Integrated Modelling of Hydrological and Hydrodynamic Processes, Dynamic Bacteria Decay with Climate Change and Intensive Farming in Riverine and Estuarine Water

by Jie Shi

A thesis submitted to Cardiff University

in candidature for the degree of Doctor of Philosophy

Cardiff School of Engineering, Cardiff University, UK

January, 2016

Dedicated to my parents Mr. Gengsheng Shi and Mrs. Qiuxia Sun for supporting and believing in me throughout this Ph.D.

DECLARATION

This work has not previously been accepted in substance for any degree and is not currently submitted in candidature for any degree.

Signed... (Jie Shi)

Date...

STATEMENT 1

This thesis is being submitted in partial fulfilment of the requirements of the degree of PhD.

Signed... (Jie Shi)

Date...

STATEMENT 2

This thesis is the result of my own independent work / investigation, except where otherwise stated. Other sources are acknowledged by explicit reference.

Signed... (Jie Shi)

Date...

STATEMENT 3

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library load, and for the title and summary to be made available to outside organisations.

Signed... (Jie Shi)

Date...

ACKNOWLEDGEMENTS

First of all, I would like to express my gratitude and appreciation to my supervisor Dr Michaela Bray and Professor Roger Falconer for their continued helps, supports and encouragements through the period of study. Particularly, special thanks to Dr Bray, for her endless patience and encouragements during my difficult time. Warmest thank to Professor Falconer who provides endless invaluable advices and helps. Also, I would like to thank him for providing Poole Harbour DIVAST model for this study. Without their supports, this study would have never been launched. A lot of thank to Professor Thorsen Stoesser for his kind suggestions and lectures in Environmental Hydraulics. Thanks to Environment Agency, Centre for Ecology & Hydrology and British Atmospheric Data Centre to provide valuable weather, flow, sediment and bacteria data. In addition, I would like to thank Dr Karim Abbaspour who provided supports during model calibration and validation, and Dr R Srinivasan for helping during early stage SWAT setup. This work is partly sponsored by CH2MHILL-Halcrow Industrial case-study studentship at Cardiff University.

Secondly, I am very much thankful to my colleagues, Yusri, Tom Harries and James Brammer for their companions and interesting talks. Lots of thanks to Drs, Zhihua Xie, Juntao Zhou, Guanghai Gao, Kuo Yan, Guoxian Huang, Hongwei Kuang, Yuheng Ren and Fei Wang, for their encouragements and understandings.

Last but not least, I am indebted to my parents, for their endless love and understanding during all stages of study. Without their continuous supports, I would have never got such achievements.

ABSTRACT

The water quality deteriorations in river and estuarine waters are a global issue. Particularly, the water quality impairment due to contamination of Faecal Bacteria Indicator, such as E. coli and Faecal Coliform in river channel, estuary bathing and shellfish waters are of special interests due to potential risks to human health. These indicators are important in water quality assessment outlined in both EU Water Framework Directive and US Clear Water Act. The hypothesis of the study is that the global climate change and intensive farming would cause severe deterioration to faecal coliform levels in these water bodies. Approaches to quantify these impacts are carried out with numerically modelling through catchment model Soil and Water Assessment Tool (SWAT) and hydrodynamic model DIVAST with the focus in the coastal catchment of river Frome and Piddle connected to a natural harbour in Dorset, southern England. Firstly, the SWAT model is employed to assess the catchment flow regime and set up the baseline condition of river flow in both hourly and daily time step. The hourly simulation using Green & Ampt infiltration has excellent model performance with Nash Sutcliff Efficiency (NSE) and R^2 between 0.7 and 0.8 with calibrated and validated spatially in three sub-basins. The storm events flow calibration and validation performance (NSE and R^2) is between 0.5 and 0.6. This is due to model limitations in sub-daily base flow distribution and sub-daily unit hydrograph, in this groundwater dominated catchment. Secondly, the SWAT model is modified to included sediment deposition and re-suspension effects as well as solar radiation induced die-off in sub-daily in-stream simulation. Consider of catchment agricultural management, such as livestock grazing, manure spreading with local farming practise, the bacterial faecal coliform simulation in SWAT model is calibrated with daily observation in both rivers in 2005. The performance is acceptable, where is R^2 in river Frome is around 0.6. Hourly simulation is further validated with a modified SWAT model, which indicates a significant improvement for hourly faecal coliform prediction due to solar radiation derived die off. Thirdly, the storm event prediction of bacteria showed seasonal responses to future scenarios with climate change and intensive farming projections, with a total of six scenarios. Finally, SWAT model is coupled with DIVAST model to investigate the faecal coliform variations in downstream Poole Harbour. Future projection scenario 5 is used for accessing the magnitude of impacts from climate change and intensive farming. Results show there is a significant response of faecal coliform output in Poole harbour due to high flow. Steady increases of river baseflow due to intensive rainfall, and tidal condition could be important factor to causes high level of bacterial contamination in the studied water body.

TABLE OF CONTENT

LIST OF FIGURE

LIST OF TABLE

ABBREVIATIONS

ADAS	Agricultural Development and Advisory Service
ADE	Advective Diffusion Equation
ADI	Alternative Direction Implicit
ANN	Artificial Neutron Network
CAMS	Catchment Abstraction Management Scheme
CCC	Climate Change Condition
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CFM	Cattle Farmyard Manure
DEM	Digital Elevation Model
DIVAST	Depth Integrated Velocity and Solute Transport
DWF	Dry Weather Flow
E. coli	Escherichia coli
EFDC	Environmental Fluid Dynamics Code
FAO	Food and Agriculture Organisation
FBA	Freshwater Biological Association
FDC	Flow Duration Curve
FEH	Flood Estimation Handbook
FIB	Faecal Indicator Bacteria
FYM	Farm Yard Manure
HRU	Hydrologic Response Unit

HSPF	Hydrologic Simulation Program FORTRAN
IFC	Intensive Farming Condition
MDF	Mega Dairy Farm
NSM	National Soil Map
NSE	Nash-Sutcliffe Efficiency
R^2	Coefficient of Determination
SM	Sludge Manure
SWAT	Soil and Water Assessment Tool
SWAT-CUP	Soil and Water Assessment Tool – Calibration and Uncertainty Program
UH	Unit Hydrograph

Chapter 1

Introduction

1.1 Motivation and Research Background

All organisms on earth need clean water to live and stay healthy. Clean rivers, lakes and seas are full of wildlife. Polluted water harms all living things. In recent decades, there has been a growing concern of water quality in river, estuary and coastal waters. Faecal indicator bacteria such as total coliform, faecal coliform, Escherichia coli (E.coli) and enterococci are the leading causes of water quality impairment in bathing and shellfish harvesting waters (Thomann 1987; EPA 2003) and (Sanders, Arega et al. 2005). Excessive faecal pathogens in bathing water can result in water-borne disease, defined as incidences in which more than two people have suffered illness after ingesting or recreational contact with water (Benham, Baffaut et al. 2006). For example, E. coli produces an enteric toxin that could result in gastroenteritis disease. Epidemiological investigations have demonstrated that intestinal enterococci, principally derived from anthropogenic sources, have become the preferred microbiological indicator of health risks in marine recreational waters (Kay, Stapleton et al. 2005; Kay, Wyer et al. 2005). Microbiological contamination can result in beach closure or prohibited shellfish sale, both of which have direct effects on the coastal economy (European Parliament 2006; Bougeard, Le Saux et al. 2011). Therefore, it is very important to predict faecal indicator bacteria accurately in the above water bodies to control contamination, and minimize health risks to the general public.

1.1.1 Cause and Source of Faecal Indicator Bacteria Contamination

The UK population reached 64.1 million by 2013. The UK is experiencing the fastest population growth in Europe with half of the increase since 1964 in the last 12 years alone. Such rapid growth in population stimulates the domestic demands for water and food. Increased human activity has exacerbated the rate of use of fertilisers on the land surface, and intensive agriculture catchments have been regarded as the major sources of nutrient and pathogen pollution in surface and coastal waters (Worrall, Burt et al. 2009). Urbanization also substantially degrades water quality (Foley, DeFries et al. 2005) especially where wastewater treatment is absent.

Bacteria pathogen contamination into the rivers, estuaries and bathing water has three major sources: agricultural runoff, failed sewerage and septic system and wild life (Kim, Pachepsky et al. 2010). In many countries, most of the countryside is used by farmers to grow crops or feed animals. Farmers require a large amount of water, and they should understand what farm land yield dirty water does to clean water supply. Livestock have to be washed and their accommodation is cleaned out using water, and the effluent dirty water could carry bacteria. Nowadays, dairy farms are under pressure to supply more milk with limited land. According to the UK national agricultural census (DEFRA 2013), the total farmed cattle were 6.6 million in 1990, more recently in 2013 were 1.7 million. Such enormous scale of dairy production directly leads to excessive pathogen pollution in land, rivers and coastal waters due to manure waste. Intensive farming such as mega dairy farm was first introduced to UK in the early 1990s. Faecal bacteria sources cause severe water pollution due to failed manure management, most of which is from diffuse sources. For example, the Nocton mega dairy farm in Yorkshire was planned to house over 8,000 dairy cattle. Similar mega dairy farm was proposed in Carmarthenshire, in the west of Wales. Point source pollution such as septic tank and waste water treatment plants also contributes to pathogen contamination. However, due to strict regulation, large-scale outbreaks of point source pollution are not a major concern in the UK.

1.1.2 Target and Modelling of Faecal Indicator Bacteria Level

Faecal contaminations are not uncommon across Europe. In the light of the deterioration of quality in water bodies, the European Union Water Framework Directive (WFD) was introduced in all its member states in December 2000. The Directive requires all inland and coastal water to reach at least good status by 2015. However, in order to achieve this goal river basin management plans would need to be accessed in consultation with regard to agricultural land management, biodiversity, and tourism and flood protection. Under the EU Water Framework Directive, only 27% of the water bodies including rivers, lakes, estuary and coastal waters in the UK are classified as in good status. The Bathing Water Directive aims to access and monitor bathing waters to protect bather's health in Europe. A report showed that 94% of the total bathing waters in Europe met the minimum requirement. However, despite the establishment of legislation and regulation for protection from contaminated waters, there are still failures to meet EU standards each year in every member state. Precise prediction and control of the bacteria pollution in river and estuary is urgently required to guide member states meeting WFD targets. However, there is a limited capability to predict the occurrence of faecal bacteria pathogens at policy-relevant scale such as watersheds and estuaries (Milne, Curran et al. 1986; Ferguson, Croke et al. 2005; Ferguson, Croke et al. 2005; Kashefipour, Lin et al. 2006; Carroll, Dawes et al. 2009; Frey, Topp et al. 2013). Mathematical modelling of faecal coliform or E. coli in rivers and coastal waters is highly beneficial. In the thesis, a coupled model which links a hydrodynamic estuary model with a catchment model is examined. This coupled model offers the power to integrate parameters that drive water and pollutant fluxes out of a watershed and into an estuary area. Soil and Water Assessment Tool (SWAT) is used for catchment modelling. A two-dimensional hydro-dynamic model called Depth Integrated

Velocity and Solute Transport (DIVAST) is used to model the downstream estuary (Falconer, Harris et al. 2001). One of the motivations of this study is that there is lack of sophisticated integrated model which is capable of modelling faecal coliform bacteria with precision and reliability, in coastal basin and estuary water. Coupled SWAT-DIVAST model is therefore created to help solve the problem.

1.2 Scope and Objective

Catchment size ranges from a few to thousands of square kilometres (km^2). UK has one of the longest coastlines in Europe. However, its width and length are nowhere comparable with those of big river basins such as the Mississippi in North America, the Yangtze China and the Rhine in Europe. For example, the flow travel time from the head water in catchment to its outlet in giant river basin ranges from months to weeks. However, the flow travel time in smaller watersheds in the UK, only takes from minutes to hours. Most of the SWAT model applications simulate in daily or monthly time step. However, the most recent SWAT model (version 2012) is only capable of simulating bacteria on a daily basis, leaves its sub-daily bacteria algorithm an undeveloped area. Regarding small to medium coastal watersheds in UK, if the flow travel time is less than 24 hours, daily bacteria prediction would not be able to capture the variations of bacteria flux in the rivers. Thus, the knowledge gap of sub-daily bacteria modelling in rivers needs to be filled.

Bacterial decay in rivers and estuaries exhibits dynamic rather than first-order static decay. If the SWAT model could be applied with dynamic bacteria decay, the SWAT bacteria sub-model would be further improved with more accurate and realistic results. For example, when the downstream water Poole harbour receives river flow and contaminates from connected rivers Frome and Piddle. The hydrodynamics model could continue the simulation by picking up the output from catchment, rather than use estimated constant river input. Such integrated modelling would enable simulation of pollutants from land to receiving water body within a connected system without interruption and isolation. Lastly, it would be possible to provide a new tool for monitoring and prediction of faecal coliform for bathing and shellfish waters. The following are the four objectives that this thesis aims to achieve.

Objective 1 aims to set up SWAT modelling in Frome and Piddle catchment as a test bed for examining flow and bacteria modelling in the rivers with daily time step for general model sensitivity, calibration and verification, and more importantly to test the hourly time step model prediction of flow and bacteria with SWAT.

Objective 2 aims to build upon the basis of the capability of SWAT daily and hourly models, further to improve the current bacteria sub-model which only considers first-order decay in the reaches, to include multiple influences to the decay rate such as sub-hourly solar radiation intensity and in-stream sediment deposition and resuspension.

Objective 3 aims to identify the relationship between diffuse pollution and faecal coliform in a southern England county in Dorset. It could be achieved through testing the model prediction with different agricultural management plans.

Objective 4 is to develop and test an integrated model from catchment to estuary with coupled SWAT-DIVAST model. This approach intended to model a connected system, and not rely on individual models. It is also determined to find the effects of intensive farming plans to local bathing and shellfish waters.

1.3 Thesis Layout and Structure

Chapter 1 describes the background information, the research motivations, objectives and layout of this thesis.

Chapter 2 summarises past experiences and literature. It has four main parts (i) Introduces the literature from integrated modelling approaches that solve environmental problems. (ii) Reviews the catchment models that are widely used and with focus in the applications of SWAT model. (iii) Literature reviews of hydrodynamics and its modelling in catchment and estuary. Evolution of bacteria model with an overview of bacteria dynamic decay (iv) Reviews of applications of modelling in the catchment and estuary with effects of climate change and land management plans including intensive farming.

Chapter 3 summarises all the background information for setting up the SWAT and DIVAST model, including data availability adopted in the thesis.

Chapter 4 introduces the SWAT model setup and analysis of model sensitivity of flow and bacteria; likewise, calibration and validation of flow and bacteria in the daily time step. Further to the daily simulation, the hourly simulation of flow is calibrated and validated both in a one-year period as well as in storm events.

Chapter 5 develops the SWAT bacteria sub-model. It shows how the modified SWAT model is enabled to take the sediment-associated bacteria in stream into account, including solar radiation-dependent decay rate in both daily and sub-daily routing. This chapter also includes the SWAT modelling of Frome and Piddle catchment at hourly time step. The calibration and verification of hourly flows and developments of faecal coliform sub-model in the SWAT with improved dynamics decay algorithms are introduced for testing and validation.

Chapter 6 is about future scenario analysis. According to the baseline condition, the climate change condition and intensive farming condition has been projected according to suggestion from literatures. A total of six different future scenarios were selected, each scenario represents different combination of climate and farming conditions. Simulations have been conducted using year 2002 as baseline condition, where sub daily faecal coliform baseline condition has been validated in Chapter 5.

Chapter 7 presents the model coupling of SWAT and DIVAST which enables the coupled model system to simulate the flow and faecal coliform in catchment as well as in the estuary. Faecal coliform modelling analysis and discussion of the integrated model then follow. Simulation use baseline condition, Scenario 3 and Scenario 5 from Chapter 6 for comparison to access the impacts of climate and intensive farming to faecal coliform bacteria in Poole Harbour.

Chapter 8 summarise the previous chapters and introduce a conclusion of the thesis. And finally discusses the limitations, and potential of future work.

Chapter 2

Literature Review

2.1 Introduction

Integrated modelling often combines multiple models to simulate within a system that single model could not compare. A study successfully incorporated an integrated approach in assessing the impact of climate change to water quality (Wilby, Whitehead et al. 2006), which linked the state-of-art model regional climate (SDSM), water resources (CATCHMOD) and water quality (INCA). This case study was examined in River Kennet, UK. However, the findings showed that there are large uncertainties due to general circulation model (GCM), which caused considerable variations between flow and the surface water quality. This integrated approach provides a tool for assessing risks from multiple anthropogenic stresses. Studies of coupling upland watershed and downstream water body hydrodynamics and water quality models (SWAT and CE-QUAL-W2) was conducted (Debele, Srinivasan et al. 2008). By linking two models, the author reported that the coupling approach was successful with compatibility and complementary in complex watersheds and downstream water bodies. However, the applying object of the hydrodynamic model in this research was only limited to large water bodies such as in river channels and lakes. The work could have been further improved if they extend the coupling approach to link estuary or coastal waters. (Yuan, Lin et al. 2007) has developed an integrated model for water management in coastal watersheds, through linking pollution loads from land with a GIS model. The coupled approach was examined in Bohai Bay, China. SWAT has been linked with CE-QUAL-W2 to simulate the water and quality in a reservoir watershed (Liu, Chen et al. 2013). However, there are very few studies that link with estuary model with catchment for coastal water quality assessment. Except that link SWAT with MARS-2D, to simulate coliform bacteria in shellfish water in a coastal river basin. Coupling SWAT with Water Quality Analysis Simulation Program (WASP) was completed (Park, Park et al. 2013), which accessed climate change to Chungju Lake in Korea. Further study has been conducted in modelling river Ribble catchment in the UK by coupling the costal EFDC model with catchment HSPF model (Huang, Falconer et al. 2015).

2.2 Catchment Model

A study from ADAS and CEFAS investigated the shellfisheries production of runoff from land receiving organic wastes showed significant result on bacteria population in River Frome and Poole Harbour (CEFAS 2012). Among the initial screening on 22 selected areas for the study across the UK, the results from Poole and Devon Avon showed a relationship between rainfall and shellfish E. coli, which implies the E. coli increase with rain. Further work was carried out for research in development of a catchment tool called Coliform Source Apportionment Tool (CSAT), hydro-dynamic modelling in the estuary in order to extrapolate the predictions from the catchment, basal and storm condition sampling of river waters within the catchments and seawater within the estuary. The results of further study showed that the bacteria in shellfish in river Frome and Poole peak in winter where in Devon Avon peak in summer (CEFAS 2003). Further, the predicted concentration is more consistent with observation during high flow events where the predictions are much less than the observation during low flow condition. In Poole Harbour, the spring and neap tidal cycle did not have a significant effect to the bacteria contamination, but with some effects from the high and low condition. The bacteria level is higher on an outgoing tide. It implies that the river and catchment is significant causes of bacterial contamination of the shellfishes. The CSAT model results showed that more that 95% of the annual faecal coliform loads exported from the catchment are attributed to point source pollution. During storm events, manure related diffuse pollution contributes up to 80% of the instantaneous yielding. CASCADE and QUESTOR

Catchment Scale Delivery operates on daily time-step, where this model stands for the dynamics of diffuse pollution, the QUESTOR model represents for the point pollution modelling and in river processes (Hutchins 2010). This modelling divides the catchment into smaller hydrological response units with a size of about 5 km^2. Two headwater catchments in the River Derwent (North Yorkshire, UK) were studied which aims to discover the impacts to the water bodies after land use changes. Hydrologic Simulation Program Fortran (HSPF) model (Bicknell, Imhoff et al. 1995; Donigian, Bicknell et al. 1995) is one of the widely used watershed model (Van Liew, Arnold et al. 2003; Saleh and Du 2004; Im, Brannan et al. 2007; Liu and Tong 2011; Duda, Hummel et al. 2012). One of the comparison studies, (Nasr, Bruen et al. 2007) modelled diffuse phosphorus from agricultural land with three different models, SWAT, HSPF and System Hydrologic European Transport (SHETRAN), concluded that HSPF give best daily flow prediction and SWAT has best calibration results for daily total phosphorus. MIKE-SHE is another watershed model (Refsgaard and Storm 1995; Hoang, van Griensven et al. 2014) ,which is competitive to SWAT and HSPF, and widely used Europe and Asia.

Green & Ampt and Curve Number

Most SWAT hydrological modelling selects SCS curve number method (SCS 1972) as its model infiltration theory, due to the wide uses of river flow estimation in daily and monthly time-step. However, daily time-step model using curve number method in SWAT applications can be expected to overestimate infiltration and underestimate runoff (King, Arnold et al. 1999; Garen and Moore 2005). The Green & Ampt infiltration method is developed to estimate the rate of water that infiltrates through soil layers. It could be used for sub-daily catchment modelling with each modelled time step from one hour to minutes, when there is sufficient rainfall input corresponding to the time step (Maharjan, Park et al. 2013). However, there is very few applications which uses the Green & Ampt infiltration in SWAT modelling (Dourte, Shukla et al. 2014). It is found that there is no significant changes to the flow when switch from curve number method (SCS) to Green & Ampt for same model application (King, Arnold et al. 1999). However, another study reported that the curve number method is much better than the Green & Ampt method (Kannan, White et al. 2007) when simulating hydrology conditions in one small catchment in the UK.

SWAT Bacteria Modelling

Watershed bacteria simulation function of SWAT model is one of its strength compare with other models SWAT model can perform the evaluation of faecal coli form and another pathogen with different characteristics. In addition, SWAT's bacteria function enables to set the pathogen soluble rate against the sediment bound bacteria. Furthermore, it can be used to assess the impacts of both point and diffuse bacteria sources, such as livestock, poultry and human depositions. However, the model (Benham, Baffaut et al. 2006) can be developed to perform better in the following aspects.

SWAT model is one of the primary models used for watershed scale bacteria fate and transport modelling in the U.S.A. (Benham, Baffaut et al. 2006; Gassman, Reyes et al. 2007; Arnold, Moriasi et al. 2012; Gassman, Sadeghi et al. 2014). Another catchment hydrologic model is called HSPF (Donigian, Bicknell et al. 1995; Bricknell 2001; Im, Brannan et al. 2007; Nasr, Bruen et al. 2007; Duda, Hummel et al. 2012) and is widely used world widely. A number studies examined the catchment bacteria transport model using SWAT (Jayakody, Parajuli et al. 2014) (Coffey, Cummins et al. 2007; Coffey, Cummins et al. 2010; Coffey, Cummins et al.

2010; Coffey, Cummins et al. 2010) (Parajuli 2007; Niazi, Obropta et al. 2015). Bacteria source inputs are critical for model simulation. Typical sources from agricultural land are livestock such as cattle and sheep (Moore, Smyth et al. 1989; Kay, Edwards et al. 2007; Stumpf, Piehler et al. 2010).

SWAT bacteria sub-model is able to take into account point sources as well as diffuse sources, with re-growth and die-off processes. However, the current bacteria die-off rate is based on a first order equation. Further development of bacteria life cycle equations with dynamic die-off rate from varied factors is urgently needed (Arnold, 2012). There are a number of transport and fate processes in modelling bacteria in SWAT. For example, (Jayakody, Parajuli et al. 2014) investigated the seasonal and spatial bacteria variation in the Pelahatchie catchment. This application considered key bacteria related parameters, such as BACTKDDB, BACTKDQ, TBACT, WDLPQ, and WDLPS. Details of each parameter will be further explained in Chapter 5. These control parameters represent the transportation processes of bacteria simulation in the catchment. Such as bacteria on leaves, bacteria in soil solution, bacteria absorbed to soil particles, bacteria with die off and re-growth effects, and transportation into streams via runoff. The analysis shows a best fit relationship between the Nash efficiency and BACTKDDB. If the value of BACTKDDB is equal to 0.95, the better of model performance occurs. Therefore, 0.95 is regarded as the guideline value for BACTKDDB soil partitioning coefficient as outlined in Chapter 5. However, this study runs in daily time steps, and analysis the monthly average bacteria population. In this thesis, study is based on at sub-daily time step model with hour rainfall inputs with particular focus on the daily and sub daily model performance. (Chin, Sakura-Lemessy et al. 2009) conducted a comparison study on bacteria predicting between SWAT and HSPF, and concluded that HSPF makes accurate flow prediction (daily flow Nash coefficient 0.87, and

SWAT and much higher accuracy of faecal coliform prediction (Nash coefficient 0.73 compare to 0.33 for HSPF). (Ludicello 2013) compared SWAT in-stream bacteria module with HSPF (Bricknell 2001) and Characteristic Concentration (CC) model, with a conclusion that all three models over predict low bacteria level and under predict the peak level. Model performance is more related to the in-stream parameters rather than catchment process parameters.

Getting sufficient data is a key barrier to achieve better bacteria modelling performance. This is mainly due to the high cost of collection and analysing the water samples. In addition, faecal coliform water sample are not commonly taken after the significant rainfall events, leaving the data not representative for peak value calibration (Ludicello 2013). A study investigated (Niazi, Obropta et al. 2015) how the bacteria transported in the watershed by calibrate the model at multiple stations with Nash coefficients range between -0.94 and 0.47. Another study (Jayakody, Parajuli et al. 2014) performed spatial and temporal faecal coliform assessment, indicating that bacteria level are influenced by soil property, weather conditions, bacteria sources and manure application, which have the same conclusion with (Coffey, Cummins et al. 2010). Moreover, the first bacteria source tracking study (Parajuli, Mankin et al. 2009) using SWAT 2005 bacteria sub-model with the calibration and sensitivity results indicating the current uncertainty of source tracking approach are high (Parajuli, Mankin et al. 2007). Further study is conducted with source tracking study (Frey, Topp et al. 2013) which employs a Classification and Regression Tree Analysis (CART) method. SWAT also has been successfully used in modelling Cryptosporidium oocysts, i.e. one type of bacteria present in drinking water, (Tang, McDonald et al. 2011) that simulating in ungauged agricultural catchments. In this study, baseline catchment characteristics and local weather are regarded as critical in modelling bacteria with ungauged catchment.

Change of bacteria in rivers between one and two orders of magnitude is reported within hours (Jamieson, Gordon et al. 2004). Therefore, the variation due to storm event is another key to access the faecal bacteria pollution in the river. However, (Bougeard, Le Saux et al. 2011) revealed the relationship between bacteria modelling and monitoring by conducting SWAT daily simulation and compare prediction with after storm event based sub-daily bacteria record. Such approach is a modelling compromise due to limits for sub daily simulation. The study further urged that there is an urgent need to get more and accurate sub-daily bacteria measurement, particularly after storm, as high faecal contamination often occurs after 2-3 hours of rain. Sub-daily modelling could open a way from SWAT that links to other models and extend the model capability. Another study from same person, coupled SWAT with MARS-2D, a two dimensional hydrodynamic model, the coupled system is capable of simulating the coastal basin (Bougeard, Le Saux et al. 2011) as well as the downstream estuary bacteria level.

SWAT was originally developed by the United States Department of Agriculture - Agriculture Research Service (USDA-ARS) to evaluate the impact of land management on water, sediment and agricultural chemicals in the watersheds and catchments (Arnold, Srinivasan et al. 1998; Gassman, Reyes et al. 2007). SWAT allows a number of physical processes to be simulated in a watershed. It use various input data sources such as topography, soil profile, land use, weather and the hydrology (Santhi, Srinivasan et al. 2006). SWAT has gained an international reputation as an integrated multi-disciplinary modelling tool in United States, Europe and Asia. It was used to assess the progresses of the implementation of Best Management Practices (BMPs) and Water Quality Management Plans (WQMPs) in Texas, USA. Large scale hydrological and water resource assessment has been conducted in the US (Arnold, Srinivasan et al. 1998; Srinivasan, Ramanarayanan et al. 1998; Zhang, Srinivasan et al. 2007; Zhang, Srinivasan et al. 2008). Similar studies at different catchment scale has been conducted for accessing the model performance (Bracmort, Arabi et al. 2006; Arabi, Govindaraju et al. 2007; Schuol, Abbaspour et al. 2008), limited applications in the UK include (Bouraoui, Galbiati et al. 2002; Kannan, White et al. 2006; Kannan, White et al. 2007), and applications in European countries has (Conan, Bouraoui et al. 2003; Schmalz, Tavares et al. 2008; Guse, Reusser et al. 2014) and China (Hao, Zhang et al. 2004; Ouyang, Hao et al. 2008; Ouyang, Hao et al. 2010). Another study of the SWAT model in soil erosion and sedimentation processes, and the impacts on sediments reduction by implementing BMPs (Betrie, Mohamed et al. 2011), which shows SWAT could help to evaluate the cost and benefits in policy decision making.

Best Management Plan and Land Use Impact

SWAT is an international comprehensive watershed hydrologic model that is capable of predicting nutrients loss. A few studies have been focused in predicting the nitrogen losses of the catchments of Texas in the U.S. It is confirmed that the simulated results has showed a consistence that most the average monthly validation Nash-Sutcliffe Coefficient (NSE) from the studies had a value of above 0.60, which means generally acceptable for model performance In addition, for the phosphorus prediction, the validation NSE obtained in the same studies had a range of between 0.39 and 0.93 (Saleh, Arnold et al. 2000; Di Luzio, Srinivasan et al. 2002; Saleh and Du 2004; Stewart, Munster et al. 2006). The performance of the SWAT model in predicting the nutrient loss was satisfactory based on these results. Furthermore, it is believed that SWAT can be simulated to evaluate the effects of climate change effectively to the water quality if sufficient calibration works have been done properly (Hanratty and Stefan 1998).

It was estimated that half of the published SWAT studies simulated the catchment pollutant loss. R^2 and NSE index are two key indicators in the SWAT model calibration and validation processes (Moriasi, Arnold et al. 2007; Arnold, Moriasi et al. 2012).

The study carried out on the upper North Bosque River watershed in Texas concluded the model prediction matched the monthly sediment loss but showed poor correlation in daily simulation (Saleh, Arnold et al. 2000). However, the other study focused at Warner Creek watershed in Maryland (Chu and Shirmohammadi 2004) indicated the simulation of the monthly output was inadequate while the annual prediction was satisfactory.

Catchment agriculture production can cause server nutrient rich related pollutions affecting the downstream catchment. Therefore, it is to replace to assess the impact of livestock and cropland to the watershed. SWAT model can not only simulate the nutrients losses but also evaluate the effects of land use alternation and Best Management Practises (BMPs). For example, (Santhi, Srinivasan et al. 2006) studied the impact of manure and cropland associated BMPs on the catchment water quality in the West Fork watershed in Texas. Another study reported the impacts of BMPs to the local dairy industry and the effects to the water quality from the local municipal wastewater treatment (Santhi, Arnold et al. 2001). Different BMPs choices could affect the outcome of implementing BMPs (Vache, Eilers et al. 2002) Furthermore, even single choice of BMPs could result varying results. For example, (Bracmort, Arabi et al. 2006) simulated the impacts of BMPs under three different scenarios for two watersheds. The results showed the BMPs functioning with good conditions has completely different outcome compare to the BMPs with poor conditions. (Nelson, Ascough et al. 2006) reported that the nutrients and sediment loss has been simulated and experienced considerably reduction under the land use alternation from cropland to switch grass in the Delaware River basin in Kansas.

The SWAT study on the upper North Bosque River watershed in north central Texas predicted monthly sediment loss which was in proportional to the measured sediment loss while the daily prediction showed relatively poorer correlation (Saleh, Arnold et al. 2000). Another study based in Maryland, showed the strong agreement which the measured annual sediment loss matched the annual simulation results very well. However, it indicated the poor consistency in monthly simulations (Chu and Shirmohammadi 2004). Several researches indicated the satisfactory of the simulated results against the measured recording on sediment losses in different parts across USA (Arabi, Govindaraju et al. 2006; Jha, Gassman et al. 2007). The studies had also been examined in other parts of the world. For example, the model has been applied to two Chinese rivers, Yellow River and Heihe River respectively. The results showed the model was accurate (Hao, Zhang et al. 2004; Cheng, Ouyang et al. 2007). However, (Barlund, Kirkkala et al. 2007) reported a case study on one Finnish catchment with no calibration for the sediment simulation, the results was described as very poor.

Calibration and Validation Procedures

The calibration process can be divided into three main parts, including parameter selection, calibration process and validation of the model review (Arnold, Moriasi et al. 2012).

1. Determine the parameter

Determine of the most sensitive parameters for a given watershed or sub watershed. The user decide which variables to adjust based on expert judgement or on sensitivity analysis; The first step helps to determine the predominant processes for the component of interest; Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). Two types of sensitivity analysis are generally performed. The first one is local, by changing the values one at a time, and global, by allowing all parameters to change. The two ways of sensitivity may give different results.

Disadvantage of global sensitivity analysis is the amount of work required in large number of simulation.

2. Calibration process

Calibration is an effort to better parameterize a model to give a set of local conditions, thereby reducing the prediction uncertainty; Model calibration was performed by carefully selecting values for model input parameters (within their respective uncertainty range) by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions.

3. Validation process

The final step is validation for the component of interest (flow, nutrients, etc.) Model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations. Validation involves running a model using parameters that were determined during the calibration process, and comparing the predictions to observed data not used in the calibration. A good calibration and verification should involve the following four aspects.

(i). Observed data that include the wet average and dry years.

(ii). Multiple evaluation techniques.

(iii). Calibrating all constituents to be evaluated.

(iv). Verification that other model outputs are reasonable.

Calibration could be conducted manually or by using auto-calibration or by SWAT-CUP. In general, graphical and statistical methods with some form of objective statistical criteria are used to determine when the model has been calibrated and validated.

4. Strategy of Calibration

Ideally, calibration and verification should be performed spatially. A good example of process based calibration involved stream flow. Stream flow processes are stream flow processes are comprised of the water balance in the land phase of the hydrology, including ET, lateral flow, surface runoff, return flow, tile flow, channel transmission losses, and deep aquifer recharge. Sediments, nutrients, pesticides and bacteria, sources and sinks should be considered. It is better to use all the data of hydrology for calibration and verification to capture long term trends. Even hydrology data are much longer than the water quality recording. The calibration should be carried out at the sub watershed level instead of only determine global watershed process i.e. at the whole watershed outlet. Time series plots, Nash-Sutcliffe efficiency and metric and methods used to compare observed data to model predictions are also important. The water balances components are recommended to be checked first, to make sure the simulation is reasonable. To distinguish clearly the difference between base flow and surface runoff, it is suggested to separate base flow from the observed total daily stream flow, using a base flow filter developed by (Arnold, Allen et al. 1995; Arnold and Allen 1999). However, base flow separation is optional. A program called SWAT-CHECK (White, Harmel et al. 2014) was developed to inform users if model outputs are outside of typical ranges and further checks should to carried out. Thus, the program ensures the model is getting reasonable results. By adopting its recommendations, modeller could avoid major mistakes during model setup stage. Mean, standard deviation, coefficient of determination (R^2), Nash-Suttcliffe Efficiency (NSE) (Nash 1970) and sorted efficiency or prediction efficiency (RE) were used to evaluate model prediction. R^2 is an indicator of strength of relationship between the observed and simulated result (Arnold, Moriasi et al. 2012). NSE indicates how well the plot of observed versus simulated value fits the 1:1 line. The Prediction Efficiency (RE) indicates the model's ability to describe the probability distribution of the observed results.

2.3 Hydrodynamic Model

Hydrodynamic in estuary and coastal waters including water elevations, magnitude and direction of velocity must be predicted with accuracy before modelling the sediment and bacteria faecal coliform level. These hydrodynamic features are modelled by solving the hydrodynamic governing equations. The Navier-Stokes equations govern unsteady turbulent flow in estuary and coastal waters. The Navier-Stokes equations are derived by combining the general stress-strain equations for solids which is based on Hookes's law (Timoshenko 1970), and the shear stress-strain relationship for fluids under laminar flow which is based on Stokes's law (Douglas 2011).

Hydrodynamic models can be divided into three categories: one dimensional, two-dimensional and three dimensional models. One dimensional models are generally used in rivers whereas depth averaged two dimensional models are widely used for estuarine and nearshore coastal waters. Hydrodynamic governing equations in research were simplified by adopting one dimensional and two dimensional flows by making several simplifying assumptions. Numerical solution significantly simplified by assuming vertical advection must be much smaller than the pressure gradient and gravitational acceleration (Lin and Falconer 1995). The performance of numerically solution of rapid varying flooding flows has been improved significantly with TVD-MacCormack scheme from (Liang D. 2003; Liang D. 2007; Gao, Falconer et al. 2011).

Different method for solving the hydrodynamics in water body includes Finite Difference Method (FDM), the Finite Element Method (FEM), the Finite Volume Method (FVM) and the Smooth Particle Hydrodynamics method (SPH). TELEMAC is finite element software which solves the shallow water equations and widely used in the industry and researches (Galland, Goutal et al. 1991; Villaret, Hervouet et al. 2013). Finite Volumn Coastal and Ocean Model (FVCOM) employ the FVM method that is applied to several coastal and estuarine basins (Wu and Tang 2010; Bai, Wang et al. 2013). DIVAST model was initially developed by (Falconer 1977; Falconer and Lin 1997; Falconer 2001). DIVAST has been continuously developed and applied to a number of case studies in the UK and worldwide. Such as the faecal coliform modelling in the Ribble Estuary (Falconer, Harris et al. 2001; Kashefipour, Lin et al. 2002; Kashefipour, Lin et al. 2002; Kashefipour, Lin et al. 2006), Severn Estuary (Ahmadian and Falconer 2012; Gao, Falconer et al. 2013), Cardiff Bay (Harris, Falconer et al. 2002), and Poole & Holes Bay (Falconer 1986). Other two dimensional finite difference modelling tools such as MIKE 21, ISIS-2D, and EFDC (Environmental Fluid Dynamics Code) (Zhou, Falconer et al. 2014; Bray, Ahmadian et al. 2016) are also widely used in the UK.

2.4 Faecal Coliform Modelling

Faecal Coliform Modelling from Catchment

Both US Clean Water Act and EU Water Framework Directive paid strong attention to the quantification of faecal coliform concentration in small catchments and large river basins (Wilkinson, Jenkins et al. 1995; Kay, Edwards et al. 2007). A recent study on a dairy farm in Scotland, has shown the assessments of faecal coliform loads from the dairy farm to a stream in the Irvine catchment (Vinten, Sym et al. 2008). It is estimated that there is a farm FC load threshold that would cause potential bathing water failure of between 8.9 x 10^8 colony forming units (cfu) $ha^{-1}d^{-1}$ (mandatory standards) and 1.7 x 10^{10} colony forming units (cfu) $ha^{-1}d^{-1}$ (mandatory standards). Further, it indicated that there is a reduction of risks on FC concentration due to the downstream pond and wetland of up to 20% and <1%, respectively.

(Crowther, Kay et al. 2002) conducted faecal coliform budget studies at two coastal resorts near Staithes and Newport. The results show the water quality of bathing water at selected site is under high risks from upstream catchments. Study indicate the relationship between land use, livestock manure, slurry application, farm number, and faecal coliform output budges estimated, where during high flow events there is a high correlation. Climate and topography are suggested to be key contributing factor to catchment water quality. Further study to quantify the impacts from land use to the faecal coliform indicator organism concentrations in surface waters has been conducted by (Kay, Wyer et al. 2005). Similar work has been carried out in Seine River France (Servais, Billen et al. 2007). Furthermore, a study employed (Kay, Wyer et al. 2005) digital elevations model (DEM) for accessing the classifications of land uses in the Ribble catchment UK. Extensive faecal coliform was measured at 41 locations with 20 samplings over a 44 days' period. Such sampling plan is much advanced compare to other locations in the UK during bathing season. Results indicating that sewerage associated sources are critical to faecal indicator contamination.

(Kay, Aitken et al. 2007) analysed the impact of catchment farming remediation measures to the faecal coliform concentration output. There is a significant reduction of between 66 % and 81 % during high flow events when implement riparian zone or prevention of livestock access. A comprehensive statistical budge study in the catchment export coefficient with measurements at 205 river samplings locations in the UK is studied in (Kay, Crowther et al. 2008). The study gives a summary of catchment export coefficients with the unit ($cfu\, km^{-2} h^{-1}$) under different conditions such different land use types, seasonal variations as well as the base flow high flow conditions.

(Edwards, Kay et al. 2008) analysed the farm scale faecal coliform contribution to the runoff. It suggested that the farm hard standings generated runoff contains high concentration of faecal coliform that are believed from the faecal and urine of livestock. Such farm faecal coliform source would potential at higher risks to small and headwaters. Recent study (Kay, Anthony et al. 2010) concluded that the faecal coliform concentration in improved grassland are as high as it in highly urbanised catchments. Remarkably, in the rural catchment in northwest and southwest England, more than 40% of total faecal coliform comes from the lowland livestock farming. Majority of faecal source are from point sources such as sewerage effluents during base flow condition. High flow under climate change condition could be potentially playing a major role to increase faecal concentration. It also suggested further study could be using sophisticated models to get a better understanding.

Another study has been focused on geometric mean of presumptive faecal coliform and presumptive intestinal enterococci during base and high flows in the Humber river basin (Hampson, Crowther et al. 2010). Seven different types of land use are accessed which suggested livestock rates would be further evaluated and studied for policy decision making purpose. An innovative approach that use hydrograph based model Variable Residence Time model (VART) that integrated the processes of unsteady flow, sediment transport, and bacteria decay in the in-stream transport and fate process. The result shows an excellent agreement with observation of faecal coliform simulation (Ghimire and Deng 2013). It is suggested that (Cho, Cha et al. 2010) storm wash-off and solar radiation processes are the two controlling factors to faecal indicator bacteria during high and base flow conditions or wet and dry conditions in an urbanised catchment. The study also included the sediment re-suspension process with different weather conditions. (Desai and Rifai, 2013) conducted a research that have recorded around 700 sub-daily E. coli measurements with 10 and 30 minutes' resolution. The observations have a good match with predictions. It is under scoured that there is a bacteria Diurnal Sag (BDS) found within 24 hours for each measurement. The observation varies between 1 to 5 orders of magnitude. Morning and night time bacteria concentrations are at least 10 times higher than afternoon concentrations.

Faecal Coliform Modelling in Estuary

2D depth integrated hydrodynamic model DIVAST has been used for many studies for assessing hydro environment pollution - faecal coliform concentration within riverine and estuary environment. Studies in (Falconer 1993) carried out a series hydro environment water quality modelling including assessment of faecal coliform outfalls from sewerage in Whitby Bay and Whitby Harbour, in Yorkshire, UK. The study included the effects of T_{90} die-off rate in coliform.

(Kashefipour, Lin et al. 2002) carried out the study of faecal coliform modelling in the river and the estuary in the Ribble coastal catchment to access the impacts from the sewerage system. The study employed the linked 1D FASTER model and 2D DIVAST model towards a comprehensive modelling. Different decay rates of faecal coliform have been applied for day and night and wet and dry conditions. Another study focused on the die off rate of faecal coliform from the solar radiation (Kashefipour, Lin et al. 2002). Another further study indicated that varies inputs and the high flow and base flow condition could affect the level of bacteria in the coastal basin of River Irvine (Kashefipour, Lin et al. 2006). Integrated modelling approach that covers a further wide range of decay rates of faecal coliform has been studied in Ribble Basin, UK (Boye, Falconer et al. 2015). More influencing factors include temperature, solar radiation turbidity and salinity.

Severn estuary in south west of England, has also been an important scientific interest for assessing the hydro - environment water quality, particularly the faecal coliform. (Gao, Falconer et al. 2013) showed the sediment associated effects to the bacteria level in the estuary under varied weather and tidal conditions. (Ahmadian and Falconer 2012) modelled the impacts of installing tidal stream turbines to the estuary hydrodynamics, suspended solid and faecal coliform levels in the Severn estuary. Similar investigations has also been conducted in Cardiff Bay, UK (Harris, Falconer et al. 2002) for bacteria contamination modelling.

Faecal indicator bacteria (FIB), including total coliform, faecal coliform and Enterococcus has been modelled to access the impact from river inputs in south California beaches in San Diego (He and He 2008). An Artificial Neutron Network (ANN) based model employed in this study indicated several remarkable conclusions. (1) During the first 24 to 48 hours after a storm event, there is a significant increasing response of faecal indicator bacteria (FIB) due to the runoff from storms. (2) There are many factors could affect the bacteria concentration in the beaches that including geomorphology of beach shoreline, tidal effects, base flow, rainstorm events as well as the winds. (3) There is an urgent need of a much more rapid way of testing FIB, as the current method would require 18-96 hours before getting results, and it is much slower than the variations of FIB in real practice. Similar study using ANN to access the bacteria is (Lin, Kashefipour et al. 2003; Lin, Syed et al. 2008).

FIB also studies in surface waters in river and estuary with effects from wetlands (Sanders, Arega et al. 2005). It is suggested that the key contributing factors of FIB are urban runoff, and re-suspension of contaminated wetland sediments in the inland rivers, while the solely the sediment re-suspension process controls the concentration around the river mouth. Remarkably, it also indicated that the wildlife near the wetland could be an important natural source of faecal coliform, however leaving the human faecal source non-sensible near wetlands.

(Kay, Stapleton et al. 2005) Real time T_{90} decay rate has been considered as an important factor for modelling the intestinal enterococci concentrations in recreational waters in Severn Estuary and Bristol Channel, UK. The study focused on the effect of different level of turbidity and suspended solids in water column that could determine the decay rate T_{90}. This study has made a range of statistics with conclusion that the die off rate with high turbidity is almost equivalent to the rate under dark condition.

Another study (Stumpf, Piehler et al. 2010) has evaluated the impacts of tidal creek headwaters to the downstream estuary shellfish waters in North Carolina. The study has a comprehensive assessment of relationships between the bacteria load (Escherichia coli and Enterococcus spp.) and hydrological indicators during ten storms events. Such indicate like base flow, high flow during storm events as well as in-stream sediments are measured and interpolated with the automatic sampler (ISCO) fitted. It concluded that Faecal Coliform are weakly correlated with sediment but strongly correlated with flows at different hydrograph section (i.e. base, rising, peak, and falling). Also, it is imperative to have high resolution faecal coliform measurement in order to further studies. Another study in a tidal creek (DiDonato, Stewart et al. 2009) also taken into account of the land uses effects in the study. And also (Yakirevich, Pachepsky et al. 2013) simulated three years of artificial high flow event to model E. Coli in a coastal tidal creek in Maryland. A new model (SLIM-EC) (de Brauwere, De Brye et al. 2011) has been built for accessing the potential contribution of poor microbiological water quality condition in the tidal Scheldt River and estuary in Belgium. The new model employs hydro dynamic advection-diffusion-reaction equation for calculating depth averaged E. coli concentration in estuary. The study shows the tidal water determines the increases of faecal coliform concentration upstream of inputs. The river stream and die off process are controlling the long-term E. coli variations whilst that sediment effect and waste water treatment plants are relatively weak factors compare to others. It is important to identify the sources of faecal coliform in the estuary or coastal waters. Antibiotic resistance (Webster, Thompson et al. 2004) was used to analysis and access the potential sources of faecal coliform contamination in South Carolina estuaries. It shows there is remarkable difference of faecal coliform concentrations from Waste Water Treatment Plans between those in developed and undeveloped coastal area, with developed area has significantly higher concentration. There is an increased correlation between the antibiotic resistance in samples in urbanized catchment, indicating that AR testing could be a promising tool for differentiate the faecal source between human and wildlife.

2.5 Dynamic of Faecal Coliform

Sediment Associated Bacteria

The streambed sediment is acting as the reservoir to attract the bacteria in stream. SWAT 2005 has incorporated a bacteria transport subroutine which the bacteria die off is the only in stream process modelled (Kim, Pachepsky et al. 2010) further developed the sediment related bacteria transport in stream that evaluated the significance of streambed Escherichia coli (E.coli) release and deposition processes in stream. The modifications of SWAT bacteria module are attached to the sediment re-suspension and deposition processes, from a sub-routine called rtsed.f. The structure of SWAT model could be found in APPENDIX I.

The in-stream sediment transport in SWAT includes the re-suspension and deposition and is also functioned with the peak stream velocity. Then the re-suspended sediments are determined as a function of channel edibility factor and channel cover factor. Based on these assumptions, the modified model included the following three parts.

1. When the streambed sediment is re-suspended. The released E. coli is determined by the re-suspended sediment times the bacteria sediment concentration.
2. The suspended bacteria are partitioned into free floating, attached to suspended sediment, and attached to the deposited sediment.
3. The net amount of bacteria settled down from stream water is determined by multiplies the partitioning coefficients (K_p) between suspended sediment and water.

