chapter 6 for sensitivity analysis. For example, for cropland and pasture land use in the study area, the average value of surface runoff, interflow, baseflow, flow from deep groundwater, and evaporation from soil upper zone between year 2000 and 2005 were, 13.2, 23.4, 24.9, 1.3 and 17 mm respectively; the average NO3 export coefficient for cropland and pasture land, bare land, urban land, mixed forest land, deciduous forest land, evergreen forest land and forested wetland between 2000 and 2005 in study area were 28.7, 7.5, 3.0, 5.7, 5.5, 5.3, and 7.6 kg/ha respectively. The cropland and pasture land use is the biggest source of nutrients entering water bodies. The quantitative nitrogen cycling in the cropland and pasture land use in the study area (Fig. 7.10) shows that the upper soil layer has higher nitrification and plant uptake rates than that in lower layer. Nitrogen export and leaching rates in cropland and pasture land use are 31.7 kg/ha and 22.1 kg/ha respectively.

4.2. Groundwater pollution risk

Groundwater nutrient risk in the study area was calculated using D-DRASTIC based on the nutrient leaching and export rates of different land uses derived from the calibrated HSPF model. Groundwater nitrate risk was taken as an example in this paper. Although there are not many detailed groundwater monitoring sites in the catchment, the existing observed groundwater nitrate concentration trend is in line with the risk assessment result. Fig. 7.11 shows groundwater nitrate pollution risk result in the study area with four risk ranks, i.e. "very high", "high", and "moderate" and "low" risk zones occupying 5%, 11%, 47% and 37% of the study area. Very high risk zones are mainly located at undulating drumlin and low-lying areas; high risk zones develop along rivers; moderate risk zones and "low" risk areas are everywhere especially in the Mourne Mountains to the southeast and towns (nutrient hazards in urban area were not included in this study). Within "very high" risk zones, the dominant land cover types are 'arable horticulture' (66%) and 'improved grassland' (24%). The areas of 'Arable horticulture' and 'improved grassland' occupy 22% and 66% of "high" risk zones respectively. In "moderate" and "low" risk zones, the dominant land cover type is 'improved grassland'.

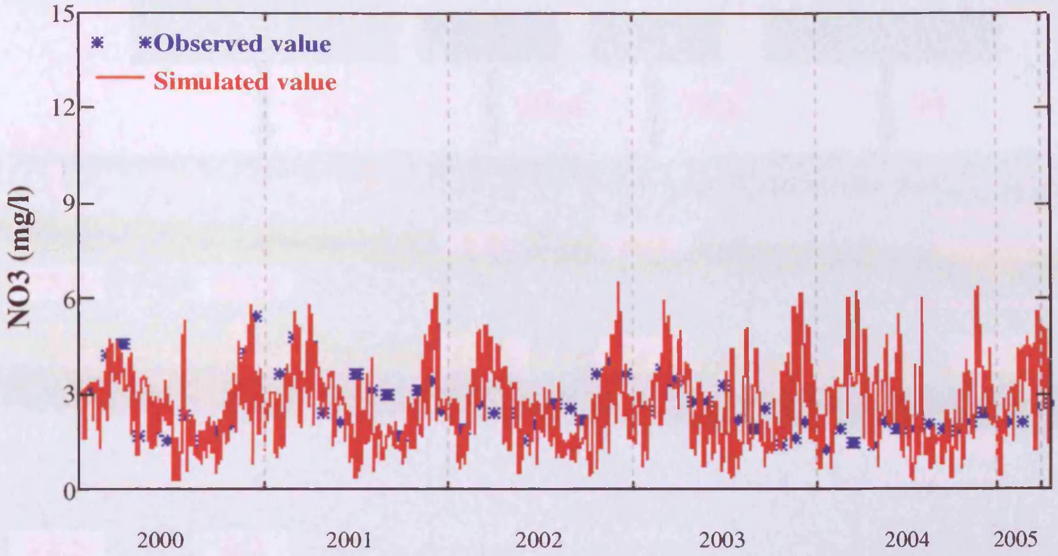

Fig. 7.8. Simulated and observed nitrate concentrations at Gamble's Bridge in study area

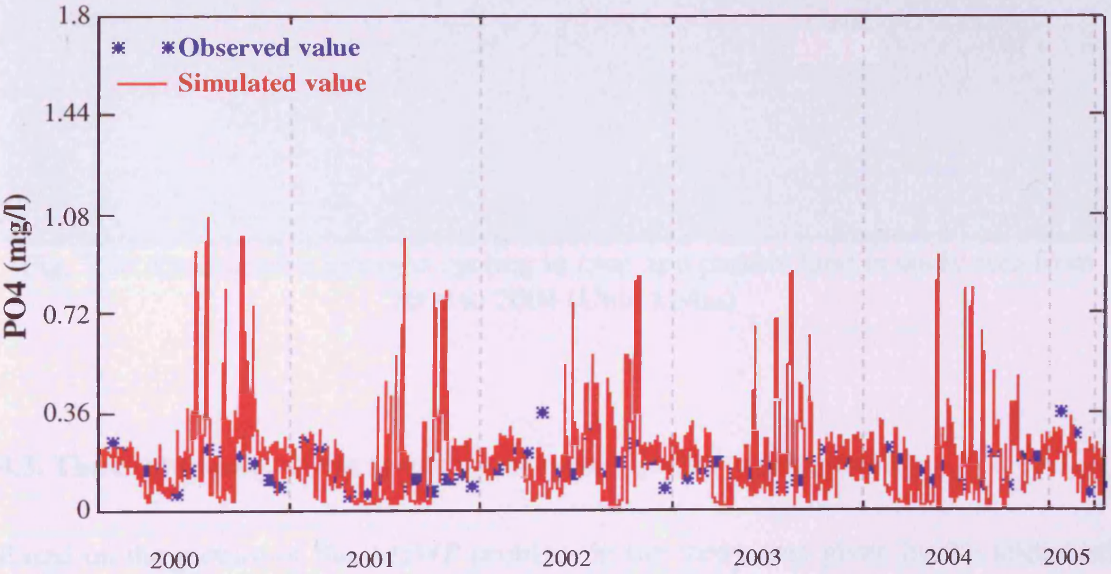

Fig. 7.9. Simulated and observed PO4 concentrations at Gamble's Bridge in study area

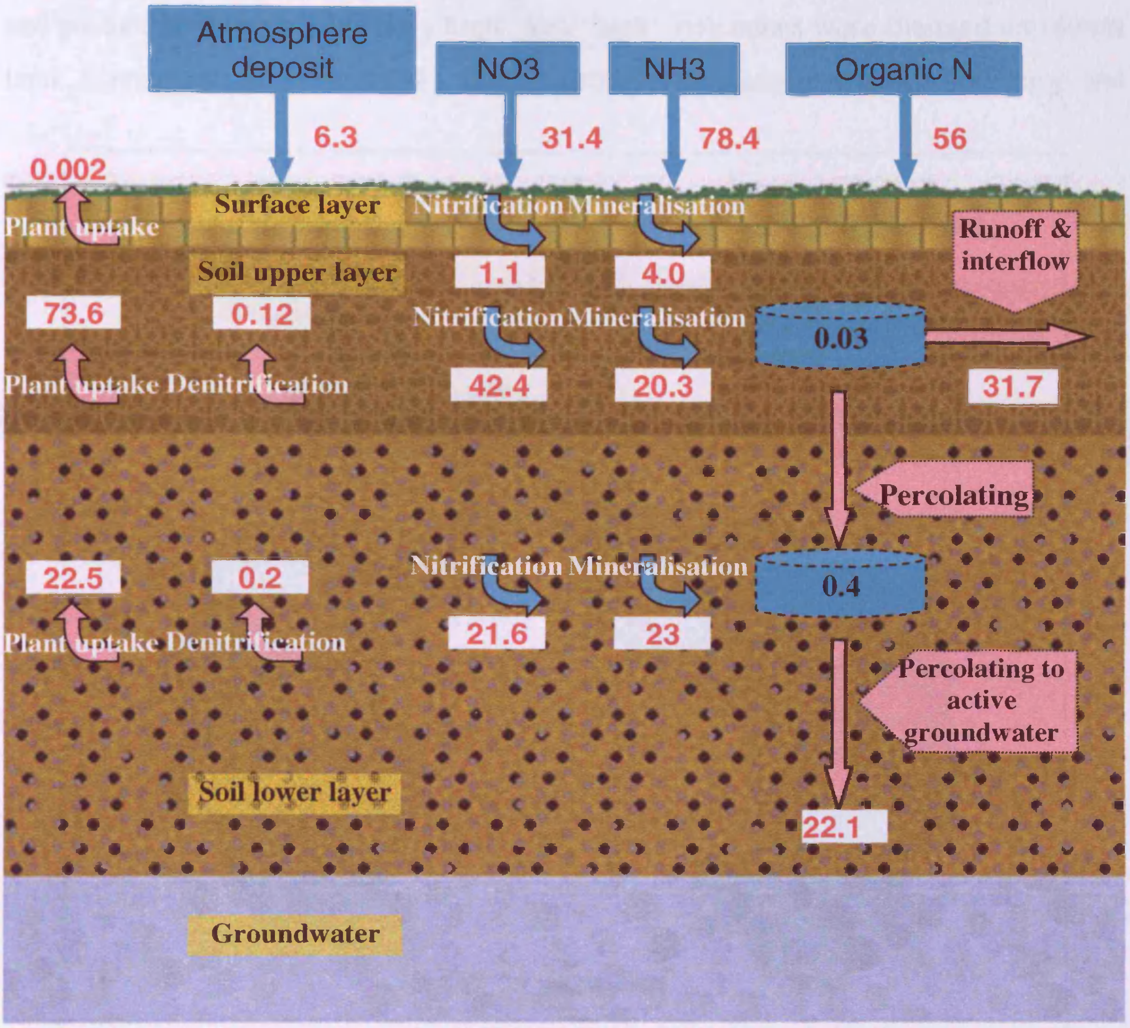

Fig. 7.10. Quantitative nitrogen cycling in crop and pasture land in study area from 2000 to 2004 (Unit: kg/ha)

4.3. The evaluations of the scenarios of water quality management

Based on the picture of the ADWP problem in the study area given by the integrated modelling using ICEMAN, decision makers can make the strategies of the ADWP prevention accordingly. It is supposed that two kinds of plans for water quality management in the Gamble's Bridge watershed (Fig. 7.12) were going to be made. Scenario 1, land use change - changing 20% crop and pasture land (3104 ha) into the forest land. In preparing the scenario data, the locations of land parcels changing were selected according to the groundwater pollution risk result in the watershed. All crop and pasture land parcels in "very high" and "high" risk zones were changed into forest land. Scenario 2, BMP method - implementing filter strip method in 80% crop and

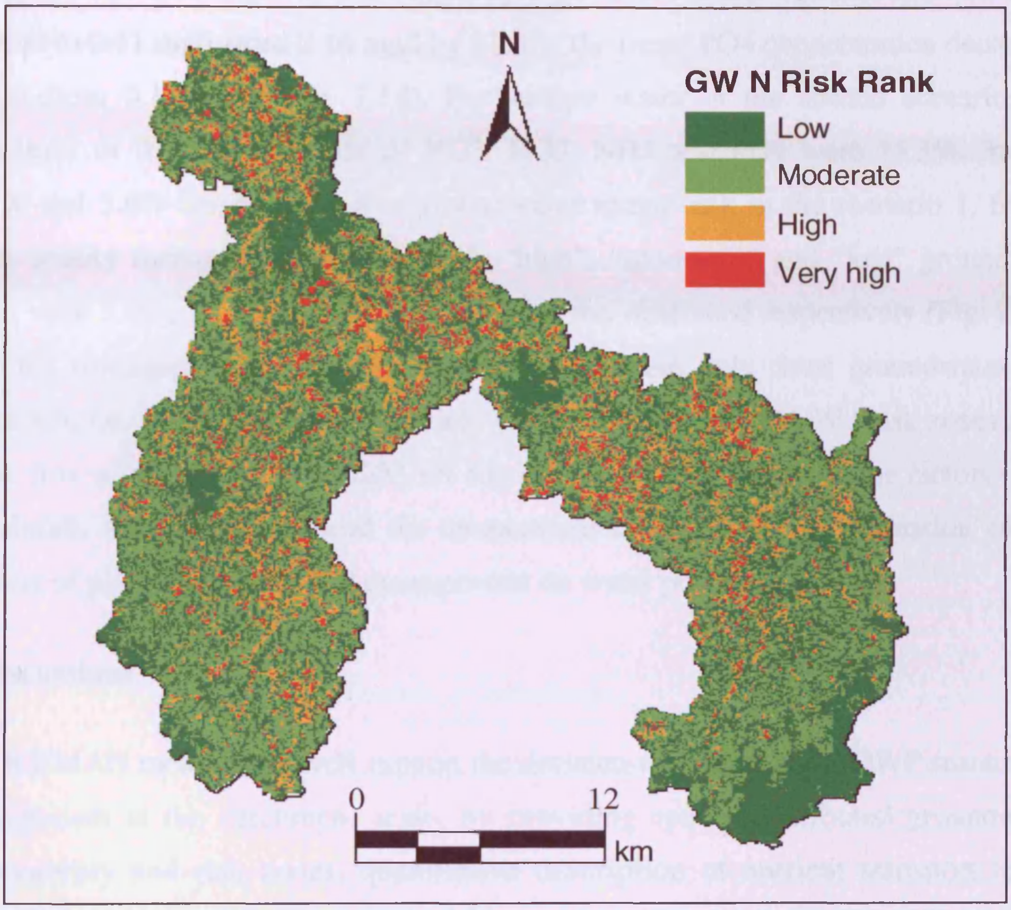

Fig. 7.11. Groundwater nitrate pollution risk in study area

pasture land of the study watershed. BMP are effective, practical, structural or non-structural methods, which prevent or reduce the movement of sediment, nutrients, pesticides and other pollutants from the land to surface water or groundwater for the ADWP management. The assumption of both scenarios was that all other situations (such as climate, soil and topography, etc.) were not changed. The impacts of two scenarios on water quality over five years were evaluated using the ICEMAN method. The hourly weather data, such as hourly precipitation, hourly air temperature, daily maximum and minimum temperature, solar radiation, evapotranspiration were from the weather station "Glenanne_Saws" in the study area.

In the first scenario, the mean nitrate concentration of the river decreased by 19.4% from original 2.68 mg/l to 2.16 mg/l (Fig. 7.13); the mean nitrite concentration changed from 0.06 mg/l to 0.04 mg/l by 33.3%; the mean concentration of NH4 reduced to 0.11 mg/l from 0.16 mg/l by 31.3%; the mean PO4 concentration decreased 31.3% from 0.16 mg/l (Fig. 7.14). For surface water in the second scenario, the reductions of the concentration of NO3, NO2, NH4 and PO4 were 15.3%, 33.3%, 31.3% and 5.6% respectively. For groundwater nitrate risk in the scenario 1, before water quality management, "very high", "high", "moderate" and "low" ground risk zones were 3.9%, 10.3%, 48.6% and 37.2% of the watershed respectively (Fig. 7.15); after the management of land use change, there were only three groundwater risk zones left, i.e. "high"(0.2%), "moderate" (45.5%) and "low" (54.3%) risk zones (Fig. 7.16). It is worth noting that ICEMAN can also consider climate change factors (such as rainfall, solar radiation, and air temperature changes) in the evaluation of the impacts of plans for the ADWP management on water processes.

5. Discussions

The ICEMAN method can well support the decision-making of the ADWP sustainable management at the catchment scale, by providing spatial distributed groundwater vulnerability and risk zones, quantitative description of nutrient transport in the catchment hydrological cycle in a specific catchment. For example, in the case study area, the application of ICEMAN can provide the nutrient contribution of each land use to water bodies, the quantitative description of nutrient biochemical cycle in unsaturated zone, the surface water quality and quantity process, nutrient pathways to

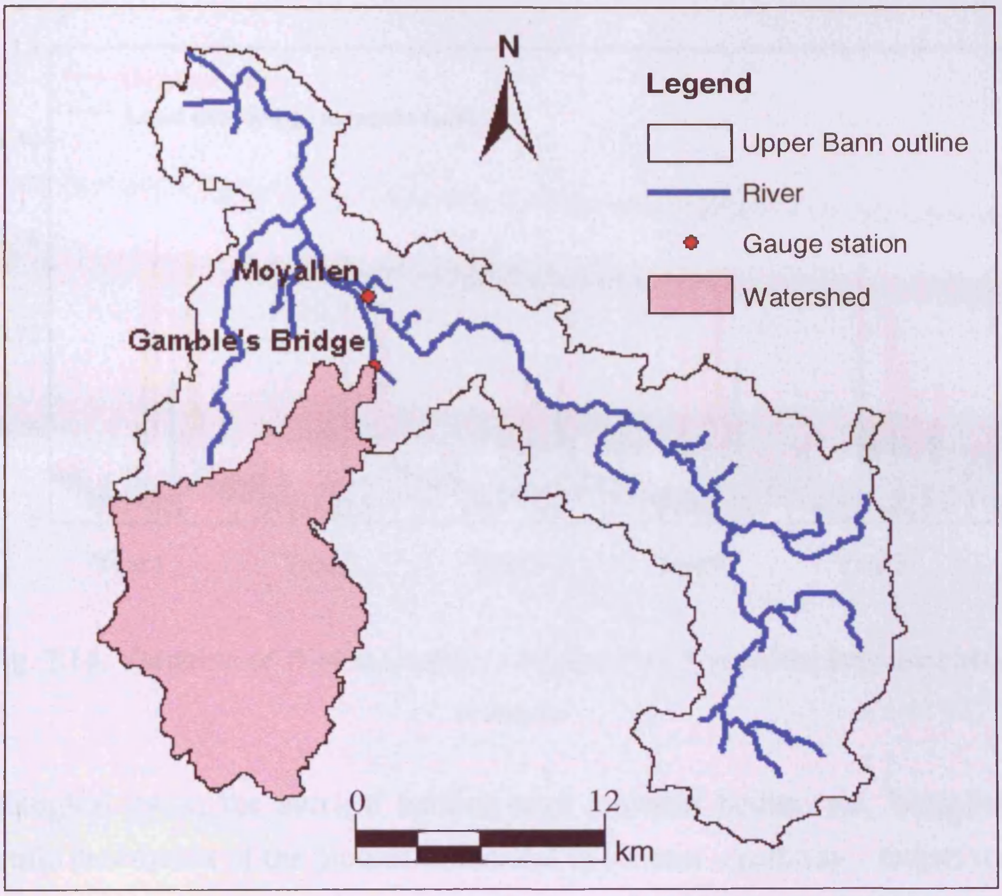

Fig. 7.12. The location of Gamble's Bridge watershed

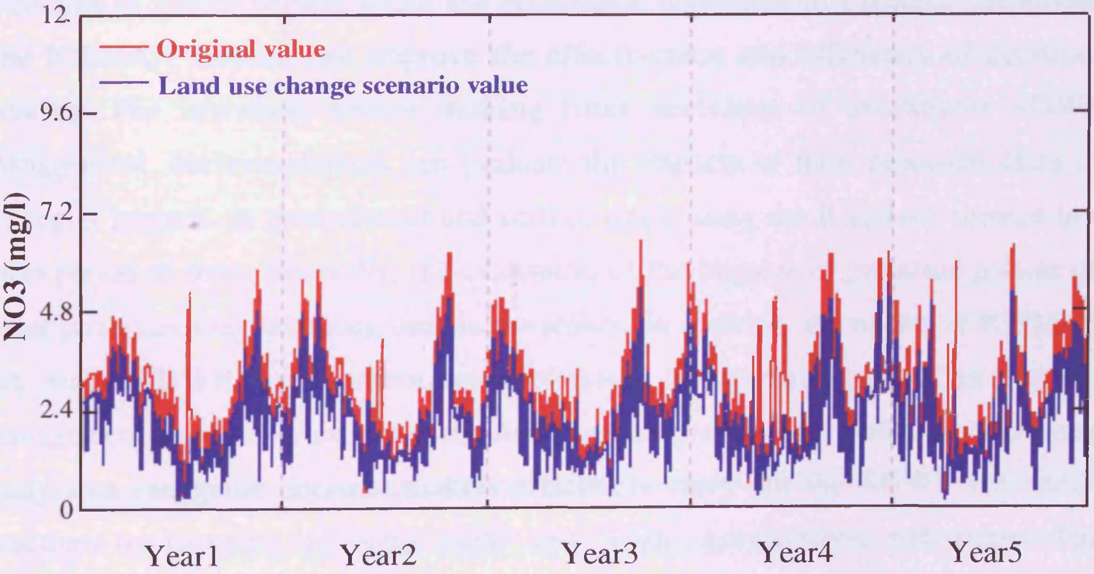

Fig. 7.13. Variation of NO3 at Gamble's Bridge over 5 years for land use change scenario

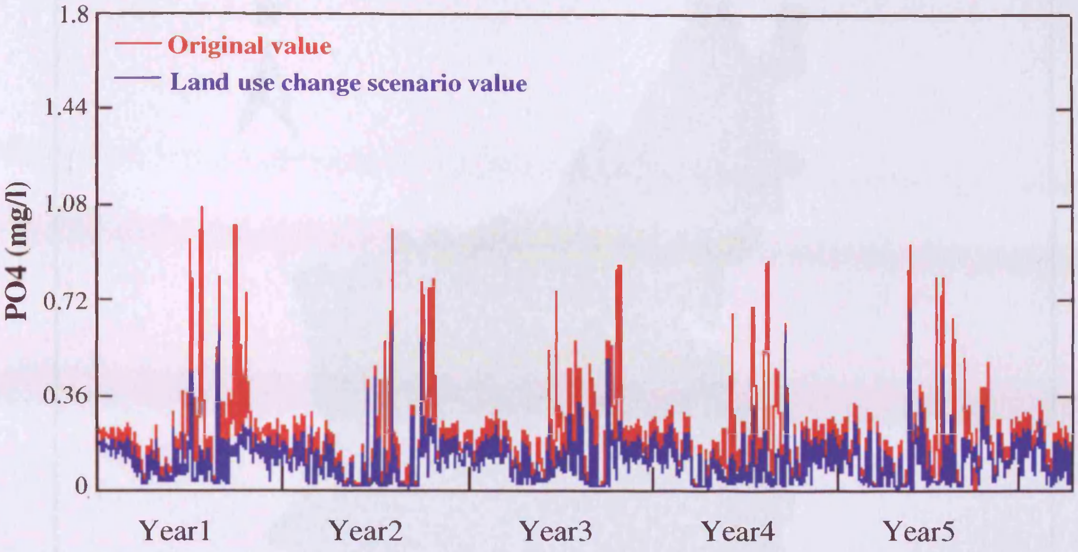

Fig. 7.14. Variation of PO4 at Gamble's Bridge over 5 years for land use change scenario

hydrological cycle, the nutrient loading rates to water bodies, etc. With detailed scientific description of the process of nutrient in sources – pathway – targets (targets in surface water), decision makers can make sound decision for the ADWP prevention according to special natural, social and economical conditions in a specific catchment. The ICEMAN method can improve the effectiveness and efficiency of decision-making. For instance, before making final decisions of catchment ADWP management, decision makers can evaluate the impacts of their proposed plans or strategies impacts on groundwater and surface water using the ICEMAN method in a short period of time. Generally, the evaluation of the impacts of proposed polices on water processes may take long time in the reality. In addition, the results of ICEMAN can make ADWP management more efficient by spatially providing explicit management targets. For example, the risk zones of groundwater pollution in the case study area can guide decision makers efficiently carry out the ADWP prevention practices by focusing on "very high" and "high" groundwater risk zones. The groundwater ADWP vulnerability represents the degree of pathway weakness for pollutants entering groundwater, thus the land use planning or management in high

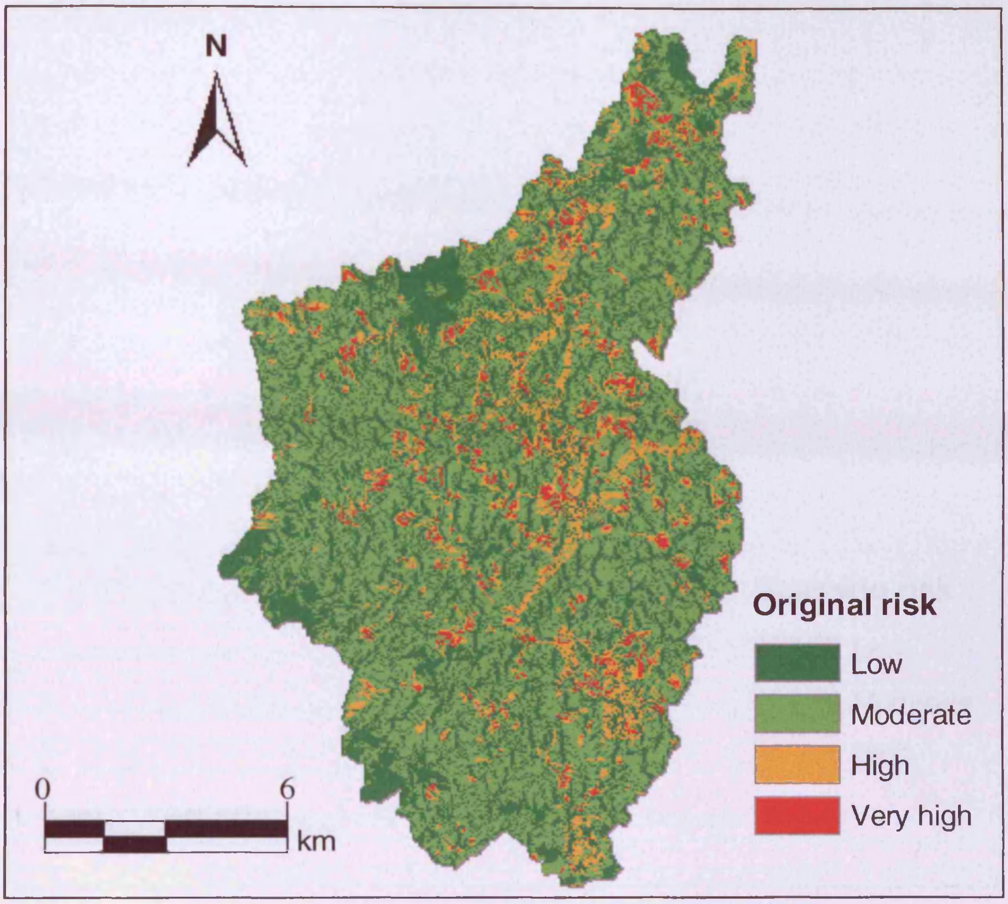

Fig. 7.15. Original groundwater risk in Gamble's Bridge watershed

groundwater vulnerable zones should be careful, although current groundwater risks might be low in these zones. ICEMAN may provide a good starting point for tackling the ADWP problem.

The ICEMAN method can bridge the "method and tool" and "research scale" gaps between current scientific research and successful implementation of the EU WFD in the ADWP field. Wang and Yang (Chapter 2) discusses these gaps in detail.

For "method and tool" gap, more efforts should be made to develop pragmatic numeric models and methods of tackling the ADWP problem. ICEMAN is an integrated decision-support modelling method for the ADWP sustainable management. Reliability is important in the decision-making process. Nevertheless, there are great

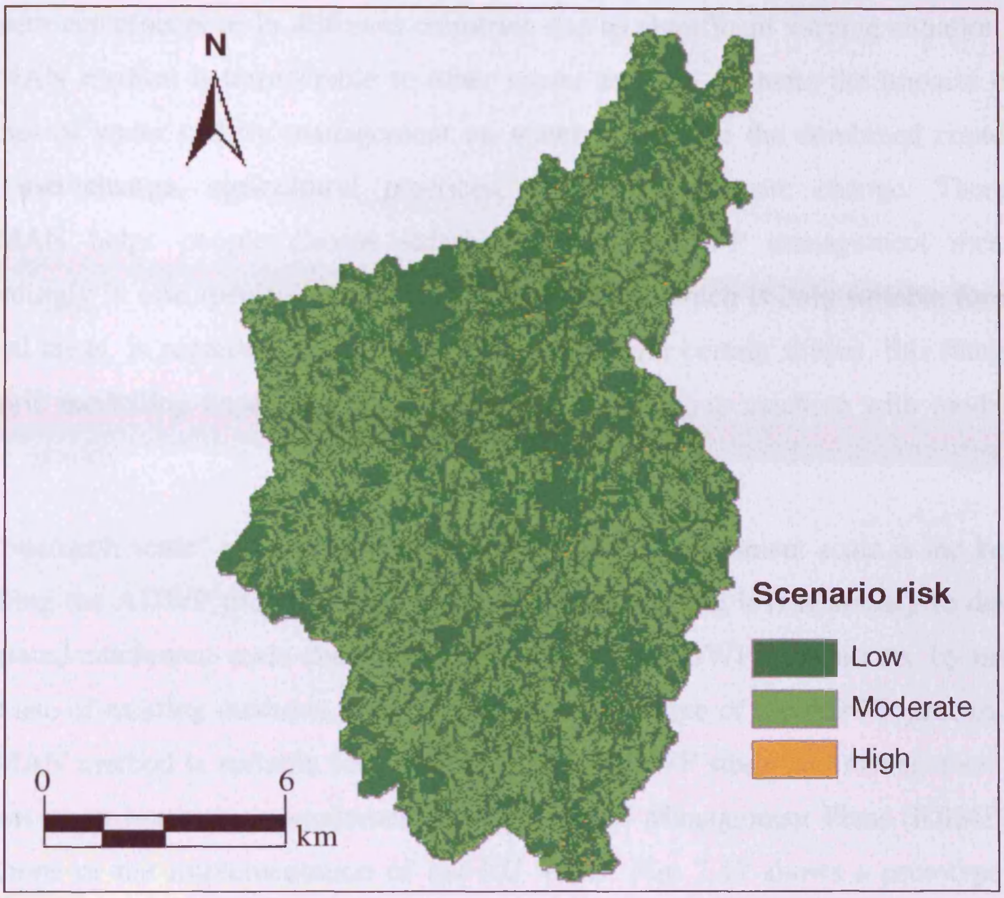

Fig. 7.16. Groundwater risk of land use change scenario in Gamble's Bridge watershed

uncertainties in existing ADWP studies. For example, the fact that only few factors have been considered in the UK existing groundwater vulnerability assessment led to high uncertainty in the result (Palmer et al., 1995; Palmer and Lewis, 1998; UKTAG, 2004; Giupponi and Vladimirova, 2006). By considering weather data, soil type, land use, nutrient cycling, soluble pollutant dynamic nature with surface water, topography, aquifer media, vadose zone media factors, and the interaction between surface water and groundwater, ICEMAN is capable of describing the catchment ADWP process with low uncertainty, and then guiding the catchment ADWP management. So far, many measures have been developed for handling the ADWP problem, such as land use change, BMP, contaminated water remediation and drinking water treatment. However, each EUMS have difficulties in choosing and applying these measures in different catchments or in different countries due to significant varying situation. The ICEMAN method is transferable to other areas; and can evaluate the impacts of the policies of water quality management on water process in the combined context of land use change, agricultural practices, BMP, and climate change. Therefore, ICEMAN helps people choose suitable existing ADWP management measures accordingly in one specific catchment. If the method, which is only suitable for some special areas, is regarded as providing chocolates with certain shapes, this integrated numeric modelling based ICEMAN method is a chocolate machine with modifiable shape moulds.

For "research scale" gap, the prevention of ADWP at catchment scale is the key for handling the ADWP problem in a sustainable manner, and it is necessary to develop integrated catchment-scale decision support tools for ADWP preventions, by making good use of existing methods, models, and the knowledge of the ADWP process. The ICEMAN method is suitable for catchment-scale ADWP study and management, and can act as an important complement of River Basin Management Plans (RBMP), the backbone of the implementation of the EU WFD. Fig. 7.17 shows a prototype of a possible systematic workflow of the management of the ADWP problem in the implementation of the EU WFD. RBMP will be established in each RBD by corresponding EUMS for long-term water resources management. In each RBMP, the monitoring plan, environmental objectives (including the handling of the ADWP problem), programme of measures, and management plans will be made. In handling the ADWP problem, these river basin scale based plans or measures will be used in the assessment of current agricultural pressures and their impacts on water quality, and then find out catchments with high priorities of the ADWP management within a River Basin Districts (RBD). As discussed above, ICEMAN can well support the decision-making of catchment-scale ADWP sustainable management. Therefore, in catchments with higher priority of the ADWP management, the ICEMAN method can be an important complement of the programme of measures in a RBMP for sustainable management of the ADWP problem. After carrying out the ADWP

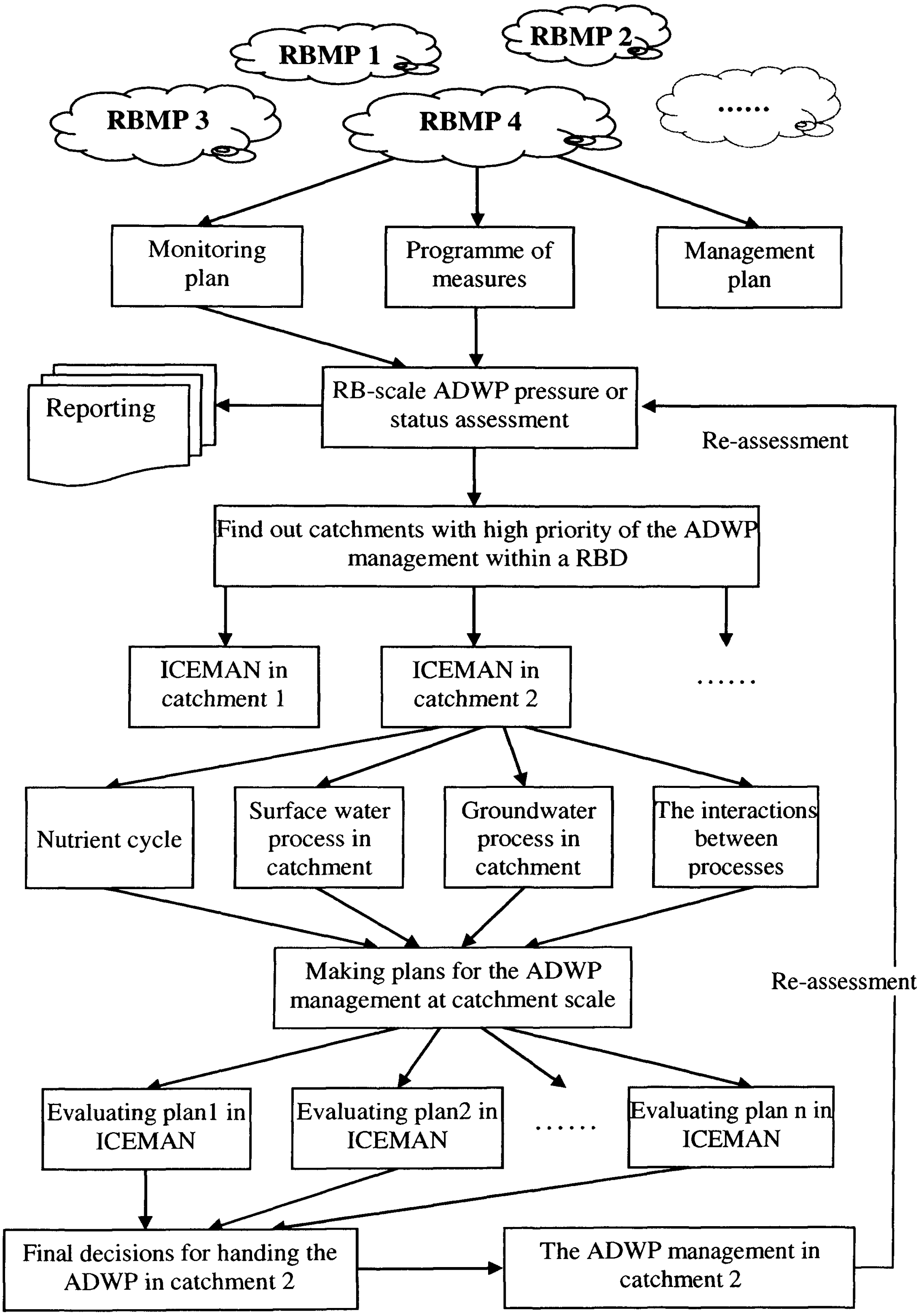

Fig. 7.17. The prototype of a possible systematic workflow for handling the ADWP problem for better implementation of the EU WFD

prevention plans in target catchments in the reality, the second round assessment of setting the priorities of the ADWP management in catchments with a RBD will be carried out. This repeating workflow can effectively and efficiently support the prevention of the ADWP problem in a sustainable manner.

Apart from nutrients, the ICEMAN method has potential of modelling other pollutants from diffuse agricultural sources, such as pesticides, sediments, and faecal materials because of the capabilities of the models integrated into the ICEMAN method. Further studies are needed to test and improve the suitability of ICEMAN in modelling other pollutants. The ICEMAN method has an open framework, which can be extended using better catchment-scale models. GIS based ICEMAN method can pass the knowledge to all stakeholders in an easy understanding way by using the advantage of spatial data management and visualisation functions of GIS. It is worth noting that ICEMAN has the potential of promoting the public participation demanded by the EU WFD by extending Web-GIS functions. This study is not only useful for better implementation of the EU WFD, but also helpful for tackling the ADWP problem outside of the EU, especially for developing agricultural countries. Further research should be carried out to test ICEMAN in other areas.

There are limitations in the ICEMAN approach. Firstly, although ICMAN integrates the complex models of surface water, soil, and groundwater, it is still simple in the description of physical and chemical processes in hydrological cycle in comparison with the reality. For example, models in ICEMAN do not cover the nutrient biochemical process in stream and groundwater. In order to improve the accuracy of these models, more multi-disciplinary or inter-disciplinary fundamental studies should be carried out to find key driving forces that control the ADWP process. Secondly, the ICEMAN method provides scientific evidences for better understanding of the catchment ADWP process, instead makes concrete plans for ADWP management plans. Decision-making will be done by decision makers with the help of experts in many other fields. However, further work could be done based on ICEMAN by introducing expert system. Thirdly, not all ADWP management strategies can be evaluated. The strategy other than land use, climate change, agricultural practices and BMP can not be evaluated. However, GIS based ICEMAN is extensible to evaluate more strategies of the ADWP management in future studies. Fourthly, the ICEMAN approach can not be used in one area less than 0.405 km^2 because of the assumption of the DRASTIC and D-DRASTIC methods. Finally, further computer programming work is necessary for developing integrated and friendly software interface of ICEMAN.

6. Conclusion

The ICEMAN method, developed in this multi-disciplinary study by integrating the models of GIS hydrology, groundwater vulnerability assessment, groundwater risk assessment, and surface water diffuse pollution models simulation into ArcGIS, can effectively and efficiently support the decision-making of the ADWP sustainable management at the catchment scale. ICEMAN is transferable to other areas; and can bridge the gaps of “method and tool” and “research scale” in the implementation of the EU WFD. It can be an important complement of RBMP for better implementation of the EU WFD. This study may provide a good starting point for tackling the ADWP problem in an integrated and sustainable manner. Further studies are needed to test ICEMAN in different areas, and improve the suitability of ICEMAN in modelling other pollutants from agricultural diffuse sources. ICEMAN has limitations and can be improved from several aspects in future research.

Acknowledgements

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Chapter 8

Summary, conclusions, and outlook

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1. Research summary

This thesis focuses on developing an integrated catchment-scale modelling approach to support the decision-making of the management of the agricultural diffuse water pollution (ADWP) at the pollution source level, in order to find a better way for handling the ADWP problem, a biggest remaining water pollution problem in the world and the major threat in the implementation of the EU Water Framework Directive (WFD).

Firstly, the project plan was made based on the discussion the scientific gaps between current ADWP research and the successful implementation of the EU WFD (chapter 2). Secondly, GIS and Arc Hydro model were selected to prepare the data and spatial analysis functions for developing and applying the final integrated catchment-scale modelling method (Chapter 3). Thirdly, DRASTIC model was adopted in groundwater pollution pathway vulnerability assessment in the study area. The pitfalls of applying DRASTIC in groundwater pollution risk assessment were found, thus demanding the development of a new method for more reliable groundwater pollution risk assessment (Chapter 4). Therefore, fourthly, A D-DRASTIC method was developed for guiding the activities of groundwater pollution prevention at the catchment scale (Chapter 5). Fifthly, a numeric surface water modelling is necessary for the study of catchment-scale ADWP process in providing the quantitative description of water quantity and quality to temporal and spatial detail. HSPF model was carefully selected based on the review of popular and free surface water models. Then, the assessment of HSPF in the study area was carried out (Chapter 6). These methods or models, selected and tested in this study, cover the catchment processes of hydrology, hydrogeology, and nutrient biochemical cycling in soil. Finally, an integrated modelling approach ICEMAN was developed by integrating the methods or models mentioned above into an ArcGIS environment. ICEMAN was tested in the study area (chapter 7).

2. Major conclusions

2.1. Challenges in the implementation of the EU WFD for handling ADWP

In the field of the ADWP, scientists are facing the challenges of bridging the gaps of "method and tool", "research scale", and "fundamental knowledge" to meet the water quality requirements of EU WFD by 2015. It is timely to develop integrated catchment-scale numeric modelling tools and methods to support the prevention of ADWP at the catchment scale, by making best use of existing knowledge of the ADWP process covering the complete hydrological and pollutants cycles.

2.2. A new method for groundwater pollution risk assessment

The GIS-based D-DRASTIC developed in this study overcomes the drawbacks of DRASTIC in groundwater risk assessment by integrating pollutant loading for different land uses and groundwater pollution pathways. It reflects the interactions between runoff, soil, vadose zone and groundwater, thus playing a role of continuously describing the soil and groundwater processes in the catchment ADWP. In comparison with DRASTIC, D-DRASTIC is more helpful in guiding prevention practices for groundwater pollution at the catchment scale. The application of this improved approach in the Upper Bann Catchment showed better presentation of the risk assessment from surface land uses. The D-DRASTIC method is transferable other catchments. Further research may be needed to test and improve the suitability of D-DRASTIC for groundwater risk assessment from other soluble pollutants.

2.3. Surface water model

Based on the review of popular surface water models, HSPF was selected for catchment-scale modelling of surface water pollution from agricultural diffuse sources. The assessment of HSPF in the Upper Bann Catchment showed that HSPF is suitable for surface water simulation in supporting the ADWP management at the catchment. Therefore, HSPF is helpful for better implementation of the EU WFD in the field of handling ADWP.

2.4. The ICEMAN method

The ICEMAN method, developed in this multi-disciplinary study by integrating the models of GIS hydrology, groundwater vulnerability assessment, groundwater risk assessment, and surface water diffuse pollution models simulation into ArcGIS, can effectively and efficiently support the decision-making of the ADWP sustainable management at the catchment scale. ICEMAN can describe the nutrient biochemical cycles in soil, whole hydrological quantity and quality processes, and groundwater pollution vulnerability and risk. The application of ICEMAN in the Upper Bann Catchment showed that it can well support the decision-making of the catchment ADWP sustainable management. ICEMAN provides satisfied simulation of river flow and quality, groundwater pollution vulnerability and risk zones. ICEMAN can also quantitatively describe the catchment-scale nutrient biochemical cycle in soil, surface water process, groundwater pathway vulnerability, groundwater risk, water and nutrient dynamic nature with surface runoff and interflow, the interaction between soil water and groundwater, and the soil water cycling relationship with stream water process. In addition, ICEMAN can evaluate the impacts of water management plans on water processes under the climate change.

ICEMAN is transferable to other areas; and can bridge the gaps of “method and tool” and “research scale” in the implementation of the EU WFD. It can be an important complement of RBMP for better implementation of the EU WFD. This study may provide a good starting point for tackling the ADWP problem in a sustainable and integrated and sustainable manner. Further studies are needed to test ICEMAN in different areas, and improve the suitability of ICEMAN in modelling other pollutants, such as pesticides, sediments, and faecal materials, from agricultural diffuse sources. ICEMAN has limitations and can be improved from several aspects in future research.

2.5. The ADWP conditions in the Upper Bann Catchment

Based on the results of the ICEMAN application in the study area, the ADWP conditions in the Upper Bann Catchment were found.

"Very high" groundwater nitrate risk zones, 5% of the Upper Bann Catchment, are located in undulating drumlin and low-lying areas; "high" groundwater nitrate risk zones, 11% of the area, are found around streams/rivers; "moderate" risk zones occupy 47% of the area; and "low" risk zones, 37% of the area, are found everywhere especially in the Mourne Mountains to the southeast of the study area.

The average NO3 export coefficient for cropland and pasture land, bare land, urban land, mixed forest land, deciduous forest land, evergreen forest land and forested wetland between 2000 and 2005 in study area were 28.7, 7.5, 3.0, 5.7, 5.5, 5.3, and 7.6 kg/ha respectively. If the hypothetic surface water nitrogen standard is 6 mg/L, the nitrogen total maximum daily load is 68.1 kg.

Infiltration, upper soil, interflow recession, lower soil zone nominal storage, fraction of groundwater inflow to deep recharge, fraction of remaining ET from baseflow, BOD decay rate, denitrification rate of nitrate, temperature coefficient for the nitrogen oxidation rate, etc. play important roles in surface water quantity and quality in the study area.

The scenario simulation in the study area using ICEMAN showed that:

(1) When 20% of crop and pasture land in a watershed were changed into the forest land, the mean nitrate concentration of the river decreased by 19.4% from original 2.68 mg/l to 2.16 mg/l; the mean nitrite concentration changed from 0.06 mg/l to 0.04

mg/l by 33.3%; the mean concentration of NH4 reduced to 0.11 mg/l from 0.16 mg/l by 31.3%; the mean PO4 concentration decreased 31.3% from 0.16 mg/l. For groundwater pollution risk, there are only three groundwater risk zones left, i.e. "high"(0.2%), "moderate" (45.5%) and "low" (54.3%) risk zones.

(2) When filter strip method (one of the Best Management Practices) was implemented in 80% crop and pasture land of the study watershed, the concentration of NO3, NO2, NH4 and PO4 reduced 15.3%, 33.3%, 31.3% and 5.6% respectively.

3. Suggestions for future work

Below are some suggestions for future similar work. In surface water simulation, the agricultural land use classification can be in more detail. The crop and pasture land use was classified into one land use type in the surface water modelling because of the time limitation and trying to reduce to complexity of the HSPF application which needs the efforts of a group of experts. In order to study the agricultural activity contributions to the ADWP, the agricultural land used should be divided as detailed as possible for more accurate modelling results. For example, in HSPF, the agricultural land use could be classified into arable land, arable horticulture, improved grassland, neutral grassland, acid grassland, broad-leaved woodland, coniferous woodland, dwarf shrub heath, etc.

Only one catchment was used in the testing of D-DRASTIC and ICEMAN methods, due to time and budget limitations in this study. Two or more catchments are needed for testing methods developed in this study.

More groundwater monitoring data are need in the validation of the D-DRASTIC method. There were few groundwater monitoring sites in the study area from the existing monitoring network. No further groundwater monitoring work was carried out because of budget limitation. The trend of groundwater quality derived from these few monitoring sites is in line with the risk assessment result of the D-DRASTIC method. However, the purpose of the D-DRASIC method is for detailed groundwater pollution risk assessment at catchment scale. Therefore, detailed groundwater monitoring data are needed for further validation and improvement of the D-DRASTIC method.

4. Possible further work based on this study

Further studies might be carried out based on this study for better supporting the decision-making of the ADWP handling at the catchment scale.

4.1. Fundamental knowledge about the ADWP process

As mentioned in this study, there is "fundamental knowledge" gap between current research and the implementation of the EU WFD in the field of ADWP handling. The ICEMAN can be improved by carrying out inter-disciplinary fundamental studies to better understand the complex transport and biochemical transformation processes of diffuse pollutants within and between air, plants, soil, rocks, groundwater and surface water under different natural and human agricultural activity conditions. The results of such fundamental studies could be used to develop better catchment-scale water quality models; and to find innovative measures to control the ADWP problem at the catchment scale. For example, tracing the complete nutrient bio-chemical processes not only in soil, but also in unsaturated zone, saturated zone, and streams can help people better understand the nutrient processes and the driving factors affecting these processes, thus leading to better modelling tools and ADWP handling measures.

4.2. Study the complete ADWP process

Although there are many good and powerful methods or tools for some phases of the ADWP process, effective management of the ADWP needs to consider the complete ADWP process. ICEMAN developed in this study may be improved in two ways: 1) Developing/improving and evaluating better models of soil process, surface water process and groundwater process; and 2) integrating more models describing different phases of the ADWP process into ICEMAN, such as atmosphere and groundwater transport models. The integration of models is not a simply adding action, but a process of trying to reflect the interactions between different phases of the ADWP process. There are two examples.

4.2.1. Accurate groundwater simulation for water remediation

Although the water prevention is the key for handling the ADWP, the water remediation can also be used in some situations for the ADWP management. More accurate groundwater simulation can be carried out by coupling nutrient soil model with groundwater model (such as MODFLOW). On the one hand, the results of such kind of study can evaluate the reliability of the groundwater risk assessment model. On the other hand, such study can tell where pollutants go with the groundwater flow, thus helping the groundwater remediation when it is necessary.

4.2.2. The interaction of surface water and groundwater at riparian zone

It is necessary to study the interaction of surface water and groundwater at riparian zone of rivers to improve the accuracy of the modelling of surface and groundwater. For example, several sets of boreholes crossing the riparian zones of rivers could be designed to monitor and study the hydraulic heads and water quality in observing wells and rivers in different seasons. The knowledge of these field experiments can then be converted into mathematical models for more accurate surface water and groundwater modelling.

4.3. The expert knowledge database for ADWP handling measures

Since each EUMS has special natural, economic, and social situations, the exact measures used for the ADWP management differ greatly from place to another. Therefore, it would be helpful to establish an expert knowledge database for the ADWP management. Based on the expert database to be built, the decision-support system can help people efficiently and effectively choose suitable ADWP controlling measures (such as BMP, land use change, or farming activity change) according to the natural and human activity conditions, and the characteristics of ADWP processes in a specific catchment.

4.4. Introducing the WebGIS into the ADWP management

WebGIS can be used in developing GIS functionality in the Internet to make distributed geographic information available to a very large worldwide audience through web browsers. The introduction of the WebGIS into ICEMAN can make the results of catchment ADWP process study to be easily fetched by all stakeholders; and help government operate sound and transparent decisional processes with high efficiency in better communications with stakeholders and general public.