Solar radiation associated die off

The bacteria sub-routine in SWAT 2005 has static in-stream decay only. In other words, the decay rate remains constant at all time. SWAT was modified to incorporate the daily solar radiation associated die-off and the contribution from wild life where improvements were made by from (Cho, Pachepsky et al. 2012). The in-stream bacteria module was modified by adding a new parameter related to solar radiation (by adding a new variable SOLLPCH) to evaluate the effect of daily solar intensity. However, it could be explained by the following equation.

$$K_n = K + I\ (t) * K_s \quad (2\text{-}1)$$

The natural die off rate K_n is then re calculated by adding the effects from solar radiation. I (t) represent the solar radiation, and the K_s represent the solar radiation coefficient which is the added parameter SOLLPCH. Furthermore, the model assumes an initial die-off rate at 20 degree Celsius. Therefore, a temperature adjustment factor is used for re-calculation (Cho, Pachepsky et al. 2012). However, no study has been conducted with SWAT model, that to find the sub-daily variation effects to in-stream bacteria variation. The development is further illustrated in Chapter 5.

There are multiple factors that could affect the die-off processes of bacteria in water courses. Such factors are as natural die-off, solar radiation and temperature induced, salinity, acidity, turbidity and or sediment related die-off. The die off rate of faecal coliforms is quantified by two commonly used indicators, the die-off rate coefficient k, and T_{90}. The die-off rate coefficient k is derived from fist order decay by Chick's Law (H. 1908) that represent an exponential decline from an initial population.

$$k = \frac{log_{10}N_0 - log_{10}N_t}{t} \quad (2\text{-}2)$$

T_{90} is the time required for the population to fall by one log_{10} cycle from the beginning.

$$k = \frac{1}{T_{90}} \quad (2\text{-}3)$$

T_{50} in the term means the time required for 50% of the bacteria die-off. It is found that there is a relationship between k and T_{50} as shown (McFeters and Stuart 1972) which assume there is simple first order decay for calculating T_{50}.

$$k = \frac{log_{10}\ 0.5}{T_{90}} \quad (2\text{-}4)$$

again,

T_{90} can also be expressed as follow.

$$T_{90} = \frac{ln_{(10)}}{Decay\ rate\ k} \quad (2\text{-}5)$$

For example, if the decay rate k is 0.5/d, the equivalent T_{90} is worked out as 110 hours (Wilkinson 2000).

Natural Die-off

The natural die-off rate is estimated as 0.8/d for total coliforms present in freshwaters. This is equivalent to 69.1 hours as T_{90} representation (Mancini 1978 ; Thomann 1987). The natural dark die-off rate is around 0.73/d or T_{90} = 75.7 hours suggested by(Auer and Niehaus 1993; Boye 2014).

Solar Radiation and Temperature Die-off

Sunlight influences the bacteria die-off rate directly through cell damage and indirectly by altering the physical environment, such as sunlight could heat the water column and make water temperature rise, result more evaporation or enhance algae growth that release toxic substance that harm the bacteria (Mezrioui, Oudra et al. 1994). Sunlight accelerates the rate of faecal coliform die-off in catchment, rivers and seawaters (Kim, Pachepsky et al. 2010; Cho, Pachepsky et al. 2012). It showed the high die-off rate of coliforms (Gameson 1967) when exposed in seawater during day light. A similar study is (Bellair 1977). By contrast, (Gameson 1975) conducted experiments to compare the darkness die-off rate with daylight die-off rate, and concluded that bacteria die-off in the daylight are much greater due to sunlight. Bacteria in water samples exposed to intensive sunlight have been reported to decay 90% within a few hours, but have much less mortality a few days in darkness (Bellair 1977; Fujioka 1981).

2.6 Climate Change and Intensive Farming

The scientific consensus is that future increases in atmospheric greenhouse gas will result in elevated global mean temperature, and even with subsequent effects on regional hydrological processes (Arnell and Reynard 1996; Wilby, Whitehead et al. 2006). Human activities exacerbated the rate of N-based fertilisers to the land surface and agriculture intensive catchments have been regarded as the major sources of nutrients pollution in surface and coastal waters (Worrall, Davies et al. 2012). Organic nutrient inputs often come with attachment of faecal coliform that could be diluted with runoff that deteriorates the water course. Urbanization also substantially degrades water quality, especially where wastewater treatment is absent (Foley, DeFries et al. 2005). Effective water resources programs have always incorporated detailed analyses of hydrological and water quality processes in the upland watershed and downstream water body (Debele, Srinivasan et al. 2008).

Intensive Farming on Nitrogen (non-Faecal Coliform source)

A study (Whitehead, Johnes et al. 2002) conducted the research in accessing the annual nitrogen yield from the land in the terrestrial area to the river system, by prediction based on the land use changes. Its results give the confirmation of the increasing trend in nitrogen transportation in River Kennet, UK. It was suggested that the rise in nitrogen was attributed to both non-point source pollution from agriculture and point source discharges. However, these results were based upon the daily hydrological time series data of one single year simulation. The finding could have been more persuasive if the author could adopt longer term hydrological and meteorological data with impact of land use change under different climate projection scenarios. In addition, this study has only focused on the dynamic modelling of nitrogen by using INCA model (Wade, Durand et al. 2002). The researcher from University of Cincinnati conducted a comprehensive investigation in establish the relationship between land use and a range of surface water quality indicators (Yong and Chen 2002; Tong and Naramngam 2007) including faecal coliform. This is a study not only focused on the large regional scale but also the small local scale watersheds in an 8-year's simulation with statistics and spatial analysis.

Recreational Waters with Faecal Indicators

Coastal waters along public beaches can be polluted by urban runoff (Dwight, Baker et al. 2004), which is water that carries non-point source pollutions. The study suggested that discharging untreated urban runoff onto public beaches can pose health risks. The study selected two watersheds from urban and rural respectively to study the individual's symptom from exposure to coastal water. The conclusion is that the higher reporting rates of symptoms among urban NOC participants during the rainy 1998 El Nono winter. Coastal water along public beaches can be polluted by urban runoff that the water carries the diffuse source pollution via surface waterways to the ocean (Mallin, Ensign et al. 2001; Cha, Park et al. 2016). Precipitation events in southern California are an important driver for microbiological contamination of coastal water from surface runoff (Dwight, Baker et al. 2004; He and He 2008) in urbanized area often discharge untreated into coastal water. (Semenza, Caplan et al. 2012) projected daily precipitation for the twenty first century was derived from downscaled CNRM CM3 global climate model was used to compare with daily microbiological water quality over 6 years, a positive association between precipitation and microbiological water contamination ($P<0.001$) was established based on the analysis. Future projection of precipitation results in a decrease in predicted Enterococcus at California beaches.

Chapter 3

Study Area and Data

3.1 Introduction

Chapter 3 focuses on the background and characteristics of the study area in the River Frome and River Piddle catchment, and the linked downstream inter-tidal estuary of Poole Harbour. The aim of this chapter is to give the reader an overview of the focused area that would be further developed and deepened in the subsequent results and modelling in chapters 4 to 7. In this chapter, the detailed content includes the geographical location and topology, area geology and soil, local climate and hydrology conditions and the water quality of the study area that lays a rigid foundation for the thesis.

As guidance, this chapter is divided into four parts.

1. The first part describes the geographical information of the study area, which is the foundation of Chapters 5 and 6.
2. The second part contains the information related to the climate and hydrology of the Frome and Piddle catchment and Poole Harbour.
3. The third part describes the general background of water quality in the catchment and Poole Harbour.
4. The last part of this chapter provides a comprehensive summary of the data used in the thesis.

As the thesis focus is on integrated modelling in the flow and faecal coliform, in section 3.3, there is an expansion of nitrate, sediment and faecal coliform modelling and related studies. In Section 3.4, there is a comprehensive data summary used in the thesis. It includes spatial and temporal data used for the input, model calibration and validation that will be presented in the following Chapters 4 to 6.

3.2 Spatial Background

3.2.1 Location

River Frome and River Piddle are in Dorset County, South West England. The catchments are groundwater dominated rivers which are the western-most chalk stream in the United Kingdom. The total area that covers all rivers draining into Poole Harbour is about 820 square kilometres km^2 as shown in Figure 3.1. Both the Frome and Piddle rivers rise in the Dorset Downs in the north west of the catchment. The River Frome and its tributaries have been the focus of much research over the last 50 years, mainly because of the presence of the Freshwater Biological Association (FBA) at East Stock, Dorset.

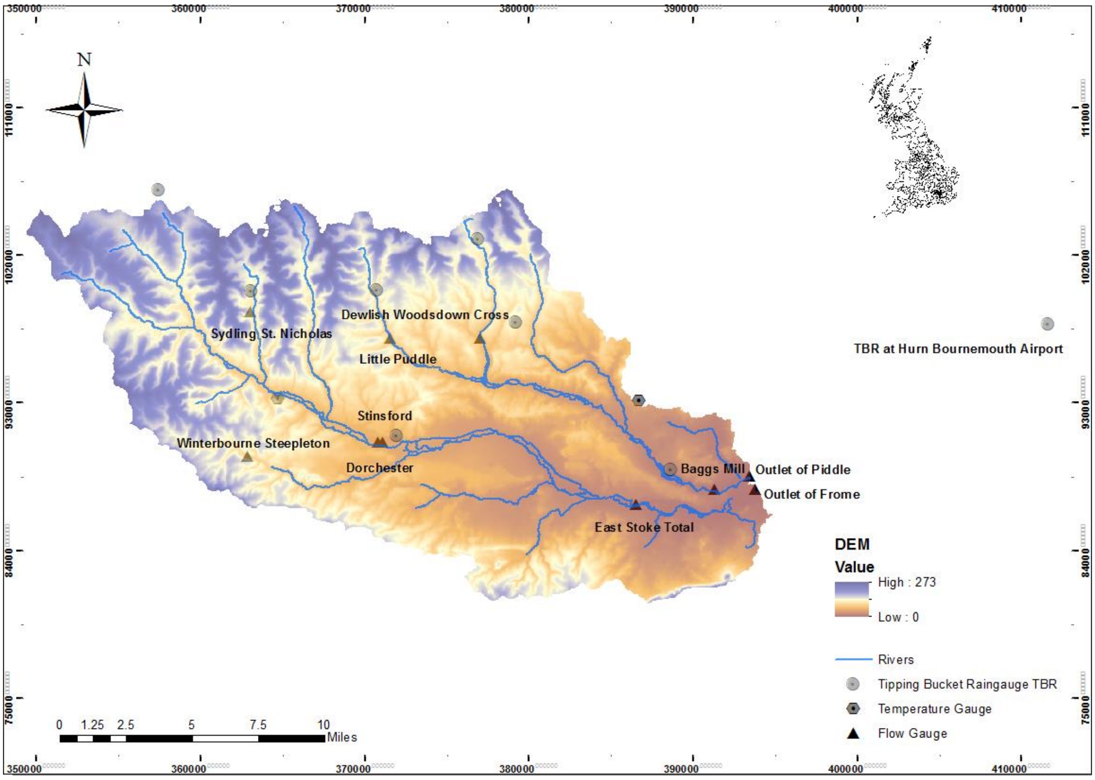


Figure 3.1 Location of the Study Area

Poole Harbour is a large natural harbour occupying an area of approximately 36 km^2 of the Dorset coastline in southern England. There are four river catchments that drain into the Harbour. The largest of which are the River Frome and the River Piddle. The harbour is designated as a Site of Special Scientific Interests (SSSI), a Special Protection Area (SPA) under the EC Birds Directive, and as a RAMSAR site. Poole Harbour is classified as a transitional water body and flows into the Dorset-Hampshire coastal water body, as shown in Figure 3.2. The estuary is shallow and the tidal regime is characterised by an unusual double high water (Group 2011). The north side of the harbour is urbanised, whereas the south side of the harbour is rural dominated. The estuary is a very important commercial shellfishery, containing wild and farmed beds for the production of oysters, mussels, cockles and clams.

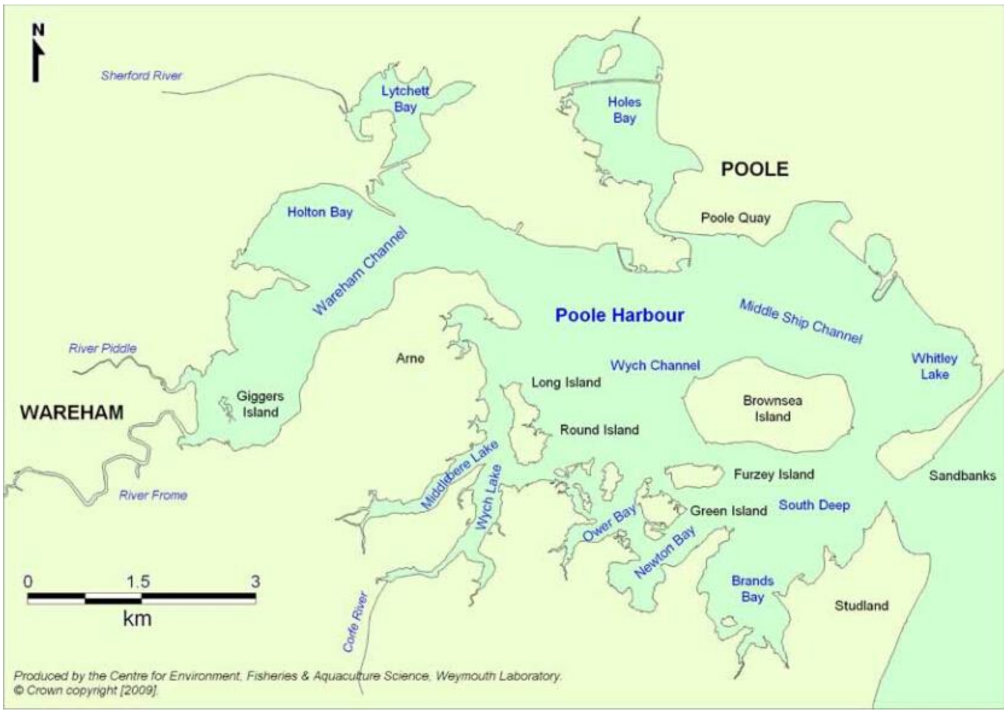


Figure 3.2 Location of Poole Harbour (CEFAS 2003)

3.2.2 Geology and Soil

The Frome and Piddle catchment is underlain throughout by chalk. The chalk is exposed at the ground surface over most the catchment, with the exception of the sand and clay (Palaeogene) cover around Wareham, and the underlying Upper Greensand and Gault clay deposits exposed in valley headwaters. The exposed chalk, in the upstream catchment, readily absorbs and transmits rainwater, which falls on it, or river water, which flows over it. The chalk is a good groundwater supply aquifer and is used for the public water supply. Where the chalk is covered by a significant thickness of Palaeogene clay, in the downstream catchment around Wareham, the chalk aquifer is isolated from river water and rainfall infiltration and is a poor aquifer. The upstream chalk is a significant source of spring flow. The main areas of spring flow are the Frome and Piddle headwaters and downstream at the edge of the Palaeogene cover. The downstream chalk spring is used to grow watercress. Chalk spring flows form a significant portion of the river flows, particularly in the summer months that represent a significant amount of base flow. The depletion of chalk springs due to chalk public water supply abstraction is a concern within the catchment (EA 2005). In the upper part of the catchment area, the soils are shallow, well drained and chalky, although there are areas of heavier, clay-influenced soils. In the middle part of the catchment area, the soils are sandy and more acidic. In the lower part of the catchment, the soils tend to be waterlogged by groundwater or winter flooding. Throughout the catchment, the river valleys contain alluvium and therefore exhibit clayey characteristics, whilst some areas are more calcareous and contain flint deposits. The soils on the valley sides tend to be well-drained and sandy, most commonly over gravel (EA 2005).

3.2.3 Land Use

The Frome and Piddle catchments are dominated by a rural landscape and are relatively free from heavy industry. Most the countryside is used for animal pasture or arable farming, with small villages, woodlands, and heathland towards the catchment outlet in the southeast. More than 75% of the estuary catchment is farmed, with cereal, dairy and cattle and sheep farming being predominant. It is almost equally divided between arable and pasture. Cereals are dominant over the chalk lands, with more dairy and beef farming in the west and on the lower floodplains. Land use tends to be arable or dairy farming in the upper and middle catchments, with extensive heathlands in the area between Dorchester and Wareham (Partnership 2014) (Environment Agency, 1999). The extensive water meadow system is another feature of the floodplains of the rivers Frome and Piddle (EA 2005). The land use around Poole Harbour is in marked contrast between the north and south of harbour. There are urban and industrial developments in the north of Poole Harbour and with a majority of rural areas to the south of Poole Harbour. Frome and Piddle catchment contains one of the highest concentrations of designated areas for nature conservation in England, with many sites of local, national and international importance. The EC Habitat Directive seeks to protect habitats and species of European importance by designating Special Areas for Conservation (SACs), including the Purbeck and Wareham, and Studland dunes, the west Dorset Alderwoods, and the Cerne and Sydling Downs. The Dorset Heathlands is also a Special Protection Area (SPA) under the EC Birds Directive and a RAMSAR site designated for its internationally important wetland feature. The SAC and SPA areas together are made up of the existing Sites of Special Scientific Interest (SSSI) which are statutory sites of national conservation importance.

3.3 Climate and Hydrology

3.3.1 Climate

The rain, wind and cloud in the study area are relatively quiescent due to the geographical location lying far away from the Atlantic depressions. There is a network of rain and climate gauges in the area of over 80 previous and current gauging sites. There are weather parameters that are measured daily or sub-daily. The rain gauging station at Hurn (Bournemouth Airport) is the only one that has both daily and hourly weather records. Hurn is located 10 km north east of the study site. Table 3-1 shows the monthly weather statistic at Hurn. The average annual precipitation decreased from 1020mm to 840 mm in the Frome and Piddle (Bowes, Smith et al. 2009; Howden, Bowes et al. 2009).

Table 3-1 Mean Precipitation and Temperature in Frome and Piddle Catchment

Month	Rainfall (mm)	Min Temp (Celsius)	Max Temp (Celsius)	Day Light (Hours)
Jan	85	2.2	9.3	71
Feb	61	1.8	9.4	90
March	60	2.9	11.4	123
April	60	4.6	14.2	181
May	62	7.9	17.3	203
June	46	10.3	20.0	229
July	59	12.1	22.0	224
August	53	12.2	21.9	204
September	60	10.1	20.0	164
October	110	7.5	15.7	110
November	111	3.9	11.8	82
December	103	1.9	9.0	65

3.3.2 Hydrology

Rivers are more significant sources of contamination than the sewerage effluent that discharges into Poole Harbour. The main freshwater inputs to the harbour are river Frome and river Piddle. Both rivers discharges to the west of Poole Harbour, with the catchment outlets are near Wareham as shown in Figure 3-1. The river Frome has an average flow rate of $6.4m^3/s$, while the river Piddle has an average flow of $2.4m^3/s$, giving a total of around $8.8\ m^3/s$ of flow as freshwater input to Poole Harbour as shown in Figure 3-1. There are other smaller inputs to the harbour. One is from the Corfe River draining into Wych Lake, and the other is the river Sherford discharge into Lytchett Bay. However, neither of Sherford and Corfe River is gauged, but with an estimated mean flow of about $0.5m^3$/s (CEFAS 2012).Both river Frome and river Piddle are groundwater dominated, with base flow indices of 78% for the Frome and 86% for the Piddle.

3.3.3 Tide and Hydrodynamic

The tides of Poole Harbour have a range of approx. 1.6m on mean spring tides and 0.5m on mean neap tides. The highest astronomical tide is 2.6m above chart datum (CD) and the lowest astronomical tide is at the level of CD. The CD at Poole Harbour is defined as 1.4m below Ordnance Datum (Newlyn). Table 3-2 shows the tidal levels at Poole Harbour entrance, taken from Admiralty Tide Tables.

Table 3-2 Tidal Levels at Poole Harbor Entrance (m CD)

HAT	MHWS	MHWN	MWL	MLWN	MLWS	LAT
2.6	2.2	1.7	1.6	1.2	0.6	0.0

The tides at Poole Harbour are highly variable due to the proximity of a local minimum in the amplitude of the main semi-diurnal tidal constituents in Poole Bay.

Higher order tidal waves are more significant, resulting in a double high water (i.e. two maximum in tidal height) during spring tides.

3.3.4 Water Abstraction

There are 308 water abstraction sites within the Frome and Piddle and Purbeck Catchment Abstraction Management Scheme (CAMS) area. Although the abstractions are spread across the whole CAMS area, the large groundwater abstractions are concentrated on the chalk aquifer. Approximately 72% of abstraction licences issued in the CAMS area are from groundwater, which represent less than half of the total annual licensed volume. Water abstracted for spray irrigation results in a total loss of that resource to the catchment. This indicated that such as irrigation with lower abstraction volumes could attributes to greater impact to the flows than those with higher abstraction. Figure 3-5 shows the irrigation contributes 4% of total abstraction by volume. The largest abstraction by volume is aquaculture for fish farms at 57%, however the most of water abstracted for fish farms is returned to the watercourse close to the point of abstraction ultimately. Abstraction in summer and autumn could undermine river ecosystem during drought months.

A map from (EA 2005), which contains the number and location of the water abstractions was used to calculate the amount of water lost in the surface river channel. Regarding the surface abstractions only, there are around 4 locations abstracts 20Ml/d, 2 locations abstract 10-20Ml/d, 3 locations abstract 5-10 Ml/d, 18 locations abstract 0.5-5 Ml/d and 32 locations abstract <0.5Ml/d. To sum it up, there are around 170-230Ml/d of water has been abstracted from the surface water in the Frome and Piddle catchment.

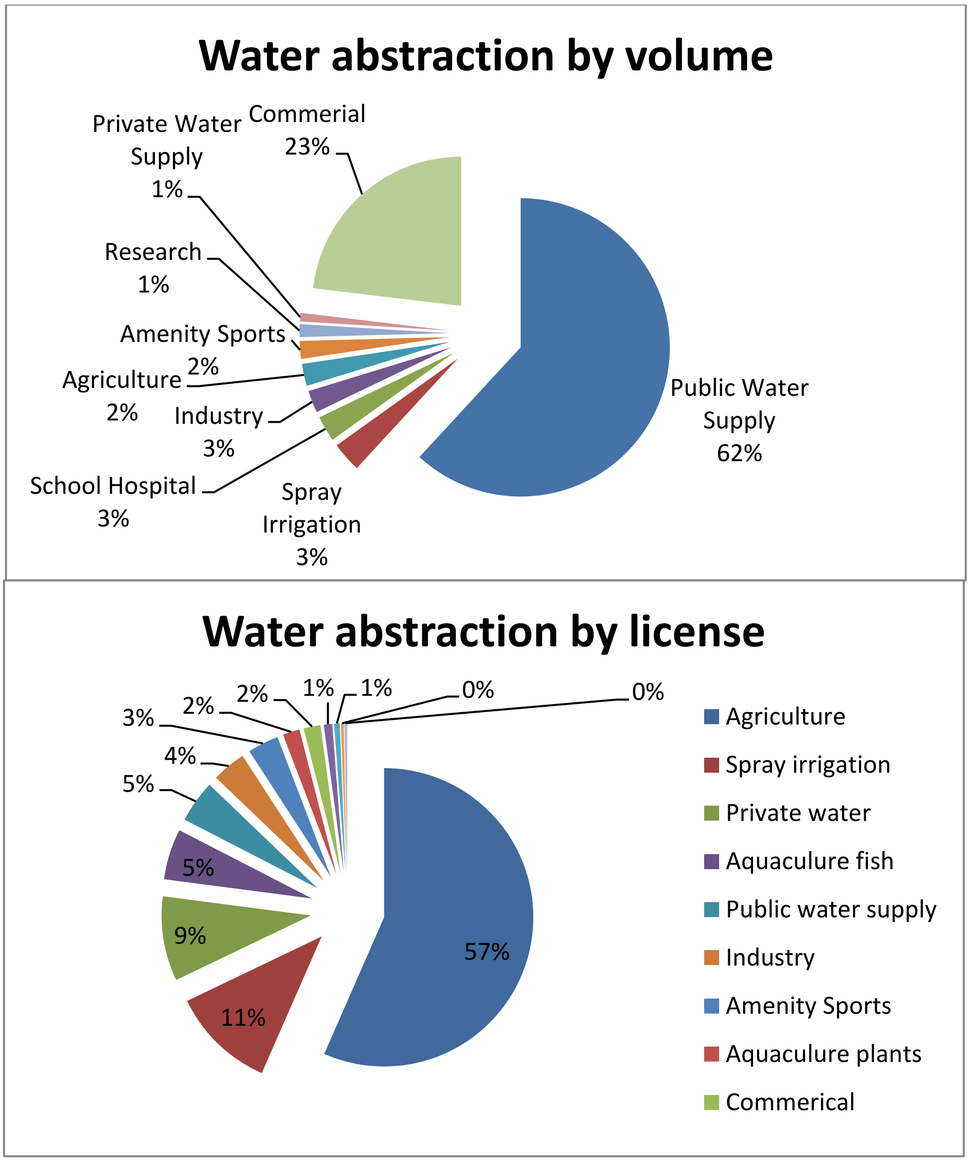


Figure 3-5 Distribution of Water Abstraction in Frome and Piddle (EA 2005)

3.3.5 Waste Water Treatment Work

A total consented volume of approx. 17.1Ml / day (equivalent to $0.2m^3/s$) of treated effluent is discharged directly into the rivers. 98% of discharges from sewerage treatment works operated by Wessex Water, with the remaining 2% from private sewerage treatment plants. Of these treatment plants, the largest are Dorchester STW, Wool STW and Blackheath STW.

Table 3-3 Continuous Sewerage Discharges in and around Poole Harbor

STW name	NGR	DWF (m^3/day)	Treatment Level	Suspended Solid (mg/l)
Poole Harbor Area				
Poole STW	SZ 0071 9356	47,000	Tertiary (UV)	45
Wareham STW	SY 9364 8863	2,502	Tertiary (UV)	*35*
Lytchett Minster STW	SY 9682 9228	1,600	Tertiary (UV)	40
Corfe Castle STW	SY 9611 8314	370	Secondary	30
Studland STW	SZ 0235 8454	227	Secondary	35
Brownsea Island STW	SZ 0270 8784	190	Secondary	*35*
Holton Heath STW	SY 9518 9062	182	Secondary	40
Frome and Piddle Catchment				
Wool STW	SY 8226 8733	2,205	Tertiary (UV)	40
Dorchester STW	SY 7093 9024	9,450	Tertiary (UV)	40
Mainden Newton STW	SY 6045 9725	291	Secondary	35
Piddlehinton STW	SY 7216 9632	350	Secondary	35
Puddle Town STW	SY 7510 9495	240	Secondary	35
Blackheath STW	SY 8977 9326	1,200	Tertiary (UV)	30

3.4 Water Quality

3.4.1 Nitrogen and Phosphorus

The mean concentration of nitrate in the River Frome is around 6.5mg/l compared to 2mg/l previously in 1965. This showed the seriousness of the problem arise from the high level of nitrogen draining into Poole. Consequently, it leads to the occurrence of dense algal bloom in the Poole Harbour Special Protection Area (Group 2011). Around 80% of nitrogen in Poole Harbour is from agriculture, and another 15% is from sewerage treatment works. Nitrogen from fertilizer and manure leaches into chalk groundwater but can enter rivers directly as overland runoff or via drains during storm events. Leaching is the main source of nitrogen pollution with a time lag of as long as 30 years on the higher land of the chalk streams. The Phosphorus concentration peaked in the River Frome in the early 1990s. But it has decreased over the last 20 years, mainly due to phosphorus removal using chemical treatment at Dorchester and Wool STWs and the decline in the use of phosphorus in fertilisers and better manure management practices. High P levels in the river, especially during low flow, would lead to excessive algal growth. The Lower Frome and Lower Piddle are classified under WFD as 'Poor' for diatoms (river bed algae) and 'Moderate' for macrophytes (aquatic plants). Diffuse sources from agricultural land (manure, fertilizer, soil and sediment) and septic tanks are estimated to account for 64% and 77% of the phosphorus load to river Frome and Piddle, respectively. Once in the river bed, phosphorus can be released from the sediment into water. Point sources mainly from the STW account for 36% and 23% of the total Phosphorus load to the river Frome and Piddle.

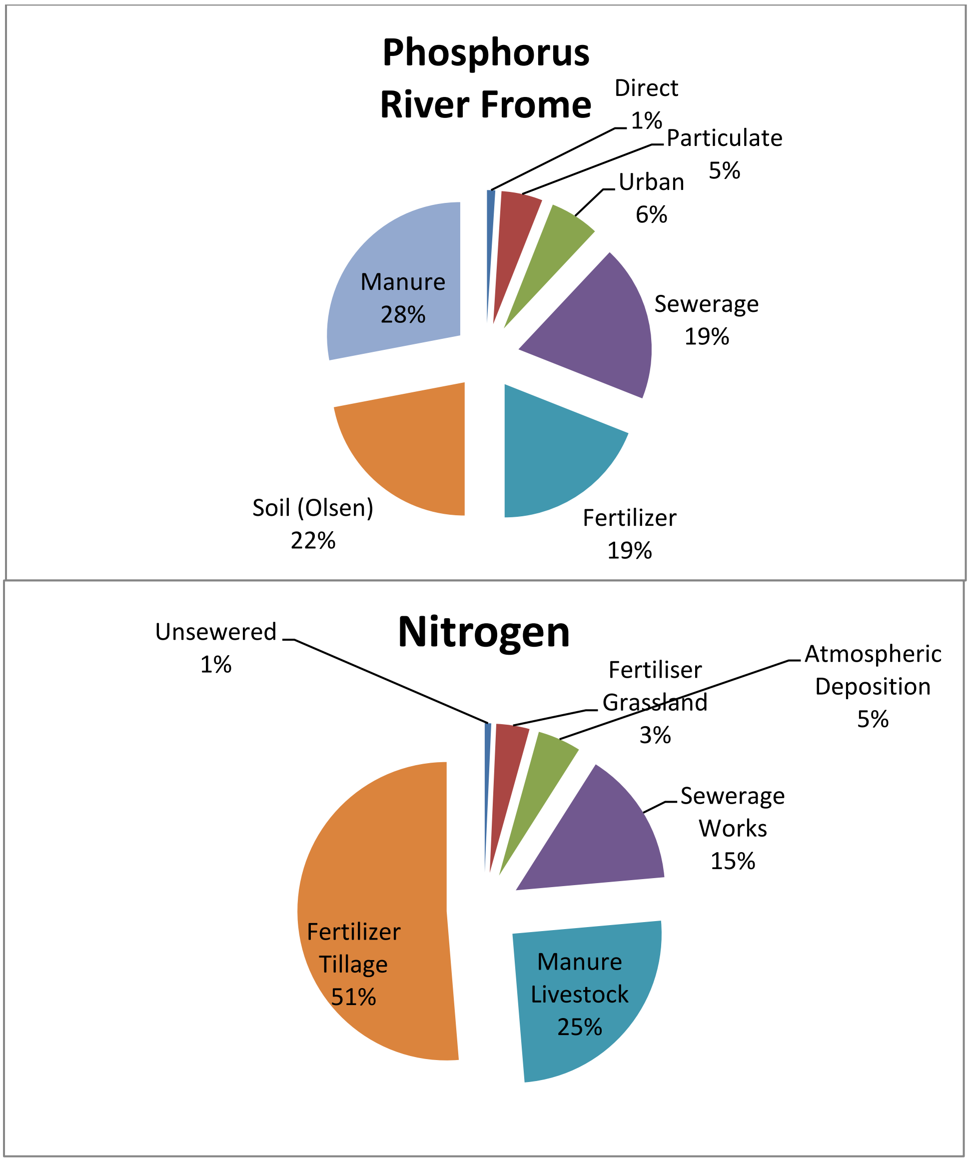


Figure 3-6 Percentage Contribution of Phosphorus and Nitrogen in the Frome catchment (EA 2008)

3.4.2 Sediment

Sediment can be measured directly in water samples as suspended solids or turbidity, or as deposited particles on, or in, the stream bed. Its movement through rivers is important for ecosystem succession processes. Sediment is a key water quality parameter measured in the Frome and Piddle streams. The River Frome SSSI fails to meet the favourable condition assessment for suspended solids. Siltation is regarded as one reason for the failure of the Bere stream SSSI. Sediment can also carry bacterial faecal indicator organisms and may account for the failure of bathing and shellfish water quality in Poole Harbour. During high rainfall events, the sediment concentration in rivers within the catchment is much higher than normal. In addition, there is a reasonably strong seasonal pattern, that the highest concentration found in rivers occurs in winter months, as a response of intensive rainfall. Low concentrations of fewer than 5mg/l are usually recorded during late summer with low flow. Around 10% of the sediment was from roads, which was likely to originate in fields. It is estimated that around 70% of the total contribution of suspended sediment load in the Upper Frome (Chilfrome) is from cultivated land, with 2% from woodland and 18% from pasture respectively**.** Erosion from land and channel banks is a natural process which leads to rise in suspended solids in rivers. Maize cultivation, intensive dairy and ploughing on steep slopes in the upper Frome and Piddle catchment have been reported to produce very silty runoff during high rainfall events. Salad cropping in the lower catchment can have a similar effect. The results indicate that much of the farmer's top soil is ending up in the rivers and ultimately Poole Harbour. The aggregated industry has also been reported as a source on the River Frome and Tadnoll Brook. However, there is an exception in that the Bere Stream sub-catchment of the River Piddle does not appear to have the same input from agriculture, with around a third of the sediment originating from damaged road verges and nearly two fifths from within the channel. The cultivated and pasture land’s contribution is less than 5% each. This suggests that the lake at the top of the catchment is acting as a silt trap.

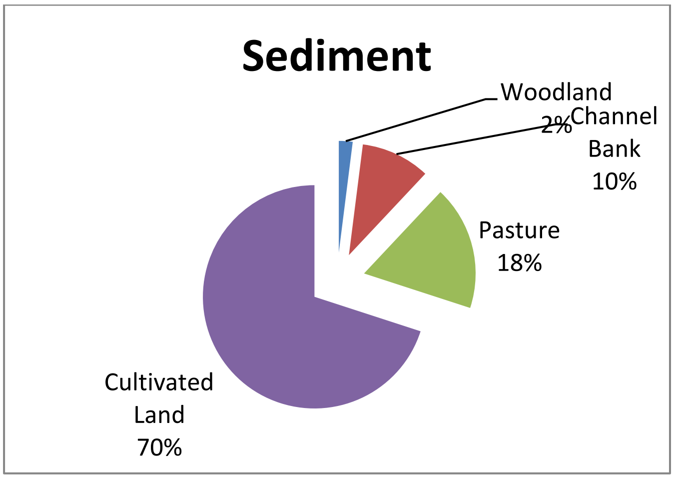


Figure 3-7 Percentage Contribution of Suspended Sediment in Frome and Piddle

3.4.3 Bacteria

Bacteria Monitoring

There are three designated bathing water sites within the harbour. One is located at Rockley Sands near the exit of Lychett Bay. The other one is at the Poole Harbour Lake to the west of Lower Hamworthy, as shown in Figure 3-2.

Table 3-4 Summary of Faecal Coliform in Poole Harbour (Agency 2003; CEFAS 2012)

Site	No. of Samples	Mean (cfu/ml)	Minimum (cfu/ml)	Maximum (cfu/ml)	Frequency
Rockley Sands	120	30	2	1240	Weekly
Lake	120	12	<2	1632	Weekly
Hamworthy Park	80	7	<2	450	Weekly

Shellfish Water Monitoring

The Directive on the quality of shellfish waters protects the shellfish population e.g. bivalve and gastropod molluscs from pollution. It specifies quality standards of water supporting shellfish populations. Samplings are carried out monthly at sites within Poole Harbour and in Poole Bay. The Shellfish Hygiene Directive (91/492/EEC) aims to protect the public health of consumers of live bivalve molluscs such as clams, cockles and mussels. It has four categories according to the concentrations of bacteria found in the shellfish flesh (Group 2011). The Shellfish waters are monitored for various parameters based on water quality standards established by the Shellfish Water Directive. These parameters include suspended solids, salinity, Dissolved Oxygen (DO), Organo-halogenated substances, metals and coliform. For each parameter, the Directive specifies the minimum number of samples that must meet these standards.

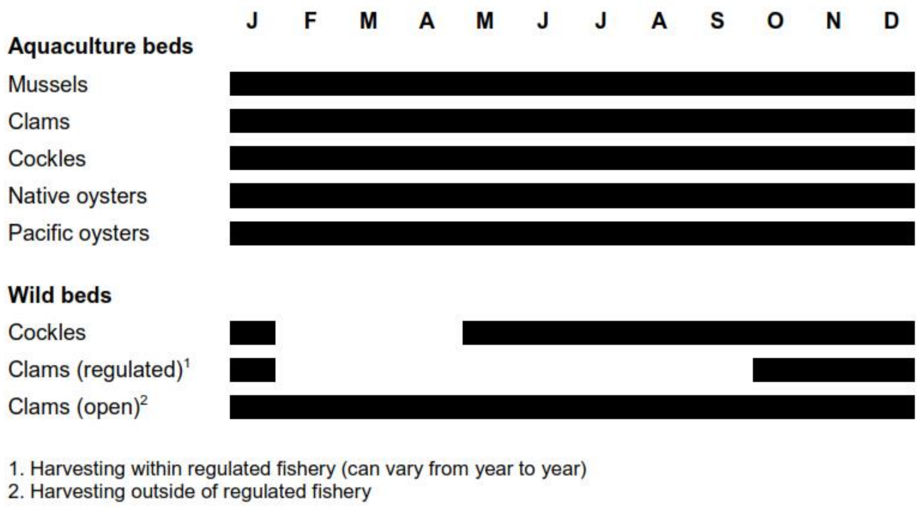


Figure 3-8 Shellfish Harvesting Seasons in Poole Harbour (CEFAS 2012)

River Monitoring

Rivers and streams that receive point and diffuse pollution can be significant input of faecal bacteria contamination of coastal waters, particularly during high flow conditions (Kay, Crowther et al. 2008).

Table 3-5 Faecal Coliform data in Rivers (EA 2005)

Site	No. of Sample	Mean (cfu/100ml)	Minimum (cfu/100ml)	Maximum (cfu/100ml)
Corfe River d/s Corfe STW	24	990	102	7,000
River Frome at Wareham	18	740	240	4,000
Holton Heath Stream STW	3	10,000	3,200	37,000
River Piddle at West Millls	16	420	36	2,600
Sherford River at King Bridge	154	1,200	115	73,000

Point sources to shellfisheries from municipal (STWs) could be significant risk to human health due to the large population and volume of effluent discharges. The potential point source sewerage that could cause microbiological contamination is listed in Table 3-5. However, due to the research aims to investigate the impacts of diffuse pollutions, the STWs are regarded as not major sources of bacterial contamination.

Table 3-6 Observed Storm Event (6-hours) Faecal Coliform (CEFAS 2003; CEFAS 2012)

Station	Purpose	Frequency	Duration	No. of Sample
Affpuddle (Little Puddle)	Research (ADAS)	6 hours	2 weeks	30
East Stock	Research (ADAS)	6 hours	2 weeks	30
West Mill	Research (ADAS)	6 hours	2 weeks	30
Maiden Newton	Research (ADAS)	6 hours	2 weeks	30

Intermittent sewerage discharges including storm and emergency overflows to the harbour represent a significant risk to human health. Storm sewerage is untreated sewerage in a mixture with surface runoff from combined sewerage systems that discharge via combined sewer overflows (CSOs) and or storm sewer overflows (SSOs). Although some dilution from rainwater is afforded, the bacteria loading of storm discharges is significantly higher that treated sewerage effluent with faecal coliform concentrations of typically around 10^5 - 10^6 cfu per 100ml (Harris, Falconer et al. 2002; Kay, Blankenship et al. 2005; Lee, Lin et al. 2006; Lee, Lee et al. 2014).

Table 3-7 CSO and Overflow in Frome and Piddle (EA 2005)

Overflow name	NGR of outfall	Receiving Water
West Mill Crescent CSO	SY 9162 8792	River Piddle
Sandford Lane CSO	SY 9210 8818	River Piddle
Wareham STW storm overflow	SY 9364 8863	River Piddle
Abbots Quay CSO	SY 9230 8717	River Frome
Kings Arms Stoborough CSO	SY 9240 8650	River Frome
South East Wareham SPS	SY 9280 8730	River Frome
Corfe Castle STW storm overflow	SY 9611 8314	River Corfe
Corfe Castle Red Lane SPS	SY 9647 8169	River Corfe
Rockley Road SPS	SY 9957 9006	Poole Harbour
East Quay SPS	SZ 0140 9025	Poole Harbour
Seacombe Road (Poole) SPS	SZ 0380 8760	Poole Harbour
Sandbanks Pavilion SPS	SZ 0430 8770	Poole Harbour
Lytchett Minster STW SSO	SY 9682 9228	Lytchett Bay
Moorland Way SPS CSO/EO	SY 9757 9266	Lytchett Bay
Turlin Main SPS	SY 9836 9220	Lytchett Bay
Creekmoor Lane (Poole) CSO	SZ 0037 9309	Holes Bay
Blandford Road (Poole) SPS	SZ 0047 9047	Holes Bay
Fairview Rd (Poole) CSO	SZ 0050 9639	Holes Bay
Poole Bridge SPS	SZ 0063 9037	Holes Bay
Poole STW storm overflow	SZ 0073 9360	Holes Bay
Holton Heath STW storm overflow	SY 9518 9062	Stream to Holton Mere
Elgin Road (Poole) SPS	SZ 0400 8930	Whitley Lake

A summary of the spill data for these assets is given in Table 3-8. It is notable that Moorland Way SPS, which discharges to Lytchett Bay, has split over 20 times in each of the last three years against a design standard of 10 significant (>50m^3) spills per year. In addition, there are continuous and intermittent discharges in the

Table 3-8 Spills of Intermittent Sewerage Discharges to Poole Harbour (03-09)(EA 2005)

Location	03-04	04-05	05-06	06-07	07-08	08-09
Poole STW	4	2	4	26	1	4
Lytchett Minster STW	14	13	N/A	4	17	5
Wareham STW	1	4	0	8	2	6
Moorlands Way SPS	12	12	7	24	20	23

catchment that would contribute to E. coli in the two rivers. The major sources are discharges from Dorchester STW and Wool STW, which are around 20 km and 10 km upstream of the tidal limit. The geometric mean faecal coliform concentrations for the Frome, Piddle, Corfe and Sherford are higher than disinfected effluents from the STWs. This implies that the rivers are more significant source of faecal bacterial contamination to bathing and shellfish waters.

3.5 Data Availability

Data source and spatial and temporal information are summarized as shown in Table 3-9. It includes the data on model setup, calibration and verification in the study of flow, sediment and bacteria modelling.

Table 3-9 Data Availability

Type	Source	Frequency	Period	Gauge	No. Data
Spatial Data Summary					
DEM	EDINA	N/A	2012	N/A	N/A
Soil	World Harmonized	N/A	2010	N/A	N/A
Land Use	CEH	N/A	2000	N/A	N/A
Wetland and Pond	DERC	Count	2000 – Present	N/A	1,100
RAMSAR	JNCC	N/A	2012	N/A	N/A
SPA SAP	JNCC	N/A	2012	N/A	N/A
Wildlife	DERC	N/A	2009 – 2014	N/A	2,000
Temporal Data Summary					
Precipitation	BADC	Daily	1990 – Present	3	10,950
Precipitation	BADC	Hourly	1990 – Present	1	86,700
Solar Radiation	BADC	Hourly	1990 – 2005	1	86,700
Flow	NRA	Daily	1960 – Present	5	N/A
Flow	CEH	15 minutes	1995 – 2005	5	350,400
Water Elevation	Admiral	N/A	N/A	N/A	N/A
Sediment	CEH	6 hours	2004 – 2006	1	1,177
Sediment	EA	Fortnightly	1999 – 2009	1	275
Faecal Coliform	EA	River monthly	2004 – 2006	5	100
Faecal Coliform	CEFAS	River 6-hours	2001 – 2002	4	120
Faecal Coliform	EA	Harbor monthly	2004 – 2006	8	100

Chapter 4

SWAT Rainfall Runoff Modelling

Key Words:

Hydrological Modelling

Green & Ampt Infiltration

Sub – Daily Modelling

Sensitivity and Uncertainty

Calibration and Validation

4.1 Introduction

Chapter 4 is about hydrological modelling of river flows at different time steps. First, the chapter introduced the method to setup SWAT in the study catchment and key model optimisations. Then the main model routing method i.e. the governing equation was introduced for surface runoff process and sub daily routing. After the theoretical method, the model calibration and validation has been described with hydrographs, key model performance statistics and flow duration curves for high and low flow analysis.

Chapter 4 aims to address the following problems:

1. Getting the hourly flow as accurate as possible is an objective for hydrology. As the output of SWAT model would be used as input for coupling with the DIVAST model.
2. Set up the baseline condition. Analysis of uncertainty and sensitivity of catchment hydrology.
3. Green & Ampt method for the simulation of sub-daily flow.

Chapter 4 is critical, because it builds the foundation of this thesis on catchment hydrological modelling. It is the base for the following chapter 5 on sediment and bacteria modelling with model development and modifications. Good results for the hydrological modelling will provide a useful foundation for the consequent water quality modelling and analysis as the important driving force and stability.

4.2 Model Setup

The SWAT model requires a digital elevation model (DEM) and soil and land use maps to delineate the catchment as shown in Figure 4-1. This includes creating the catchment boundary and dividing the catchment into several sub-basins according to the location of outlets. The resolutions of the DEM, land use maps are 50 meters and 1,000 meters respectively, the scale of the soil map are1: 5,000,000.

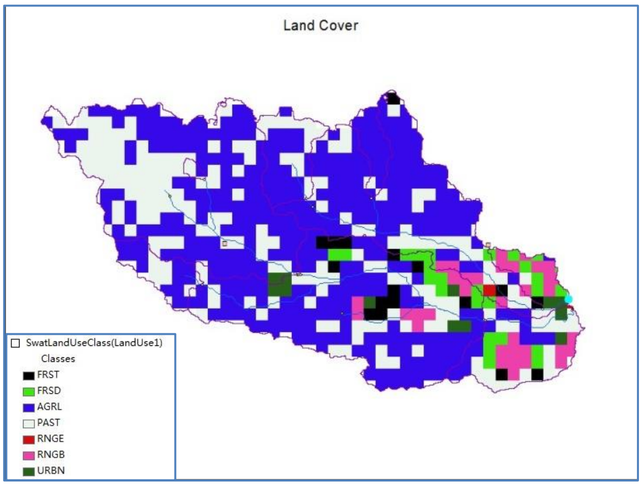


Figure 4-1 Land use distribution in the Frome and Piddle catchment

Table 4-1 shows the classifications of land use in the catchments, with symbols used in SWAT, areas of each class and the proportions of each class to the whole catchment.

Table 4-1 Land Use Classifications

Land use	Symbol	Area (ha)	Percentage (%)
Forest Mixed	FRST	1724.37	2.59
Forest Deciduous	FRSD	2474.43	3.72
Agricultural Land	AGRL	38038.69	57.12
Pasture	PAST	19682.41	29.56
Range Grasses	RNGE	119.40	0.18
Range Brush	RNGB	3331.13	5.00
Urban/Residential	URBN	1224.33	1.84

Table 4-1 shows that the major land use in the Frome and Piddle catchment is Agricultural Land (57.12%) followed by Pasture Land (29.56%), Range Brush (5%), Forest Deciduous (3.72%), Forest Mixed (2.59%) and Urban (1.84%).

Table 4-2 Agricultural and Pasture Land in each Sub-basin

Sub-basin	Agriculture (ha)	Agriculture (%)	Pasture (ha)	Pasture (%)
1	1958	62.95	1139	36.63
2	1235	92.70	85	6.40
3	55	27.24	152	74.81
4	11672	57.89	8185	40.60
5	12	63.44	7.14	38.61
6	1321	65.90	587	29.27
7	58	3.11	226	12.10
8	9627	69.68	3176	22.99
9	10879	57.93	4346	23.14
10	1223	23.07	1779	33.57

Agricultural and pasture land are the two dominant land uses in Frome and Piddle catchment, as shown in Table 4-2. Sub-basin 4 ranks the top that have the largest land in size (ha) in terms of both agricultural (11,672 ha) and pasture (8,185 ha). Sub-basin 9 is the second largest sub-basin with agricultural land of 10,879 hectares and second largest pasture land which is of 4,346 hectares.

The soil map used in this SWAT setup is the Harmonized World Soil Database (HWSD) which was published in February 2012. The portion of soil map is extracted from the European Soil Database. The state-of-the-art world soil map was created and archived with the following partnerships.

- Soil Map of the World FAO 1995, 2003. The Digitized Soil Map of the world including Derived Soil Properties (version 3.5).

- The Soil Map of China (1:1 Million Scale) Chinese Academy of Sciences, Second National Soil Survey in China (1995), the Institution of Soil Science in Nanjing.

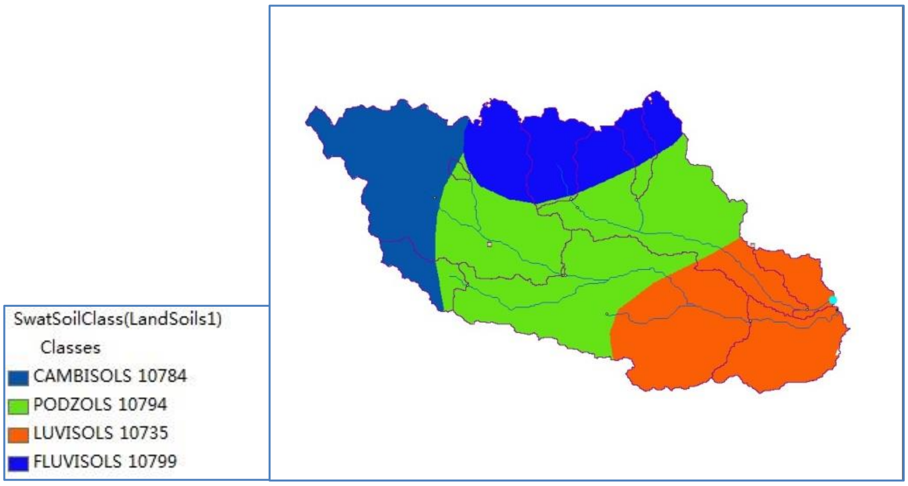


Figure 4-2 Soil Type Distribution in Frome and Piddle Catchment

There are two options for soil map input at the Frome and Piddle catchment. The first one is called National Soil Map (NSM) from the National Soil Institution at Cranfield University. The second option is called the Harmonized World Soil Database published by the Food and Agriculture Organisation (FAO). The latter is open access from online archives whereas the NSM requires access request. The classifications of soil used in the SWAT model are summarized in Table 4-4.

Table 4-4 Distribution of Soil Class

Soil Type	Area (ha)	Percentage (%)
Cambisols 10784	10,806.46	16.23%
Fluvisols 10799	10,240.60	15.38%
Luvisols 10735	18,301.43	27.48%
Podzols 10794	27,246.26	40.91%

Table 4-4 Description of Soil Class

Soil Type	Description
Fluvisol	*Fluvisol is soil in alluvial deposits. It can be found as river, lacustrine, and marine deposits. Fluvisol can be found in coastal lowland, that have severe constraints for agricultural use due to the low pH values, toxic aluminium levels and high concentrations of salts.*
Podzols	*Podzols are soils of coniferous or boreal forests, normally found in areas that are wet and cold. Most Podzols are poor soils for agriculture in the terms of being sandy and excessively drained. In western Europe, Podzols are developed on heathland which are well maintained through grazing and burning.*
Cambisol	*Cambisol are medium and fine textured materials derived from a wide range of rocks. Cambisol make good agricultural land, particularly as it is very productive soil for crops, and widely present in temperate climates.*
Luvisols	*Luvisol soils typically occur in forested areas of sub humid to humid climate where the parent materials contain clay that has been leached after snowmelt or heavy rain. Luvisols with a good internal drainage are potentially suitable for a wide range of agricultural uses because of their moderate stage of weathering and high base saturation and infiltration rate.*

4.2.1 Model Configuration

SWAT model is set up in ArcSWAT interface (with ArcMap 10.1) by overlaying multiple GIS inputs described in section 4.2. ArcSWAT helps to generate a folder called ‘txtinout’ that stores all the input and output files used in the model. This is for set up the fundamental I/O files of SWAT model. There are various files that control and operate which represent different hydrological processes. For example, such as .sol file which contains the parameters used for soil related algorithms such Green & Ampt infiltration. Similarly, .rte files control river channel process, .res files govern reservoir simulation, and a .sub file is responsible for sub-basins. The two control files that end with .cio and .bsn. are critical to initialise simulations.

Daily and Sub-daily Routines in SWAT Model

The elementary SWAT simulation is based on each Hydrological Response Unit (HRU). The model integrates all HRUs as sub-basins, and ultimately calculates flow paths through to the outlet of catchment. There are four methods that can be selected for catchment flow routing method, as shown in Table 4-5.

Table 4-5 Model Configurations with Varied time-steps

Options	Requirements and Performance
IEVENT = 0	Daily Rainfall Input, Daily Flow Output. SCS Curve Number Method
IEVENT = 1	Daily Rainfall Input, Daily Flow Output. Green & Ampt Infiltration Method
IEVENT = 2	Sub-daily Rainfall Input, Daily Flow Output. Green & Ampt Infiltration Method
IEVENT = 3	Sub-daily Rainfall Input, Sub - daily Flow Output. Green & Ampt Infiltration Method

For instance, when IEVENT equals 1, the model requires daily rainfall input which requires the SCS curve number method. Whereas, when IEVENT equals 3, the model reads sub-daily rainfall input and simulates with sub daily time steps, and yields sub daily flow and water quality output. In this thesis, the following two options were used. i.e. When IEVENT=2, model reads sub-daily rainfall inputs and runs every 60 minutes and gives the aggregated daily flow output. The aggregated daily flow is used for comparing with observed daily flow for model calibration and validation. When set IEVENT=3, the model reads hourly rainfall as input, and runs every hour. To run the model at varied time step, the time steps of input data should always be consistent with expected model output.

Unit Hydrograph for Sub-daily simulation

When the model operates in hourly time steps, the flow is routed using the unit hydrograph method for surface runoff yield. Unit hydrograph offer two options.

(1) When IUH=1, model use triangular UH method (regarding parameter tb_adj that adjust the hydrograph shape)

(2) When IUH=2, model use gamma distribution UH method (regarding parameter UHALPHA that adjust the hydrograph shape)

The sub-daily flow is controlled by another parameter called BFLO_DIST, which represents the base flow distribution factor that is required for sub-daily simulation. It works like the UH method, which routes the surface runoff within each 24 hour.

(1) When BFLO_DIST=0, the base flow is evenly distributed through each time step.

(2) When BFLO_DIST=1, the base flow is distributed related to rainfall events.

4.2.2 Model Optimisation

Aerial Rainfall using Thiessen Polygon

The meteorological station used in this study is located at Hurn with the ID number 842 from British Atmosphere Data Centre (BADC). The station at Hurn is the only station that has hourly rainfall records during the study period (1999-2006) in County Dorset. Thiessen Polygon is the weighted mean method for adjusting the rainfall input for catchment models. Due to rainfall never being uniform over the entire area of the catchment, due to the rainfall varies in intensity and duration spatially. Therefore, the rainfall is recorded at each rain gauge should be re-weighted using Thiesson Polygon. The Thiessen Polygon model is set up in ArcGIS that including 7 rain gauges in the catchment. Therefore, the catchment is divided into 7 sub areas and weighted according to area and location. Mean monthly rainfall is worked out using Thiessen Polygon method as shown in Figure 4-4.

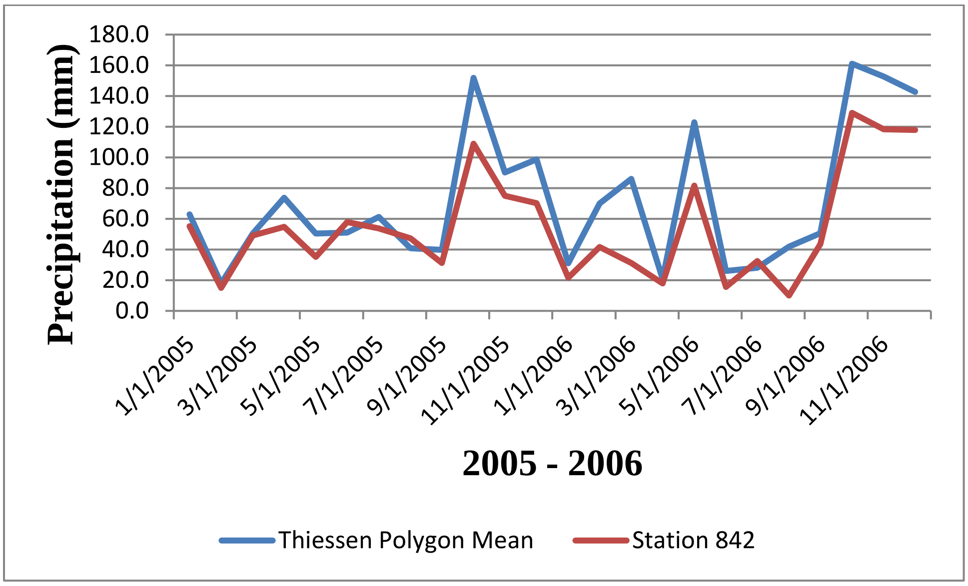


Figure 4-3 Average Monthly Rainfall for Gauge Hurn

By analysing the calculated daily rainfall from station 842 at Hurn near Bournemouth airport, and comparing it with the other six BADC gauging stations distributed across the catchment shown in Figure 4-4, it was found that there is a general underestimation of the rainfall at Hurn compared with the calculated monthly mean using the thiessen polygon method. Figure 4-3 shows the plot of this comparison of monthly mean across 24 months between 2005 and 2006.

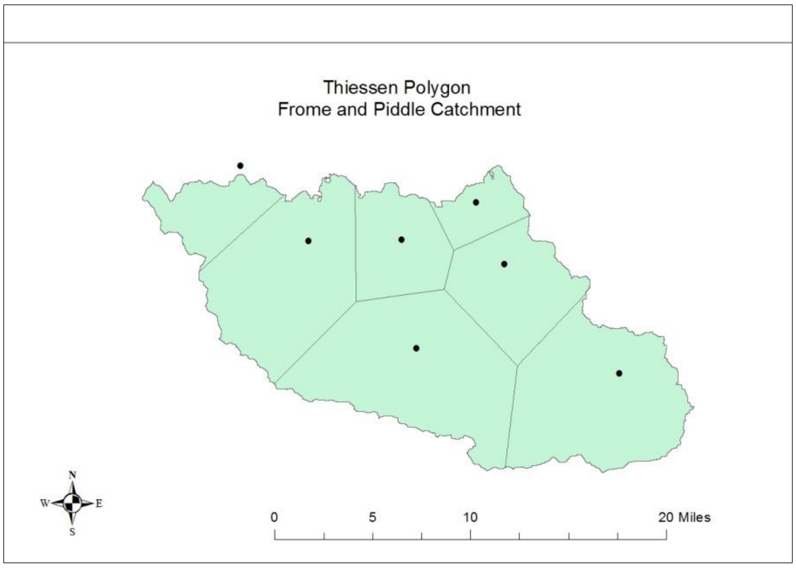


Figure 4-4 Thiessen Polygon at Frome and Piddle

The study has been conducted for flow calibration and validation between 2005 and 2006 and, between 2001 and 2002 respectively. The model was run for a 4-year period with the first 2 years being treated as a warm-up period (i.e. skips outputting results for first 2 years). This is because the model requires part of the simulation for stabilising the calculation before giving reasonable results. Therefore, a total of 8 years of sub-daily precipitation between 1999 and 2006 has been used. The monthly Thiessen Polygon rainfall adjustment has been conducted throughout the 8-year modelling period. The plots of comparisons between the monthly Thiessen Polygons means, and rain gauge means at Hurn during 1999 to 2006 are shown in Figure 4-3. The aerial rainfall obtained from the Thiesson Polygon was used as the hourly rainfall input in this thesis.

Weather Generator and Rain Gauging Network

Weather Generator (WG) is the component developed to tackle the limitation of input weather data temporally and spatially by using the statistics of weather data records. It includes average values of daily rainfall, daily max and min temperature, maximum half hour rainfall, humidity, solar radiation and wind speed. It is recommended that to have as long as possible a period and with as less as possible gaps. After filling all statistics of the user database, the WG component can fill the gap of missing weather data. All weather inputs included in this study are acquired from British Atmospheric Date Centre (BADC). Although this study only requires hourly rainfall, and there is only one option in the BADC database, a comprehensive, in terms of temporal and spatial extent, rain gauge network in the Frome and Piddle catchment was established during an early stage of the research. A gauge network with a total of 82 rain gauging stations, which record could date back to as early as the 1900s, and archived up to date. A long record of rainfall is critical to the accuracy of weather generator.

Water abstraction, Pond and Wetland

The wetland in Frome and Piddle was analysed in ArcGIS by using the map of RAMSAR, SPAs, SACs, and ANOB. As described in Chapter 3, Frome and Piddle has some wetland areas with a wealth of wildlife. The calculation of the water storage in the pond assumes that the pond size varies from 1 square meter to 2 hectares. In this study, the pond size is assumed to be 1 hectare per pond, which is equivalent to the average size between 1 square meter and 2 hectares. The depth of each pond is assumed as 1 meter. Water abstraction can be included in the hydrological modelling, representing the artificial influences on the water balance. The water use files (.wus) are used. The water consumption is modelled in SWAT as the removal of water outside the watershed for urban and industrial use. The modelled water removal is considered a permanent loss from the system such as from the shallow aquifer, the deeper aquifer, the river and the pond. The unit in SWAT water use input is 100,000 m^3 per day. Due to a different focus of this study, the modelled results of the effects from wetland and pond are not included in this thesis. However, it is worth of further study of these influences on hydrology in the Frome and Piddle catchments.

4.2.3 Catchment Delineation

Catchment is delineated into ten sub-basins. Hydrological Response Unit (HRU) is a unique combination of the DEM, land cover and soil map in SWAT model. It is the basic computing unit in each simulation. According to each class of land cover, soil and DEM, there are many combinations of HRU. Each sub-basin can contain as many HRUs as possible.

Table 4-6 Sub-basin Features at Frome and Piddle

Sub basin	Area (Ha)	Slope (Degree)	Range (m)	Mean Elevation (m)
Sub 1	3,109.8	11.31	78-254	155
Sub 2	1,332.0	8.68	64-227	133
Sub 3	203.3	13.77	107-236	167
Sub 4	20,161.3	9.66	52-267	151
Sub 5	18.5	2.51	50-70	57
Sub 6	2,004.5	8.99	89-241	160
Sub 7	1,870.3	2.69	0-67	18
Sub 8	13,815.3	6.78	3-273	91
Sub 9	18,780.3	5.27	9-203	70
Sub 10	5,299.8	4.22	0-197	37

4.3 Governing Equation

4.3.1 Rainfall Runoff

There are two rainfall runoff options. The first option is called SCS Curve Number method, which is a set of coefficients based on the statistics of catchment characteristics such as vegetation canopy size. The second option is the Green & Ampt infiltration method that is derived from calculation of excessive amount of rainfall that infiltrates the soil.

SCS Curve Number method

The SCS runoff equation is an empirical model that has been used frequently since the 1950s. It involves the rainfall runoff relationships from all sizes of watersheds across the U.S., and the model is able to predict the runoff with varied land use and soil types as shown in Figure 4-5.

The curve number equation (SCS 1972) is as follow,

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \quad (4.1)$$

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (4.2)$$

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \quad (4.3)$$

Q_{surf} is the accumulated runoff or rainfall excess (mm H_2O)

R_{day} is the rainfall depth of the day

I_a is the initial abstractions which include surface storage, interception, and infiltration prior to runoff (mm H_2O)

S is the retention parameter (mm H_2O). It is a function of CN value which varies according to land use, soil, management and slope.

$$I_a = \text{approx. } 0.2\, S \tag{4.4}$$

There are two methods to calculate CN value. One method shows CN is variable to soil water content, the other method relates CN to the accumulated plant evapotranspiration. The second method is used in this study, as the first method tends to overestimate runoff in shallow soil layers. The second algorithm has an advantage over the first when calculating the curve number, the algorithm referring to the local weather condition, rather than only relying on soil property.

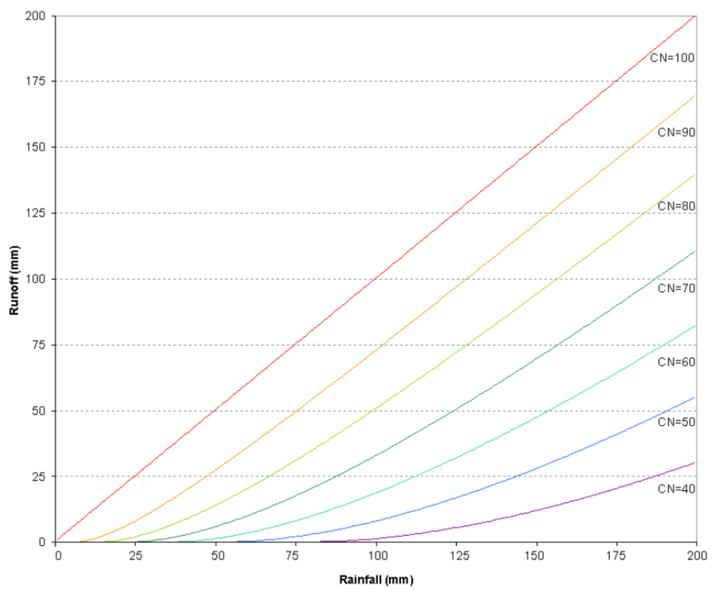


Figure 4-5 Relationship of Rainfall Runoff with SCS Curve Numbers (Neitsch, Arnold et al. 2005)

Green & Ampt Infiltration

The Green & Ampt equation was developed to predict infiltration, assuming excess water at the surface at all times (Neitsch, Arnold et al. 2005). The equation assumes that the soil layer(s) is homogenous and that the antecedent moisture is uniformly distributed in the profile. As water infiltrates through the soil, the model assumes the soil above the wetting front is completely saturated and there is a sharp break in moisture content at the wetting front. It is illustrated graphically as shown in Figure 4-6 that the difference between the moisture distributions with a depth modelled by the Green & Ampt equation and what occurs in reality.

Figure 4-6 Illustration of Green & Ampt Infiltration (Neitsch, Arnold et al. 2005)

$$f_{inf,t} = K_e.(1 + \frac{\Psi_{wf}.\Delta\theta_v}{F_{inf,t}}) \quad (4\text{-}5)$$

$f_{inf,t}$ is the infiltration rate at time t (mm/hr)

K_e is the effective hydraulic conductivity (mm/hr)

Ψ_{wf} is the wetting front matric potential (mm)

$\Delta\theta_v$ is the change in volumetric moisture content across the wetting front (mm/mm)

$F_{inf,t}$ is the cumulative infiltration at t (mm H_2O)

$$F_{inf,t} = F_{inf,t-1} + R_{\Delta t} \quad (4\text{-}6)$$

$F_{inf,t}$ is the cumulative infiltration at t (mm H_2O)

$F_{inf,t-1}$ is the cumulative infiltration at previous time step (mm H_2O)

$R_{\Delta t}$ is the amount of rainfall during the time step (mm H_2O)

$$F_{inf,t} = F_{inf,t-1} + K_e.\Delta t + \Psi_{wf}.\Delta\theta_v.\ln\left[\frac{F_{inf,t} + \Psi_{wf}.\Delta\theta_v}{F_{inf,t-1} + \Psi_{wf}.\Delta\theta_v}\right] \quad (4\text{-}7)$$

$$K_e = \frac{56.82\,.K_{sat}{}^{0.286}}{1+0.051.\exp^{(0.062.CN)}} - 2 \quad (4\text{-}8)$$

K_{sat} is saturated hydraulic conductivity (mm/hr)

K_e is the Green & Ampt effective hydraulic conductivity (mm/hr)

4.3.2 Channel Routing

The variable storage method and Muskingum method are the two governing methods for flow routing in river channel in SWAT modelling.

Channel Routing Variable Storage Method

Variable storage method is the default method for stream flow routing in SWAT.

For a given reach segment, storage routing is based on the continuity equation.

$$V_{in} - V_{out} = \Delta\,.V_{stored} \quad （4\text{-}9）$$

$$q_{in,ave} = \frac{q_{in,1} + q_{in,2}}{2} \quad (4\text{-}10)$$

$q_{in,ave}$ is the average flow rate during time step

$q_{in,1}$ is the inflow rate at the beginning of the time step

$q_{in,2}$ is the inflow rate at the end of the time step

Travel time is computed by dividing the volume of water in the channel by the flow rate. Where TT is the travel time (s), V_{stored} is the storage volume and is the discharged rate.

$$\text{TT} = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,1}}{q_{out,1}} = \frac{V_{stored,2}}{q_{out,2}} \quad (4\text{-}11)$$

$V_{stored,1}$ is the storage volume at the beginning of the time step

$V_{stored,2}$ is the storage volume at the end of the time step

$$q_{out,2} = \left(\frac{2\,.\Delta t}{2\,.TT + \Delta t}\right). q_{in,ave} + \left(1 - \frac{2\,.\Delta t}{2\,.TT + \Delta t}\right).q_{out,1} \quad (4\text{-}12)$$

The equation is then simplified to the following, where the SC represents the storage coefficient in the equation.

$$q_{out,2} = SC. q_{in,ave} + (1 - SC).q_{out,1} \quad (4\text{-}13)$$

$$SC = \frac{2\,.\Delta t}{2\,.TT + \Delta t} \quad (4\text{-}14)$$

This is further simplified to the following,

$$q_{out,2} = SC.\left(q_{in,ave} + \frac{V_{stored,1}}{\Delta t}\right) \quad (4\text{-}15)$$

$$V_{out,2} = SC\,.\left(V_{stored,1} + V_{in}\right) \quad (4\text{-}16)$$

Muskingum Method

The Muskingum flow routing method assumes the storage volume in a channel length as a combination of wedge and prism storages. As defined by Manning's equation, the cross-sectional area of flow is assumed to be directly proportional to the discharge of a given reach segment.

$$V_{\text{stored}} = K \,.\, q_{out} + K \,.\, X \,.\, (q_{in} - q_{out}) \quad (4\text{-}17)$$

The equation is rearranged to (2),

$$V_{\text{stored}} = K \,.\, (X \,.\, q_{in} + (1 - X) \,.\, q_{out}) \quad (4\text{-}18)$$

V_{stored} is the storage volume ($m^3\ H_2O$),

q_{in} is the inflow rate ($m^3\ H_2O$),

q_{out} is the outflow rate ($m^3\ H_2O$),

K is the storage time constant for reach (s),

X is the weighting factor with a lower limit of 0, and an upper limit of 0.5.

When the previous equation 2 is incorporated into the continuity equation and simplified to the following,

$$V_{out,2} = C_1 . V_{in,2} + C_2 \,.\, V_{in,1} + C_3 \,.\, V_{out,1} \quad (4\text{-}19)$$

$V_{out,2}$ is the volume of outflow at the end of the time step (m^3)

$V_{in,2}$ is the volume of inflow at the end of the time step (m^3)

$V_{in,1}$ is the volume of inflow at the beginning of the time step (m^3)

$V_{out,1}$ is the volume of outflow at the beginning of the time step (m^3)

$$C_1 = \frac{\Delta t - 2.K.X}{2.K.(1-X)+\Delta t} \quad (4\text{-}20)$$

$$C_2 = \frac{\Delta t + 2.K.X}{2.K.(1-X)+\Delta t} \quad (4\text{-}21)$$

$$C_3 = \frac{2.K.(1-X)-\Delta t}{2.K.(1-X)+\Delta t} \quad (4\text{-}22)$$

$$C_1 + C_2 + C_3 = 1 \quad (4\text{-}23)$$

$$K = coef_1.K_{bnkfull} + coef_2.K_{o.1bnkfull} \quad (4\text{-}24)$$

K is the storage time constant for the reach segment

$K_{bnkfull}$ is the storage time constant for the reach segment with bank full flows

$coef_1$ is the weighting factor for the influence of the normal flow on the storage time constant value (.bsn)

$coef_2$ is the weighting factor for the influence of the low flow on the storage time constant value (.bsn)

4.3.3 SWAT Flow Routing Processes

For each time step, the model calculates the excessive rainfall of each HRU. The amount of water that lags is added to the excess rainfall of each HRU at the next time step. The HRU calculation is aggregated to each sub-basin for further calculation. There are three layers of temporal loop that start from Δt to day and year. Surface runoff, river flow, and pond and reservoir storage are routed at a sub-daily time step, but the base flow and evapotranspiration are calculated on a daily time step and evenly distributed for each time step.

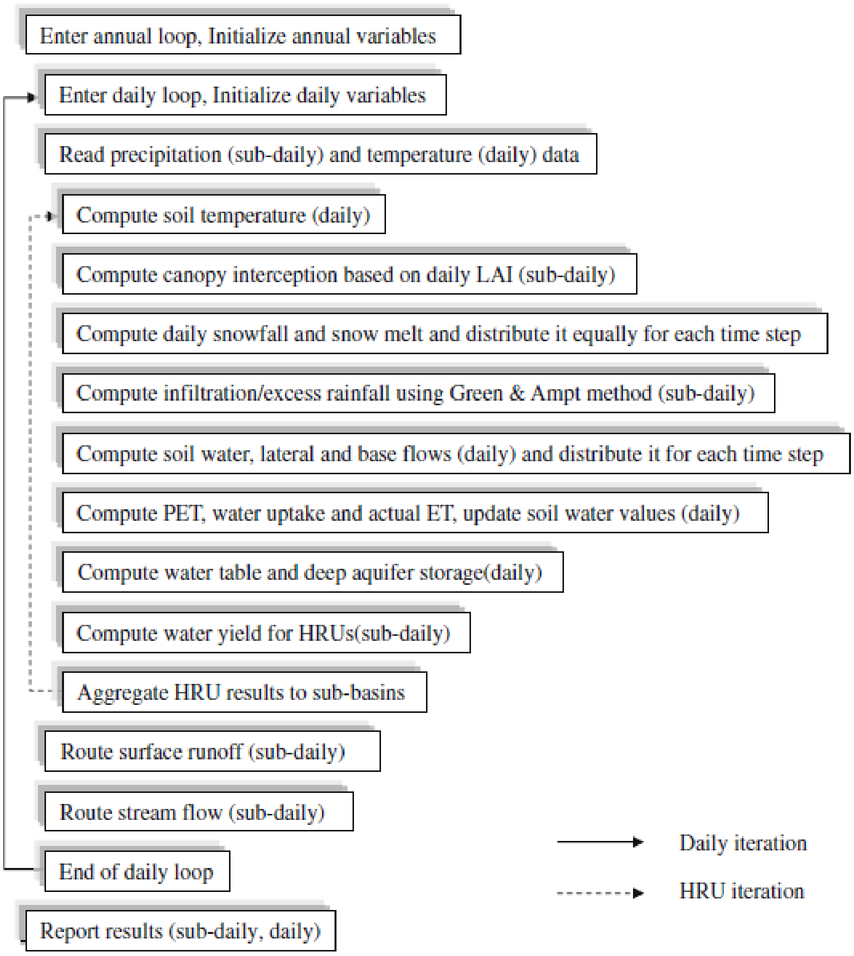


Figure 4-7 Flow Chart of Daily and Sub-daily Flow Routing in SWAT (Neitsch, Arnold et al. 2005)

4.3.4 Sub-Daily Routing

Surface Runoff Lag

Once the total amount of excess rainfall is determined by the Green & Ampt equation, a fraction that lags in the HRU is estimated by a lag equation. The existing lag equation in SWAT (Neitsch, Arnold et al. 2004) is developed for daily simulation and is insufficient for sub daily runoff lag process (Jeong, Kannan et al. 2010).

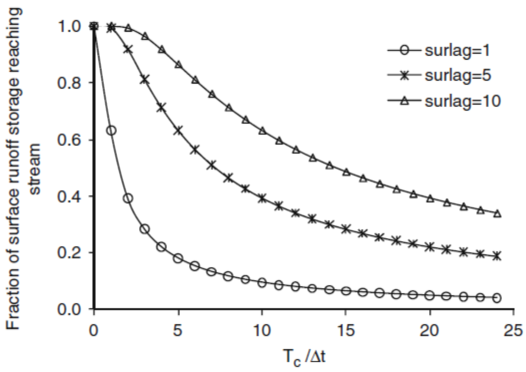


Figure 4-8 Surface Lag Impact to Main Channel (Neitsch, Arnold et al. 2005)

Unit Hydrograph

The surface runoff generated at each time step is routed using unit hydrograph (UH) method in which a hydrologic response to input of excess rainfall is distributed in a triangular shape. Alternatively, a gamma distribution function based on the hydrologic property of the watershed could be used. Triangular UH is defined as the following.

$$q_{uh} = \frac{t}{t_p}, if\ t \leq t_p \quad (4\text{-}24)$$

$$q_{uh} = \frac{t_b - t}{t_b - t_p}, \text{if t} > t_p \quad (4\text{-}25)$$

$$t_b = 0.5 + 0.6t_c + tb\_adj \quad (4\text{-}26)$$

q_{uh} is unit flow rate at time t

t is the timestep at t

t_b is the time of recession

t_p is the time to peak flow from when the direct runoff starts

tb_{adj} is a user input factor or adjusting sub daily unit hydrograph

The time to peak flow is estimated based on the SCS dimensionless unit hydrograph (SCS 1972) method, in which 37.5% of the total volume is assigned to the rising side.

$$t_p = 0.375 t_b \tag{4-27}$$

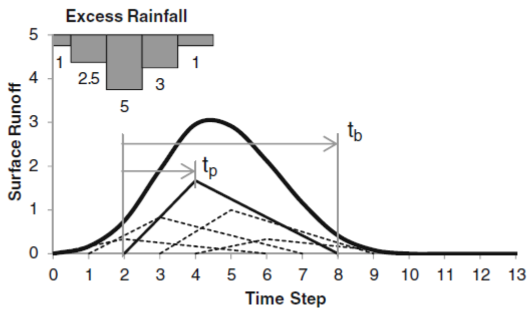


Figure 4-9 Triangular Unit Hydrograph (Neitsch, Arnold et al. 2005)

Apart from the triangular unit hydrograph method, there is an alternative option for the sub-daily unit hydrograph routing, which is called the gamma distribution hydrograph method.

$$q_{uh} = \left(\frac{t}{t_p}\right)^a * \exp\left(\left(1 - \left(\frac{t}{t_p}\right)\right)^a\right) \tag{4-28}$$

a is a dimensionless shape factor $(a > 0)$

Base Flow Distribution

Sub-daily base flow is estimated by re-distributing aggregated daily base flow by using base flow distribution equations (4-29) to (4-31). The equations use base flow flag (bf_flg) as an indicator. When bf_flg is close to zero, the sub-daily base flow is distributed evenly. When bf_flg is close to 1, the sub-daily base flow is distributed correlating to rainfall.

bf_fr = bf_flg * precipdt (ii+1) / sum (precipdt) + (1. - bf_flg) * 1. / nstep

(4-29)

sub_hwyld (ii) = sub_hhqd (sb,ii) + baseflw * bf_fr **(4-30)**

else

sub_hwyld (ii) = sub_hhqd (sb,ii) + baseflw / nstep **(4-31)**

bf_flg is the base flow flag (0<bf_flg<1)

sub_hwyld is the hourly sub-basin water yield

sub_hhqd is the hourly sub-basin surface runoff

4.4 Calibration and Validation

This section contains the method, result and analysis of SWAT model calibration and validation for daily as well as sub-daily simulations. Daily simulations are these models simulated using the Green & Ampt infiltration method, and the results are summarized as daily output. The observed daily flow measured from the Environment Agency is used to determine model performance. Manual calibration was the first method for getting the model calibrated, although it has both pros and cons. There are two types of model calibration. One is called deterministic optimisation which is a trial and error process. In the study, it is regarded as the manual calibration that keeps adjusting the parameters until one set of parameters is reached that result in a good match between simulation and observation. However, this type of calibration could be time consuming and may not lead to acceptable results. The other type of calibration is called stochastic calibration that seeks to capture a range of uncertainty and error with the understanding of the processes in the water environment. In this study, it is regarded as semi-automatic calibration using SWAT-CUP. The stochastic calibration using SWAT-CUP is used as a robust tool for model calibration and validation within an acceptable range of error and confidence.

4.4.1 SWAT-CUP Calibration

SWAT CUP Parameterisation

Table 4-7 Sensitivity of Flow in River Piddle (Sub-basins 1, 2, 7 and 8)

Parameter	Definition	Parameter Value		
		Max	Min	Fit
Sol_K.sol	Saturated hydraulic conductivity (mm/hr)	1	600	164.83
Sol_BD.sol	Soil density of soil layer	0.9	2.6	2.40
Clay.sol	Clay content in soil layer (%)	0	90	36.14
Sand.sol	Sand content in soil layer (%)	0	90	18.14
Sol_Z.sol	Soil depth in soil layer (mm)	0	2500	1926.25
Sol_awc.sol	Available water content (%)	0	1	0.89
CN2.mgt	SCS curve number / coefficient	20	90	38.51
Gwqmn.gw	Threshold water level in shallow aquifer for base flow (mm)	-1000	2400	1476.90
Revapmn.gw	Threshold water level in shallow aquifer for revamp (mm)	0	1300	77.35
Alpha_bf.gw	Base flow recession constant (days)	0.048	0.85	0.138
Gw_delay.gw	Delay time for aquifer recharge (days)	0	150	97.88
Gw_revap.gw	Groundwater revamp coefficient	-0.5	1	0.00625
Rchrg_dp.gw	Deep aquifer recharge coefficient	-0.5	1	-0.0733
GWHT.gw	Initial groundwater height (m)	0	25	12.14
Shallst.gw	Initial depth of water in the shallow aquifer	0	50000	4775
Deepst.gw	Initial depth of water in the deep aquifer (mm)	0	50000	7425
Surlag.bsn	Surface runoff lag coefficient (days)	0	50	23.53
CH_N2.rte	Manning's value for main channels	0	1	0.5275
CH_K2.rte	Effective hydraulic conductivity (mm/hr)	0	200	114.9
Canmx.hru	Maximum canopy storage	0	100	69.15
ESCO.hru	Evaporation Compensation Factor	0	1	0.972
EPCO.hru	Evaporation Compensation Factor	0	1	0.266

Table 4-8 Sensitivity of Flow of River Frome (Sub-basins 3, 4, 5, 6, 9 and 10)

Parameter	Definition	Parameter Value		
		Max	Min	Fit
Sol_K.sol	Saturated hydraulic conductivity (mm/hr)	1	600	428.99
Sol_BD.sol	Soil density of soil layer	0.9	2.6	1.04
Clay.sol	Clay content in soil layer (%)	0	90	1.94
Sand.sol	Sand content in soil layer (%)	0	90	68.08
Sol_Z.sol	Soil depth in soil layer (mm)	0	2500	848.75
Sol_awc.sol	Available water content (%)	0	1	0.233
CN2.mgt	SCS curve number / coefficient	20	90	67.43
Gwqmn.gw	Threshold water level in shallow aquifer for base flow (mm)	-1000	2400	18.30
Revapmn.gw	Threshold water level in shallow aquifer for revamp (mm)	0	1300	585.65
Alpha_bf.gw	Base flow recession constant (days)	0.048	0.85	0.69
Gw_delay.gw	Delay time for aquifer recharge (days)	0	150	129.23
Gw_revap.gw	Groundwater revap coefficient	-0.5	1	0.03625
Rchrg_dp.gw	Deep aquifer recharge coefficient	-0.5	1	-0.0807
GWHT.gw	Groundwater Highest Depth	0	25	19.14
Shallst.gw	Shallow Aquifer Depth	0	50000	10975
Deepst.gw	Deep Aquifer Depth	0	50000	16575
Surlag.bsn	Surface runoff lag coefficient (days)	0	50	20.925
CH_N2.rte	Manning's value for main channels	0	1	0.4715
CH_K2.rte	Effective hydraulic conductivity (mm/hr)	0	200	74.9
Canmx.hru	Canopy efficiency	0	100	96.75
ESCO.hru	Evaporation Compensation Factor	0	1	0.6895
EPCO.hru	Evaporation Compensation Factor	0	1	0.3045

Table 4-9 Flow Sensitivity Rank of River Frome

Parameter Name	Rank	t-Stat	P-Value
23:V__SOL_K(..).sol	1	-16.41	0.00
24:V__SOL_BD(..).sol	2	-15.47	0.00
27:V__SOL_Z(..).sol	3	5.27	0.00
33:V__GW_DELAY.gw	4	5.07	0.00
43:V__ESCO.hru	5	-2.52	0.01
40:V__CH_N2.rte	6	2.25	0.02
39:V__SURLAG.bsn	7	2.14	0.03
41:V__CH_K2.rte	8	1.60	0.11
36:V__GWHT.gw	9	-1.25	0.21
42:V__CANMX.hru	10	1.18	0.24
30:V__GWQMN.gw	11	0.95	0.34
28:V__SOL_AWC(..).sol	12	-0.91	0.36
32:V__ALPHA_BF.gw	13	-0.90	0.37
29:V__CN2.mgt	14	0.57	0.57
37:V__SHALLST.gw	15	0.47	0.64
38:V__DEEPST.gw	16	-0.44	0.66
44:V__EPCO.hru	17	-0.41	0.68
35:V__RCHRG_DP.gw	18	-0.39	0.69
31:V__REVAPMN.gw	19	0.24	0.81
25:V__CLAY(..).sol	20	-0.20	0.84
34:V__GW_REVAP.gw	21	0.16	0.87
26:V__SAND(..).sol	22	-0.13	0.90

Table 4-10 Flow Sensitivity Rank of River Piddle

Parameter Name	Rank	t-Stat	P-Value
1:V__SOL_K(..).sol	1	-9.92	0.00
11:V__GW_DELAY.gw	2	6.31	0.00
19:V__CH_K2.rte	3	3.01	0.00
5:V__SOL_Z(..).sol	4	2.78	0.01
22:V__EPCO.hru	5	-2.65	0.01
10:V__ALPHA_BF.gw	6	-1.59	0.11
12:V__GW_REVAP.gw	7	1.59	0.11
18:V__CH_N2.rte	8	1.55	0.12
13:V__RCHRG_DP.gw	9	1.39	0.16
14:V__GWHT.gw	10	1.35	0.18
15:V__SHALLST.gw	11	0.77	0.44
4:V__SAND(..).sol	12	0.67	0.50
6:V__SOL_AWC(..).sol	13	0.55	0.59
21:V__ESCO.hru	14	-0.49	0.63
9:V__REVAPMN.gw	15	0.45	0.65
8:V__GWQMN.gw	16	-0.44	0.66
7:V__CN2.mgt	17	0.37	0.71
20:V__CANMX.hru	18	0.34	0.73
3:V__CLAY(..).sol	19	0.30	0.77
2:V__SOL_BD(..).sol	20	0.22	0.83
16:V__DEEPST.gw	21	-0.20	0.84
17:V__SURLAG.bsn	22	0.13	0.89

SWAT model was set up in the Frome and Piddle catchment and was calibrated spatially at Dorchester Total (sub-basin 4 of river Frome), East Stoke Total (sub-basin 9 of river Frome) and at Baggs Mill (sub-basin 8 of river Piddle). Flows through the catchment with the two rivers have different catchment properties; the model is calibrated as two separate sub-catchments. Each calibration process has the same sensitive parameters, but with independent fitted values as shown in Table 4-7 and Table 4-8. The result of the sensitivity analysis is summarized in Table 4-9 and Table 4-10. There are two types of test employed to rank model sensitivity. The t-stat is the coefficient of a parameter divided by its standard error. It is a measure of the precision with which the regression coefficient is measured. The larger the absolute value of the t-stat, the more sensitive the parameter is. The p-value for each parameter tests the null hypothesis that the coefficient is equal to zero (i.e. with no effect). A low p-value (< 0.05) indicates the rejection of the null hypothesis. If a parameter that has a low p-value, it is likely to be a meaningful parameter. By contrast, a larger p-value indicates the parameter is not sensitive.

The saturated hydraulic conductivity (Sol_K.sol) was found to be the most sensible parameter for both sub-catchments. It is then followed by the soil bulk density (Sol_BD.sol), soil depth (Sol_Z.sol), groundwater delay coefficient (GW_DELAY.gw), and evaporation compensation factors (ESCO.hru), as the top five most sensible parameters in Frome catchment. The Piddle catchment responses are different from the Frome, with the next four most sensible parameters in descending order: groundwater delay coefficient (GW_DELAY.gw), channel saturated hydraulic conductivity (CH_K2.rte), soil depth (SOL_Z(..).sol) and evaporation compensation factors (EPCO.hru). The summary shown in Table 4-9 and Table 4-10 for the Frome and Piddle, indicates that Sol_K(No.1), Sol_Z(No.2), and GW_DELAY(No.3) are the top three most sensible parameters for Frome and

Piddle catchment. River Frome have Sol_BD and ESCO (soil and evaporation properties) whilst river Piddle have CH_K2 and EPSO (channel and evaporation properties) as its fourth and fifth most sensible parameters respectively.

4.4.2 Daily Hydrograph

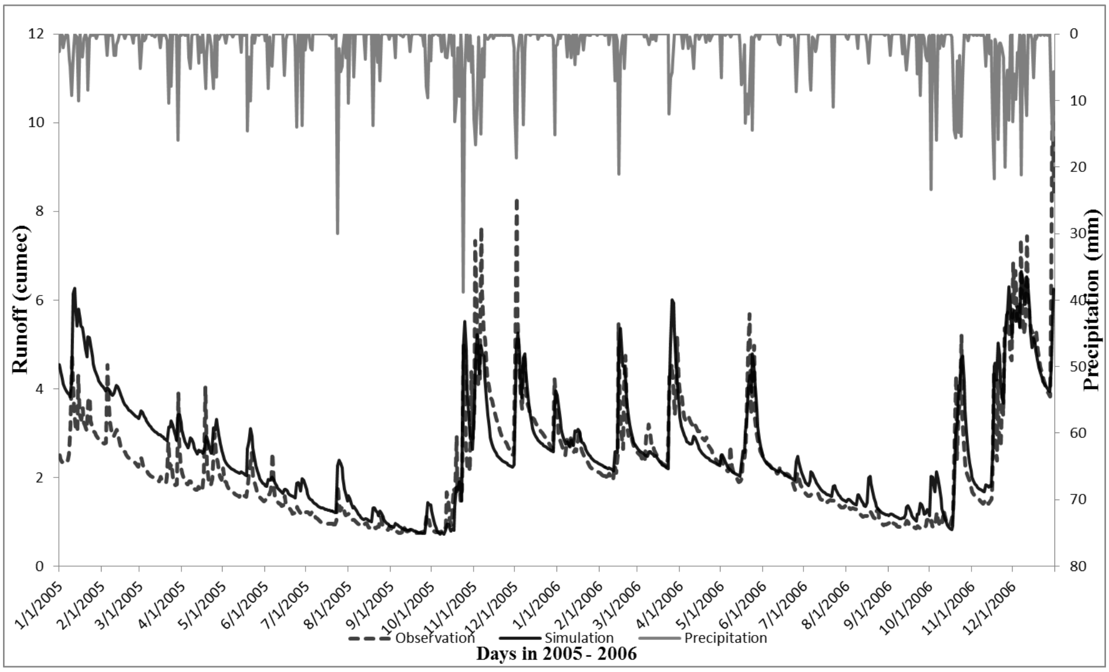


Figure 4-10 (a) Flow Calibration Sub - basin 4 (2005-2006)

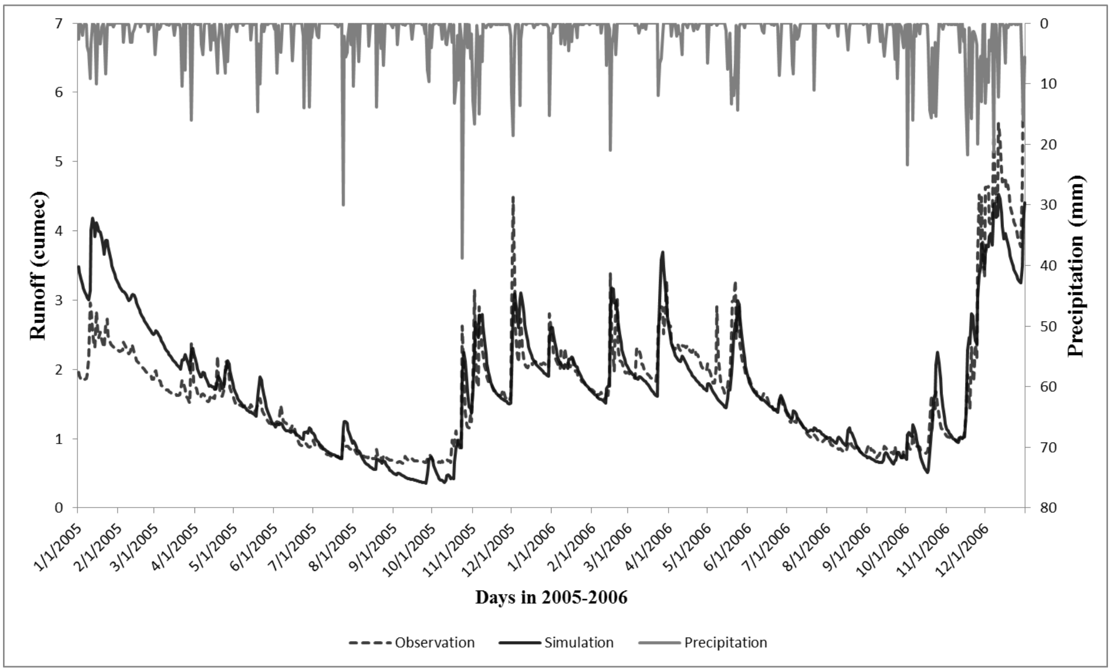


Figure 4-10 (b) Flow Calibration Sub - basin 8 (2005-2006)

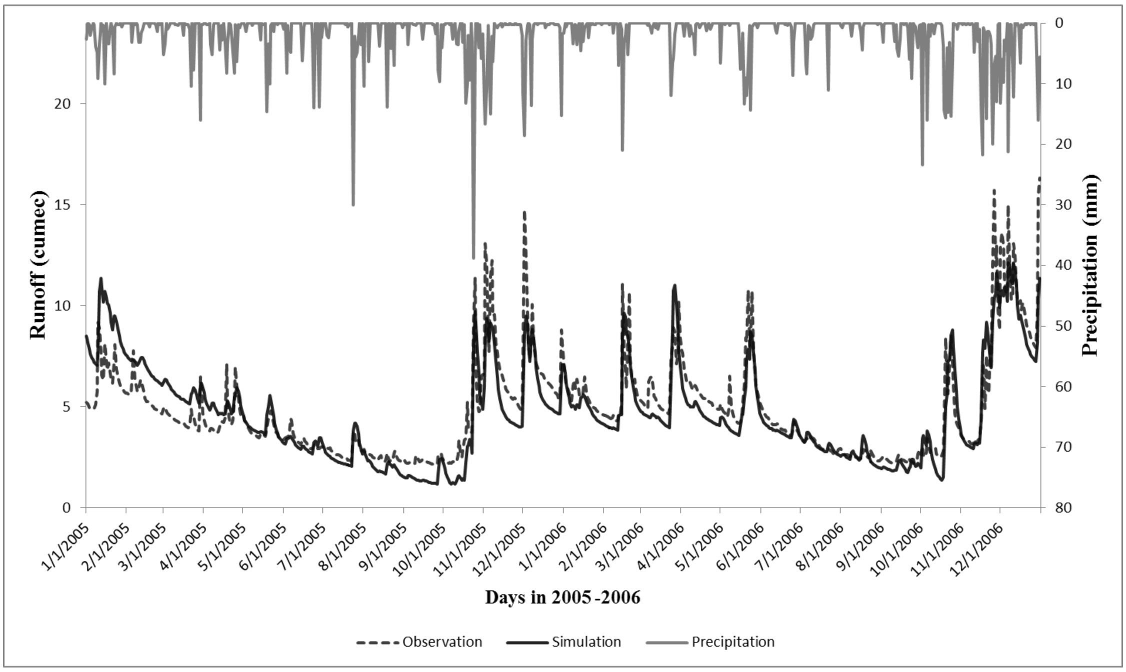


Figure 4-10 (c) Flow Calibration Sub - basin 9 (2005-2006)