4.5. Computer programming

Computer programming work may be done based on ICEMAN in developing friendly user interface, and seamless coupling models of soil process, groundwater, and surface water in a GIS environment.

Four research funding application proposals submitted during this PhD study in Appendix C partially reflect the possible further work based on this study discussed above.

Appendix A

The study area – Upper Bann Catchment

This appendix describes the conditions of terrain, land use, soil, geology, hydrogeology, river flow, borehole, river quality monitoring, weather, and hydrological features in the Upper Bann Catchment, Northern Ireland, based on the multi-sphere GIS database of the study area established for further integrated water modelling at the catchment scale.

1. Introduction to the Northern Ireland

Northern Ireland (NI), with an area of 14,120 km^2, consists of 6 counties, namely, County Antrim, County Armagh, County Down, County Fermanagh, County Londonderry, and County Tyrone. These counties remain a popular means of describing where places are, but they are no longer used for local government purposes. Instead there are 26 districts of NI which have different geographical extents. There are 5 cities in NI: Belfast, Armagh, Derry, Lisburn, and Newry. The current population of NI stands at almost 1.7 million with 627,000 households. 66% of population live within 50km radius of Belfast – the capital of NI, the second largest city in Ireland. 36% of the population are under the age of 25, compared with 38% in the Republic of Ireland and 29% in the EU (DARD, 2004). The towns of Craigavon, Lurgan and Portadown combined in the 1960s as part of the 'New Town' development schemes in the UK. They form one large continuous urban sprawl that covers an area of 260 km^2 (about 30% of which is in the Upper River Bann catchment), which has a population of approximately 80,000 inhabitants today, about 30% of which live in Portadown. Agri-food industry, with total processed sales worth £2.0bn, plays a vital role in NI economy. In NI, there are 1.07 million hectares farmed in total; and 3,100 farms that are large enough to provide full-time work for one or more people. The total on-farm employment is 54,500 people including full and part-time (DARD, 2004).

Around 75% of land area of NI is used for agriculture, including common rough grazing, and a further 6% is used for forestry. Most farmland in NI is under grass. Only 3,991farms (15%) have arable or horticultural crops. These crops occupy 51,200 hectares and make up only 5 % of the total area farmed. Barley (22,800 hectares) is the main crop grown followed by wheat with 9,200 hectares. In 2007, the cropped area also included approximately 3,000 hectares of horticultural crops, mainly apple orchards (1,400 hectares) and vegetables (1,300 hectares). All but 6% of NI farms have cattle or sheep (DARD, 2007). Intensive market gardening is carried out in the Newtownards or Comber area. The remaining 25% of the land in NI comprises urban and industrial use.

NI was covered by an ice sheet for most of the last ice age, the legacy of which can be seen in the extensive coverage of drumlins in Counties Fermanagh, Armagh, Antrim and particularly Down. Upland areas, including the Sperrin and Mourne Mountains, offer numerous catchments suitable for the collection and storage of surface water. These gathering grounds are complemented by Lough Neagh (388 km^2), the largest inland freshwater lake in the British Isles, for public supply throughout the low-lying land. Six major rivers flow into Lough Neagh which has a mean depth of 12m, and is drained to the north by the Lower River Bann which reaches the sea at Coleraine. The Lower and Upper River Bann, River Foyle and River Blackwater form extensive fertile lowlands, with excellent arable land also found in North and East Down (Wikipedia, 2008). The elevation of the Lough Neagh's surface is controlled at about 15m above Ordnance Datum (OD). The land around the Lough is flat or undulating, rising to about 100m above OD. To the west the Sperrin Mountains rise to 680m above OD at Sawel Mountain; to the east are the Glens of Antrim and in the southeast of the Mourne Mountains with the highest peak of NI, Slieve Donard reaching an elevation of 852m above OD (Robins, 1996). The predominant lowland, approximately 75% of NI, is below 150m above OD, with most of it forming an extensive saucer-shaped lowland around Lough Neagh (Cruickshank, 1997).

NI has a temperate maritime climate, rather wetter in the west than the east. Generally, NI is cloudier than England, because of the hilly nature of the terrain. The seasons of NI are distinct, nevertheless, they are considerably less pronounced than in interior Europe or the eastern seaboard of North America. Average daytime maximum temperature in Belfast are 6.5 °C in January and 17.5 °C in July (Wikipedia, 2008). Mean daily sunshine of NI reach a maximum in May or June, and are at their lowest in December. Rainfall in Northern Ireland varies widely. Fig. App.A.1 shows that western part of NI is the wettest. The average annual rainfall is approximately 1080 mm/year and in a dry year may be just less than 900 mm/year. The highest average annual totals have been recorded in the Sperrin, Antrim and Mourne Mountains, where the yearly fall of around 1,600 mm. However, in the east, close to the coast, and near to the southern and eastern shores of Lough Neagh, the annual totals of just less than 800 mm (Met Office, 2008).

NI offers the most compact and diverse range of solid geology, quaternary deposits and soil types anywhere in Europe. The Permian and Triassic sandstones are the most important aquifers in the NI. In the Lagan Valley the porosity of the Permian Sandstone is locally as high as 30%. This high secondary fracture permeability enables the aquifer to sustain very high abstraction rates. The Silurian and Ordovician strata crop out over a large part of Counties Down and Armagh. Lithologies include greywackes, shales, sandstones and mudstones, and limited shallow circulation of groundwater may occur wherever weathering has produced suitable cracks and joints. The Chalk and the Hibernian Greensand are largely concealed by Palaeogene volcanic rocks. They form thin aquifer around the Antrim coast. The Palaeogene basalt lavas are very extensive are very extensive and cover an area of 4,000 km^2 in County Antrim (Fig. App.A.2). The widespread occurrence of relatively poor aquifers has promoted the development of groundwater in the Quaternary (most notably the

Glarryford sand and gravel aquifer). The principle soil associations are climatic peat the elevations above 200m, and acid brown earth and gleys at lower elevations (Robins, 1996).

The rivers, lakes, estuaries, seas and groundwater in NI are important natural resources for drinking water, agriculture, industry and fisheries, for amenity and recreational use. In NI, surface water is the dominant source of public water supply with groundwater estimated to provide only 8% of the total public water supply. Despite the small direct contribution to public supply, groundwater still has an important role to play because of its contribution to baseflow of surface water especially in times of low flow, where most of public supply originates, and widely used as sources of private supply. In addition, the real value of groundwater is its widespread distribution, and hence availability throughout the NI, and its stable quality. Therefore, both surface water and groundwater are vital to social and economic development throughout the rural community. However, some of the human activities can threaten the water quality. For example, the pollutants can come from point sources such as industrial or sewage effluent discharges, or can be diffuse such as agricultural sources and road in the surrounding catchment. Lough Neagh, Lough Erne, and many other lakes, rivers, estuaries and coastal waters in NI are affected by eutrophication caused by the enrichment of nutrients, especially compounds of nitrogen and phosphorus. The results of a number of lake surveys carried out between 1988 and 1994 indicated that some 63% of NI lakes were either eutrophic or hypertrophic (EHS, 2000). It was considered that only lakes were affected, it has now been demonstrated that rivers and estuaries are also showing signs of impact. Agricultural diffuse sources are the primary cause of current levels of eutrophication in NI.

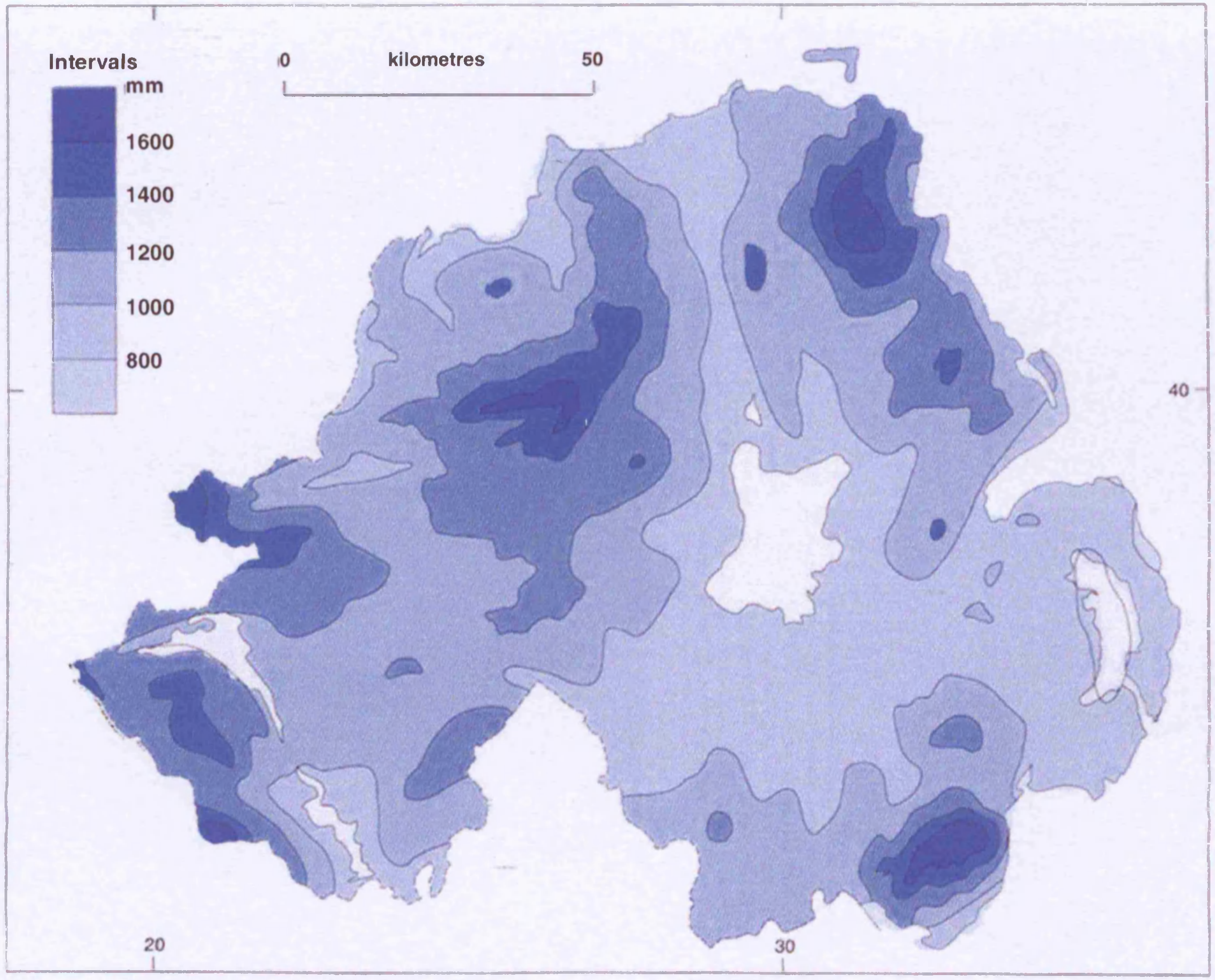


Fig. App.A.1. Average annual rainfall for the period of 1941-1970 in the Northern Ireland (from Robins, 1996)

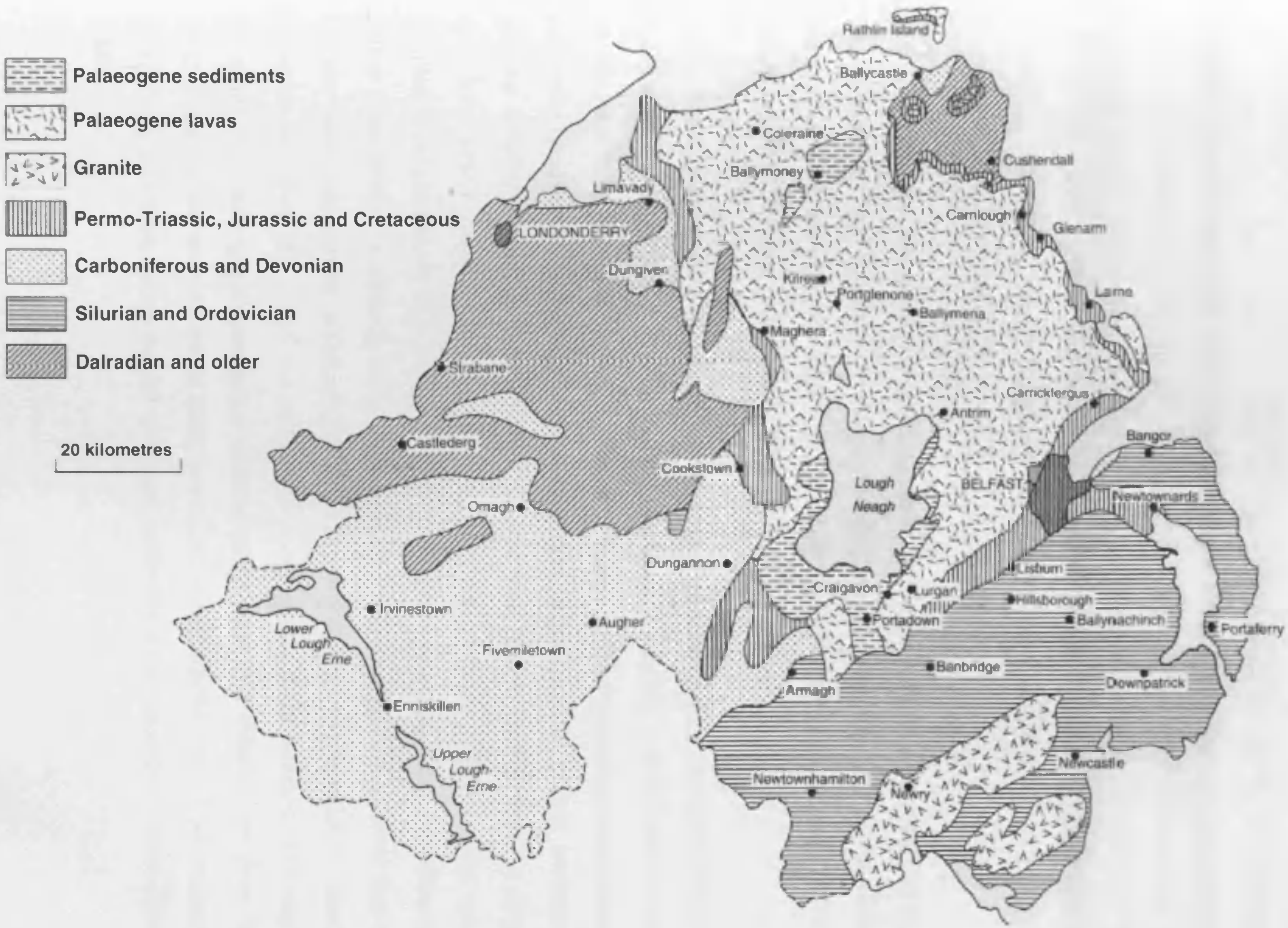


Fig. App.A.2. Geological setting of Northern Ireland (from Robins, 1996)

2. Upper Bann Catchment

The Upper Bann Catchment, covering an area of 674 km2, lies in the southeast of Northern Ireland, UK (Fig. App.A.3). The Upper River Bann rises on the western slopes of the Mourne Mountains and discharges to Lough Neagh at Bannfoot about 15 km north west of Portadown. The river has considerable game fishery potential in its middle and upper reaches, and is a highly valued coarse fishery from upstream of Portadown through to Lough Neagh. It has two major tributaries, the Cusher and Ballybay Rivers (EHS, 2000).

The Upper Bann Catchment is a complex rural catchment with a wide range of land uses, including fruit growing, livestock farming, arable farming and urbanisation. Agriculture land accounts for 92.9% of the study area, including grassland (76.3%), arable land (10.2%), and woodland (6.5%).

There is widespread non-compliance with chemical general quality assessment targets in the designated reaches in the study area. The Muddock River, which flows into the Upper Bann near Rathfriland, and the Ballybay River, failed by two and three classes respectively. There are tributaries throughout the catchment with poorer biological quality. Smaller watercourses throughout the area have poorer quality than the larger river into which they flow. Environment and Heritage Service (EHS) carried out a detailed biological study of the Upper Bann in Autumn 1999 to provide a baseline for future management initiatives in the river system. This investigation showed that by far the most widespread problem affecting the system was biodegradable organic pollution and that this could not be attributed to known point sources. The major pressures on water quality including nutrient enrichment and siltation are from the agricultural diffuse sources. More likely causes of biodegradable organic pollution are agricultural activities, urban run-off and septic tanks, or a combination of these (EHS, 2000).

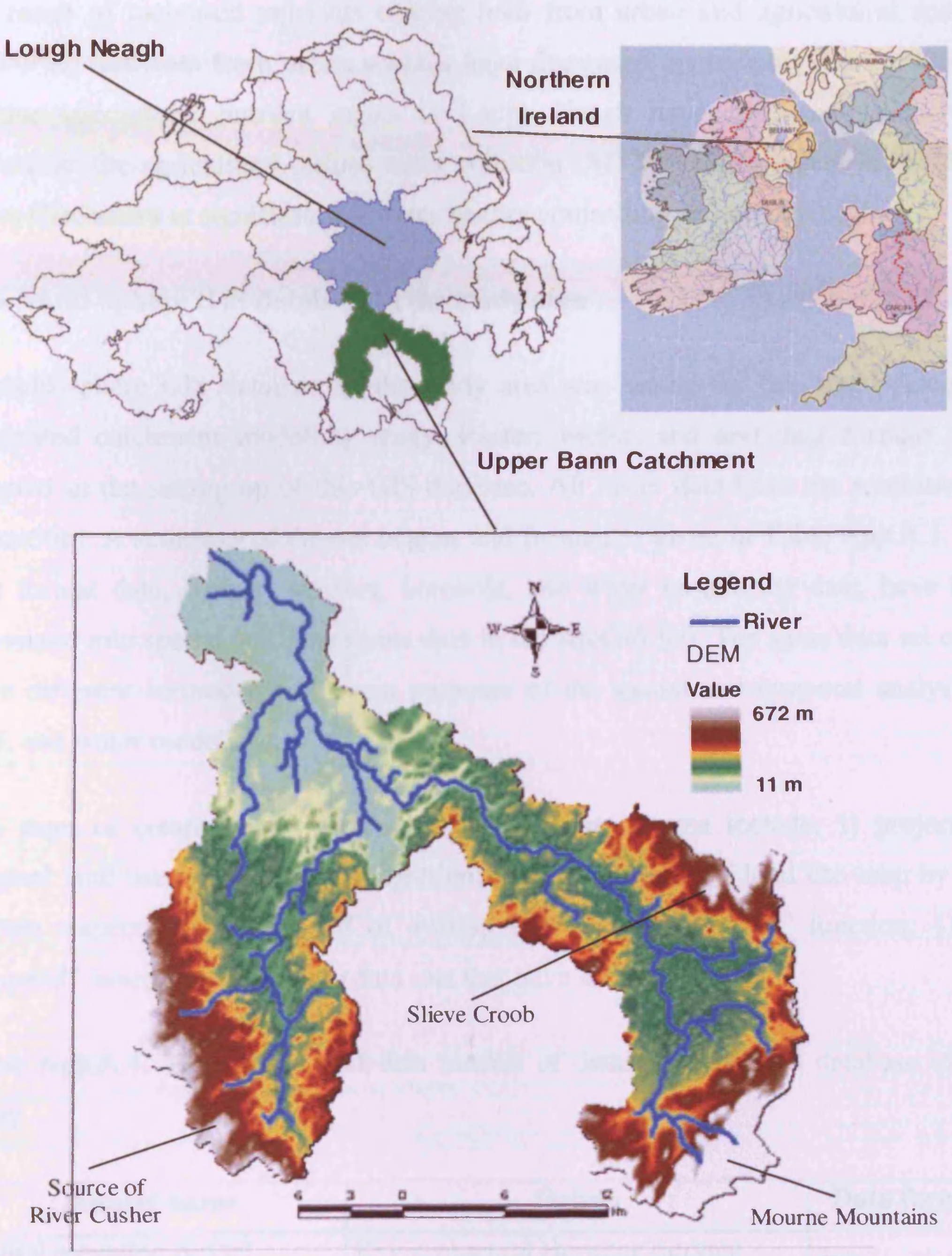


Fig. App.A.3. The location of the Upper Bann Catchment in Northern Ireland

The Upper River Bann in the study area is the largest river that supplies Lough Neagh. According to Lough Neagh & Lower Bann Advisory Committees, the dramatic nutrient enrichment in Lough Neagh, which occurred in the 20th Century, had been the result of increased nutrients coming both from urban and agricultural sources. While the nutrients from urban sources have decreased appreciably since 1986, the diffuse agricultural nutrient inputs to Lough Neagh have continued to increase. Therefore, the agricultural diffuse water pollution (ADWP) management in the Upper Bann Catchment is significant for water quality controlling in Lough Neagh.

3. A Multi-sphere GIS database in the study area

A multi-sphere GIS database of the study area was set up for this multi-discipline integrated catchment modelling study. Raster, vector, and text data formats were adopted in the setting up of this GIS database. All raster data have the resolution of 50m×50m. A summary of dataset origins and formats is given in Table App.A.1. The text format data, such as weather, borehole, and water monitoring data, have been converted into spatial and time series data in the ArcGIS 9.0. The same data set could have different formats for different purposes of the spatial and temporal analysis in GIS, and water modelling.

The steps of creating land use map in the case study area include: 1) project the original land use map to target projection; 2) clip two parts of land use map by area outline respectively; 3) get rid of overlap part using the "Erase" function; 4) use "Append" function to unite two data sets that have no overlap part.

Table App.A.1. The origins and data models of dataset in the GIS database of this study

Dataset name	Origin	Data format
Digital elevation model (DEM)	Environmental Heritage Service (EHS)	GIS raster data
Land cover map 2000	Centre for Ecology & Hydrology (CEH)	GIS vector data
Soil data	Department of Agriculture and Rural Development (DARD) of Northern Ireland	GIS vector data
Catchment boundary	Geological Survey Northern Ireland, GSNI	GIS vector data

Drift & solid geological data	GSNI	GIS vector data
Daily river flow (four stations)	Rivers Agency	Text file
Borehole data	GSNI	Text file
Monthly river chemical quality	EHS	Text file
Weather data (precipitation, wind, temperature, solar radiation, etc.)	British Atmospheric Data Centre (BADC)	Text file
Potential Evaporation (PE)	-	Calculated based on weather data
River network data (river, flow direction and topology)	-	Derived based on DEM
Drainage areas of points	-	Derived by GIS hydrology model

4. The conditions of the study area

4.1. Terrain

The average altitude in the study area is 110m above OD. The steepest area is located in the Mourne Mountains to the southeast; steeper areas are found at the source of the Cusher River to the southwest and Slieve Croob to the east of the study area. The topography gently undulates throughout the rest of the study area, rising from 11m above OD at Lough Neagh to a maximum of 672m above OD in the Mourne Mountains (Fig. App.A.4).

4.2. Land uses

The land use data is showed in Fig. App.A.5. Table App.A.2 shows the structure of the land use in the study area. Agricultural land use occupying 92.9% of the study area is the major land use type. The grassland is the dominated land use in the agricultural land use.

Table App.A.2. The land use structure of the Upper Bann Catchment

Land use type	Land use	Area (Sq. meters)	Percentage of the catchment (%)	Percentage of the catchment (%)
Agriculture	Improved grassland	423762941.7	62.9	92.9
	Neutral grass	58380672.65	8.7	
	Acid grass	24493428.81	3.6	
	Calcareous grass	7687484.06	1.1	
	Arable horticulture	68609974.81	10.2	
	Bracken	2087335.532	0.3	
	Open dwarf shrub heath	12768479	1.9	
	Broad-leaved woodland	7960203.766	1.2	
	Coniferous woodland	3954249.855	0.6	
	Dwarf shrub heath	16260285.76	2.4	
Non-agriculture	Bog	1750534.913	0.3	7.1
	Fen, marsh, swamp	2556303.284	0.4	
	Continuous Urban	1662756.99	0.2	
	Suburban/rural developed	17768165.69	2.6	
	Inland Bare Ground	3155341.522	0.5	
	Water (inland)	21157507.67	3.1	

4.3. Soil

The major soil types in NI are Gleys (60%), Peat (14%), Brown soils (13%), Rankers (9%), and Podzols (4%). The high percentage of Gleys reflects a very wet environment in the NI (Cruickshank, 1997).

The result of a detailed investigation of the NI's soils by the Department of Agriculture and Rural Development (DARD) of NI shows that soils in the study area are predominantly comprised of clay, with pockets of peat and alluvial deposits of sand, silt and gravel (Cruickshank, 1997). Although clay soils dominate the study area, lenses of sand and gravel are frequent, thus creating pathways for solute transport from the ground surface to the unconfined water table (Doherty, 2002). Table App.A.3 shows soil types and their characteristics in the case study area. Fig. App.A.6 shows the soil spatial distribution in the study area. Table App.A.4 shows the name of each soil type code in Fig. App.A.6, and soil texture.

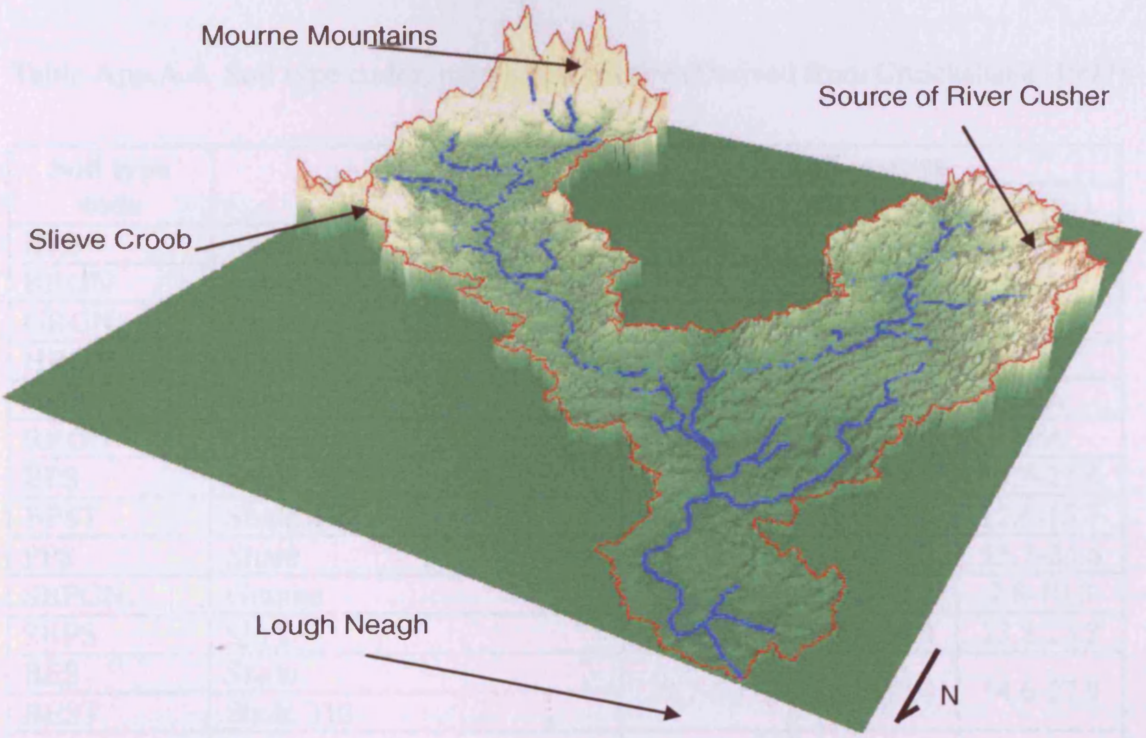


Fig. App.A.4. The topography of the Upper Bann Catchment

Table App.A.3. Soil types and their descriptions in the study area (Derived from Cruickshank, 1997)

Soil Classification	Code	Description
Rankers	BR	Brown rankers < 40 cm mineral soil
	GR	Gleyed rankeres < 40 cm gleyed minieral soil
	HR	Humic rankers < 40 cm with high ferrric iron content

Podzols	BP	Brown podzolics
	SBP	Shallow brown podzolics 40 - 60 cm deep
Brown Earths	BE	Brown earths
	SBE	Shallow brown earths 40 - 60 cm deep
Gleys	SWG1	Surface water gley - impeded drainage
	SWG2	Surface water gley - poor drainage
	G2	Ground water gley - poor drainage
	G3	Ground water gley - very poor drainage
	SWHG	Surface water humic gley

Table App.A.4. Soil type codes, names, and texture (Derived from Cruickshank, 1997)

Soil type code	**Soil parent material**	**Soil texture**		
		Sand (%)	**Silt (%)**	**Clay (%)**
BRS	Shale	N/A	N/A	N/A
BRGN	Granite	N/A	N/A	N/A
GRGN	Granite	N/A	N/A	N/A
HRGN	Granite	N/A	N/A	N/A
HRS	Shale	N/A	N/A	N/A
RRGN	Granite	N/A	N/A	N/A
BPS	Shale	41.7-47.8	34.6-39.7	15.7-23.6
BPST	Shale Till	46.3-61.65	22.6-38.8	12.6-15.7
PPS	Shale	41.7-47.8	34.6-39.7	15.7-23.6
SBPGN	Granite	63.4-80.9	15.6-25.7	2.8-10.3
SBPS	Shale	49.8-65.8	20.4-26.4	13.8-23.8
BES	Shale	29.7-50.8	38.6-42.4	14.6-27.9
BEST	Shale Till			
SBES	Shale	29.7-50.8	38.6-42.4	14.6-27.9
SBEST	Shale Till			
SWG1BRT	Basalt Red SandStone Till	45.4-48.9	24.2-26.6	26.9-28.8
SWG1BST	Basalt shale Till			
SWG1BT	Basalt Till			
SWG1GNT	Granite	61.5-68.3	18.8-22.5	10.8-15.5
SWG1RST	Red SandStone Till	34.5-38.9	38.8-42.1	20.5-25.7
SWG1RT	Red Trias SandStone Till	61.2-67.5	17.4-20.1	12.5-19.6
SWG1S	Shale	38.3-40.5	41.2-44.1	17.6-18.3
SWG1ST	Shale Till			
SWG2BST	Basalt shale Till	27.2-39.2	33.1-35.1	27.5-37.5
SWG2BT	Basalt Till			

SWG2LNCT	Lough Neagh Clay Till	34.7-52.7	28.1-30.5	19.2-35.2
SWG2ST	Shale Till	35.8-51.5	31.9-43.1	16.2-21.1
G2ALL	Alluvium	41.0-55.7	25.4-36.7	18.9-22.9
G2OA	Organic Alluvium	25.2-32.7	43.4-43.8	23.4-31.4
G3ALL	Alluvium	7.5-21.9	70.0-77.6	0.5-22.5
G3OA	Organic Alluvium	25.2-32.8	43.4-43.8	23.4-31.4
SWHGGN	Granite	83.3	13	3.8
SWHGS	Shale	52.7-61.5	36.0-36.4	2.5-10.9
SWHGST	Shale Till	52.7-61.5	36.0-36.5	2.5-10.10
PT	Peat	N/A	N/A	N/A
URB	Urban	N/A	N/A	N/A
WAT	Water	N/A	N/A	N/A

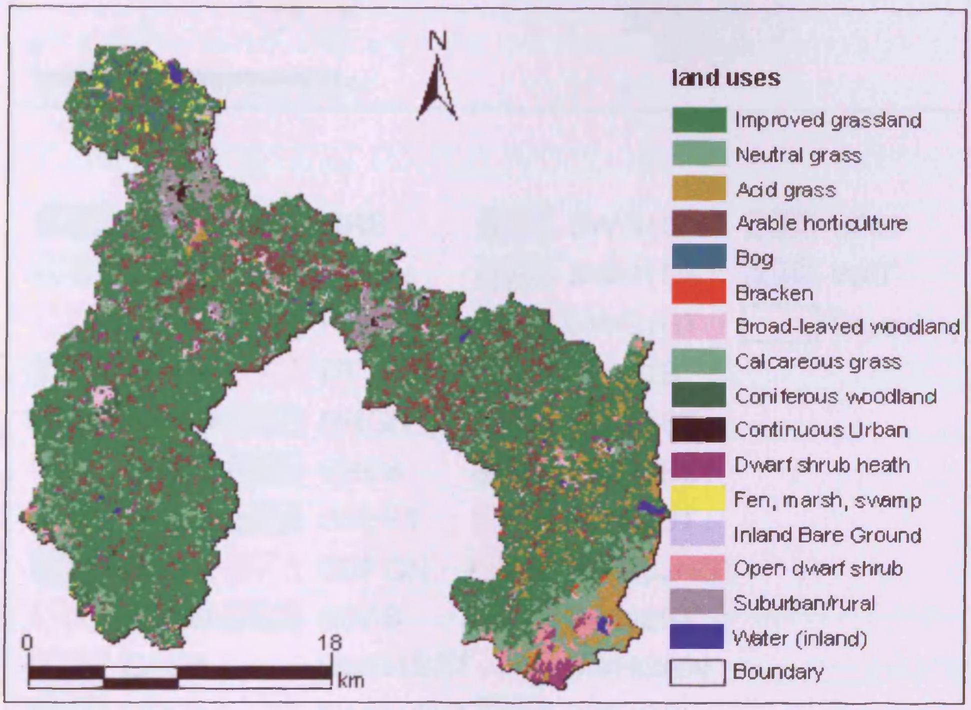


Fig. App.A.5. The land use in the Upper Bann Catchment

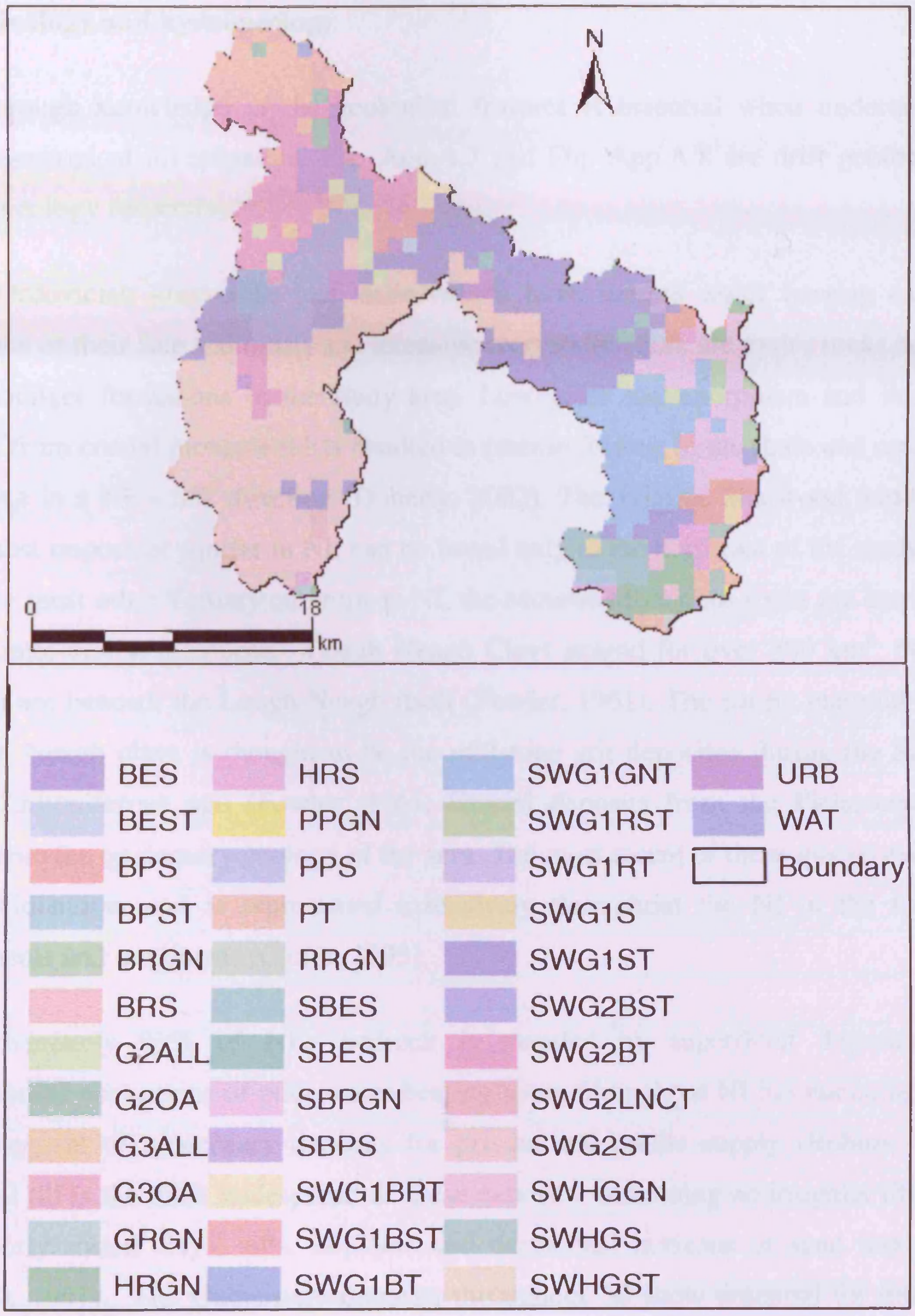


Fig. App.A.6. The soil map of the Upper Bann Catchment

4.4. Geology and hydrogeology

A thorough knowledge of the geological features is essential when undertaking a hydrogeological investigation. Fig. App.A.7 and Fig. App.A.8 are drift geology and solid geology respectively.

The Ordovician greywacke and shale, which have limited water bearing capacity because of their fine sediments and intensive recrystallisation, are major rocks beneath the younger formations in the study area. Low-grade metamorphism and intensive stress from crustal movement has resulted in intense folding in the shale and repetitive faulting in a NE - SW direction (Doherty, 2002). The Triassic Sherwood Sandstone, the most important aquifer in NI, can be found only to the northeast of the study area. Unlike most other Tertiary outcrops in NI, the Mourne Mountains rocks are composed of granite and granodiorite. Lough Neagh Clays extend for over 500 km^2, 60% of which are beneath the Lough Neagh itself (Fowler, 1961). The parent material of the Lough Neagh clays is thought to be the millstone grit deposited during the Silurian and Carboniferous age (Fowler, 1961. Glacial deposits from the Pleistocene age dominate the quaternary geology of the area. The most recent of these glacial events is the Midlandian and is represented extensively throughout the NI in the form of sediments and landforms (Carter, 1993).

Approximately 90% of NI's bedrock is mantled by superficial deposits. The widespread occurrence of poor water bearing strata throughout NI has encouraged the development of quaternary deposits for private and public supply (Robins, 1996). Glacial till is the most widespread of these deposits, containing an irregular lithology of poorly sorted clays, silts, boulders and occasional horizons of sand and gravel (GSNI, 1991). The Quaternary deposits throughout NI show potential for moderate exploitation, particularly where private industrial and agricultural demands of approximately 10 Ml/d exist (Robins, 1996).

In the study area, the widespread occurrence of relatively poor aquifers has resulted in limited exploitation of groundwater. Although there are high permeable Cretaceous limestone and Triassic sandstone in the area immediately south of Lough Neagh, these rocks are capped by Lough Neagh Clays, thus resulting limited vertical groundwater recharge. The presence of glacial till mantle (5–20m thick) in the study area also impedes the vertical flow of water from the surface to the geological deposits beneath. Bearing in mind the impermeable nature of the geological and drift deposits, vertical groundwater recharge is expected to be very low, with an unconfined water table forming above the impermeable glacial clay pan.

The unconfined aquifer media in the catchment include glacial till, peat, sand and gravel, Sand and gravel with significant silt and clay, alluvium, and outcrop rock. Outcrop rock consists of dolerite (basalt), felsite, granite, granodiorite, mudstone (shale), and sandstone. Glacial till is mixtures of unconsolidated to semi-consolidated gravel, sand, silt and clay-size particles that are poorly sorted and stratified. Peat consists of un-decomposed to partially decomposed plant material that is fresh enough to be identified. The organic matter in peat may be significant for contaminant attenuation, but they are relatively permeable, thus pollution potential is high. “Sand and gravel with significant silt and clay” is the unconsolidated mixture of sand and gravel, which contain an appreciable amount of fine material. These deposits are commonly referred to as "dirty" and have a lower pollution potential than "clean" sands and gravels. In general, finer-grained and "dirtier" sands have a lower pollution potential than coarser-grained "dirtier" gravels. Felsite, granite, granodiorite belong to igneous rock.

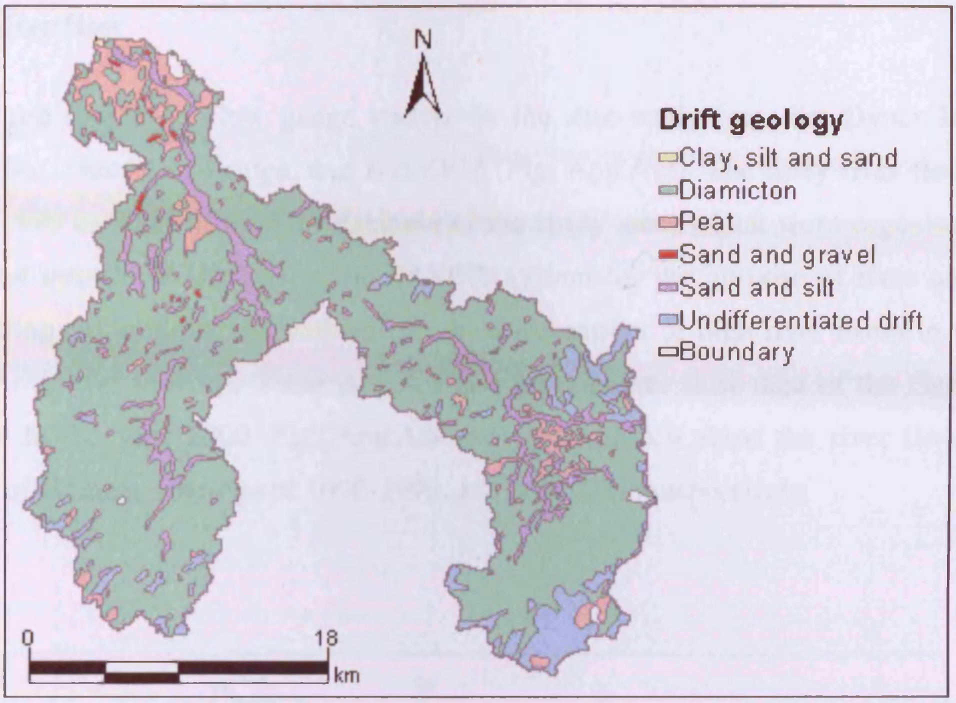


Fig. App.A.7. The drift geology map of the Upper Bann Catchment

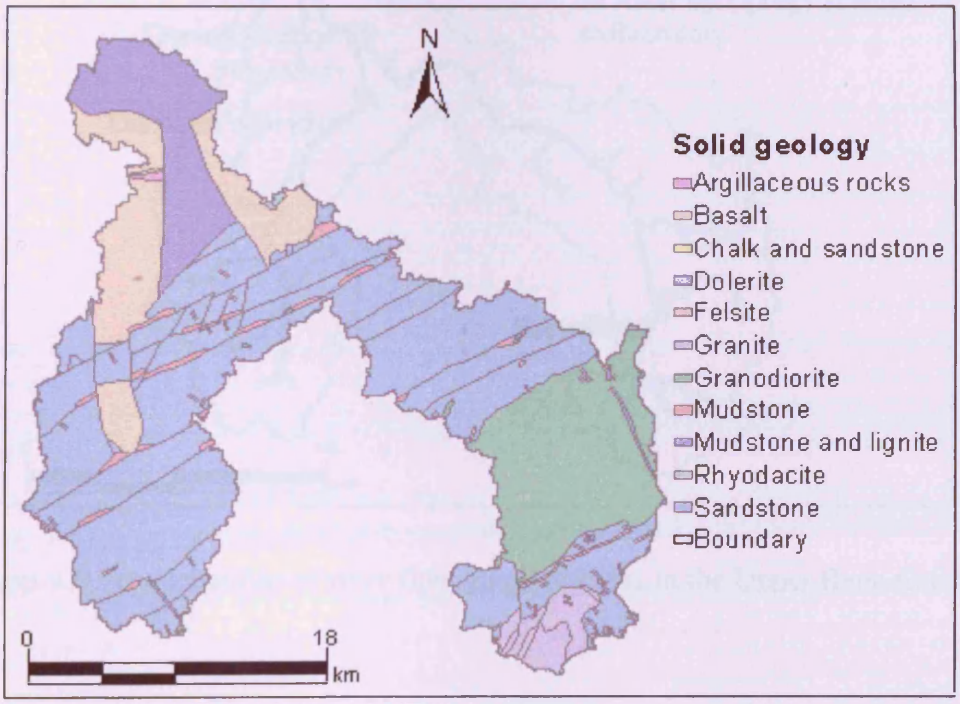


Fig. App.A.8. The solid geology map of the Upper Bann Catchment

4.5. River flow

There are four river flow gauge stations in the case study area, i.e. Dynes Bridge, Moyallen, Gamble's Bridge, and Bannfield (Fig. App.A.9). The daily river flow data from 1990 to 2005 in the GIS database of the study area, which were organised and inputted into the WDMUtil of the BASINS system for the purpose of river quantity modelling calibrations and validations, show the pattern of high river flows in winter and spring wet seasons. Table App.A.5 is a part of river flow data of the Gamble's Bridge in the year 2000. Fig. App.A.8 and Fig. App.A.9 show the river flow time series of Gamble's Bridge of 1990-1999, and 2000-2005 respectively.