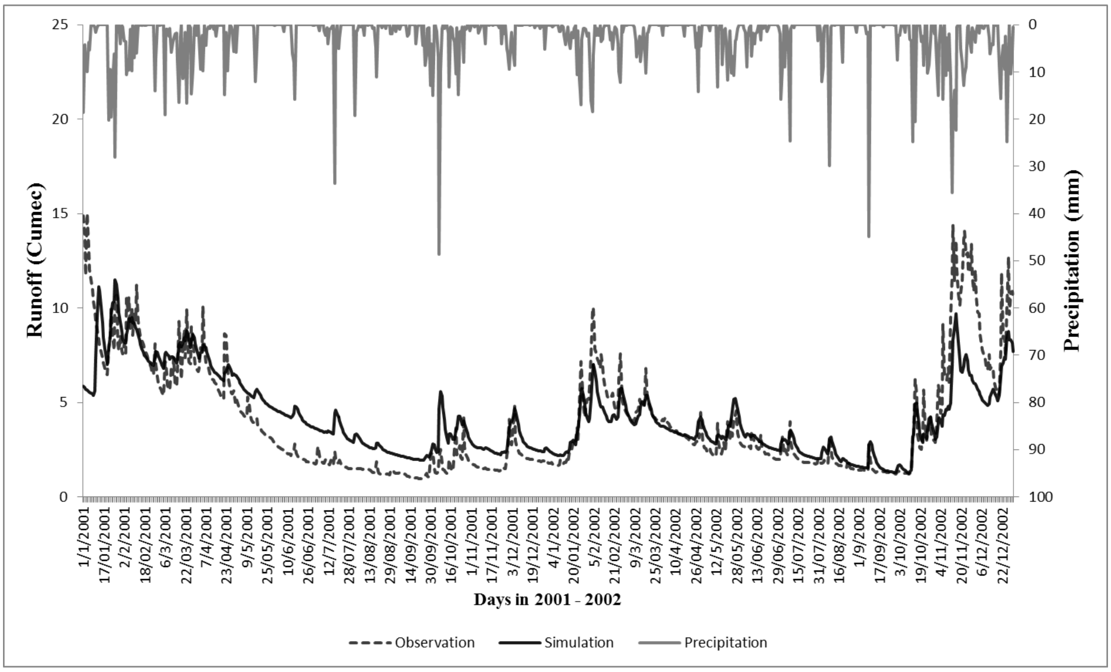


Figure 4-10 (d) Flow Validation Sub - basin 4 (2001-2002)

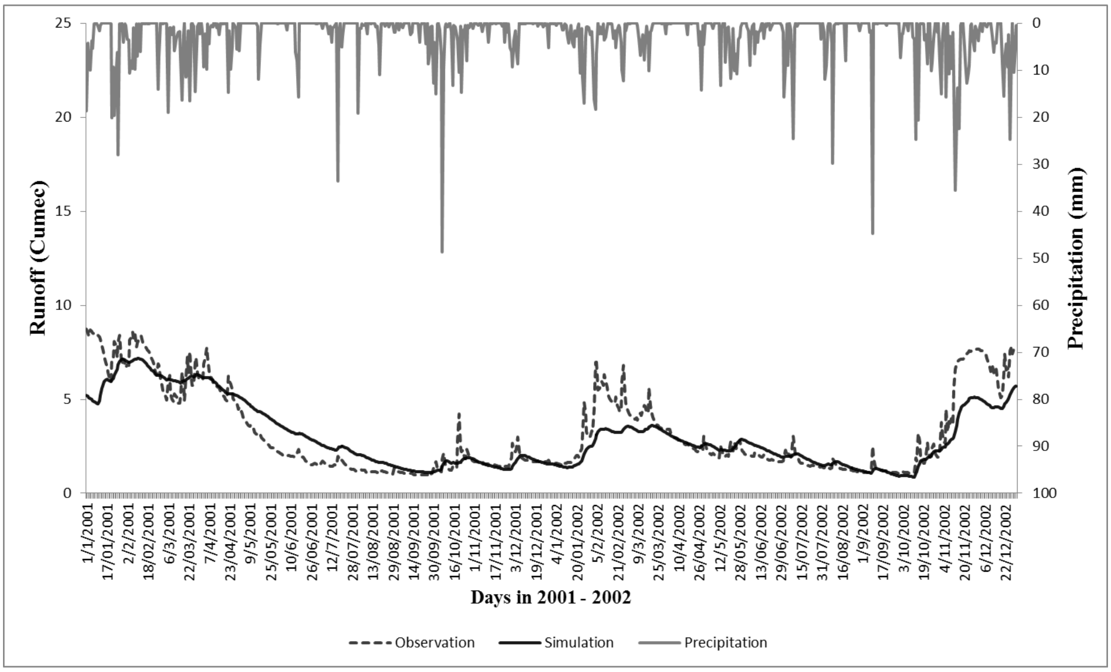


Figure 4-10 (e) Flow Validation Sub - basin 8 (2001-2002)

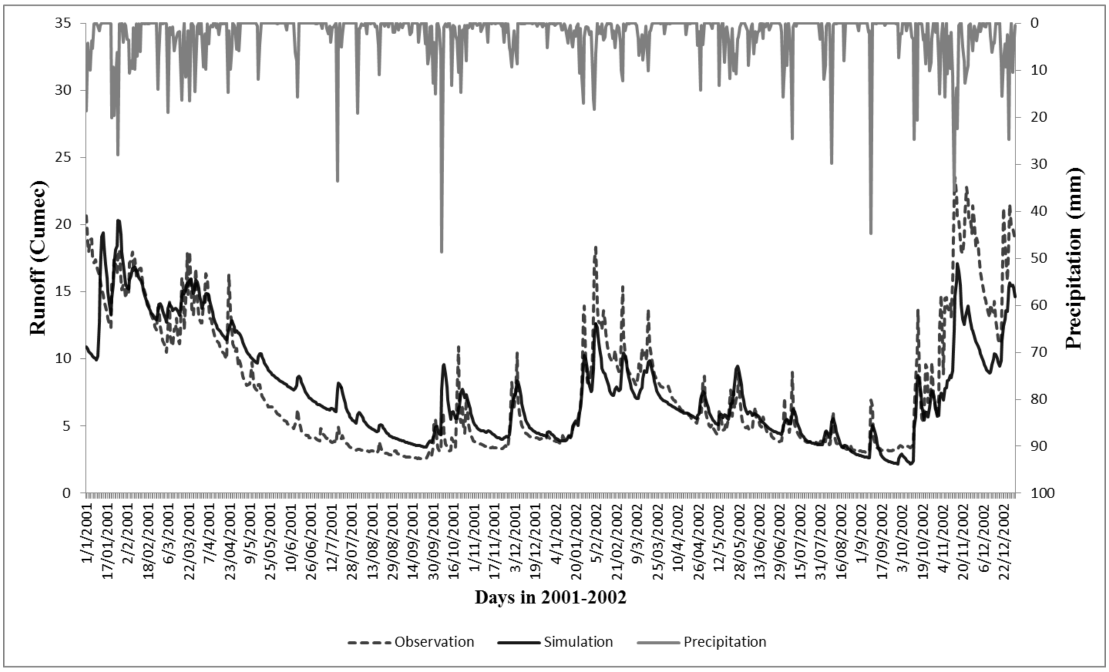


Figure 4-10(f) Flow Validation Sub - basin 9 (2001-2002)

4.4.3 Model Performance

Goodness-of-fit Statistics

There are different ways to measure the model efficiency. The widely-recognized goodness-of-fit statistics in hydrology have been used which are the Spearman correlation coefficient (R^2), the Nash-Sutcliffe model efficiency coefficient NSE (Nash and Sutcliffe 1970) and the percent bias (PBIAS). These are described as follows:

(a) Coefficient of determination (R^2)

$$R^2 = \frac{\left[\sum(Q_{m,i}-\bar{Q}m)(Q_{s,i}-\bar{Q}s)\right]^2}{\sum(Q_{m,i}-\bar{Q}m)^2\sum(Q_{s,i}-\bar{Q}s)^2} \quad (4\text{-}32)$$

(b) Nash-Sutcliffe coefficient

$$NSE = 1 - \frac{\sum(x-y)^2}{\sum(y-\bar{y})^2} \quad (4\text{-}33)$$

(c) Percent bias (bias)

$$bias = \frac{\sum x-\sum y}{\sum y} * 100 \quad (4\text{-}34)$$

The model performance for flow with both daily simulation and sub-daily simulation (hourly) are summarized in Appendix II. The calibration period is between 2005 and 2006, the validation period is between 2001 and 2002 for daily simulation. The year 2002 data is used for the sub-daily validation. The goodness-of-fit indicator, such as the Nash Sutcliffe coefficient (NSE), the determination (R^2), the PBIAS, and the comparisons of observed and simulated mean value can be found in this table.

Spatially, calibration has been conducted at sub-basins 4 and 9 for the rivers Frome and sub-basin 8 in the river Piddle. Nash coefficients of daily calibration (between 2005 and 2006) are between 0.70 and 0.77 and R^2values are between 0.76 and 0.79. Two years' validation (between 2001 and 2002) is performed with a slightly lower range Nash coefficients, between 0.58 and 0.62, but a higher range of R^2 between 0.71 and 0.80. Given the excellent PBIAS and mean values, together with the excellent Nash coefficients and R^2 statistics, the model performance is satisfying and regarded as good compared with previous studies using the Green & Ampt method (Jeong, Kannan et al. 2010; Maharjan, Park et al. 2013) for daily and hourly simulations.

Regarding hourly calibration and validation, SWAT output was applied to test the one year calibration in 2002 with one storm event calibration from each year at sub-basins 4 and 9. The NSE values range between -0.39 and 0.74, and R^2 range between 0.65 and 0.80. There are also high variations in the model performance. For example, the NSE at sub-basin 4 in 2006 is 0.74; By contrast, at sub-basin 9 in 2005 there is a negative NSE value. The hydrograph shows that the model has been over-estimating the flow during over 70% of this period which will be further discussed later in Chapter 4.

The validation results are better than the calibration results. One year hourly calibration in 2002 has NSE of 0.69 at sub-basin 4 and with 0.72 at sub-basin 9. R^2 is 0.81 at sub-basin 4 and is 0.87 at sub-basin 9. The one year hourly validation showed excellent model prediction. The storm event analysis is based on the hourly output. The storm event outputs are extracted from the whole year hourly output with regard to a particular rainfall event. However, the event based prediction performance has slightly lower performance regarding NSE and R^2. It implies more uncertainty when using SWAT for rainfall event based simulation. The calibration performance ranged between 0.58 and 0.63 for NSE and between 0.62 and 0.72 for R^2. The validation of storm event flow ranged between 0.41 and 0.60 for NSE and between 0.47 and 0.70 for R^2. Nevertheless, calibration and validation of storm event flow with SWAT sub-daily rainfall runoff module is a new trial. It is also suggested that the potential improvements for sub-daily flow routing, even if the performance is not as good as long term simulation.

4.4.4 Flow Duration Curve (FDC)

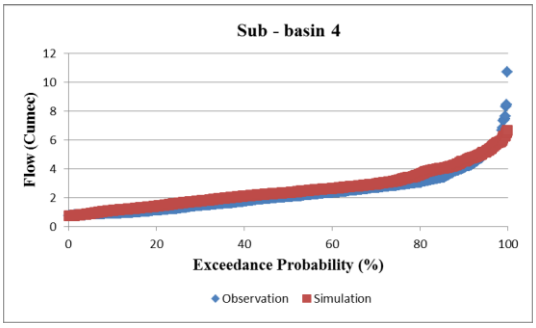


Figure 4-11 (a) Calibration of the FDC Sub-basin 4 (2005-2006)

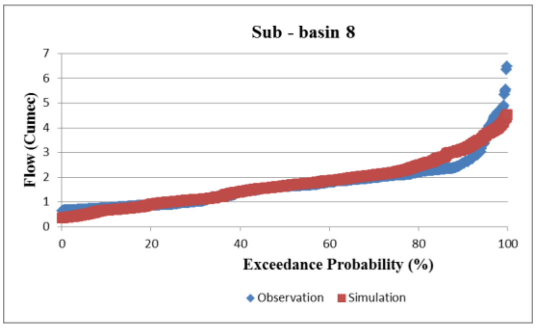


Figure 4-11 (b) Calibration of the FDC Sub-basin 8 (2005-2006)

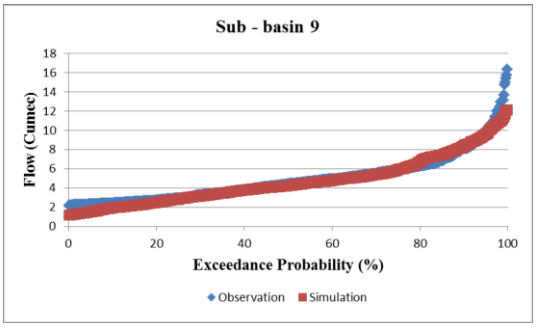


Figure 4-11 (c) Calibration of the FDC Sub-basin 9 (2005-2006)

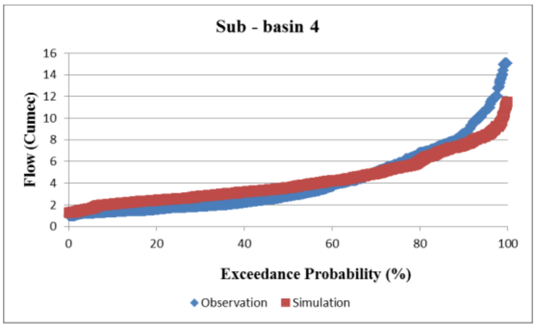


Figure 4-11 (d) Validation of the FDC Sub-basin 4 (2001-2002)

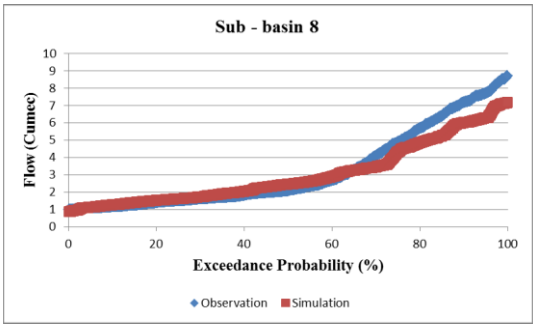


Figure 4-11 (e) Validation of the FDC Sub-basin 8 (2001-2002)

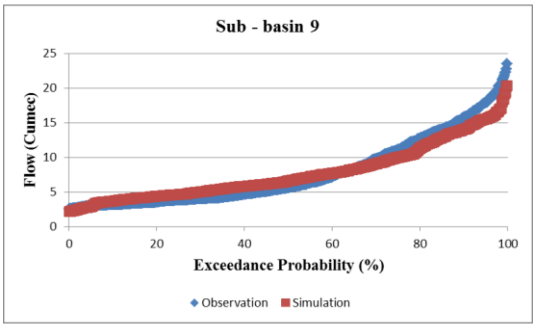


Figure 4-11 (f) Validation of the FDC Sub-basin 9 (2001-2002)

High Flow and Low Flow

Flow duration curve (FDC) plots for calibration can been seen in Figure 4-11 (a-c). Generally, the model has the capability for predicting low to medium flow, i.e. up to Q20 of the flow in all three sub-basins during calibration. However, the high flow which is higher than Q10 has been under-estimated for all three sub basins. In particular, sub-basin 8 shows variations for flow above Q20.

FDC plots from validation can be seen in Figure 4-11 (d-f). The high flow and low flow prediction have been shown to vary within an acceptable margin. The FDC results show a slight over-estimation of the low to medium flows at sub-basins 4 and 9, and an under-estimation of the medium to high flow i.e. Q30. Again, the Piddle catchment at sub-basin 8 shows slight differences under-estimating Q30 during validation period. Even though the high flow is underestimated, the model's performance in terms of the high and low flows varies within the acceptable range, and it is regarded as good simulation and model performances.

4.4.5 Sub-Daily Simulation

Strategy and Method

Sub-daily simulation is calibrated for individual storm event rather than a long-term prediction. Previous sub-daily studies combined sub-daily and sub-hourly runs during a comprehensive calibration study (Jeong, Kannan et al. 2010). However, SWAT model is initially developed for long term continuous simulation based on daily routing algorithms. The model has been developed to extend its capability in sub-daily flow estimation (Vandenberghe, van Griensven et al. 2001; van Griensven, Meixner et al. 2006). Therefore, the SWAT model is expected to display adequate model performance not only in the long-term processes, but also being capable of sub-daily flow simulation with relatively good results. Previous results showed better outcomes were found when the weather was wetter than during droughts (Van Liew and Garbrecht 2003; Kannan, White et al. 2007). Accurate estimations of the base flow are important for the calibration (Arnold and Allen 1996; Arnold, Srinivasan et al. 1998). In particular, this would be beneficial for the Frome and Piddle catchment studies, as the groundwater influenced the watershed with a high groundwater index, i.e. a groundwater contribution to surface runoff of above 0.85. It is confirmed that the sub-daily model could adequately estimate the stream flow with a different percentage contribution of surface runoff of between 50% and 98% of base flow contribution. The stream flow was calibrated at the three sub-basins including the watershed outlet through a combination of manual and automatic procedures. During the initial manual calibration, the range of parameters was tested with a wider range to narrow down the parameters based on statistical measures and the water balance. Then, the semi-automatic calibration identifies a set of parameters with sensitivity tests, and gives the best efficiency values (NSE, R^2, and PBIAS).

The sub-daily calibration uses the same parameters for daily simulation for same case study in the same simulation period, which gives the detailed sub-daily flow pattern and hydrograph. Statistics of the sub daily flow are then applied manually to find the best efficiency values i.e. such as NSE, R^2, and PBIAS.

Hourly Flow Sensitivity

A sub daily sensitivity analysis has been conducted via a manual analysis. Parameters like IUH, UHALPHA, TB_ADJ and BFLO_DIST have been modified with distributed values. The model is not sensitive to either the unit hydrograph method, i.e. either the triangular UH method or gamma distribution method. In addition, the shape adjustment factor such as TB_ADJ and UHALPHA has been tested for model sensitivity, and the test values are evenly distributed between 0 and 20 i.e. (0, 5, 10, 15 and 20) for both TB_ADJ and UHALPHA. Due the insensitivity of the above parameter, the plot was skipped for presentation. However, the model shows that it is very sensitive to the base flow distribution factor BFLO_DIST, with a value between 0 and 1. The manual sensitivity plot is shown in Figure 4-12. The model showed better performance when BFLO_DIST was equal to 0.02, and therefore, this is determined to be the baseline condition for the hourly flow.

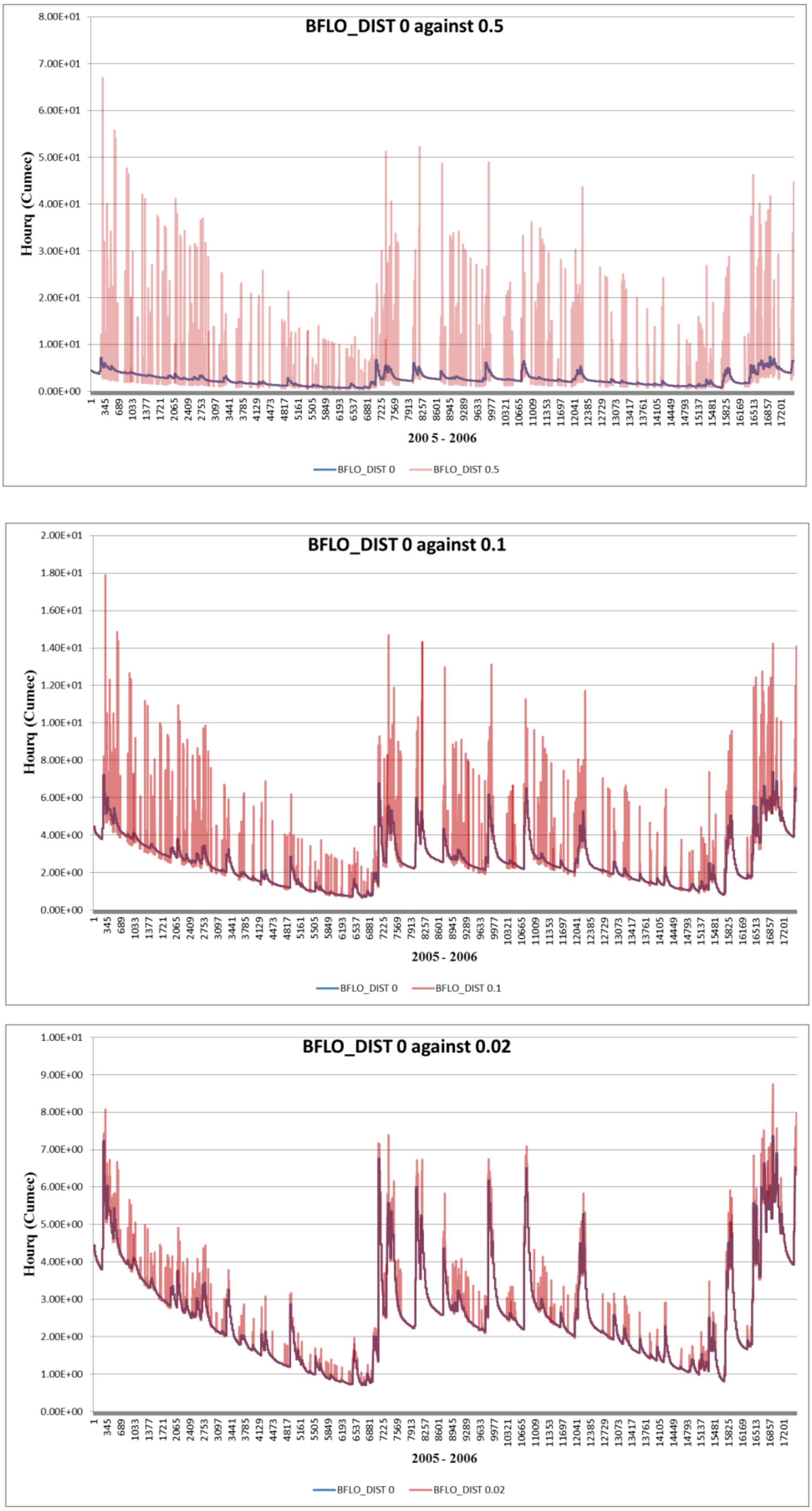


Figure 4-12 BFLO_DIST Sensitivity Analysis

4.4.6 Sub-daily Hydrograph

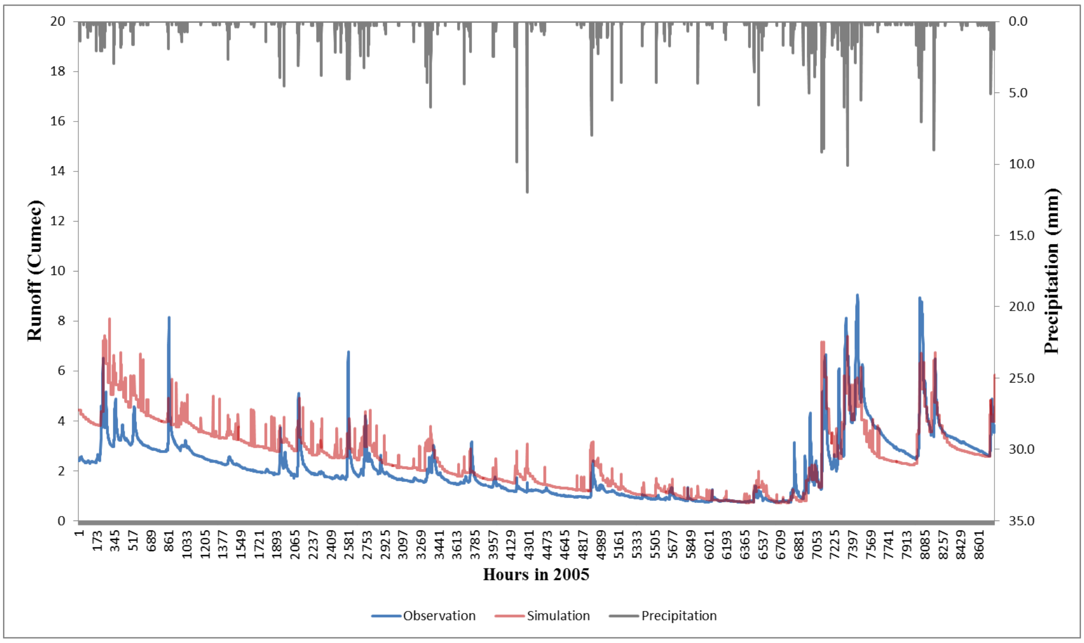


Figure 4-14(a) Hourly Simulation at Sub-basin 4 (2005)

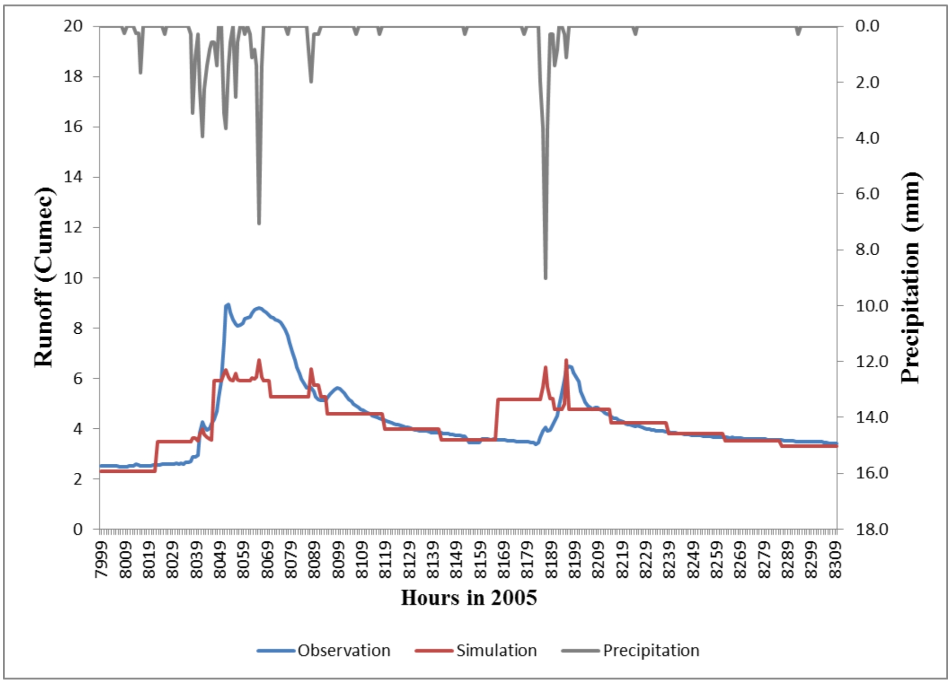


Figure 4-13(a) Event Calibration at Sub-basin 4 (2005)

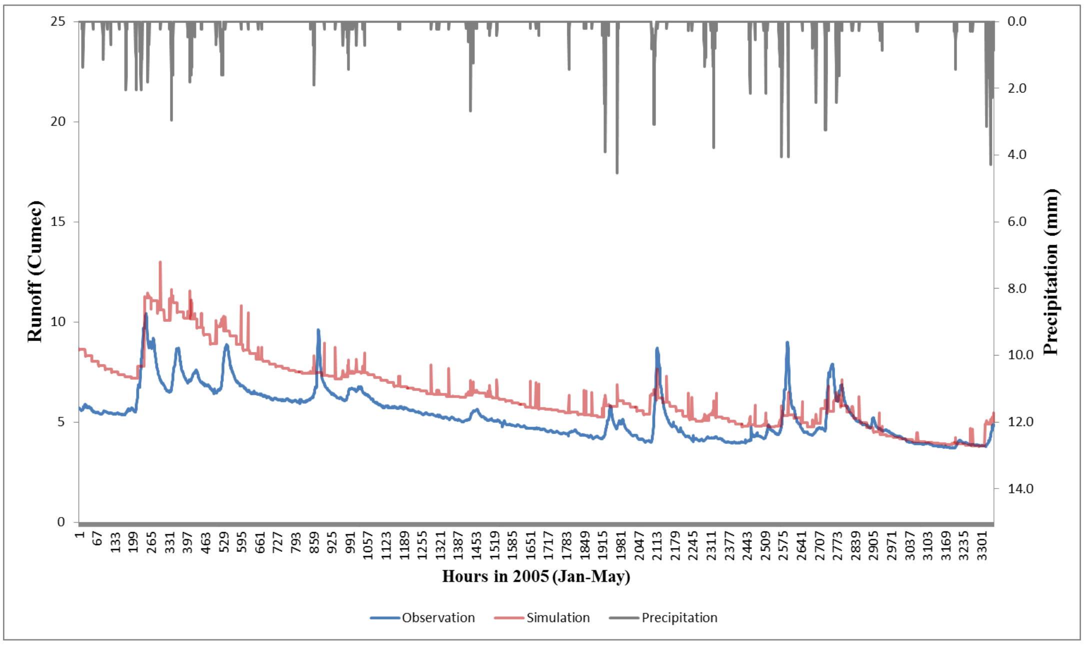


Figure 4-14 (b) Hourly Calibration at Sub-basin 9 (Jan – May 2005)

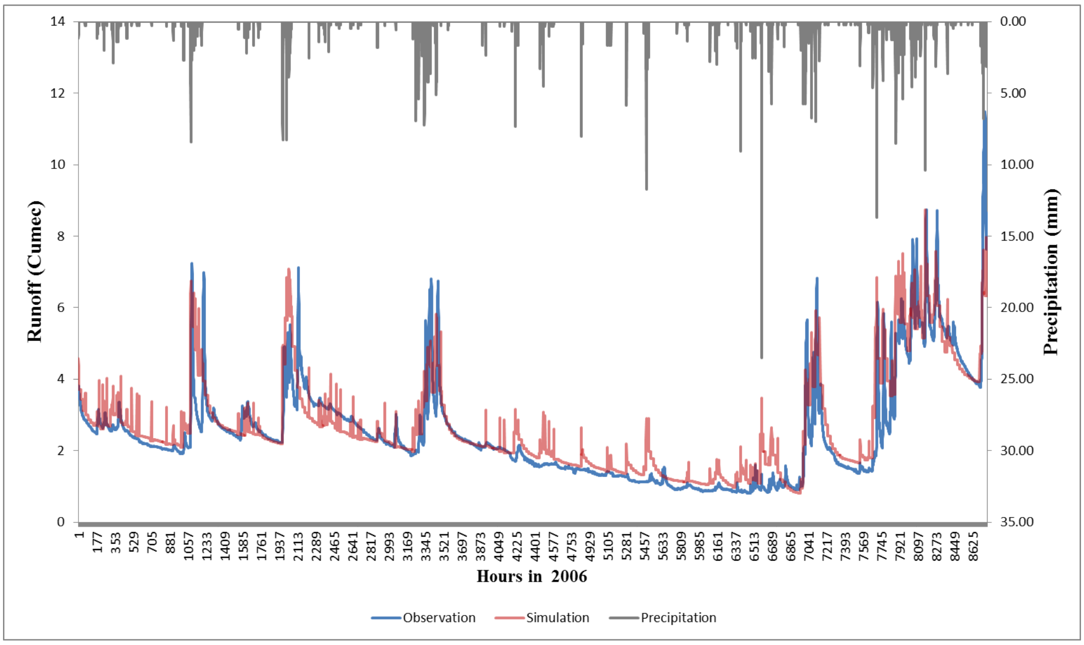


Figure 4-14 (c) Hourly Calibration at Sub-basin 4 (2006)

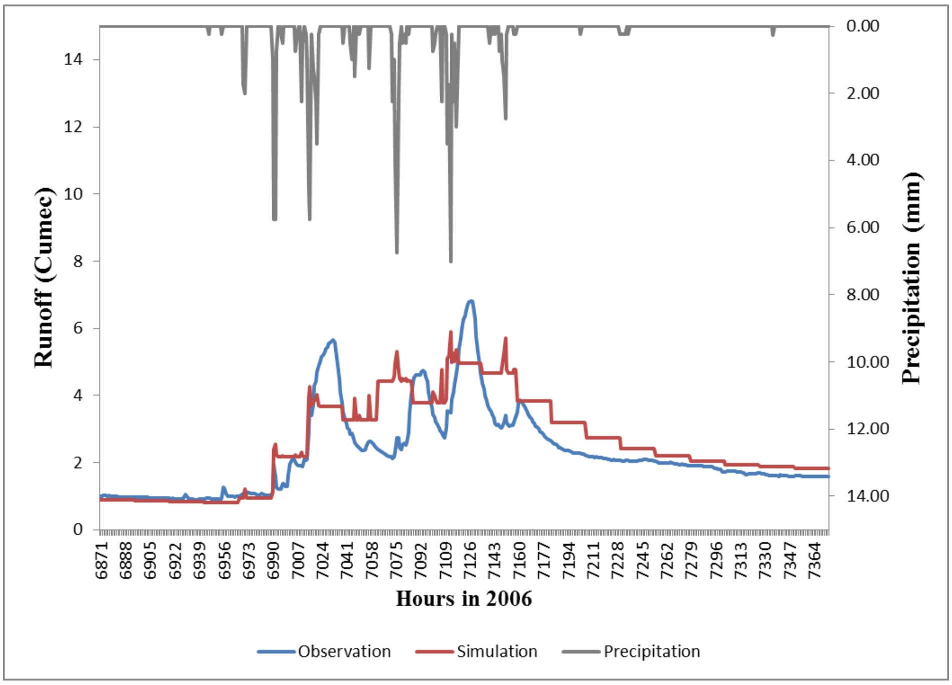


Figure 4-13 (b) Event Calibration at Sub-basin 4 (2006)

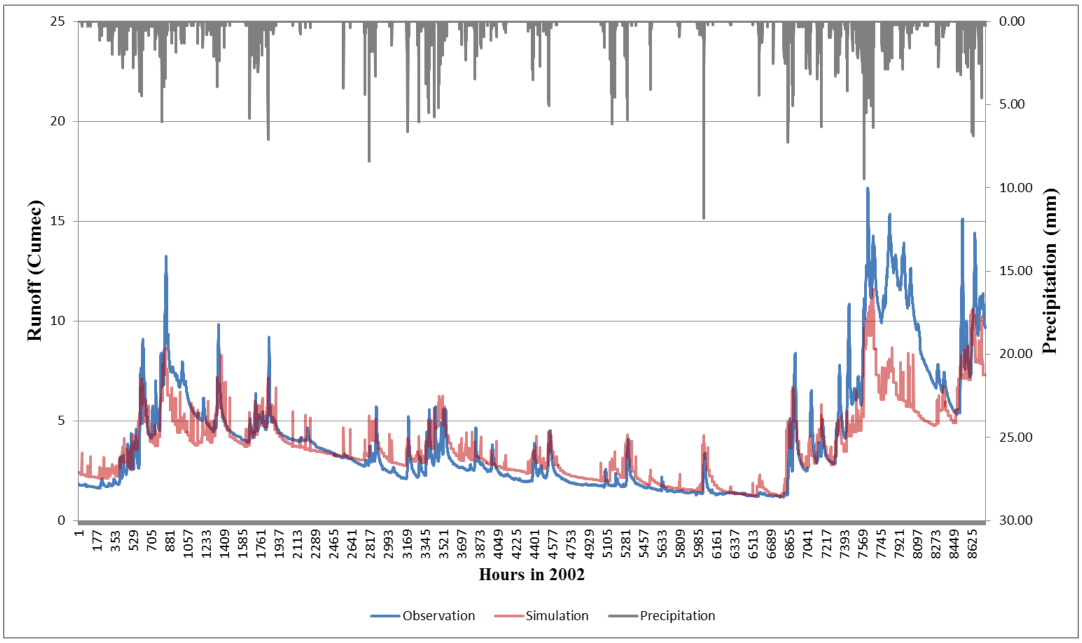


Figure 4-15 (a) Validation at Sub basin 4 (2002)

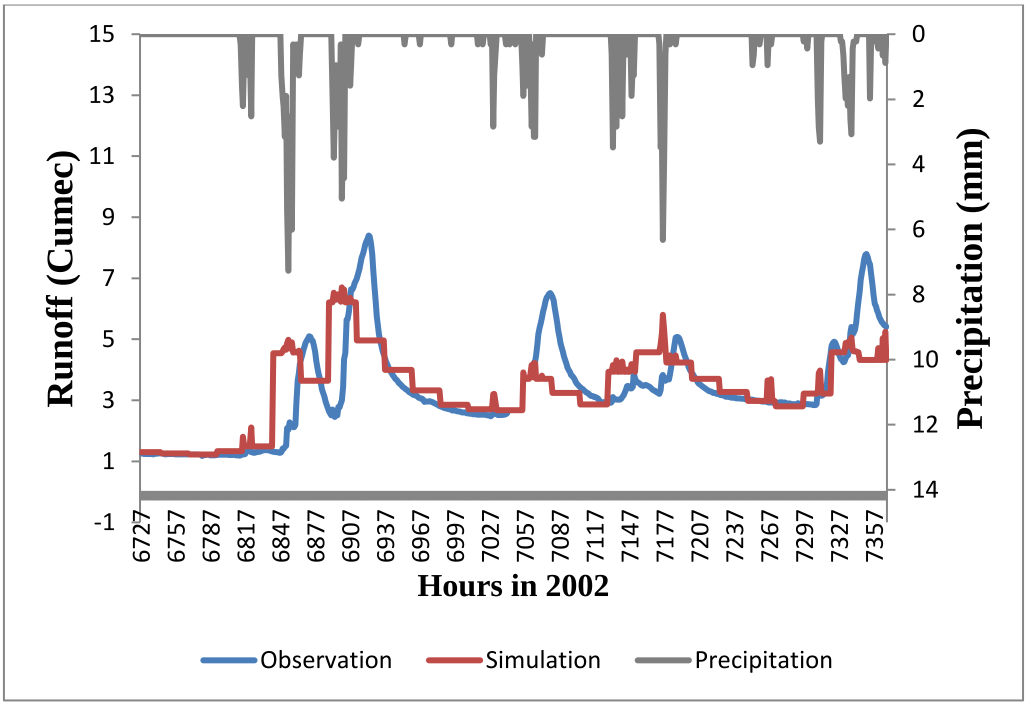


Figure 4-16 (a) Hourly Event Validation at Sub-basin 4 (2002)

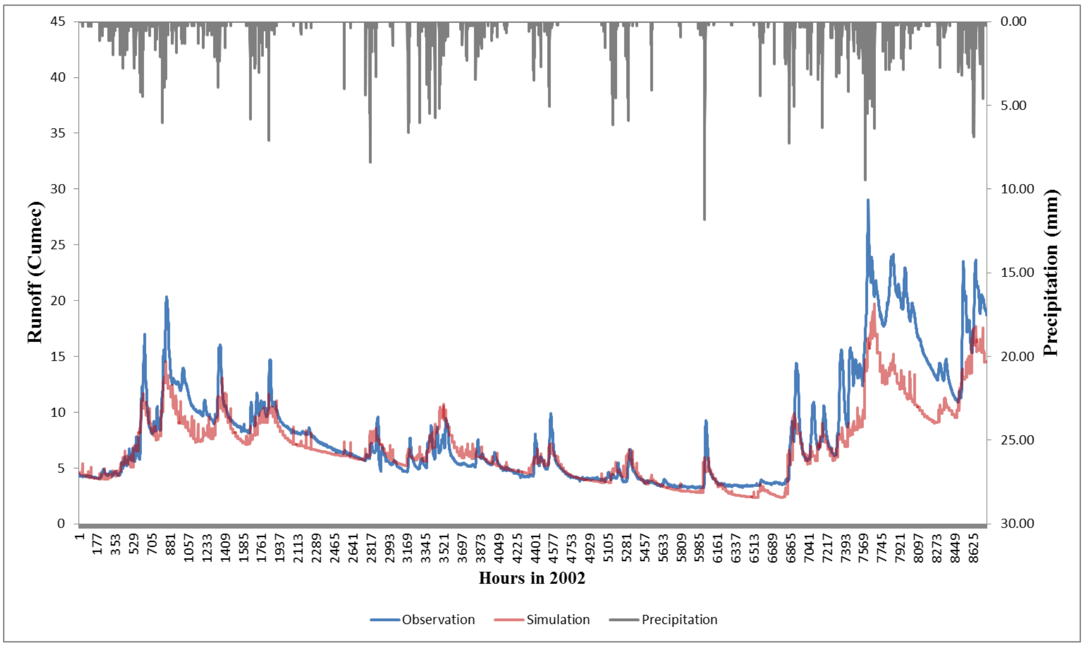


Figure 4-15 (b) Validation at Sub-basin 9 (2002)

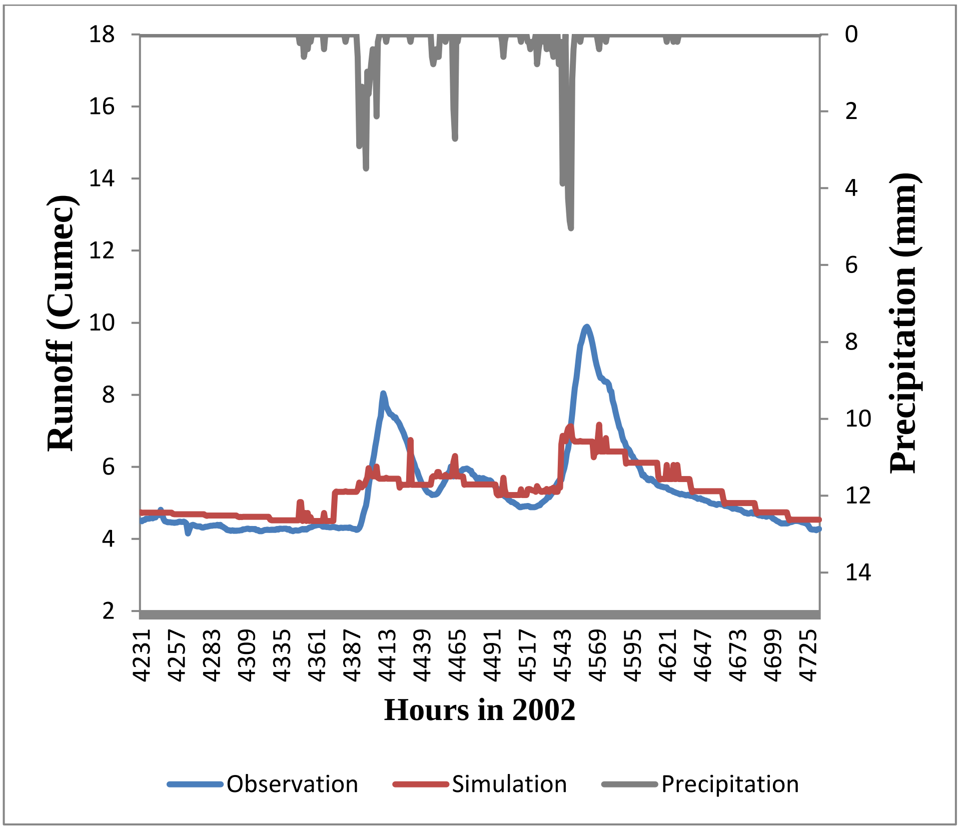


Figure 4-16 (b) Hourly Event Validation at Sub-basin 9 (2002)

4.4.7 Sub daily Flow Duration Curve (FDC)

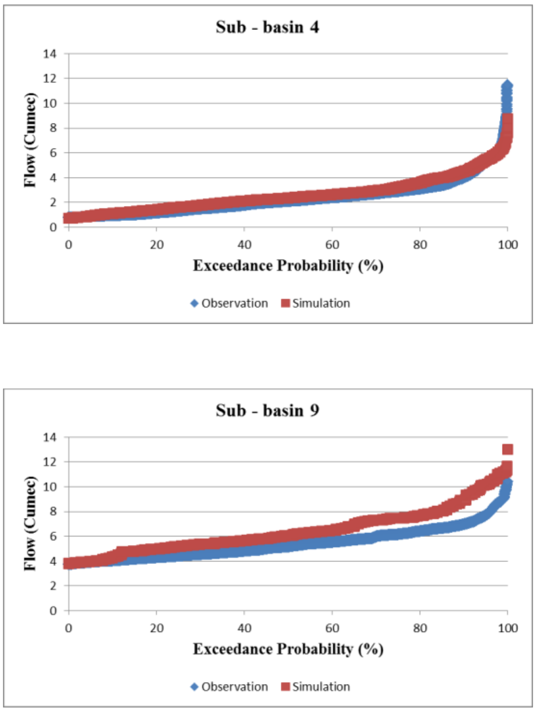


Figure 4-17 Sub-daily FDC at Sub-basin 4&9 (Calibration)

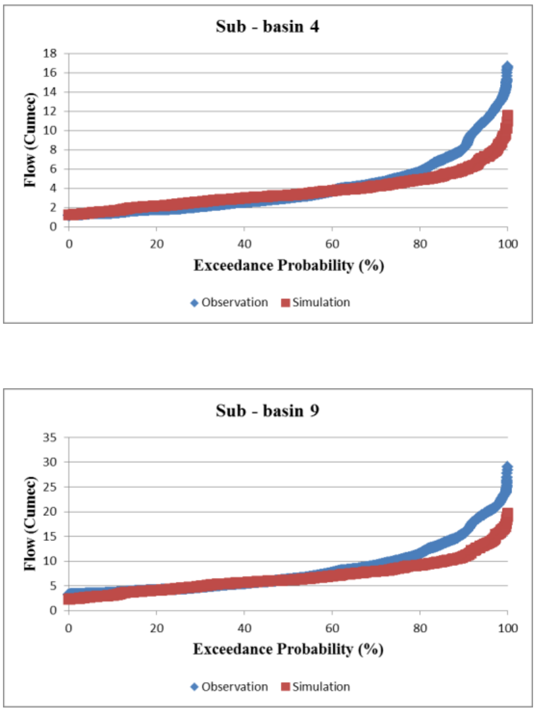


Figure 4-18 Sub-daily FDC at Sub-basin 4&9 (Validation)

Sub-daily High and low Flow

The flow duration flow (FDC) for hourly calibration and validation are summarized in Figure 4-17 and Figure 4-18. The calibrated model at sub-basin 4 in 2002 showed a positive performance that successfully captured both the low and high flows for the whole year, with only slight underestimates of the top 2% high flow. This could be attributed to the case study being a groundwater dominated catchment, and this model not can predict the highest flow. The model at sub-basin 9 over-estimates all the flows. However, the analysis for sub-basin 9 is between January and May in 2005 due to a lack of flow data. The model validation showed better results for estimation of low to medium flow, but underestimated the top Q20 in sub-basins 4 and 9 in 2002.

4.5 Discussion

Model Setup and Inputs

A. Quality of Rainfall Inputs

Weather inputs are the main driving force of the SWAT. Without accurate rainfall data, the model would be regarded as building a sand dune. In this study, the hourly precipitation input is calculated and optimised by using Thiesson Polygon method. Since the nature of the input rainfall is based on the aerial rainfall, and the original gauging station is around 10km away from the catchment boundary. The hourly rainfall might not be representative for all parts of the catchment due to geographical and altitude differences, though the the amount of monthly rainfall is optimised to match with aerial value. Previously studies pointed that temporal and spatial precipitation inputs could be the problems of inaccuracies in runoff and sediment yield (Beeson, Sadeghi et al. 2014; Lu, Kayastha et al. 2014; Zabaleta, Meaurio et al. 2014). Therefore, it is suggested that more spatial hourly or sub hourly rainfall inputs would further improve the model performance.

B. Resolution of GIS Map

The input GIS maps in this study are between 50 and 1000 meters by resolution as mentioned in Section 4.2. Current maps are acceptable for most of Frome and Piddle catchment particularly in the lowland areas. However, the runoff output in high altitude area such as the headwater catchment remains not satisfied. It is anticipated by using refined land use map (100 meters) or soil map (100 meters) would increase the classes of key parameters, so that ideally to improve the results particularly in the headwater areas in Frome and Piddle catchment. But nevertheless, modelling with high resolution maps means more computations due to more generated HRU units, and correspondingly more uncertainties. For example, the study from (Beeson, Sadeghi et al. 2014) used varied resolutions of DEMs (90, 30, 10 and 3 m) to investigate the impacts to sediment yield, the result shows much finer resolution DEM derives significant higher slopes compares with coarse DEM, and presents considerable variability in modelled sediment output.

C. Warm up Period

The calibration has demonstrated good model performance both in terms of daily flow as well as hourly flow simulation. However, among these results, the calibration at 2005 at sub basin 9 was particularly noteworthy as shown in Figure 4-14. The model keeps over estimating the flow during two thirds of the period. Similar model behaviour has been observed in the daily flow calibration at sub basin 8 and 4 in 2005 and daily flow validation in 2001 in all validated sub basins. Therefore, it is suggested that the model is over estimating the flow during at least the first 6 months in the first calibration and validation year. This implies that the model might need a longer warm up period before stable results are obtained. As the current warm up period was set at 2 years, therefore, it is suggested that the warm up period should be at least 3 years for further study at the Frome and Piddle catchment.

Unit Hydrograph (UH)

Unit hydrograph are used for routing the sub-daily flow. Routing processes at different time step have varied algorithms. The sub-daily routing using the Green & Ampt infiltration (Green 1911) is based on the daily simulation, the later summarizes the runoff quantity at the end of each 24 hour period. In the model configuration, there are option 2 when IEVENT = 2, and option 3 when IEVENT = 3. The difference between these two methods is that, in option 3, the flow output is determined by the unit hydrograph for routing sub-daily flow. Therefore, establishing the appropriate unit hydrograph is one of the keys for successes in sub-daily routing. There are two methods for sub-daily unit hydrograph algorithm. First method is called triangular method, and the second method is called Gamma distribution. In this study, Triangular method is used as the default unit hydrograph routing method that inherited from the SWAT model. In the UK, there is a sophisticated UH method called Flood Estimation Handbook (FEH) (Svensson and Jones 2010)which is another program based on the long term weather records of the UK catchments, and uses a range of statistics methods. It is suggested if the FEH method is used as the UH in SWAT, the sub daily output (substitute the baseflow distribution factor) might be improved in the Frome and Piddle catchment.

Base Flow Distribution Factor

As shown in Table 4-12 described the sub-daily model sensitivity, the model is not very sensitive to the unit hydrograph parameter, but it is more sensible to another controlling parameter – BFLO_DIST, which routes the base flow for sub daily flow simulation. The reason could be attributed to that the Frome and Piddle catchment is lowland permeable catchments which are dominated by the groundwater contribution in the hydrological processes. As the base flow contribution is between 0.8 and 0.9 of total flow in almost all reaches in the catchments.

The current equation for the base flow distribution is incapable of simulating all types of catchment, including Frome and Piddle catchment. The problem is (1) when the base flow distribution factor close to zero, the model evenly distributes the base flow during each 24 hour; when the base flow distribution factor close to 1, the base flow change according to the rainfall, which is regarded as a function that is not applicable. (2) As the soil moisture change daily rather than corresponding time step, there is a sharp change of baseflow between two adjacent days, which should be adjusted in further model improvements. Therefore, a more explicit base flow distribution equation is urgently required for hourly flow routing for Frome and Piddle and similar catchment. Improved algorithms should contain the following function that to enable the model to yield soil moisture corresponding to each time step i.e. every hour or minute. So, that the base flow could be simulated and give output at each time step rather than redistributes the daily base flow. Alternatively, improvements could be completed to substitute both UH and base flow distribution with the FEH (Svensson and Jones 2010) method to estimate sub daily flow, and this could be particularly beneficial to the modelling in the UK catchments.

4.6 Summary

In summary, this chapter presented the hydrological modelling in the Frome and Piddle catchment. The model's performance proved to be good when comparing with daily flow, and acceptable when compare with hourly and or event based flow. The hydrological modelling and approaches can further assist in the sediment and bacteria modelling study in Chapter 5. However, as suggested previously, the base flow distribution process is urged to have further improvement so that could to develop a new base flow distribution algorithm that better suits lowland modelling, particularly when flow is highly groundwater dominated with very permeable soil layers of watershed.

Chapter 5

SWAT Bacteria Modelling

Key words:

Catchment Agriculture Management, Intensive Farming

Modified SWAT model, In-stream Bacteria Subroutine Development

Sensitivity Analysis and Model Calibration & Validation

In-stream sediment-influenced bacteria

Sub-daily in-stream solar-radiation influenced bacteria

Green & Ampt, Sub-daily

5.1 Introduction

Filter-feeding bivalve shellfish can accumulate bacterial and viral pathogens from sewerage contaminated water and polluted rivers (Partnership 2014). The consumption of raw or under cooked shellfish harvested from such waters can cause illness and lead to outbreaks of infectious disease, e.g. Noro virus associated gastroenteritis. To protect public health, Under European Commission Regulation (854/2004), shellfish harvesting areas are classified on the basis of monitoring levels of faecal indicator organisms such as E. coli in shellfish. Same contamination source also expose risks to bathing waters in UK. Crop and food demand increases as the population grows. Defra RB209 Fertilizer Manual (DEFRA 2010) helps farmers better understand the fertilizer required for the crops they grow in order to achieve maximum profit for farm business. The nitrate vulnerable zones were identified in most Frome and Piddle catchments. Meanwhile, considering nitrates water pollution, there is a high risk of river contamination due to bacteria pathogen caused by livestock manure deposition and slurry spreading. In this chapter, different types of agricultural management input sources are included in SWAT bacteria modelling and the impacts are quantified. Traditional agriculture has been identified as an important source of diffuse faecal microbial pollution of water. Our current knowledge of the losses of faecal microbes from grazed pasture systems is poorly understood. To help synthesise our current knowledge, SWAT in-stream bacteria sub model was further modified to include the sub-daily sediment and solar-radiation influences so that the original first-order decay equation is transformed to include dynamic variations. SWAT bacteria modelling is calibrated and validated at different locations, timescales and different time steps, i.e. at daily and sub-daily output respectively. This chapter sets up the baseline of bacteria model prediction. It would be further analysed regarding future scenario projection in Chapter 6, and bacteria modelling in Poole Harbour in Chapter 7*.5.2*

5.2 Governing Equation and Model Development

5.2.1 SWAT Model Compilation

SWAT model could be used through ArcSWAT GUI interface (ArcMap based), and Visual Studio IDE is used for running through source code debugging. The model source code is open source. Version 2012 with revised number 591 is used and referred in this study. There are 302 source code files, with a total size of 2.73 mb. The model includes a main program, a model parameters control file (modparm.f) which summarizes all model parameters and allocate all variables to its size and locations, and 300 subroutines. The concise structure of SWAT could be found in the APPENDIX I.

5.2.2 SWAT Model Structure

The structure of the model is complicated. There are at least four layers of relationships from a sub-routine network tree. The main program calls 26 subroutines to initialize the model. From the 26 subroutines, simulate.f functions to begin the model simulation. The command.f subroutine from simulate.f initials to give the computer tasks. The subroutine subbasin.f is a major function that simulates land-based processes which controls the hydrological cycle of the model. The subroutine route.f is the key to simulate the processes in the river channels. In-stream calculations are all launched in this subroutine. The simulation in land is governed in key subroutine subbasin.f.

5.2.3 SWAT Bacteria Transport

SWAT considers faecal coliform as an indicator of pathogenic organism contamination. Different bacterial pathogens may follow different growth or die-off patterns. SWAT allows two species of pathogens with independent die-off and re-growth rates to be defined in the model. SWAT simulates bacteria on foliage (plant leaves) in the top 10 mm of soil that interact with surface runoff. Faecal bacteria in the surface soil layers may be in solution state or is attached to the solid. Bacteria losses through tillage or transport with percolation of water into a deeper soil layer are treated as die-off.

Wash-off Process

A portion of the bacteria on plant foliage may be washed off during rainfall events. The model set up a threshold level on rainfall on a given day, which the precipitation exceeds 2.54 mm of rain, the bacteria wash-off process begins. The amount of bacteria washed off from plant foliage during particular precipitation event on a given day is calculated and illustrated in the following equations.

$$bact_{lp,wsh} = fr_{wsh,lp} * bact_{lp,fol} \tag{5-1}$$

$$bact_{p,wsh} = fr_{wsh,p} * bact_{p,fol} \tag{5-2}$$

WOF_P: $fr_{wsh,p}$ wash off fraction for persistent bacteria

WOF_LP: $fr_{wsh,lp}$ wash off fraction for less persistent bacteria

Bacteria die-off and re-growth (occurs in soil solution and soil particle)

Chick's law first order decay equation is used to determine the quantity of bacteria that is removed from the system when coliform dies off and added to the process by re-growth. The equation for die-off was taken from (Reddy, Khaleel et al. 1981) as modified by (Crane and Moore 1986) and later by (Moore, Smyth et al. 1989). The equation was further modified in SWAT to include a user defined minimum daily loss of coliform. The equations used to calculate daily bacteria levels in the different pools are as following,

$$bact_{lpfol,i} = bact_{lpfol,i-1} * \exp(-u_{lpfol,net}) - bact_{min,lp} \quad (5\text{-}3)$$

$$bact_{pfol,i} = bact_{pfol,i-1} * \exp(-u_{pfol,net}) - bact_{min,p} \quad (5\text{-}4)$$

Equations for bacteria present on foliage die-off and re-growth on a particular day.

$$bact_{lpsol,i} = bact_{lpsol,i-1} * \exp(-u_{lpsol,net}) - bact_{min,lp} \quad (5\text{-}5)$$

$$bact_{psol,i} = bact_{psol,i-1} * \exp(-u_{psol,net}) - bact_{min,p} \quad (5\text{-}6)$$

Equations for bacteria present in soil solution die – off and re-growth on a particular day.

$$bact_{lpsorb,i} = bact_{lpsorb,i-1} * \exp(-u_{lpsorb,net}) - bact_{min,lp} \quad (5\text{-}7)$$

$$bact_{psorb,i} = bact_{psorb,i-1} * \exp(-u_{psorb,net}) - bact_{min,p} \quad (5\text{-}8)$$

Equations for bacteria absorbed in soil solution die-off and re-growth on a particular day.

Leaching Process

Bacteria can be transported with percolation into soil layers. Only bacteria present in soil solution are likely to leach. Bacteria removed from the surface soil layer by leaching are assumed to die in the deeper soil layers.

$$bact_{lp,perc} = \frac{bact_{lpsol} * w_{perc,surf}}{10 * \rho_b * depth_{surf} * k_{bact,perc}} \quad (5\text{-}9)$$

BACTMIX: $k_{bact,perc}$ is the bacteria percolation coefficient

Bacteria in Surface Runoff

This section reviews the algorithms govern the movement of bacteria from land catchment to river streams Due to the low mobility of bacteria in soil solution, surface runoff will only partially interact with the bacteria present in the soil solution. The amount of bacteria transported in surface runoff is described in the following equation:

$$bact_{lp,surf} = \frac{bact_{lpsol} * Q_{surf}}{\rho_b * depth_{surf} * k_{bact,surf}} \quad (5\text{-}10)$$

ρ_b is the bulk density of the soil in top 10 mm

$k_{bact,surf}$ is the bacteria soil partitioning coefficient (m3/Mg) [BACTKDQ]

Attachment to Sediment in Surface Runoff

Bacteria attached to soil particles may be transported via surface runoff to the main channel. Bacteria associated with the sediment loading derive from each HRU. Changes in sediment loading will be reflected in the loading of this form of bacteria. The amount of bacteria transported with sediment to the stream is calculated with a loading function developed by (McElroy, Chiu et al. 1976) and modified by (Williams 1978).

$$bact_{lp,sed} = 0.0001 * conc_{sedlpbact} * \frac{sed}{area_{hru}} * \varepsilon_{bact,sed} \quad (5\text{-}11)$$

$conc_{sedlpbact}$ is the concentration of less persistent bacteria attached to sediment in the top 10 mm (cfu / metric ton soil)

$\varepsilon_{bact,sed}$ is the bacteria enrichment ratio

The concentration of bacteria in sediment is calculated with the following equation.

$$conc_{sedlpbact} = 1000 * \frac{bact_{lp,sorb}}{\rho_b * depth_{surf}} \quad (5\text{-}12)$$

$bact_{lp,sorb}$ is the amount of less persistent bacteria sorbed to the soil (cfu / m^2)

$depth_{surf}$ is the depth of the soil surface layer (10 mm)

Enrichment ratio is the fraction of the concentration of bacteria transported with the sediment to the concentration of bacteria attached to soil particles in the soil surface layer. This fraction is calculated for each individual storm event for loading calculation.

$$\varepsilon_{bact,sed} = 0.78 * \left(conc_{sed,surq}\right)^{-0.2468} \qquad (5\text{-}13)$$

$conc_{sed,surq}$ is the concentration of sediment in surface runoff (mg / m3 H_2O)

$$\mathrm{conc}_{\mathrm{sed,surq}} = \frac{\mathrm{sed}}{10 * \mathrm{area}_{\mathrm{hru}} * \mathrm{Q}_{\mathrm{surq}}} \qquad (5\text{-}14)$$

sed is the sediment yield on a given day (metric ton)

$area_{hru}$ is the HRU area (ha)

Q_{surq} is the surface runoff on a given day (mm H_2O)

Parameter is sediment yielding, refer to the sediment routing.

Bacteria Lag in Surface Runoff

In large sub-basins with a time of concentration greater than one day only a portion of the surface runoff will reach the main channel on that day it yields.

$$bact_{lp,surf} = \left(bact'_{lp,surf} + bact_{lp,surstor,i-1}\right) * \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad (5\text{-}15)$$

$$bact_{lp,sed} = \left(bact'_{lp,sed} + bact_{lp,sedstor,i-1}\right) * \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad (5\text{-}16)$$

$bact_{lp,surf}$ is the amount of surface runoff less persistent bacteria generated in the HRU on a given day (cfu /m^2)

$bact_{lp,sed}$ is the amount of sediment attached less persistent bacteria discharged to the main channel in surface runoff on a given day (cfu /m^2)

5.2.4 Bacteria in-stream sub-model

The SWAT model shares the following general idea to estimate the change of bacteria in stream (Bowie 1985). A first-order decay equation is adopted to represent the only process of bacteria in the stream.

$$bact_{lprch,i} = bact_{lprch,i-1} * \exp(-\mu_{lprch,die}) \quad (5\text{-}17)$$

$$bact_{prch,i} = bact_{prch,i-1} * \exp(-\mu_{prch,die}) \quad (5\text{-}18)$$

where,

$bact_{lprch,i}$ = the amount of less persistent bacteria present in the reach on day i (cfu/100mL)

$bact_{lprch,i-1}$ = the amount of less persistent bacteria present in the reach on day i -1 (cfu/100mL)

$u_{lprch,die}$ = the rate constant for die-off of less persistent bacteria in streams (1/day)

In SWAT model, first-order decay equation from Chick's law is the primary calculation in bacteria die-off, which the total die-off rate is estimated assuming that temperature remains at 20 degree Celsius. Therefore, a temperature adjustment factor is used for re-adjusting the die-off rate with regard to water temperature.

$$C_t = C_0 e^{-KtA\,(T-20)} \quad (5\text{-}19)$$

where,

C_t = concentration at time t

C_0 = the initial concentration

K = the decay rate (1/day)

A = the temperature adjustment factor (THBACT)

T = the temperature (°C)

5.2.5 Recent Development

(a) Sediment Suspension and Deposition (Jung Woo Kim 2009)

$$conc_{sed,max} = SPCON.(PRF.v_{ch})^{SPEXP} \quad (5\text{-}20)$$

Where, $conc_{sed,max}$

$SPCON$ is sediment routing linear adjustment coefficient

$SPEXP$ is sediment routing exponential adjustment coefficient

PRF is peak rate adjustment factor

v_{ch} is stream velocity

$$M_{S,res} = (\text{conc}_{sed,max} - \text{conc}_{sed,i}) * Q * K_{ch} * C_{ch} \quad (5\text{-}21)$$

Q is the water in stream segment (m^3)

$M_{S,res}$ is the amount of suspended sediments

$$M_{S,dep} = (\text{conc}_{sed,i} - \text{conc}_{sed,max}) * Q \quad (5\text{-}22)$$

$M_{S,dep}$ is the deposited sediment in stream segment

(b) Streambed E. coli release and deposition

$$M_{B,res} = M_{S,res}.C_{B,B} \quad (5\text{-}23)$$

$M_{B,res}$ is the amount of bacteria attached to the re-suspended sediment in reach

$M_{S,res}$ is the deposited sediment in stream segment

$C_{B,B}$ is the E coli concentration in streambed sediment (cfu/g suspended solid)

$$M_{B,dep} = M_{B,W} \cdot \frac{K_P . M_{S,dep}}{Q + K_P . M_{S,W}} \quad (5\text{-}24)$$

$M_{B,dep}$ is the amount of bacteria attached to the sediment deposition

$M_{B,W}$ is the number of bacteria in water

$M_{S,dep}$ is the amount of deposited sediment

$M_{S,W}$ is the mass of sediment in water

K_P is the partitioning coefficient of bacteria between sediment and water

(c) Light Dependent Bacteria Decay

Recent SWAT model do not have the effect of solar radiation on die-off process in bacteria cycle, despite that the effect of light-dependent decay per day was considered and modified in previous study (Cho, Cha et al. 2010; Cho, Pachepsky et al. 2012). It is suggested that a new parameter (a model variable) called SOLPCH is integrated to the in-stream bacteria sub-model, to observe the effects of solar intensity. The modified die-off rate could be expressed in the following equation.

$$K_T = K_N + I_{(T)} * K_S \quad (5\text{-}25)$$

where,

K_N is the die off rate [/day], which indicates WDLPRCH parameter in the model

K_T is the total die-off rate [/day], which indicates TDLPRCH parameter in the model

K_S is the solar radiation associated die off rate [/day], which indicates SOLLPCH parameter in the model

$I_{(T)}$ is the solar radiation [MJ/m2/day] [refer to variable 'algi' in hhwqal.f]

Daily solar radiation received in each sub-basin is estimated by SWAT model using inverse distance estimation method, derived from mean daily solar radiation in the study.

5.2.6 Bacteria Sub model Modification

Sub-daily Sediment Associated Bacteria

Up to date SWAT model have not included the algorithm of sediment effects to in-stream bacteria prediction. The theory of sediment-related bacteria is explained in SWAT theoretical handbook, but no algorithm was found in the source code from up to date v2012 rev591. Sediment and erosion sub-model is developed to extend its capability in model hourly simulation (Jeong, Kannan et al. 2010; Jeong, Kannan et al. 2011). Due to the principle of bacteria attachment to sediment, and the capability of hour sediment, the sub-model was further modified in this thesis to take account the effects of sediment to bacteria in water column. The modification of the model is made to link sub-daily sediment prediction subroutine to bacteria prediction sub-routine.

Solar Radiation Associated Die-off (Sub-daily)

SWAT does not include the effect from solar radiation to coliform die-off rate. The bacteria in-stream sub-routine (rtbact.f) was further modified by adding a new parameter LDLPRCH to control bacteria routing. It stands for representation of the light dependent bacteria decay coefficient in rivers. Following equation is used to estimate the die-off rate.

(Bowie 1985) have identified a light and level-dependent disappearance rate coefficient as,

$$k' = k_l l_0 e^{-az} \tag{5-26}$$

Where,

k' = the light-dependent coliform disappearance rate, 1/hr.

k_l = proportionality constant for the specific organism, cm^2/cal

l_0 = incident light energy at the surface, cal/cm^2-hr

a = light attenuation coefficient per unit depth

z = depth in unit consistent with a

Table 5-1 In-stream Bacteria Input & Output

Variables	Variables I/O
Subroutine rtbact.f I/O	
hrchwtr (:)	Water stored in the reach at the beginning of the time step (m^3)
	From rthr.f; thmusk.f; rchinit.f
hhvaroute (2, :, :)	Water flow into reach at each hour
	From hhwatqual.f; hhnoqual.f; bmp_wet_pond.f; bmp_det_pond.f; apex_day.f;
hhvaroute(18,:,:)	Persistent bacteria at each hour
	From rtout.f (subroutine summarize data for reach)
hhvaroute(1,:,:)	Less persistent bacteria at each hour
	From rtout.f (subroutine summarize data for reach)
rch_bactlp (:)	Less persistent bacteria in reach / outflow at the end of day
Or rch_bactp(:)	From rtout.f (subroutine summarize data for reach)
Rchwtr (:)	Water stored in river at the beginning of each day
	From watqual.f; watqual2.f; noqual.f
tmpav(:)	Average air temperature on current day
	From clicon.f (Subroutine control the weather inputs)
varoute (2, :)	Water at reach during the day
	From reachout.f (Subroutine summarize data for reach)
varoute (18, :)	Persistent bacteria at reach during the day
Or varoute (19, :)	From reachout.f (Subroutine summarize data for reach)
Variable Modified to rtbact.f	
hru_ra	Daily average light intensity in reach I(t)
Deg	Sediment re-entrained in water by channel degradation
Dep	Sediment deposited on river bottom

5.2.7 Bacteria Transport

Faecal bacteria transport processes in catchment are important as they determine the total number of bacteria population flow to stream. Descriptions of main input parameters are summarized from below.

(i) Bacteria Concentration in Manure [BACTPDB]

Parameter BACTPDB is the concentration of bacteria coliform present in livestock manure when input as fertilizer. SWAT requires concentration of bacteria in deposited manure saved in fertilizer database. The unit of this parameter means number of colonies per gram of livestock. The guideline value refer to BACTPDB is recommended from the ASAE database (ASAE 2003; ASAE 2005).

Table 5- 2 Summaries of Bacteria Transport Processes

Processes	Bacteria Transport Processes
1	Wash-off
2	Die-off and re-growth Process of bacteria in soil solution
3	Die-off and re-growth process of bacteria absorbed in soil particles
4	Die-off and Re-growth process of bacteria in foliage
5	Bacteria leaching to deeper aquifer
6	Bacteria in surface runoff
7	Bacteria attached to sediment in surface runoff
8	Bacteria lag in Surface Runoff
9	Bacteria flow in to river channel In stream bacteria component activate

(ii) Partition coefficient of manure present in soil solution and soil particle [BACTKDDB]

BACTKDDB is the partitioning coefficient for bacteria. This parameter is a mandatory value to each type of manure. The BACTKDDB helps to partition total bacteria organism population into soluble and adsorbed bacteria. The specified parameter BACTKDDB ranges between 0 and 1. If the value is close to zero, bacteria are mostly attached to soil particles. If the parameter is close to one, bacteria are mostly present in soil solution. The adsorbed manure is considered to be the nutrient for the crops in agricultural land, whilst the manure in soil solution is the input source carried with surface runoff. So that it is suggested that a value of 0.9 is appropriate for pasture land use (Parajuli 2007).

(iii) [BACTKDQ] Soil - Bacteria Partitioning Coefficient in Surface Runoff

BACTKDQ is the soil-bacteria partitioning coefficient in surface runoff. The SWAT bacteria sub-model estimates the colonies transported from surface runoff from the soluble bacteria, which presents in the top 10 mm of soil surface. Bacteria present below the first top 10 mm soil layer, would be considered to have died off. Bacteria present in surface runoff are considered as partially in connection with bacteria in soil solution. This parameter determines the number of bacteria transported with surface runoff. It is the ratio between bacteria concentration in surface runoff and bacteria concentration in soil solution. (Parajuli 2007) recommended that in order to achieve best performance, the default value of BACTKDQ should be selected as 175.

(iv) [BACTMIX] Percolation coefficient

BACTMIX controls the number of bacteria that percolate to deep soil layer. The percolation coefficient is the ratio of bacteria concentration in the soil solution in the top 10 mm soil surface to the number of bacteria which percolate into deep soil. The default value for BACTMIX is suggested as 10.

(v) Fraction of manure applied to land areas that have active organisms [BACT_SWF]

This parameter allows identification of how much of the manure deposited on land contains live bacteria colonies. Table 5-3 summarises the variation of bacteria prevalence in livestock manure. The geometric mean of bacteria prevalence rate per type of manure is used in this study (Coffey, Cummins et al. 2010; Coffey, Cummins et al. 2010).

Table 5-3 Bacteria Prevalence in Livestock

References	Prevalence (%)				
	Calves	**Cattle**	**Cows**	**Lambs**	**Ewes**
(Graczyk, Evans et al. 2000)	68	26	26	n/a	n/a
(McEvoy, Duffy et al. 2005)	n/a	7.3	n/a	n/a	n/a
(Hutchinson 2004)	n/a	5.4	n/a	n/a	29
(Sturdee 2003)	52	3.6	3.5	12.9	6.4
Geometric Mean	***59.5***	***7.8***	***9.5***	***12.9***	***13.6***

5.3 Catchment Agricultural Management

5.3.1 Agricultural Manure

Livestock produces manure which is valuable sources for crops that demand nutrition to grow. It is essential to calculate nutrient quantity and application rate of organic manure deposited to agricultural land from livestock. The method for calculation considers the quantity of farm yard manure yielding (i.e. manure and slurry) and the fertilizing application rate. NVZ establishes a limit on the amount of livestock manure that can be applied to farm land (via spreading or grazing livestock). It is mandatory for farm owners to ensure in any year (from 1 January) the total amount of nitrogen in livestock manure does not exceed 170 kg multiplied by farm size in hectares. There is further advice contained in the Code of Good Agricultural Practice, which establishes another limit of applying maximum 250 kg of nitrogen per hectare per year, subject to farm outside an NVZ. Minimum slurry storage which allows for at least four months without spreading is required in a NVZ. Large slurry storage allows control and flexibility in timing and location to spread manure spread to avoid water pollution. It is suggested that a farm located in the NVZ should have storage minimum capacity of six months for pig slurry and poultry manure or five months for other.

Application Decision

Total slurry production is equal to volume of slurry multiplied by the volume of rainfall and multiplied by the volume of water. Fertiliser Manual (RB209) (DEFRA 2010) gives recommended fertilizer quantities for each crop per hectare. In addition, there is an upper limit mandatory requirement which all farms should ascertain that no more than 250 kg per hectare of total nitrogen, which originated from manure, is applied within any 12-months' period. If the actual application exceeds the mandatory level, catchment and river eutrophication occurs.

Timing of Manure Fertilizer Application

Manure is usually applied when the crops need nutrients to grow in late winter, spring and summer, taking weather and soil conditions into account to minimise the risk of water pollution and soil compaction. Late winter and early spring is the best time of year to spread manure, due to the crops is most likely to be able to take up nutrients. Fertilizing during this period can maximise the crop yield and reduce the cost and minimise nutrient losses to cold and frozen land. However, manure spreading during autumn or early winter is normally not required. Nitrogen would be lost through runoff and leaching. Manure spreading in summer is less likely to leach. Therefore, there is more fertilizer applied in late winter and spring compared with summer and autumn. Timing of spreading the manure fertilizer is critical for the bacteria modelling, if the amount of manure fertilizer is significant to better understand the impact of spreading organic manure sludge on water quality, particularly the faecal coliforms. The recording of manure spreading timing is critical due to the manure fertilizer spreading is critical to faecal contamination in the catchment and the downstream water bodies.

Frome and Piddle catchment is located across three local counties, West Dorset, North Dorset, Purbeck and Poole. The table 5-5 shows mean livestock manure, with a unit (kg per hectare per day) deposited in the study catchment.

Table 5-4 Stocking Rate of Supplying 170kg N/ha from Manure on Organic Farm (ADAS 2002)

Livestock Type	Max. No. of Livestock per ha	Nitrogen Yield per Livestock (kg / year)
Dairy cow (500kg)	2	85
Dairy cow (450kg)	2.2	77
Ewes (65kg)	19	9
Lamb (6 months old)	140	1.2
Pig (baconer 35 - 105 kg)	16	10.6
Cutter (35 - 85 kg)	18	9.4
Laying hens	260	0.65
Turkey - male	120	1.42

Due to the HRU and sub basin is the fundamental calculation unit in SWAT model, therefore the statistics of livestock distributed in three counties i.e. West Dorset, East Dorset and Purbeck and Poole are used in combination with catchment delineation (as shown in Section 4.2.3) i.e. ten sub basins were used to work out the estimation of the number of four types of livestock fed in each sub basin using GIS technique. The estimation was presented as shown in Table 5-5.

Table 5-5 Livestock Stocking Rate in Sub-basins

Sub Basin	**Cattle**	**Sheep**	**Pig**	**Poultry**
Unit	kg/ha/day	kg/ha/day	kg/ha/day	kg/ha/day
Sub1	56.24	5.41	4.40	0.209
Sub2	54.32	4.47	3.14	0.898
Sub3	56.24	5.41	4.40	0.209
Sub4	56.24	5.41	4.40	0.209
Sub5	56.24	5.41	4.40	0.209
Sub6	56.24	5.41	4.40	0.209
Sub7	30.94	2.79	0.36	0.016
Sub8	46.61	3.95	2.27	0.575
Sub9	46.12	4.36	2.79	0.132
Sub10	30.94	2.79	0.36	0.016

Table 5-6 Manure Derived Nitrogen

Livestock Type	No. of Livestock	Total N per Livestock (kg Nitrogen/year)	Total N Produced kg Nitrogen / year
1 dairy cow[1]	150	101	15,150
1 finish pig place[2]	1,200	10.6	12,720
1,000 laying hen places	50	400	2,000

Stocking rate with number of Livestock Unit (LU) per Hectare (AU/Ha) is used.

Table 5-7 Bacteria Inputs in Frome and Piddle Catchment

Type	Point/Diffuse	Input File	Database	Frequency
Livestock Grazing	Diffuse	.mgt	.fert	Seasonal and Continuous
Manure Spreading	Diffuse	.mgt	NVZ Guideline	Intermittent

1 A dairy cow: normally yield from 6 to 9 thousand of litres of milk per year.

2 Finish pig place: 66kg and over.

5.3.2 Grazing

The catchment of Frome and Piddle covers three local authority counties that are West Dorset, North Dorset, and Purbeck as shown in Table 5-5. Sizes of each sub basin are used to calculate the catchment area that has been divided by three local counties. Table 5-8 illustrated the proportions of corresponding sub-basins that are located in each local area. Catchment area in each authority county is 43,326 ha of West of Dorset, 3,987 ha of North Dorset and 19,287 ha of Purbeck & Poole.

Table 5-8 Summaries of Sub-Basins Geographical

Sub basin	Area (Ha)	Elevation Range (m)	Catchment in North Dorset	Catchment in West Dorset	Catchment in Purbeck and Poole
Sub1	3,110	78-254	n/a	All Sub-1	n/a
Sub2	1,332	64-227	40% Sub-2	60% Sub-2	n/a
Sub3	203	107-236	n/a	All Sub-3	n/a
Sub4	20,161	52-267	n/a	All Sub-4	n/a
Sub5	19	50-70	n/a	All Sub-5	n/a
Sub6	2,005	89-241	n/a	All Sub-6	n/a
Sub7	1,870	0-67	n/a	n/a	All Sub-7
Sub8	13,815	3-273	25% Sub-8	41.7% Sub-8	33.3% Sub-8
Sub9	18,780	9-203	n/a	60% Sub-9	40% Sub-9
Sub10	5,300	0-197	n/a	n/a	All Sub-10
Total (ha)	66,595	0-273	3987	43326	19287

5.3.3 Manure Spreading

The farmer's guideline gives the maximum amount of each type of manure or sludge that can be applied as fertilizer for crops and grazing purposes. This value is derived from the maximum amount of total nitrogen that can be spread on agricultural land, in accordance with legislation protecting Nitrogen Vulnerable Zones that was introduced in parallel with the UK river basin management regulation and EU Water Framework Directive. For example, the maximum quantity of cattle farmyard manure (CFM) or slurry that may be spread is 42 tonnes per hectare per year, which is equal to 42,000 kg per hectare. This table together with the number type of livestock determines the maximum application rate of spreading manure or slurry for each sub-basin in the Frome and Piddle catchment. However, in reality this number might not be achieved, and it is normally considered a guideline value for complying with NVZ regulation.

Table 5-9 Typical Maximum Annual Manure Application Rates (DEFRA 2003)

Manure or sludge Type	Application Rate	Total N (kg/m^3)
Cattle farmyard manure	42 tonnes/ha	6
Pig farmyard manure	36 tonnes/ha	7
Sheep farmyard manure	42 tonnes/ha	6
Poultry layer manure	16 tonnes/ha	16
Dairy cattle slurry (10% dry matter)	63 m^3/ha	4
Beef cattle slurry (10% dry matter)	71 m^3/ha	3.5
Pig slurry (6% dry matter)	50 m^3/ha	5.0

Table 5-10 Estimations of Manure Storages of Livestock during in-house Period in Frome and Piddle Catchments

Livestock Type	Number (Livestock Unit)	Fresh Manure (kg/LU/day)	In House Period (days)	Winter Manure Storage (kg)
Cattle[3]	50,595	64	151	$4.89 * 10^8$
Sheep[4]	62,062	4.84	62	$1.86 * 10^7$
Swine	18,590	10.9	292	$5.92 * 10^7$
Poultry	148,434	0.115	315	$5.38 * 10^6$

Total livestock manure production during a winter in-house period is about 10,700 kg per hectare if applied as a one-off application to 53,332 ha[5] (Coffey, Cummins et al. 2010). Cattle are housed between November and April, a total of 6 months. Sheep are housed for a minimum period of 62 days. Sheep are free ranged livestock that are only in-house during the coldest time. Pigs are kept in-house for a guideline period of 80% of time which equal to 292 days. Poultry such as chicken and duck are housed for most of the time with only 10% free range throughout the year (ADAS 2001) The manure produced is calculated per each type of livestock housed. Overall, it is estimated that a total of 572k tonnes of manure would be spread over the Frome and Piddle catchment with a total area of 665 km^2in one year.

Table 5-11 shows the estimated dates, area of manure spreading and quantity of manure spreading to agricultural land. All manure spreading inputs are stored in model management files (.mgt). Date of manure application is assumed based on the crops growing in the modelled catchment. Table 5-7 shows the types of crops

---

[3] Cattle 151 days (Nov 1 - April 1)

[4] Sheep 62 days (Dec 1 - January 31)

[5] Equal to 80% of total catchment due to compliance with NVZ suggestion to avoid pollution

growing in Dorset where Frome and Piddle catchment is located as well as the percentage of each crop to total crop land area.

Table 5-11 Manure Spreading in Frome and Piddle Catchments

Date	Spreading Area (Ha)	Portion Spread from Storage (%)	Application Rate (kg ha^{-1})	Input File
January 15	53,332	25%	2680 kg/ha	.mgt
April 27	53,332	20%	2150 kg/ha	.mgt
July 12	53,332	20%	2150 kg/ha	.mgt
September 10	53,332	10%	1070 kg/ha	.mgt
November 12	53,332	25%	2680 kg/ha	.mgt

Table 5-12 summarise crops that grow in Dorset in 2007. It gives the area devoted to each crop and the percentage it represents. Wheat is the dominant crop in Dorset, representing 38.4% of the total crop area. Barley and Maize are the second and third dominant crops, at 18% and 16.9% of total crop area respectively. It is noted that barley has spring and winter as its two sub-types, and represents 12.4% and 5.6% of total crops respectively. Oilseed rape is the fourth largest crop in Dorset, constituting 10.5% of total crops. The top four largest crops in Dorset occupy a total of 84% of all crops in the county. Each crop shows a varied growth pattern. It is widely known that UK farmers are among the best in the world. They apply slurry and manure to crop land to achieve maximum yield while protecting water and the environment. A guide from ADAS stated the timing opportunities for farmers to apply manure and slurry (ADAS 2001). For example, the best fertiliser application window for winter cereal is between mid-February and the end of April and the best fertilizer supplement should be applied between mid-July and the end of October.

Table 5-12 Summaries of Crops in Dorset (DEFRA 2013)

Crop Type	Area (ha)	Percentage
Wheat	9,233	38.35%
Winter Barley	1,351	5.61%
Spring Barley	2,992	12.43%
Oats	948	3.94%
Other Cereals	221	0.92%
Potato	102	0.42%
Field Bean	733	3.04%
Oilseed	2,529	10.50%
Lin Seed	97	0.40%
Root Crops	165	0.69%
Other Crops	309	1.28%
Maize	4,056	16.85%
Other Arable Crops	398	1.65%
Bare Fallow	825	3.43%
Total Fruit	116	0.48%

Winter cereals are sown in autumn and early winter, it harvests in late spring and early summer. Winter cereals make better use of water and prepare the soil for spring cereals. Spring cereals are sown in early spring, and harvested in summer. Overall, winter cereals have higher yields and require less irrigation than spring cereals. Manure fertilizers are required for both type of cereal before seeding. In this study wheat, barley, maize and oilseed rape are the four dominant crops in the study catchment. The manure and slurry spreading timing is selected regarding have five applications in total, which distributed in January, April, July, September and November as shown in Figure 5-3. The quantity of manure spreading is derived from the total manure stored in-house period. The quantity of manure spreading for each sub-basin is assumed to be proportional to sub-basin area.

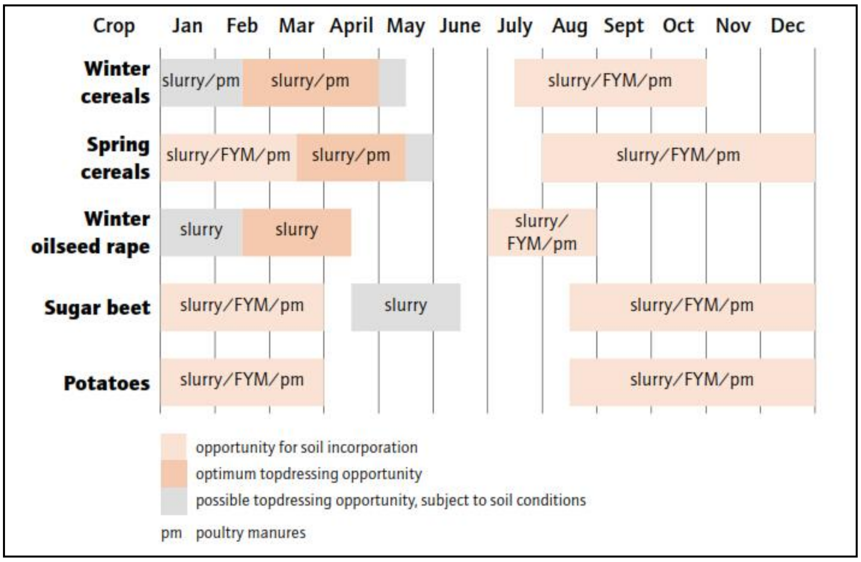


Figure 5-3 Best Window of Manure Spreading in the UK (ADAS 2001)

5.4 Bacteria Model Performance

5.4.1 Model Calibration and Sensitivity (Bacteria)

Like the flow calibration the sediment and bacteria calibrations are conducted with SWAT CUP. A total of 20 parameters are selected in this sensitivity and uncertainty analysis. Among these parameters some are regarded as sensitive to sediment and bacteria individually, others are sensitive to both routing processes.

A list of recommended parameters that are associated with bacteria transport processes is shown in Table 5-13. Parameter THBACT is allocated a value of 1.07 in three studies. Parameter BACTKDQ varies between 166.14 and 4800, suggesting that variation is due to soil type difference in previous studies.

Table 5-13 Suggested Value of Bacteria Parameters in Transport Processes

Parameters	(Jayakody, Parajuli et al. 2014)	(Cho, Pachepsky et al. 2012)	(Tang, McDonald et al. 2011)	(Coffey, Cummins et al. 2010)	(Kim, Pachepsky et al. 2010)
THBACT	1.07	-	1.07	1.07	-
BACTKDDB	0.95	0.75	0.2	0.9	0.36
BACTKDQ	175	166.14	4800	175	175
WDPQ	0.23	-	0.05	0.03	-
WDPS	0.023	-	1.4	0.003	-
WDPF	-	-	0.02	-	-
BACT_SWF	-	0.61	0.5	-	0.97
BACTMIX	-	18.31	-	10	10
WOF_P	-	0.15	0.8	-	0.5

Table 5-14 Model Parameterizations for Sediment and Bacteria

Parameter	Definition	Parameter Value		
		Max	Min	Fit
3:V__CH_COV2.rte	Channel erodibility factor	-0.001	1	0.025
6:V__PRF.bsn	Peak rate adjustment factor for sediment routing in the main channel	0	1	0.23
10:V__SED_CON.hru	Sediment concentration in runoff (mg/l)	10	1000	530
15:V__BIOMIX.mgt	Biological mix coefficient	0	1	0.67
20:R__SOL_K(..).sol	Soil saturated hydraulic conductivity (mm/hr)	-80%	-10%	1.2
13:V__BIO_INIT.mgt	Initial dry weight biomass (kg/ha)	10	500	268
11:V__PHU_PLT.mgt	Total number of heat units or growing degree days needed to bring plant to maturity (days)	10	2000	50
16:V__BIO_EAT .mgt	Dry weight of biomass consumed daily (kg/ha/day)	10	100	85
9:V__SPEXP.bsn	Exponent parameter for calculating the channel sediment routing	1	2	1.3
7:V__ADJ_PKR.bsn	Peak rate adjustment factor for sediment routing in tributary channels	0.5	2	1.2
19:V__FRT_KG .mgt	Amount of fertilizer spreading (kg/ha)	2000	9000	5600
17:V__BIO_TRMP .mgt	Dry weight of biomass tramped daily (kg/ha/day)	10	100	58

2:V__CH_COV1.rte	Channel cover factor	-0.001	1	0.45
8:V__SPCON.bsn	Linear parameter for calculating the channel sediment routing	0.0001	0.015	0.008
18:R__FRT_SURFACE .mgt	Fraction of manure applied to top 10mm surface soil	-50%	100%	0.6
14:V__LAI_INIT.mgt	Initial leaf area index	0	1	0.67
1:V__USLE_P.mgt	USLE equation support practice factor	0	1	0.63
4:V__LAT_SED.hru	Amount of sediment transport with lateral flow (mg/l)	0	5000	4,377
5:V__USLE_K(..).sol	USLE equation soil erodibility (K) factor	0	0.65	0.35
12:V__BIO_MIN.mgt	Minimum plant biomass for grazing (kg/ha)	50	300	150

Table 5-15 Recommended Default Value for Bacteria Model

Parameters	Definition	Fixed Value
BACTKDQ	Bacteria soil partitioning coefficient .bsn (m3/Mg)	175
THBACT	Temperature adjustment factor for bacteria die – off / growth	1.07
BACTKDDB	Bacteria Partition Coefficient (partition between adsorb to soil particle and in soil solution)	0.95
BACTMX	Bacteria percolation coefficient (Mg/m3) Percolation / Leaching	10
BACT_SWF	Fraction of manure applied to land areas that has active colony forming units	0.65
WDLPQ	Die off factor for less persistent bacteria in soil solution at 20 degree	0.02
WGLPQ	Growth factor for less persistent bacteria in soil solution at 20 degree	0
WDLPS	Die-off factor for less persistent bacteria adsorbed to soil particles at 20 degree	0.02
WGLPS	Regrowth factor for less persistent bacteria adsorbed to soil particles at 20 degree	0
WOF_LP	Wash-off factor for less persistent bacteria	0.9
WDLPF	Die- off factor for less persistent bacteria on foliage at 20 degree	0.02
WGLPF	Regrowth factor for less persistent bacteria on foliage at 20 degree	0

5.4.2 Model Sensitivity (Bacteria)

The result of model sensitivity test of sediment (suspended solid) is summarized in Table 5-16. The most sensitive parameter of sediment is channel erodibility factor (CH_COV2 &CH-EROD), with t-test value of 3.78, which is regarded as the highest among 20 selected parameters.

Table 5-16 Sediment Model Sensitivity

Parameter	Rank	t-test	P value
3:V__CH_COV2.rte	1	3.78	0.00
6:V__PRF.bsn	2	-3.38	0.00
10:V__SED_CON.hru	3	2.43	0.02
15:V__BIOMIX.mgt	4	-1.84	0.07
20:R__SOL_K(..).sol	5	-1.59	0.11
13:V__BIO_INIT.mgt	6	1.32	0.19
11:V__PHU_PLT.mgt	7	1.13	0.26
16:V__BIO_EAT.mgt	8	-0.99	0.32
9:V__SPEXP.bsn	9	0.98	0.33
7:V__ADJ_PKR.bsn	10	0.87	0.38
19:V__FRT_KG.mgt	11	-0.86	0.39
17:V__BIO_TRMP.mgt	12	0.82	0.41
2:V__CH_COV1.rte	13	0.62	0.53
8:V__SPCON.bsn	14	0.61	0.54
18:R__FRT_SURFACE.mgt	15	0.31	0.76
14:V__LAI_INIT.mgt	16	-0.26	0.80
1:V__USLE_P.mgt	17	-0.25	0.80
4:V__LAT_SED.hru	18	0.23	0.82
5:V__USLE_K (..).sol	19	-0.17	0.87
12:V__BIO_MIN.mgt	20	-0.16	0.87

The second and third most sensitive parameters are Peak Rate adjustment Factor for sediment (PRF) and Sediment Concentration in runoff (SED_CON) with t-test values -3.38 and 2.43 respectively. It is contradictory when compared with previous studies which indicated that channel cover factor (CHCOV1), exponential factor for channel erosion (SPEXP) and linear factor for channel erosion (SPCON) are the most sensitive parameters.

Table 5-17 Bacteria Model Sensitivity

Parameter Name	Rank	t-Stat	P-Value
12:V__BIO_MIN.mgt	1	-14.97	0.00
14:V__LAI_INIT.mgt	2	9.13	0.00
13:V__BIO_INIT.mgt	3	-2.38	0.02
11:V__PHU_PLT.mgt	4	2.03	0.04
19:V__FRT_KG.mgt	5	-1.55	0.12
18:R__FRT_SURFACE.mgt	6	-1.48	0.14
10:V__SED_CON.hru	7	-1.46	0.14
17:V__BIO_TRMP.mgt	8	-1.38	0.17
4:V__LAT_SED.hru	9	1.14	0.25
20:R__SOL_K (..).sol	10	0.94	0.35
8:V__SPCON.bsn	11	-0.89	0.37
1:V__USLE_P.mgt	12	-0.83	0.40
5:V__USLE_K (..).sol	13	-0.73	0.47
16:V__BIO_EAT.mgt	14	0.61	0.54
2:V__CH_COV1.rte	15	-0.58	0.56
3:V__CH_COV2.rte	16	-0.36	0.72
9:V__SPEXP.bsn	17	-0.21	0.83
7:V__ADJ_PKR.bsn	18	-0.15	0.88
15:V__BIOMIX.mgt	19	0.09	0.93
6:V__PRF.bsn	20	0.05	0.96

By contrast, with sediment sensitivity, the parameters that are sensitive to bacteria prediction differs from parameters related to sediment. The most sensitive parameter to bacteria is minimum plant biomass for grazing (BIO_MIN, kg per ha per day), with a t-stat value of -14.97. The second and third most sensitive parameters are LAI_INIT and BIO_INIT, with the t-stat value of 9.13 and -2.38 respectively. If compared with a sensitivity study conduct by (Kim, Pachepsky et al. 2010), the result shows sediment attached bacteria are most sensitive to SPCON, SPEXP and PRF. However, these three parameters are not sensitive to bacteria prediction in this study. If only parameters from bacteria transport processes are taken into account, two parameters from grazing operation (BIO_MIN and PHU_PLT) and two partitioning parameters (BACT_SWF and BACTKDDB) where found to be the most sensitive. When streambed bacteria release is considered the results were reversed. The most sensitive are those from sediment routing (SPEXP, PRF AND SPCON) and sediment erosion in streambed CH_COV and CH_EROD. Content of clay in sediment (CLAY) which is a determinant parameter of bacteria partitioning and deposition is ranked low, where as it is sensitive in flow prediction.

5.4.3 Hydrograph

Sediment Hydrograph

In-stream suspended solids (sediment) have been plotted in hydrograph as shown in Figure 5-4. The observed values are obtained from a high-frequency sampling project that measured during a 2-years period (2005-2006) in River Frome. The observation from this project is sampled averagely three times a day. The daily sediment observation is the mean of sub-daily records. Model prediction of suspended solid concentration is in a strong consistent trend compared with the mean observed values. However, the model fails to predict the peak values. This implies (1) that the current calibrated SWAT model (river flow) has potential to further adjustment in peak flow; (2) the observed daily mean suspended solid is not representative to calibrate with predicted peaks. Sub-daily suspended solid observation would be better or appropriate for accessing performance of sediment prediction.