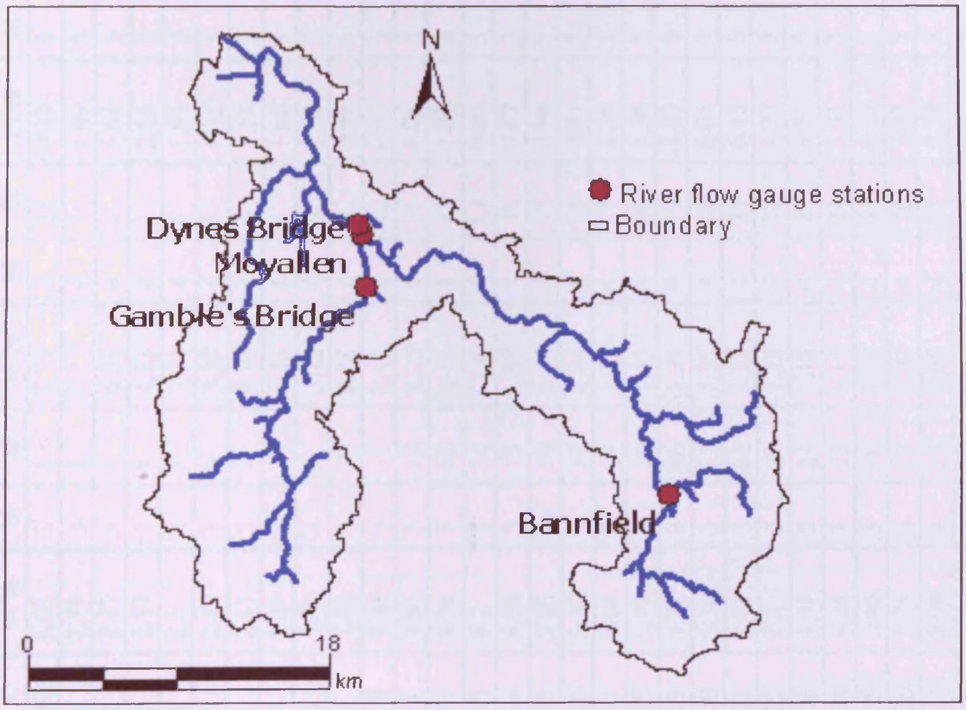


Fig. App.A.9. The locations of river flow gauge stations in the Upper Bann Catchment

Table App.A.5. A part of river flow data of the Gamble's Bridge in the year 2000

M	D	m^3/s	M	D	m^3/s	M	D	m^3/s	M	D	m^3/s	M	D	m^3/s	M	D	m^3/s	M	D	m^3/s
1	1	5.84	1	31	3.03	3	1	3.71	3	31	0.89	4	30	5.89	5	30	1.42	6	29	0.64
1	2	4.82	2	1	2.79	3	2	7.7	4	1	1.49	5	1	4.17	5	31	1.21	6	30	1.1
1	3	4.08	2	2	2.47	3	3	6.07	4	2	5.61	5	2	3.23	6	1	1.26	7	1	0.79
1	4	4.18	2	3	2.37	3	4	4.23	4	3	2.54	5	3	2.65	6	2	3.48	7	2	1
1	5	5.83	2	4	2.5	3	5	3.74	4	4	1.67	5	4	2.27	6	3	1.97	7	3	0.94
1	6	5.64	2	5	2.47	3	6	3.38	4	5	1.32	5	5	1.98	6	4	2.01	7	4	0.76
1	7	5.19	2	6	2.41	3	7	3.16	4	6	1.14	5	6	1.73	6	5	1.84	7	5	3.04
1	8	4.55	2	7	5.89	3	8	3.38	4	7	1.06	5	7	1.51	6	6	1.81	7	6	2.07
1	9	3.76	2	8	5.46	3	9	3.02	4	8	1.02	5	8	1.36	6	7	3.44	7	7	1.07
1	10	3.46	2	9	7.03	3	10	2.78	4	9	0.96	5	9	1.25	6	8	4.63	7	8	0.92
1	11	9.9	2	10	7.64	3	11	2.49	4	10	0.97	5	10	1.15	6	9	2.33	7	9	1.09
1	12	9.75	2	11	5.88	3	12	2.23	4	11	1.08	5	11	1.05	6	10	1.82	7	10	1.26
1	13	6.46	2	12	8.54	3	13	2.13	4	12	1.01	5	12	0.98	6	11	1.55	7	11	0.89
1	14	4.8	2	13	6.2	3	14	2.08	4	13	0.93	5	13	0.95	6	12	1.38	7	12	0.78
1	15	3.92	2	14	6.08	3	15	1.88	4	14	0.87	5	14	0.89	6	13	1.19	7	13	0.74
1	16	3.49	2	15	5.26	3	16	1.75	4	15	0.84	5	15	0.85	6	14	1.08	7	14	0.69
1	17	3.19	2	16	8.32	3	17	1.64	4	16	4.27	5	16	1.75	6	15	0.99	7	15	0.64
1	18	2.81	2	17	8.04	3	18	1.55	4	17	2.36	5	17	1.62	6	16	0.91	7	16	0.61
1	19	2.56	2	18	6.73	3	19	1.45	4	18	1.76	5	18	1.26	6	17	0.86	7	17	0.58
1	20	2.3	2	19	5.21	3	20	1.39	4	19	1.83	5	19	1.11	6	18	0.82	7	18	0.56
1	21	2.13	2	20	5.36	3	21	1.35	4	20	5.05	5	20	1.04	6	19	0.78	7	19	0.56
1	22	1.97	2	21	4.91	3	22	1.32	4	21	6.13	5	21	1.31	6	20	0.78	7	20	0.54
1	23	1.75	2	22	4.4	3	23	1.25	4	22	4.37	5	22	1.05	6	21	1.03	7	21	0.53
1	24	1.57	2	23	4.51	3	24	1.19	4	23	4.51	5	23	1.3	6	22	1.11	7	22	0.52
1	25	1.45	2	24	4.28	3	25	1.13	4	24	3.31	5	24	2.07	6	23	0.98	7	23	0.51
1	26	1.39	2	25	3.86	3	26	1.17	4	25	4.97	5	25	2.1	6	24	0.83	7	24	0.52
1	27	1.37	2	26	3.75	3	27	1.07	4	26	3.22	5	26	2.26	6	25	0.76	7	25	0.53
1	28	1.43	2	27	8.99	3	28	0.95	4	27	0.53	5	27	1.67	6	26	0.72	7	26	0.52
1	29	2.78	2	28	4.99	3	29	0.9	4	28	9.81	5	28	1.97	6	27	0.67	7	27	0.52
1	30	2.95	2	29	4.32	3	30	0.89	4	29	8.9	5	29	1.77	6	28	0.64	7	28	0.65

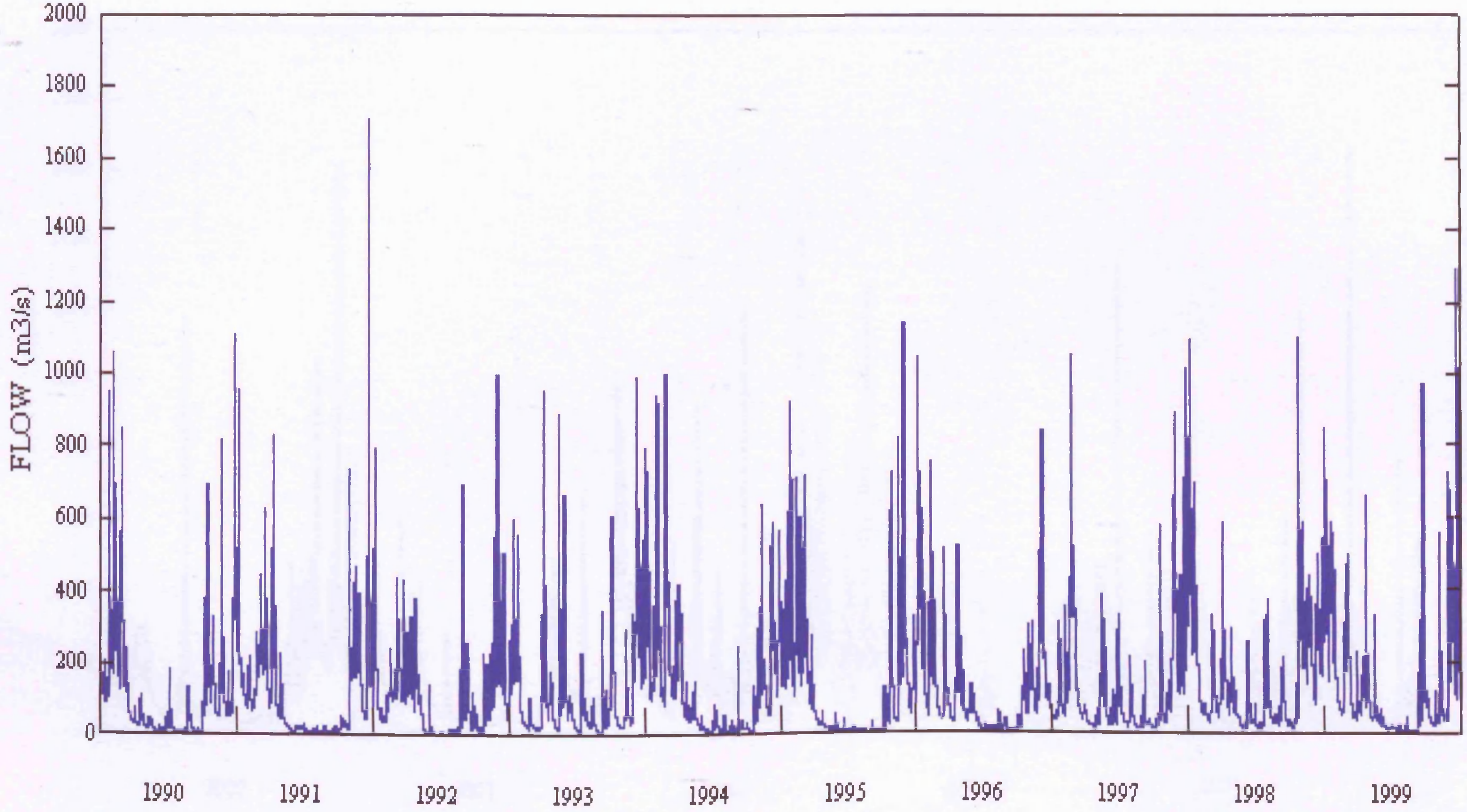


Fig. App.A.10. The river flow time series of Gamble's Bridge of 1990-1999

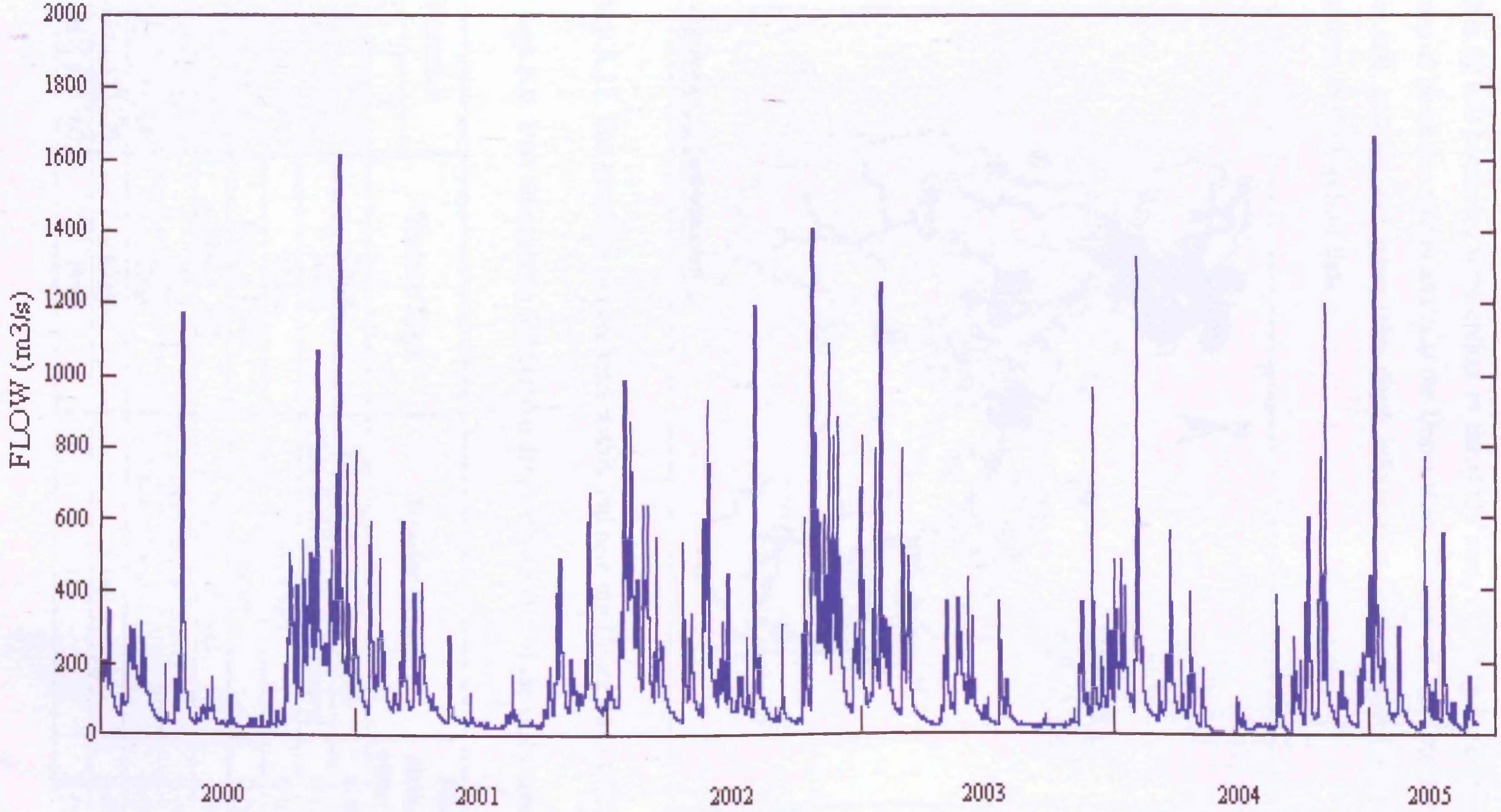


Fig. App.A.11. The river flow time series of Gamble's Bridge of 2000-2005

4.6. Boreholes in the study area

The data of 660 boreholes were collect in the study area. Fig. App.A.12 shows the locations of boreholes within and near the Upper Bann Catchment. The borehole data contain soil, geology and water table depth information. Table App.A.6 shows part information of the borehole data.

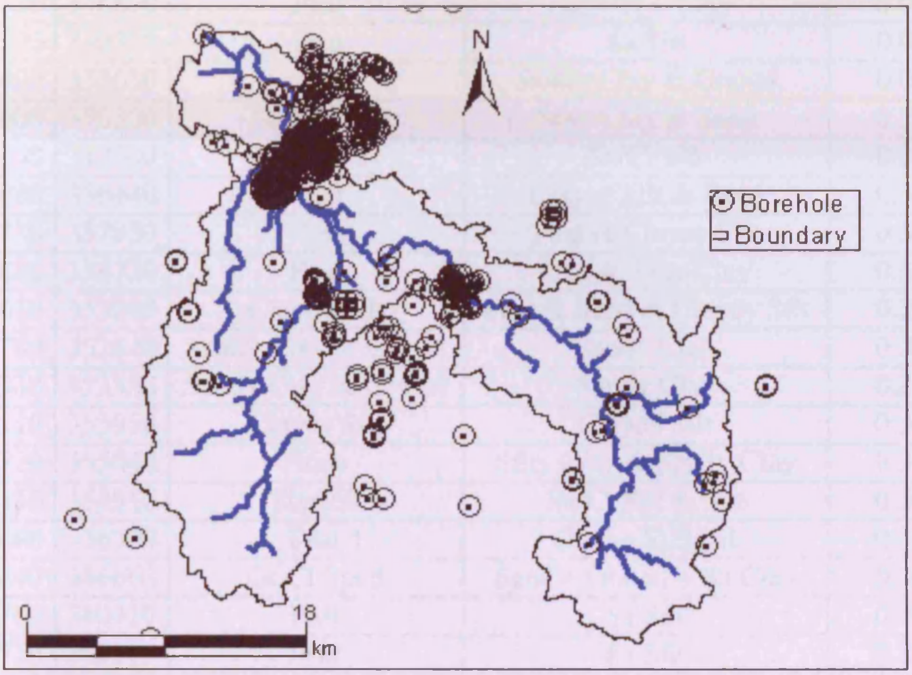


Fig. App.A.12. The locations of boreholes within and near the Upper Bann Catchment

Table App.A.6. Part information of borehole data within and near the study area

Location		Vadose Type	Aquifer Media	First strike of water (m)
X	Y			
303650	354050	None	Silty Clay & Clayey Silt	0.00
303350	354360	None	Clay & Silty Clay & Gravel	0.00
303860	354950	None	Silty Clay	0.00
307635	340435	Peat + Clay	Gravel	0.00
307585	340685	Peat + Silt	Clay + Gravel	0.00
307060	336490	Peat	Sa Clay + Gravel	0.00
307145	336500	Peat	Clay + Sand + Gravel	0.00
307445	337325	Clay	Clay	0.00
307580	337560	Peat	Clay	0.00

303410	345400	Sa Gravel	Sand + Gravel	0.00
303370	345405	Si Sa Gravel	Sa Gravel	0.00
303515	345525	Si Sa Gravel	Si Sa Gravel	0.00
303505	345485	Si Sa Gravel	Si Sa Gravel	0.00
303490	345390	Si Sand + Gravel	Si Sand + Gravel	0.00
303345	345405	Si Sand + Gravel	Si Sand + Gravel	0.00
303320	345420	Gr Sand	Gr Sand	0.00
303305	345470	Si Sand	Si Sand	0.00
303295	345490	Si Sand + Gravel	Si Sa Gravel	0.00
309620	346590	Peat	Gravel + Clay	0.00
309720	340375	Peat	Sa Silt	0.00
300490	353650	Fill	Sandy Clay & Gravel	0.08
305600	358300	Sa/Si Clay	Silty Clay & Sand	0.30
306250	357500	Sa/Si Clay	Sa/Cl Silt	0.30
307080	356440	Peat	Clayey Silt & Sand	0.30
300730	357950	Peat	Peat & Clayey Silt	0.30
301880	358730	Peat	Peat & Silty Clay	0.30
301610	353280	Clayey Silt	Peat & Sand & Clayey Silt	0.30
299780	352620	Sandy Clay & Gravel	Sandy Clay	0.30
300380	353550	Sandy Clay & Gravel	Sandy Clay	0.30
303110	353950	Clayey Silt	Clayey Silt	0.30
303720	355040	None	Silty Clay & Sandy Clay	0.30
302410	354910	Topsoil	Sa/Cl Silt & Silt	0.30
307080	336300	Peat	Clay + Si Sand	0.30
311840	346660	Gr Cl Sand	Sand + Gravel + Sa Clay	0.30
309760	340410	Peat	Sa Silt	0.30
309750	340375	Peat	Sa Silt	0.30
301390	353800	Topsoil	Peat & Clayey Silt & Gravel	0.40
301610	354310	Sa/Si Clay	Sandy Silt + Gravel + Clay	0.40
301050	354030	Gravel	Gr/Cl Silt	0.40
303050	359460	Cl/Sa Silt	Silty Clay	0.46
300040	352010	Silty Clay	Silty Clay & Clayey Sand	0.46
299970	352180	Sandy Peat	Peat & Silty Clay	0.46
303100	353920	Topsoil	Sand & Silt	0.46
302810	355480	Sa/Cl Silt	Sandy Silt	0.46
302450	355780	Sand & Gravel	Sand & Gravel	0.46
301270	354320	Clay	Sa/Si Clay	0.50
304450	359400	Sandy Clay w/ Gravel	Sandy Clay w/ Gravel	0.53
303820	356250	Sandy Clay	Sandy Clay & Clay	0.60
303255	346420	Sa Gr Clay	Sa Gr Clay	0.60
303275	346415	Sa Gr Clay	Si Clay	0.60
309760	340352	Si Peat	Sa Silt + Gravel	0.60
321750	336750	Peat	Sand + Si Clay	0.60
305930	357210	Sa/Cl Silt	Sa/Cl Silt	0.61
303030	359350	Cl/Sa Silt	Sandy Silt	0.61

300270	353450	Sandy Clay & Gravel	Sandy Clay	0.61
303660	354270	Sa/Cl Silt	Silt & Sandy Silt	0.61
302820	355450	Sa/Cl Silt	Sa/Cl Silt	0.61
312025	364995	Silt	Sand + Silt	0.61
302900	356500	Sand & Gravel	Sand & Gravel	0.70
300350	354550	Sa/Si Clay	Silty Clay & Peat & Sand	0.70
301000	353940	Sa/Si Clay	Clayey Silt + Sand	0.70
301090	353930	Sa/Cl Silt	Clayey Silt + Sand	0.70
302350	355940	Sa/Gr Clay	Sa/Gr Clay	0.75
309755	340563	Peat	Sa Silt	0.75
304700	359850	Peat	Peat & Silty Clay & Sand & Silt	0.76
306250	357350	Sandy Clay	Sandy Clay & Silt	0.76
303200	358760	Clay	Clay	0.76
299910	352330	Peat	Peat & Clayey Silt	0.76
300560	352280	Silty Clay	Peat & Clayey Silt & Sand & Gravel	0.76
303620	353960	Sa/Si Clay	Sandy Silt w/ Gravel	0.76
302860	355470	Clayey Silt	Sa/Cl Silt	0.76
302270	356230	Sa/Gr/Cl Silt	Sa/Gr/Cl Silt	0.80
300580	352330	Sa/Cl Silt & Gravel	Clayey Silt	0.80
301500	354010	Sand	Sand	0.80
301500	354010	Clayey Sand	Sand	0.80
296125	339935	Cl Silt	Cl Silt	0.80
322740	338500	Gr Sa Silt	Sa Clay	0.82
303330	353720	Sand	Sand & Silt	0.84
322765	338485	Gr Sa Silt	Sa Clay	0.85
311870	345725	Fill	Fill	0.85
302470	354980	Fill	Cl/Sa Silt	0.90
302130	356010	Sa/Si Clay	Sa/Si Clay	0.90
301500	354500	Sa/Si Clay	Sa/Si Clay + Clayey Silt + Peat	0.90
296105	339930	Cl Silt	Cl Silt	0.90
309500	338890	Gr Sa Cl Silt + Peat	Gr Sa Cl Silt	0.90
306110	356110	Sa/Cl Silt	Basalt	0.91
298850	359510	Peat	Peat & Silt & Sand & Silty Clay	0.91
299960	352140	Peat	Sandy Silt & Silty Clay	0.91
299810	352990	Sandy Silt & Sand	Sandy Silt & Silty Sand	0.91
303030	353870	Sand	Sand & Silt	0.91
300660	353860	Silty Sand & Gravel	Silty Sand & Gravel	0.91
300450	353630	Sandy Clay & Gravel	Sandy Clay & Gravel	0.91
303690	354160	Sa/Cl Silt	Silt & Clayey Silt	0.91
303440	355460	Sandy Clay	Sandy Silt & Sa/Si Clay	0.91
302970	355610	Clayey Silt	Silt (0.0m+)	0.91

303010	355630	Sa/Cl Silt	Sa/Cl Silt	0.91
303010	354780	Clay	Clay & Sand & Gravel	0.91
301740	354910	Peat	Sand + Gravel + Clay Silt	0.91
301830	354310	Si/Sa Gravel	Si/Sa Gravel	0.91
302860	361365	Sand + Gravel	Si Clay	0.91
301220	354300	Fill	Peat + Sand + Gravel	0.99
300320	352030	Silty Clay	Clay & Sandy Gravel	1.00
300990	354280	Sa/Cl Silt	Sand + Gravel + Pt/Cl Silt	1.00
313160	346320	Silt	Sa Silt	1.00
313715	346545	Sa Silt	Sa Silt	1.00
322725	338500	Sa Clay	Sa Gr Clay	1.00
332390	339670	Sa Clay + Si Peat	Sa Clay + Sand	1.00
332400	339675	Cl Silt	Sa Clay	1.00
311215	345975	Gr Sa Silt	Gr Sa Silt	1.00
312210	346960	Sa Si Clay	Sa Si Clay	1.00
295110	344480	Gr Sa Si Clay	Sa Clay + Gravel	1.00
295090	344505	Gr Sa Clay	Sa Si Clay + Gravel	1.00
318351	351250	Cl Sa Silt	Sa + Sa Silt	1.00
301120	352420	Silty Clay	Sa/Si Clay	1.05
303320	346400	Sa Gr Clay	Sa Gr Clay	1.05
312770	346080	Sa Gr Cl Silt	Sa Gr Cl Silt	1.05
301220	352870	Sandy Silt & Silty Sand	Sandy Silt	1.07
301550	354570	Sa/Si Clay	Gr/Sa/Si Clay + Peat + Sand	1.10
301170	354850	Silt + Silty Clay	Clayey Silt + Silty Sand	1.10
301340	354970	Clayey Silt	Clayey Silt + Sandy Silt + Peat	1.10
311860	345740	Fill	Fill	1.10
303783	345749	Sa Silt	Gravel	1.10
313270	344735	Gr/Sa Silt	Sa/Cl Silt	1.20
302970	355140	Silty Clay	Sa/Gr Silt	1.20
301260	352410	Silty Sand & Gravel	Sa/Gr/Cl Silt	1.20
301080	352370	Sa/Gr/Cl Silt & Peat	Peat & Silt	1.20
301030	352360	Sa/Si Clay w/ Gravel	Sa/Si Clay	1.20
301000	352360	Sa/Si Clay w/ Gravel	Sand	1.20
301330	353790	Peat	Peat & Sand & Sandy Silt	1.20
303640	356020	Sandy Clay	Sandy Clay & Silty Sand	1.20
301880	355940	Gr/Sa Clay	Sandy Clay	1.20
301470	354520	Quarry Fill	Silty Clay + Peat	1.20
301070	354840	Clayey Silt	Clayey Silt + Peat + Gravel	1.20
312995	346200	Sa Silt	Sa Silt	1.20
309790	340375	Gr sa Silt	Shale	1.20
304750	344750	Peat	Si Clay	1.20
306445	333072	Sa Silt	Sa Gravel	1.20
301133	343892	Sa Silt	Sand + Gravel	1.20

305900	358180	Sa/Si Clay	Si/Sa Clay	1.22
306600	357700	Si/Sa Clay	Si/Sa Clay	1.22
305830	356120	Sa/Si Clay	Clayey Silt	1.22
306460	355350	Sa/Cl Silt	Sandy Silt	1.22
300350	359070	Peat	Peat & Silt & Gravel & Sand	1.22
303020	359270	Sa/Cl Silt	Sa/Cl Silt	1.22
302950	359240	Silty Clay	Silty Clay & Sand	1.22
303100	358720	Sand & Gravel	Silty Clay	1.22
299760	352750	Sandy Clay	Sandy Clay & Silty Clay	1.22
301410	352650	Peat	Peat & Clayey Silt	1.22
300740	353880	Clayey Sand & Gravel	Clayey Sand & Sand & Gravel	1.22
300610	353820	Sandy Clay & Gravel	Sandy Clay & Gravel	1.22
300240	353460	Silty Clay & Gravel	Silty Clay & Sandy Clay & Gravel	1.22
303050	354650	Sandy Clay	Sandy Clay	1.22
303020	354660	Sandy Clay	Sandy Clay	1.22
301390	354540	Silty Clay + Peat	Peat + Silty Clay	1.22
301870	354850	Sa/Si Clay + Gravel	Sandy Clay + Gravel	1.22
308130	366360	Sa Clay	Sand + Gravel + Clay	1.22
306470	357800	Si/Sa Clay	Sandy Clay	1.24
305670	360180	Sandy Clay	Sandy Clay & Gravel	1.27
312240	345860	Gr Sa Silt	Gr Sa Silt	1.29
301680	354480	Sa/Si Clay	Sa/Si Clay + Peat	1.30
301490	354550	Quarry Fill	Sa/Si Clay + Peat	1.30
301260	354340	Sandy Silt	Sand + Gravel + Peat + Clayey Silt	1.30
332410	339645	Silt + Gr Sand	Sand	1.30
303210	345560	Si Sand + Gravel	Sa Gravel	1.30
307220	342860	Sa Cl Silt	Sa Cl Silt	1.30
312903	336462	Sa Silt	Sa Silt	1.30
301910	355950	Gr/Sa Clay	Gr/Sa Clay	1.35
301260	354360	Silty Clay + Peat	Sand + Gravel + Silty Clay	1.35
303295	346405	Sa Gr Clay	Sa Gr Clay	1.35
300350	352510	Sa/Cl Silt	Sa/Si Clay	1.36
300910	352830	Sa/Cl Silt	Cl/Sa Silt & Sand	1.36
306500	356900	Sandy Clay	Sandy Clay	1.37
302550	353270	Sandy Clay	Sandy Clay & Sand	1.37
299760	352510	Sandy Clay & Gravel	Sandy Clay	1.37
299780	352890	Silty Clay & Gravel	Sa/Si Clay	1.37
303110	353990	Sa/Si Clay	Sa/Si Clay & Sandy Silt	1.37
302530	353290	Sandy Clay	Sandy Clay & Gravel	1.37
302950	354980	Sandy Clay	Sandy Clay	1.37
302800	355250	Clay	Clay	1.37
300340	352040	Gr/Sa/Si Clay	Clay & Sand	1.40

302200	354420	Silty Clay	Silty Clay	1.40
301580	354440	Clay	Sa/Si Clay	1.40
301260	354900	Clayey Silt	Clayey Silt + Peaty Silt	1.40
332405	339665	Gr Sand	Gr Sand	1.40
312100	346600	Sa Gravel	Sand + Gravel	1.40
296060	362820	Gr Si Sand	Sand + Si Sand	1.40
302845	361218	Sand	Sand	1.40
305250	345250	Sa Si Clay	Peat	1.40
316330	344215	Si Clay	Sa Si Clay	1.45
309580	341535	Sa Silt	Sa Silt + Sand	1.45
304600	359800	Silt	Sa/Si Clay & Sand	1.50
303540	356050	Si/Sa Clay	Sandy Clay & Sandy Gravel	1.50
304130	355500	Silty Clay	Basalt	1.50
301100	352180	Silty Clay w/ Gravel	Silty Clay	1.50
300510	352400	Sa/Cl Silt & Peat	Sa/Cl Silt & Sand	1.50
301520	353950	Sa/Gr/Si Fill	Peaty Silt	1.50
303630	356080	Sandy Clay	Sandy Clay	1.50
303540	356060	Si/Sa Clay	Silty Clay & Sandy Clay & Gravel	1.50
303440	356010	Silty Clay	Silty Clay	1.50
303700	355850	Clay	Clay	1.50
301850	355900	Gr/Sa Clay	Sandy Clay	1.50
301900	355910	Gr/Sa Clay	Sa/Gr Clay	1.50
301900	355850	Gr/Sa Clay	Gr/Sa Clay	1.50
301860	355850	Gr/Sa Clay	Gr/Sa Clay	1.50
301500	353590	Peat	Peat & Silty Clay & Sand	1.50
300480	352040	Silty Clay & Gravel	Sa/Gr/Si Clay & Peat & Gravel	1.50
301690	354370	Silty Clay	Silty Clay	1.50
301010	354300	Silty Clay + Peat	Peat + Sand + Clayey Silt	1.50
301940	354710	Sa/Gr Clay	Sa/Gr Clay	1.50
301940	354670	Sa/Gr Clay	Sa/Gr Clay	1.50
301900	354740	Sa/Gr Clay	Sa/Gr Clay	1.50
301130	354200	Sa/Si Clay	Sandy Silt + Clay + Silt +Sa/Si Clay	1.50
322750	338420	Sa Clay	Sa Clay + Si Sand	1.50
323440	339650	Sa Clay + Gravel	Sa + Gr Sand	1.50
303315	345475	Si Sa Gravel	Sand + Gravel	1.50
294300	347930	Sa Gr Clay	Sa Gr Clay + Sand	1.50
319840	333570	Gravel	Sand + Gravel	1.50
302941	360847	Sand	Si Sand	1.50
308350	342890	Si Sand	Si Clay	1.50
328450	333170	Sa Gravel	Gr Sand	1.50
305240	359820	Sa/Si Clay	Si/Sa Clay	1.52
306880	356630	Silty Clay	Basalt	1.52

306950	356200	Sandy Clay	Silty Clay & Sand	1.52
302830	355320	Sandy Clay	Sandy Clay	1.52
301410	353180	Silty Clay & Peat	Peat & Gravel & Sandy Silt	1.52
300770	353870	Clayey Sand	Sand	1.52
300700	353850	Clayey Sand	Clayey Sand	1.52
300410	352440	Clayey Silt & Sandy Silt	Sandy Silt & Gravel	1.52
301300	352490	Sandy Silt	Cl/Sa Silt	1.52
303930	354850	Si/Sa Clay	Si/Sa Clay	1.52
303210	356840	Sandy Clay	Sandy Clay	1.52
302790	355490	Sa/Cl Silt	Sa/Cl Silt	1.52
302830	355520	Sa/Cl Silt	Silt	1.52
301590	354730	Peat	Sand + Gravel + Peat	1.52
301890	354360	Sandy Silt + Gravel	Sandy Silt + Gravel	1.52
301070	354100	Fill	Gravel + Silt + Peat	1.52
312280	345900	Gr Sa Silt	Gr Sa Silt	1.52
302905	361515	Sand	Si Clay	1.52
311845	345775	Sand + Gr Clay	Sa Silt	1.55
302300	356170	Sa/Gr/Cl Silt	Sa/Gr/Cl Silt	1.60
300360	352040	Silty Clay	Sandy Clay & Sand	1.60
301500	353930	Sa/Si Fill & Sand	Peaty Silt & Clayey Silt	1.60
301460	353680	Peat	Peat & Silty Clay & Sand	1.60
303445	345400	Si Sa Gravel	Si Gr Sand	1.60
312045	346530	Sa Si Clay	Gr Sand	1.60
304750	345250	Peat	Gravel	1.60
295765	341810	Sa Silt	Si Sand + sa Gravel	1.60
294300	347800	Si Clay	Sa Si Clay	1.60
329488	332100	Sa Cl Silt	Gr Sand	1.60
302950	354880	Sandy Clay	Clay & Sandy Clay	1.63
302960	355300	Silty Clay & Sand	Sa/Gr Silt	1.65
303000	355160	Silty Clay	Sa/Gr Silt	1.65
306700	357370	Sandy Clay	Sandy Clay	1.68
306720	357270	Sandy Clay	Sandy Clay	1.68
306320	356550	Si/Sa w/ Gravel	Sandy Silt & Sandy Gravel	1.68
305990	356740	Sa/Cl Silt w/ Peat	Basalt	1.68
306290	355840	Sa/Si Clay	Sandy Clay	1.68
303650	354350	Sa/Cl Silt	Sa/Si Clay	1.68
302550	353270	Sandy Clay	Sandy Clay & Gravel	1.68
303650	354340	Sa/Cl Silt	Clay & Sa/Si Clay	1.68
303450	354400	Sa/Cl Silt	Sandy Silt & Gravel	1.68
313050	345040	Sa/Si Clay & Sa/Gr Silt & Si/Sa Gravel	Si/Sa Gravel	1.70
302360	355670	Gr/Sa/Cl Silt	Cl/Sa Silt	1.70
301630	354440	Silty Clay	Sa/Si Clay	1.70
303510	345445	Sa Silt	Sa Gravel	1.70

311865	346745	Si Clay	Gr Clay + Sand + Gravel	1.70
303510	346200	Sa Si Clay	Sa Cl Silt	1.70
312260	345890	Gr Sa Silt	Gr Sa Silt	1.75
320990	329255	Sa Gr Silt	Si Gravel	1.75
304530	355180	Silty Clay & Basalt	Basalt	1.80
304480	355300	Silty Clay	Sandy Clay	1.80
299740	353430	Sa/Gr Clay	Sa/Gr Clay & Gravelly Sand	1.80
303720	356110	Silty Clay	Sandy Clay & Silty Clay	1.80
303670	355940	Sandy Clay	Sandy Clay	1.80
302330	355380	None	Cl/Sa Silt	1.80
301650	355910	Peat	Peat & Silty Sand & Clayey Silt	1.80
303505	345430	Sa Silt	Si Sa Gravel	1.80
311235	346040	Gr Sa Silt	Gr Sa Silt	1.80
311905	346920	Sand + Gravel	Sand + Gravel	1.80
305389	360963	Sa Silt	Sa Silt	1.80
304510	342919	Sa Silt + Clay	Si Gravel	1.80
310450	342120	Sa Gr Cl Silt	Sand + Gravel	1.80
296600	355810	Sa Cl Silt	Si Sand	1.80
303580	358820	Clay	Peat & Sandy Clay	1.83
306310	356000	Sa/Si Clay	Basalt	1.83
306090	355620	Silty Sand & Peat	Basalt	1.83
300510	358990	Peat	Peat & Sandy Silt	1.83
303020	359400	Si/Sa Clay	Si/Sa Clay	1.83
302880	359380	Sa/Si Clay w/ Gravel	Silty Clay & Sand	1.83
301680	353180	Sa/Cl Silt & Peat	Peat & Sand & Sandy Silt & Gravel	1.83
300280	353430	Sandy Clay w/ Gravel	Sandy Clay	1.83
300260	353410	Silty Clay & Gravel	Silty Clay & Gravel	1.83
301900	354330	Sandy Gravel + Silt	Sand + Silt	1.83
301280	354300	Clayey Silt	Sandy Silt + Clayey Silt	1.83
302795	361230	Sand + Gravel	Cl Silt	1.83
312025	364940	Sa Clay + Gravel	Gravel + Sa Cl Gravel	1.83
301880	355880	Gr/Sa Clay	Gr/Sa Clay	1.85
301930	355890	Gr/Sa Clay	Sa/Gr Clay	1.85
301950	354690	Sa/Gr Clay	Sa/Gr Clay	1.85
303285	346415	Sa Gr Clay	Sa Gr Clay	1.85
303260	346410	Sa Gr Clay	Sa Gr Clay	1.85
313065	345110	Silty Clay & Sandy Silt & Gr/Si Sand	Gr/Si Sand	1.90
313060	345010	Sa/Cl Silt & Gr/Si Sand & Si/Sa Gravel	Si/Sa Gravel	1.90
300240	353200	Sa/Si Clay & Sand	Silty Clay & Sand	1.90
301120	354530	Gr/Sa Silt	Sand + Gravel	1.90
301130	354570	Peat	Sand + Silty Clay	1.90

308000	343520	Sa Gr Silt + Gravel	Shale	1.90
310820	342850	Sa Gr Cl Silt	Shale	1.90
303310	356670	Sa/Si Clay	Silty Clay	1.98
302820	356670	Sandy Silt & Sa/Cl Silt	Sand & Sandy Silt	1.98
319828	347652	Gr/Sa/Cl Silt	Shale	2.00
319167	347774	Sa/Cl Silt	Shale	2.00
313060	345090	Si/Gr Sand & Si/Sa Gravel	Si/Sa Gravel	2.00
313115	344925	Gr/Sa Silt & Si/Gr Sand	Si/Sa Gravel	2.00
323170	343612	Gr/Sa/Cl Silt & Peat	Shale	2.00
310200	346150	Peat & Gr/Sa Silt	Gr/Sa Silt	2.00
307770	346630	Gr/Sa Silt	Gr/Cl Silt	2.00
304050	359300	Peat	Peat & Silty Sand & Silt	2.00
303040	355210	Si/Sa Gravel	Sa/Gr Silt	2.00
303070	354770	Sa/Gr Silt	Basalt	2.00
301480	353940	Sa/Si Fill & Sand	Silty Peat & Silty Clay	2.00
301710	355690	Peat	Peat & Sandy Silt	2.00
301540	353980	Peat	Clayey Silt + Peat	2.00
301050	354510	Sand	Sa/Si Clay	2.00
313310	346425	Si Clay	Sand + Gravel	2.00
312800	346065	Sa Gr Cl Silt	Sa Gr Cl Silt	2.00
312800	346100	Sa Silt	Sa Gr Cl Silt	2.00
323170	343612	Peat + Gr Sa Clay	Shale	2.00
321316	336707	Sa Silt	Sand	2.00
307610	343500	Gr Sa Cl Silt	Gr Sa Cl Silt	2.00
307770	346630	Sa Silt	Gr Cl Silt	2.00
318100	350250	Peat + Cl Sa Silt	Shale	2.00
328995	333315	Sand + Gravel	Sa Gravel	2.00
313250	331800	Sand	Sand	2.00
306300	357520	Clay	Basalt	2.01
319800	347663	Gr/Sa/Cl Silt	Shale	2.10
307790	347580	Silty Sand	Gr/Sa/Cl Silt	2.10
302360	355640	Sa/Cl Silt	Cl/Sa Silt	2.10
301150	353570	Silty Clay & Sand	Silty Clay	2.10
311825	346730	Gr Clay	Sand + Gravel	2.10
307990	348280	Sa Cl Silt	Sa Gr Cl Silt	2.10
306000	340300	Sa Silt	Sa Silt	2.10
303980	357180	Silty Clay	Silty Clay	2.13
303660	355170	Silty Clay	Silty Clay	2.13
307170	356600	Silt	Basalt	2.13
301250	358800	Sandy Clay w/ Gravel	Sandy Clay	2.13
300780	353480	Sa/Cl Silt	Sandy Silt	2.13
300820	353890	Clayey Sand	Clayey Sand & Gravel	2.13

300700	353860	Clayey Sand	Clayey Sand & Sandy Silt & Gravel	2.13
300240	353410	Sandy Clay & Gravel	Sandy Clay & Gravel	2.13
303590	354440	Sa/Cl Silt	Sandy Silt & Gravel	2.13
303660	355170	Silty Clay	Silty Clay	2.13
302660	356110	Silty Clay	Silty Clay	2.13
309410	364985	Sa Clay	Gravel + Sa Gravel	2.13
300630	352290	Sa/Si Clay & Gravel	Sand & Gravel	2.15
301930	354690	Sa/Gr Clay	Sa/Gr Clay	2.15
303200	346660	Sa Gr Clay	Sand	2.15
321488	345269	Gr/Sa/Cl Silt & Sand & Gravel	Sand & Gravel	2.20
301150	353970	Silty Clay + Sand	Silty Clay + Sand	2.20
311860	346710	Gr Clay	Sand + Gravel	2.20
306961	360757	Sa Silt	Sand + Sa Silt	2.20
304730	355030	Silty Clay	Basalt	2.25
305770	355550	Sa/Cl Silt	Clayey Silt w/ Gravel	2.29
303250	353930	Sa/Cl Silt	Basalt	2.29
303230	353930	Sa/Cl Silt	Sand & Gravel	2.29
302970	354830	Clay	Clay	2.29
301860	354780	Clay + Sandy Silt	Sandy Silt + Clay	2.29
321510	345258	Gr/Sa Silt & Peat & Sand & Gravel	Sand & Gravel	2.30
303080	354810	Sa/Gr Silt	Basalt	2.30
302350	355490	Sa/Cl Silt & Sand	Cl/Sa Silt	2.30
301030	354300	Silt + Peat	Silty Sand + Gravel + Peat	2.30
301210	354330	Silty Clay + Peat	Sand + Gravel + Clayey Silt	2.30
312190	345390	Sa Gr Silt	Gravel	2.30
312165	345410	Gr Cl Sa Silt	Gravel	2.30
312175	345440	Gr Cl Sa Silt	Si Sand	2.30
294305	347970	Sa Gr Clay	Sa Gr Clay + Sand	2.30
306400	360918	Silt + Peat	Silt + Sand	2.30
301100	354500	Silty Clay + Peat	Sand + Clayey Silt	2.35
301150	354300	Si/Sa Clay	Silty Clay + Sand + Gravel	2.36
313050	345065	Silty Clay & Sandy Silt & Si/Sa Gravel	Si/Sa Gravel	2.40
323540	343034	Gr/Sa/Cl Silt & Sandy Silt	Sandy Silt	2.40
300420	352050	Silty Clay & Peat	Silty Clay & Sa/Gr Clay	2.40
300490	352080	Clayey Silt & Peat	Sa/Gr/Si Clay & Peat	2.40
301520	354580	Gr/Si Clay	Silty Clay	2.40
301060	354660	Gr/Si Clay	Sand	2.40
312070	346535	Sa Si Clay	Sa Gravel	2.40
323540	343034	Sa Silt	Sa Silt	2.40
318750	351250	Si Clay	Shale	2.40
300240	353380	Sandy Clay & Gravel	Sandy Clay & Gravel	2.44

303280	355610	Sandy Clay & Silty Clay	Silty Clay	2.44
303520	355370	Silty Clay	Silty Clay	2.44
302590	356470	Silty Clay & Sandy Silt	Cl/Sa Silt	2.44
303050	354730	Sa/Gr Silt	Basalt	2.45
300880	351960	Silty Clay w/ Gravel	Sa/Si Clay	2.45
301590	354670	Sa/Si Clay	Silty Clay	2.45
303432	360851	Peat	Sa Cl Silt	2.45
313085	345000	Sandy Silt & Si/Sa Gravel	Si/Sa Gravel	2.50
301600	354480	Sa/Si Clay + Peat	Sa/Si Clay + Peat + Gravel	2.50
301540	354610	Sa/Si Clay	Peat + Gravel	2.50
301100	354460	Sa/Si Clay	Gravel + Silty Clay	2.50
316310	344210	Si Clay	Sa Si Clay	2.50
311810	346630	Gr + Cl Sand	Sand + Gravel	2.50
311780	346680	Sa Clay + Gravel	Gravel	2.50
311900	346900	Sand + Gravel	Sand + Gravel	2.50
307530	360232	Sa Silt	Basalt	2.50
304807	360931	Si Peat	Silt	2.50
292750	323017	Si Sand	Sand + Gravel	2.50
300590	347837	Sa Gr Cl Silt	Shale	2.50
329125	333818	Sa Gr Silt	Sa Gravel	2.50
301730	354440	Sa/Si Clay	Silty Clay + Sandy Silt	2.55
302760	356430	Silty Clay & Clayey Silt	Cl/Sa Silt	2.59
301310	353750	Silty Clay & Peat	Sand & Gravel	2.60
301130	353570	Si/Sa Clay & Sand	Sand	2.60
300470	354470	Silty Clay & Clay	Gravel & Silty Clay	2.60
301490	353930	Peat	Clayey Silt	2.60
301120	354010	Sa/Cl Silt + Sa/Si Clay	Sa/Cl Silt + Sandy Peat	2.60
312560	346990	Sa Si Clay	Si Clay	2.60
303800	355600	Silty Clay	Silty Clay	2.70
303750	355150	Clay	Basalt	2.70
304450	354850	Silty Clay	Basalt	2.70
302510	355260	Sa/Cl Silt	Gravel	2.70
301510	355430	Peat	Peat & Sandy Silt	2.70
301570	355350	Peat	Peat & Silty Sand	2.70
300450	354690	None	Sa/Si Clay	2.70
311275	345975	Gr Sa Silt	Sa Silt	2.70
295130	344470	Gr Sa Clay	Gravel	2.70
297533	355549	Sa Cl Silt	Basalt	2.70
305950	340100	Sa Silt	Sa Silt	2.70
304870	359450	Sandy Clay	Sand & Clayey Silt	2.74
300040	353260	Sandy Clay & Gravel	Silty Clay	2.74

300790	353850	Silty Clay	Silty Sand & Gravel	2.74
303340	353890	Cl/Sa Silt	Sandy Gravel	2.74
301490	354260	Gr/Sa/Si Clay	Sand	2.75
313150	344945	Gr/Sa/Cl Silt	Gr/Sa Silt	2.80
301220	352830	Sa/Si Clay	Sa/Si Clay	2.80
301520	354370	Silty Clay	Gr/Sa/Si Clay	2.80
301670	354340	Sa/Si Clay	Sa/Si Clay	2.80
301030	354260	Sa/Cl Silt + Peat	Sand + Sandy Silt	2.80
300097	341766	Gr Cl Silt	Sand + Gravel	2.80
327300	338200	Sa Si Clay	Si Sand	2.80
311832	344254	Sandy Silt & Gr/Cl Silt	Sandstone	2.90
313100	344930	Silty Clay & Peat & Si/Gr Sand & Silt	Si/Gr Sand	2.90
301420	353630	Peat	Peat & Silty Clay & Sand	2.90
300590	354960	Silty Clay	Sand	2.90
301200	352840	Sa/Si Clay	Silty Clay & Sand	2.90
301180	354230	Silty Clay	Sa/Si Clay	2.90
301420	354640	Peat	Silty Sand + Sandy Clay	2.90
311590	346035	Sa Si Clay	Sa Si Clay	2.90
301240	354290	Silty Clay + Peat	Sand + Sandy Silt + Silty Clay	2.95
311975	344402	Clayey Silt	Sa/Cl Silt	3.00
313105	344985	Gr/Sa/Cl Silt	Si/Sa Gravel & Sand	3.00
313135	344920	Si/Sa Gravel	Si/Sa Gravel	3.00
307700	357020	Cl/Sa Silt w/ Gravel	Cl/Sa Silt	3.00
304480	354800	Peat & Silt	Sandy Silt	3.00
301710	355600	Sa/Cl Silt & Peat	Sand & Sandy Silt	3.00
301030	352900	Gr/Sa/Cl Silt	Sand & Sandy Silt	3.00
301380	353770	Peat	Clayey Silt & Sand	3.00
299720	353450	Sa/Gr Clay	Sa/Gr Clay	3.00
299740	353460	Sa/Gr Clay	Sa/Gr Clay	3.00
301380	353650	Peat	Peat & Silty Clay & Sand	3.00
301670	354340	Sa/Si Clay	Sa/Si Clay + Sand	3.00
301550	354380	Silty Clay	Sand + Gravel + Silty Clay	3.00
301420	354010	Sa/Gr Silt + Sand + Gravel	Sandy Gravel + Peat + Sand	3.00
303290	345510	Si Sa Gravel	Sa Si Clay	3.00
312565	347005	Sa Si Clay	Sa Si Clay	3.00
312230	346975	Si Clay	Gravel	3.00
303180	346570	Gr Sa Si Clay	Sa Gr Si Clay	3.00
303858	343795	Sand + Gravel + Cl Silt	Shale	3.00
318750	350750	Si Clay	Shale	3.00
299312	354930	Sa Cl Silt	Sa Gr Cl Silt	3.00
302600	358680	Sandy Clay w/ Gravel	Sandy Clay	3.05

302620	358670	Sandy Clay w/ Gravel	Sand & Gravel	3.05
303500	353850	Sa/Cl Silt w/ Gravel	Gravel	3.05
300080	354660	Sand & Silt & Sandy Clay	Silty Sand & Gravel w/ Clay	3.05
300850	353930	Silty Clay w/ Gravel	Sa/Si Clay	3.05
300870	353940	Sandy Clay w/ Gravel	Sandy Clay & Sandy Silt	3.05
303510	353850	Sa/Cl Silt & Sandy Silt	Sandy Gravel	3.05
303330	353710	Silty Sand	Silt	3.05
302510	355840	Sandy Clay	Sandy Clay	3.05
300600	354990	Silty Clay & Clay	Sand	3.05
301650	354730	Sa/Si Clay	Sa/Si Clay	3.05
301460	354490	Peat	Silty Sand	3.05
294290	347965	Sa Gr Clay	Sa Gr Clay + Sand + Gravel	3.05
301500	353970	Sa/Cl Silt	Sandy Silt & Sand	3.10
305150	355450	Cl/Sa Silt	Basalt	3.20
300690	352070	Silty Clay & Peat	Sa/Si Clay	3.20
301030	354480	Silty Clay	Sand	3.20
311585	346055	Sa Si Clay	Sa Si Clay	3.20
306734	360858	Sa Silt	Sa Silt	3.20
301430	354350	Gr/Sa/Si Clay	Sa/Si Clay	3.25
303150	346595	Gr Sa Si Clay	Sa Gr Si Clay	3.26
301230	353730	Sa/Gr/Cl Silt	Sandy Silt & Sand & Gravel	3.30
303830	356320	Sandy Clay	Clay	3.30
300560	353710	Sandy Clay & Gravel	Sandy Clay & Gravel	3.35
301040	354030	Silty Clay	Sandy Gravel	3.35
301230	353720	Sa/Gr/Cl Silt	Sand & Gravel & Sandy Silt	3.40
301610	354280	Silty Clay	Sa/Si Clay	3.40
301580	354350	Silty Clay	Sandy Silt + Gravel	3.40
305750	345250	Si Clay	Si Clay	3.40
313130	346300	Sandy Silt & Gravel	Sandy Silt & Sand	3.50
313130	344895	Si/Gr Sand & Si/Sa Gravel & Sa/Cl/Gr Silt	Si/Sa Gravel	3.50
300640	354130	Sa/Cl Silt & Peat	Sandy Gravel	3.50
301360	354140	Si/Sa Gravel	Pt/Sa Silt + Sand + Gravel	3.50
301010	354340	Sand	Sand + Gravel	3.50
313130	346300	Sa Si Gravel	Sa Silt + Sand	3.50
311750	346825	Sa Gr Cl Silt	Sa Gr Cl Silt	3.50
303080	354450	Clay	Clay	3.51
303500	358850	Peat	Sandy Clay & Gravel	3.58
301580	354360	Sa/Si Clay	Sand + Silty Clay	3.60
301230	354290	Silty Clay + Peat	Sand + Gravel +Si/Sa Clay	3.60
312900	346120	Sa Silt	Sa Silt	3.60
301550	354750	Sandy Clay	Peat +Silty Sand + Sandy Clay	3.66
301570	354640	Silty Clay + Peat	Sandy + Silty Clay	3.70