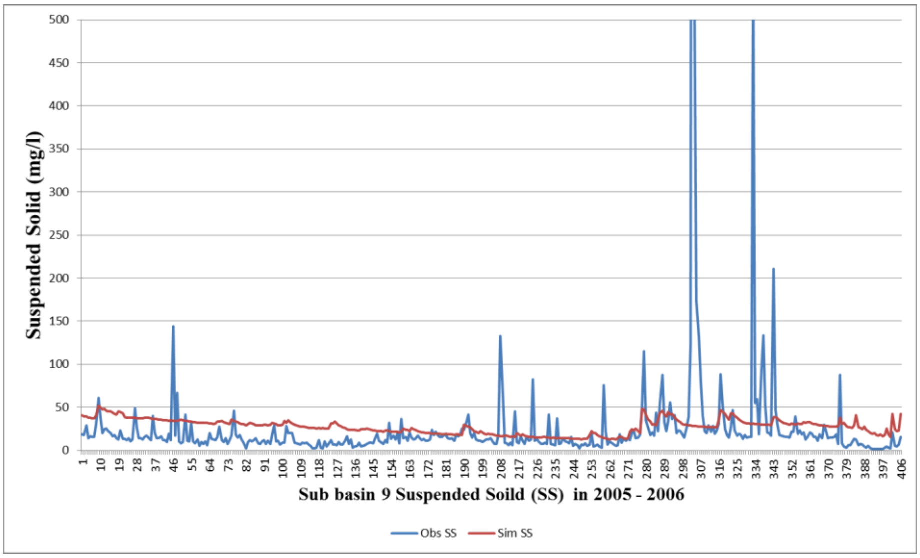
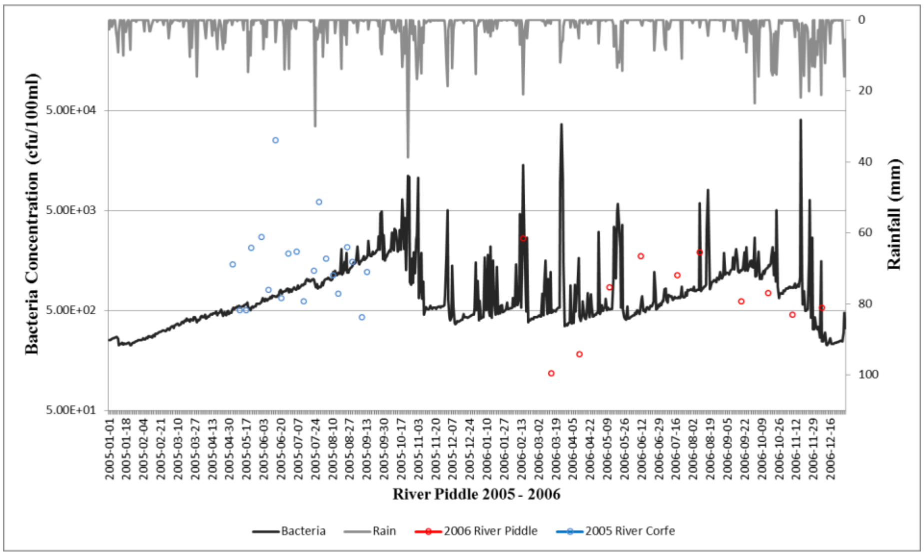


Figure 5-4 Sediment Calibration Hydrograph at River Piddle (2005-2006)

Bacteria Hydrograph, River Piddle (Daily)



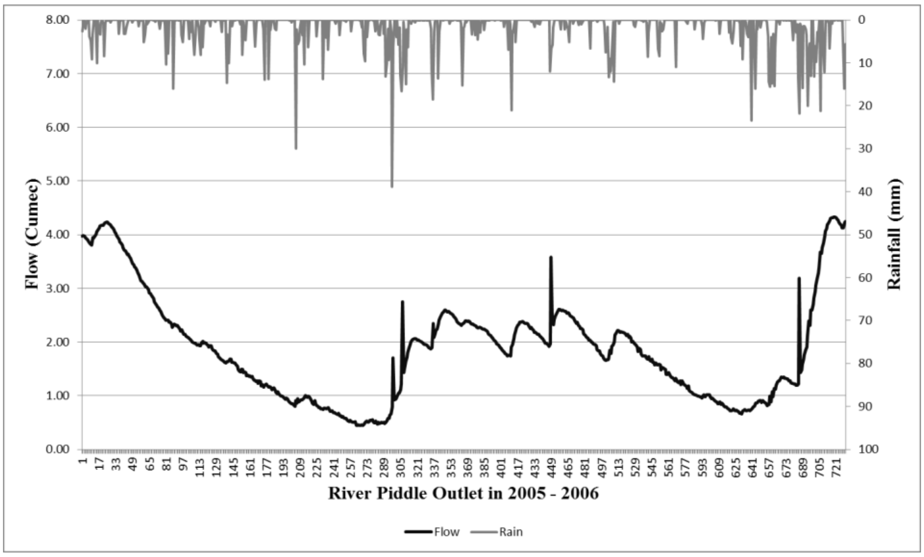


Figure 5-5 (a) Bacteria calibration at Piddle outlet (daily) (b) Flow at Piddle outlet

River Piddle Hydrograph (Hourly)

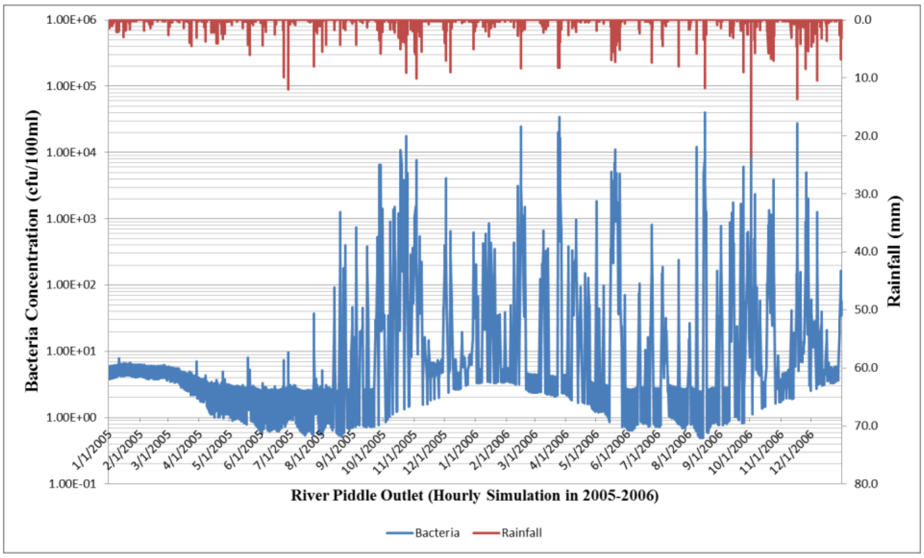


Figure 5-6 (a) Bacteria Calibration at Frome outlet (Hourly)

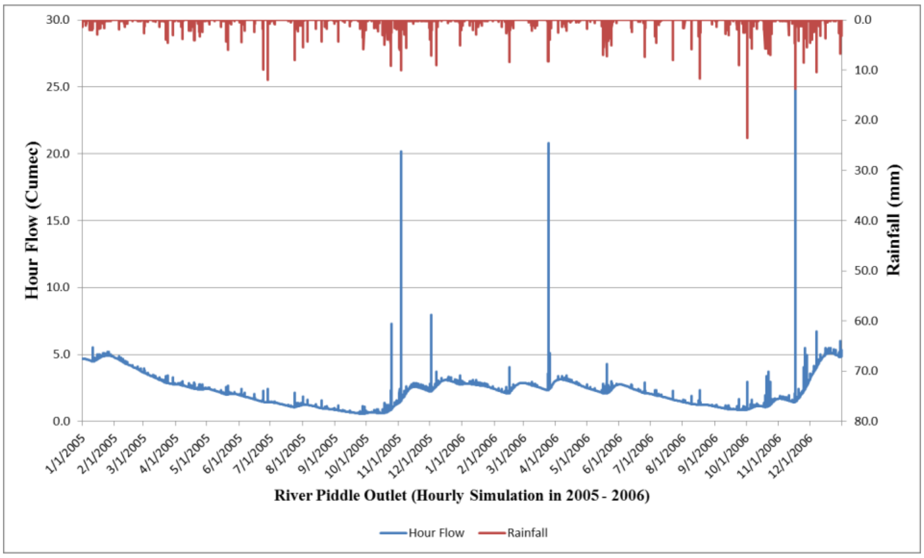


Figure 5-7 (b) Flow at Frome outlet (Hourly)

The SWAT bacteria simulation has been calibrated at the outlet of river Frome and river Piddle respectively between 2005 and 2006. Hydrograph with daily output has been plotted shown in Figure 5-5. The observed bacteria concentration from the river Corfe in 2005 has been added to the plot helping to investigate model performance due to lack of measured bacteria data in river Frome. The results show SWAT is adequate to simulate bacteria output with daily time step. However, due to limited observations, the model reliability could be further proved if high frequency sampling is present. Hourly prediction of bacteria has higher fluctuation as shown in Figure 5-6. This shows more variations in bacteria level within 24 hours. The simulated peak of hourly bacteria output reach as high as 50,000 cfu per100 ml, while the low prediction is as low as 10 cfu per 100 ml.

Hydrograph River Frome (Daily)

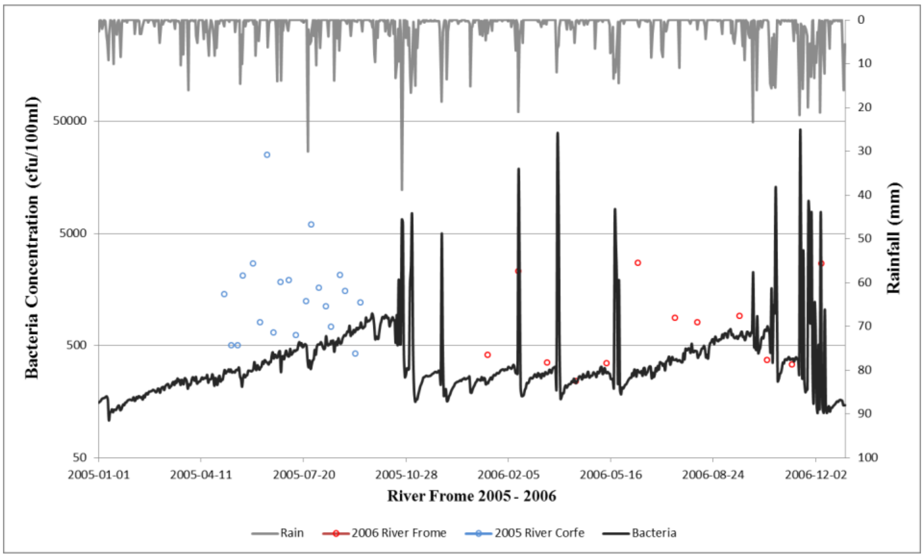


Figure 5-8 (a) Bacteria calibration Frome outlet (2005 - 2006)

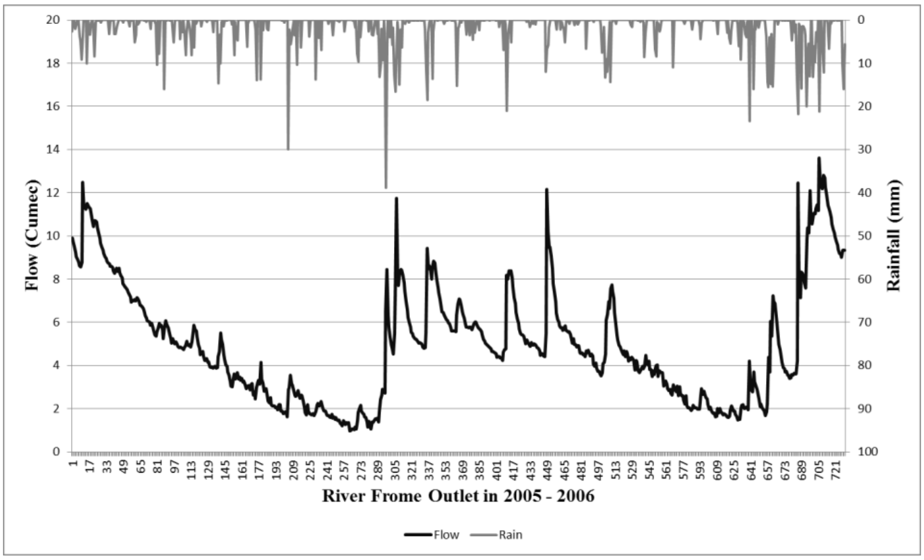


Figure 5-8 (b) Daily Flow at Frome outlet (2005 - 2006)

River Frome Hourly Hydrograph

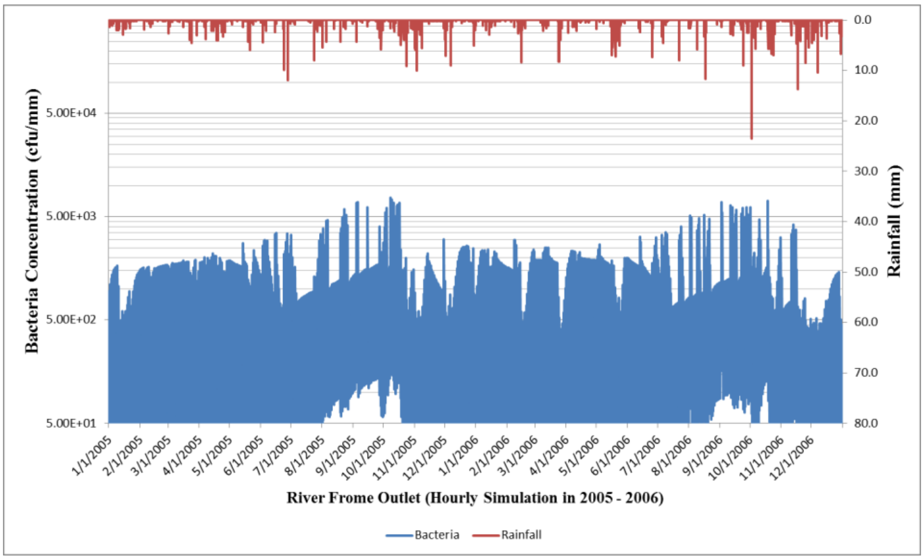


Figure 5-9 (a) Simulated Sub-daily Bacteria at Frome (2005 - 2006)

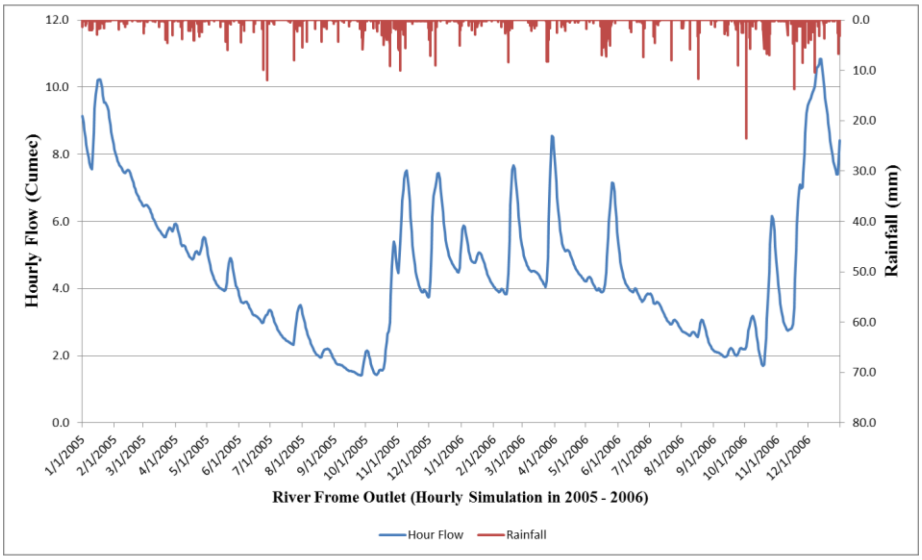


Figure 5-9 (b) Hour Flow at Frome outlet (2005 - 2006)

5.4.4 Statistics of Prediction

Duration Curve (Daily Bacteria)

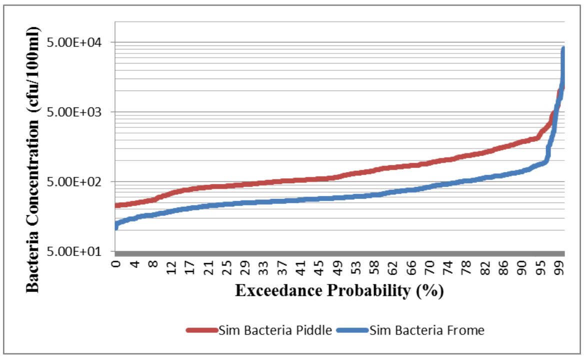


Figure 5-10 Simulated Bacteria Duration Curve at Two Catchment Outlets

Duration Curve (Hourly Bacteria)

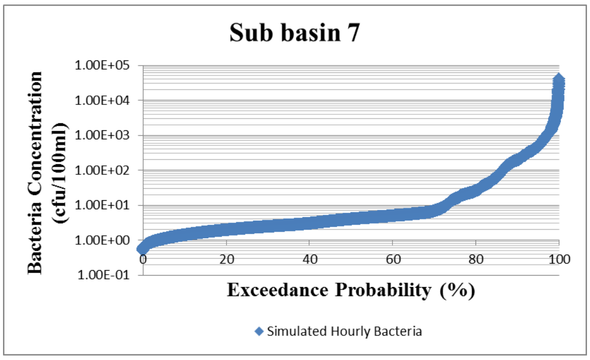


Figure 5-11 Simulated Bacteria (Hour) Duration Curve at Piddle Outlet

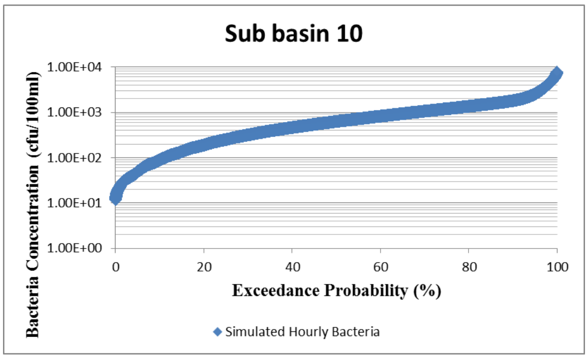


Figure 5-12 Simulated Bacteria (Hour) Duration Curve at Frome Outlet

5.4.5 Modified SWAT

With and without Sediment Re-Suspension and Deposition

The SWAT bacteria sub-model is modified to include the in-stream sediment influence on bacteria concentrations in the hourly simulations. This model improves the SWAT model in-stream component to better predict bacteria concentration. Figure 5-13 shows the significant improvement to hourly bacteria prediction. The plot in blue colour represents the simulation used for calibration and is the value with sediment effects. The plot in brown colour represents original SWAT bacteria prediction that only accounts for bacteria from runoff, but not the influence from sediment re-suspension and deposition. Brown lines are intermittent and discrete across the entire two years' simulation. The plot is in log scale. The original SWAT model can predict most peak values, but it could not simulate the medium to low levels of bacteria. This indicated that the sediment-influenced bacteria determine the low to medium bacteria level and is regarded as the base flow of bacteria levels present in the studied rivers.

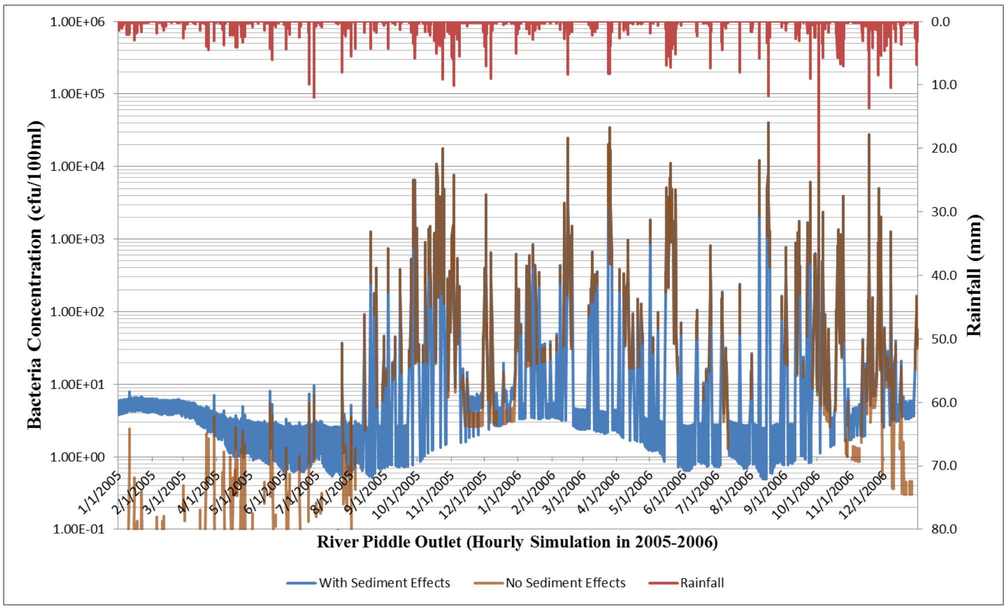


Figure 5-13 Modified SWAT with and without Sub-Daily Sediment Influence

Solar Radiation Influence

Sub-basin 7 River Piddle at West Mill

(a) Solar radiation effects inactivated

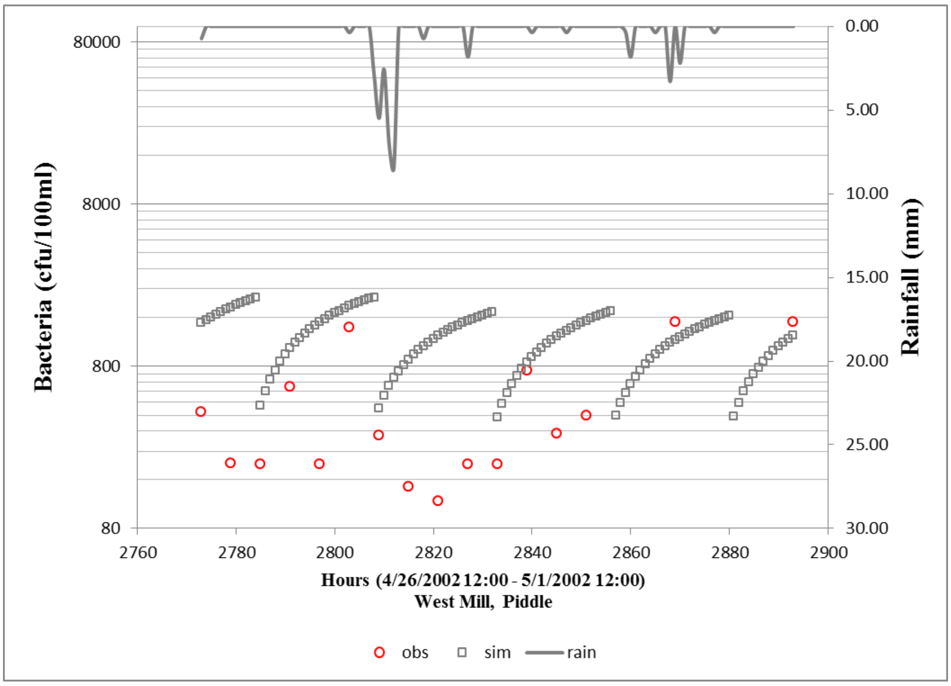


Figure 5-14 (a) Storm Event Validation with Solar Radiation Inactive, Piddle (2002)

The modified in-stream solar radiation effects module is inactivated in this plot. Figure 5-14 (a) shows the original capability of the SWAT model (v2012_rev591) for simulating bacteria (hourly prediction) in the West Mill, river Piddle. The grey hollowed square represents the model prediction. The shape of bacteria concentration is mainly attributed to the nature of sub-daily flow prediction (discussed in chapter 4). Overall, bacteria prediction is within acceptable range, while partial model prediction is overestimated.

(b) Solar Radiation Effects Activated (Bacteria Solar Radiation Adjustment Coefficient, LDLPRCH = 5)

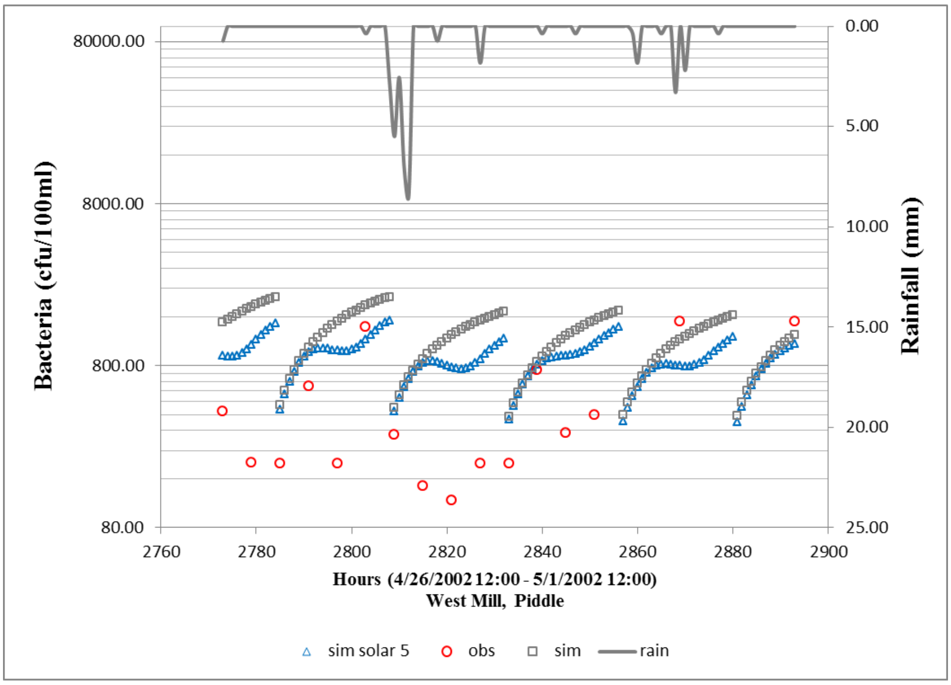


Figure 5-14 (b) Comparison of Bacteria Concentration with and Without Solar Radiation Influence (LDLPRCH = 5)

Figure 5-14 (b) compares the modified model with solar radiation influences, with prediction from original model, when bacteria solar radiation adjustment coefficient LDLPRCH is equal to 5.

(c) Solar Radiation Effects Activated (Bacteria Solar Radiation Adjustment Coefficient, LDLPRCH = 15)

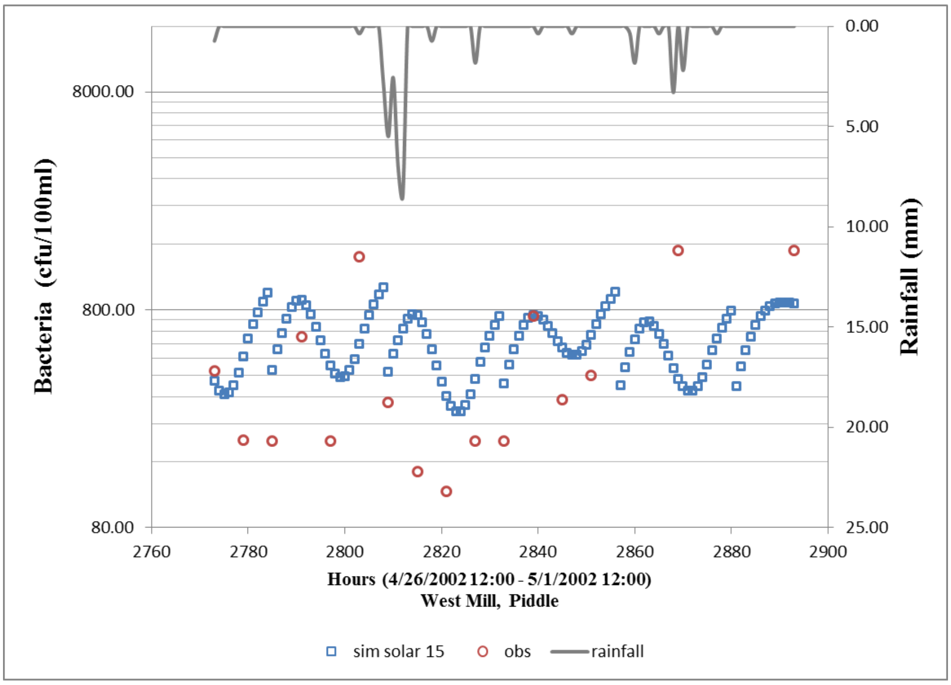


Figure 5-14 (c) Storm Event Validation with Solar Radiation Activate, Piddle (LDLPRCH = 15)

Figure 5-14 (c) shows the modified SWAT model captured influences due to solar radiation variation between 26th of April and 1st of May in 2002. Overall, modified SWAT bacteria sub model overestimated the prediction when compared with observation. However, it shows good consistency with the sub-daily variation of bacteria during this 140-hours period. The observed bacteria level shows a diurnal variation due to sunlight. The modified SWAT model (when LDLPRCH = 15) can captures bacteria variations within 24 hours. This is reflected by the shape of plot which is comprised of several sine waves with discontinued intervals. The peak could be explained with low level solar induced die-off in the nights (dark), and the bottom is attributed to day light that with high mortality rate to bacteria. Periodic intervals in the plot are suggested due to sudden changes of flow (hour prediction).

This flash change is suggested to be affected by immediate change of infiltration which is subjected to Green & Ampt infiltration algorithm that employed in this study.

Sub basin 10 River Frome at East Stock

(a) Solar radiation effects inactivated

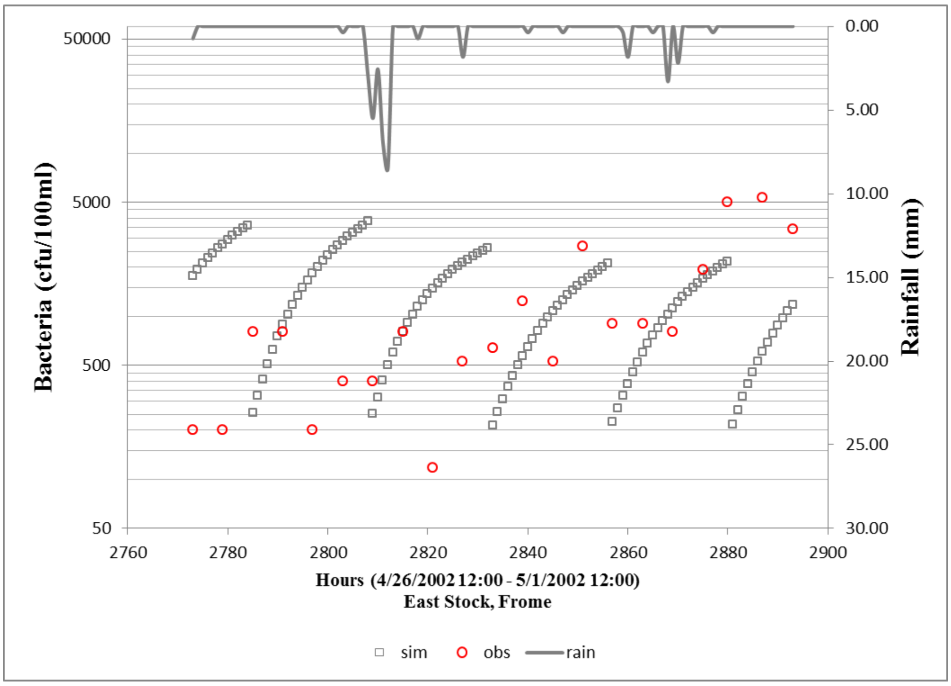


Figure 5-15 (a) Storm Event Validation with Solar Radiation Inactive, River Frome

Figure 5-15 (a) shows a general picture of bacteria concentration at East Stock, in river Frome. Original model prediction shares similar range of prediction. However, prediction does not have consistent levels when compare with observations.

(b) Solar Radiation Effects Activated (Bacteria Solar Radiation Adjustment Coefficient, LDLPRCH = 5)

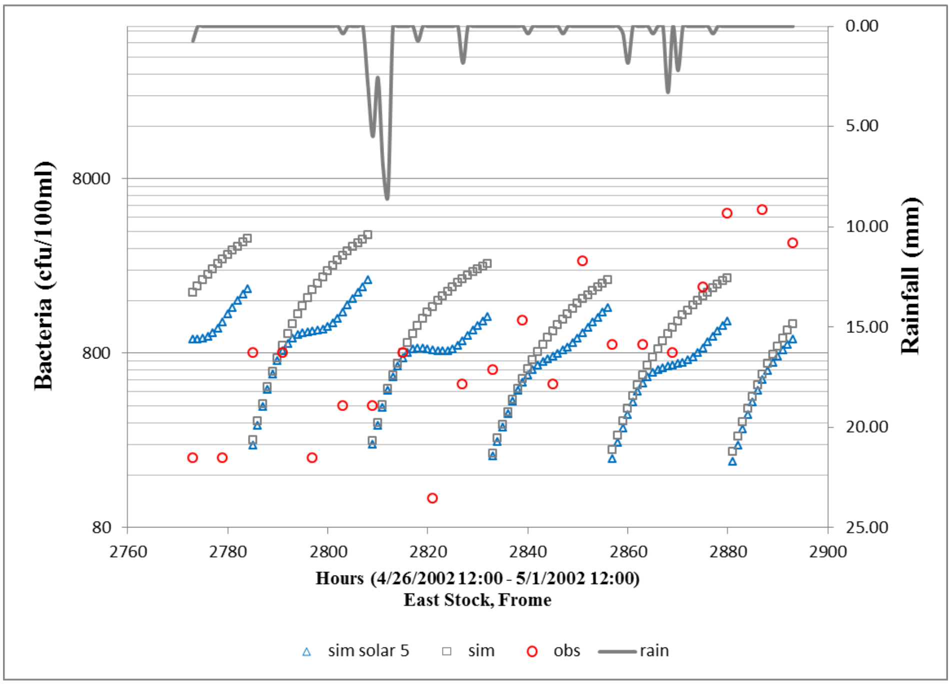


Figure 5-15 (b) Comparison of bacteria concentration with and without solar radiation influence (LDLPRCH = 5), River Frome

Figure 5-15 (b) shows better model prediction that begins to be influenced with dynamic decay, when compared with baseline SWAT model results. The prediction is visually more dynamic and indicates that simulation is associated with solar radiation variation. This plot has shown better consistency with observed values.

(c) Solar Radiation Effects Activated (Bacteria Solar Radiation Adjustment Coefficient, LDLPRCH = 15)

This storm event validation (when LDLPRCH equal to 15) is shown in Figure 5-15 (c). Even though, the modified model prediction did not pick up the high value of observations (between hrs 2840 and hrs 2900).

To points out a significant improvement in sub-daily bacteria simulations over 140 hours. Between hour 2760 and hour 2840, the model captured the high-level bacteria which are 800 cfu per 100ml, and also it predicted the low bacteria level that is 100 cfu per100ml. Between hour 2840 and hour 2900, the model underestimated the prediction. However, there is a consistency of diurnal trend with peaks and lows of bacteria prediction. This under-estimation of bacteria could be attributed to possible over-estimation of hourly flow between hour 2860 and hour 2900.

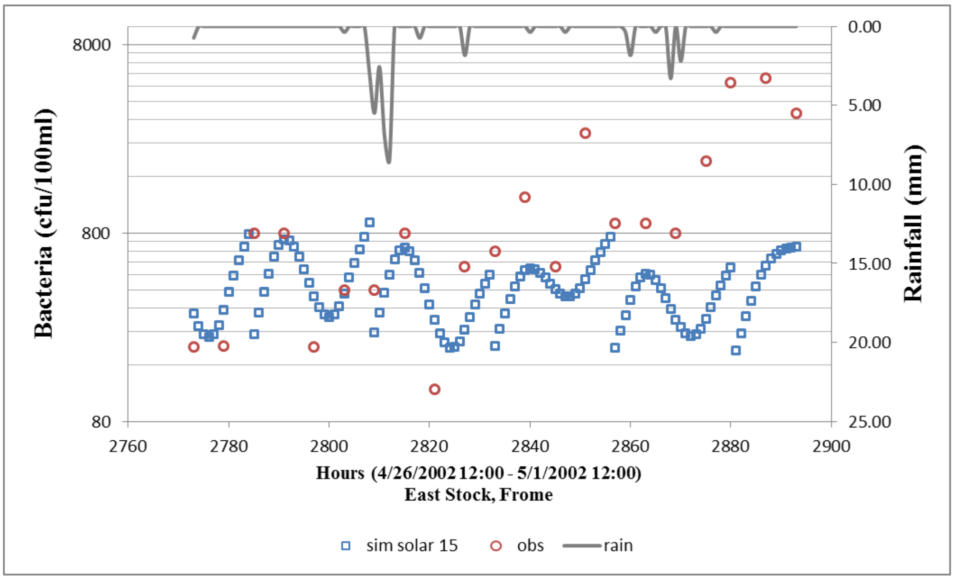


Figure 5-15 (c) Storm Event Validation with Solar Radiation Activate, (LDLPRCH = 15), River Frome

5.4.6 Bacteria Sub model Performance

The modified SWAT model is giving adequate bacteria output with relatively good accuracy as shown in Table 5-18. (Tang, McDonald et al. 2011) modelled daily pathogen Cryptospordium parvum in a small agricultural catchment with a result of, R2 from 0.20 to 0.37,$P<0.05$; with poor NSE -0.37 to -2.57. The results in (Cho, Pachepsky et al. 2012) showed the NSE of flow is between 0.53 and 0.57, the RMSE 10^2 of fecal coliform between 1.15 and 0.86 cfu, and RMSE $10^2$of sediment between 2.50 and 3.08. (Coffey, Cummins et al. 2010) simulated the E. coli has acceptable results, with R2 = 0.68 and NSE = 0.59. However, the calibration only used around 12 observed bacteria recording. Therefore, by comparing with previous studies the model performance in bacteria simulation is acceptable and satisfactory

Table 5-18 SWAT Bacteria Model Performance

Calibration Condition	R2	RMSE (10^2)	Mean (cfu/100ml)
Bacteria at Piddle **(Daily calibration 2005 - 2006)**	0.61	7.74 cfu	Sim/Obs 1080/902.83
Bacteria at Frome **(Daily calibration 2005 - 2006)**	0.17	10.48 cfu	Sim/Obs 632/1031.33
Sediment at Frome **(Daily calibration 2005 -2006)**	N/A	1.06 mg/l	Sim/Obs 24.21/23.48 (mg/l)
Bacteria at Piddle **(Hourly validation in 2002)**	0.13	4.48 cfu	Sim/Obs 536/528
Bacteria at Frome **(Hourly validation in 2002)**	0.21	2.29 cfu (for first 10 hours' period);17 cfu (for all)	Sim/Obs 397/1604

However, nevertheless there is potential to further improve the bacteria sub model. To lower down as much as uncertainty of the model, the following aspects are recommended to be considered,

(1) Current manure spreading rate is an estimation based on the livestock census data from three local counties. The application timing is based on the types of crops that grow in the catchment, and the recommended best manure application window suggested by (ADAS 2001; DEFRA 2010). Thus, recorded information of the timing and amount of manure spread from local county or farms is believed to help rebuild a more realistic of bacteria input in the model.

(2) Due to there is limited bacteria data for calibration, the result is satisfactory. However, the model could be further improved by taking into account of the effects from groundwater induced in-stream sediment associated bacteria re-suspension suggested by (Cho, Pachepsky et al. 2016).

(3) Modified SWAT shows that sediment related bacteria form the basis of bacteria concentration, and the rainfall events cause the peaks of bacteria concentration. Therefore, to get sediment yield more accurate would help to improve the accuracy. Moreover, hourly flow output also has influences to sub daily bacteria concentration. And they are related inversely in the equations. In the thesis, storm events bacteria output has been discontinued around every 24 hours (Figure 5-15), this could be attributed to the sudden changes of hourly flow output every 24 hours as shown in Figure 4-16. Therefore, getting realistic flow output would also improve the in-stream bacteria simulation. The hourly flow algorithms could be improved and modified as mentioned in Section 4.5.

5.5 Summary

Firstly, SWAT bacteria sub-model has been modified to include a dynamic die-off algorithm, with influences from sediment re-suspension, deposition, and solar radiation, which uses Green & Ampt infiltration method and outputting every hour. Modified SWAT model predicts bacteria levels in the rivers with higher accuracy. Sediment related bacteria contribute to low to medium concentrations of coliform bacteria that model yields. The agricultural activities together with rainfall events resulted high and peaks of bacteria concentrations in studied rivers as shown in Figure 5-13.

Secondly, bacteria model calibration has performed well when compared with a number of past studies modelled with SWAT as mentioned in Section 5.4.6. The R2 of calibration is 0.61, which implies the model performance is adequate, given that there is a lack of observed bacteria data for calibration.

Thirdly, the modified SWAT model shows there is a significant improvement to sub-daily bacteria modelling with diurnal variation. In particular, sub-daily events were selected for model validation. The new algorithm has been proved to work well and coincide with hypothesis that bacteria varies dynamically with solar radiation during 24 hours.

Fourthly, the agricultural livestock cause bacterial contaminations of land and water body via animal direct faecal deposit and manure spreading for growing crops. There is a potential to refine the spatial bacteria inputs, such as more information on grazing and manure spreading (Coffey, Cummins et al. 2007; Coffey, Cummins et al. 2010; Coffey, Cummins et al. 2010; Coffey, Cummins et al. 2010).

Chapter 6

Future Scenarios and Analysis

Key words:

Climate Change

High Frequency Intensive Rainfall

Intensive Farming

Bacteria Climate Change Projection

6.1 Introduction

Chapter 6 conducted future scenario analysis. Model predictions at two sites at West Mill, river Piddle and East Stoke, river Frome are selected for comparisons. Future scenarios could be classified as two sections, that the first part is assessing impact of more server intensive rainfall, where the second part is to find the influences of more intensive farming.

It is estimated there would be more intensive rainfall all year around in the UK due to high to medium greenhouse gas emission. For example, the heavy rain dropped 50 mm within a 90 minutes’ storm in Newcastle upon Tyne, which is attributed to Toon Monsoon in 28 June 2012. Such intensive rainfall is projected to be more frequent. Climate change impacts are classified into two climate change conditions with medium to high intensity. Climate change condition 1 includes five storm events which exceeds 28mm/hr and 10mm/hr, respectively. Climate change condition 2 has 9 storm events that exceed 28mm/hr and 10mm/hr respectively. Intensive farming is also classified into two subsequent conditions; the first condition is projected to have an increased number of livestock animals by 33.3%, whereas the second condition is projected to have two mega dairy farms operating in sub-basins 7 and 10. A comprehensive budget study of hour rainfall between 1999 and 2005 is summarized. The focused statistics are annual mean rain (hourly), seasonal max rain (hour), as well as the return period of max rainfall (annual and seasonal).

6.2 Baseline Weather in Frome and Piddle

Frome and Piddle catchment have one rain gauge that measures hourly. It is a BADC gauging station at Bournemouth airport. A total of eight years continuous (1999-2006) hourly rainfall data are analysis with focuses in rainfall intensity and its frequency. This aims to find annual and seasonal features to answer the question how frequent the intensive rainfall downpours are and how long the wet and dry period are in the Frome and Piddle area. It is showed in Table 6-1 that the mean percentage of total dry days during a year is around 89.6%. The driest year was 2006, with 91.67% dry period. The wettest year was 2000, with 87.02% dry period. Dry period in summer has a mean of 90.65% which is higher compare with dry period in winter 86.97%. There is a general increasing trend of dry days. Rainfall intensity has four criteria which are (1), rainfall less than 1mm per hour (0<rainfall<1mm), and classified as small rain; (2), rainfall less than 2.45mm per hour but higher than 1mm per hour (1mm<rain<2.45mm), which is classified as medium rain; (3), rainfall less than 10mm per hour but higher than 2.45mm/hour (2.45mm<rainfall<10mm) it is classified as heavy rainfall; and (4), rain higher than 10mm per hour (rainfall>10mm), which is classified as severe heavy rain. Small rainfall has the dominant occurrence. Average total length with small rainfall is around 650 hours each year, where winter has 184 hours and summer have 87.5 hours; Medium rain (1mm<rainfall<2.45mm) falls around 198 hours in total per year, with an average 27 hours in the summer and 62 hours in winter; Heavy rain (2.45mm<rainfall<10mm; mm/hr) occurs 91 times a year, with summer 14 times and winter 33 times on average. Extreme heavy rain is very rare during the eight years' period. The average annual frequency is less than 3 times. Autumn and summer occurs 0.88 and 1.13

times on average each year. However, even though the frequency is low, some of the rain is strong and flashy.

For example, the rainfall poured a total of 60 mm during 24 hours in 7 October 2001, particularly with single hour rainfall intensity leap to 35.2mm/hr at 3pm on that day. This extreme heavy rainfall would no doubted cause local or regional flash flooding with Environment Agency amber warning. Similar event also happened in 10th of February 2006 with hourly rainfall downpours of 23.5 mm of rain water.

Table 6-1 Statistics of Frome and Piddle Rainfall Intensity and Frequency

	Annual dry (%) (rain = 0 mm/hr)	**Summer dry** (%) (rain = 0 mm/hr)	**Winter dry** (%) (rain = 0 mm/hr)	**Annual** 0<rain<1 (mm/hr)	**Summer** 0<rain<1 (mm/hr)	**Winter** 0<rain<1 (mm/hr)	**Annual** 1<rain<2.45 (mm/hr)	**Summer** 1<rain<2.45 (mm/hr)	**Winter** 1<rain<2.45 (mm/hr)
1999	90.01	93.80	87.13	562	91	142	201	25	74
2000	87.02	95.15	81.20	765	70	280	250	25	99
2001	89.44	94.61	85.28	637	78	181	205	26	79
2002	87.12	91.35	87.36	723	133	199	267	38	46
2003	91.06	94.16	87.41	544	82	166	152	31	54
2004	89.43	92.44	91.30	636	106	193	190	30	38
2005	91.35	93.75	92.13	525	97	142	156	27	41
2006	91.67	96.88	83.94	453	43	173	166	16	65
Mean	**89.64**	**94.02**	**86.97**	**605.63**	**87.50**	**184.50**	**198.38**	**27.25**	**62.00**

	Annual 2.45<rain<10 (mm/hr)	Summer 2.45<rain<10 (mm/hr)	Autumn 2.45<rain<10 (mm/hr)	Winter 2.45<rain<10 (mm/hr)	Annual 10<rain (mm/hr)	Spring 10<rain (mm/hr)	Summer 10<rain (mm/hr)	Autumn 10<rain (mm/hr)	Winter 10<rain (mm/hr)
1999	96.00	20	29	30	3	0	1	2	0
2000	113.00	10	58	41	1	0	0	1	0
2001	76.00	13	22	22	3	0	2	1	0
2002	123.00	19	48	32	2	0	0	2	2
2003	77.00	14	20	34	4	1	1	0	0
2004	87.00	22	24	10	1	0	1	0	0
2005	66.00	10	27	21	2	0	1	1	0
2006	97.00	8	36	31	4	0	1	2	1
Mean	**91.88**	**14.50**	**33.00**	**27.63**	**2.50**	**0.13**	**0.88**	**1.13**	**0.38**

Return Period Analysis

Return period of hourly rainfall at 100 years, 50 years and 30 years in Frome and Piddle catchment has been summarized in Table 6-2. Return period analysis are carried out based on 8-years hourly precipitation records due to limited hourly precipitation data. Gumbel distribution analysis is used to determine the return period. For example, autumn (September to November) is the time that has more extreme heavy rains as shown in Table 6-1. 100-years return period is as high as 46 mm per hour. Return period provide a guideline for setting future intensive rainfall conditions for projected climate change conditions.

Table 6-2 Annual and Seasonal Peak Rainfall (hourly) Return Period

Return Period	Annual Max (mm)	Spring Max (mm)	Summer Max (mm)	Autumn Max (mm)	Winter Max (mm)
100 y	40.77	13.62	20.14	46.89	14.27
50 y	36.59	12.49	18.59	41.41	13.30
30 y	33.49	11.65	17.45	37.35	12.57

6.3 Future Projection

One of the objectives in this study is to find the impact of agricultural livestock and climate change to the catchment river flow and bacteria level in rivers. The study set up the projections to evaluate the impacts of these changes in catchment and the downstream natural harbour. Poole Harbour has two bathing water sites, and many shellfish sprouting and growing sites. It is believed that these sites are sensitive to these changes. A joint Met Office and Nature and Environment Research Council (NERC) funded project CONVEX (Elizabeth J. Kendon 2014) forecasted that hourly summer rainfall would increase through innovative climatic model in meteorological research. It is estimated that there would be more frequent extreme summer rainfall in the UK, due to climate change. Meanwhile there would be drier periods in the summer season. Nevertheless, there is very little research investigated the changes or trends of extreme rainfall (hourly) due to climate change. The frontier research conducted very high resolution model (Elizabeth J. Kendon 2012; Elizabeth J. Kendon 2014) showed there would be as frequent as five times more storm events which exceed 28mm per hour compared with the UK baseline climate. However, it is also suggested that, research would require further validation for comparison with observed summer extreme rainfalls, and integrated the projected results from other similar research such as (Chan, Kendon et al. 2014; Chan, Kendon et al. 2016) to form an overall view.

Short duration convective extreme rainfall would lead to flash flooding events, such as the Boscastle flood in August 2004. It is projected that hourly rainfalls are heavier over the southern UK territory in summer compared with winter. There would be about 36% overall increase in summer rainfall and is often associated to a temperature increase of 4 to 5 degrees. It is suggested that 50% of the heavy rainfall events reach the high thresholds that are often related to flood risks. And the other half events are not risky to flooding but still very heavy. In the UK, an accumulation threshold of 30mm per hour rainfall is regarded as the event that would cause severe local or regional flash flooding by the Met Office and Environment Agency (Elizabeth J. Kendon 2014). This study also predicts a significant decrease of low flow rainfall events. In other words, there would be more droughts overall. The model also shows a significant increase of frequency of high rainfall events that exceeds 28mm per hour from 24 events to 117 events during a 13-years period. This implies that the possibility of getting an average of 9 events that exceed 28mm/hour each year in the future by 2100.