301360	353910	Peat	Gravelly Sand + Gravel + Peat	3.70
302600	358900	Sandy Clay	Clay	3.73
300500	352270	Sa/Si Clay & Gravel	Sand & Gravel	3.80
301320	354290	Silty Clay + Peat	Gr/Sa/Si Clay	3.80
322775	338465	Sa Clay	Sa Clay + Si Sand	3.80
303286	345542	Sa Gr Cl Silt	Sand + Gravel	3.80
305500	359220	Sandy Clay	Sandy Gravel	3.81
305660	358140	Sa/Si Clay	Silty Sand	3.81
304640	353440	Si/Sa Clay	Silty Clay	3.81
299940	353180	Sand & Sandy Clay	Clayey Silt	3.81
302910	355310	Clay	Clay	3.81
294310	347945	Gr Clay	Sa Gr Clay	3.90
307354	360407	Gr Sa Silt	Sa Silt	3.90
304430	357300	Sa/Si Clay	Silty Clay	3.96
302850	355280	Sandy Clay & Clay	Clay	3.96
301250	354420	Silty Clay + Peat	Sand + Sa/Si Clay	3.96
308585	342225	Clay	Clay	3.96
312146	344875	Clayey Silt & Gravelly Silt	Silty Sand & Gravel	4.00
313115	344965	Gr/Sa/Cl Silt	Sandy Silt & Si/Sa Gravel	4.00
301240	354270	Silty Clay + Peat	Sand + Gravel + Sandy Silts	4.00
301440	354490	Sa/Si Clay + Peat	Sa/Si Clay	4.00
301150	354620	Sandy Clay + Peat	Sand	4.00
301300	354080	Sa/Cl Silt	Sandy Silt + Sandy Gravel	4.00
313005	346210	Sand	Sa Silt + Sand	4.00
328595	329170	Si Sa Gravel	Si Sa Gravel	4.00
303100	354750	Sa/Gr Silt	Basalt	4.10
319855	333495	Gravel	Sand + Gravel	4.10
318349	350750	Cl Sa Silt	Sa + Sa Silt	4.10
304630	356960	Sa/Cl Silt	Sand	4.20
297185	339683	Sa Cl Silt	Sand + Gravel	4.20
301540	354380	Silty Clay	Silty Clay + Gravel	4.25
305900	357200	Sa/Cl Silt	Basalt	4.27
302680	356070	Silty Clay	Basalt	4.27
296025	362770	Peat + Si Clay	Silt + Sand	4.30
306785	360800	Sa Cl Silt	Sand	4.30
303180	355000	Sa/Gr Silt & Sandy Silt	Sa/Gr Silt	4.40
328595	329175	Pt Silt	Sa Gravel	4.40
304523	343127	Gr Cl Silt	Shale	4.40
301220	354350	Peat	Sandy Silt + Gravel + Silty Clay	4.42
313100	346368	Sa/Gr/Cl Silt	Sandy Gravel	4.50
313080	344980	Fill	Sa/Cl Silt & Si/Sa Gravel	4.50

313100	344970	Fill	Si/Sa Gravel & Sand	4.50
313090	344955	Gr/Sa/Cl Silt	Sandy Gravel	4.50
301170	354660	Sa/Pt Silt	Sand + Gravel	4.50
301620	354410	Sa/Si Clay	Sand + Gravel + Silty Clay	4.55
305500	357950	Sa/Si Clay	Silty Clay	4.57
302020	355260	Sandy Clay	Sa/Si Clay	4.57
302600	355850	Sandy Clay	Sa/Si Clay	4.57
302690	356090	Silty Clay	Basalt	4.57
302880	355110	Clay	Clay	4.57
301330	354020	Clay	Silty Clay + Gravel	4.57
301370	354190	Clayey Silt + Peat + Gravel	Gravel	4.60
302900	355360	Clay	Clay	4.65
301620	355540	Cl/Sa Silt & Peat	Sand & Sandy Silt	4.70
300660	352170	Sa/Si Clay & Gravel	Sandy Gravel	4.70
305250	344750	Peat	Si Clay	4.70
301260	354390	Silty Clay + Peat	Sandy Clay	4.72
312210	345415	Sa Gr Silt	Sa Silt + Gravel	4.80
302710	356070	Silty Clay	Basalt	4.88
301450	354570	Silt	Peat + Sandy Clay +Sand/Gravel	4.88
307040	336425	Clay	Clay	4.88
304760	356200	Sa/Si w/ Gravel	Basalt	4.90
307750	332250	Si Clay	Sand + Sa Silt	4.90
301510	353880	Sandy Silt & Peat	Sa/Gr/Cl Silt	5.00
301280	354360	Silty Clay + Clayey Silt	Sand + Silty Sand	5.00
301320	354150	Sand + Gravel + Peat	Sand + Gravel + Silt	5.00
301040	353010	Sa/Cl Silt & Peat	Silty Clay & Sand	5.10
301040	354130	Silty Clay + Peat	Gravel	5.18
305100	347200	Sa Cl Silt	Gravel	5.30
303780	356400	Sandy Clay	Basalt	5.40
315825	345160	Sa Cl Silt	Sand + Gravel + Cl Silt	5.40
302948	362175	Sa Silt	Sa Silt + Sand	5.40
303450	358970	Peat & Sa/Si Clay	Sa/Si Clay	5.49
306120	357050	Sa/Si Clay	Basalt	5.49
312595	345577	Sa/Gr/Cl Silt	Sa/Gr/Cl Silt & Si/Sa Gravel	5.50
301060	353020	Sa/Si Clay & Peat	Sa/Cl Silt	5.50
301370	354160	Clayey Silt + Peat	Clayey Silt	5.50
307435	360395	Sa Cl Silt	Sa Gr Cl Silt	5.50
303670	358950	Peat & Sand/Gravel	Sandy Clay w/ Gravel	5.64
301240	354330	Silty Clay + Sandy Gravel	Sand + Gravel	5.64
301290	353850	Peat & Sandy Silt	Sa/Cl Silt & Sand	5.70
303600	355300	Silty Clay	Silty Clay	5.79

304130	354170	Sandy Clay	Sandy Clay	5.79
303590	355280	Silty Clay	Silty Clay	5.79
301120	353120	Sa/Si Clay & Peat	Sand & Gravel	5.80
309760	340480	Peat	Sa Clay	5.80
303921	360800	Sa Silt	Sa Silt	5.80
303730	356470	Clay	Basalt	6.00
299710	353430	Silty Sand & Sa/Gr Clay	Sa/Gr Clay	6.00
303720	356470	Clay	Basalt	6.00
303780	356170	Sandy Clay & Silty Clay	Clay	6.00
301230	354240	Cl/Gr Silt + Peat	Sand + Gravel + Sa/Gr Silt	6.00
301270	354150	Sa/Cl Silt	Gravelly Sand	6.00
307315	360462	Sand + Gravel + Sa Gr Cl Silt	Sa Gr Cl Silt	6.00
305750	344750	Peat	Peat	6.00
307515	338575	Clay	Clay + Gravel	6.09
303400	356790	Silty Clay	Clay	6.10
299870	353100	Sandy Clay w/ Gravel	Sandy Clay w/ Gravel & Peat	6.10
301340	354390	Sa/Si Clay	Peaty Silt + Gravel	6.10
308515	342070	Clay	Shale	6.10
301480	353780	Sandy Silt & Silty Peat	Sand & Gravel	6.20
302680	355760	Si/Sa Clay	Si/Sa Clay	6.40
305910	358560	Sandy Clay	Gravel & Sand & Clayey Silt	6.48
302940	355280	Silty Clay & Sa/Gr/Si & Basalt	Basalt	6.50
315815	345140	Sa Cl Silt + Peat	Sand + Gravel	6.50
304419	342820	Gr Sa Silt	Gr Sa Silt	6.50
309510	345050	Clay	Gravel	6.55
307149	360594	Gr Sa Silt	Sa Silt	6.60
302980	355280	Silty Clay & Sand & Basalt	Basalt	6.70
301050	353040	Silty Clay & Gravel & Peat	Silty Clay & Sand	6.70
302300	357900	Cl/Sa Silt	Sand	6.71
303130	355710	Sandy Clay	Clay	6.71
300490	353630	Sandy Clay & Gravel	Sand & Gravel	6.71
301970	355420	Cl/Sa Silt w/ Gravel	Gravelly Sand	6.90
301250	354270	Sa/Si Clay + Peat	Silty Clay + Sandy Gravel	7.01
301210	353710	Sa/Gr/Cl Silt & Sand	Sa/Gr/Cl Silt	7.20
295090	344460	Gr Sa Si Clay	Gravel	7.20
303030	354790	Sa/Gr Silt	Basalt	7.30
303250	346610	Sa Gr Clay	Sa Gr Clay	7.30
303010	358030	Clay	Clay	7.32
302670	356000	Sa/Si Clay	Silty Sand	7.32

302710	355850	Si/Sa Clay	Silty Clay	7.32
302740	356050	Silty Clay & Clay	Silty Sand & Sand & Gravel	7.32
306750	332250	Si Clay	Gravel	7.40
301350	354010	Sa/Gr Silt + Peat	Sand + Gravel + Sandy Silt	7.50
303265	346620	Sa Gr Clay	Sa Gr Clay	7.60
302730	356040	Silty Clay	Sand & Gravel	7.62
300530	353670	Sandy Clay & Gravel	Sand & Gravel	7.92
301210	354260	Sandy Clay + Peat	Sand + Gravel + Silt	8.08
308450	341850	Clay	Shale	8.23
301180	354220	Sa/Si Clay + Gravel	Sa/Si Clay + Gravel	8.53
300720	353750	Sandy Clay & Gravel	Sandy Clay & Gravel	9.14
300510	353720	Sandy Clay & Gravel	Sandy Clay & Sand & Gravel	9.14
301130	354240	Sandy Clay	Silty Clay + Sand + Gravel	9.14
302720	360960	Sa Gr Silt	Gr Si Clay	9.75
302070	356530	Peat	Clayey Silt	10.00
303235	346635	Sa Clay	Shale	10.05
305910	358560	Clay	Clay	10.06
303220	346650	Sa Gr Clay	Shale	10.65
303225	346615	Sa Gr Clay	Shale	11.00
303510	352090	Clay	Clay & Gravel	11.28
300660	353770	Sandy Clay w/ Gravel	Sandy Clay w/ Gravel	12.56
303000	358700	Sandy Clay w/ Gravel	Sand & Sandy Clay	18.14
303040	357240	Silty Clay	Basalt	42.00
302510	355120	Clay & Basalt	Till	56.40
287860	330910	NA	NA	6.10
291710	329700	NA	NA	12.19

4.7. River chemical quality monitoring

Fig. App.A.13 shows the locations of river quality monitoring sites, which monitor the surface water chemical quality in a month interval. River quality chemical parameters monitored are shown in Table App.A.7. Table App.A.8 shows parts of the monitoring data of chemical quality of rivers in the Upper Bann Catchment. In this study, river chemical quality time series data were also organised and inputted into the WDMUtil in the BASINS system for the purpose of river quality modelling calibrations and validations.

Table App.A.7. Chemical parameters and their abbreviations in river quality monitoring data

Chemical parameter	**Abbreviation in the data**
Temperature	TEMP
pH Value	PH
Dissolved Oxygen	DO
Dissolved Oxygen % Saturation	DO%
Ammoniacal Nitrogen	NH4-N
Non-ionised Ammonia	NH3
Suspended Solids	SS
Soluble Reactive Phosphorus	P(SOL)
Nitrite	NO2-N
Nitrate	NO3-N
Total Oxidized Nitrogen	TON
Total Hardness	T/HARD
Zinc (total)	ZNTOT2
Copper (dissolved)	CUSOL1
Petroleum Hydrocarbons (visual check)	OILVIS *
Water Level	WATER **

Visual check for oil on surface of water at time of sampling: 0 = absent, 1 = present; **Water level assessed at time of sampling: 1 = very low, 2 = low, 3 = normal, 4 = high, 5 = very high.

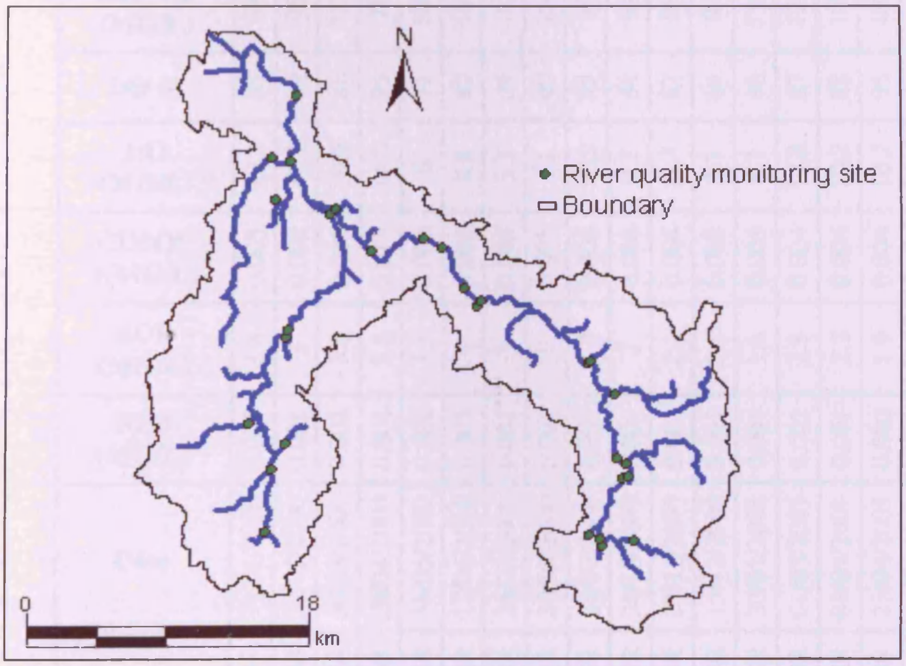


Fig. App.A.13. The locations of river quality monitoring sites in the Upper Bann Catchment

Table App.A.8. Parts of the river chemical quality monitoring data at the Knock Bridge of the Upper Bann Catchment from 2000 to 2005

Location	Date	NH3 (MG/L)	BOD (MG/L)	CUSOL 1(MG/L)	DO (MG/L)	DO %	T/HARD (MG/L)	NO3-N (MG/L)	NO2-N (MG/L)	NH4-N (MG/L)	OILVIS	PH	P(SOL) (MG/L)	WATER	SS (MG/L)	TEMP	TON (MG/L)	ZNTOT2 (MG/L)
KNOCK BR	31/01/2000	0.003	2.8	0.005	10.3	85	100	2.77	0.072	0.3	0	7.84	0.19	3	14	7	-	0.018
KNOCK BR	29/02/2000	0.001	3	0.002	11.2	89	98	3.3	0.04	0.18	0	7.58	0.1	3	10	5.5	-	0.018
KNOCK BR	30/03/2000	0.002	3.6	0.005	10.6	86	122	2.3	0.032	0.19	0	7.9	0.09	2	6	6.5	-	0.019
KNOCK BR	28/04/2000	0.001	3.4	0.011	11.3	95	74	2.63	0.031	0.29	0	7.27	0.17	5	14	8	-	0.02
KNOCK BR	31/05/2000	0.002	3.5	0.005	8	71	104	1.5	0.061	0.25	0	7.64	0.15	3	5	10	-	0.006
KNOCK BR	27/06/2000	0.003	4	0.005	8.8	89	134	1.75	0.173	0.17	0	7.79	0.19	2	2	16	-	0.006
KNOCK BR	28/07/2000	0.001	3	0.005	5.3	56	142	1.07	0.129	0.13	0	7.43	0.09	1	2	18	-	0.006
KNOCK BR	30/08/2000	0.003	1	0.005	4.1	40	154	0.07	0.011	0.95	0	7.09	0.12	2	2	14	-	0.006
KNOCK BR	28/09/2000	0.001	4.2	0.005	10.2	95	50	1.37	0.036	0.19	0	7.49	0.14	4	45	12	-	0.021
KNOCK BR	26/10/2000	0.001	2	0.008	9.7	84	94	2.92	0.047	0.16	0	7.43	0.11	4	5	9	-	0.009
KNOCK BR	27/11/2000	0.001	2.1	0.004	11.1	87	88	2.73	0.036	0.13	0	7.43	0.1	4	9	5	-	0.017
KNOCK BR	15/12/2000	0.001	2.1	0.003	8.7	68	94	2.26	0.02	0.14	0	7.3	0.1	3	5	5	-	0.013
KNOCK BR	30/01/2001	0.001	1.6	0.003	8.7	66	116	2.83	0.023	0.27	0	7.35	0.06	3	6	4	-	0.007
KNOCK BR	01/03/2001	0.001	2.8	0.004	12.4	87	126	2.22	0.029	0.24	0	7.69	0.09	3	5	1	-	0.012
KNOCK BR	02/04/2001	0.001	2.2	0.004	10.2	88	106	2.36	0.029	0.13	0	7.72	0.14	3	5	9	-	0.01
KNOCK BR	25/04/2001	0.002	1.9	0.004	10.7	95	102	1.98	0.053	0.18	0	7.8	0.1	3	5	10	-	0.008
KNOCK BR	29/05/2001	0.003	1.2	0.004	4.4	45	152	1.2	0.196	0.42	0	7.44	0.12	3	6	16	-	0.006

KNOCK BR	29/06/2001	0.002	1.8	0.004	4.7	47	138	1.75	0.201	0.21	0	7.5	0.25	2	4	15	-	0.006
KNOCK BR	30/07/2001	0.001	1	0.005	3.2	30	152	1.66	0.062	0.04	0	7.57	0.31	1	2	13	-	0.006
KNOCK BR	30/08/2001	0.001	1.2	0.005	7.1	69	146	2.33	0.088	0.06	0	7.82	0.39	2	3	14	-	0.007
KNOCK BR	28/09/2001	0.002	3.7	0.006	3.9	38	150	0.43	0.106	0.23	0	7.46	0.22	3	4	14	-	0.007
KNOCK BR	31/10/2001	0.001	1.5	0.006	10.5	93	66	0.55	0.027	0.05	0	7.52	0.04	3	2	10	-	0.006
KNOCK BR	27/11/2001	0.002	2.2	0.004	10.8	87	116	2.77	0.034	0.18	0	7.87	0.13	3	4	6	-	0.006
KNOCK BR	14/12/2001	0.001	3	0.004	11.3	86	118	4.88	0.04	0.27	0	7.58	0.1	3	4	4	-	0.01
KNOCK BR	30/01/2002	0.001	2.3	0.005	11.7	96	98	6.1	0.04	0.25	0	7.48	0.07	4	13	7	-	0.015
KNOCK BR	28/02/2002	0.001	3.5	0.004	13.2	101	84	4.61	0.04	0.3	0	7.52	0.14	3	12	4	-	0.025
KNOCK BR	29/03/2002	0.001	3.1	0.004	11.2	95	90	5.65	0.059	0.23	0	7.59	0.06	3	2	8	-	0.006
KNOCK BR	29/04/2002	0.002	5.7	0.006	10.6	92	86	2.1	0.052	0.3	0	7.61	0.14	4	27	9	-	0.028
KNOCK BR	28/05/2002	0.001	1.6	0.005	9.4	87	96	2.46	0.051	0.14	0	7.53	0.11	3	7	12	-	0.014
KNOCK BR	21/06/2002	0.003	1.5	0.005	8.8	87	114	1.7	0.09	0.2	0	7.7	0.16	2	2	15	-	0.009
KNOCK BR	29/07/2002	0.002	3.3	0.005	7.6	79	104	1.95	0.117	0.15	0	7.65	0.23	3	9	17	-	0.013
KNOCK BR	28/08/2002	0.002	2.9	0.003	6.9	70	142	1.96	0.035	0.12	0	7.72	0.13	3	9	16	-	0.006
KNOCK BR	20/09/2002	0.002	2.1	0.003	8.9	86	130	1.87	0.062	0.17	0	7.69	0.17	2	5	14	-	0.006
KNOCK BR	22/10/2002	0.001	3.4	0.004	11.2	97	46	1.68	0.016	0.13	0	6.96	0.18	5	12	9	-	0.015
KNOCK BR	21/11/2002	0.001	1.9	0.003	10.2	88	50	1.63	0.017	0.16	0	7.67	0.09	5	12	9	-	0.007
KNOCK BR	18/12/2002	0.001	3.2	0.003	12.9	93	114	2.15	0.041	0.37	0	7.55	0.09	3	5	2	-	0.01
KNOCK BR	30/01/2003	0.001	2.9	0.003	12.1	92	74	1.83	0.026	0.24	0	7.5	0.08	4	16	4	1.85	0.006
KNOCK BR	26/02/2003	0.003	2	0.003	11.1	89	82	2.05	0.049	0.38	0	7.8	0.07	2	5	6	2.1	0.006
KNOCK BR	24/03/2003	0.001	2	0.003	11.1	91	118	2.05	0.033	0.18	0	7.63	0.06	2	5	7	2.08	0.006
KNOCK BR	28/04/2003	0.001	2.8	0.003	9.2	82	60	1.59	0.036	0.11	0	7.25	0.11	3	7	10	1.63	0.008
KNOCK BR	29/05/2003	0.001	2.3	0.004	7.5	71	86	1.76	0.03	0.16	0	7.23	0.11	3	10	13	1.79	0.009

KNOCK BR	30/06/2003	0.001	1.3	0.003	8.1	79	96	1.18	0.02	0.09	0	7.83	0.13	2	3	14	1.2	0.006
KNOCK BR	29/07/2003	0.001	2.1	0.003	8.6	85	92	1.28	0.023	0.07	0	7.78	0.14	3	13	15	1.3	0.015
KNOCK BR	28/08/2003	0.001	1.1	0.003	8.3	79	108	0.89	0.02	0.09	0	7.53	0.19	2	3	13	0.91	0.006
KNOCK BR	19/09/2003	0.001	1.5	0.007	3.4	33	186	0.14	0.007	0.07	0	7.22	0.08	3	4	14	0.15	0.006
KNOCK BR	22/10/2003	0.002	6.2	0.003	10.2	80	100	1.24	0.055	0.4	0	7.59	0.22	2	3	5	1.29	0.006
KNOCK BR	21/11/2003	0.001	1.3	0.003	11	91	88	1.76	0.038	0.22	0	7.27	0.12	3	2	7	1.8	0.006
KNOCK BR	09/12/2003	0.001	2.1	0.003	12	96	100	2.54	0.033	0.08	0	7.5	0.07	3	2	6	2.58	0.006
KNOCK BR	22/01/2004	0.001	1.3	0.003	11.1	94	92	3.78	0.049	0.16	0	7.67	0.08	3	3	8	3.83	0.006
KNOCK BR	17/02/2004	0.001	1	0.003	12	96	100	3.09	0.03	0.11	0	7.87	0.07	3	3	6	3.12	0.006
KNOCK BR	15/03/2004	0.001	1.9	0.003	11.4	94	74	1.92	0.019	0.08	0	7.41	0.06	2	11	7	1.94	0.008
KNOCK BR	23/04/2004	0.001	1.3		9.2	76	90	2.76	0.026	0.1	0	7.77		3	8	7	2.78	0.012
KNOCK BR	19/05/2004	0.003	4.9	0.008	5.3	54	112	1.39	0.038	0.35	0	7.51	0.2	2	5	16	1.42	0.017
KNOCK BR	14/06/2004	0.001	3.2	0.005	8.7	92	140	0.85	0.021	0.04	0	7.66	0.23	2	8	18	0.87	0.006
KNOCK BR	09/07/2004	0.001	1.3	0.005	8.5	88	82	1	0.015	0.07	0	7.62	0.16	3	4	17	1.01	0.006
KNOCK BR	17/08/2004	0.001	1.7	0.002	3.4	37	216	0.05	0.003	0.04	0	7.34	0.07	3	6	19	0.02	0.006
KNOCK BR	15/09/2004	0.001	1.7	0.004	9.8	89	110	2.56	0.057	0.09	0	7.63	0.17	3	6	11	2.61	0.007
KNOCK BR	14/10/2004	0.001	1	0.005	7.3	62	162	1.39	0.027	0.11	0	7.54	0.11	1	7	8.5	1.41	0.009
KNOCK BR	11/11/2004	0.001	1	0.008	10.6	91	86	2.63	0.041	0.1	0	7.75	0.11	3	2	8.5	2.67	0.006
KNOCK BR	07/12/2004	0.001	1	0.003	11.1	87	106	2.45	0.03	0.08	0	7.88	0.11	3	2	5	2.48	0.006
KNOCK BR	24/01/2005	0.001	1.2	0.003	12.7	94	104	3.14	0.03	0.19	0	7.71	0.1	3	2	3	3.17	0.006
KNOCK BR	22/02/2005	0.001	1.6		12.4	95	104	2.96	0.029	0.14	0	7.58	0.1	3	3	4	2.98	0.006
KNOCK BR	23/03/2005	0.001	2	0.003	10.4	90	80	3.16	0.03	0.06	0	7.34	0.09	4	7	9	3.19	0.006
KNOCK BR	21/04/2005	0.001	1.9	0.003	10.9	90	78	3.22	0.02	0.15	0	7.54	0.08	3	5	7	3.24	0.006

4.8. Weather in the study area

The study area has a mean annual rainfall of 995 mm, a mean annual potential evapotranspiration of 516 mm, an average air temperature of 9.29 °C, an average wind speed of 15.2 km, and a mean dew-point 6.66 °C. The original weather data gathered from British Atmospheric Data Centre were in text format. Fig. App.A.14 shows the locations of weather stations within and around the Upper Bann Catchment. The time series of weather data were abstracted from original weather data format (Table App.A.9) and inputted into the WDMUtil of the BASINS system for water modelling. Weather data (2000-2005) gathered include hourly precipitation (Fig. App.A.15), hourly air temperature (Fig. App.A.16), hourly wind speed (Fig. App.A.17), hourly cloud cover, hourly dew-point (Fig. App.A.18), etc. Based on these data, daily solar radiation (Fig. App.A.19), pan evaporation (Fig. App.A.20), and potential evapotranspiration (PET) (Fig. App.A.21) were calculated.

In order to calculate the net water recharge for groundwater, the average precipitation and evapotranspiration data of each year between year 1990 and 2000 were interpolated to continuous raster layer using GIS. Fig. App.A.22 and Fig. App.A.23 show total rainfall and PET in 1998. Fig. App.A.24 and Fig. App.A.25 respectively show the average rainfall and PET between 1990 and 2000.

Table App.A.9. The original weather data format

Header of item	Parameter	Fields	Columns	Units	Comments
ID	Station Ref. Number	1	1-8	-	Station identification
IDTYPE	-	2	9-17	-	Station identification
MET_DOM	Meteorological Domain	3	18-28	-	Information types
YEAR	Year	3	29-35	-	4 characters
MON	Month	4	36-43	-	1 or 2 characters (from 1 to 12)
DAY	Day	5	44-51	-	1 or 2 characters (from 1 to 31max)

HOUR	Hour	6	52-59	-	Hour of observation from 0 to 2300
DIR	10 minutes wind direction	7	60-67	Degree true	From 0 to 360 degrees, clockwise.
SPEED	10 minutes wind speed	8	68-75	Knots	NB. A mean wind for the hour up until the reporting time.
PRST	Present weather	9	76-81	WMO Code	
PAS1	Most significant Past weather	10	82-87	WMO code	
PAS2	Least significant Past weather	11	88-93	WMO code	
TCA	Total cloud amount	12	94-98	WMO code	
CBH	Cloud base height	17	119-126	DAM	DAM = Decameters
VIS	Horizontal visibility	18	127-133	DAM	DAM = Decameters
MSLP	Mean Sea Level Pressure	19	134-146	0.1 mb	Atmospheric pressure is expressed in millibars (1 millibar = 100 pascals = 100 newtons per square metre).
VVIS	Vertical visibility	32	219-226	DAM	DAM = Decameters
TEMP	Dry-bulb air temperature	33	227-234	0.1 Degrees Celcius	
DEW	Dew-point temperature	34	235-242	0.1 Degrees Celcius	The dew point temperature is the temperature to which the air must be cooled to produce saturation with respect to water at its existing atmospheric pressure and humidity.
WETB	Wet-bulb	35	243-250	0.1	The web-bulb

	temperature			Degrees Celcius	temperature is the lowest temperature that can be obtained by evaporating water into the air. It measures the humidity of the air.
STNP	Station level pressure	36	251-262	0.1 mb	Atmospheric pressure as measured at the station level. Correction for altitude is not applied.
ALTP	Altimeter pressure	37	263-270	mb	-
SOG	State of ground	38	271-275	WMO Code	-
MGS	10 minutes maximum gust speed	39	276-283	knots	

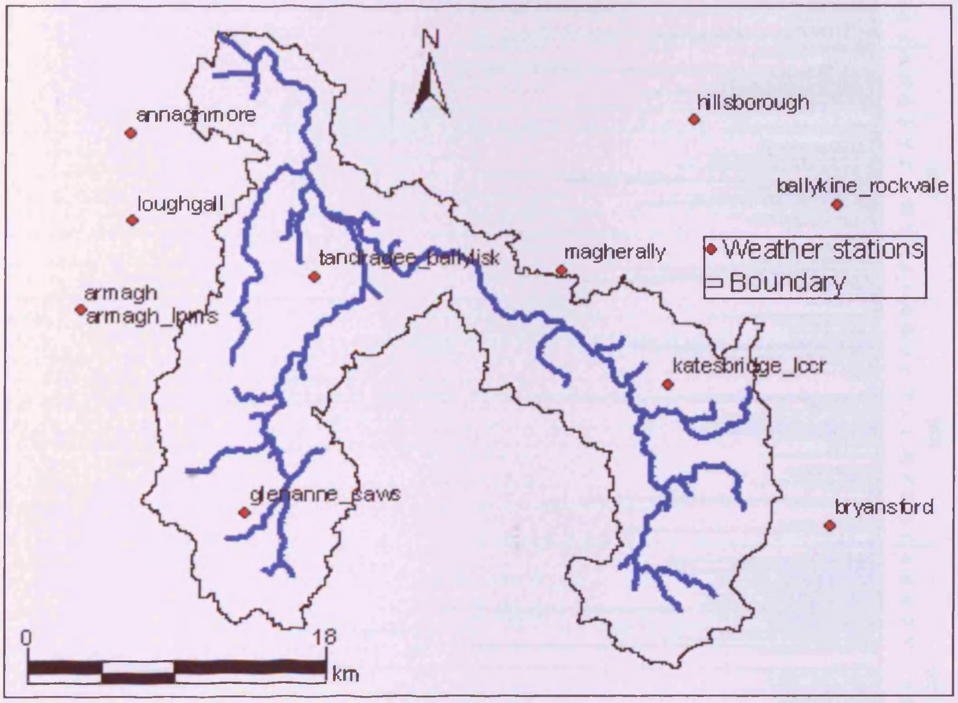


Fig. App.A.14. The locations of weather stations within and around the Upper Bann Catchment

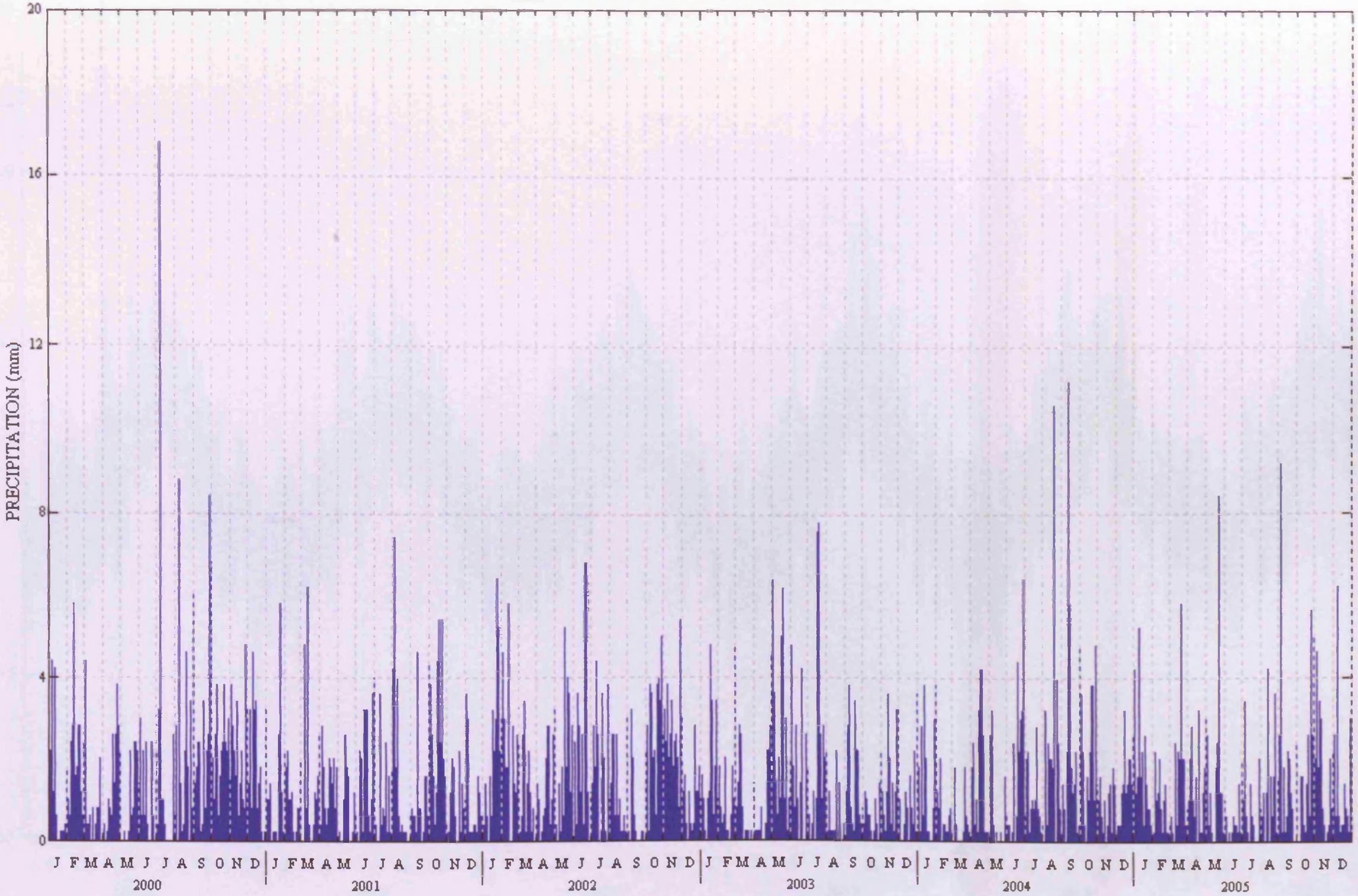


Fig. App.A.15. Hourly precipitation of Glenanne_saws weather station in the Upper Bann Catchment (from 2000-2005)

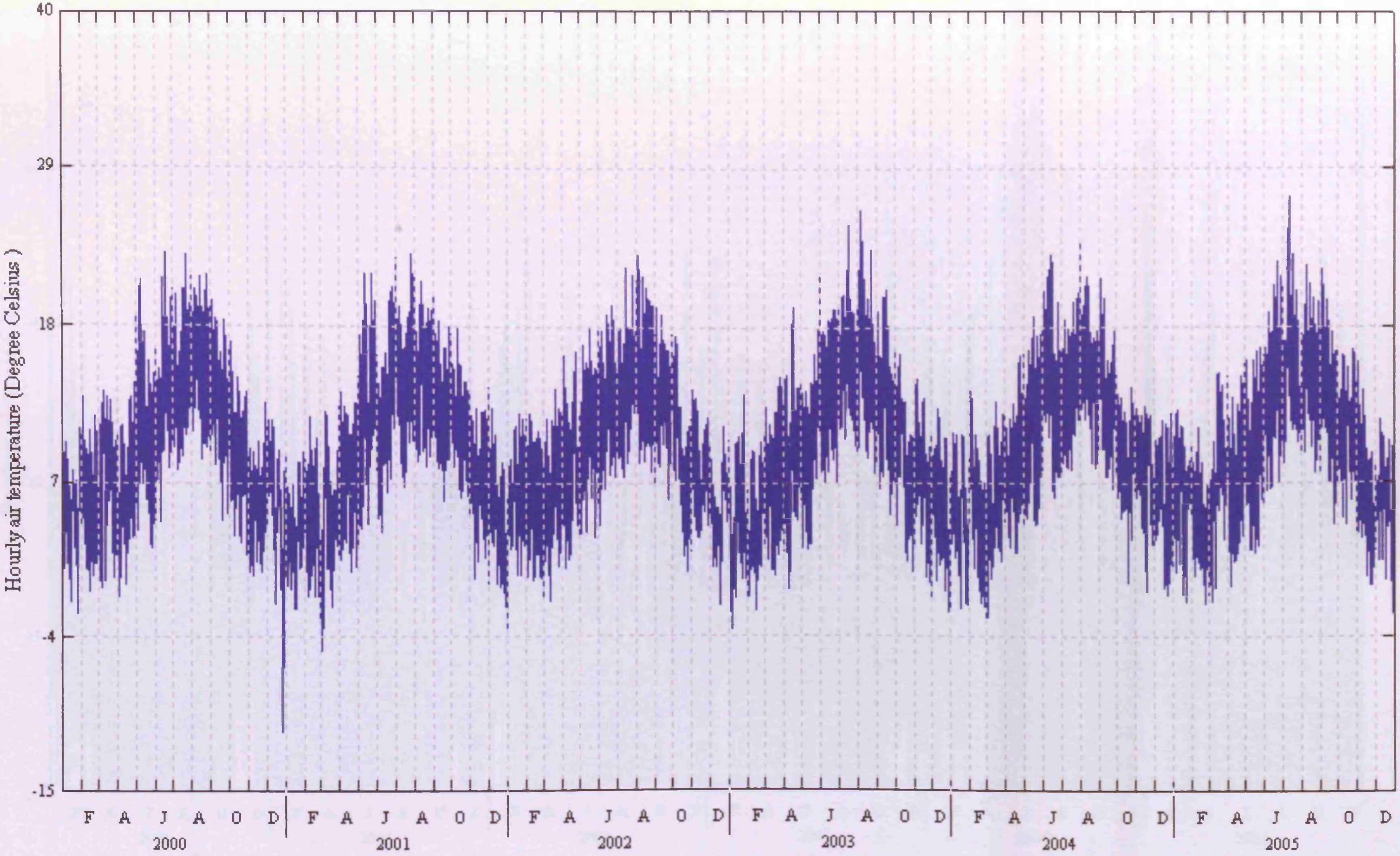


Fig. App.A.16. Hourly air temperature of Glenanne_saws weather station in the Upper Bann Catchment (from 2000-2005)

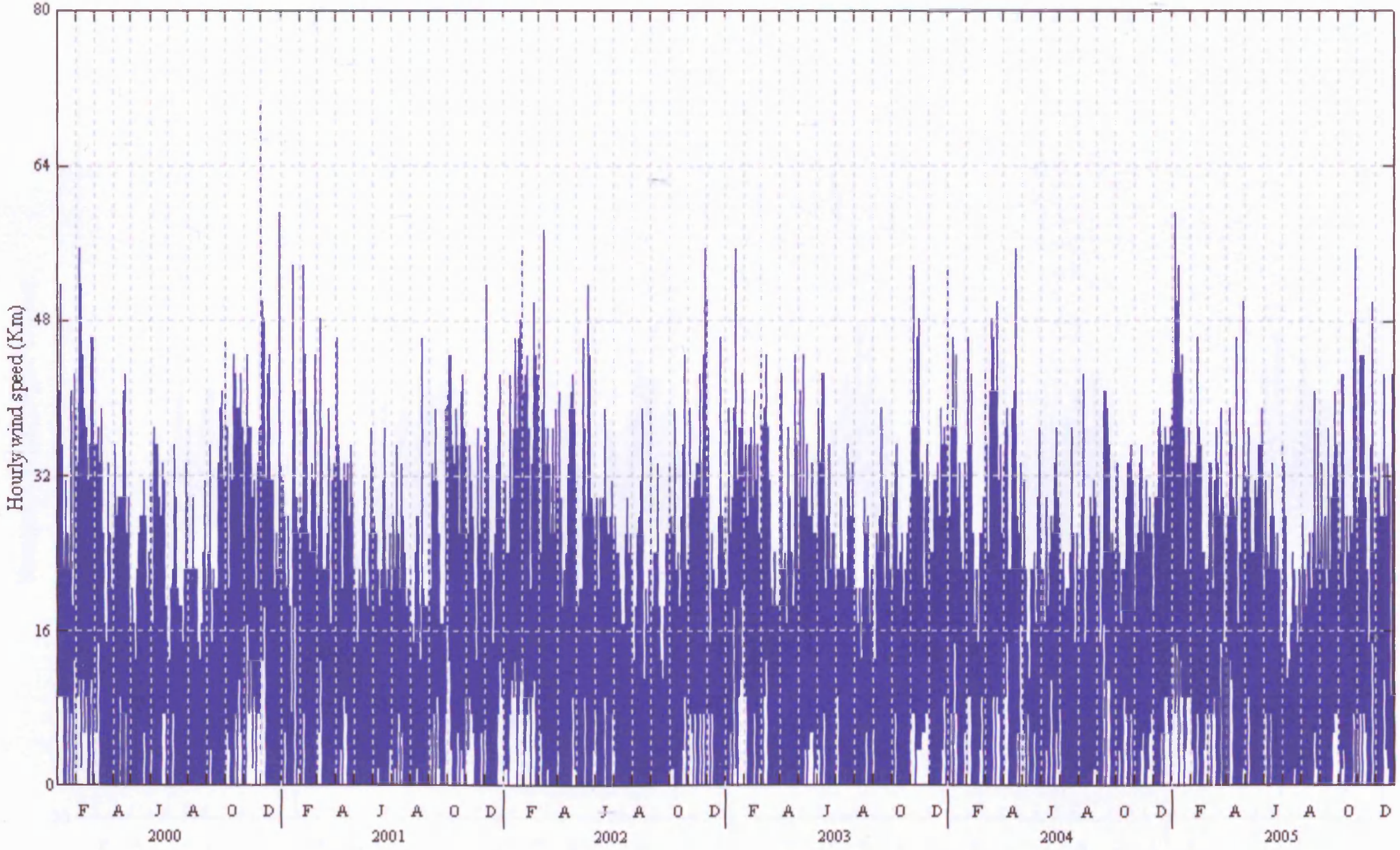


Fig. App.A.17. Hourly wind speed of Glenanne_saws weather station in the Upper Bann Catchment (from 2000-2005)

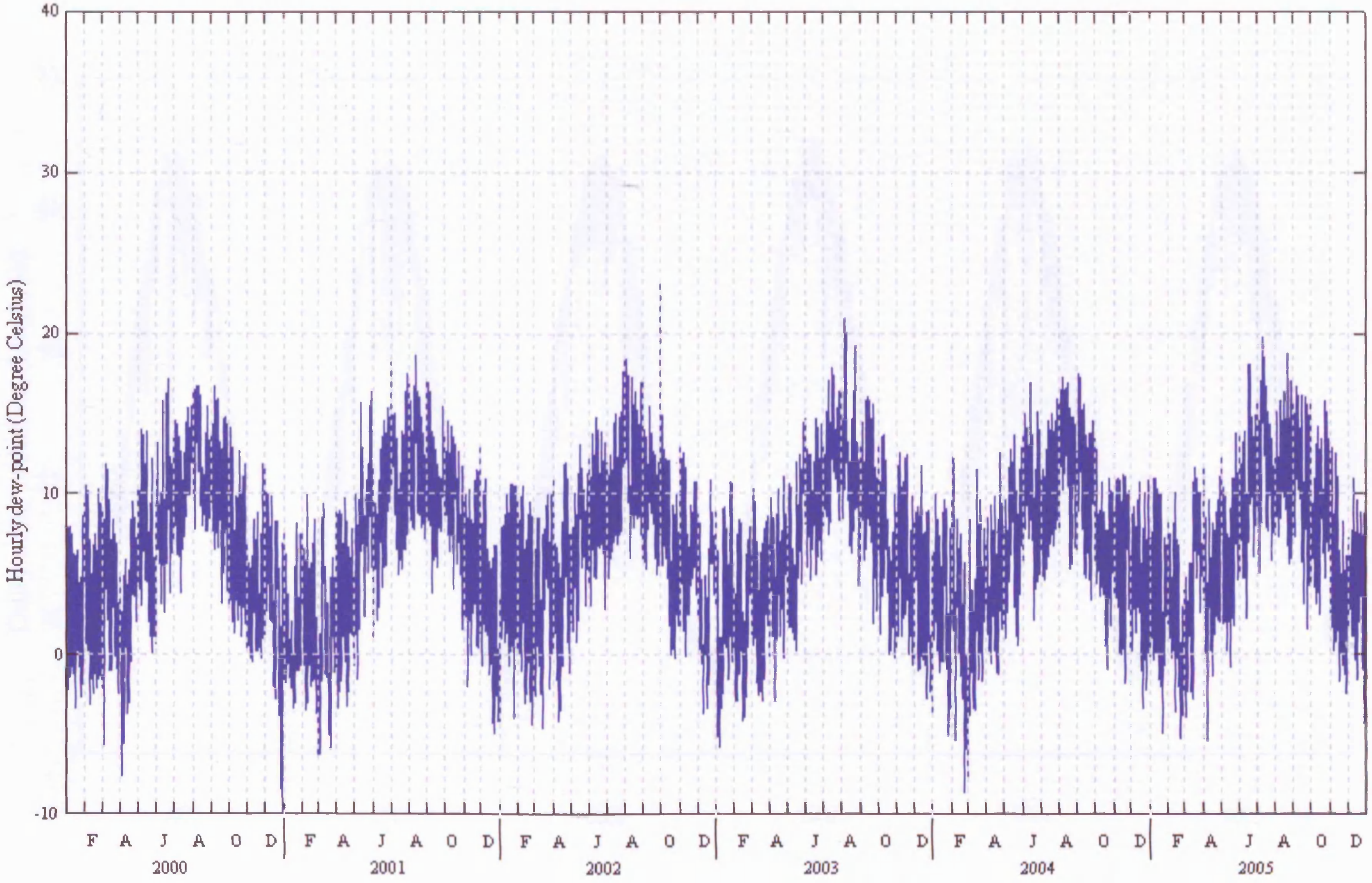


Fig. App.A.18. Hourly dew-point of Glenanne_saws weather station in the Upper Bann Catchment (from 2000-2005)

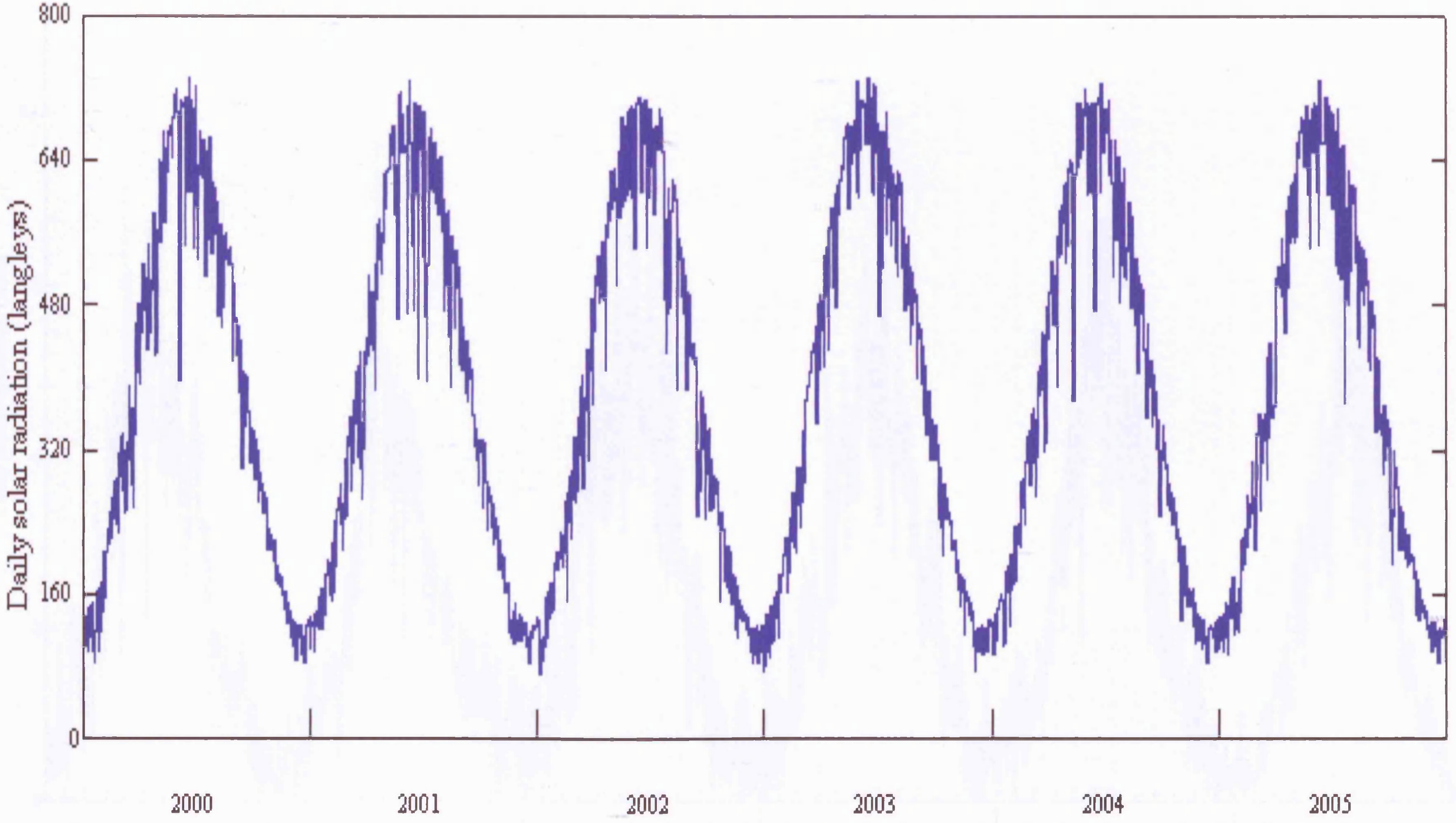


Fig. App.A.19. Daily solar radiation at Glenanne_saws weather station in the Upper Bann Catchment (from 2000-2005)

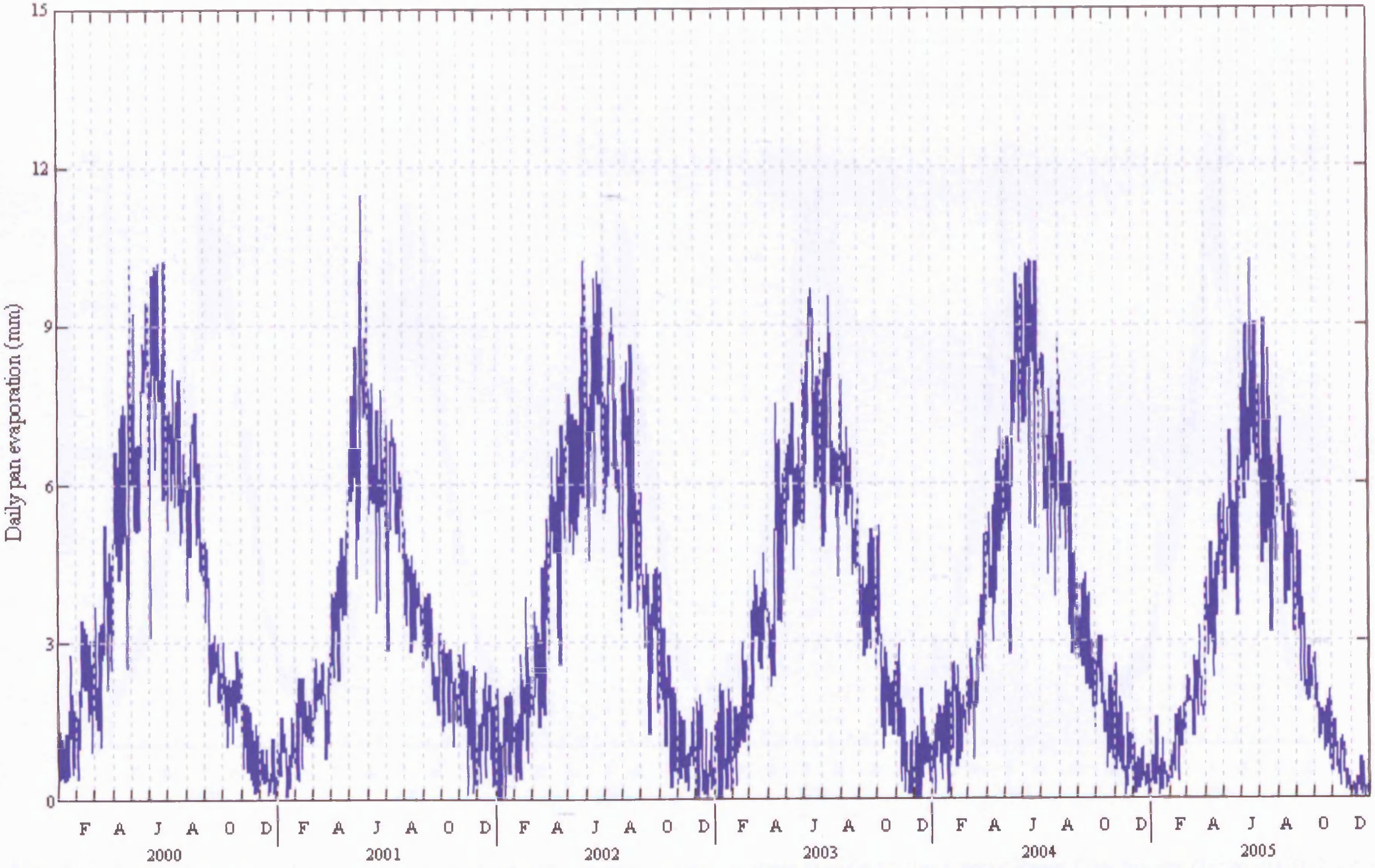


Fig. App.A.20. Daily pan evaporation at Glenanne_saws weather station in the Upper Bann Catchment (from 2000-2005)

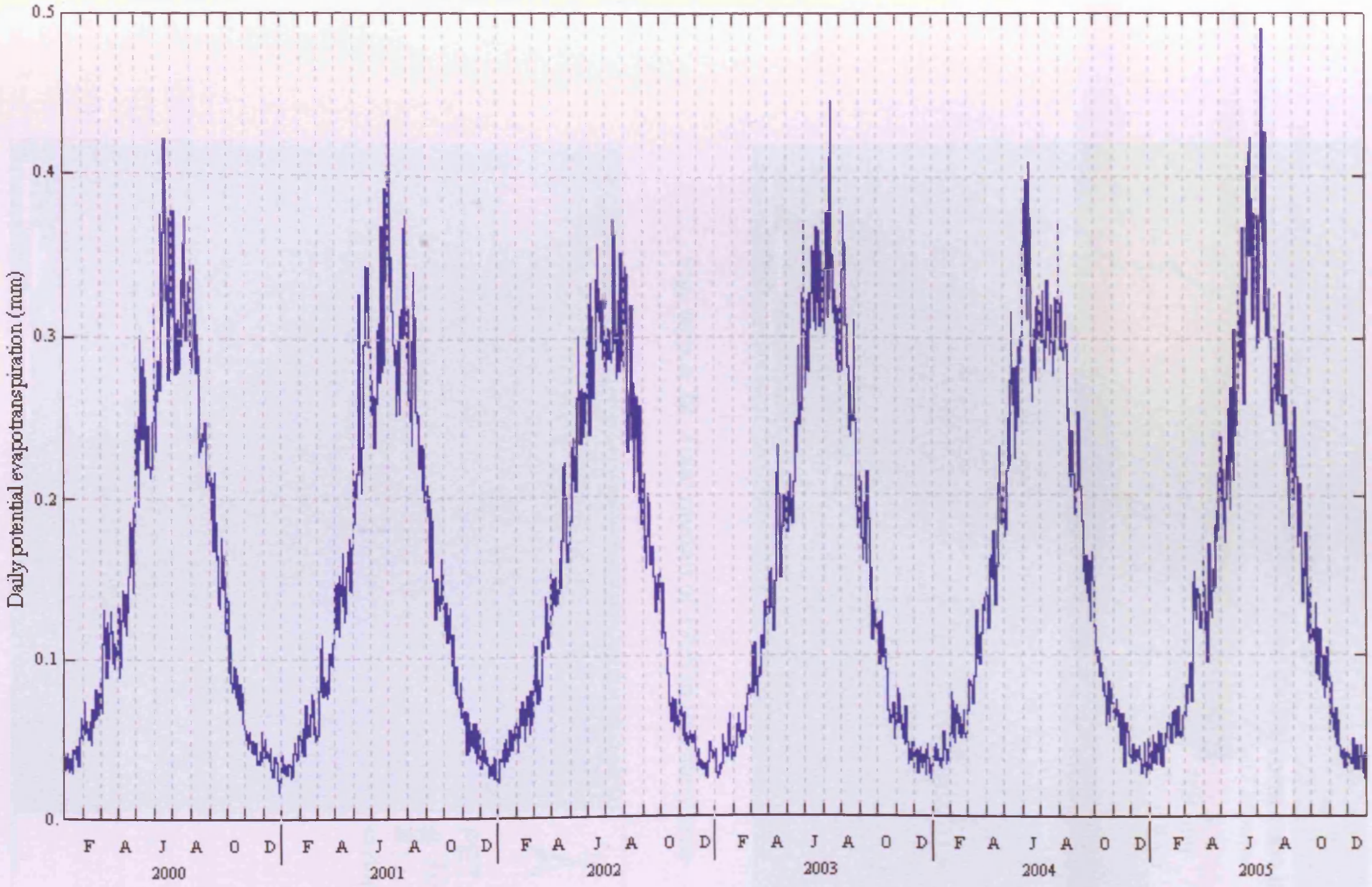


Fig. App.A.21. Daily potential evapotranspiration at Glenanne_saws weather station in the Upper Bann Catchment (from 2000-2005)

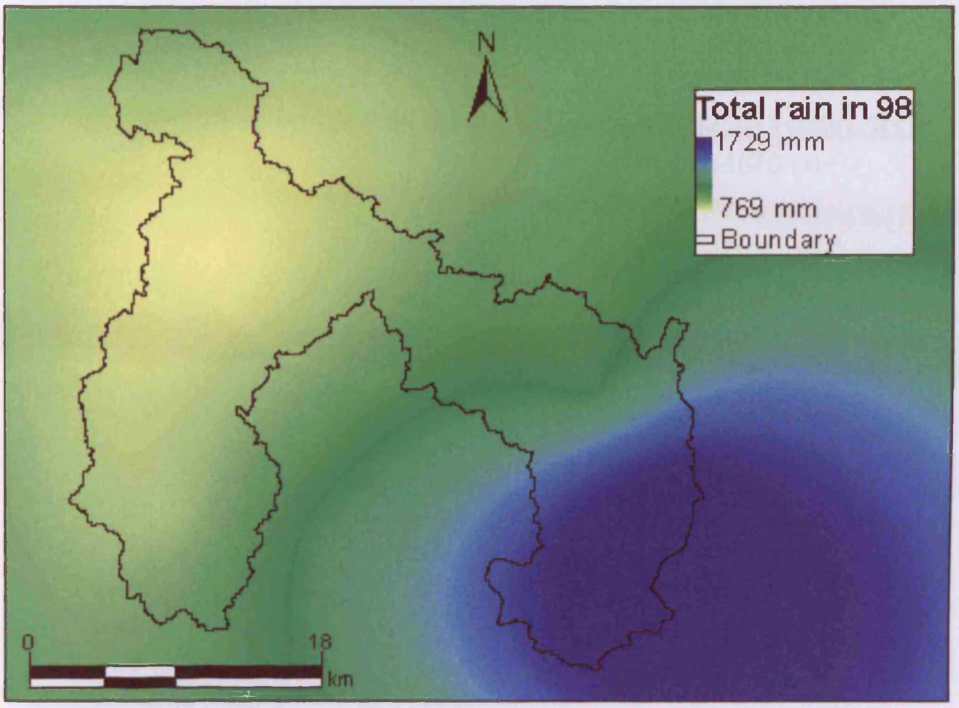


Fig. App.A.22. Total rainfall of 1998 in the study area

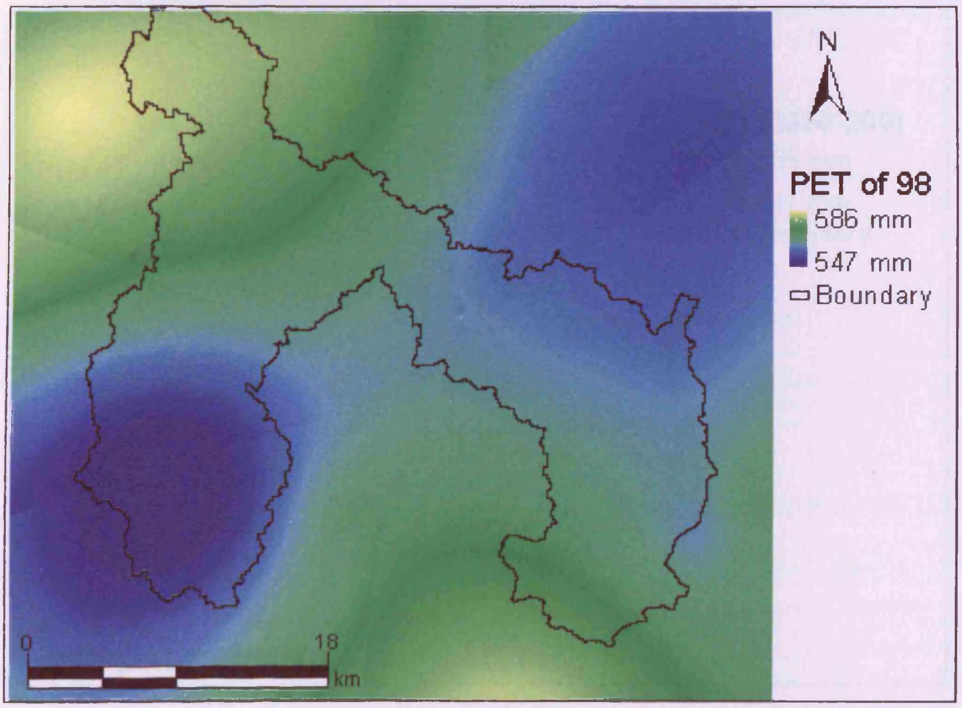


Fig. App.A.23. Potential evapotranspiration of 1998 in the study area

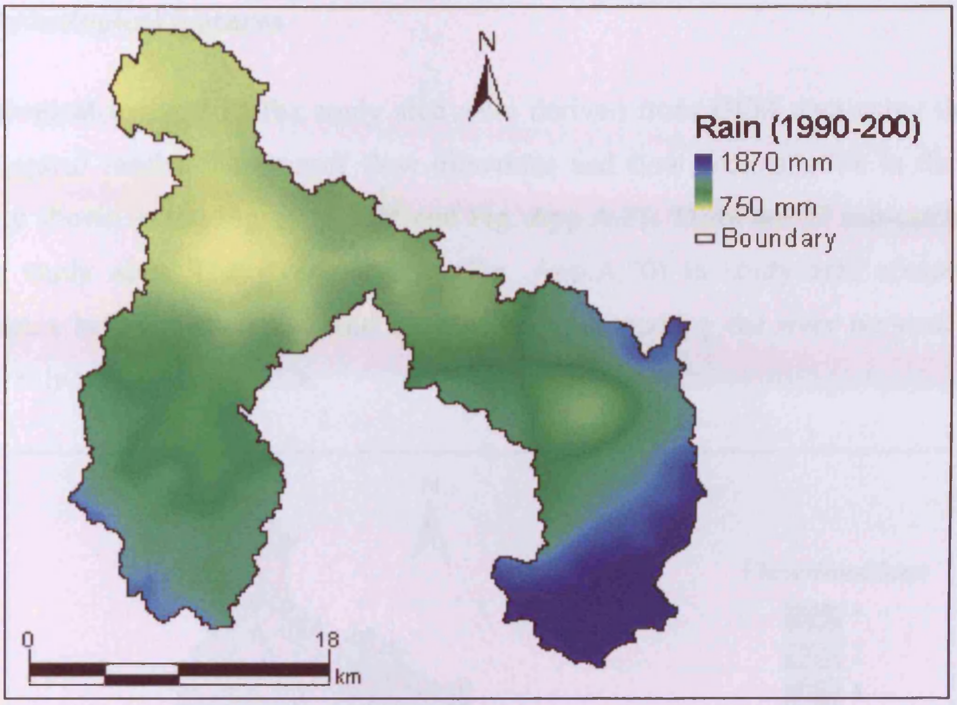


Fig. App.A.24. The average rainfall between 1990 and 2000 in the study area

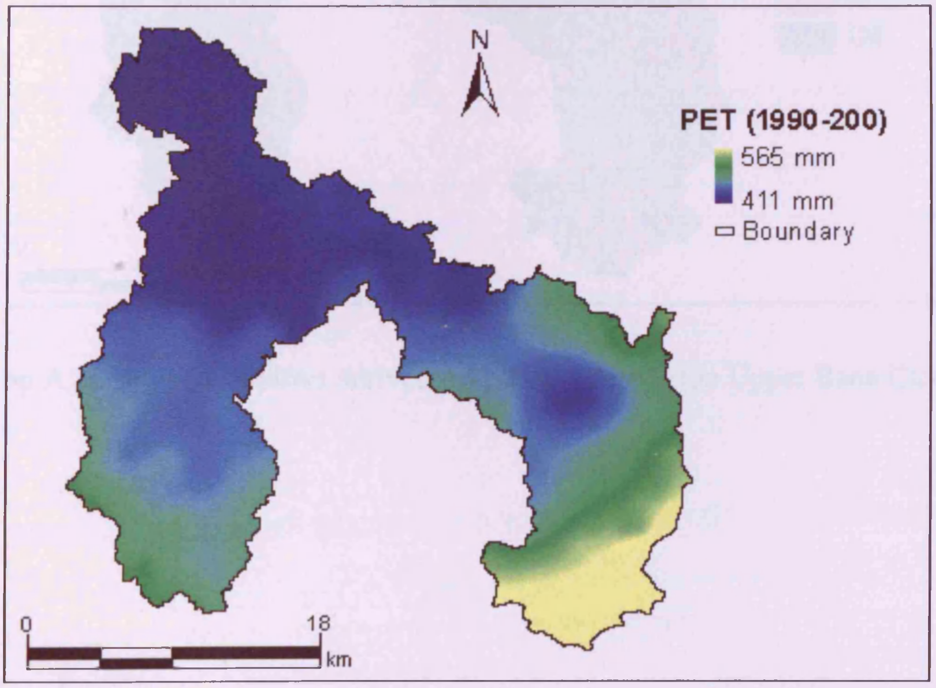


Fig. App.A.25. The average potential evapotranspiration between 1990 and 2000 in the study area

4.9. Hydrological features

Hydrological features of the study area were derived from DEM data using the GIS hydrological model. The runoff flow directions and flow accumulation in the study area are shown in the Fig. App.A.26 and Fig. App.A.27. There are 57 sub-catchments in the study area. The river network (Fig. App.A.30) in study area contains the topologies between river link and river nodes, thus making the river network based river tracing analysis possible.

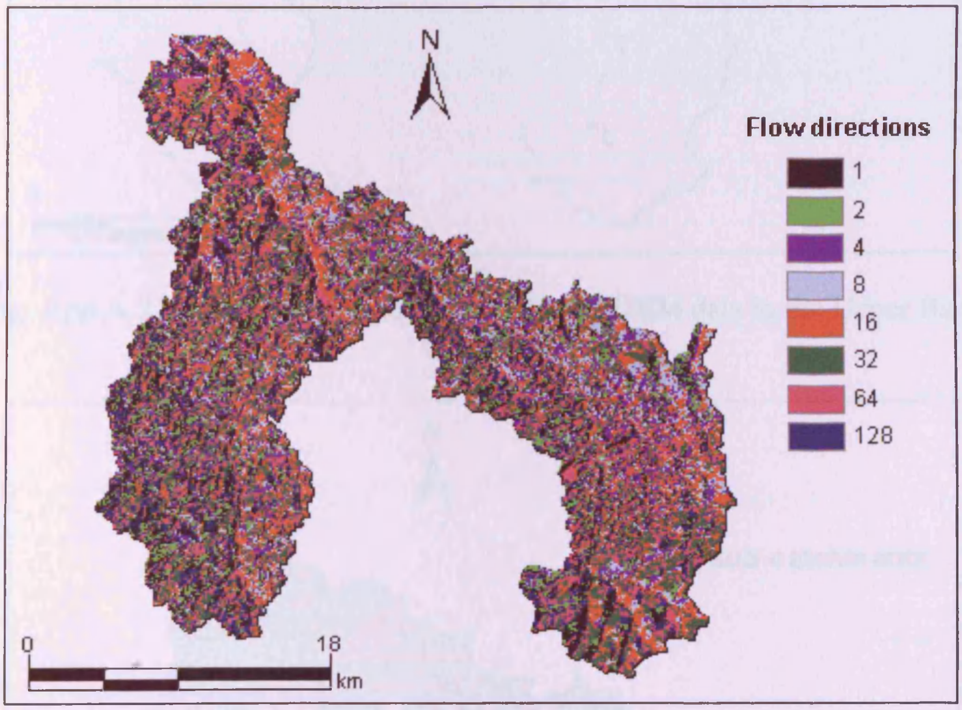


Fig. App.A.26. Flow directions derived from DEM data in the Upper Bann Catchment

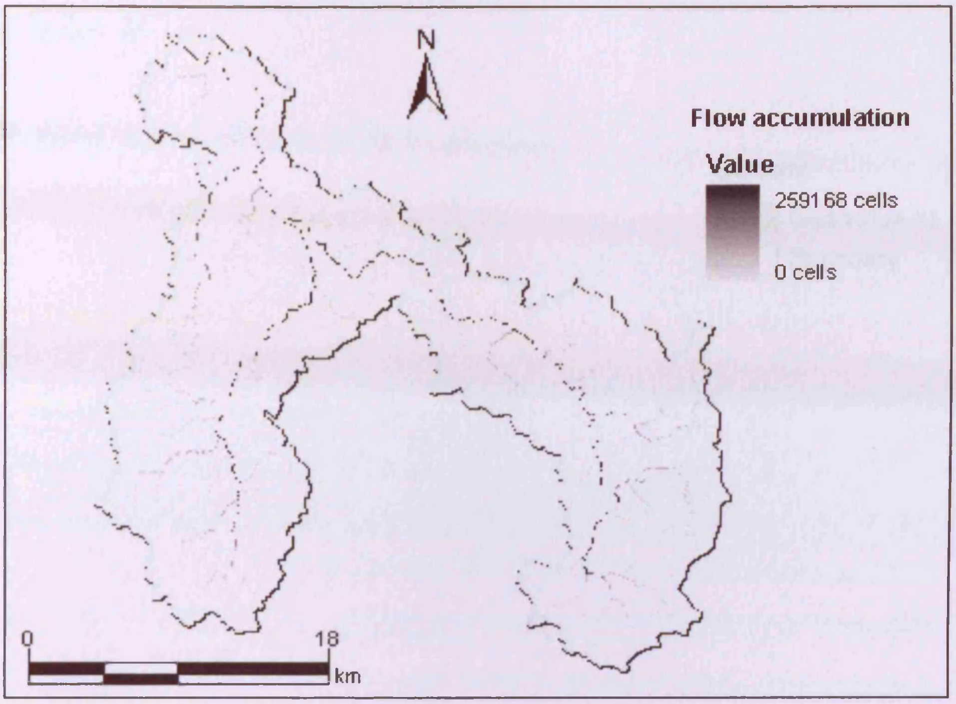


Fig. App.A.27. Flow accumulation derived from DEM data in the Upper Bann Catchment

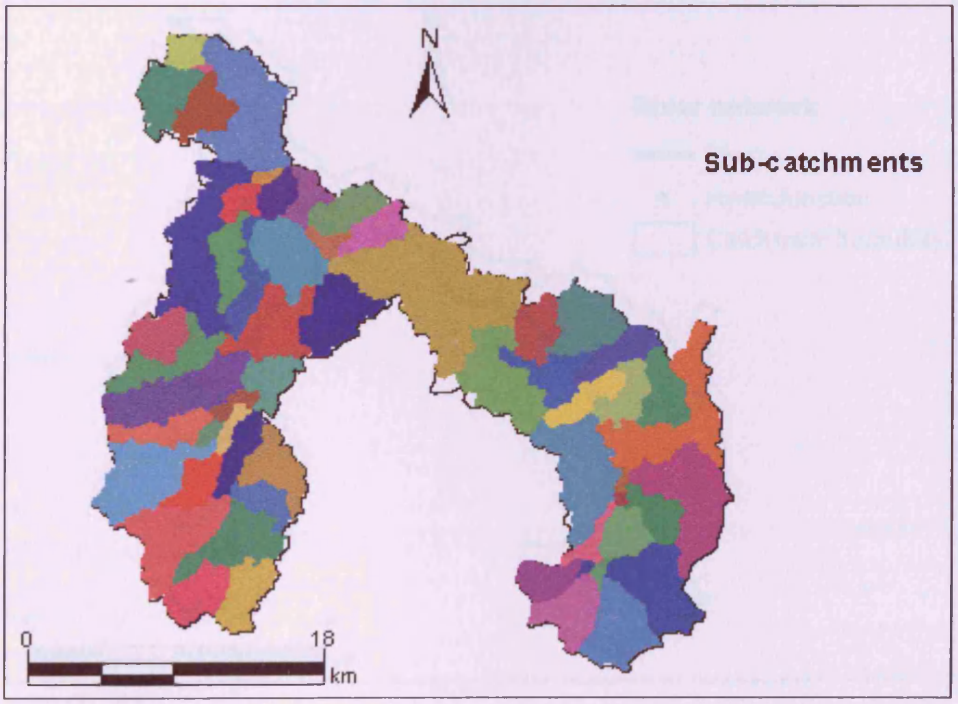


Fig. App.A.28. Sub-catchments derived from DEM data in the Upper Bann Catchment

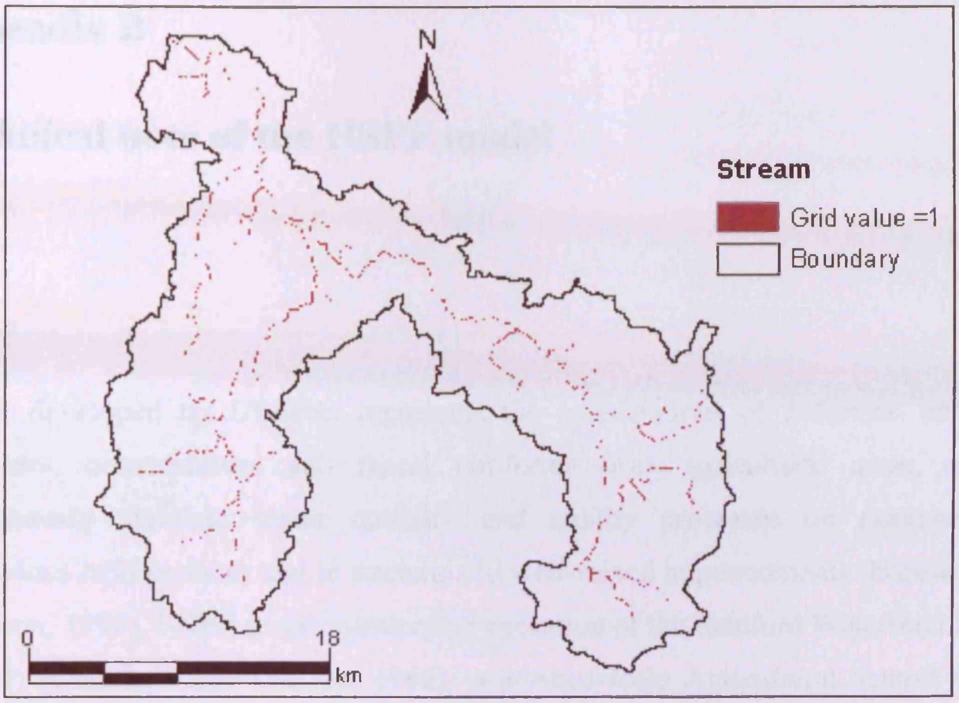


Fig. App.A.29. Stream derived from DEM data in the Upper Bann Catchment

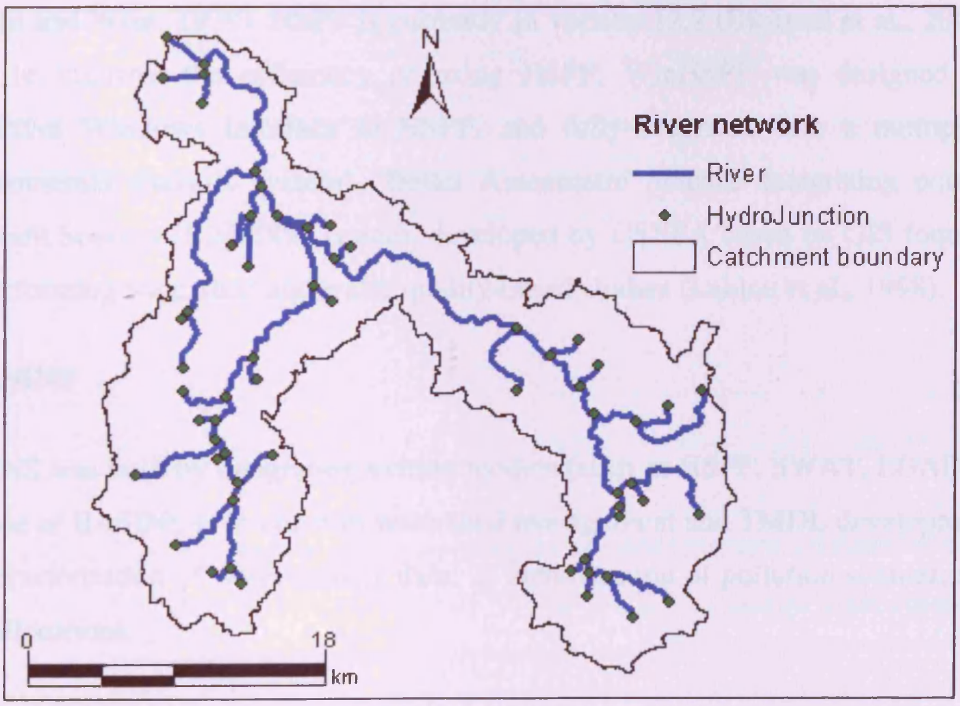


Fig. App.A.30. River network derived from DEM data in the Upper Bann Catchment

Appendix B

Technical note of the HSPF model

HSPF, developed by USEPA, represents the contributions of sediment, nutrients, pesticides, conservatives and faecal coliforms from agricultural areas, and to continuously simulate water quantity and quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments (Barnwell and Johanson, 1981). HSPF is the culminating evolution of the Stanford Watershed Model (SWM) (Crawford and Linsley, 1966), watershed-scale Agricultural Runoff Model (ARM) (Donigian et al., 1977), Nonpoint (diffuse) Source Loading Model (NPS) (Donigian & Crawford, 1976) and Sediment and Radionuclides Transport (SERATRA) (Onishi and Wise, 1979). HSPF is currently in version 12.2 (Bicknell et al., 2005). In order to improve the efficiency of using HSPF, WinHSPF was designed as an interactive Windows interface to HSPF, and fully-integrated into a multipurpose environmental analysis system - Better Assessment Science Integrating point and Nonpoint Sources (BASINS) system, developed by USEPA based on GIS foundation for performing watershed and water quality-based studies (Lahlou et al., 1998).

1. BASINS

BASINS was built by integrating exiting models (such as HSPF, SWAT, LOAD). The purpose of BASINS is to assist in watershed management and TMDL development by: 1) characterisation of water quality data; 2) identification of pollution sources; and 3) load allocations.

1.1. BASINS system overview

Fig. App.B.1 shows BASINS system overview (from AQUA TERRA Consultants).

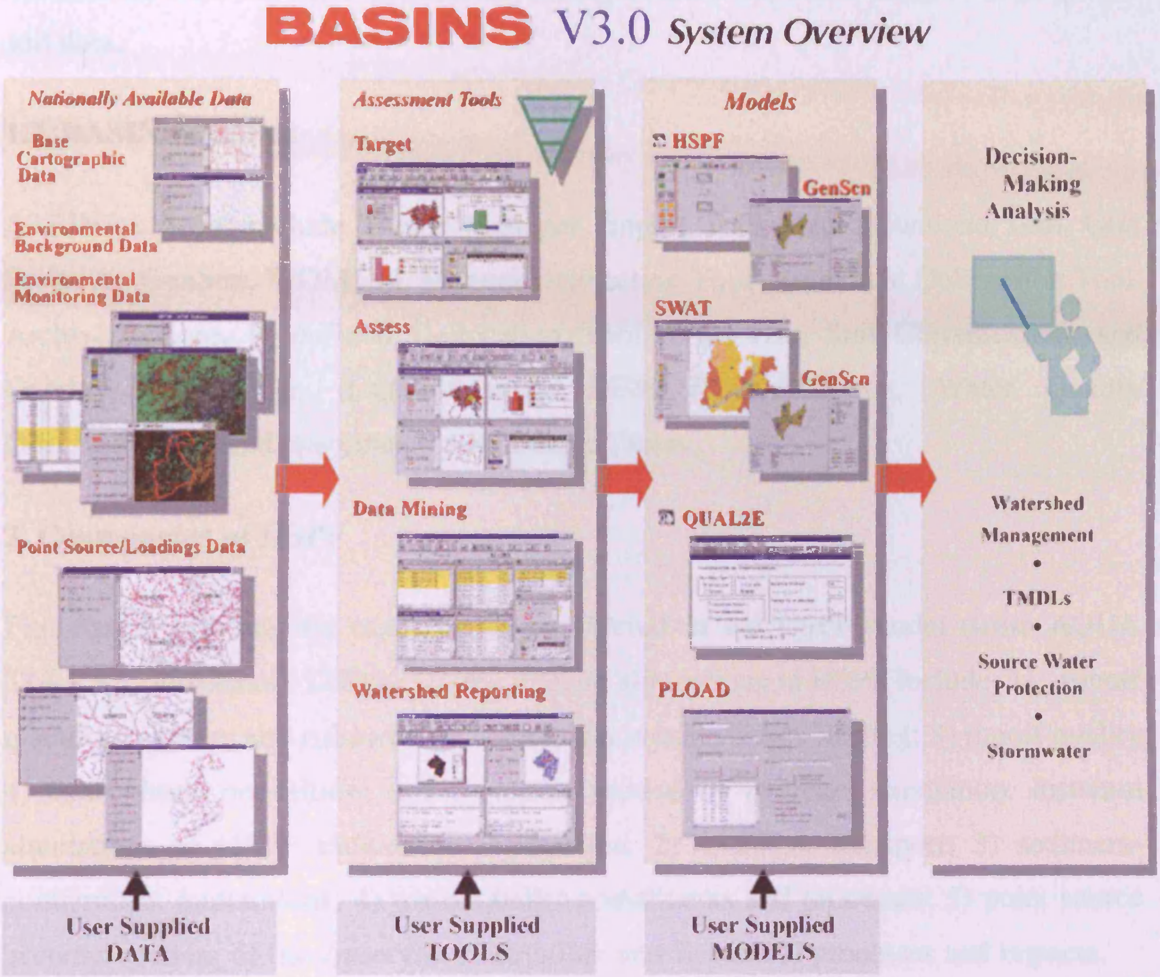


Fig. App.B.1. The system overview of BASINS

For assessment tools in BASINS, "Target" provides broad-based evaluation of watershed water quality and point source loadings. "Assess" is for watershed-based evaluation of specific water quality stations and/or discharges and their proximity to water bodies. "Data mining" provides dynamic link of data elements using a combination of tables and maps. "Watershed reporting" automates report generation with user-defined selection options.

BASINS spatially distributed data include land use and land cover (shape and grid), urbanised areas, reach file, US national Hydrography Data (NHD), major roads, USGS hydrologic unit boundaries (accounting and catalog units), EPA region boundaries, administrative boundaries, county boundaries, DEM (shape and grid), and soil data.

1.2. BASINS utilities

BASINS utilities include Theme Manager, Import Tool, Data Download Tool, Grid Projector, GenScn, WDMUtil, Manual Delineation Tool, Automatic Delineation Tool, Archive/Restore, Predefined Delineation Tool, Land Use, Soil Classification, and Overlay, Land Use Reclassification, DEM Reclassification, Water Quality Observation Data Management, and Lookup Tables.

2. Components of HSPF

Fig. App.B.2 shows the components considered in the HSPF model (from AQUA TERRA Consultants). Diffuse source loading simulations in HSPF include: 1) runoff quantity - surface and subsurface; 2) sediment erosion/solids loading; 3) runoff quality; 4) atmospheric deposition; and 5) inputs needed by instream simulation. Instream simulations of HSPF include: 1) hydraulics; 2) sediment transport; 3) sediment-contaminant interactions; 4) water quality constituents and processes; 5) point source accommodation; 6) lake/reservoir simulation; and 7) benthal processes and impacts.

3. The structure of HSPF modules

HSPF has four application modules, i.e., PERLND for pervious land segments, IMPLND for impervious land segments, RCHRES for river reaches and well-mixed reservoirs, and BMP for simulating constituent removal efficiencies associated with implementing management practices. Fig. App.B.3 (adapted from AQUA TERRA Consultants), Fig. App.B.4 (adapted from AQUA TERRA Consultants), and Fig. App.B.5 (adapted from AQUA TERRA Consultants) show the structure of PERLND, IMPLND and RCHRES respectively.

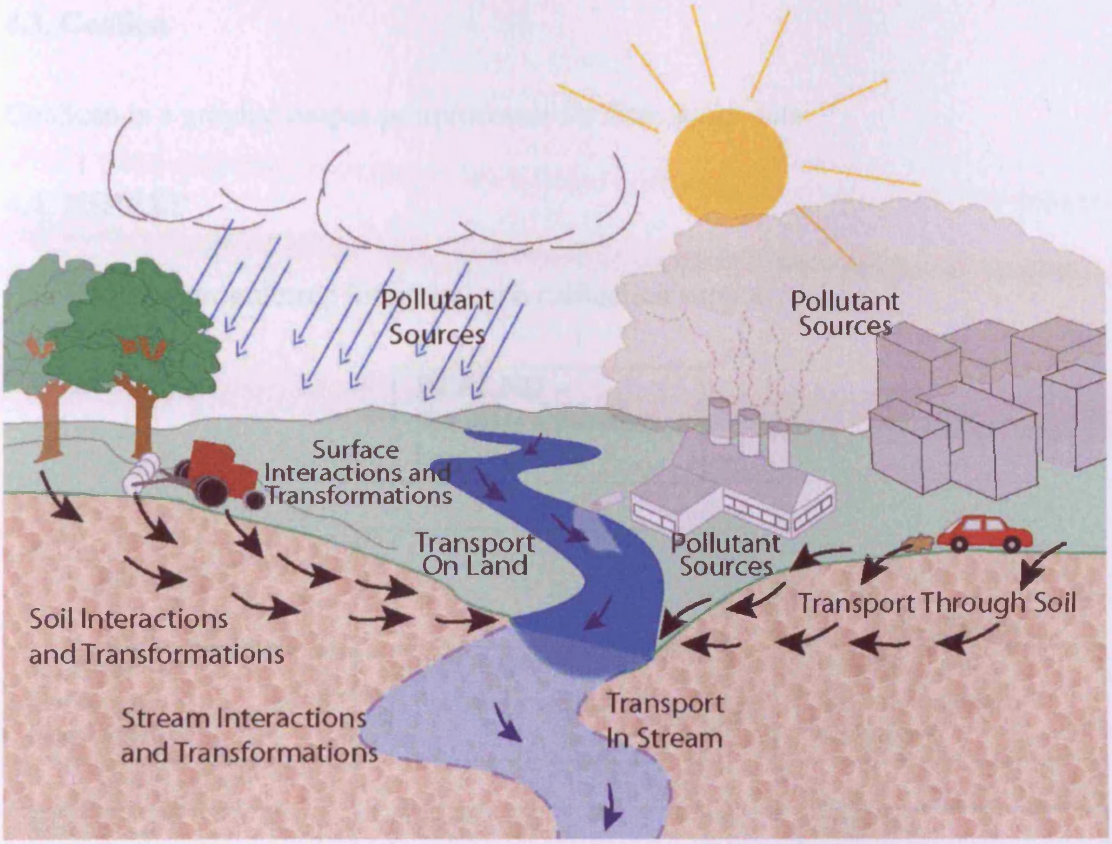


Fig. App.B.2. The components considered in the HSPF model

4. HSPF supporting programs

4.1. WinHSPF

WinHSPF is the interactive Windows interface to HSPF. All HSPF features can be accessed through the WinHSPF. WinHSPF also provides the functions for scenario development.

4.2. WDMUtil

WDMUtil was built for the management of the watershed data management (WDM) time series file and meteorological data for BASINS. WDMUtil also provides graphical and tabular display for time series data.

4.3. GenScn

GenScen is a graphic output postprocessor for time series data.

4.4. HSPEXP

HSPEXP is a programme for hydrologic calibration support.

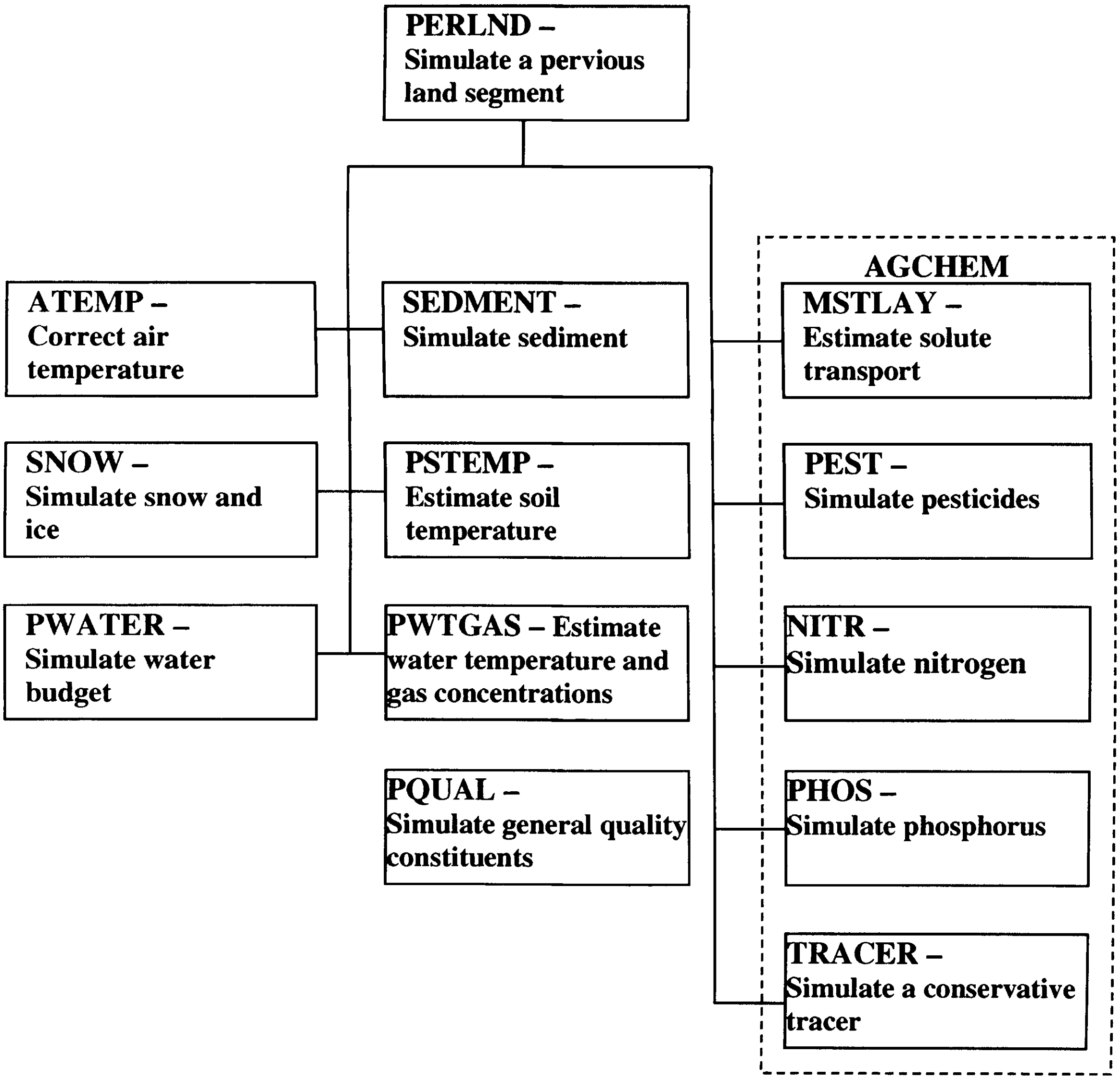


Fig. App.B.3. The structure chart of PERLND in HSPF

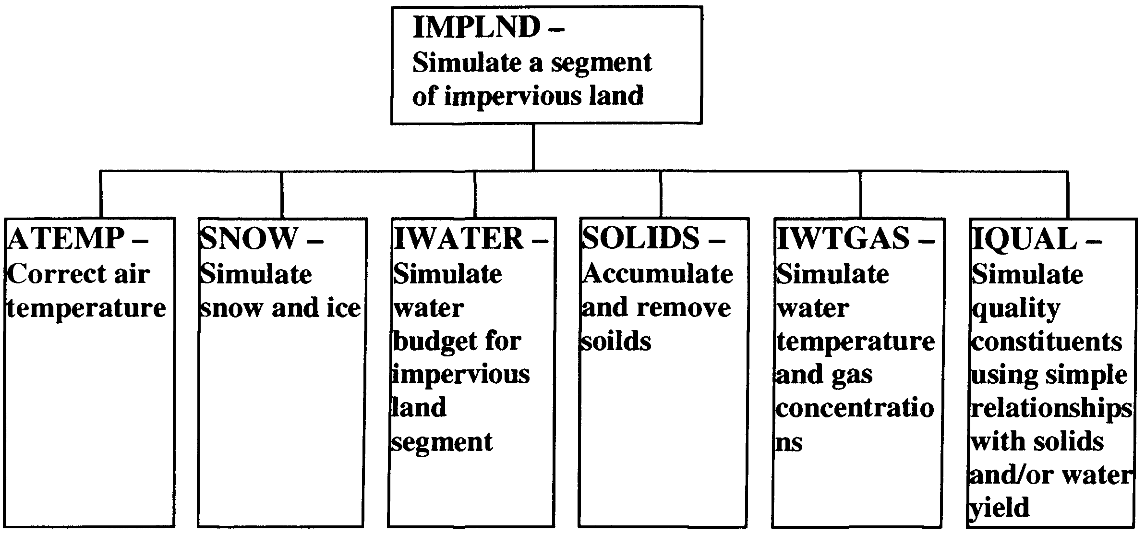


Fig. App.B.4. The structure chart of IMPLND in HSPF

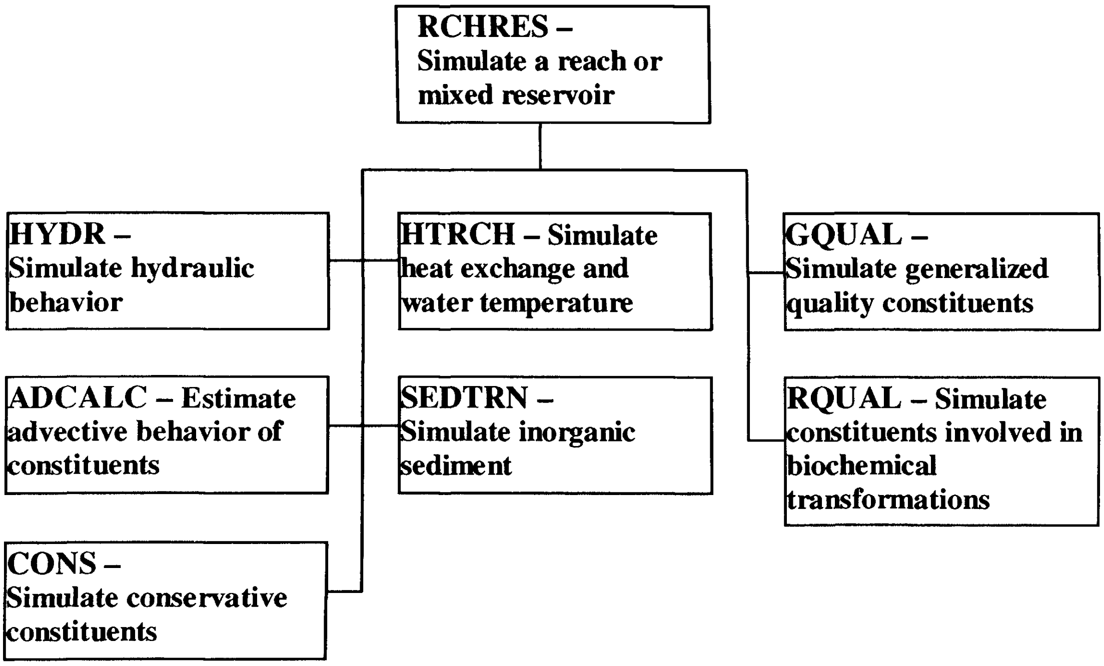


Fig. App.B.5. The structure chart of RCHRES in HSPF

5. Meteorological data in BASINS-HSPF

5.1. HSPF weather data requirements

Fig. App.B.6 shows HSPF weather data requirements (from AQUA TERRA Consultants).

	PERLND/IMPLND						RCHRES				
	Temp	Snow**	Water	Sediment	Soil Temp	Ag. Chem.*	Water	Heat	Gen. Qual.	DO	Plankton
Precipitation	●	●	●	●		● [1]	▲	▲			
Pot. ET			●	● [1]		● [1]	▲				
Air Temperature	●	●			●	● [2]		●			
Wind Speed		●						●	● [3]	● [5]	
Solar Radiation		●						●			●
Dewpoint Temp.		●						●			
Cloud Cover								●	●		

● Required

▲ Optional

[1] For PWATER

[2] For PSTEMP

[3] If volatilization from lake is simulated

[4] If photolysis is simulated

[5] If RCHRES is a lake

Fig. App.B.6. HSPF weather data requirements

5.2. Processing of meteorological data in BASINS-HSPF

Fig. App.B.7 shows the processing of meteorological data in BASINS-HSPF.

6. HSPF hydrologic modules

6.1. HSPF hydrologic components

HSPF hydrologic components include rainfall or snow, interception, depression storage, evapotranspiration, infiltration, surface storage, runoff, interflow, and groundwater flow (Fig. App.B.8).

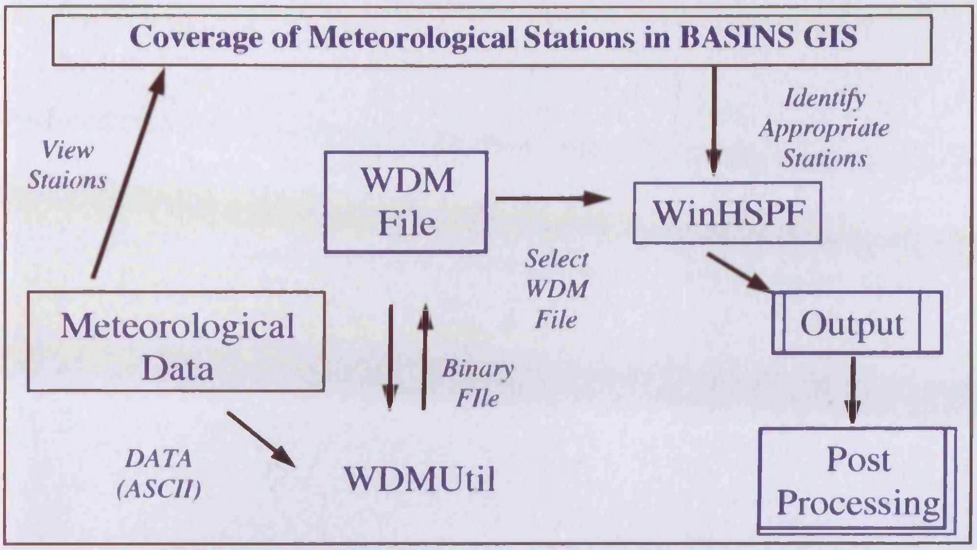


Fig. App.B.7. Processing of meteorological data in BASINS-HSPF

6.2. Water budget PWATER in pervious land

PWATER was designed to calculate the components of the water budget, and to predict the total runoff from a pervious area. PWATER, key component of module PERLND, is the basis of other major sections of PERLND (eg. SEDMNT).

The algorithms used to simulate these land related processes are the product of over 15 years of research and testing. These algorithms are based on the original research for the LANDS subprogram of the Stanford Watershed Model IV (Crawford and Linsley, 1966). LANDS has been incorporated into many models and used to successfully simulate the hydrologic responses of widely varying watersheds. The equations used in module section PWATER are nearly identical to the ones in the current version of LANDS in the PTR Model (Crawford and Donigian, 1973), HSP (Hydrocomp, 1976), and the ARM and NPS Models (Donigian and Crawford, 1976). However, some changes have been made to LANDS to make the algorithms internally more amenable to a range of calculation time steps. In addition, many of the parameter names have been changed to make them more descriptive, and some can be input on a monthly basis to allow for seasonal variation.