Two climate change conditions are summarized in Table 6-3, which shows the estimated changes of climate, i.e. warmer climate with a much more humid environment. The baseline precipitation is selected from the hourly rainfall in year 2002 in the Frome and Piddle catchment. Baseline rainfall has been used for validating bacteria sub-daily simulation. In Table 6-3, climate change condition 1 assumes that the medium greenhouse gas emission condition until the year 2100. According to the research (Elizabeth J. Kendon 2014) stated that there would be longer dry period between two rainfall events, which is with more intensified short duration rainfall. Half of the incremental is due to extreme heavy rainfall and the other half incremental is contributed from heavy rainfall. Therefore, the assumption projected the incremental of five severe heavy rainfall events and five heavy rainfall events in one year. By contrast, there will be significant decreases of small to medium rainfall events, which means longer dry periods. For climate change condition 2, the hypothesis is that there would be nine more extreme heavy rainfalls and nine heavy rainfall events in one year. The projection also includes a further 60% reduction of small to medium rainfall events.

Table 6-3 Summary of Climate Change Conditions 1 & 2

Climate Change Condition 1 (Apply Medium Emission Condition by 2100)	
Type of change	**Quantification of change**
Sever Heavy Rain (>=28mm/hr)	A total of 5 events that exceed 28mm/hr during the simulation period. (Spring 1 events; Summer 2 events; Autumn 0 events; Winter 2 events)
Heavy Rain (>=10mm/hr)	A total of 5 events that exceed 10mm/hr during the simulation period. (Spring 1 events; Summer 2 events; Autumn 0 events; Winter 2 events)
Medium Rain	30% less of medium rainfall events
Small Rain	30% less of small rainfall events
Dry Events	Keep baseline dry events unchanged
Climate Change Condition 2 (Apply High Emission Condition by 2100)	
Sever Heavy Rain (>=28mm/hr)	A total of 9 events that exceed 28mm/hr during the simulation period. (Spring1 events; Summer 4 events; Autumn 1 event; Winter 3 events)
Heavy Rain (>=10mm/hr)	A total of 9 events that exceed 28mm/hr during the simulation period. (Spring1 events; Summer 4 events; Autumn 1 events Winter 3 events)
Medium Rain	60% less medium rainfall events
Small Rain	60% less small rainfall events
Dry Events	Keep Baseline dry events unchanged

Table 6-4 Projection of Intensive Rainfall in Climate Change Condition 1 & 2

Season	**High Intensity (above 10mm/hour)**		**Severe High Intensity (above 28mm/hour)**	
	Date and Event Duration	Intensity (mm/hr)	Date and Event Duration	Intensity (mm/hr)
Spring	***March 10***[6]	***11.7 mm/hr***	***April 26***	***35.2 mm/hr***
Summer	June 5	12.8 mm/hr	June 27	28 mm/hr
	July 8	***13.5 mm/hr***	July 21	35.2 mm/hr
	July 9	***11.9 mm/hr***	***August 3***	***35.2 mm/hr***
	July 21	15.9 mm/hr	***August 9***	***28 mm/hr***
Autumn	***September 9***	***11.8*** **mm/hr**	October 13	35.2 mm/hr
Winter	***January 25***	***11.2 mm/hr***	***December 9***	***35.2 mm/hr***
	January 30	10.4 mm/hr	January 31	28 mm/hr
	December 25	***15.4 mm/hr***	***February 24***	***28 mm/hr***

[6] The bolded words represent the information from Climate Change Condition 1 only

6.3.1 Intensive Farming Condition 1 (IFC 1)

Intensive farming condition (IFC) is the proposed scheme in future if the size of livestock herds and corresponding manure spreading gets further increased. These changes may be due to the higher demand of food attributed from population boost by 2087. It is estimated that the future population is likely to reach 86.5 million in England and Wales, which is a 33.3% increased compare with the current population of 64.9 million in 2015. It is estimated that the quantity of livestock for agriculture would increase. In this study, assume the livestock would grow by 33.3% and corresponding to crops demands which would also increase by 33.3% by 2087. Thus, consequently, in SWAT model, the livestock manure deposited to grass land due to grazing would increase by 33.3%, and the same incremental rate for stored manure fertilizer spreading.

6.3.2 Intensive Farming Condition 2 (IFC 2)

Intensive farming condition 2 assumes a further expansion of the number of farmed livestock. It is proposed that the livestock growth remains the same as IFC (condition 1) i.e. an increase by 33% with crop yield increase by 33% proportionally. Apart from these change, IFC condition 2 aims to find the impact of two mega dairy farms (MDF), each can house 5,000 cattle. Proposed two MDFs are setup as point bacteria inputs established in rivers Frome and Piddle, where one MDF is located in sub-basin 7 and one in sub-basin 10. The impacts of mega dairy farms are assumed as significant. All the cattle are housed in the dairy farm 24 hours a day, seven days a week. An assumption would be made for an additional $2.34 * 10^8$ kg of manure stored during a year's in-house period from two mega dairy farms. It was assumed that 80% of the manure and slurry stored is used for crop and grassland fertilizer to supply sub-basins 7 &10 only. Through calculation, it is equivalent to 5,880 kg/ha of additional manure to be spread to sub-basins 7, 8, 9 and 10, or as much as 32,600 kg/ha of more manure spread to sub-basins 7 and 10 only. Both hypotheses in IFC conditions 1 and 2, assume that there are no other techniques to utilise additional manure produced from mega diary. The model does not consider the likely dirty water or slurry leaking to the rivers directly that would cause more bacteria contamination to connected water bodies. Further study in more detailed dirty water leaking modelling from mega dairy farms could be conducted in farm size model SWAT-APEX (Gassman, Williams et al. 2010). Regarding IFC condition 2, the average high manure quantity produced is 19,240 kg/ha that applies to sub-basins 7, 8, 9 and 10. Future scenarios have 6 different combinations in association with climate change and intensive farming change. Table 6-4 shows that two intensive farming conditions were investigated as individual scenarios with no climate influences. Furthermore, two climate change conditions are proposed in combination with intensive farming conditions.

6.4 Future Scenario Prediction

6.4.1 Future Projection of In-Stream Faecal Bacteria

Future scenarios projected the changes of in-stream bacteria concentration due to intensive farming and climate change conditions. Table 6-6 and Table 6-7 summarized how the model response to these changes. It is also worthy to notice that at West Mill in river Piddle, and East Stock in river Frome, there are different model responses. There is a significant response in bacteria prediction at West Mill, river Piddle as shown in Table 6-6. The annual means from six scenarios are classified into three groups which predictions of 1.4k cfu/100ml, 1.6k cfu/100ml and 2.8k cfu/100ml respectively. The maximum bacteria concentration increase from scenario 1 to scenario 6 as shown in Table 6-6. The peak value found in scenario 6 shows a significant increase of 720% when compared with the baseline peak. This actual peak concentration is at $6.41*10^5$ cfu/100ml. The low level of bacteria decreases in all six future scenarios. The lowest occurs in scenario 2 with a value of 63 cfu/100ml. In addition, the standard deviation has been increasing through all six scenarios, which means there will be more variations in the future. This might be attributed to intensive rainfall causing flash flooding during short periods, and with prolonged drought period. Therefore, these changes cause higher peaks and the lows to be lower. However, bacteria concentration in river Frome does not response as expected with climate change and intensive farming. It shows that the annual mean value of three intensive farming conditions under climate change condition 1 keeps the same. This implies the model predicts bacteria concentration is not sensitive to intensive farming with climate change condition 1. However, there is a gradual increase of mean, standard deviation and peak with all three farming conditions under climate change condition 2. This indicates model prediction of bacteria concentration has a proportional increase with more frequent intensive rainfalls and farming conditions. In other words, it was found that the bacteria concentration at East Stock in river Frome is associated with an increase in catchment farming intensity, only when there is more frequent heavy rainfall. The maximum prediction occurs in scenario 6 with a value of $4.3*10^4$ cfu/100ml.

Table 6-5 Future Scenarios Arrangements

Scenarios	**Arrangement**
Scenario 1	Current IFC plus CCC1
Scenario 2	Current IFC plus CCC2
Scenario 3	IFC1 plus CCC1
Scenario 4	IFC1 plus CCC2
Scenario 5	IFC2 plus CCC1
Scenario 6	IFC2 plus CCC2

Note: (IFC) represents Intensive Farming Condition; (CCC) represents Climate Change Condition

Table 6-6 Statistics of Future Scenario Projections of Bacteria in River Piddle, West Mill

Scenarios	Baseline	1	2	3	4	5	6
Statistics	**IFC + CCC**	**IFC + CCC1**	**IFC + CCC 2**	**IFC 1 + CCC1**	**IFC 1 + CCC2**	**IFC 2 + CCC1**	**IFC 2 + CCC2**
MEAN(cfu/100ml)	2,184	1,479	1,407	1,681	1,627	2,823	2,879
SD (cfu/100ml)	3,358	4,720	5,484	6,061	7,066	14,100	16,503
Max (cfu/100ml)	78,192	180,580	208,330	235,460	270,070	544,310	641,070
Min (cfu/100ml)	126	80	63	80	64	80	64
Mean Change (%)	-	-32	-36	-23	-26	+29	+32
SD Change (%)	-	+41	+63	+80	+110	+320	+391
Max Change (%)	-	+131	+166	+201	+245	+596	+720
Min Change (%)	-	-36	-50	-36	-50	-36	-49

Table 6-7 Statistics of Future Scenario Projections of Bacteria in River Frome, East Stock

Scenarios	**Baseline**	**1**	**2**	**3**	**4**	**5**	**6**
Statistics	**IFC + CCC**	**IFC + CCC1**	**IFC + CCC2**	**IFC1 + CCC1**	**IFC1 + CCC2**	**IFC2 + CCC1**	**IFC2 + CCC2**
MEAN (cfu/100ml)	1,731	877	702	877	713	877	782
SD (cfu/100ml)	2,516	1,065	1,018	1,065	1,086	1,065	1,697
Max (cfu/100ml)	21,657	10,503	14,043	10,503	18,222	10,502	43,259
Min (cfu/100ml)	47	29	23	29	23	29	23
Mean Change (%)	-	-49	-59	-49	-59	-49	-55
SD Change (%)	-	-58	-60	-58	-57	-58	-33
Max Change (%)	-	-52	-35	-52	-16	-52	+100
Min Change	-	-38	-51	-38	-51	-38	-51

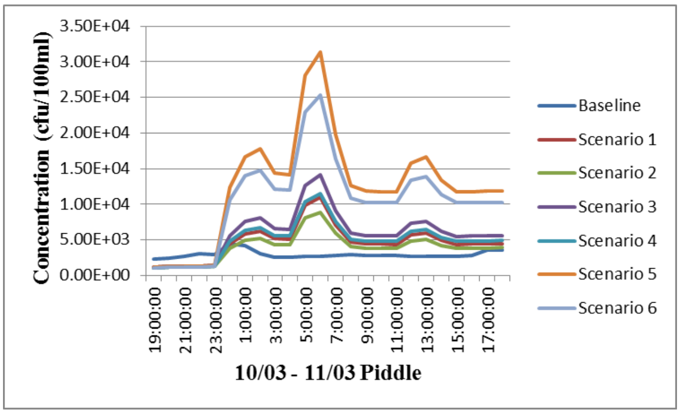
6.4.2 Future Projection of in-stream Faecal Bacteria

Projected bacteria level at two locations are analysed on occurrences frequency. The baseline prediction is compared with other six future projections. The peak is between 10^5 and $7 * 10^5$ cfu/100ml. Overall, river Piddle is more sensitive to the future changes that yield more peak bacteria concentrations, even though the peaks only represent between 0.02% and 0.42% of all prediction in Frome, and between 0.06% and 4.33% of all prediction at Piddle. Low to medium prediction ranged from 10^2 to 10^4 cfu/100ml with significant variations. Medium bacteria level weight about 55.3% of all prediction, the low bacteria concentration weight about 42.6% of all prediction, in baseline condition at Piddle. However, medium concentration with climate change condition 1 is between 32.8% and 36.2%, which indicated an overall decline of medium range prediction is around 20% from future conditions at Piddle. The low concentration with climate change condition 2 is between 70.9% and 76.9% for all future conditions, with an overall increase of around 30%. Due to bacteria concentration is not sensitive to future projection at Frome, the low to medium bacteria predictions at Frome do not vary as significantly as it is at Piddle. However, there is a consistent change that medium concentration is shifted to low and very low concentration. The medium bacteria level has declined from baseline 39.2% to between 15% and 24.4% from future scenarios. In addition, the low bacteria level has increased from 58.7% to around 80% in future predictions.

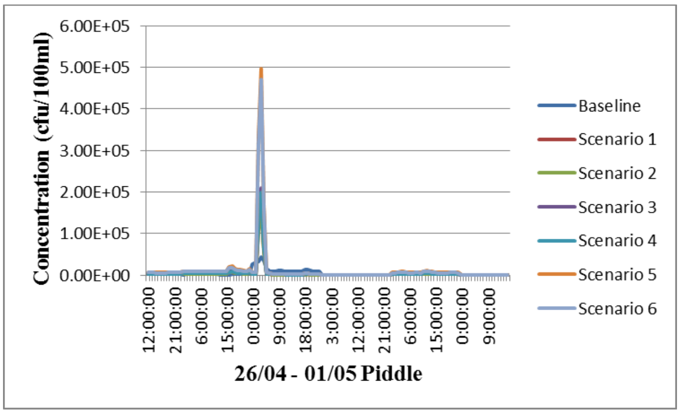
6.4.3 Storm Event Projection and Analysis

Selected bacteria projection in spring is shown in Figure 6-1. The prediction of future scenarios has a consistent trend during two storm events. The peak concentration is $3.0*10^4$ cfu/100ml and $5.0*10^5$ cfu/100ml in two storm events respectively that occurred with scenarios 5.

Storm events in spring (March - May)



(a) Bacteria concentration with Scenarios 1-6 (10/03 - 11/03 at Piddle)

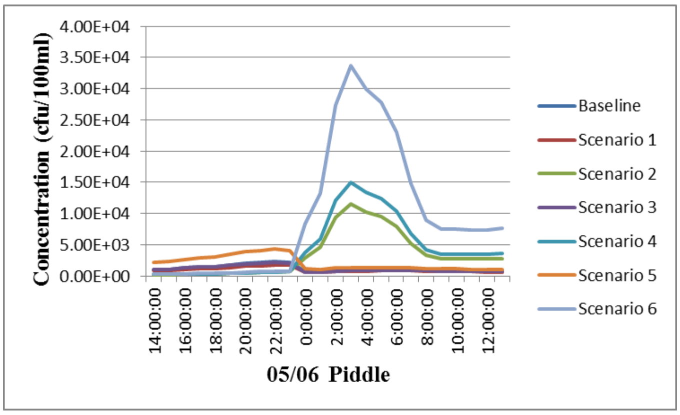


(b) Bacteria concentration with Scenarios 1-6 (26/04 - 01/05 at Piddle)

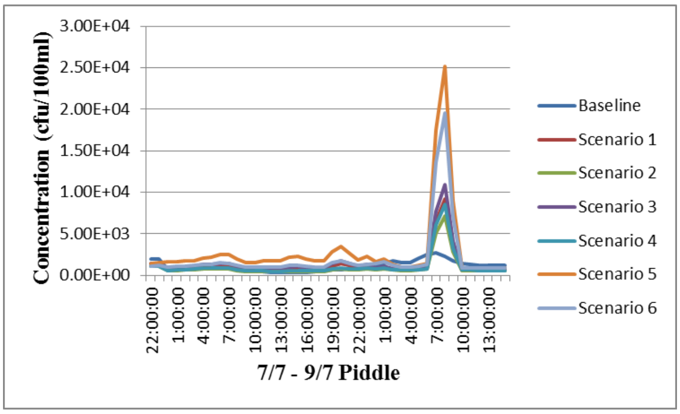
Figure 6-1 Projection of Bacteria Concentration in Spring at Piddle

Storm event in summer (June - August)

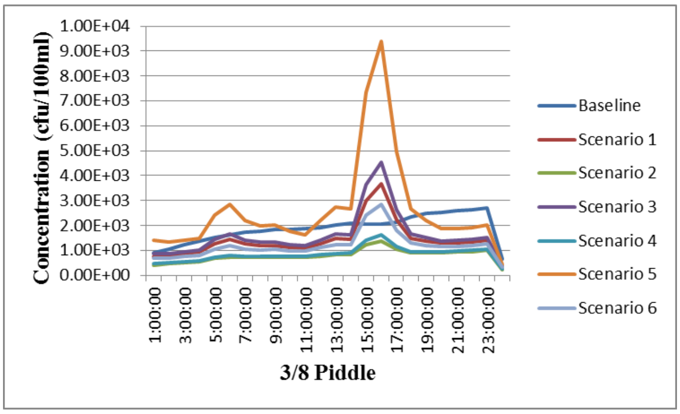
Figure 6-2 shows three selected storm events in summer with future projections. The peak values occurred at 9.0* 10^3 cfu/100ml in August with scenario 5, at 2.5*10^4cfu/100ml in July with scenario 5, and at 3.0*10^4cfu/100ml in June with scenario 6.



(a) Bacteria concentration with Scenarios 1-6 (05/June at Piddle)



(b) Bacteria concentration with Scenarios 1-6 (7/July - 9/July at Piddle)

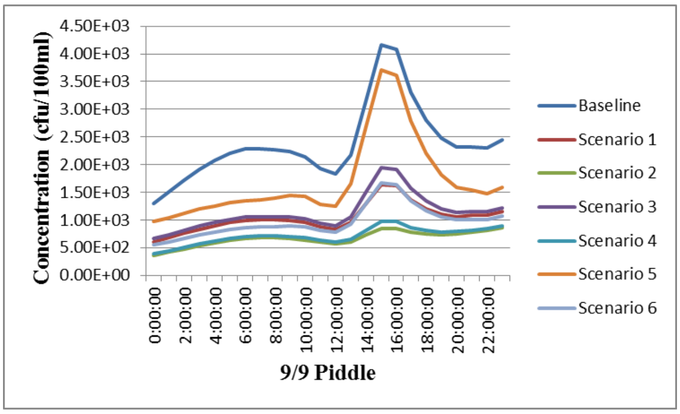


(c) Bacteria concentration with Scenarios 1-6 (3/August at Piddle)

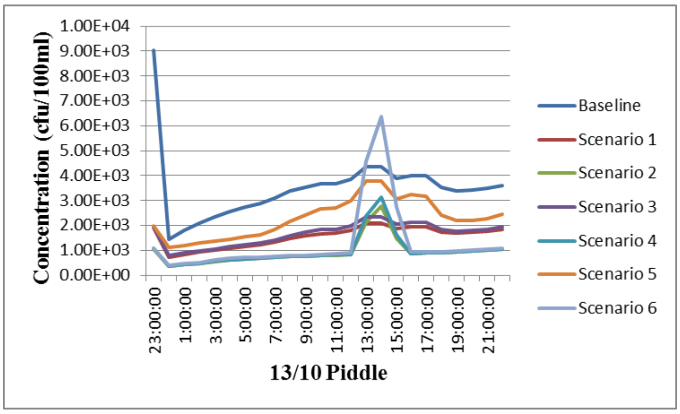
Figure 6-2 Projection of Bacteria Concentration in Summer at Piddle

Storm events in autumn (September - November)

Projection for two storm events in autumn does not have a consistent trend. The projected peak value is picked up by scenario 6. However, projected changes are not significant compared with baseline condition. Figure 6-3 (a) also show that no future projection is higher than the baseline condition. This is the opposite of the expected results in autumn. This could be attributed to that the increases of bacteria concentration is much less than the quantity of the runoff in autumn, so that the concentration decrease as flow increase.



(a) Bacteria Concentration with Scenarios 1-6 (9th/September at Piddle)

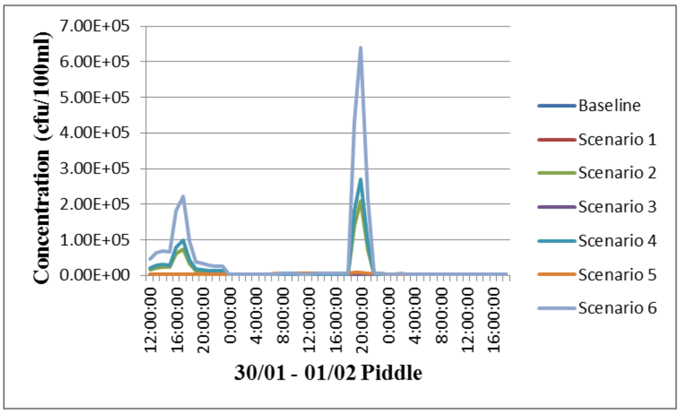


(b) Bacteria Concentration with Scenarios 1-6 (13th/October at Piddle)

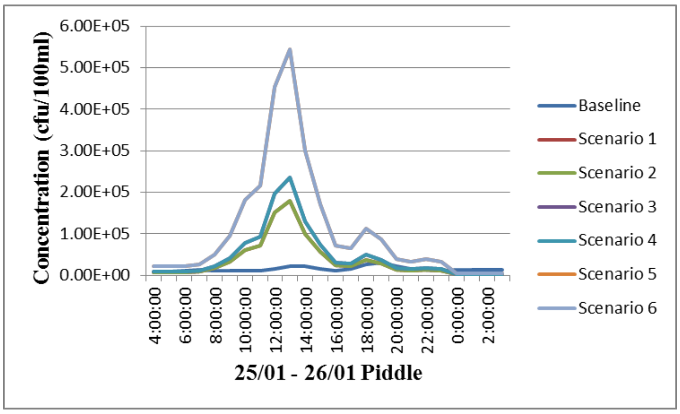
Figure 6-3 Projection of Bacteria Concentration in Autumn at Piddle

Figure 6-4 shows there is a significant increase of bacteria concentrations due to flash storms of a three-day event between 30/January and 01/February in 2002. The peak rocketed to $6 * 10^5$cfu/100ml, which occurred at 20:00 pm in 31 January (scenario 6). Scenarios 5 and 6 simulated the peak values, while scenarios 2 & 4 outputted the lower peaks around $2 * 10^5$cfu/100ml.

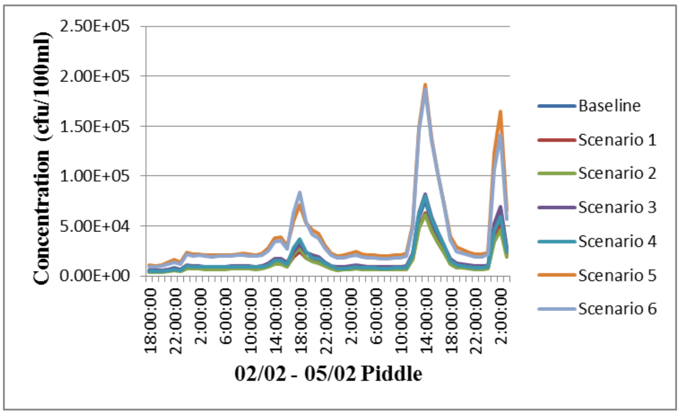
Storm events in winter (December - February)



(a) Bacteria Concentration with Scenarios 1-6 (30/Jan - 01/Feb at Piddle)



(b) Bacteria concentration with Scenarios 1-6 (25/Jan - 26/Jan at Piddle)



(c) Bacteria concentration with Scenarios 1-6 (02/Feb - 05/Feb at Piddle)

Figure 6-4 Projection of Bacteria Concentration in Winter at Piddle

6.5 Summary

This chapter shows the work conducted to find the impact of climate change with particular focuses in intensive rainfall, as well as intensive farming to bacteria concentrations in the rivers Frome and Piddle. The baseline weather condition with high resolution hourly rainfall was studied with statistics such as mean and standard deviation and peak and low values. Return periods of mean and extreme rainfall suggested that there would have harsher weather conditions in the future. Scenarios 4, 5 and 6 are found to be sensible in predicting peak values due to climate change and farming in winter, summer and spring. There is an unclear future trend and behaviour in the projection in autumn.

Chapter 7

Modelling Faecal Bacteria in Poole Harbour

Key Words:

Hydrodynamics

SWAT - DIVAST Coupling

Estuary Faecal Coliform Bacteria Modelling

7.1 Introduction

Poole Harbour and Holes Bay is a natural coastal basin which located on the south coast of England, near Bournemouth. The harbour has a narrow entrance that link the inner area to Poole bay and English Channel. One of the previous applications of DIVAST (Falconer 1986; Falconer 1993) investigated the influence of nitrogen discharge from Poole Waste Water Treatment Plant across the harbour. This study set up the basis of faecal coliform modelling in Poole Harbour in this study. This thesis aims to find the impact of climate change and intensive farming to the estuary in Poole Harbour with the connected rivers and catchment. Chapter 5 modelled the faecal coliform in river Frome and Piddle, and Chapter 6 projected the faecal coliform with future scenarios. These results derive the inputs of faecal bacteria modelling in Poole Harbour.

Figure 7-1 Poole Harbour from Poole (captured from police helicopter in 2013)

This chapter has three parts. The first part Section 7.2 describes the governing equations of hydrodynamic and water quality module of the models. The second part of Section 7.3 describes the method of how the coupled model DIVAST-SWAT works. It includes the method of linking two models with regard to data input and output (I/O). The third part of Section 7.4, describes the results of simulation of scenario 5 of a 72-hour storm events (between 7 July and 9 July) in the summer in 2002. Simulated faecal coliforms from scenario 5 are compared with baseline condition and modified base flow condition from scenario 5. Such comparisons are used to test the responses of faecal coliform concentrations in Poole Harbour during varied climate change and intensive farming conditions with particular focus on high flow and base flow effects.

7.2 Governing Equations of DIVAST Model

7.2.1 SWAT-DIVAST Coupling

Poole Harbour and Holes Bay is a natural coastal basin located on the south coast of Dorset, UK. The model modification and refinement has been applied to predict the water elevations, the depth average velocity and nitrates and bacteria. Particularly, the model is refined to couple with the upstream catchment model SWAT, to use the output from the watershed model as model inputs for DIVAST. So that DIVAST can predict the water elevation, velocity and water quality with the impact of upstream land use and in stream changes. In addition, the models also include the impacts from the major sewerage treatment plants in the surrounding area. Historically, surface water and coastal water models have been developed separately as two individual entities. The interaction between them is usually considered as a boundary condition in estuary and coastal modelling, while it is ignored in surface modelling. However, there are many water resources and water quality problems that require a more realistic linkage between surface runoff and coastal water. Understanding how surface water quantity and quality are related to adjacent estuary systems is important. For example, for the management of bathing water and shellfish water with impacts from the upstream catchment. There have been many models that attempt to simulate the interactions between surface runoff and estuary coastal water. In this study, a 2-D depth integrated velocity and solute transport (DIVAST) is employed in this study to simulate hydrodynamics and water quality in estuarine waters. This model is now been extended to link with SWAT to simulate the holistic water quantity and water quality from surface water to estuary water. The numerical scheme uses finite difference method with orthogonal grids. The momentum and mass conservation equations are the governing equations for estuary water flow and water quality.

7.2.2 Governing Equation for Hydrodynamic Processes

The model DIVAST is a depth integrated numerical model, developed in Hydro-environment Research Centre at Cardiff University, for simulating hydrodynamics, solute and sediment transport processes in estuarine and coastal waters (Falconer, Harris et al. 2001; Kashefipour, Lin et al. 2002). Hydrodynamic module of the DIVAST is based on the solution of the depth integrated Navier-Stoke equations and includes the effects of location acceleration, advective acceleration, earth's rotation, pressure gradient, wind stress, bed resistance and turbulent share force. A quadratic friction law is used to represent the surface wind stress (Kashefipour, Lin et al. 2006). In the hydrodynamic module of this numerical model, the water elevations, and depth averaged velocities in the x and y directions are determined by solving the depth integrated Navier-Stocks equations, through an Alternative Direction Implicit (ADI) scheme. The water quality module solves Advective Diffusion Equation (ADE) to predict a range of water quality parameters including total and faecal coliforms, salinity, biochemical oxygen demand, dissolved oxygen, the nitrogen and phosphorous cycles and algal growth. The ADE defines the hydrodynamic distributions of the bacterial indicators due to the flow characteristics, diffusion processes and die-off rates with the two dimensional depth integrated form of the equation developed by (Falconer 1991).

Conservation of Mass

$$\frac{\partial n}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = q_m \tag{6.1}$$

Conservation of momentum

$$\frac{\partial p}{\partial t} + \frac{\partial \beta p U}{\partial x} + \frac{\partial \beta p V}{\partial y} = fq - gH\frac{\partial \eta}{\partial x} + \frac{\rho_a}{\rho} C_w W_x \sqrt{W_x^2 + W_y^2} - \frac{gp\sqrt{p^2+q^2}}{H^2C^2} + \varepsilon\left[2\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 q}{\partial x \partial y}\right] - C_d m D \frac{p\sqrt{p^2+q^2}}{H} \tag{6.2}$$

$$\frac{\partial p}{\partial t} + \frac{\partial \beta p U}{\partial x} + \frac{\partial \beta p V}{\partial y} = fq - gH\frac{\partial \eta}{\partial y} + \frac{\rho_a}{\rho} C_w W_y \sqrt{W_x^2 + W_y^2} - \frac{gp\sqrt{p^2+q^2}}{H^2C^2} + \varepsilon\left[\frac{\partial^2 q}{\partial x^2} + 2\frac{\partial^2 q}{\partial y^2} + \frac{\partial^2 p}{\partial x \partial y}\right] - C_d m D \frac{q\sqrt{p^2+q^2}}{H} \tag{6.3}$$

where,

p (=UH), q(=VH) discharge per unit width in the x and y directions respectively (m^3/s/m);

q_m source discharge per unit horizontal area (m^3/s/m);

U,V depth average velocity components in the x and y directions respectively (m/s);

β momentum correction factor for a non-uniform vertical velocity profile;

f coriolis parameter due to the Earth's rotation (=2ω Sinϕ, with ω = latitude; ω = 2 π/(24x3600) = 7.27 x 10^{-5} radians/s);

g gravitational acceleration (=9.806 m/s^2)

H total water depth = $\eta + h$;

η water surface elevation above datum;

h water depth below datum;

ρ_a density of air (= 1.292 kg/m^3)

ρ density of fluid (kg/m^3)

C Chezy roughness coefficient ($m^{\frac{1}{2}}/s$)

C_w air / fluid resistance coefficient (assumed to be 2.6 x 10^{-3}[5])

ε depth averaged turbulent eddy viscosity (m^2/s)

C_d vegetation drag coefficient

m vegetation density

D vegetation diameter

x, y coordinates (m)

Governing Equations for Solute Transport Processes

$$\frac{\partial HS}{\partial t} + \frac{\partial HUS}{\partial x} + \frac{\partial HVS}{\partial y} = \frac{\partial}{\partial x}\left[D_{xx}H\frac{\partial S}{\partial x} + D_{xy}H\frac{\partial S}{\partial y}\right] + \frac{\partial}{\partial y}\left[D_{yx}H\frac{\partial S}{\partial x} + D_{yy}H\frac{\partial S}{\partial y}\right] + \Phi_s \qquad (6.4)$$

S = depth averaged solute concentration (unit/volume) or temperature C

$D_{xx}, D_{xy}, D_{yx}, D_{yy}$ = depth averaged dispersion-diffusion coefficients in the x and y directions respectively (m^2/s), which were shown (Holly 1984; Preston 1985) to be of the following form,

$$D_{xx} = \frac{(k_l p^2 + k_t q^2)\sqrt{g}}{C\sqrt{p^2+q^2}} = \frac{(\alpha U^2 + \beta V^2)H\sqrt{g}}{C\sqrt{U^2+V^2}} \qquad (6.5)$$

$$D_{yx} = D_{yx} = \frac{(k_l - k_t)pq\sqrt{g}}{C\sqrt{p^2+q^2}} \qquad (6.6)$$

$$D_{yx} = D_{yx} = \frac{(k_l - k_t)pq\sqrt{g}}{C\sqrt{p^2+q^2}} \qquad (6.7)$$

k_l and k_t are the depth averaged longitudinal dispersion and lateral turbulent diffusion coefficients respectively, and have values of 5.93 for k_l and 0.23 for k_t after (Elder 1959).

Faecal Coliform Bacteria Representation

$$SOURCE_{TC} = -\frac{d_t}{2} * \text{TCLK5} * [\text{TC}] \qquad (6.8)$$

TCLINT = Background TC level (data file)

TCLK5D = Decay rate for TC (data file)

DIVAST Model Setup

The computational domain was divided into 138 x 114 grid cells. A rectangular mesh of 75m × 75m was used with an overall dimension of 10.35 km × 8.55 km, i.e. 138 ×114 mesh points, covering the model domain including Poole Harbour and Holes Bay. A 3 m/s south westerly wind was assumed across the whole basin, but the variance of the water level in open sea mainly drives the flow (Liang D. 2003). The start and end time of simulation were set at 13:00 on 16th September and 23:00 on 21st September, respectively, to cover two surveyed days derived in Chapters 5 and 6. Water elevation data at the specified points were provided by the Proudman Oceanographic Laboratory, UK. The only hydrodynamic parameter for calibrating the model is bed roughness coefficient. The best fit Nikuradse equivalent roughness value of 80 mm is determined.

The output of SWAT model includes surface runoff at each river channel within sub-basin and stored in file (.rch). HRU output file summarize the output of all parameters from each HRU per sub-basin; one sub-basin can contain multiple HRUs. Sub output file summarized all the variables in each sub-basin. These three are the main outputs from SWAT. It depends on which type of data is required for the project, so that researcher could extract what they require accordingly. In this study, the model work focuses on the .rch file, which contains all variables from the river channel. From the .rch file, there are around 40 parameters mainly including flow, sediment, nutrients, bacteria, and heavy metals. There are not only the values during each time step that go into the channel, but also the output that leaves the channel. The current study, focused on the values that are leaving the channel. The temporal resolution of the output of the simulation is conducted at the daily time step. In this study, the output was written for all 10 reaches daily. Therefore, a data extraction was required to get continuous data at each reach. DIVAST requires the selected outputs from the SWAT model as its inputs. For example, such parameters are flow_out, sed_out and bactp_out which represent the flow, sediment and persistent bacteria concentrations from the reach. Apart from the output from reach, DIVAST takes into account the input from sewerage treatment plants which are the main source of point pollution. However, the STWs are not the focus of this study, the centre of the work is associated with the effects from rivers to the estuary.

7.2.3 Numerical Solution of Governing Equations

In this study, the finite difference method has been used to solve the governing differential equations described in previous section. A two-dimensional depth integrated model with a regular mesh is set up covering grids cells and modelling area. This model can be illustrated in a space staggered grid system as shown in Figure 7-2.

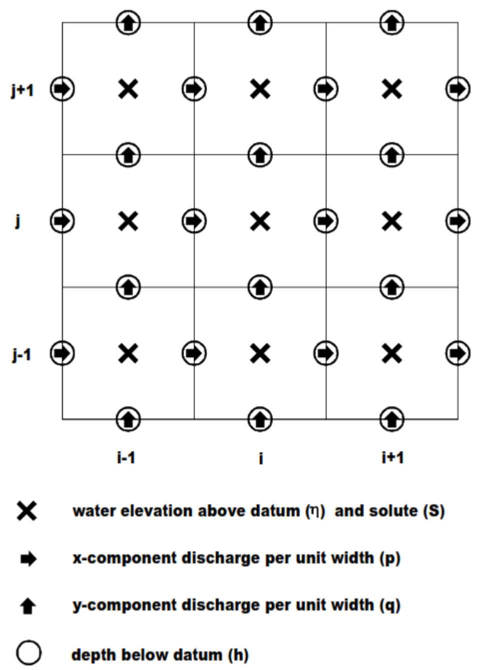


Figure 7-2 Illustration of Space Staggered Grid System (Falconer 2001)

7.3 Model Result

The results from the estuary hydrodynamic model is summarized and presented in 1D times series and 2D plots. There are a total of 7 designated water quality sensitive locations in the Harbour. Three of them are designated bathing water sites. The other four are sea food growing sites that would require high standard cleanness for food hygiene purposes.

Table 7-1 Bathing and shellfish site location in Poole DIVAST Model

Site Name	Purpose	Location in DIVAST (I,J)
Poole Harbour Lake	Bathing	(33,65)
Poole Harbour Rockley Sands	Bathing	(15,61)
Hamworthy Park	Bathing	(49,74)
Wareham Channel	Shellfish	(24,32)
Hutchins Buoy	Shellfish	(54,65)
South Deep	Shellfish	(92,57)
Salterns Marina	Shellfish	(90,103)

Baseline Water Elevation

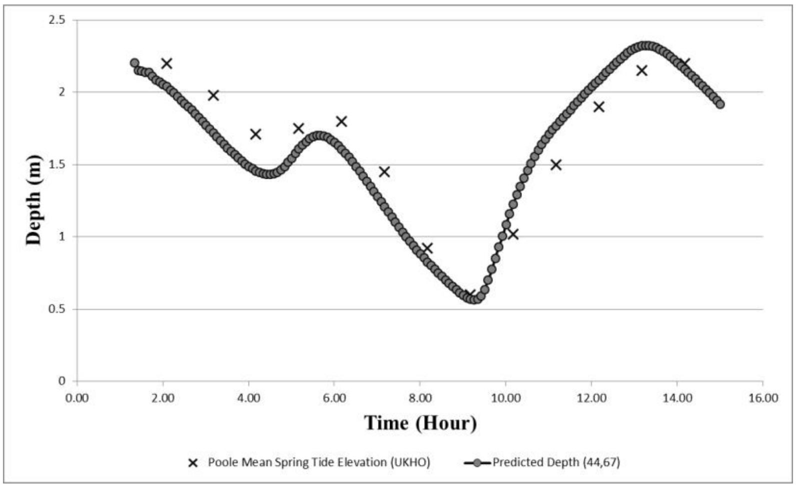


Figure 7-3 Validation of Water Elevation during Spring Tide

DIVAST simulation relies on the accuracy of water depth prediction. The predicted depth at model domain location (44, 67) is validated with observed mean spring tide elevation in Poole Harbour. The validation data are from the Admiral Chart 2013 and its 1984 version. As shown in Figure 7.3, the measured water depth represented as crosses, matched the model prediction represented by dots, shows the model is capable of capturing water depth at selected location in Poole Harbour. The first objective in this chapter is to set up the baseline condition in Poole Harbour. This is conducted by supplying the hourly flow and hourly bacteria concentrations in regard with the baseline condition outlined in Chapter 5. The second objective is to find the impacts of climate change and farming to the estuary in future conditions. Due to one of the WFD is biggest issue being the bathing water quality in the summer season, a 72-hour storm event (7 July - 9 July) 2002 is used for this case study with scenario analysis.

Baseline Water Depth

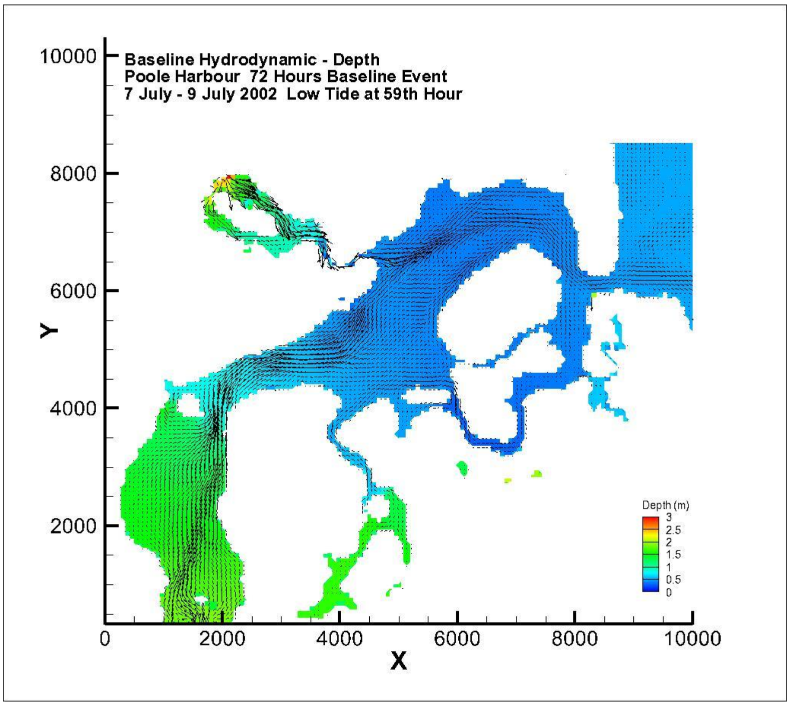


Figure 7-4 (a) Baseline Elevation at Low Tide at 59 Hour

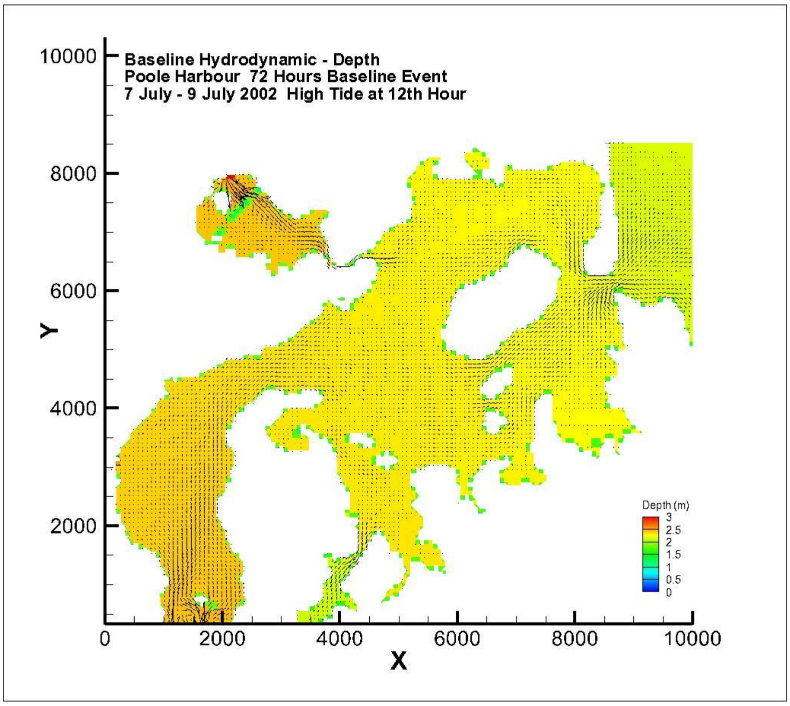


Figure 7-4 (b) Baseline Elevation at High tide at 12 Hour

Baseline Bacteria Concentration

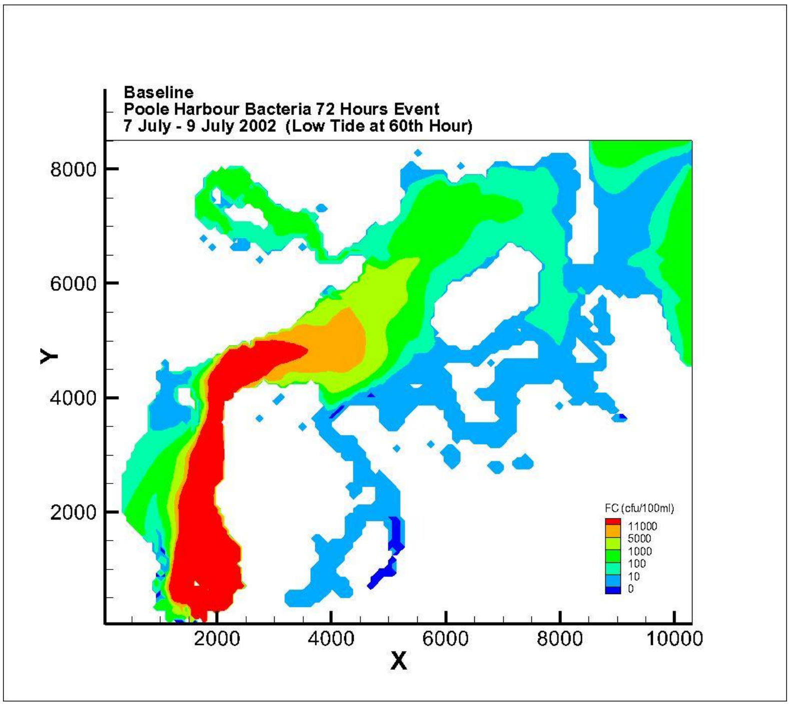


Figure 7-5 (a) Baseline Bacteria at Low Tide

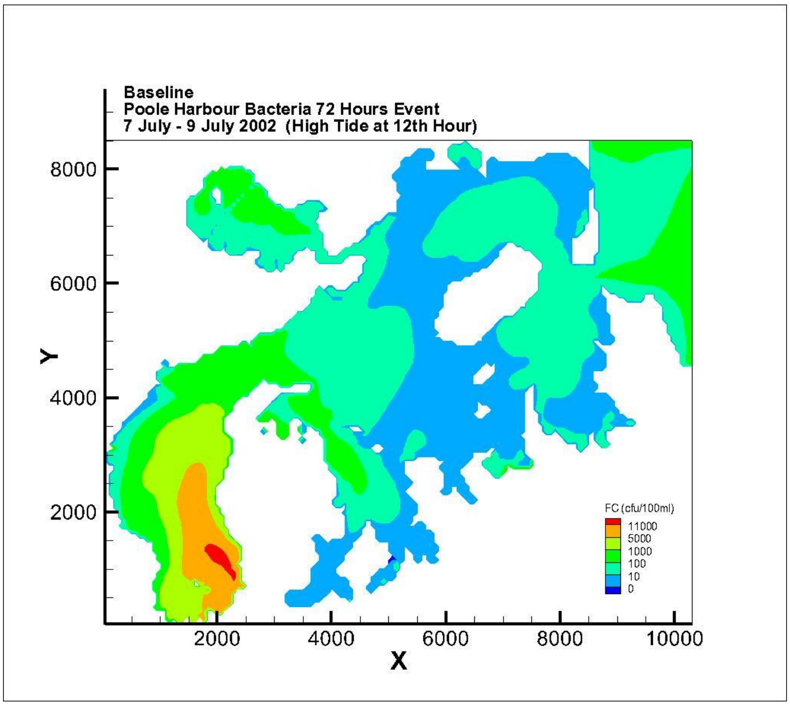


Figure 7-5 (b) Baseline Bacteria at High Tide

Future Scenario (Bacteria Scenario 5)

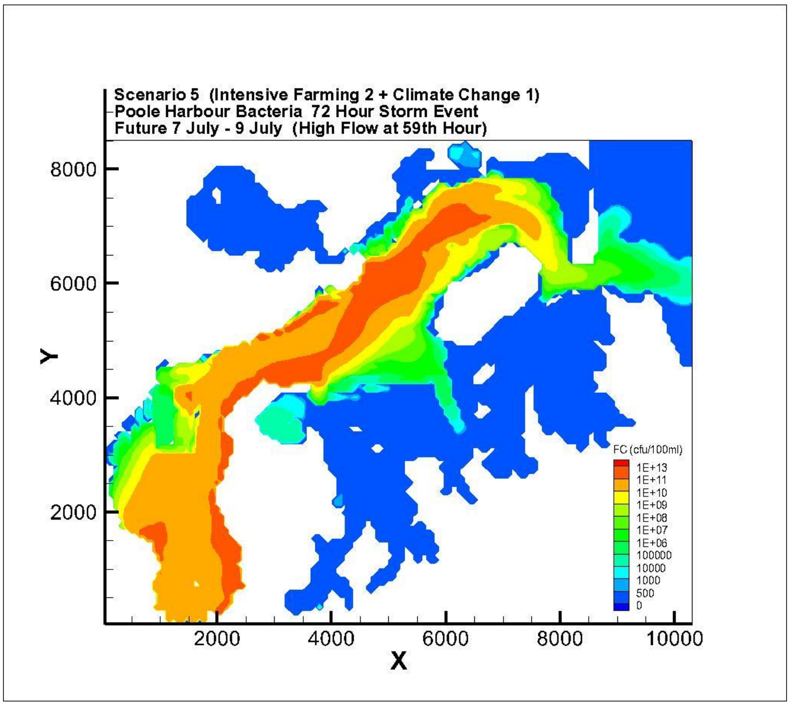


Figure 7-6 (a) Scenario 5 Bacteria Prediction in Poole

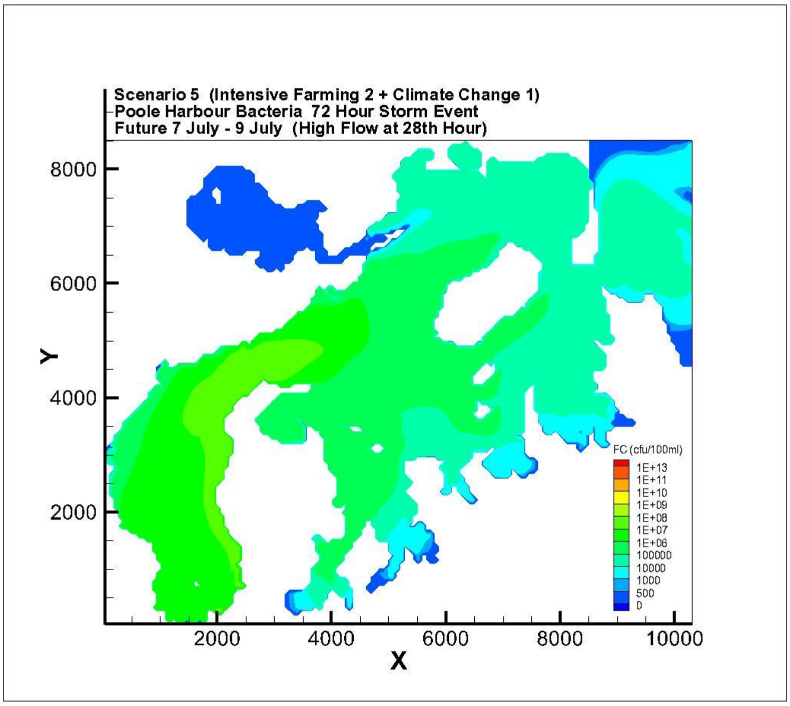


Figure 7-6 (b) Scenario 5 Bacteria Prediction in Poole

Tides are the driving force of hydrodynamic process in Poole Harbour. Each tidal cycle is around 13 hours. High tide causes a sea wave from outside the Harbour travels upstream to outlet of Frome and Piddle catchments. During the high tide, the flow direction is opposite to the river outflow which prohibits the diffusion of flow and faecal coliform bacteria from upstream catchment.