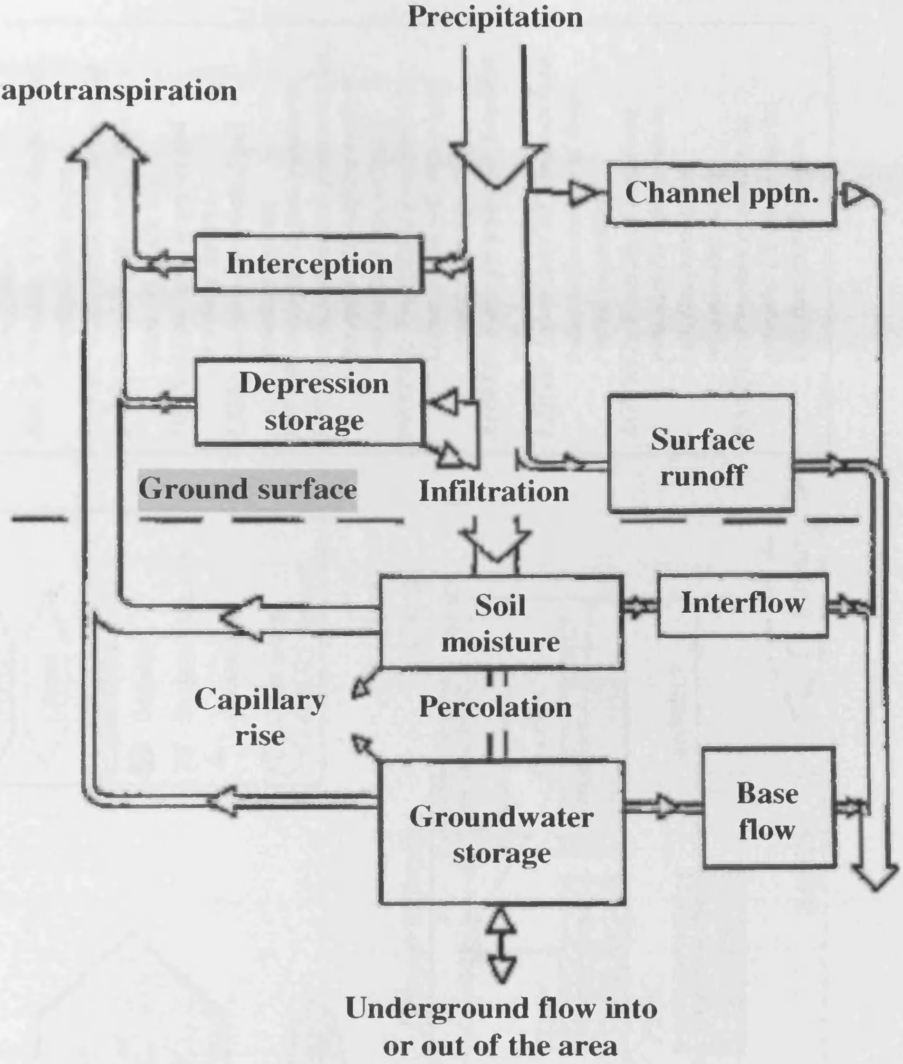
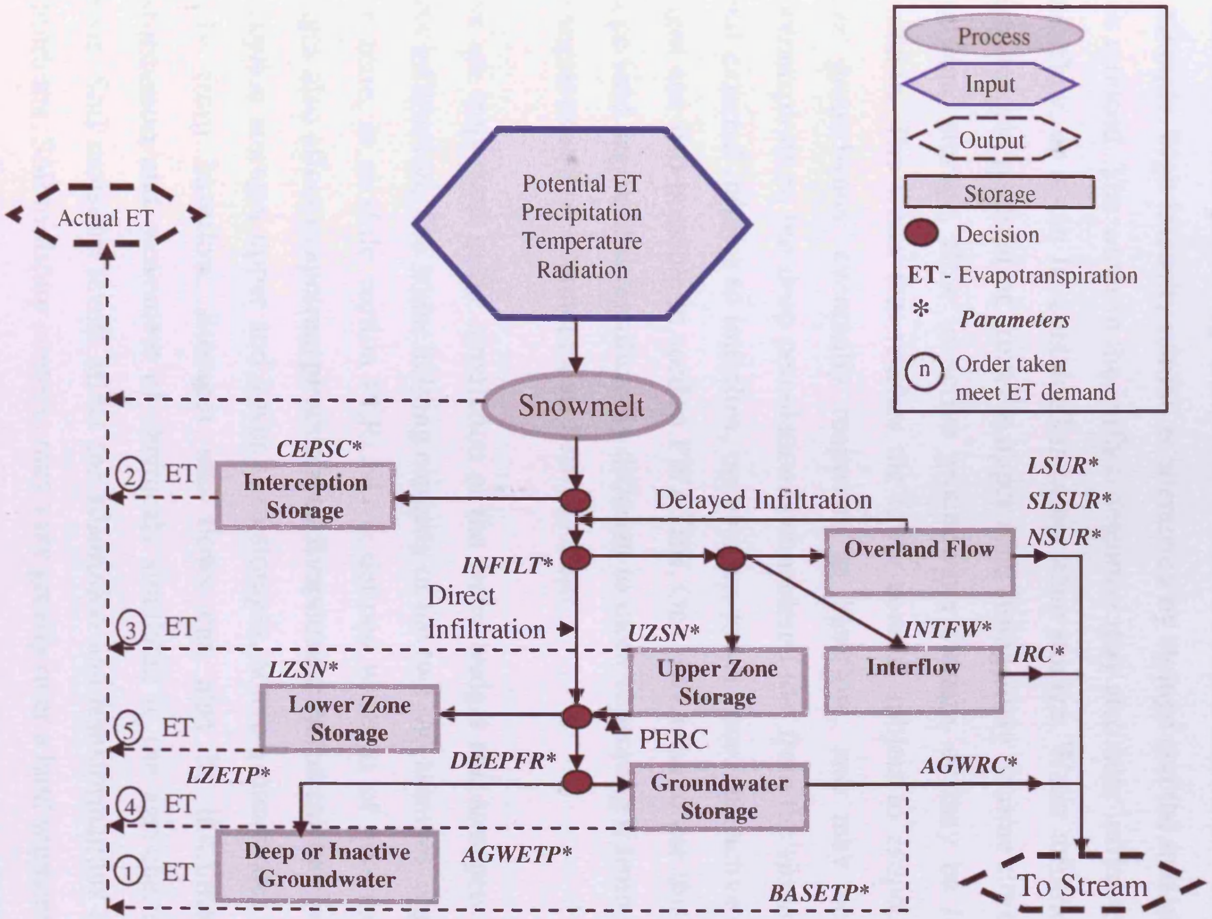


Fig. App.B.8. HSPF hydrologic components

6.2.1. Stanford watershed model

Fig. App.B.9 shows the fluxes and storages simulated in Stanford watershed model. The interception storage is water retained by any storage above the overland flow plane. For pervious areas, interception storage is mostly on vegetation. Any overflow from interception storage is added to the optionally supplied time series of surface external lateral inflow to produce the total inflow into the surface detention storage. Inflow to the surface detention storage is added to existing storage to make up the



LSUR: Length of the assumed overland flow plane
SLSUR: Slope of the assumed overland flow plane
NSUR: Manning's N for the assumed overland flow plane
CEPSC: Interception storage capacity
INFILT: Index to the infiltration capacity of the soil
UZSN: Upper zone nominal soil moisture storage
LZSN: Lower zone nominal soil moisture storage
INTFW: Interflow inflow parameter
IRC: Interflow recession parameter, i.e., the ratio of interflow outflow rate today / rate yesterday
DEEPFR: Fraction of groundwater inflow which will enter deep (inactive) groundwater
AGWRC: Basic groundwater recession rate
LZETP: Lower zone ET parameter; an index to the density of deep-rooted vegetation
AGWETP: Fraction of remaining potential ET which can be satisfied from active groundwater storage
BASETP: Fraction of remaining potential ET which can be satisfied from baseflow

Fig. App.B.9. The fluxes and storages in Stanford watershed model water available for infiltration and runoff. Moisture that directly infiltrates moves to the lower zone and groundwater storages. Other water may go to the upper zone storage, may be routed as runoff from surface detention or interflow storage, or may stay on the overland flow plane, from which it runs off or infiltrates at a later time. The processes of infiltration and overland flow interact and occur simultaneously in nature. Surface conditions such as heavy turf on mild slopes restrict the velocity of overland flow and reduce the total quantity of runoff by allowing more time for infiltration. Increased soil moisture due to prolonged infiltration will in time reduce the infiltration rate producing more overland flow. Surface detention will modify flow. For example, high intensity rainfall is attenuated by storage and the maximum outflow rate is reduced. The water in the surface detention may also later infiltrate reoccurring as interflow, or it can be contained in upper zone storage. Water infiltrating through the surface and percolating from the upper zone storage may become stored within the lower zone storage, flow to active groundwater storage, or may be lost by deep percolation. The water that reaches the lower zone is subject to evapotranspiration. Active groundwater eventually reappears as baseflow, and may be subject to evapotranspiration, but deep percolation is considered lost from the simulated system. Lateral external inflows to interflow, upper zone, lower zone, and active groundwater storages are also possible in section PWATER. One may wish to use this option if an upslope land segment is significantly different to merit separating it from a downslope land segment and no channel exists between them.

Flows are important in the simulation of the water budget and storages. Soil storage affects infiltration. The water holding capacity of the two soil storages, upper zone and lower zone, in module section PERLND is defined in terms of nominal capacities. Storages also affect evapotranspiration loss. Evapotranspiration can be simulated from interception storage, upper and lower zone storages, active groundwater storage, and directly from baseflow. Storages and flows can also be instrumental in the transformation and movement of chemicals simulated in the agri-chemical module sections. Soil moisture levels affect the adsorption and transformations of pesticides and nutrients. Soil moisture contents may vary greatly over a land segment. Therefore, a more detailed representation of the moisture contents and fluxes may be needed to simulate the transport and reaction of agricultural chemicals.

6.2.2. Water balance

Eq. App.B.1 shows water balance:

$$R = P - ET - IG - S \qquad \text{(App.B.1)}$$

where R is runoff; P is precipitation; ET is evapotranspiration; IG is deep or inactive groundwater; S is the change in soil storage.

6.2.3. PWATER structure

Fig. App.B.10 shows the structure of PWATER.

6.3. Methods used in the PWATER module

6.3.1. ICEPT – interception

The purpose of ICEPT is to simulate the interception of moisture by vegetal or other ground cover. Moisture is supplied by precipitation, or under snow conditions, it is supplied by the rain not falling on the snowpack plus the water yielded by the snowpack. In addition, irrigation water that is applied to the crop canopy is subject to interception.

Users of HSPF may supply the interception capacity on a monthly basis to account for seasonal variations, or may supply one value designating a fixed capacity. The interception capacity parameter can be used to designate any retention of moisture which does not infiltrate or reach the overland flow plane. Typically, for pervious areas this capacity represents storage on grass blades, leaves, branches, trunks, and stems of vegetation.

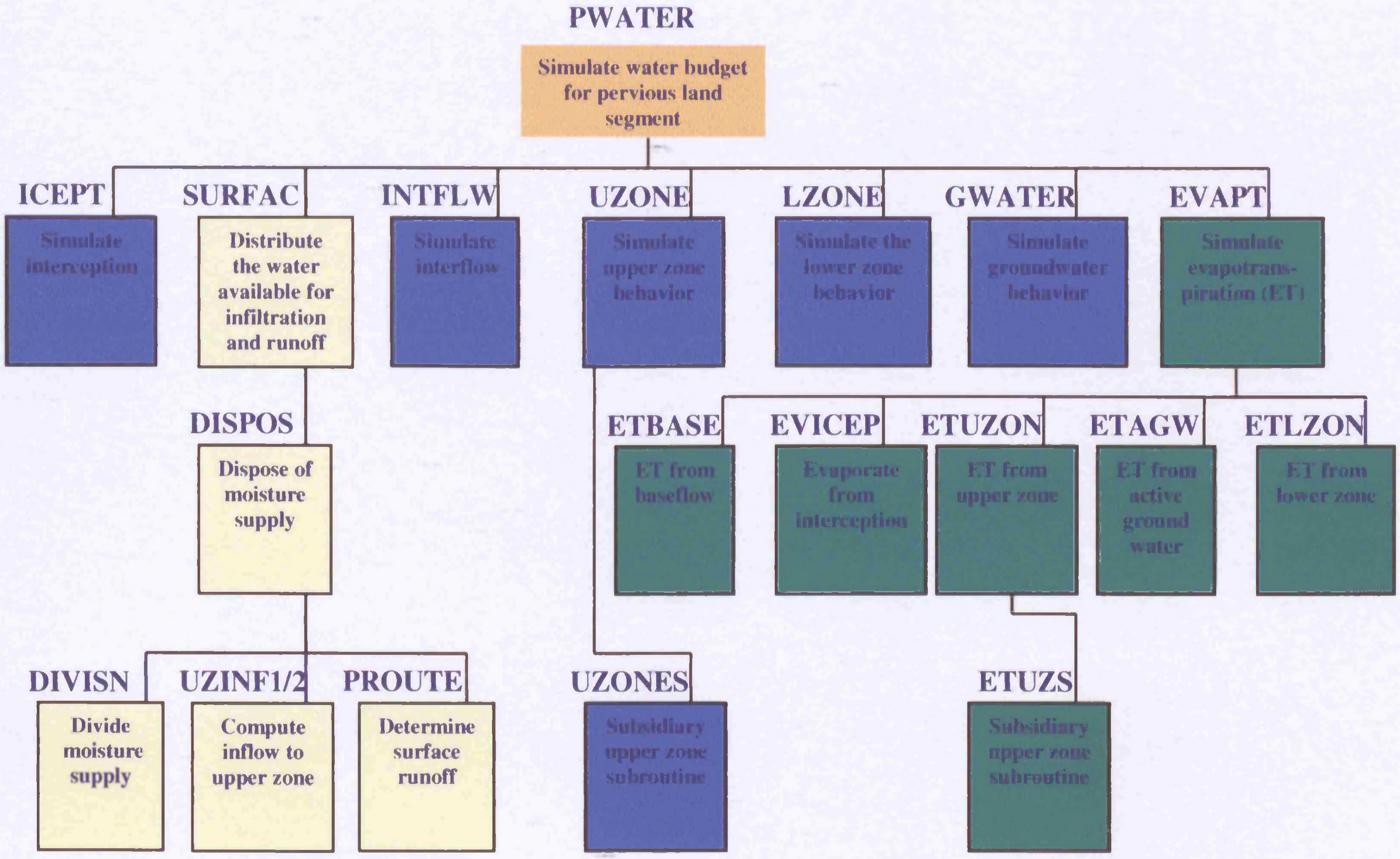


Fig. App.B.10. The structure of PWATER

Moisture exceeding the interception capacity overflows the storage and is ready for either infiltration or runoff as determined by subroutine group SURFAC. Water held in interception storage is removed by evaporation; the amount is determined in subroutine EVICEP.

6.3.2. SURFAC – water available for infiltration and runoff

SURFAC calculates the moisture on the surface of the land. The moisture may infiltrate, go to the upper zone storage or interflow storage, remain in surface detention storage, or run off.

The algorithms of infiltration simulating represent both the continuous variation of infiltration rate with time as a function of soil moisture and the areal variation of infiltration over the land segment. The equations representing the dependence of infiltration on soil moisture are based on the work of Philips (1957).

The infiltration capacity, the maximum rate at which soil will accept infiltration, is a function of both the fixed and variable characteristics of the watershed. Fixed characteristics include primarily soil permeability and land slopes. Variable characteristics are soil surface conditions and soil moisture content. Fixed and variable characteristics vary spatially over the land segment. Fig. App.B.11 shows the infiltration, interflow, and surface runoff distribution function of the PWATER section. The infiltration distribution is focused around the two lines that divide the moisture available to the land surface (MSUPY) into what infiltrates and what goes to interflow. SURFAC calculates a number of the variables that are used to determine the location of lines I and II using equations below:

$$IBAR = \left(\frac{INFILT}{\left(\frac{LZS}{LZSN} \right)^{INFEXP}} \right) \times INFFAC \qquad \text{(App.B.2)}$$

$$IMAX = INFILD \times IBAR \qquad \text{(App.B.3)}$$

$$IMIN = IBAR - (IMAX - IBAR) \qquad \text{(App.B.4)}$$

$$RATIO = INTFW \times 2^{\frac{LZA}{LZSN}} \qquad \text{(App.B.5)}$$

where *IBAR* is mean infiltration capacity over the land segment; *INFILT* the infiltration parameter (in/interval); *LZS* is lower zone storage (inches); *LZSN* is parameter for lower zone nominal storage (inches); *INFEXP* is exponent parameter greater than one; *INFFAC* the factor to account for frozen ground effects, if applicable; *IMAX* is the maximum infiltration capacity (in/interval); *INFILD* is the parameter giving the ratio of maximum to mean infiltration capacity over the land segment; *IMIN* is the minimum infiltration capacity (in/interval); *RATIO* is the ratio of the ordinates of line II to line I; *INTFW* = interflow inflow parameter.

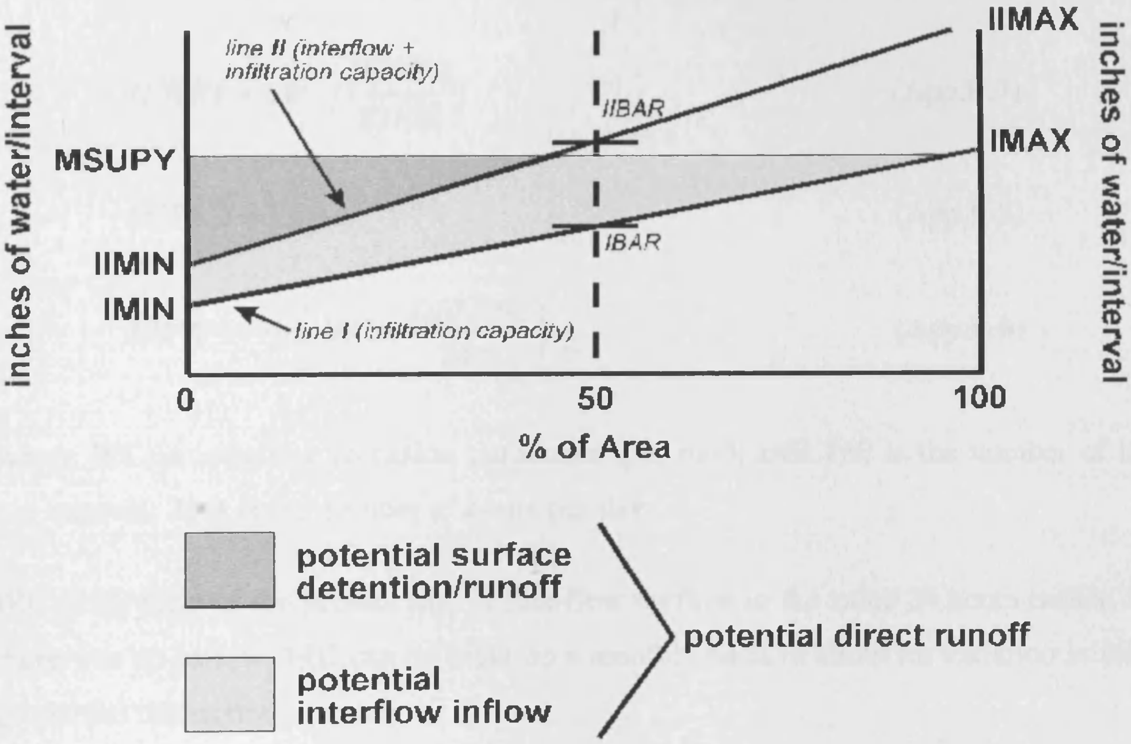


Fig. App.B.11. Determination of infiltration and interflow inflow (Bicknell et al., 2005)

6.3.3. INTFLW – interflow

INTFLW determines the amount of interflow and the update of storage. Interflow can have an important influence on storm hydrographs particularly when vertical percolation is retarded by a shallow, less permeable soil layer. The calculation method of interflow outflow assumes a linear relationship to storage. Outflow is a function of a recession parameter, inflow, and storage. Moisture that remains will occupy interflow storage. Below are equations for interflow discharge calculation:

$$IFWO = (IFWK1 \times INFLO) + (IFWK2 \times IFWS) \qquad \text{(App.B.6)}$$

where *IFWO* is the interflow outflow (in/interval); *INFLO* is inflow into interflow storage, including lateral inflow(in/interval); *IFWS* is interflow storage at the start of the interval (inches); *IFWK1* and *IFWK2* are variables determined by:

$$IFWK1 = 1.0 - (\frac{IFWK2}{KIFW}) \qquad \text{(App.B.7)}$$

$$IFWK2 = 1.0 - e^{(-KIFW)} \qquad \text{(App.B.8)}$$

$$KIFW = -\ln\left(IRC \times \frac{DELT60}{24.0}\right) \qquad \text{(App.B.9)}$$

where IRC is interflow recession parameter (per day); DELT60 is the number of hr per interval; 24.0 is the number of hours per day.

IRC is the ratio of the present rate of interflow outflow to the value 24 hours earlier, if there was no inflow. IRC can be input on a monthly basis to allow for variation in soil properties throughout the year.

6.3.4. UZONE – upper zone behaviour

UZONE and its subsidiary subroutine UZONES are used to calculate the water percolating from the upper zone. The evapotranspiration in sub-module ETUZON is from water in upper zone storage. Percolation from the upper zone storage is calculated by the empirical expression:

$$PERC = 0.1 \times INFILT \times INFFAC \times UZSN \times (UZRAT - LZRAT)^3 \quad \text{(App.B.10)}$$

where *PERC* is the percolation from the upper zone (in/interval); *INFILT* is the infiltration parameter (in/interval); *INFFAC* is the factor to account for frozen ground, if any; *UZSN* is the parameter for upper zone nominal storage (inches); *UZRAT* is the ratio of upper zone storage to *UZSN*; *LZRAT* is the ratio of lower zone storage to lower zone nominal storage.

Percolation only occurs when *UZRAT* minus *LZRAT* is greater than 0.01. The upper zone nominal capacity can be input on a monthly basis to allow for variations throughout the year. The monthly values are interpolated to obtain daily values.

6.3.5. LZONE – lower zone behaviour

LZONE determines the quantity of infiltrated and percolated water that enters the lower zone. The percolated moisture from the upper zone is found in subroutine UZONE. The fraction of the lower zone inflow (the sum of direct infiltration, percolation, lower zone lateral inflow, and irrigation application) that enters the lower zone storage (LZS) is determined by the lower zone storage ratio of LZS/LZSN where LZSN is the lower zone nominal capacity. The inflowing fraction is determined by the empirical expression:

$$LZFRAC = 1.0 - LZRAT \times \left(\frac{1.0}{1.0 + INDX} \right)^{INDX} \quad \text{(App.B.11)}$$

When LZRAT is less than 1.0, then by:

$$LZFRAC = \left(\frac{1.0}{1.0 + INDX}\right)^{INDX} \qquad \text{(App.B.12)}$$

When LZRAT is greater than 1.0. INDX is defined by:

$$INDX = 1.5 \times ABS(LZRAT - 1.0) + 1.0 \qquad \text{(App.B.13)}$$

where *LZFRAC* is the fraction of infiltration plus percolation plus lower zone lateral inflow that enters *LZS*; *LZRAT* = *LZS*/*LZSN*; *ABS* is the function for determining absolute value.

The groundwater storage is the fraction of the moisture supply remaining after the surface, upper zone, and lower zone components are subtracted.

6.3.6. GWATER – groundwater behaviour

LZONE determines the amount of the water lost to deep/inactive groundwater. The amount of active groundwater outflow can be calculated based on this. These two fluxes will in turn affect the active groundwater storage. The quantity of direct infiltration plus percolation from the upper zone will be inflow to the lower zone. The part that does not go to the lower zone (determined in LZONE) will enter either inactive or active groundwater. The distribution to active and inactive groundwater is user designated by parameter DEEPFR that determines the amount of water going to inactive groundwater. The remaining portion of the percolating water plus all lateral inflow and/or irrigation application make up the total inflow to the active groundwater storage. The outflow from active groundwater storage is based on a simplified model. It assumes that the discharge of an aquifer is proportional to the product of the cross sectional area and the energy gradient of the flow. Further, a representative cross sectional area of flow is assumed to be related to the groundwater storage level at the start of the interval. The energy gradient is estimated as a basic gradient plus a variable gradient that depends on past active groundwater accretion. The groundwater outflow is estimated by equation below:

$$AGWO = KGW \times (1.0 + KVARY \times GWVS) \times AGWS \qquad \text{(App.B.14)}$$

where $AGWO$ is the active groundwater outflow (in/interval); KGW is the groundwater outflow recession parameter (/interval); $KVARY$ is the parameter which can make active groundwater storage to outflow relation nonlinear (/inches). $KVARY$ is introduced to allow variable groundwater recession rates. When $KVARY$ is nonzero, a semi log plot of discharge versus time is nonlinear. This parameter adds flexibility in groundwater outflow simulation that is useful in simulating many watersheds. $GWVS$ is the index to groundwater slope (inches). $GWVS$ is increased each interval by the inflow to active groundwater but is also decreased by 3 percent once a day. It is a measure of antecedent active groundwater inflow. $AGWS$ is the active groundwater storage at the start of the interval (inches).

$$KGW = 1.0 - AGWRC^{\frac{DELT60}{24.0}} \qquad \text{(App.B.15)}$$

where $AGWRC$ is daily recession constant of groundwater flow if $KVARY$ or $GWVS$ = 0.0; i.e. the ratio of current groundwater discharge to groundwater discharge 24-hr earlier; $DELT60$ = hr/interval.

6.3.7. EVAPT – evapotranspiration

EVAPT was developed for the simulation of evaporation and evapotranspiration fluxes from all zones of the pervious land segment. Evaporation is an important aspect of water budget, because the volume of water that leaves a watershed as evapotranspiration exceeds the total volume of streamflow in most hydrologic regimes. There are two separate issues involved in estimating evapotranspiration (ET), i.e. potential ET and actual ET must be estimated. ET potential or demand is supplied as an input times series, typically using U.S. Weather Bureau Class A pan records plus an adjustment factor. The data are further adjusted for cover in the parent subroutine

PWATER. Actual ET is usually calculated as a function of moisture storages and the potential. The actual ET is estimated by trying to meet the demand from five sources in the order described below (Fig. App.B.9). The sum of the ET from these five sources is the total actual evapotranspiration from the land segment.

6.3.7.1. ETBASE

The first source from which ET can be taken is the active groundwater outflow or baseflow. This simulates effects such as ET from riparian vegetation in which groundwater is withdrawn as it enters the stream. The user may specify by the parameter BASETP the fraction, if any, of the potential ET that can be sought from the baseflow. That portion can only be fulfilled if outflow exists. Any remaining potential not met by actual baseflow evaporation will try next to be satisfied in subroutine EVICEP.

6.3.7.2. EVICEP

Remaining potential ET exerts its demand on the water in interception storage. Unlike baseflow, there is no parameter regulating the rate of ET from interception storage. The demand will draw upon all of the interception storage unless the demand is less than the storage. When the demand is greater than the storage, the remaining demand will try to be satisfied in subroutine ETUZON.

6.3.7.3. ETUZON

There are no special ET parameters for the upper zone, but rather ET is based on the moisture in storage in relation to its nominal capacity. Actual evapotranspiration will occur from the upper zone storage at the remaining potential demand if the ratio of UZS/UZSN, upper zone storage to nominal capacity, is greater than 2.0. Otherwise the remaining potential ET demand on the upper zone storage is reduced; the adjusted value depends on UZS/UZSN. Subroutine ETAGW will attempt to satisfy any remaining demand.

6.3.7.4. ETAGW

Like ET from baseflow, actual evapotranspiration from active groundwater is regulated by a parameter. The parameter AGWETP is the fraction of the remaining potential ET that can be sought from the active groundwater storage. That portion of the ET demand can be met only if there is enough active groundwater storage to satisfy it. Any remaining potential will try to be met in subroutine ETLZON.

6.3.7.5. ETLZON

The lower zone is the last storage from which ET is drawn. Evapotranspiration from the lower zone is more involved than that from the other storages. ET from the lower zone depends upon vegetation transpiration. Evapotranspiration opportunity will vary with the vegetation type, the depth of rooting, density of the vegetation cover, and the stage of plant growth along with the moisture characteristics of the soil zone. These influences on the ET opportunity are lumped into the LZETP parameter. Unlike the other ET parameters, LZETP can be input on a monthly basis to account for temporal changes in the above characteristics.

6.3.7.6. Method for evapotranspiration calculation

If the LZETP parameter is at its maximum value of one, representing near complete areal coverage of deep rooted vegetation, then the potential ET for the lower zone is equal to the demand that remains. However, this is normally not the case. Usually vegetation type and/or rooting depths will vary over the land segment. To simulate this, a linear probability density function for ET opportunity is assumed (Fig. App.B.12). This approach is similar to that used to handle areal variations in infiltration/percolation capacity. The variable RPARM, the index to maximum ET opportunity, is estimated by:

$$RPLARM = \left(\frac{0.25}{1.0 - LZETP}\right) \times \frac{LZS}{LZSN} \times \frac{DELT60}{24.0} \qquad \text{(App.B.16)}$$

where *RPARM* is the maximum ET opportunity (in/interval); *LZETP* is lower zone ET parameter; *LZS* is the current lower zone storage (inches); *LZSN* is lower zone nominal storage parameter (inches); *DELT60* is hr/interval.

The quantity of water lost by ET from the lower zone storage, when remaining potential ET (REMPET) is less than RPARM, is given by the cross-hatched area of the figure below. When REMPET is more than RPARM the lower zone, ET is equal to the entire area under the triangle, RPARM/2.

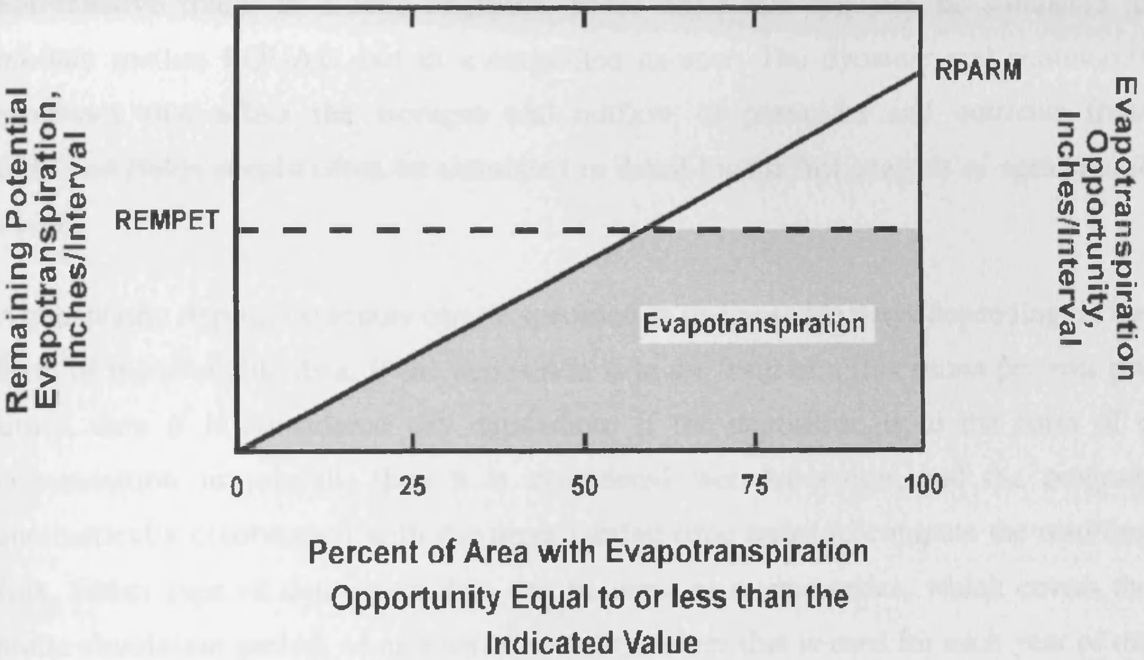


Fig. App.B.12. Potential and actual evapotranspiration from the lower zone (Bicknell et al., 2005)

ET from the lower zone storage is further reduced when LZETP is less than 0.5 by multiplying by LZETP*2.0. This is designed to account for the fraction of the land segment devoid of any vegetation that can draw from the lower zone.

7. AGCHEM – agri-chemical sections

The entering of agricultural chemicals into streams, lakes, and groundwater from agricultural land may be detrimental. Pesticide, nitrogen, and phosphorus compounds are important to agricultural production, but prediction of their removal from the field is essential for wise management of both land and water resources.

The module of AGCHEM in the PERLND of HSPF is able to simulate detailed nutrient and pesticide biological and chemical processes, and the movement of any non-reactive tracer in a land segment. These chemicals can also be simulated in module section PQUAL, but in a simplified manner. The dynamic and continuous processes that affect the storages and outflow of pesticides and nutrients from fertilized fields should often be simulated in detail for the full analysis of agricultural runoff.

Atmospheric deposition inputs can be specified in two possible ways depending on the form of the available data. If the deposition is in the form of a flux (mass per area per time), then it is considered dry deposition. If the deposition is in the form of a concentration in rainfall, then it is considered wet deposition, and the program automatically combines it with the input rainfall time series to compute the resulting flux. Either type of deposition data can be input as a time series, which covers the entire simulation period, or as a set of monthly values that is used for each year of the simulation.

The basic algorithms in the AGCHEM module of HSPF were originally developed for use on agricultural lands, but can be used on other pervious areas where pesticides and plant nutrients occur, for example, orchards, nursery land, parks, golf courses, and forests. All pervious land contains nitrogen and phosphorus in the soil; it is possible to use this module to simulate the behaviour of agricultural chemicals in any such area. The methods used to simulate pesticide processes in the agri-chemical sections were developed originally for the Pesticide Transport and Runoff (PTR) Model (Crawford and Donigian, 1973), then expanded to include nutrients in the ARM Model.

There are five agri-chemical module sections, i.e. MSTLAY, PEST, NITR, PHOS, TRACER (Fig. App.B.3).

7.1. MSTLAY – moisture content of soil layers

MSTLAY estimates the storages of moisture in the four soil layers. MSTLAY takes and adapts the fluxes and storages computed in PWATER to fit the storage/flow path picture in the Fig. App.B.13, which schematically diagrams the moisture storages and fluxes used in subroutine MSTLAY. Note that the fluxes are represented in terms of both quantity (e.g., IFWI, in inches/interval) and as a fraction of the contributing storage (e.g., FII, as a fraction of UMST/interval). In MSTLAY, the moisture storages (the variables ending in MST, such as SMST, UMST, ISMST, LMST, and AMST) are calculated by the equation below:

$$MST = WSTOR + WFLUX \qquad \text{(App.B.18)}$$

where $WSTOR$ is the related storage calculated in module section PWATER; $WFLUX$ generally corresponds to the flux of moisture through the soil layer.

For example, in the calculation of the lower layer moisture storage (LMST), $WSTOR$ is the lower zone storage (LZS); and $WFLUX$ is the sum of water percolating from the lower zone to the inactive (IGWI) and active groundwater (AGWI). Note that these equations are dimensionally non-homogeneous, because storages (inches) and fluxes (inches/interval) are added together. Thus, the results given are likely to be highly dependent on the simulation time step.

The upper layer has been subdivided into two storages, principal and transitory. The transitory (interflow) storage is used to transport chemicals from the upper layer to interflow outflow. The chemicals in the transitory storage do not undergo any reactions. However, reactions do occur in the principal storage.

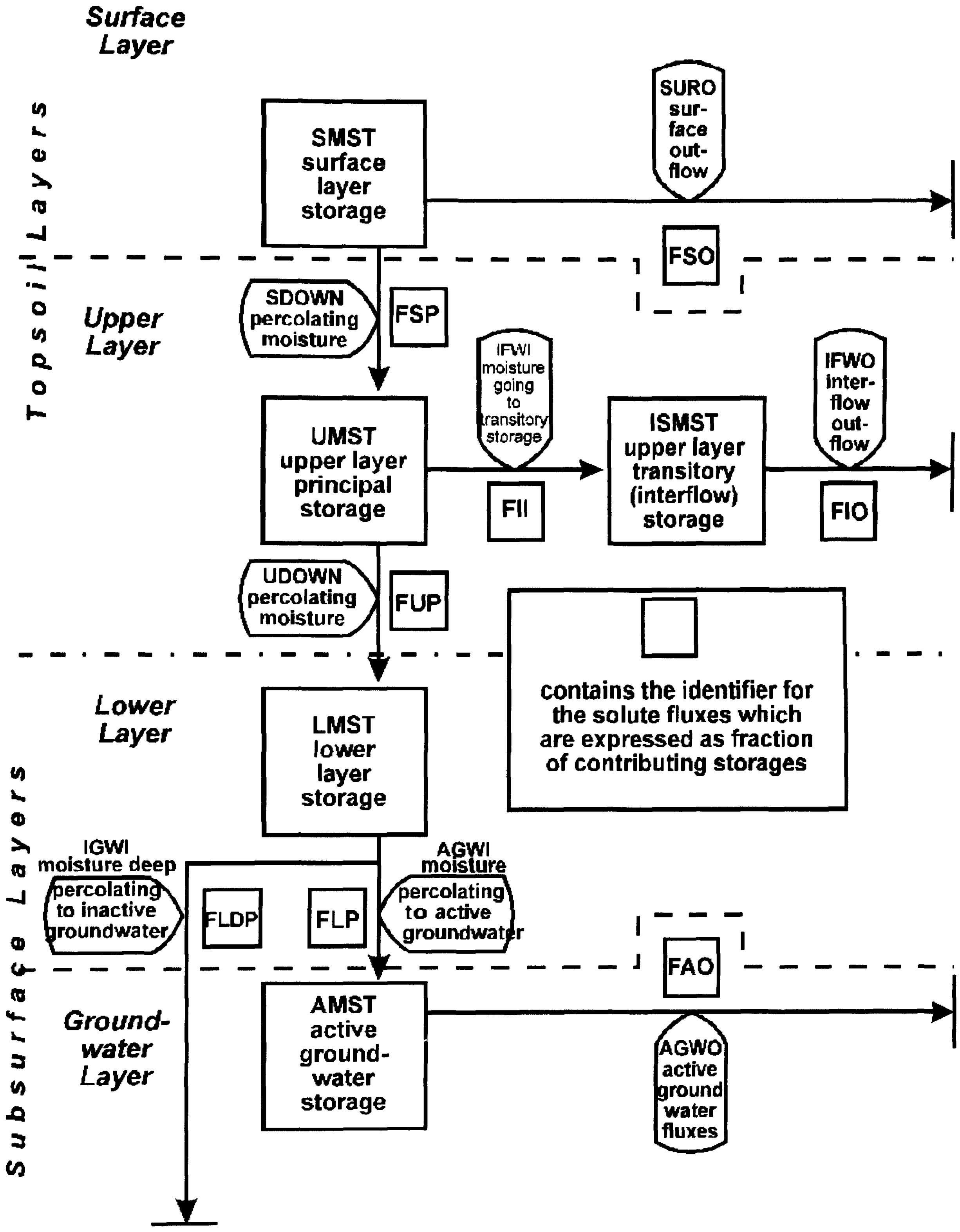


Fig. App.B.13. The transport of moisture and solutes as estimated in the MSTLAY section of the PERLND in HSPF (Bicknell et al., 2005)

SDOWN encompasses all the water that moves downward from the surface layer storage. SDOWN is the combination of the water infiltrating from the surface detention storage directly to the lower zone (INFIL), the inflow to the upper zone (UZI), and the water flowing into interflow storage (IFWI). UDOWN, INFIL plus the percolation from the upper zone storage to the lower zone storage (PERC), is all the water percolating through the upper layer.

Each fractional solute flux is the appropriate moisture flux divided by the contributing storage. For instance, the fraction of chemical in solution that is transported overland from the surface layer storage (FSO) is the surface moisture outflow (SURO) divided by the surface layer moisture storage (SMST). This is based on the assumption that the concentration of the solute being transported is the same as that in storage. It also assumes uniform flow through the layers and continuous mixing of the solutes. However, these assumptions may need to be revised or implemented differently for some of the transport.

In Fig. App.B.13, the relationship between the solute fraction percolating (FSP) and the percolation factor (SLMPF) is shown below:

$$FSP = SLMPF \times \frac{SDOWN}{SMST} \qquad \text{(App.B.19)}$$

The variables *SDOWN* and *SMST* are defined in the figure above. *FSP* will typically be between 0 and 1. For the upper or lower layer percolating fraction (*FUP*, *FLDP*, or FLP), the retardation factor only has an influence when the ratio of the respective zone storage to the nominal storage times the factor $\frac{ZS}{ZSN \times LPF}$ is less than one. The relationship under this condition is:

$$F = \frac{ZS}{ZSN \times LPF} \times \frac{PFLUX}{MST} \qquad \text{(App.B.19)}$$

where *F* is the layer solute percolating fraction; *ZS* is zone moisture storage, either *UZS* or *LZS*; *ZSN* is zone nominal moisture storage, either *UZSN* or *LZSN*; *LPF* is the factor which retards solute leaching for the layer, either *ULPF* or *LLPF*; *PFLUX* is the percolation flux, either *UDOWN*, *IGWI*, or *AGWI*; *MST* is layer moisture storage, either *UMST* or *LMST*.

7.2. Solutes movements in soil

Chemicals in solution move to and from the storages according to the fractions calculated in section MSTLAY. Fig. App.B.14 schematically illustrates the fluxes and storages used in the calculation of solutes movements in soil. The fractions (variables beginning with the letter "F") of the storages are used to compute the solute fluxes. The equations used to compute the solute transport fluxes from the fractions and storages are given in the figure. Subroutine TOPMOV performs the calculations of the fluxes and the resulting changes in storage for the topsoil layers (surface and upper), while SUBMOV performs them for the subsurface layers (lower and active groundwater).

Biological and chemical reactions are performed on chemicals in each layer storage. Chemicals in the upper layer principal storage undergo reactions while those in the transitory (interflow) storage do not. The upper layer transitory storage is a temporary storage of chemicals on their way to interflow outflow. The modules of solutes calculation are the basses of pesticides and nutrients biochemical process simulations in HSPF. Fig. App.B.15 shows the structure chart of pesticide simulation module.

7.3. NITR – nitrogen behaviour

The NITR module simulates the behaviour of nitrogen in the soil profile of a land segment by handling the nitrogen species of nitrate, ammonia, and organic nitrogen. This involves simulating nitrogen transport and soil reactions. Nitrogen, like phosphorus, may be a limiting nutrient in the eutrophication process in lakes and streams.

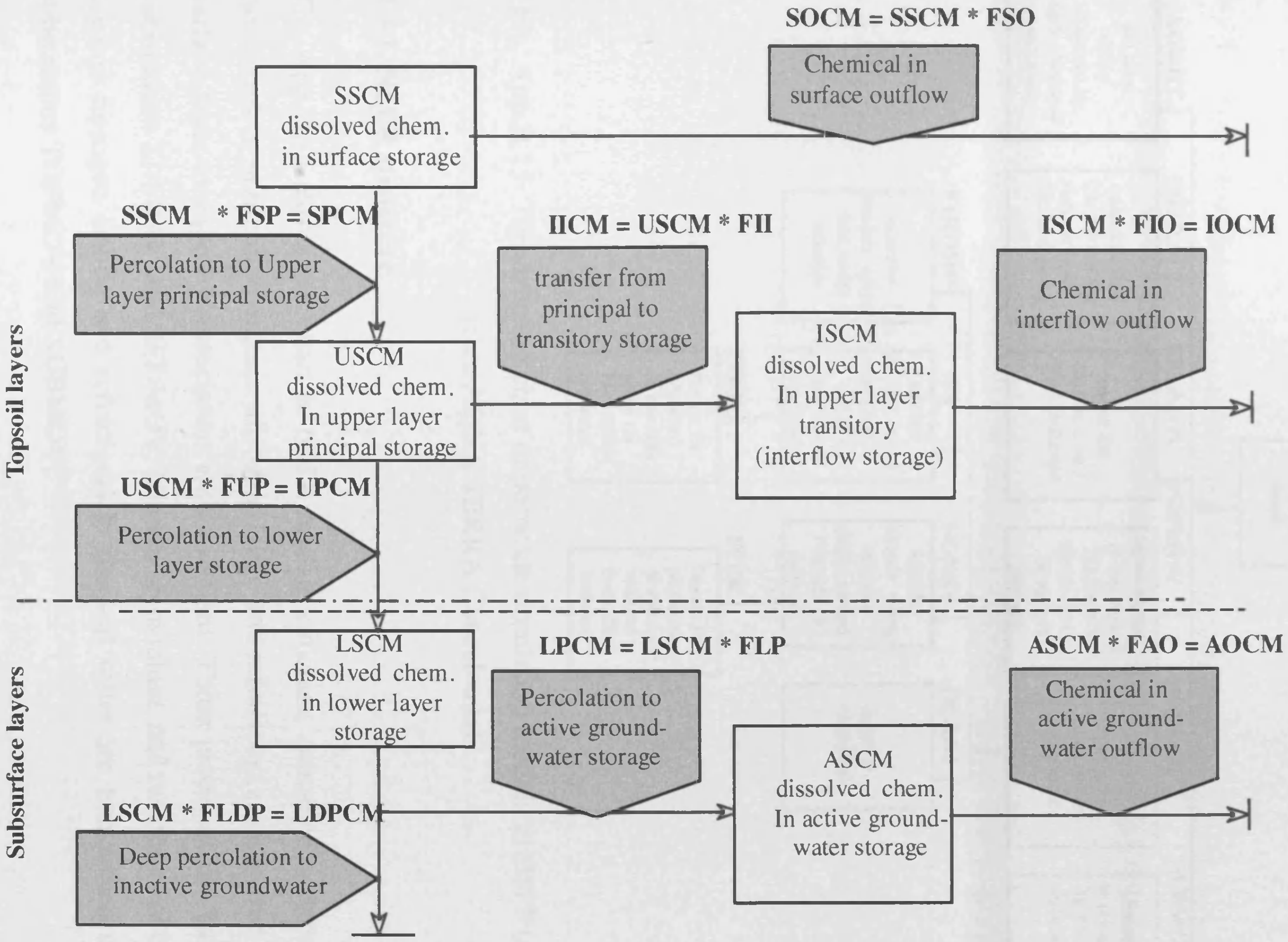


Fig. App.B.14. Flow diagram for movement of solutes (adapted from AQUA TERRA Consultants)

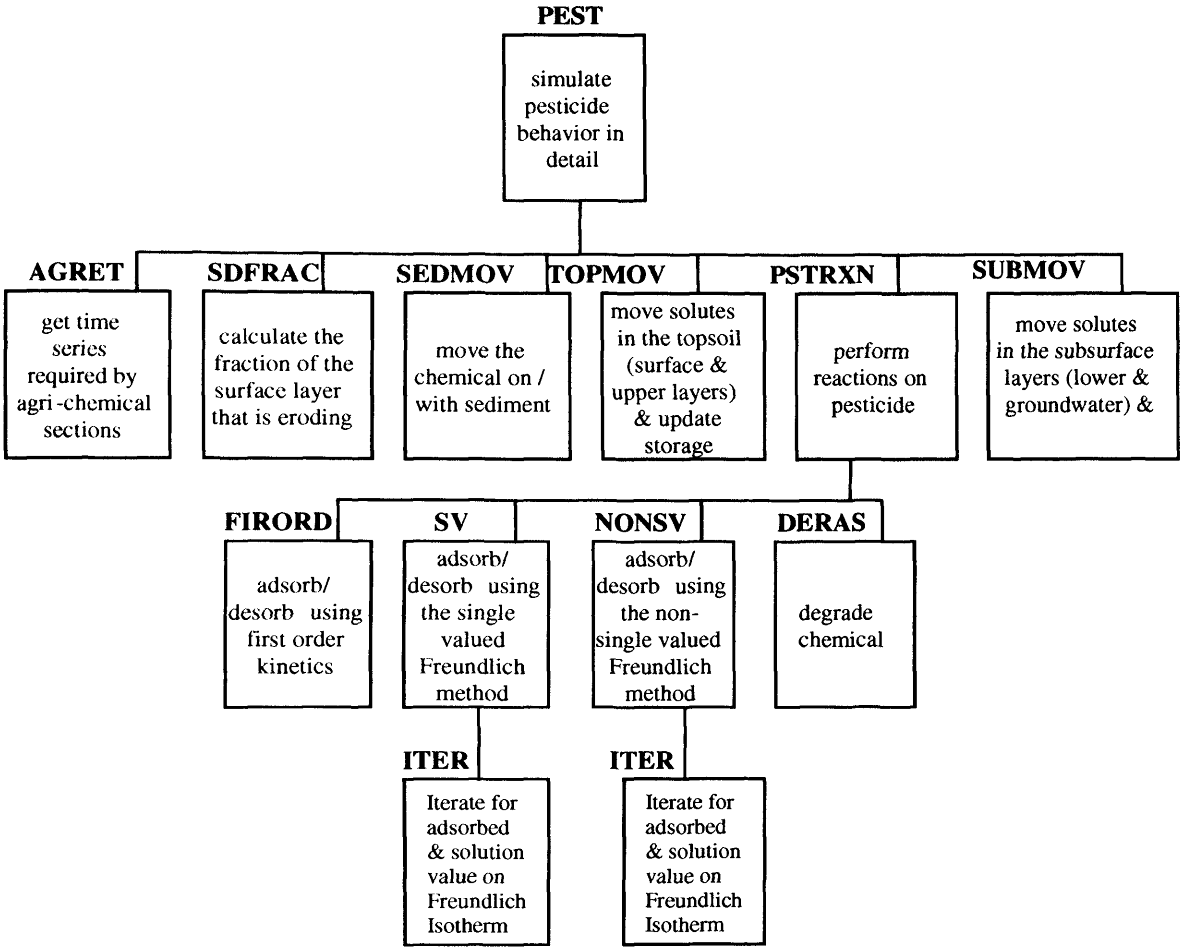


Fig. App.B.15. The structure chart of pesticide simulation module in HSPF (adapted from AQUA TERRA Consultants)

7.3.1. NITR structure

Fig. App.B.16 shows the chart of NITR module structure. Adsorbed ammonium and two forms of particulate organic nitrogen (labile and refractory) are removed from the surface layer storage by association with sediment. These processes are handled by subroutines SDFRAC and SEDMOV. Nitrate, ammonium, and two forms of dissolved organic nitrogen (labile and refractory) in the soil water are transported using the subroutines TOPMOV and SUBMOV.

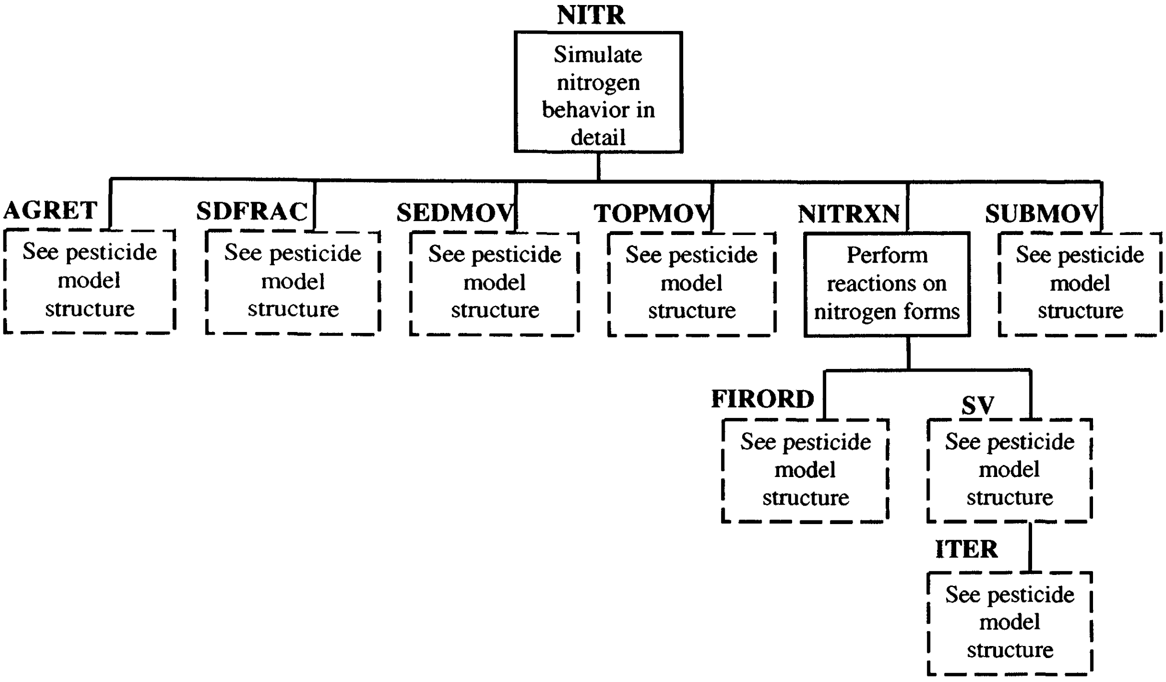


Fig. App.B.16. The chart of the NITR module structure (adapted from AQUA TERRA Consultants)

7.3.2. Nitrogen input

Natural and agricultural inputs of nitrogen to the surface and upper soil layers can be simulated using either or both of two methods: 1) as changes to storage variables in the SPEC-ACTIONS block, or 2) as atmospheric deposition inputs. Atmospheric deposition inputs are implemented for three species: nitrate, ammonium, and particulate labile organic nitrogen. If atmospheric deposition data are input to the model, the soil storage is updated for each of the three species of nitrogen in each soil layer (surface and upper) using the general equaiton:

$$NSTOR = NSTOR + ADFX + PREC \times ADCN \qquad \text{(App.B.20)}$$

where $NSTOR$ is the storage of nitrogen species in the soil layer (mass/area); $ADFX$ is dry or total atmospheric deposition flux (mass/area per interval); $PREC$ is precipitation (depth per interval); *ADCN* is concentration of nitrogen species in rainfall (mass/volume).

7.3.3. NITRXN – nitrogen soil biochemical process simulation

NITRXN simulates soil nitrogen transformations. This nitrogen biochemical process includes plant uptake of nitrate and ammonium, return of plant nitrogen to organic nitrogen, denitrification or reduction of nitrate-nitrite, immobilisation of nitrate-nitrite and ammonium, mineralization of organic nitrogen, fixation of atmospheric nitrogen, volatilisation of ammonium, adsorption/desorption of ammonium, and partitioning of two types of organic nitrogen between solution and particulate forms (Fig. App.B.17).

Nitrogen reactions are simulated separately for each of the soil layers. The methods used for nitrogen soil process simulation are schematically shown in Fig. App.B.18.

7.3.3.1. Adsorption/desorption of ammonium

Nitrogen reactions can be divided between those that are chemical in nature and those that are a combination of chemical and biological reactions. The adsorption and desorption of ammonium is a chemical process. The user has the option of simulating ammonium adsorption and desorption by first-order kinetics with subroutine FIRORD or by the Freundlich isotherm method with subroutine SV. The user has the option of specifying how often the adsorption and desorption rates are calculated. When adsorption/desorption is simulated by the Freundlich method, the solution and adsorbed storages of ammonium are determined instantaneously at the specified frequency of reaction. However, when the first-order method is used, the temperature-corrected reaction fluxes are recomputed intermittently, but the storages are updated every simulation interval.

7.3.3.2. Organic nitrogen partitioning

Organic nitrogen is assumed to exist in the following four forms in each soil layer, i.e. particulate labile, solution labile, particulate refractory, and solution refractory. The

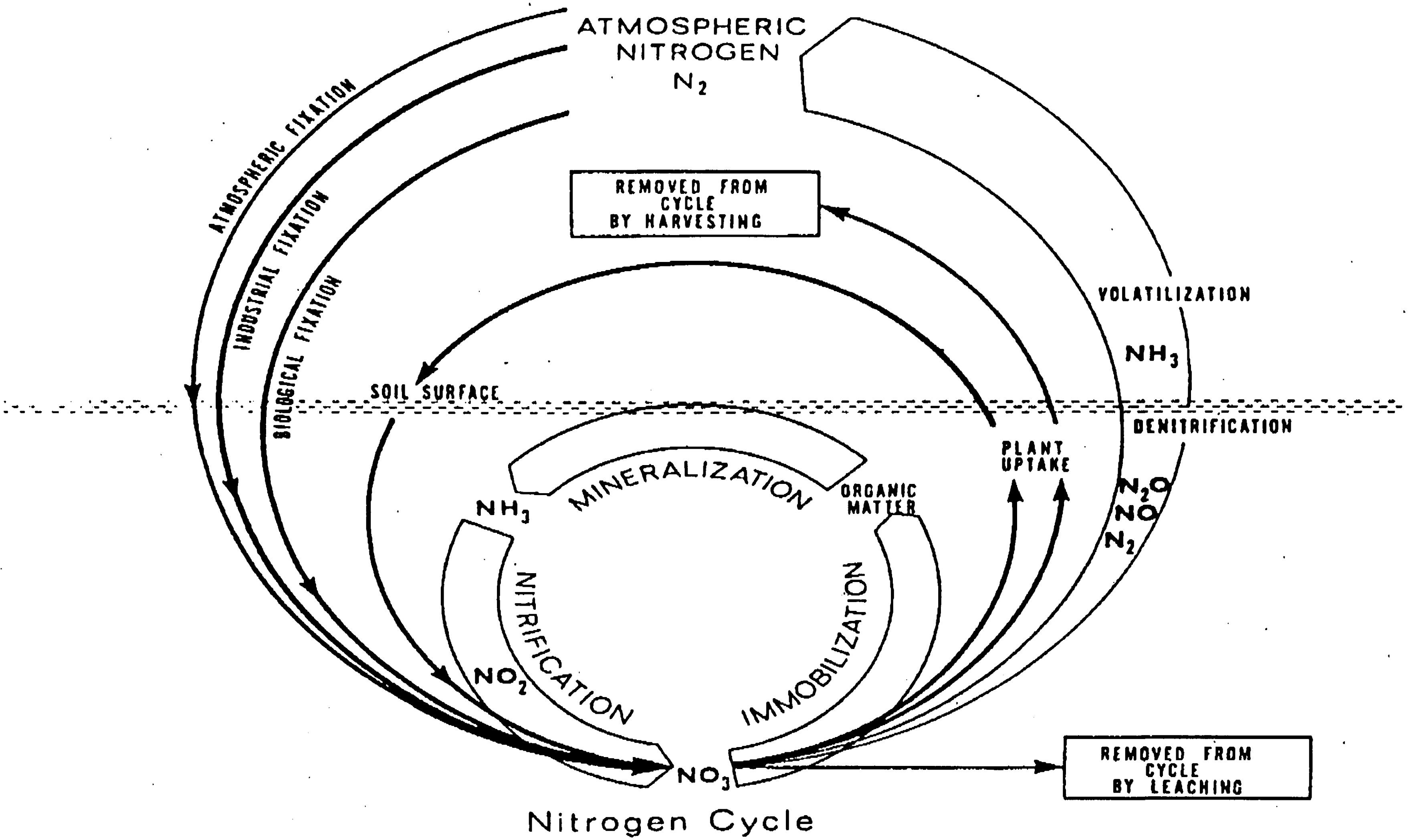


Fig. App.B.17. Nitrogen cycle (from AQUA TERRA Consultants)

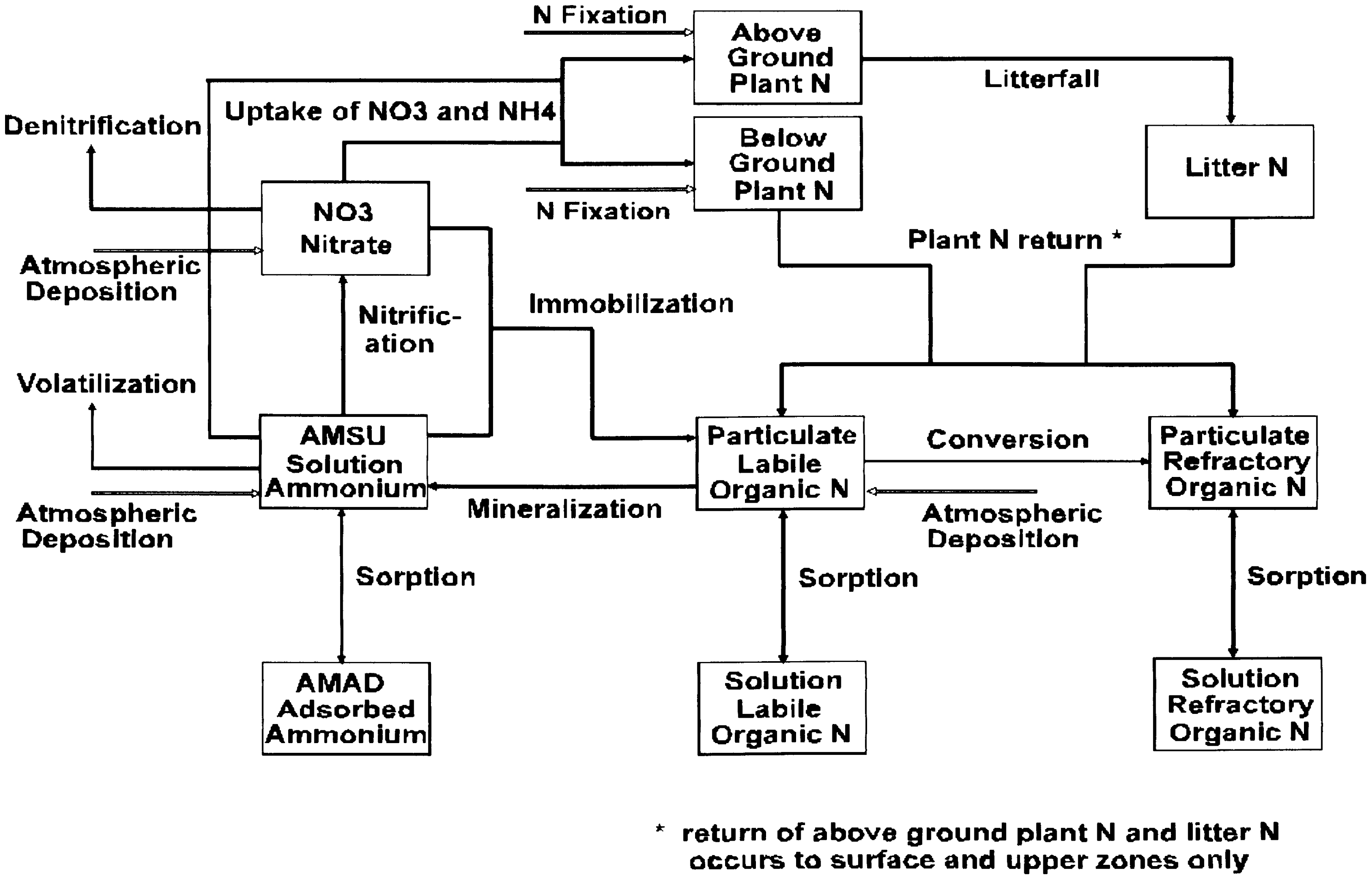


Fig. App.B.18. Flow diagram for nitrogen reactions in soil (from Bicknell et al., 2005) particulate labile species is the default form of organic N in the model; if default values of organic N-related sorption parameters and reaction rates are used, only this form will exist. This species is formed by immobilisation of nitrate and ammonia, and is converted back to ammonia by mineralisation in the soil. It also is transported on the surface by association with sediment. However, if the user inputs non-zero values of the relevant parameters, it can undergo conversion by first-order rate to the particulate refractory form, and it can also desorb to the solution labile form. The particulate refractory species can also desorb to the solution refractory form. The two solution species are available for transport with surface runoff and within the soil profile, and the particulate refractory form can be transported on the surface with sediment. The organic nitrogen partitioning reactions (sorption-desorption) are described by equilibrium isotherms as shown in the following equations:

$$KLON = \frac{PLON}{SLON} \qquad \text{(App.B.21)}$$

$$KRON = \frac{PRON}{SRON} \qquad \text{(App.B.22)}$$

where $KLON$ and $KRON$ are partition coefficients for the labile and refractory organic nitrogen, respectively; $PLON$ is particulate labile organic N (lb N/ac or kg N/ha); $SLON$ = solution labile organic N (lb N/ac or kg N/ha); $PRON$ = particulate refractory organic N (lb N/ac or kg N/ha); $SRON$ = solution refractory organic N (lb N/ac or kg N/ha).

The four organic nitrogen forms and their assorted reactions are illustrated in Fig. App.B.18. Note that the storages and transformations in Fig. App.B.18 are generally repeated in each soil layer except for the aboveground plant N and the litter compartments.

7.3.3.3. Other nitrogen transformations

The other N reactions are a combination of biological and chemical transformations. All of these reactions can be modelled using first-order kinetics; optional algorithms can be used for plant uptake of N and immobilisation of organic N. The optimum first-order kinetic rate parameter is corrected for soil temperatures below 35 degrees Celsius by the generalised equation:

$$KK = K \times TH^{(TMP-35.0)} \qquad \text{(App.B.23)}$$

where KK is the temperature-corrected first-order reaction rate (/interval); K is optimum first-order reaction rate at 35 degrees Celsius (/interval); TH is the temperature correction coefficient for reaction (typically about 1.06); TMP is the soil layer temperature (degrees C).

When temperatures are greater than 35 degrees Celsius, the rate is considered optimum, that is, KK is set equal to K. When the temperature of the soil layer is below 4 degrees Celsius or the layer is dry, no biochemical transformations occur. The corrected reaction rate parameters are determined every biochemical reaction interval and multiplied by the respective storages as shown in Fig. App.B.18. Plant uptake can vary monthly and can be distributed between nitrate and ammonium by the parameters NO3UTF and NH4UTF. These parameters are intended to designate the fraction of plant uptake from each species of N; the sum of NO3UTF and NH4UTF should be 1.0.

Immobilisation of nitrate and ammonia (conversion to particulate labile organic N) can be simulated using either first-order kinetics as described above, or a saturation kinetics (Michaelis-Menten) method. The saturation kinetics option is intended primarily for forests, and is activated when NUPTFG = 2 or -2.

7.3.3.4. Ammonia volatilisation

Ammonia volatilisation is included as an optional (AMVOFG = 1) first-order reaction in order to allow large concentrations of ammonia in the soil, resulting from animal waste and fertiliser applications, to be attenuated by losses to the atmosphere. The original formulation by Reddy et al., (1979) included adjustment for variable soil cation exchange capacity (CEC) and wind speed, and it could be "turned off" after seven days. In HSPF, there are assumptions: (1) the CEC factor can be incorporated into the first-order rate constant by the user, and (2) the wind (air flow) is always high enough to result in maximum loss; Reddy's original method reduced the volatilisation rate only when wind speed was less than 1.4 km/day. Downward adjustment of the rate, after an initial period of high losses, requires use of the special actions capability. The temperature correction for volatilisation of ammonia is slightly different than the standard method used for the other reactions. The reference temperature is user-specified, instead of 35 degrees Celsius, since rates in the literature are often given at a temperature of 20 degrees Celsius. Also, instead of attaining a maximum value at the reference temperature, the volatilisation rate is adjusted upwards when the soil temperature exceeds the reference temperature.

7.3.3.5. Plant nitrogen

There are two options in HSPF for simulating plant nitrogen. There is a switch ALPNFG in HSPF controlling the selection of the method of the plant nitrogen simulation. If the switch is “0”, plant N is simulated in each of the four standard soil layers (i.e. surface, upper layer, lower layer, and active groundwater). If the switch is “1”, plant N is also simulated in aboveground and litter compartments, in addition to the standard belowground layers. Plant N simulation involves the uptake of ammonium and nitrate by the plant, and "return" of plant N to organic N in the soil. Aboveground plant N returns to the litter compartment, and litter plant N returns to the particulate organic N compartments in the surface and upper soil layers. These return reactions from above-ground plant N to litter and from litter to surface/upper organic N are simulated using first-order kinetics. No other reactions affect these nitrogen storages except for plant uptake to the above-ground compartment. Return of plant N to particulate organic N is divided into labile and refractory fractions. By using default values of the return parameters, all plant return becomes labile organic N.

There are three optional methods for simulating plant uptake, including the default, first-order method described above. These options are selected using the input flag NUPTFG. When the flag is "1", a yield-based algorithm will be used. This approach is a modification of the algorithm used in the Nitrate Leaching and Economic Analysis Package (NLEAP) model (Shaffer et al., 1991). NLEAP was designed to be less sensitive to soil nutrient levels and nutrient application rates than the first-order rate approach (flag = 0); thus, it allows crop needs to be satisfied, subject to nutrient and moisture availability, without being calculated as a direct function of the soil nutrient level. This approach allows a better representation of nutrient management practices, because uptake levels will not change dramatically with changes in application rates. In NLEAP, a total annual target, NUPTGT, is specified by the user, and is then divided into monthly targets during the crop-growing season. The target is further divided into the four soil layers. The monthly target for each soil layer is calculated using the equation below:

$$\begin{aligned} MONTGT = NUPTGT \times NUPTFM(MON) \times \\ NUPTM(MON) \times CRPFRC(NON, ICROP) \end{aligned} \qquad \text{(App.B.24)}$$

where *MONTGT* is monthly plant uptake target for current crop (lb N/ac or kg N/ha); *NUPTGT* is the total annual uptake target (lb N/ac or kg N/ha); *NUPTFM* is monthly fraction of total annual uptake target; *NUPTM* is soil layer fraction of monthly uptake target; *CRPFRC* is the fraction of monthly uptake target for current crop; *MON* is current month; *ICROP* is the index for current crop.

Planting and harvesting dates can be specified for up to three separate crops during the year. Plant uptake is assumed to occur only during a growing season, defined as the time period between planting and harvest. When portions of two growing seasons are contained within one month, the total monthly target is divided between the two crops in proportion to the number of days in each season in that month. The daily target is calculated by starting at zero at the beginning of a crop season and using a trapezoidal rule to solve for monthly boundaries. Linear interpolation is used to solve for daily values between the monthly boundaries, and between a monthly boundary and a planting or harvest date.

Yield-based plant uptake only occurs when the soil moisture is above the wilting point, which is specified by the user for each soil layer. No temperature rate adjustment is performed, but all uptakes are stopped when soil temperature is below 4 degrees Celsius. If the uptake target is not met during a given interval, whether from nutrient, temperature, or moisture stress, then an uptake deficit is accumulated, and applied to the next interval's target. When uptake later becomes possible, the program will attempt to make up the deficit by taking up nitrogen at a rate higher than the normal daily target, up to a user-specified maximum defined as a multiple of the target rate. The deficit is tracked for each soil layer, and is reset to zero at harvest, i.e., it does not carry over from one crop season to the next.

When using the yield-based plant uptake option, it is also possible to represent leguminous plants (e.g., soybeans) that fix nitrogen from the atmosphere. The algorithm is designed to allow N fixation only to make up any shortfall in soil nitrogen, i.e., fixation is only allowed if the available soil nitrogen (nitrate and solution ammonium) is insufficient to satisfy the target uptake. The maximum daily nitrogen fixation rate is subject to the same limits as the uptake under deficit conditions noted above.

The third option for simulating plant uptake is to use a Michaelis-Menten or saturation kinetics method. This algorithm is included in HSPF primarily for simulating forest areas, and whenever it is selected, the same method is used to simulate immobilisation of ammonium and nitrate as well. The saturation kinetics method is activated for both uptake and immobilization by setting NUPTFG to 2 or -2.

The user specifies a maximum rate and a half-saturation constant for each of the four processes (uptake of nitrate and ammonia, and immobilisation of nitrate and ammonia). The input maximum rates can vary monthly. The corresponding reaction fluxes are computed using the general equation below:

$$FLUX = KK \times \frac{CONC}{CS + CONC} \qquad \text{(App.B.25)}$$

where $FLUX$ is the amount of flux (mg/l/interval). The flux is then converted to units of mass per interval; KK is the temperature corrected maximum rate (mg/l/interval); $CONC$ = concentration of nitrogen species in soil layer (mg/l); CS is half-saturation constant (mg/l).

7.4. PHOS – phosphorous behaviour

The PHOS module simulates the behaviour of phosphorus in a pervious land segment by modelling the transport, plant uptake, adsorption/desorption, immobilisation, and mineralization of the various forms of phosphorus. Because phosphorus is readily tied to soil and sediment, it is usually scarce in streams and lakes. In fact, in many cases it is the limiting nutrient in the eutrophication process. Because of its scarcity, accurate simulation is particularly important.

7.4.1. PHOS structure

Fig. App.B.19 shows the structure of the PHOS module. The method used to transport and react phosphorus is the same as that used for nitrogen in module section NITR. The subroutines used to transport phosphorus are described in section 7.2. Organic phosphorus and adsorbed phosphate are removed with sediment by calling subroutine SEDMOV. Phosphate in solution is transported in the moving water using subroutines TOPMOV and SUBMOV. Phosphorus reactions are simulated in the soil by subroutine PHORXN.

7.4.2. PHORXN – phosphorus soil biochemical process simulation

Fig. App.B.20 shows phosphorus cycle. Inputs of phosphorus to the surface and upper soil layers, natural or agricultural, can be simulated using either or both of two methods: 1) as changes to storage variables in the SPEC-ACTIONS block, or 2) as atmospheric deposition. Atmospheric deposition inputs can be specified in two possible ways depending on the form of the available data, i.e., dry deposition and wet deposition. Either type of deposition data can be input as a time series, which covers the entire simulation period, or as a set of monthly values that is used for each year of the simulation.

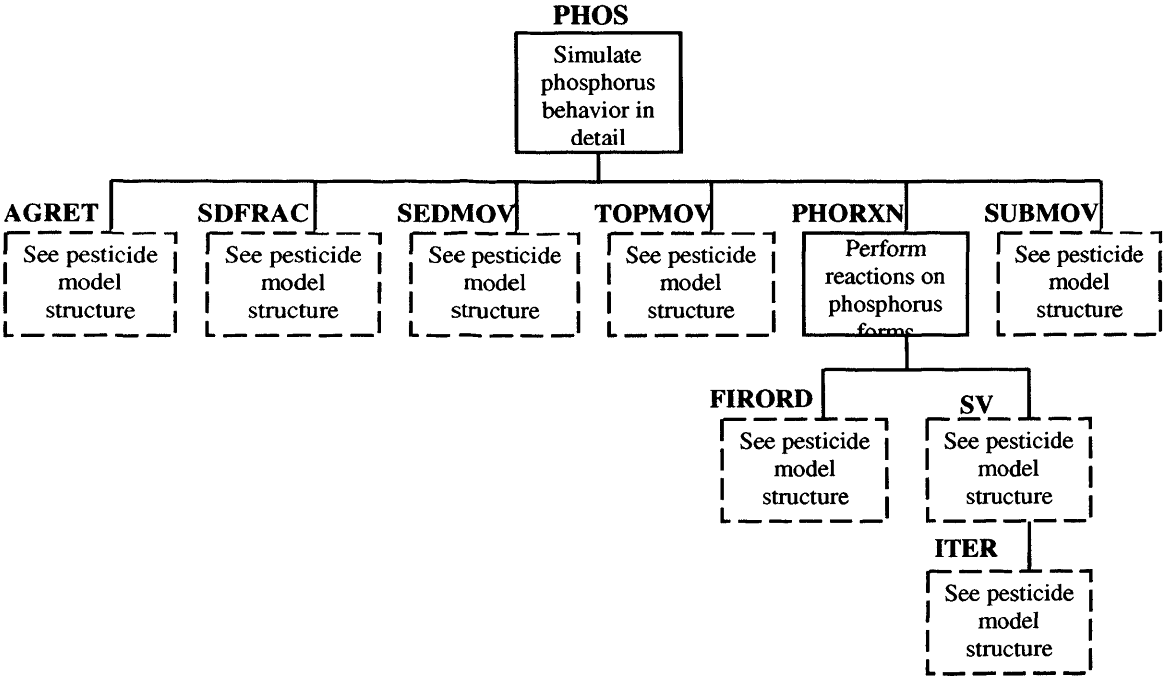


Fig. App.B.19. The chart of the PHOS module structure (adapted from AQUA TERRA Consultants)

If atmospheric deposition data are input to the model, the soil storage is updated for each of the two species of phosphorus for both affected soil layers using the equation below:

$$P = P + ADFX + PRCE \times ADCN \qquad \text{(App.B.26)}$$

where P is the storage of phosphorus species in the soil layer (mass/area); ADFX is dry or total atmospheric deposition flux (mass/area per interval); PREC is precipitation depth; ADCN is the concentration for wet atmospheric deposition (mass/volume).

In PHORXN, phosphate is adsorbed and desorbed by either first-order kinetics or by the Freundlich method. The mechanics of these methods are described in the NITR section. As with the simulation of ammonium adsorption/desorption, the frequency of this chemical reaction for phosphate can also be specified. Unlike ammonium, typically phosphate includes a large portion, which is not attached to the soil particle but is combined with cations. This is because phosphate is much less soluble with the ions found in soils than ammonium.

Phosphorus biochemical processes of mineralisation, immobilisation, and plant uptake are performed by subroutine PHORXN. These are accomplished using temperature dependent, first-order kinetics; the same method used for the nitrogen reactions. As for nitrogen, a yield-based plant uptake option is available for phosphorus and is activated when PUPTFG is set to "1". The saturation-kinetics option for uptake and immobilisation is not available for phosphorus. The only other difference between nitrogen and phosphorus plant uptake is that only solution phosphate can be taken up by the plant and no fixation process is modelled. Fig. App.B.21 shows the parameters and equations used to calculate the reaction fluxes for phosphorus. Reactions are simulated for each of the four soil layers using separate parameter sets for each layer. As with nitrogen, the biochemical phosphate reaction fluxes of mineralisation, immobilisation, and plant uptake can be determined at an interval less frequent than the basic simulation interval.

8. HSPF application process

The HSPF application process includes: 1) study definition; 2) development of modeling strategy; 3) learn operational aspects of HSPF; 4) input/management of time series data; 5) parameter development; 6) calibration/verification; and 7) analysis of alternate scenarios. The relative effort for each HSPF application step is shown in table App.B.1.

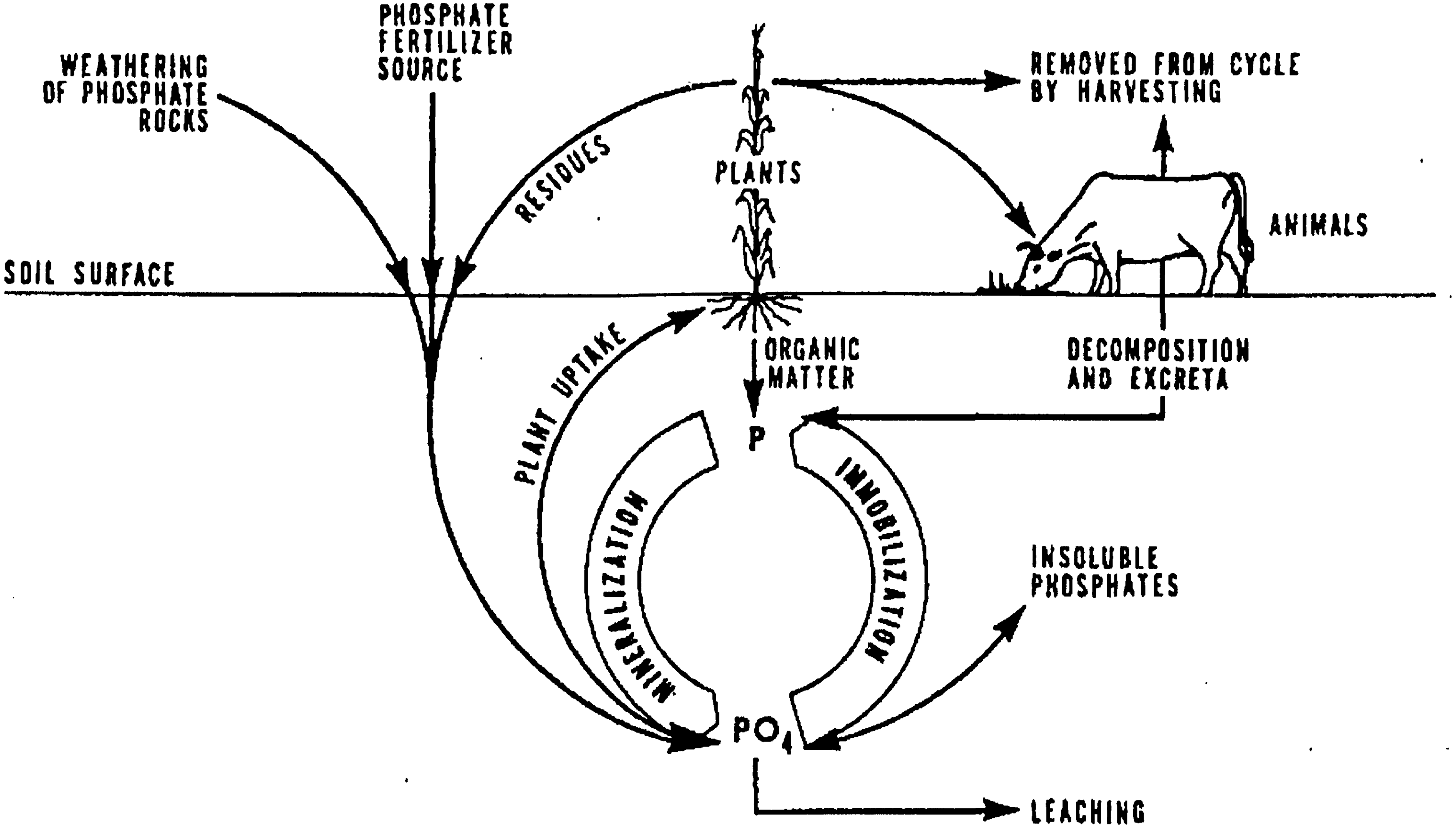


Fig. App.B.20. Phosphorus cycle (from AQUA TERRA Consultants)

The study definition includes: 1) defining problems/questions for analysis, and studying goals; 2) studying data availability; and 3) assessing project resource availability (such as time, money, and expertise).

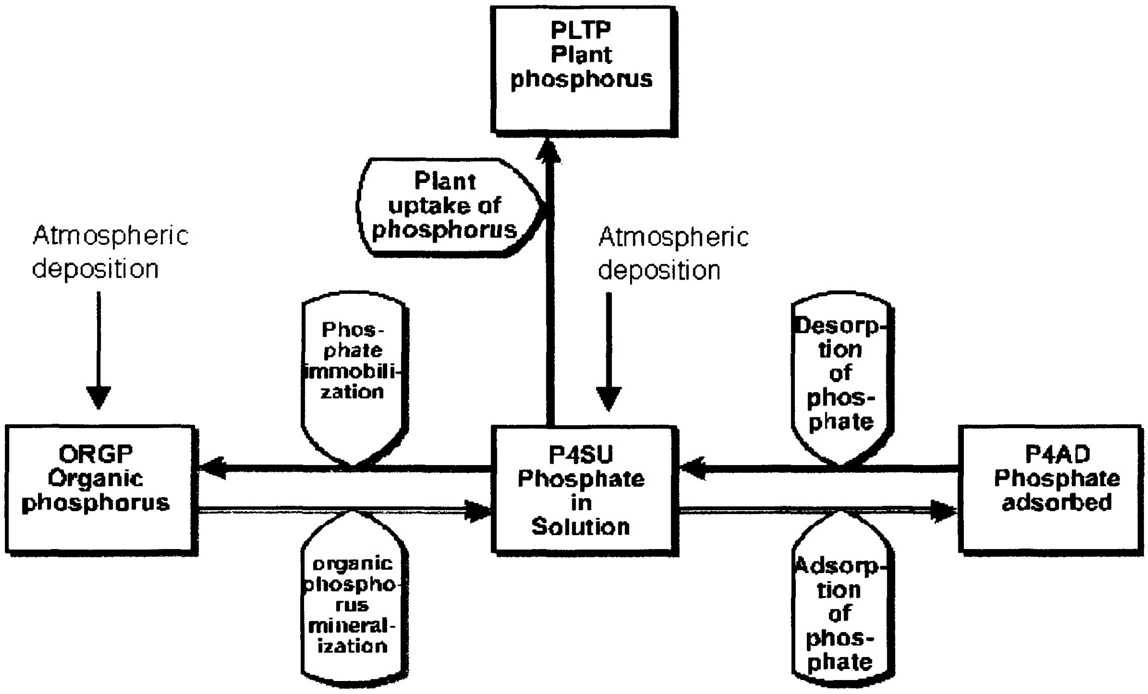


Fig. App.B.21. Flow diagram for phosphorus reactions in soil (from Bicknell et al., 2005)

The development of modelling strategy includes: 1) defining processes, constituents, and sources to be modelled; 2) watershed segmentation in spatial and temporal detail; 3) channel segmentation and tributary areas; 4) data to support modeling effort; 5) human impacts, alternatives to be analysed; and 6) develop simulation plan.

Table App.B.1. The relative effort of each step of HSPF application

Task	%Effort
Problem definition	5
Modelling strategy	10
Learn operational aspects	10

The development and input of time series	30
Parameter development	15
Calibration and validation	30

Constituent sources in HSPF are: 1) initial storages; 2) non-point loadings; 3) point loadings; 4) atmospheric deposition; 5) chemical transformations; 6) releases from the channel bottom; and 7) atmospheric gas invasion.

9. HSPF strengths and weaknesses

The strengths of HSPF include: 1) comprehensive representation of watershed land and stream processes; 2) comprehensive representation of watershed pollutant sources, including nonpoint sources (by multiple land uses), point sources, atmospheric, etc.; 3) flexibility and adaptability to a wide range of watershed conditions; 4) well-designed code modularity and structure; 5) companion database and support programs to assist model users (e.g., WDMUtil, WinHSPF, GenScn, HSPEXP); 5) ongoing development and support by U.S. EPA and USGS; 6) continuing code enhancements funded by numerous groups; 7) strict code version control through joint agreement of USEPA & USGS.

The weaknesses of HSPF are: 1) extensive data requirements (e.g., hourly rainfall); 2) user training normally required; 3) no comprehensive parameter estimation guidance available; 4) limited spatial definition (i.e., lumped parameter approach); 5) hydraulics limited to non-tidal freshwater systems and unidirectional flow; 6) simplified representation of urban drainage systems; 7) limited representation of algal species - phytoplankton, zooplankton, and benthic algae.

Appendix C

Research proposals in this PhD study

This appendix contains four proposals composed by the author during this PhD study for European Research Council (ERC) first grant, Natural Environment Research Council (NERC) research grants, and NERC Flood Risk from Extreme Events (FREE) call.

1. Proposal for ERC first grant 2007

Title: A Novel Integrated Approach of Catchment Water Management for Agricultural Diffuse Pollution under Climate Change

Principal Investigator: Lei Wang

Hosting Institution: Cardiff University

Project duration in months: 60

Project vision: "to develop a novel and integrated approach that can resolve water agricultural diffuse pollution problem in a more pragmatic and transferable way, and can be adopted by all EU Member States for better implementation of the EU Water Framework Directive."

1.1. State-of-the-art and objectives

1.1.1. Background

Water pollution is not only an environmental issue but also an economic and human health problem. In the year 2000, EU Water Framework Directive (WFD) set a framework for comprehensive management of water resources in the European Community aiming at achieving at least "good status" for all the waters in the EU Member States (EUMS) by 2015. Compared with point pollution, diffuse pollution is more complex and more difficult to be controlled. At present, water agricultural diffuse pollution (WADP), the biggest remaining water pollution problem in the world, has been realized as a main threat for water quality and the implementation of the EU WFD. Currently, there are gaps between current WADP researches and the implementation of the EU WFD:

(1) ***Measure and tool gap***. What scientific measures and tools will actually be used or developed for the implementation of the EU WFD is still largely unknown for EUMS. Traditional measures include land use change, Best Management Practices (BMP), contaminated water remediation and drinking water treatment, etc. While the arguments between the advocates for each of traditional measures are still going on, there are two main reasons why WADP is still a world-class problem and a main threat of the implementation of the EU WFD: the lack of decision-support tools for guiding the selecting and application of proper measures in different situations, and the lack of unconventional measures for tackling WADP.

(2) ***Study scale gap***. Many studies for WADP have been carrying out at national and even European scales. However, it is crucial to control WADP at headstream – catchment. Although several studies of catchment WADP were newly lunched in Europe, more studies for catchment scale WADP problem management are urgently needed for all EUMS.

(3) ***Fundamental knowledge gap***. More inter-disciplinary and integrated fundamental researches are essential for the development of more accurate and reliable measures and tools, and for making better WADP management policies on the basis of better understanding WADP catchment process.

(4) ***Knowledge/Methodology transfer gap***. The results only suitable for some specific areas can hardly be transferred to other areas with significant varying situation, i.e.

land use, climate, agriculture activity, soil, topography, hydrogeology conditions and the sensitivity of particular water bodies to pollution. Thus, transferable knowledge, measures and tools are essential for better implementation of the EU WFD for all EUMS.

1.1.2. Aim and objectives of ICEMAN

Based on an inter-disciplinary research, i.e. hydrology, hydrogeology, isotopic biogeochemistry, agronomy and information technology, ICEMAN aims at developing a novel and integrated approach to resolve WADP problem under climate change. The objectives of ICEMAN are:

- ***O1 – Fundamental biogeochemical study of complete nutrient processes in soil:*** 1) studying nutrient cycling mechanisms in soil at the combination of typical land uses and soil types using isotope method; 2) investigating climate change and agricultural activities (fertilisers application rate, live-stock pressure, crop rotating, ploughing, harvesting, and artificial wetlands, etc.) impacts on nutrients process in soil; 3) extrapolating laboratory/plot scale biogeochemical processes in soil to spatial distributed catchment scale to develop soil nutrient cycling and balancing simulation model at catchment scale; 4) to find unconventional and feasible measure to maximize soil nutrient availability to plants and minimize soil nutrient movement to water course without side-effect to ecosystem
- ***O2 – Develop better water quality models based on O1 studies:*** 1) establish a more accurate catchment scale groundwater pollution risk assessment model (GWRA) for groundwater pollution prevention under climate change by considering nutrient biogeochemical and transport process in soil, hydrogeological factor and hydrological factor; 2) develop a groundwater pollution fate assessment model (GWFA) to guide catchment groundwater remediation; 3) Improve existing surface water quality model by recoding its modules of nutrient cycling and transport in soil based on O1 studies
- ***O3 – Develop and test an accurate, pragmatic and transferable decision-support system decision-support system for catchment WADP sustainable management***

based on O1 and O2. This new tool is able to: 1) provide thorough understanding of the characteristics of WADP in complete process of sources-pathways-targets in any specific catchment; 2) provide evidence for the selection and application of WADP handling measures in a catchment; 3) and evaluate the impacts of catchment water quality management policies on water quality in the combined context of land use, climate change, agricultural practices and BMP

- ***O4 – Set up a WebGIS based online system to:*** 1) disseminate the results of ICEMAN world widely; 2) facilitate public participation demanded by the EU WFD; 3) and provide a online framework for government to operate 'sound' and 'transparent' decisional processes with high efficiency in better communications with stakeholders and general public.

1.1.3. Significance of ICEMAN

1) ICEMAN challenges a multi-disciplinary method to integratively study the complete 4D nutrient process in soil, groundwater, surface water and their interactions at catchment scale under climate change. ICEMAN will provide a breakthrough in the field of resolving WADP problem.

2) By bridging the gaps mentioned above, ICEMAN is not only useful for better implementation of the EU WFD, but also helpful for tackling WADP problem all over the world, especially for developing agricultural countries.

3) While WebGIS system promote the dispersion of the results of ICEMAN, the templates of WebGIS system produced in ICEMAN can be duplicated to provide an efficient online platform for both catchment water quality management and public participation.

1.2. Methodology

1.2.1. Studying complete nutrient process in soil

Isotope method will be adopted to trace nutrient sources (fertilisers, atmospheric deposition and the part produced by biological activity within the soil organic matter), nutrient biogeochemical transformation process and nutrient transport in soil. The change of nutrient process in soil will be studied by choosing sites with different conditions of land uses, soil types, climate types and agricultural activities. Better understanding of complete nutrient biogeochemical and transport process in soil will be the base of finding unconventional measures to reduce nutrient entering water course from soil.

1.2.2. Setting up dynamic groundwater pollution risk assessment model

GWRA plays an important role in groundwater pollution prevention. Dynamic GWRA model will be developed based on D-DRASTIC model developed by PI (submitted to *Journal of Hydrology,* 2007; presented in two conferences) by combining nutrients cycling, transport in soil and their interactions with ground and surface water. Thus, the final dynamic GWRA model will be more reliable by considering atmosphere, geosphere, hydrosphere and biosphere factors.

1.2.3. Building up groundwater pollution target assessment model

GWRA is essential for groundwater pollution prevention whilst GWFA is important for contaminated groundwater remediation. GWFA model will be developed based on GWRA by introducing the groundwater flow direction calculation component in MODFLOW (3D groundwater flow and contaminant transport model) to reliably predict the target of contamination in aquifer with the advantage of easier use than MODFLOW.

1.2.4. Improving surface water model

ICEMAN concerns the characterising catchment surface water quantity and quality to temporal and spatial detail, and evaluating the impacts of WADP managing policies, thus a numeric surface water model is needed. Since the quality and complexity of selected model will directly affect the reliability of decision-support system, a proper surface water model with open source code should be selected from existing models. Such work has been done by PI (Submitted to *Journal of Hydrology,* 2007). The nutrient cycling components in selected model will be improved based on its open source code using the results from the fundamental study of O1 in ICEMAN.

1.2.5. Develop decision-support system for catchment scale WADP management

The decision-support system will be developed based on an open decision-making framework for catchment water quality management developed by PI (submitted to *Science of the Total Environment*, 2007). The GWPRA, GWPTA, GIS hydrology and improved surface water models will be fed into this framework on GIS platform by developing necessary internal data exchange and user interfaces.

1.2.6. Geographic Information Systems – GIS and WebGIS

ICMEAN inherently involves 4D activities and requires the handling of multiple forms of spatial and time data. The advantages of spatial data management and analyzing in GIS have been greatly facilitating water resources studies. All of the studies will be carried out on GIS platform. WebGIS, developing GIS functionality in the Internet to make distributed geographic information available to a very large worldwide audience through web browsers, will be used for ICEMAN online system development. Different templates of WebGIS designing will be created to support general public, WADP experts and government respectively.

1.2.7. Computer Programming Language

In the development and improvement of models, software interface and online system, computer programming language of Visual C++, FORTRAN and JavaScript will be will compositely used.

1.2.8. Pilot catchments

Four catchments will be selected. The selection of pilot catchments in ICEMAN will consider the factors of data availability, previous study foundations, number and distribution of boreholes, agricultural nature and costs of travel for access, etc.

1.3. Resources

1.3.1. New independent research team

New team will consist of 7 people from different disciplines with different academic levels. In hosting institution – Cardiff University, School of Earth, Ocean and Planetary Sciences (Earth) and School of Biosciences (Biosciences) will collaborate for this project. PI from Earth will be the team leader and is responsible for team establishing, funding and resource allocation, team members supervising, and overall management of project from conception to completion. PI will take part in O1-3, O2-1-2, O3 and O4. There will be other two key team members, i.e. KI1 from Biosciences and KI2 from Earth. KI1 will be responsible for task O1-1, O1-2 and O1-4, while KI2 will be the key person for task O2-3 and O3 (code programming part).

1.3.2. Needed and existing resources

Needed resources include: IRMS, piezometers, water quality dip meters, Web server computer, data backup hardware, and fundamental data for some catchments, etc. Existing resources that will contribute to the project include: 1) Environmental Hydrogeology Lab, field groundwater dippers, sampling equipments, pumps, Arc-Info 9, Visual MODFLOW; Aquichem, and Aquitest, and geographical database in some pilot catchments in Earth; and 2) 2 HPLC for NO_3^-, NH_4^+, NO_2^-, PO_4^{3-}, SO_4^{2-}, Cl^-, 1 ICP-AES for Na, K, Ca, Mg, and 1 EA-IRMS for $\delta^{15}N$-NO_3^-, $\delta^{15}N$-NH_4^+, $\delta^{18}O$-NO_3^- in Biosciences.

1.4. Ethical issues

There is no ethical issue for this project.

2. Proposal for NERC research grant 2007

Title: Fate and transport of nitrogen in complete water cycle for better management of agricultural diffuse water pollution at catchment scale

Principal Investigator: Yuesuo Yang

Hosting Institution: Cardiff University

Project duration in months: 36

2.1. Background to scientific issue

By comparison to point source water pollution, diffuse agricultural source water pollution is more complex and difficult to control, and is not only a serious environmental issue but also a threat to economics and human health. Water with high concentration of nutrients (nitrogen and phosphorus) can cause eutrophication in rivers, lakes and estuaries by producing algae and phytoplankton blooms, and depleting the water of oxygen. Nitrate removal represents a significant fraction of the total UK water treatment costs: the approximate annual costs in the UK of treating drinking water for pesticides are about £120 million, for phosphate and soil about £55 million, for microorganisms around £23 million and for nitrate around £16 million. Nitrate concentrations in excess of 10 mg dm^{-3} in drinking water may reduce the ability of human blood to carry oxygen and, in the very young, cause 'blue baby syndrome'. In addition, a potential cancer risk from nitrate (and nitrite) in water and food has been reported.

Diffuse water pollution is the biggest remaining problem of water pollution in the world, and the largest source of diffuse water pollution is agriculture. In England, it is estimated that over 70% of nitrates in natural waters are derived from agricultural land. Agricultural diffuse water pollution (ADWP) has been identified as a major threat to water quality and the implementation of the EU Water Framework Directive (WFD).

Once water is contaminated, it is very costly to clean-up and can take a long time to recover. In addition, spatial variability and data constraints preclude the monitoring of all waters and this makes remediation activities expensive and often impractical. Prevention of water pollution before the pollution occurs by reducing contaminants in the source water is perhaps more feasible and effective than the remediation of polluted water. Although politically, remediation is implemented at the regional scale, because it is difficult to determine the contribution of diffuse sources to water pollution at regional scale, surface and groundwater protection practices are best implemented at catchment or watershed scale.

Good scientific understanding of the biochemical and physical processes of diffuse pollutants in the water cycle is essential for the prevention of ADWP at catchment scale. However, there are gaps between current research and catchment-scale ADWP prevention.

1) Fundamental knowledge and method gaps

Currently, there is limited scientific knowledge of the four-dimensional (i.e. three spatial dimension plus time dimension) transport and biochemical transformation processes of diffuse pollutants within and between air, plants, soil, rocks, groundwater and surface water, resulting in the need of improved methods/tools for the efficient and effective management of the ADWP. What scientific measures will actually be used or developed for the implementation of the EU WFD is still largely unknown. Many measures have been developed for tackling the ADWP problem, namely, land use change, Best Management Practices (BMP), contaminated water remediation and drinking water treatment, etc. Recently, some tools were developed for better nutrient management in agricultural activities. For example, MAGPIE was developed to calculate total nitrate leaching losses from all agricultural activities; PLANET was developed for farmers to build a nutrient and manure application plan for a group of fields. The ongoing catchment sensitive farming programme is trying to work with stakeholders to develop an effective package of good farming practices to tackle ADWP. These studies focus on the good controlling of agricultural activities and can contribute to the solving of ADWP. However, the sustainable management of ADWP problem needs all types of efforts along the ADWP process of source – pathway – target. This demands that future methods/tools should consider the complete process of the agricultural diffuse pollutants in the water cycle to help better understanding ADWP mechanism, guiding the selection of ADWP management measures and evaluating the impacts of these measures on water quantity and quality process. Therefore, multidisciplinary research should be carried out for tackling ADWP based on better scientific understanding of complete ADWP process in the water cycle.

2) Study scale gap

Many ADWP studies have been published at national or even European scales. For example, the Soil Survey and Land Research Centre (SSLRC – now NSRI) and the British Geological Survey (BGS) generated the England and Wales national series of fifty-three 1:100,000 scale groundwater vulnerability maps. These small scale ADWP studies are helpful for setting the priority of the management of ADWP, but do not guide the prevention practices of ADWP at catchment scale. Studies on the nutrient biochemical processes have largely been carried out in the laboratory or at plot scale in the field. This data needs to be extrapolated to determine what is relevant at catchment scale. Although some catchment-scale framework or models have been developed for the study of nutrient cycle in the soil or surface water, such as LANAS and INCA, the complete nutrient transport and transform within and between soil, groundwater and surface water at catchment scale should be carried out for better ADWP management.

2.2. Aim and objectives

The proposed project will use a multidisciplinary approach (atmosphere, hydrology, hydrogeology, biochemistry and information technology) to develop accurate and pragmatic decision-support approach for the prevention of diffuse nitrogen pollution of both groundwater and surface water from agricultural sources at catchment scale. Objectives are (Fig. App.C.1):

- Study complex interaction between groundwater and surface water to develop more accurate coupled surface water and groundwater model.
- Develop an accurate catchment-scale groundwater risk assessment model by introducing nitrogen biochemical and physical processes in the soil and nitrogen dynamic activity above the water table.
- Simulate the processes of nitrogen movement in the groundwater.
- Investigate the impact of the nitrogen biochemical and physical processes in the soil on water quality at catchment scale by improving existing water simulation model.

2.3. The significance of proposed project

1) The interdisciplinary study of nitrogen biochemical process in the soil and water process will provide scientific evidence for better understanding and reducing nitrogen ADWP at catchment scale.

2) The scientific knowledge of the interaction between surface and groundwater can provide better understanding of the mechanism of pollutant pathways to water bodies.

3) New surface and groundwater models can act as decision-support tools for sustainable nitrogen management at catchment scale by providing explicit risk zones for spatial planning of preventing nitrogen entering water bodies and evaluating the impacts of these plans on the quality of surface and groundwater.

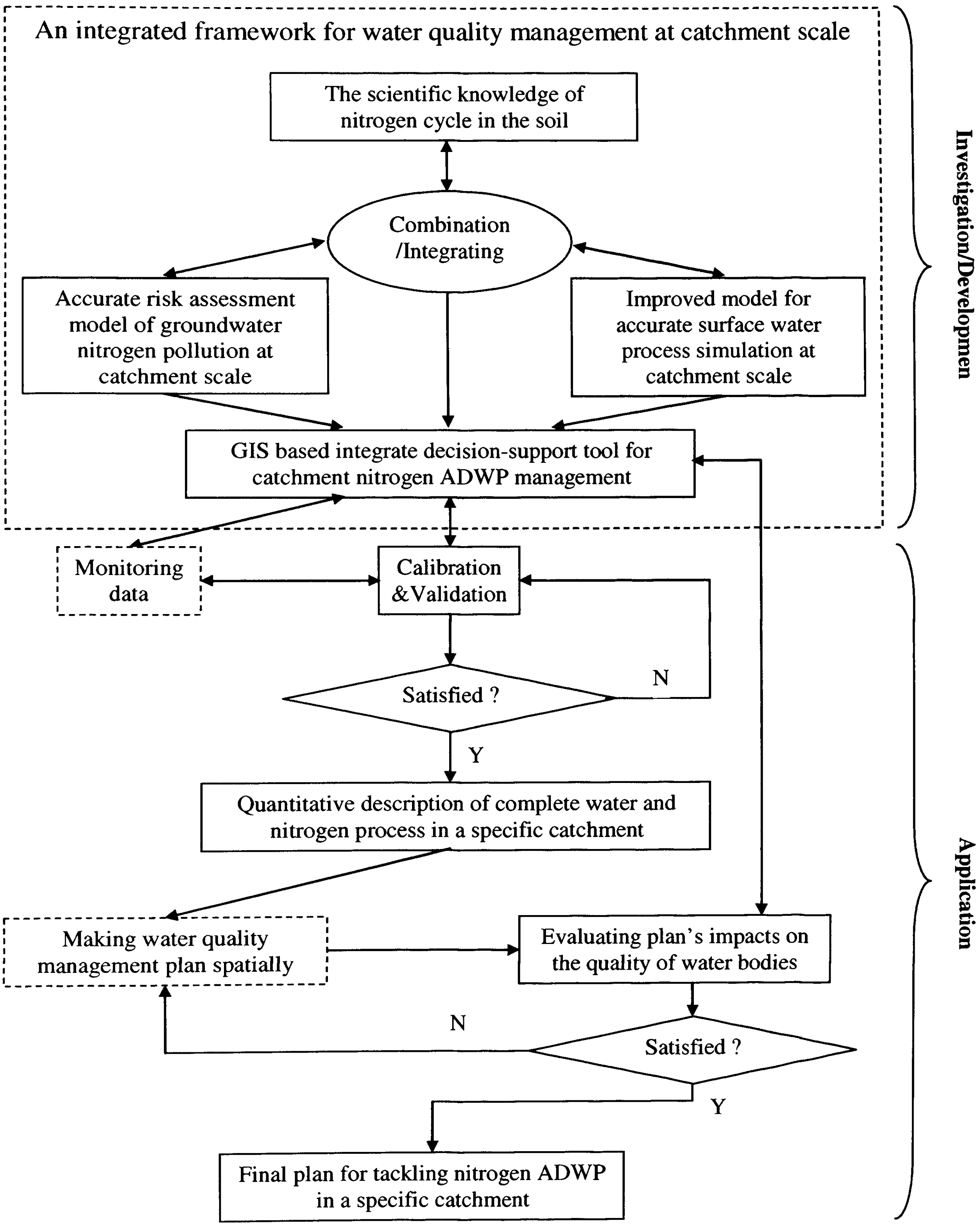


Fig. App.C.1. The framework of the proposal for ERC first grant 2007

4) Pragmatic and transferable knowledge, measures and tools for handling ADWP problem are urgently needed for the implementation of the EU WFD for all EU Member States. The results of this project will bridge the gaps mentioned above; thus, they will be not only helpful for better implementation of the EU WFD, but also be useful for tackling the nitrogen ADWP problem all over the world.

2.4. Methodology

2.4.1. Integrated conceptual framework

An open and extendable framework for catchment-scale water quality management will be set up. This framework will allow the function of models to be translated into decision support tools, and will be of value not only in this proposed project, but also for other similar ADWP studies.

2.4.2. Groundwater and surface water interaction in water cycle

A better characterisation of water and solute movement in the unsaturated zone will allow a more accurate coupled surface water and groundwater model to be developed. The 3D numerical models based on current experience and expertise can provide a more reliable ground-surface water interaction for the integrated diffuse pollution modelling under agricultural activity. A spatially distributed GIS index model will be coupled with 3D MODFLOW and MT3D/RT3D. Modelling calibration and validation will be based on fieldwork data. In order to study the interaction between groundwater and rivers, two or three sets of boreholes crossing the riparian zones of rivers will be designed in each catchment for monitoring hydraulic heads and water quality in observing wells and rivers.

2.4.3. Incorporating nitrogen soil cycle models

INCA-N model and ECOSSE model will be used for investigating the nitrogen transformation and transport in the soil under different land uses, crop types and soil temperatures and moisture levels. INCA-N is a process-based and semi-distributed model for the simulation of the catchment nitrogen process. The nitrogen turnover model, ECOSSE, was derived from two well-established plot scale models; a model of nitrogen turnover, SUNDIAL and a model of carbon turnover, RothC. ECOSSE describes all of the major plot-scale processes of carbon and nitrogen turnover in the soil / crop system, including mineralisation / immobilisation and nitrification turnover within the soil as well as gaseous and leaching losses of carbon and nitrogen to the atmosphere and groundwater. The results of the catchment scale and plot scale model can well complement each other. The scientific knowledge of the nitrogen soil processes will be integrated into the methods of the groundwater risk assessment and the surface water quality simulation.

2.4.4. Developing accurate groundwater pollution risk assessment approach

Among four types of methods for groundwater risk assessment, the index method will be adopted due to its advantages of data availability, easy understanding and application, and extensibility. The DRASTIC method, one of index methods, was developed by the U.S. Environmental Protection Agency (EPA). DRASTIC is being used worldwide for groundwater vulnerability assessment at both large and small scales, but it has pitfalls. For example, DRASTIC does not include the concept of risk and considers no pollutant dynamic nature with runoff. In order to overcome the shortcomings of the DRASTIC method, a D-DRASTIC method was developed by our team. The D-DRASTIC method will be use in the development of a more accurate risk assessment of groundwater pollution to guide catchment-scale groundwater pollution prevention. By introducing the concept of risk and the dynamic nature of soluble pollutants on the ground surface and in soil layers, D-DRASTIC is suitable for the risk assessment of groundwater pollution from all soluble contaminants (Eq. App.C.1 - 4).

$$RI_i = \frac{DVI_i}{DVI_{\max}} \times \frac{H_i - H_{\min}}{H_{\max} - H_{\min}} \qquad \text{(APP.C.1)}$$

$$H_i = VH_i + HH_i \qquad \text{(APP.C.2)}$$

$$VH_i = \frac{LR_i \times K_1}{NR_i \times K_2} = \frac{LR_i}{NR_i} \times K \text{ (mg N/liter)} \qquad \text{(APP.C.3)}$$

$$HH_i = \frac{EC_i \times K_1}{RO_i \times K_2} = \frac{EC_i}{RO_i} \times K \text{(mg N/liter)} \qquad \text{(APP.C.4)}$$

where RI_i is the result of the D-DRASTIC risk assessment in cell i, $RI_i \in [0, 1]$; DVI_i the index of the DRASTIC groundwater pollution vulnerability in cell i; $DVI_{\max}$ the maximum DRASTIC groundwater pollution vulnerability index in the study area(s); H_i the soluble pollutant hazard to groundwater, standing for the nitrate hazard to groundwater in cell i, or the nitrate concentration in cell i; $H_{\min}$ and $H_{\max}$ represents the minimum and maximum hazard concentrations in the study area(s) respectively. VH_i is the vertical nitrate flux reaching groundwater via leaching and percolation in cell i; HH_i the extra nitrate carried by runoff to cell i that can promote further nitrate leaching and percolation through soil and unsaturated vadose zone, then contaminate groundwater. LR_i is the nitrate-leaching rate (Kg N/ha/a) in cell i; NR_i (inch) net recharge in cell i; EC_i the accumulated nitrate runoff export coefficient (Kg N/ha/a) in cell i; RO_i the accumulated runoff (inch) in cell i, the process of rainfall producing runoff and river and will be explained in the following section 3.4 in detail. $K_1 = 2.50 \times 10^5$ (mg N/a) is a converter of the nitrate-leaching rate or runoff export coefficient from Kg N/ha/a to mg N/cell/a; $K_2 = 6.35 \times 10^4$ another converter of the net recharge from inch/m^2/a to liter/cell/a; $K = K_1/K_2 = 3.94$ (cell size: 50m×50m).

The soil profile nitrogen model will be integrated into the risk assessment model of groundwater pollution. This will provide a reliable and accurate groundwater risk assessment and the guidance for the prevention of ADWP in the catchment.

2.4.5. Nitrogen fate in groundwater

3D Visual MODFLOW (3D groundwater flow and contaminant transport model) will be used to simulate the nitrogen movement in groundwater. The fate of nitrogen in the groundwater will be used to guide groundwater remediation activities in the catchment.

2.4.6. Improving surface water model

The Hydrological Simulation Program—FORTRAN (HSPF) is designed to simulate water quantity and quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. This model will be used to simulate surface water movement. HSFP is one of the few available models that can simulate continuous dynamic events or steady-state behaviour over the required range of both hydrologic/hydraulic and water quality processes through both the surface and groundwater regimes in a catchment (Re. our other recent works for the details of selecting and assessing HSPF as water modelling tool for the implementation of the EU WFD). The proposed work on the nitrogen processes in the water cycle and the interaction between surface and groundwater will be used to improve the nitrogen soil components in HSPF.

2.4.7. Geographical Information System

A geographical information system will be adopted in the integrated framework to allow improved spatial data management, analysis, and visualisation. In the developing of GIS models and tools, 'loose coupling' and 'embedding' methods will be used.

2.4.8. Computer Programming Language

In the development and improvement of the models and tools, the computer-programming languages, Visual C++ and FORTRAN will be used.

2.4.9. Pilot catchments

This study will be carried out in two catchments: 1) the Wye Catchment (4010 km^2) located in the Welsh borders. The DEM, land use, geology, soil, river flow, and water quality monitoring data will be provided by UK Environment Agency. 2) The Upper Bann Catchment, covering an area of 674 km^2, lies in the southeast of Northern Ireland, UK. Previous surface and groundwater studies have been carried out in this catchment. This catchment will be used as a testing area for newly developed methods/models.

2.5. Project Management

2.5.1. Project activities

The activities of this project will include: (1) Initial review; (2) data acquisition; (3) investigating nitrogen cycle in the soil; (4) studying the interaction between surface and groundwater; (5) developing accurate groundwater risk assessment method and simulating the nitrogen movement in groundwater; (6) improving HSPF model; (7) Evaluating newly developed methods/models by applying them to the Upper Bann Catchment and analysing the differences between new results and previous results.

2.5.2. Gantt-chart

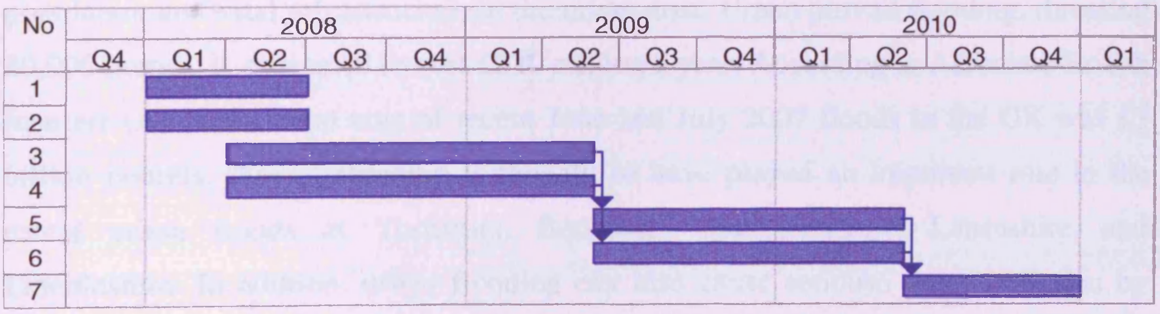


Fig. App.C.2. The Gantt-chart of the proposal of NERC research grant 2007

2.5.3. Research Staff

Principle investigator: Dr Yuesuo Yang (Cardiff Earth Sciences)

Co-investigator: Dr Bettina Bockelmann-Evans (Cardiff Engineering)

Co-investigator: Dr Tim Jones (Cardiff EARTH) (Cardiff Earth Sciences)

Named PDRA: Dr Lei Wang

3. Proposal for NERC FREE call

Title: A Novel Spatial GIS Index Model for Urban Pluvial Flooding Risk Assessment

Principal Investigator: Yuesuo Yang

Hosting Institution: Cardiff University

Project duration in months: 24

3.1. Background to scientific issue

Urban flooding is caused by heavy rainfall overwhelming drainage capacity. Pluvial flooding, resulted from rainfall generated overland flow before the runoff enters any watercourse or sewer, is one of important elements in urban flooding that may cause costly demage, distress and sometimes loss of life beause of high density of population and vital infrastructure in the urban area. Urban pluvail flooding, threating 80,000 homes, is estimated to cost £270 million a year. According to Associate British Insurers (ABI), the total cost of recent June and July 2007 floods in the UK was £3 billion pounds. Pluvial flooding is thought to have played an important role in the recent urban floods at Yorkshire, Berkshire, Gloucestershire, Lancashire, and Lincolnshire. In addtion, urban flooding can also cause seriouse water pollution by picking up potentially harmful substances from surfaces, such as oil, houshold chemicals and faceal material.

According to the Foresight Flood and Coastal Defence Project, the cost of damage from urban flooding in Britain could rise by 20 times (between £1-10 billion pounds a year) over the next century, if no action were taken to reduce the risks. Therefore, it is urgent to find effective ways to predict, manage, and respond urban flooding, which have already had large economic and social impacts. However, from the scientific point of view, there are two major problems in current urban flooding management.

(1) Lack of effective warning method for the urban pluvial flooding. Both the Environment Agency and the Scottish Environment Protection Agency operate flood-warning schemes; however, these schemes have little help in warning those likely to be affected by very suddenly urban pluvial flooding.

(2) Lack of scientific understanding of the causes of urban pluvial flooding is a major barrier to developing methods for urban flooding handling. Moreover, the land uses or urbanisation planning based on this could cause more urban flooding problems.

Therefore, it is necessary to develop new methods for effective urban pluvial flooding management based on better scientific knowledge of the urban flooding.

3.2. Aim and objectives

This project aims at developing a novel spatial GIS index model for the risk assessment of the urban pluvial flooding based on better scientific understanding of urban pluvial flooding mechanism.

The detailed objectives of this project:

1) **Carry out the modelling of urban flood routes and complete hydrodynamic routing in the storm sewers**

Review the existing potential urban flooding models and to select a few useful models to be utilised as effective urban flooding tools. The urban flood modelling will not only provide a basis for the mechanism study of the urban pluvial flooding, but also evaluate and find suitable models for better urban flooding simulation.

2) Study the mechanisms of the urban pluvial flooding

Find out key driving factors that trigger the occurrence of urban pluvial flooding, and investigate how these factors affect the process of urban flooding by carrying out different scenarios simulation using the above-selected urban flooding models. For example, the critical rainfall values that trigger the urban pluvial flooding in study areas will be found out. This study will establish relationships between the critical rainfall value and the depth of flood water, the capacity of existing urban drainage system, urban land use structure, urban topography, urban air temperature, surrounding catchment topography, river level, aquifer type, and water table depth, etc.

3) Develop a spatial GIS model for urban pluvial flooding risk assessment

The urban pluvial flooding risk (UPFR) is the result of the combination of the urban pluvial flooding vulnerability (UPFV) and the hazard – the intensity of rainfall. The urban pluvial flooding vulnerability (UPFV) mentioned here means the potential possibility of occurring urban flooding determined by objective conditions of urban and its surrounding catchment without considering the factor of rainfall. Cities/towns with the history of urban pluvial flooding might have low UPFV, while areas without urban flooding history may have high UPFV. However, it will never be wrong to carry out actions to make plans of urban flooding management and fast response for the mitigation of flooding damage in high UPFV areas.

3.3. The significance of proposed project

1) This study may provide a strating point for handling the urban pluvail flooding in an effective and sustainable manner. Firstly, this spatial GIS model will be transferable to other areas in the UK. Secondly, compared to process based urban

flooding modelling, this spatial GIS model can be easily understood and applied with less costs for decision support. The model will effectively find out high risk areas for urban flooding by considering key driving forces which likely cause urban pluvail flooding. Finally, it may become a basis of setting up systemic work flow for sustainable management of urban flooding in the UK. Fig. App.C.3 shows a prototype of possible systematic work flow. The spatial GIS model for UPFR can be applied in the UK because of its characteristics of easy application and low costs; and then the priority of the urban flooding management can be set by focuing on areas with high UPFR; further investigation, such as detailed urban flooding modelling, detaied assessment of drainage system, and field survey in surrounding catchment, will be carried out in the areas with higher priority; actions will be taken to reduce the UPFV, and to mitigate the damage of possible urban pluvial flooding. The assessment of UPFR in the UK will be re-carried out after the first round of management, and to find out areas with high UPFR in the next round. This repeating work flow will not only efficiently reduce urban flooding risk in the UK, but also provide precious time for making urban flooding mitigation plans.

2) The scientific knowledge in this study will help scientists, decision makers, and industrial scientists better understand urban pluvial flooding mechanisms.

3) The GIS index model provide a potential for accurate urban flooding forecasting by integrating the methods of accurate extreme rainfall events forecasting.

4) The result of the evaluation of process-based urban flooding models in this project can guide future detailed urban flooding modelling in high UPFR areas.

3.4. Methodology

3.4.1. Study areas

The selection of a study area (s) will consider the urban flooding history, the availability of Light Detection and Ranging (LiDAR), detailed land use, urban drainage system, river network, and hydrogeology data.

3.4.2. Urban flooding modelling

The two-dimensional hydrodynamic model MIKE 21, developed by the Danish Hydraulics Institute (DHI), is a professional engineering software package with an advanced numerical scheme capable of modelling the complex flow fields associated with overland flows. By providing a complete and effective design environment, an advanced GUI combined with a series of highly efficient computational engines, GIS integration, integration with urban and water resource models for flood modelling, modules for virtually any kind of 2D water modelling needs, sophisticated tools for data handling, analysis and visualization, and well-proven technology with more than 30 years of track record, MIKE 21 is a suitable tool for urban flood modelling. A novel methodology - a link between InfoWorks drainage model and Mike 21 developed by Hyder Consulting will be used in this study.

SWMM, Storm Water Management Model, was developed for US EPA as single-event model specifically for the analysis of combined sewer overflows. SWMM consists of several modules, namely, Runoff, Transport and Extran, designed to simulate both continuous and single event quantity and quality processes in the urban hydrologic cycle. Storm sewers, combined sewers, and natural drainage systems can be simulated.

Both MIKE21 and SWMM are powerful models for urban flooding simulation, and will be employed for the modelling of urban flooding routes and storm sewer routing. Modelling results from two models will be compared and evaluated.

In order to study the mechanisms of urban pluvial flooding process, scenarios (such as extreme climate event, different land use structure, river level, groundwater level) will be designed, modelled, and analysed. This is the foundation of the developing a GIS index model for the UPFR assessment.

3.4.3. GIS index model for the UPFR assessment

This GIS index model can be expressed by the Eq. App.C.5:

$$UPFR = UPRV \times RF \qquad \text{(APP.C.5)}$$

where RF is the amount of rainfall estimated using rainfall forecasting method.

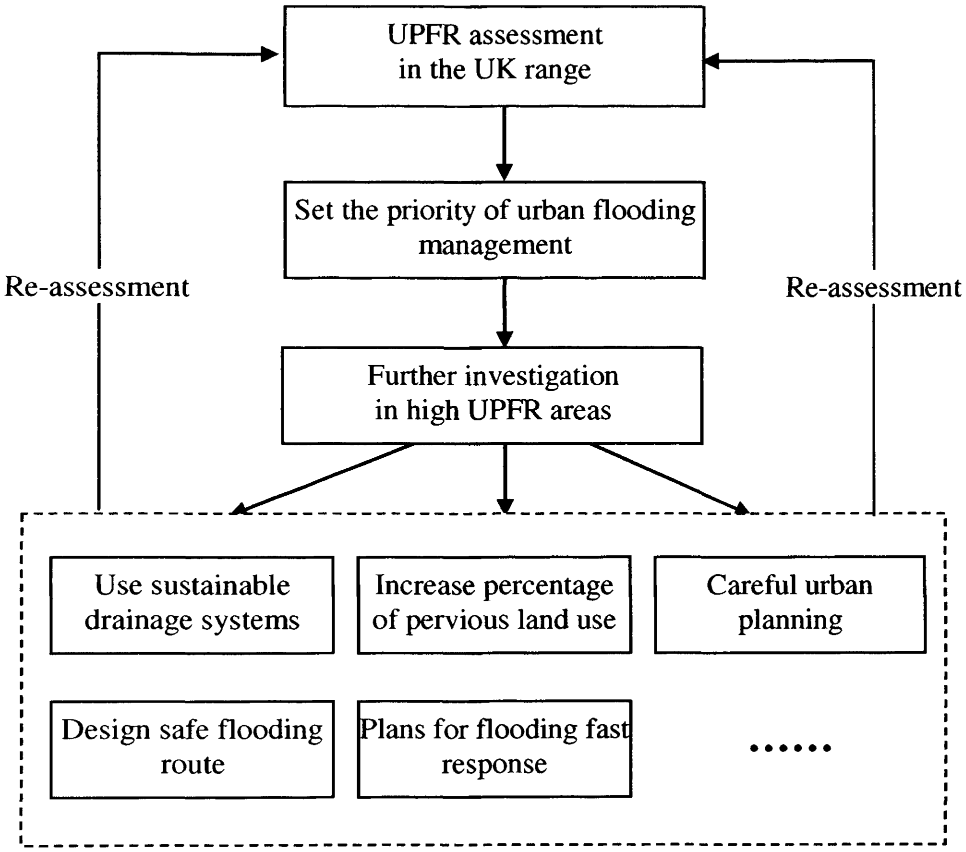


Fig. App.C.3. A prototype of systematic work flow for urban pluvial flooding management

The development of the GIS index model for the UPFV assessment will be based on raster data format in GIS. This means that the study area will be equally divided into grids. Eq. App.C.6 is the definition of the UPFV:

$$UPFV_g = \sum_{i=1}^{n} W_{ig} F_{ig} \qquad \text{(APP.C.6)}$$

where $UPFV_g$ is urban pluvial flooding vulnerability in the grid g; F_{ig} is No. i factor that makes urban vulnerable to pluvial flooding in the grid g. the value range of i is from 1 to n, n is the total number of factors considered for the assessment; W_{ig} is the weight of the factor F_{ig} in the grid g representing the importance of factor i in the UPFV assessment.

The selection of factors F_i and determination of W_i value will be based on not only the scientific analysis after the urban flooding modelling, but also the existing experience and knowledge of urban pluvial flooding. The availability and possibility of quantification of data will also be considered in the selection of factors for developing this GIS index model. For instance, the capacity of drainage system, permeability of urban land use at different season, the difference between elevation at one location and the average urban elevation, the difference between urban average elevation and its surrounding catchment average elevation, river water level, and groundwater table depth, etc., can be selected as factors for this study.

In order to improve the reliability of the calculation of the weight of each factor, two methods will be used, namely, statistic analysis method, and the analytic hierarchy process (AHP) method. The first method will be based on the spatial correlation analysis between rasterised factors and flood water depth layer in GIS. The AHP method is an effective systematic analysis method that quantitatively expresses and processes the human being's qualitative opinion using fuzzy relationship matrix. Many outstanding studies using AHP have been published in the fields of planning, the best alternative selecting, resource allocations, conflicts resolving, optimisation, and so on. This study will employ AHP for the calculation of the weight of each factor by making best use of the existing knowledge of urban flooding from experts.

This GIS index model is a non-process based model by simplifying the controlling factors in urban flooding based on both objective scientific evidence from urban flooding modelling and subjective opinions from experts of urban flooding. This model will be able to be easily used and transferred to other areas in the UK.

3.5. Project Management

3.5.1. Project activities

The activities of this proposed project will include: (1) Initial review; (2) data acquisition; (3) urban flooding modelling; (4) the evaluation of models for urban flooding simulation (5) better understanding of the mechanisms of urban pluvial flooding based on the analysis of driving factors in urban flooding using modelling results; (6) developing a GIS index model; (7) improving this GIS index model in the application of it in different study areas. These activities are scheduled in the following section.

Project start date: 01/12/2007;

Project end date: 30/11/2009

3.5.2. Gantt-chart

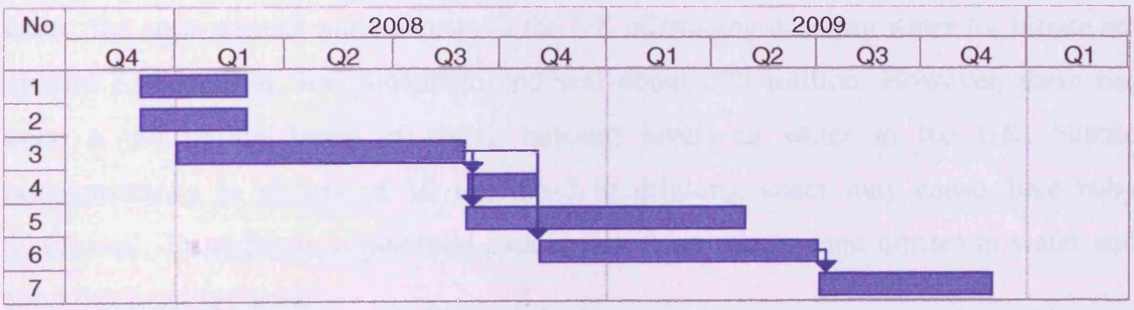


Fig. App.C.4. The Gantt-chart of the proposal for NERC FREE call

3.5.3. Research Staff

Principle investigator: Dr Yuesuo Yang (Cardiff Earth Sciences)

Named PDRA: Dr Lei Wang

Subcontractor: Hyder Consulting

4. Proposal for RAEng/EPSRC Research Fellowships 2007-08

Title: A GIS-based decision support system for sustainable catchment-scale management of water pollution from diffuse agricultural nitrogen

Principal Investigator: Lei Wang

Hosting Institution: Cardiff University

Project duration in months: 60

4.1. Background

The diffuse source water pollution is more complex and difficult to control in comparison to point source pollution. It is not only a serious environmental issue but also a threat to economics and human health. For example, water with high concentration of nutrients can cause eutrophication in rivers, lakes and estuaries. Nutrients removal represents a significant fraction of the total UK water treatment costs: the approximate annual costs in the UK of treating drinking water for nitrate are around £16 million, for phosphate and soil about £55 million. However, there has been a continuing trend of rising nutrient levels in water in the UK. Nitrate concentrations in excess of 10 mg dm-3 in drinking water may cause 'blue baby syndrome'. In addition, a potential cancer risk from nitrate (and nitrite) in water and food has been reported.

The EU Water Framework Directive (WFD) came into force in 2000, aiming at achieving at least “good status” for all the waters in the EU Member States (EUMS) by 2015. Diffuse water pollution is the biggest remaining problem of water pollution in many countries. The largest source of diffuse water pollution is agriculture. In England, it is estimated that over 70% of nitrates in natural waters are derived from agricultural land. Agricultural diffuse water pollution (ADWP) has been identified as a major threat to water quality and the implementation of the EU WFD.

Great efforts have been made for the implementation of the EU WFD. However, from scientific and technical points of view, there are still gaps between current research and the implementation of the EU WFD in the field of ADWP. Water environmental scientists are facing challenges of bridging these gaps before 2015.

4.1.1. Method and tool gap

River Basin Management Plan (RBMP), the backbone of the EU WFD implementation, is a mechanism or system of reporting and administration that ensures the successful implementation of the EU WFD. Although RBMP has the Programme of Measures that set out the specific measures to achieve the improvements to the water environment, the answer of the question of what these measures will actually look like, or specifically what they will include, is still largely unknown. In addition, EUMS do not know how best to deal with the requirements of the EU WFD. Similarly, Common Implementation Strategy (CIS) and Pilot River Basins (PRB) network do not directly contribute the developing new methods or tools. Therefore, each EUMS has to start work on the better definition and guidance on producing measures for effective water resources management. However, many of the research tasks from the EU WFD are new, and often no useable methodologies exist. Alternatively, if useable methodologies do exist (such as in England and Wales), these methods are not enough for the implement of the EU WFD. Moreover, there is not enough effort made in existing programmes relating to the implementation of the EU WFD in the ADWP field. For example, among 15 finished projects of CATCHMOD in the fifth EC Framework Programmes (FP), only EUROHARP was directly dealing with ADWP problems. Therefore, more efforts should be made to develop integrated and pragmatic numeric models and methods of tackling the ADWP problem for successful implementation of the EU WFD.

4.1.2. Research scale gap

The prevention of ADWP at catchment scale is the key for handling the ADWP problem in a sustainable manner. Once water is contaminated, it will be very costly to clean-up and can take a long time to recover, especially for groundwater. Since it is difficult to determine at the regional scale the contribution of diffuse agricultural sources to water pollution, water protection practices should be carried out at catchment or watershed scale.

RBMP, utilising the River Basin Distract (RBD) as the natural unit, is helpful to decide the priority of water management in the scale of RBD. However, the practical control of ADWP in each catchment of a RBD needs catchment-scale ADWP prevention measures to complement the RBMP. Many ADWP studies have been carried out at river basin, national, and even European scales. For example, Giupponi and Vladimirova (2006) developed a screening model (Ag-PIE) for the assessment of pressures from agricultural land use and the consequent impacts on water at the European scale. Each EUMS has been carrying out national-scale water quality studies. Within the UK context, the generations of maps of groundwater vulnerability and Nitrate Vulnerable Zones (NVZs) of England, Wales, Scotland, and Northern Ireland were based on the national scale. UK Technical Advisory Group (2004) carried out the studies of assessing agricultural pressures and impacts risk on water quality at a national scale in the UK. These small-scale (national-scale) ADWP studies have limitation in guiding the prevention practices of ADWP at catchment scale. For instance, most of Northern Ireland should be designated as NVZs. This result is helpless for guiding the prevention of the ADWP at catchment scale.

Recently, more and more attention has been paid to the research of the catchment-scale water quality modelling. For example, in small-scale dominated CATCHMOD cluster of the FP5, there were several projects based on catchment-scale research, such as GOUVERNE, MULINO and TempQSim. UK Environment Agency (EA) has been developing the strategy of solving environmental problems using the Integrated Catchment Science. The MAGPIE tool was developed to calculate total nitrate leaching losses from all agricultural activities. Many models of nutrient process in the water and land phases were developed, such as ANIMO, INCA, HSPF, SWAT, and SHETRAN models. The ongoing catchment sensitive farming programme is trying to work with stakeholders to develop an effective package of good farming practices to tackle ADWP. However, the sustainable management of the complicated ADWP problem, which includes many factors in multi-spheres, requires integrated modelling methods covering ADWP phases of source – pathways – targets. Therefore, it is necessary to develop integrated catchment-scale decision support tools to guide the handling of the ADWP problem, by making good use of existing methods, models, and the knowledge of the ADWP process.

4.1.3. Fundamental knowledge gap

Good scientific understanding of the physical and biochemical processes of diffuse pollutants in the water cycle is essential for catchment-scale prevention of ADWP. Currently, there is still limited scientific knowledge of the fate, transport, and biochemical processes of nutrients within and between air, plants, soil, rocks, groundwater and surface water under different natural and human agricultural activity conditions. It was from the 1970's and early 1980's when scientists have been developing and updating methods to solve the ADWP problem – an old problem. However, the ADWP is still an important issue in resolving water pollution problems demanded by the EU WFD. Therefore, it is timely to develop innovative measures for effective handling of ADWP before 2015. Thus, it is also necessary to carry out more multi-disciplinary fundamental studies for better understanding of the ADWP process, and then to support the development of innovative measures for pragmatic and sustainable management of ADWP.

4.2. Programme and methodology

4.2.1. Aim of proposed project

To develop an integrated decision support modelling system based on GIS for sustainable management of diffuse water pollution from agricultural nitrogen-N at the catchment scale, in order to complement the RBMP for better implementation of the EU WFD in the UK.

4.2.2. Objectives of proposed project

Objective 1: Assess the existing ICEMAN modelling method, developed by the applicant for catchment-scale ADWP management, in a Welsh catchment Tywi;

Objective 2: Improve the ICEMAN method by introducing INCA, SWAT and PLANET modelling components for better presentation of vegetations/crops, soil water system, and also proper connection with farming activities; for a more complete surface, soil and groundwater modelling; and for a better capability of N bio-chemical process modelling in soil and surface water.

Objective 3: Assess the improved ICEMAN method in the River Tywi Catchment. The detailed surface water and groundwater quality monitoring data gathered from fieldwork will be used to validate the integrated modelling of N process in catchment water cycle.

Objective 4: Develop a GIS-Based, integrated decision support modelling system based on improved ICEMAN method, and develop a Website for better dissemination of the results of this project.

4.2.3. Methods

4.2.3.1. The River Tywi Catchment

The River Tywi system in South Wales is 78 km in length and drains southwest towards Camarthen from the upland areas surrounding Llyn Brianne. The River Tywi catchment (1090 km2), belongs to Western Wales RBD, is an ideal test catchment for applying the ICEMAN method, which integrates surface water and groundwater modelling, due to the various land uses from coniferous forests-Sitka spruce, Lodgepole pine and moorland in the upper reaches to pasture and some arable in the lower reaches. Nitrogen deposition is an issue of concern in the region and a number of the plantation forests are thought to be ‘nitrogen-saturated’ in that they are leaching nitrate in excess of plant and microbial demand. There is considerable quantity of river flow and surface water chemical quality data available from EA Wales for the calibration and validation of the surface modelling. In addition, there are 17 groundwater-sampling sites (including 3 boreholes, and 14 wells and springs) available for the validation of the method of groundwater risk assessment.

4.2.3.2. ICEMAN modelling method

The ICEMAN method, developed by the applicant, can quantitatively model the catchment-scale N biochemical cycle in soil, surface water process, groundwater pathway vulnerability, groundwater N risk, the dynamic nature of N with surface runoff and interflow, the interaction between surface water, soil water and groundwater. In addition, ICEMAN can help decision makers efficiently evaluate (model) the impacts of their proposed plans or strategies on the process of surface water and groundwater before making final decisions of catchment ADWP management. After the evaluation in the river Tywi Catchment, ICEMAN will be improved in following two major aspects:

1) Accurate groundwater risk assessment method. D-DRASTIC, a groundwater risk assessment method in ICEMAN, overcomes the drawbacks of DRASTIC by integrating the risk concept and nutrient dynamic nature – nutrient loading and transport with runoff. D-DRASTIC can well guide the practices of groundwater pollution from diffuse agricultural nutrients by spatially delineating risk zones in a catchment. D-DRASTIC can be expressed as Eq. App.C.1.

D-DRASTIC will be improved by introducing more accurate N bio-chemical process in soil; hence to improve the accuracy of ICEMAN method in the groundwater risk assessment part.

2) N soil bio-chemical process, and surface water models. To better simulate the flow pathways and tracks fluxes of both nitrate-N and ammonium-N in the land phase and riverine phase, the INCA model will be used to investigate the fate and distribution of nitrogen in the surface & soil water environment. Day-to-day variations in flow, N

fluxes and concentrations can be investigated following a change in N inputs such as atmospheric deposition, sewage discharges or fertiliser application. INCA will be employed in modelling soil N bio-chemical process modelling (such as the fluxes of plant uptake, mineralisation, immobilisation, nitrification, export to surface water, and leaching); in surface water quality modelling; and in improving the D-DRASTIC method by introducing more accurate N leaching rate in different land uses and soil types.

Parallel to INCA, the Soil Water and Analysis Tools (SWAT), a physical-based model developed by US Department of Agriculture, will be also used in the prediction of the long-term impact of agricultural management practices on water in complex watersheds with varying soils, land use, and management conditions. The application process and the results of SWAT and INCA will be compared in order to select a suitable model to improve the accuracy of ICEMAN in N soil process and surface water modelling. In FP5, SWAT was assessed in a Finnish catchment for the implementation of the EU WFD.

4.2.3.3. Calibration and validation of models

Since the final groundwater risk assessment method is a slump (no-process based) model, its spatial risk zone results will be validated using the 5-year (2003-2008) average groundwater nitrogen quality data of 3 boreholes in study are; and 1-year detailed groundwater nitrogen quality monitoring data from 17 groundwater sampling sites (2009) in the study catchment. The modelling of N bio-chemical process in soil using INCA will be calibrated and validated using N fluxes of the major transformations from experimental and field studies in the literature. The river flow modelling using INCA and SWAT will be calibrated and validated using 5-year (2003-2008) and 1-year (2009) daily river flow data respectively. The river quality modelling will be respectively calibrated and validated using 5-year monthly (2003-2008) and 1-year half-monthly (2009) river chemical quality monitoring data in the study area. The EA's water quality monitoring data (groundwater: half-yearly data in 3 boreholes; surface water: monthly data) are not enough for the validation of models.

Therefore, the fieldwork of monthly water sampling (groundwater in 17 sites; surface water data will be half-monthly in 4 gauge stations) and N lab analysis in the study catchment for 12 months (2009) are necessary for the validation of models.

4.2.3.4. Interface with farming activities

This is a modelling research directly related to agriculture. This project aims to solve four questions in the decision support system:1) make the final system capable of minimising the side effect of agriculture activities to water ecosystem without harming farmers' profits by achieving good crop yields and quality with low expense of fertilisers; 2) to provide easy and effective connection to farmers, e.g. support to the various soil type, NVZs information and rainfall data; 3) to spatially visualise the fertiliser application plans for the straightforward understanding of farmers; 4) to be capable of evaluating the impact of new fertiliser application plans on water quality. Therefore, the PLANET software developed by ADAS with funding from Defra, the EA, and the DARDNI, capable of developing a nutrient and manure application plan for a group of fields by taking account of the crop nutrient requirement as well as the nutrients supplied from organic manures, soil, and fertilisers, will be employed in this study.

4.2.3.5. Developing the integrated decision support system

To effectively integrate the soil, groundwater, surface water models, and PLANET tool, ArcEngine and C# will be adopted as the modelling tools in developing the decision support system on the ArcGIS 9.1 platform. The integration will 'melts' models of each phase of N process in water cycle into an enhanced system that can well reflect the N process in the reality. GIS will be used to generate model input files and model results visualisation. To improve the efficiency of system application, a user-friendly GIS interface will be developed to include the spatial data exchange between models and complex modelling calculations. For example, the nitrate transformation flux result of INCA, and runoff result of surface water model will be automatically input into the groundwater risk assessment model. The system can automatically generate the input data for PLANET and then input its results into other models to evaluate the impacts of these fertiliser application plans on water quality.

4.2.3.6. Website based dissemination

A website will be designed using C#.net and hosted by Cardiff School of Earth, Ocean and Planetary Sciences (School of Earth). The system will provide different interfaces for different users (e.g. government, scientists, farmers, and public). This website will be the starting point of further development of a more powerful WebGIS-based decision support system.

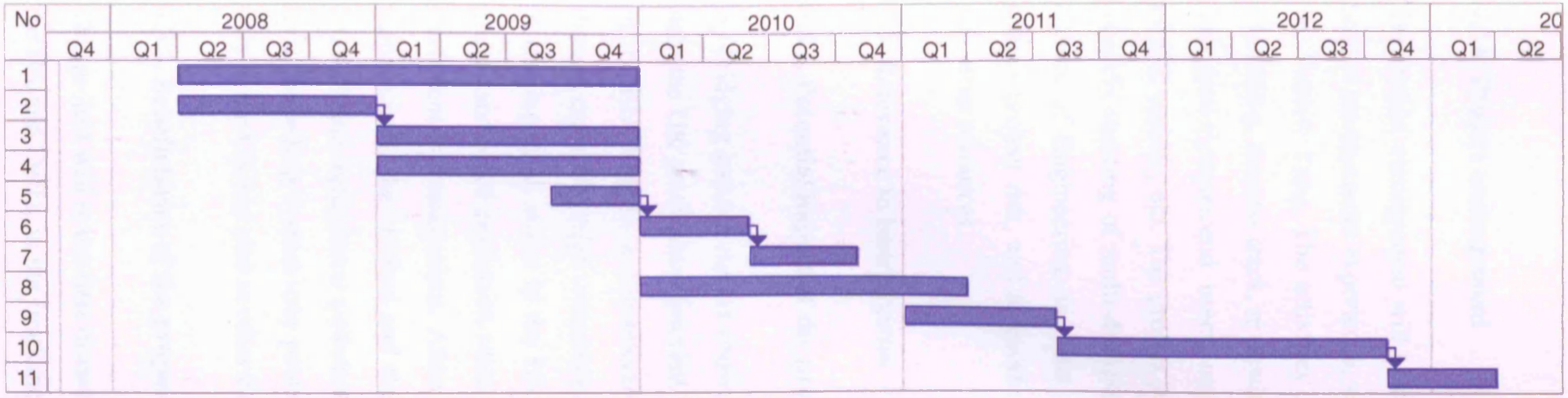
4.2.4. The timeliness and novelty of the proposed project

Next 7 years from 2008 are pivotal for successful implement of the EU WFD in the UK, especially in ADWP field. According to the timetable of the EU WFD, the Programme of Measures in the RBMP is required to be operational by 2012. By providing a pragmatic and transferable decision support modelling system, this project, capable of complementing the RBMP in sustainable management of N at the catchment scale, is timely for better implementation of the EU WFD in the UK.

The novelties of this project include: 1) the quantitative modelling of complete ADWP phases of source – pathways – targets, including the integration of surface, soil and ground water processes in the decision support of catchment-scale water quality management; 2) GIS-based and transferable decision support system that provides better scientific understanding of N processes in complete hydrological cycle in a specific catchment, thus leading to sound ADWP prevention decisions; 3) The integrating of PLANET into the decision support system that can improve the enthusiasm of farmers in aquatic environment prevention.

4.2.5. Programme of work and milestones

Objective 1 includes tasks 1-5; objective 2 includes tasks 6-8. objective 3 includes task 9; and objective 4 includes tasks 10 and 11 (Fig. App.C.5).



1. Initial literature review (21 months – overlap with task 2, 3, 4, and 5);
2. Data preparation and GIS database setup (9 months – overlap with task 1);
3. Application of ICEMAN in the River Tywi Catchment, including calibration and validation using river flow, surface and groundwater chemical quality monitoring data (12 months – overlap with task 4 and 5);
4. Fieldwork of water sampling and N quality lab analysis for detailed water quality data (12 months– overlap with task 1, 3 and 5);
5. Assessing the ICEMAN method (**Milestone 1**) (4 months – overlap with task 1, 3 and 4).
6. Simulating soil & water N bio-chemical process using INCA model (5 months – overlap with task 8);
7. Improving groundwater risk assessment method by introducing accurate N soil process (5 months – overlap with task 8);
8. Simulating surface water quantity and quality processes using INCA and SWAT models, and then comparing the application process and results of two models (15 months – overlap with task 6, 7, and 9);
9. Assessing the improved ICEMAN by applying it in the study area (**Milestone 2**) (8 months – partially overlap with task 8);
10. Developing and testing an GIS-based integrated decision support system, including the integration of PLANET tool into the system, based on improved ICEMAN method (**Milestone 3**) (15 months);
11. Developing a Website to demonstrate the GIS-based decision support system (**Milestone 4**) (5 months).

Fig. App.C.5. The Gantt-chart of the proposal of RAEng/EPSRC Research Fellowships 2007-08

4.2.6. Project management

The project management will be carried out by applicant, who has two-year industrial project management experience, with necessary supports from the School of Earth and Dr. Yuesuo Yang. The activities of project management include project planning and scheduling, process track, reviewing and revising schedule if required, communication with beneficiaries/end users, cost assessments and seasonal validation, preparing project reports, etc. The project progress and scientific issue will be presented in the monthly meeting of multi-disciplinary research teams in the School of Earth and the School of Engineering, in order to make sure that problems be solved in time to reduce project risk, and to ensure the quality of the project within the range of time and other resources.

4.3. Relevance to beneficiaries

4.3.1. Potential impact of the proposed work

By bridging gaps discussed above, the decision support modelling system can directly help the UK government prevent the diffuse agricultural N for better implementation of the EU WFD in a cost-effective manner, thus reducing the chance of the human disease caused by high concentration of N in freshwater, eutrophication, and the costs in treating drink water in the UK. This modelling system can improve the scientific understanding of catchment-scale N process leading to better sustainable measures for catchment N management. Although this project takes N as an indicator for ADWP management, the method and the system has potential of handling phosphorus and other diffuse agricultural pollutants (such as sediment and pesticides). In addition, the final modelling system may provide a starting point of successful handling of N not only in the UK but also in other EUMSs.

4.3.2. Beneficiaries of the proposed project

This project will in the first instance benefit the UK government organisations, such as the EA and Defra, in the implementation of the EU WFD in ADWP field using cost-effective numeric modelling measures. This cross-school and interdisciplinary research at Cardiff University will benefit water environmental sciences research communities, with beneficiaries including scientists, environment advisers, and industrial scientists. This project will benefit farmers in achieving good crop yields and quality with low expense of fertilisers, thus improving their enthusiasm in water environment protection. The introduction of Website can promote the general public participation demanded by the EU WFD. In addition, this project may improve the water environment in ADWP aspect for the benefit of people and wildlife.

4.3.3. The collaboration with beneficiaries

This project will be finished through the collaboration between the School of Earth and the School of Engineering in the Cardiff University. Meanwhile, the EA Wales is interested in this project, and will be able to provide water quantity and quality monitoring data in the study catchment, and advice in fitting this project into the context of RBMP in the implementation of the EU WFD. Hyder Consulting and Parsons Brinckerhoff show great interests in this project, and are willing to provide technical suggestions; and to attend important management and progress meetings of the project.

4.4. Justification for the Fellowship

After two years experience in industry following my original PhD studies, I have undertaken a second PhD as a foundation to a career in the area of water environment. This Fellowship represents a prestigious opportunity to build on these studies and establish an academic career in my area of research interest. If this application is successful I intend to capitalise on my previous research and industry experience, and through existing and new collaborations with other researchers at Cardiff University, establish my own multi-disciplinary environmental and water research programme; leading ultimately to building my own research team.

Cardiff University (Cardiff), and specially the School of Earth, is an ideal setting for a project of this nature. The university is internationally recognised as being among the very top tier of Britain's research intensive universities and is a member of the prestigious Russell Group of leading universities. Research awards to Cardiff in 2006-2007 were over £110 million. School of Earth scored a 5 in the last RAE. The head of School of Earth is a Fellow of the Royal Society. School of Earth is a large international research department and is home to around 40 leading international research scientists (including currently two Fellows of the Royal Society), burgeoning graduate student, and postdoctoral communities. Earth is also home to a large and growing number of water environmental science research scientists. Therefore, School of Earth is a good academic environment in which to be based and one where I will gain a lot of support and benefit in developing my academic career. In addition, the Cardiff School of Engineering hosts the Institute of Sustainability, Energy and Environment Management which comprises the Hydro-environmental Research Centre and the Centre for Research in Energy, Waste and the Environment. Staff members in School of Engineering are also experienced in water modelling and may be a good source of advice and expertise in this project.

The proposed project differs from my PhD study in three ways: 1) This project will improve the method developed in my PhD study by considering more complete catchment ADWP process. 2) This project focus on Welsh catchment in the context of the implementation of WFD in Wales. 3) This project will develop a decision support system based on the improved method using GIS development method. 4) The setting up Website for better dissemination of the results of this project. This project also differs from my supervisor's work, i.e. the contaminated land remediation.

4.5. The timeliness of the Fellowship for career development

I will finish my PhD study in February 2008. Currently, I am on the crossroad of looking for the chances of starting my academic career in water environment based on my PhD research. This fellowship, which will start from April 2008, is very timely for my research career development.

4.6. Dissemination and exploitation

The results of this project will be disseminated to the EA through the direct contacts (such as meeting, results presentation), and UK conference or workshop held by the EA or Defra (such as The Chartered Institution of Water and Environmental Management conference in the UK). The knowledge of this project will be transferred to scientists through journal papers, internal seminars, external seminars, and conferences. In this project, some industrial scientists will join the progress meetings and internal seminars in the Cardiff University. The Website developed in this project will greatly promote the knowledge transfer to government, scientists, farmers, and general public.

The GIS-based decision support system and Website developed in this project could be useful for industrial consultancy in water environment; thus, the software of this project has potential of commercial exploitation and application. The university has internal policies, procedures and resources for the identification of intellectual property arising from the research base and securing of associated rights e.g. patents. The GIS-based decision support system could be licensed commercially as a tool as well as being the basis for consultancy. The patent and commercialisation process is managed alongside dissemination of knowledge in such a way that delays in dissemination and publication are kept to a minimum.

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