During low tide, the direction of river flow at catchment outlet is in the same direction as the tidal flow that superimposes two flows. The faecal bacteria flux normally travels further and close to the harbour entrance during low tide period. The faecal coliform contamination diffuses and expands during low tide. Figure 7.4 shows the baseline high and low tides in Poole Harbour. Part of Poole harbour becomes temporarily dry during low tide. The harbour is filled with sea tidal water when high tide occurs.

Baseline prediction of bacteria in Poole Harbour is displayed in Figure 7.5. The baseline condition in the DIVAST model uses the data from the validated SWAT simulation for 2002 presented in Chapter 5. The outcome from a 72-hrs baseline condition, shows the predicted bacteria has a peak value of around 1.1 * 10^4 cfu per 100ml. With high tide influences, the faecal bacteria remain around the Wareham channel, and do not travel further as shown in Figure 7.5(b)**.** With low tide effects, the bacteria travel further downstream and the area of high level of bacteria concentration expands from outlet through Wareham Channel and Rockley Point to around Poole Lake area, where the bathing water sites are located. The future scenario aims to find the impacts of climate change and intensive farming on the local water quality in the catchment and the estuary. There are six future scenarios in total as indicated in the previous chapter. DIVAST model is found not appropriate for simulating long term hydrodynamics for this study. One of the reasons is the limitation of computation capability of running DIVAST model. In the study, the time step of DIVAST model is 30 seconds. Therefore, subsequently monthly and annual simulation would take as long as hours to days to be completed. Due to the purpose of the study is to quantify the impacts to the velocity and faecal coliform during storm events, rather than long term study. Therefore, the hydrodynamic and solute simulation is event based study. For example, a 72hrs summer events between 7 July and 9 July are extracted from one year simulation from SWAT. Among SWAT future scenario analysis, scenario 3 & 5 were found that have the highest and medium level faecal contamination. Both scenario 3 &5 have the same climate change impact (condition 1), but with different intensive farming impacts.

However, further study shows that the bacteria concentrations differ between scenario 3 and scenario 5 within a small range. There is no significant change in Poole Harbour due to slightly increase in bacteria concentration due to scenario 5. In other words, bacteria variation in the Poole Harbour is not sensitive due to the change of farming condition in this particular storm event. And the bacteria is more responsible to the increased level of river flow that consequently cause bacteria pollution expansion i n the harbour. Therefore, scenario 5 is further analysis.

Future scenario 5 in Figure 7.6 (a) shows a dramatic super pollution event during this 72-hrs storm period. At hour 59, there is a low tide in the Harbour. Low tide always has low level of water depth in baseline condition. However, there is no sign of any decreases of water depth in this plot, which implies there is significant amount of water remains in harbour during low tide. And the hydrodynamics is dominated by the outflow from catchment due to flooding. This abnormal could be attributed to the significant amount of river flow entered the harbour. The flow peaks in 3 consecutive hours between 56 and 58, that each hour gives an additional of 18-20 CUMEC of flood water. This is due to the significant rainfall dropped with a peak value of 35mm/hr. There is an additional of at least 15 CUMEC of river flow highly contaminated with faecal coliform bacteria that entered Poole Harbour within 3 hours. This is equivalent of an additional of $5.4 * 10^4\ m^3$ of water per hour. However, it must not be ignored that the assumption that the boundary (domain) of Poole Harbour remains same during the flash flood event. In other words, the flood water from River Frome and Piddle could only flow through the open boundary (the catchment outlet) before entering the harbour, so that it assume that there is no flood plain is created that flood could flow through to the harbour via other boundary condition. However, this might be unrealistic in practise. Modelling with flood water inputs as open boundary Poole Harbour, might require a completed 1D-2D model linkage that could detect the flood plain created during floods.

In order to further understand the reason of this very high level of bacterial contamination events due to projected conditions, the scenario 5 input data is modified with the storm events but instead to employ the baseline base flow condition, i.e. much lower river flow in most of time during event. The bacteria contributions from two river boundaries remain the same. Figure 7.6 shows the response to this change. There is a significant drop of bacteria concentration in the peak value compare with actual scenario 5. The result indicates that the base flow with bacterial contamination in scenario 5 plays a critical role that determines the level of pollution in Poole Harbour. The peak value dropped to 10^5cfu/100ml level, a downgrade of 6 numbers of power compare with original scenario 5. This is due to the continuous contribution of bacteria source from base flow drops. Even the flow rate change is small (around 5-10%), consider the nature of continuity of base flow, it could be the largest source leading to bacterial contamination within this relative confined and tidal influences estuary environment, particularly sensitive in this study. Compared the baseline with scenario 5*, the contaminated area is almost the same but with higher bacteria concentrations due to farming and storms. Compared with the original scenario 5 simulation in Poole, this simulation with much reduced base flow has much smaller contaminated area in the Harbour whereas original scenario 5 simulation contaminated the whole Wareham channel, entire north Poole Harbour, and also through the inlet of the Harbour and flows into adjacent coast as shown in Figure 7.6.

Future Scenario 5 Modified Baseflow (Scenario 5*)

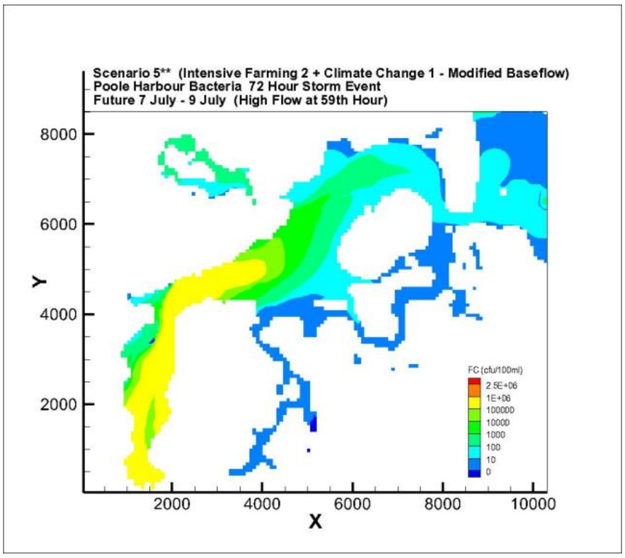


Figure 7-7 (a) Scenario 5 Bacteria with Modified Base Flow at Low Tide

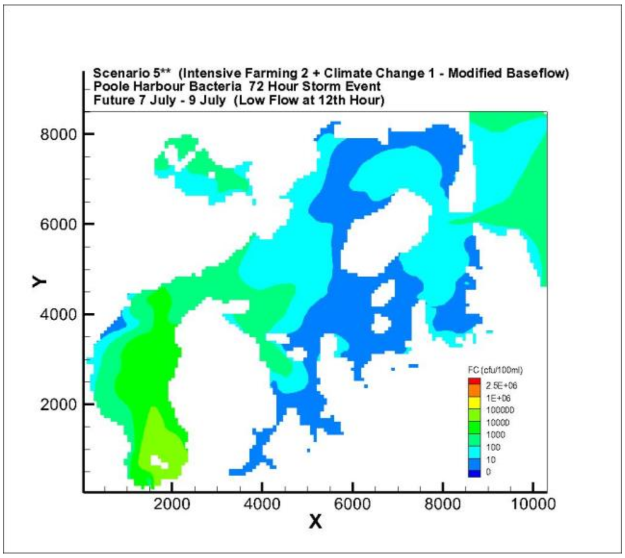


Figure 7-7 (b) Scenario 5 Bacteria with Modified Base Flow at High Tide

Bacteria Concentration at Bathing Water Sites

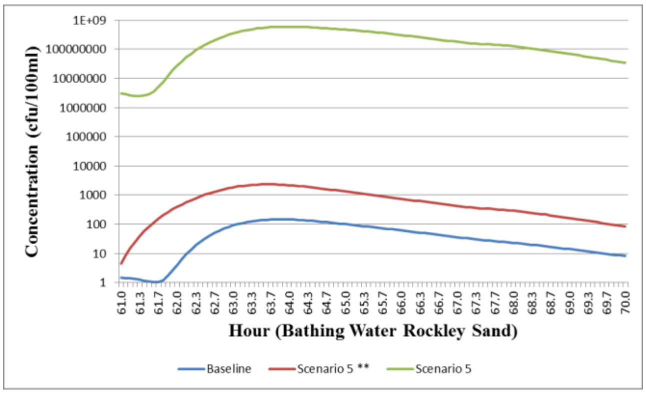


Figure 7-8 (a) Bacteria Time Series at Bathing Water Rockley Sand

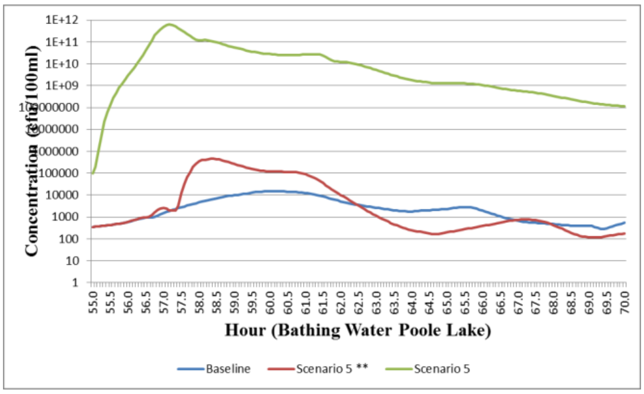


Figure 7-8 (b) Bacteria Time Series at Bathing Water Poole Lake

Bacteria Concentration at Shellfish Water Sites

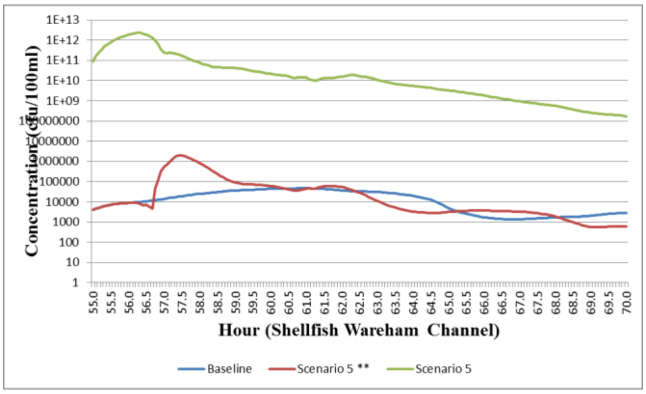


Figure 7-9 (a) Bacteria Variation at Shellfish Water Wareham Channel during High Flow Event

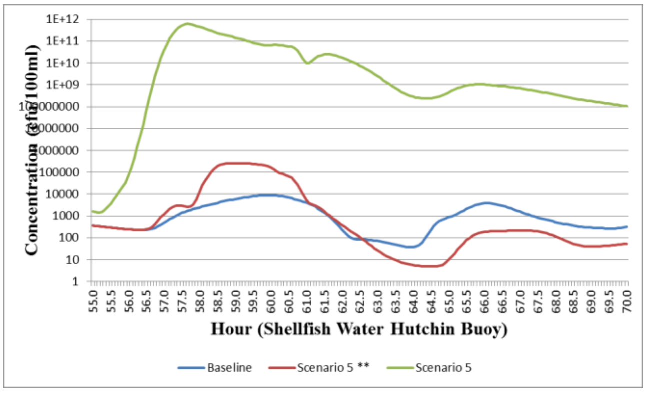


Figure 7-9 (b) Bacteria Variation at Shellfish Water Hutchin Buoy during High Flow Event

7.4 Summary

This chapter aims to develop a way to link the catchment model SWAT and the 2D model DIVAST which specialise in simulations of hydrodynamics and water quality in the open channel, such as in the river, estuary. In this study, DIVAST model is set up in the Poole Harbour that used to predict nitrates pollution due to proposed electricity station and the possible pollution to this designated area (Falconer 1986), with environmental interests described in Chapter 3. The aim of the chapter is to find the impacts from intensive farming and climate change from the catchment to the water quality of the estuary in Poole Harbour. Hourly storm event outputs from SWAT model is used as input for DIVAST model. The baseline output is from Chapter 5, the output from future scenarios are from Chapter 6.

Simulations of scenario 3 and 5 showing the bacteria levels under intensive farming are not sensible to the bacteria concentration in the estuary during this 72 hours' storm event. Tide plays an important role in estuary modelling particularly in Poole Harbour when compared with river inputs. There is a consensus that the pollution is prohibited during high tide, and it expanse further during low tidal in Poole. Therefore scenario 5 was focused for further studies to test these impacts.

The results show a dramatic super bacterial contamination due to flash flooding and increased base flow even at low tidal condition. Further investigation on the effects of base flow indicated that the base flow with bacterial contamination is critical to significantly drive the level of bacteria concentration up during this 72-hours event. It is suggested that while the bacteria are continuously accumulated in a tidal dominated estuary and within limited influence from broader coast environment, the contamination is very sensitive to the contaminated base flow, particularly in Poole Harbour.

Faecal contamination of six bathing water sites has been assessed spatially, and the lists of these sites are indicated in Table 7-1. There are three selected sites has been used in this study. The results show that bathing water at Poole Lake and Hamworth Park (located at the north of Poole Harbour and adjacent to a narrow channel) is more likely to be exposed to bacterial contamination, while the site at Rockley Sand is less affected. The shellfish water at Wareham channel (located north of the two rivers boundary, see Figure 3.2) has highest risk in all scenarios. It is very likely to be frequently contaminated by bacteria due to its location is very close to the source inputs.

The other shellfish site at Hutchin Buoy (located south of Poole Quay, see Figure 3.2) is under medium level of risk. However, it is highly variable that some period at Hutchin has very low contamination, but sometimes it could be highly polluted subject to tide and river flow factors, as shown in Figure 7-9(b).

The site at South Deep (located south of Brownsea Island, see Figure 3.2) is regarded as the place that is most suitable for growing sea food, as most of the harvesting period. The water quality keeps a low level of bacterial contamination with high level of hygiene. The conclusion is subject to the assumption that only the boundary conditions from the Frome and Piddle rivers are considered in the study. It is assumed that no point source pollutions are considered in this study, assumption has been made all STWs meet the effluent standards.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

Hydrological Modelling

There are not many studies that are focused on sub-daily hydrological modelling using SWAT. In this thesis, the SWAT model showed its capabilities of simulating both daily and sub-daily runoff, sediment and faecal coliforms with good and satisfactory performance. In particular, this study is one of the frontier studies that modelled the sub-daily rainfall runoff processes in a coastal agricultural lowland catchment in the UK using SWAT model. The model performed well spatially in daily simulations with R2 between 0.65 and 0.87, and NSE between 0.46 and 0.77. The runoff performance in multiple sub-basins could be found in APPENDIX IV.

SWAT Bacteria Modelling

Previous studies (Cho, Pachepsky et al. 2010; Cho, Pachepsky et al. 2012) in SWAT bacteria modelling only included the effects of solar radiation and sediment to bacteria concentration on a daily basis, which its model could not zoom in to detect the bacteria variation within 24 hours. The modified SWAT model in this thesis, successfully captured the variation of sub-daily faecal coliform with a significant improve to in-stream bacteria component in SWAT model. The model gave a good result in sub daily bacteria output as well. The daily bacteria prediction is acceptable, giving that there is lack of faecal coliform measurements for further study.

Climate Change and Intensive Farming

The future projection with climate change and intensive farming shows the varied responses of faecal bacteria level. There is a much less response in river Frome compare with river Piddle. Also, hourly prediction in autumn is not sensitive to these changes. This may be due to different responses to flow regime. Such as autumn in the study area may already has similar wet condition, so that is not sensitive to these changes.

The Bacterial Modelling using SWAT-DIVAST

In conclusion, the approach of numerical modelling to access the faecal coliform concentration in the catchment and the natural harbour shows the coupled SWAT-DIVAST model is capable of simulating river flow, faecal coliform and hydrodynamics processes in a one way linked river-estuary system. Faecal coliform prediction in the Poole Harbour show the 5 out of 6 bathing water and shellfish water site are under server risks that could have high level of faecal coliform contamination under current baseline condition. The only one that is with low risk is in South Deep north of Brownsea Island near the harbour mouth. This may be due to its location is far from the river outlet. Among all, shellfish water site at Wareham Channel is under the highest risk of getting microbiological contamination. With the projected simulation scenario 5, the harbour is more sensitive to the change due to intensive rainfall compare with the change of intensive farming upstream. This indicates that the river inflow to the harbour is an instant strong influence. The results show that high flow due to flash flood could cause a severe contamination of faecal bacteria under tidal condition. However, flash floods with constant increased contaminated base flow due to patch rains with flash flood would even be devastating that could cause a dramatic super-contamination of faecal coliform to an unprecedented level of 10^{13} cfu/100ml during flood peaks.

8.2 Future Recommendations

Unit Hydrograph and Base Flow Distribution in SWAT

Due to the limitation of base flow distribution equation and UH method, the storm event prediction still has potential for further improvement. In the UK, there is a sophisticated UH method called Flood Estimation Handbook (FEH) (Svensson and Jones 2010)which is another program based on the long term weather records of the UK catchments. It is suggested if the FEH method is used as the UH in SWAT (substitute the baseflow distribution factor), the sub daily output might be improved in the Frome and Piddle catchment, and this would be particularly beneficial to the modelling in the UK catchments.

Catchment Bacteria Modelling in SWAT

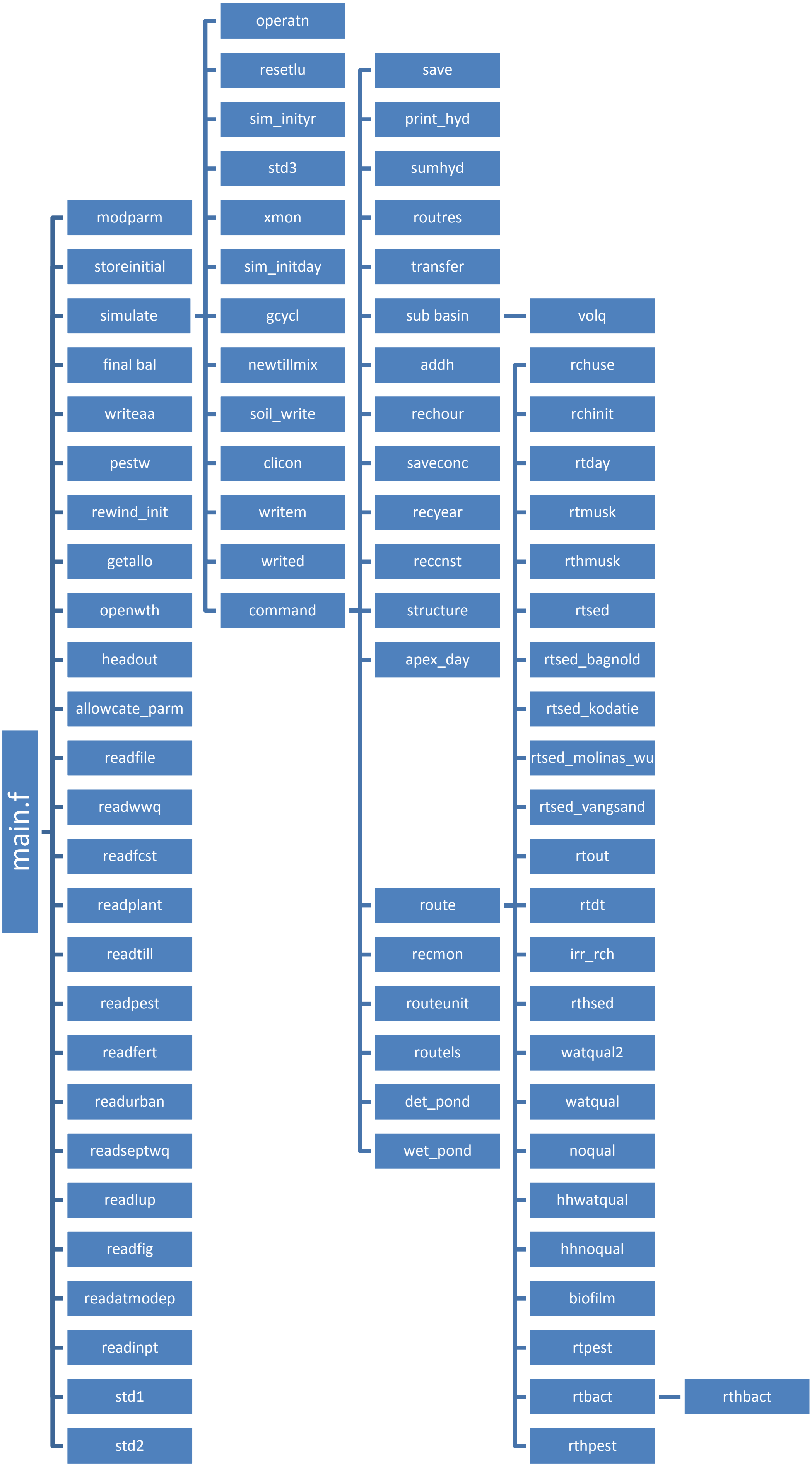
Future works of catchment bacteria modelling could be focus on the following two, (1) to include other influencing factors for sub daily bacteria die off, such algae or turbidity or groundwater induced bacteria re-suspension. (2) diffuse source input could further include a wildlife database to consider the local wildlife mammal contribution to the bacteria concentration in a rural catchment like Frome, Piddle and Poole area. (3) long term as well as event based intensive bacteria sampling and monitoring are greatly recommended, for research and public interest purposes.

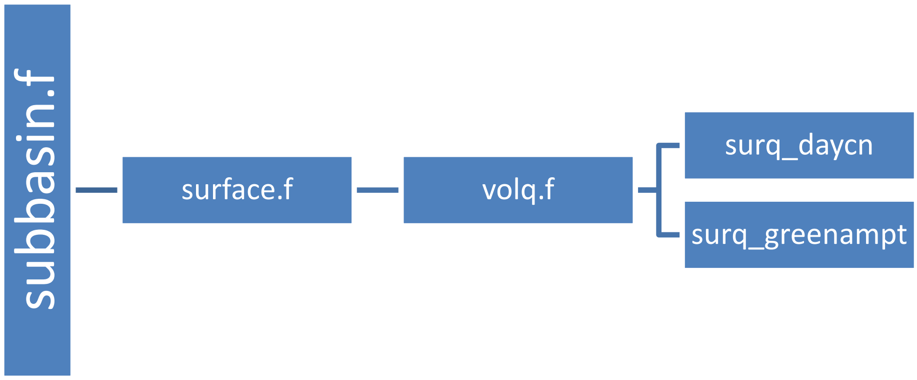
Linked 1D-2D Boundary during Flood Event in Poole Harbour

During the flooding events, the boundary (domain) of Poole Harbour remains same during high flows. In other words, the flood water from Rivers Frome and Piddle could only flow through the the narrow open boundary (the catchment outlets) before entering the harbour, so that it assumes that there is no flood plain is created and the flood water could not flow through to the harbour via other boundary condition. However, this might be unrealistic in practise. Modelling with flood water inputs as open boundary of Poole Harbour, would require a completed 1D-2D model linkage that could detect the flood plain created during floods from the catchment to estuary waters and vice versa.

APPENDIX I

1. **Structure of SWAT Source Code (First Four Layers)**
2. **Chart of Green & Ampt Routing**


main.f
modparm
storeinitial
simulate
final bal
writeaa
pestw
rewind_init
getallo
openwth
headout
allowcate_parm
readfile
readwwq
readfcst
readplant
readtill
readpest
readfert
readurban
readseptwq
readlup
readfig
readatmodep
readinpt
std1
std2
operatn
resetlu
sim_inityr
std3
xmon
sim_initday
gcycl
newtillmix
soil_write
clicon
writem
writed
command
save
print_hyd
sumhyd
routres
transfer
sub basin
addh
rechour
saveconc
recyear
reccnst
structure
apex_day
route
recmon
routeunit
routels
det_pond
wet_pond
volq
rchuse
rchinit
rtday
rtmusk
rthmusk
rtsed
rtsed_bagnold
rtsed_kodatie
rtsed_molinas_wu
rtsed_vangsand
rtout
rtdt
irr_rch
rthsed
watqual2
watqual
noqual
hhwatqual
hhnoqual
biofilm
rtpest
rtbact
rthbact
rthpest



subbasin.f
surface.f
volq.f
surq_daycn
surq_greenampt

APPENDIX II

SWAT Model Performance Evaluations (River Flow)

Sub-basin and Correspondence Flow Gauges

River and Sub-Basin Connectivity

Model Performance Evaluation (River Flow)

Time step	Rainfall input	Period	NSE	R^2	PBIAS (%)	Mean Sim / Obs
1 day	1 h	Calibration (2005-2006)	Sub 4 (0.70) Sub 8 (0.76) Sub 9 (0.77)	Sub 4 (0.76) Sub 8 (0.79) Sub 9 (0.79)	Sub 4 (-12.1) Sub 8 (- 4.0) Sub 9 (3.2)	Sub 4 (2.58 / 2.30) Sub 8 (1.75 / 1.68) Sub 9 (4.69 / 4.84)
1 day	1 h	Validation (2001-2002)	Sub 4 (0.58) Sub 8 (0.62) Sub 9 (0.61)	Sub 4 (0.71) Sub 8 (0.80) Sub 9 (0.76)	N/A	Sub 4 (4.23/4.00) Sub 8 (3.02/3.22) Sub 9 (7.74/7.78)
1 h	1 h	Calibration (2005-2006)	Sub 4 2005 (0.46) Sub 4 2006 (0.74) Sub 9 2005 (-0.39)	Sub 4 2005 (0.65) Sub 4 2006 (0.80) Sub 9 2005 (0.70)	N/A	Sub 4 2005 (2.53/2.12) Sub 4 2006 (2.64/2.47) Sub 9 2005 (6.42/5.38)
1 h	1 h	Validation (2002)	Sub 4 2002 (0.69) Sub 9 2002 (0.72)	Sub 4 2002 (0.81) Sub 9 2002 (0.87)	N/A	Sub 4 2002 (3.65/4.04) Sub 9 2002 (7.85/8.10)
1 h	1 h	Calibration (Storm in 2005-2006)	Sub 4 2005 (0.58) Sub 4 2006 (0.63)	Sub 4 2005 (0.62) Sub 4 2006 (0.72)	N/A	Sub 4 2005 (4.17/4.34) Sub 4 2006 (2.57/2.28)
1 h	1 h	Validation (Storms in 2002)	Sub 4 2002 (0.41) Sub 9 2002 (0.60)	Sub 4 2002 (0.47) Sub 9 2002 (0.70)	N/A	Sub 4 2002 (3.33/3.29) Sub 9 2002 (5.29/5.30)

Sub-basin and Correspondence Flow Gauges

Sub-basin	Gauging Station	Location	Flow Direction	HYD	Coordinates	Base flow Index
1	Little Puddle	North	Sub-basin 8	1	50.77189 -2.40270	N/A
2	Dewlish Woodsdown Cross	North	Sub-basin 8	2	50.78564 -2.31629	N/A
3	Sydling at Sydling St Nicholas	North West	Sub-basin 4	3	50.79569 -2.52351	0.88
5	Stinsford	Middle	Sub-basin 4	28	50.7152 -2.41071	N/A
6	South Winterbourne at W'bourne Steepleton	South West	Sub-basin 9	6	50.70575 -2.52675	N/A
4	Frome at Dorchester Total	South	Sub-basin 9	24	50.71159 -2.41493	0.83
8	Piddle at Baggs Mill	South East	Sub-basin 7	16	50.68798 -2.12452	0.89
9	Frome at East Stoke Total	South East	Sub-basin 10	34	50.6798 -2.19102	0.86
7	Outlet of River Piddle	South East	Poole Harbour	18	50.69598 -2.09272	N/A
10	Outlet of River Frome	South East	Poole Harbour	35	50.68879 -2.08765	N/A

Note: HYD represent hydrologic yield location. HYD is used for Green & Ampt sub-daily calibration as a location indicator for extracting the hourly flow.

River and Sub-Basin Connectivity

1. River Piddle Catchment: (Sub - basin 1, Sub - basin 2)>>>(Sub - basin 8);
2. River Frome Catchment: (Sub - basin 3, Sub - basin 5)>>>(Sub - basin 4); (Sub - basin 6, Sub - basin 4)>>>(Sub - basin 9);

APPENDIX III

Modified SWAT code - subroutine rtbact.f

```
subroutine rtbact
      use parm
      implicit none

      real :: kp, con_bact_sed
      real, parameter :: pi = 3.1416

      real :: sedin, deg, dep


      real :: rtbacthe, rtbacthe1, test1, algi
      real, external :: Theta

      integer :: ii, jrch
      real :: totbactp, totbactlp, netwtr, initlp, initp
      real :: tday, wtmp

      jrch = 0
      jrch = inum1

      wtmp = 0.
      wtmp = 5.0 + 0.75 * tmpav(jrch)
      if (wtmp <= 0.) wtmp = 0.1

      if (ievent > 2) then
        initlp = 0.
        initp = 0.
        initlp = rch_bactlp(jrch)
        initp = rch_bactp(jrch)
        do ii = 1, nstep
```

```
     totbactp = 0.
     totbactlp = 0.
     totbactp = hhvaroute(18,inum2,ii) * hhvaroute(2,inum2,ii) *    &
&                               (1. - rnum1) + initp * hrchwtr(ii)
     totbactlp = hhvaroute(19,inum2,ii) * hhvaroute(2,inum2,ii) *   &
&                              (1. - rnum1) + initlp * hrchwtr(ii)
con_bact_sed = 1e6 * 10**(bsc1*sin(bsc2*pi*(tday-bsc3)/366)+bsc4)

if (deg <= 1.08E-04) deg = 4.08E-04
totbactlp = totbactlp + con_bact_sed * deg / 1e4
totbactp = totbactp + con_bact_sed * deg / 1e4

kp = (10**(-1.6)) * (clay**(1.98))
     netwtr = 0.
     netwtr = hhvaroute(2,inum2,ii) * (1. - rnum1) + hrchwtr(ii)

totbactlp = totbactlp * (1 - (kp*dep)/(netwtr+kp*sedin))
totbactp = totbactp * (1 - (kp*dep)/(netwtr+kp*sedin))
algi = frad(hru1(jrch),ii) * hru_ra(hru1(jrch)) * tfact
tdprch = wdprch/24 + (ldprch*algi)
tdlprch = wdlprch/24 + (ldlprch*algi)
     totbactp = totbactp * Exp(-Theta(tdprch,thbact,wtmp))
     totbactp = Max(0., totbactp)
     totbactlp = totbactlp * Exp(-Theta(tdlprch / 24.,thbact,wtmp))
     totbactlp = Max(0., totbactlp)
     if (netwtr >= 0.01) then
       hbactp(ii) = totbactp / netwtr
       hbactlp(ii) = totbactlp / netwtr
     end if
     initlp = 0.
     initp = 0.
     initp = hbactp(ii)
```

```
    initlp = hbactlp(ii)
  end do
end if
totbactp = 0.
totbactlp = 0.
totbactp = varoute(18,inum2) * varoute(2,inum2) * (1. - rnum1)     &
&                                       + rch_bactp(jrch) * rchwtr
totbactlp = varoute(19,inum2) * varoute(2,inum2) *                  &
&                          (1. - rnum1) + rch_bactlp(jrch) * rchwtr

write (519, *), 'totbactlp', totbactlp, 'totbactp', totbactp
con_bact_sed = 1e6 * 10**(bsc1*sin(bsc2*pi*(tday-bsc3)/366)+bsc4)
if (deg <= 1.08E-04) deg = 4.08E-04
totbactlp = totbactlp + con_bact_sed * deg / 1e4
totbactp = totbactp + con_bact_sed * deg / 1e4
write (516, *), 'totbactlp', totbactlp, 'totbactp', totbactp,      &
& 'con_bact_sed', con_bact_sed, 'deg', deg
kp = (10**(-1.6)) * (clay**(1.98))
totbactlp = totbactlp * (1 - (kp*dep)/(netwtr+kp*sedin))
totbactp = totbactp * (1 - (kp*dep)/(netwtr+kp*sedin))
test1 = 1 - (kp*dep)/(netwtr+kp*sedin)
write (511, *), 'totbactlp', totbactlp, 'sedin', sedin,
& 'dep', dep, 'kp', kp, 'test1', test1
tdlprch = wdlprch + (sollpch * (hru_ra(hru1(jrch))                 &
&          *tfact/dayl(hru1(jrch))))
tdprch = wdprch + (solpch * (hru_ra(hru1(jrch))                    &
&          *tfact/dayl(hru1(jrch))))
write (506, *), 'tdlprch', tdlprch, 'sollpch', sollpch,            &
&                'hru_ra(hru1(jrch))', hru_ra(hru1(jrch)),         &
&                'tdprch', tdprch
tday = 0.
tday = rttime / 24.0
```

```
if (tday > 1.0) tday = 1.0

rtbacthe =  Exp(-Theta(tdprch,thbact,wtmp)*tday)
rtbacthe1 =  Theta(tdprch,thbact,wtmp)

totbactp = totbactp * Exp(-Theta(tdprch,thbact,wtmp)*tday)
totbactp = Max(0., totbactp)
totbactlp = totbactlp * Exp(-Theta(tdlprch,thbact,wtmp)*tday)
totbactlp = Max(0., totbactlp)
write (517, *), 'totbactp', totbactp, 'totbactlp', totbactlp
print *, 'rtbacthe', rtbacthe, 'rtbacthe1', rtbacthe1
write (518, *), 'rtbacthe', rtbacthe, 'rtbacthe1', rtbacthe1
netwtr = 0.
netwtr = varoute(2,inum2) * (1. - rnum1) + rchwtr

write (512, *), 'netwtr', netwtr
 if (totbactp < 1.e-6) totbactp = 0.0
 if (totbactlp < 1.e-6) totbactlp = 0.0
  if (netwtr >= 0.01) then
   rch_bactp(jrch) = totbactp / netwtr
   rch_bactlp(jrch) = totbactlp / netwtr
   print *, 'rch_bactp', rch_bactp, 'rch_bactlp', rch_bactlp
   write (515, *), 'rch_bactp', rch_bactp, 'rch_bactlp', rch_bactlp
 else
   rch_bactp(jrch) = 0.
   rch_bactlp(jrch) = 0.
 end if
 return
 end
```

APPENDIX IV

(1) Future Scenarios Impacts, Frome at East Stock

(2) Future Scenarios Impacts, Piddle at Baggs Mill

Classes (cfu / 100ml)	IFC + Baseline Rain Frequency Count	IFC + CCC1 Frequency Count	IFC + CCC2 Frequency Count	IFC1 + CCC1 Frequency Count	IFC1 + CCC2 Frequency Count	IFC2 + CCC1 Frequency Count	IFC2 + CCC2 Frequency Count
10^5 – 7*10^5	0	0	0	0	0	0	0
10^4 – 10^5	189	2	9	2	12	2	36
10^3 – 10^4	3,396	2,119	1,301	2,119	1,302	2,119	1,321
10^2 – 10^3	5,086	6,401	7,042	6,402	7,039	6,402	6,996
10^1 – 10^2	87	237	407	237	407	237	407
	Baseline (%)	**Scenario 1 (%)**	**Scenario 2 (%)**	**Scenario 3 (%)**	**Scenario 4 (%)**	**Scenario 5 (%)**	**Scenario 6 (%)**
10^5 – 7*10^5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10^4 – 10^5	2.18	0.02	0.10	0.02	0.14	0.02	0.42
10^3 – 10^4	39.2	24.4	15.0	24.4	15.0	24.4	15.2
10^2 – 10^3	58.7	73.8	81.2	73.8	81.2	73.8	80.7
10^1 – 10^2	1.0	2.7	4.7	2.7	4.7	2.7	4.7

(1) Future Scenario Impacts to Bacteria Concentration in River Frome at East Stoke

Classes (cfu / 100ml)	IFC + Rain Frequency Count	IFC + CCC1 Frequency Count	IFC + CCC2 Frequency Count	IFC1 + CCC1 Frequency Count	IFC1 + CCC2 Frequency Count	IFC2 + CCC1 Frequency Count	IFC2 + CCC2 Frequency Count
$10^5 - 7*10^5$	0	5	7	6	8	24	28
$10^4 - 10^5$	271	80	89	121	138	354	375
$10^3 - 10^4$	4796	2844	1946	2951	2001	3138	2161
$10^2 - 10^3$	3693	5813	6671	5666	6566	5229	6150
$10^1 - 10^2$	0	17	47	16	47	15	45
	Baseline (%)	**Scenario 1 (%)**	**Scenario 2 (%)**	**Scenario 3 (%)**	**Scenario 4 (%)**	**Scenario 5 (%)**	**Scenario 6 (%)**
$10^5 - 7*10^5$	0.00	0.06	0.08	0.07	0.09	0.28	0.32
$10^4 - 10^5$	3.13	0.92	1.03	1.40	1.59	4.08	4.33
$10^3 - 10^4$	55.3	32.8	22.4	34.0	23.1	36.2	24.9
$10^2 - 10^3$	42.6	67.0	76.9	65.4	75.7	60.3	70.9
$10^1 - 10^2$	0.0	0.2	0.5	0.2	0.5	0.2	0.5

(2) Future Scenario Impacts to Bacteria Concentration in River Piddle at Baggs Mill

REFERENCE

ADAS (2001). Making better use of livestock manures on arable land (Booklet 1). ADAS, DEFRA**:** 14.

ADAS (2002). Managing Manure on Organic Farms (Booklet 4). Managing Livestock Manures. M. S. P. G. E. F. R. C. L. Philipps, DEFRA**:** 13.

Agency, F. S. (2003). Evaluation of the impact on shellfisheries production of runoff from land receivin organic wastes. ADAS and CEFAS, ADAS Ltd.

Ahmadian, R. and R. A. Falconer (2012). "Assessment of array shape of tidal stream turbines on hydro-environmental impacts and power output." Renewable Energy **44**: 318-327.

Arabi, M., R. S. Govindaraju, et al. (2007). "Multiobjective sensitivity analysis of sediment and nitrogen processes with a watershed model." Water Resources Research **43**(6).

Arabi, M., R. S. Govindaraju, et al. (2006). "Role of watershed subdivision on modeling the effectiveness of best management practices with SWAT." Journal of the American Water Resources Association **42**(2): 513-528.

Arnell, N. W. and N. S. Reynard (1996). "The effects of climate change due to global warming on river flows in Great Britain." Journal of Hydrology **183**(3-4): 397-424.

Arnold, J. G. and P. M. Allen (1996). "Estimating hydrologic budgets for three Illinois watersheds." Journal of Hydrology **176**(1-4): 57-77.

Arnold, J. G. and P. M. Allen (1999). "Automated methods for estimating baseflow and ground water recharge from streamflow records." Journal of the American Water Resources Association **35**(2): 411-424.

Arnold, J. G., P. M. Allen, et al. (1995). "Automated base flow separation and recession analysis techniques." Ground Water **33**(6): 1010-1018.

Arnold, J. G., D. N. Moriasi, et al. (2012). "Swat: Model Use, Calibration, and Validation." Transactions of the Asabe **55**(4): 1491-1508.

Arnold, J. G., R. Srinivasan, et al. (1998). "Large area hydrologic modeling and assessment - Part 1: Model development." Journal of the American Water Resources Association **34**(1): 73-89.

ASAE (2003). Manure Production and Characteristics. ASAE D384.1 FEB03. Nilles Rd., St. Joseph, MI 49085-9659, USA, American Society of Agricultural Engineers**:** 4.

ASAE (2005). Manure Production and Characteristics. ASAE D384.2 MAR2005. Niles Rd., St. Joseph, MI 49085-9659, USA, American Soiety of Agricultural Engineers**:** 20.

Auer, M. T. and S. L. Niehaus (1993). "Modeling fecal coliform bacteria-I. Field and laboratory determination of loss kinetics." Water Res **27**(4): 693-701.

Bai, X., J. Wang, et al. (2013). "Modeling 1993-2008 climatology of seasonal general circulation and thermal structure in the Great Lakes using FVCOM." Ocean Modelling **65**: 40-63.

Barlund, I., T. Kirkkala, et al. (2007). "Assessing SWAT model performance in the evaluation of management actions for the implementation of the Water Framework Directive in a Finnish catchment." Environmental Modelling & Software **22**(5): 719-724.

Bautista-Avalos, D., G. Cruz-Cardenas, et al. (2014). "Application of the SWAT model to evaluate the diffuse contamination sources at lake Chapala sub-basin, Mexico." Revista Internacional De Contaminacion Ambiental **30**(3): 263-274.

Beeson, P. C., A. M. Sadeghi, et al. (2014). "Sediment delivery estimates in water quality models altered by resolution and source of topographic data." Journal of Environmental Quality **43**(1): 26-36.
Bellair, J., Parr-Smith, G. and Wallis, I., (1977). "Significance of diurnal variations in faecal colfiorm die-off rates in the design of ocean outfalls. ." Journal of the Water Pollution Control Federation **49**(9): 2022-2030.
Benham, B. L., C. Baffaut, et al. (2006). "Modeling bacteria fate and transport in watersheds to support TMDLs." Transactions of the Asabe **49**(4): 987-1002.
Betrie, G. D., Y. A. Mohamed, et al. (2011). "Sediment management modelling in the Blue Nile Basin using SWAT model." Hydrology and Earth System Sciences **15**(3): 807-818.
Bicknell, B. R., J. C. Imhoff, et al. (1995). "Hydrological simulation program-FORTRAN." User'S Manual for Release: 11.
Bougeard, M., J. C. Le Saux, et al. (2011). "Modeling of Escherichia coli Fluxes on a Catchment and the Impact on Coastal Water and Shellfish Quality." Journal of the American Water Resources Association **47**(2): 350-366.
Bougeard, M., J. C. Le Saux, et al. (2011). "Combining modeling and monitoring to study fecal contamination in a small rural catchment." J Water Health **9**(3): 467-482.
Bouraoui, F., L. Galbiati, et al. (2002). "Climate change impacts on nutrient loads in the Yorkshire Ouse catchment (UK)." Hydrology and Earth System Sciences **6**(2): 197-209.
Bowes, M. J., J. T. Smith, et al. (2009). "The value of high-resolution nutrient monitoring: A case study of the River Frome, Dorset, UK." Journal of Hydrology **378**(1-2): 82-96.
Bowie, G. W., W.Mills, D. Porcella, C. Campbell, J.Pagenkopf, G.Rupp, K. Johnson, P.Chan, S.Gherini, and C. Chamberlin. (1985). Rates, Constants and kinetics formulations in surface water quality modeling USEPA. **600/3-85/040**.
Boye, B. A. (2014). Integrated Modelling of Hydrodynamics Processes, Faecal Indicator Organisms and Related Parameters with Improved Accuracy using Pralell (GPU) Computing. Ph.D., Cardiff University.
Boye, B. A., R. A. Falconer, et al. (2015). "Integrated water quality modelling: Application to the Ribble Basin, U.K." Journal of Hydro-Environment Research **9**(2): 187-199.
Bracmort, K. S., M. Arabi, et al. (2006). "Modeling long-term water quality impact of structural BMPs." Transactions of the Asabe **49**(2): 367-374.
Bray, S., R. Ahmadian, et al. (2016). "Impact of representation of hydraulic structures in modelling a Severn barrage." Computers and Geosciences **89**: 96-106.
Bricknell, B., Imhoff, J., Kittle, J.Jr., and Donigian, A., Jr. (2001). "Hydrological Simulation Program - Fortran (HSPF): User's manual for release 12." National Exposure Research Labratory, Office of Research and Development, U.S. Environmental Protection Agency, Athens, GA.
Carroll, S. P., L. Dawes, et al. (2009). "Faecal pollution source identification in an urbanising catchment using antibiotic resistance profiling, discriminant analysis and partial least squares regression." Water Research **43**(5): 1237-1246.
CEFAS (2012). Classification of Bivalve Mollusc Production Areas in England and Wales, Sanitary Survey Poole Harbour**:** 25.
CEFAS, A. a. (2003). Project B 05006 Evaluation of the impact on Shellfisheries production of runoff from land receiving organic wastes Technical Report. S. R. (ADAS).

Cha, Y., M. H. Park, et al. (2016). "Modeling spatiotemporal bacterial variability with meteorological and watershed land-use characteristics." Water Res **100**: 306-315.

Chan, S. C., E. J. Kendon, et al. (2014). "The value of high-resolution Met Office regional climate models in the simulation of multihourly precipitation extremes." Journal of Climate **27**(16): 6155-6174.

Chan, S. C., E. J. Kendon, et al. (2016). "Downturn in scaling of UK extreme rainfall with temperature for future hottest days." Nature Geoscience **9**(1): 24-28.

Cheng, H. G., W. Ouyang, et al. (2007). "The non-point source pollution in livestock-breeding areas of the Heihe River basin in Yellow River." Stochastic Environmental Research and Risk Assessment **21**(3): 213-221.

Chin, D. A., D. Sakura-Lemessy, et al. (2009). "Watershed-scale fate and transport of bacteria." Transactions of the Asabe **52**(1): 145-154.

Cho, K. H., S. M. Cha, et al. (2010). "Meteorological effects on the levels of fecal indicator bacteria in an urban stream: A modeling approach." Water Research **44**(7): 2189-2202.

Cho, K. H., Y. A. Pachepsky, et al. (2010). "Release of Escherichia coli from the bottom sediment in a first-order creek: Experiment and reach-specific modeling." Journal of Hydrology **391**(3-4): 322-332.

Cho, K. H., Y. A. Pachepsky, et al. (2012). "The modified SWAT model for predicting fecal coliforms in the Wachusett Reservoir Watershed, USA." Water Res **46**(15): 4750-4760.

Cho, K. H., Y. A. Pachepsky, et al. (2016). "Modeling fate and transport of fecally-derived microorganisms at the watershed scale: State of the science and future opportunities." Water Res **100**: 38-56.

Chu, T. W. and A. Shirmohammadi (2004). "Evaluation of the SWAT model's hydrology component in the Piedmont physiographic region of Maryland." Transactions of the Asae **47**(4): 1057-1073.

Coffey, R., E. Cummins, et al. (2010). "Development of a pathogen transport model for Irish catchments using SWAT." Agricultural Water Management **97**(1): 101-111.

Coffey, R., E. Cummins, et al. (2007). "Microbial exposure assessment of waterborne pathogens." Human and Ecological Risk Assessment **13**(6): 1313-1351.

Coffey, R., E. Cummins, et al. (2010). "Analysis of the soil and water assessment tool (SWAT) to model Cryptosporidium in surface water sources." Biosystems Engineering **106**(3): 303-314.

Coffey, R., E. Cummins, et al. (2010). "Pathogen sources estimation and scenario analysis using the soil and water assessment tool (SWAT)." Human and Ecological Risk Assessment **16**(4): 913-933.

Conan, C., F. Bouraoui, et al. (2003). "Modeling flow and nitrate fate at catchment scale in Brittany (France)." J Environ Qual **32**(6): 2026-2032.

Crane, S. R. and J. A. Moore (1986). "Modeling enteric bacterial die-off: A review." Water Air Soil Pollut **27**(3-4): 411-439.

Crowther, J., D. Kay, et al. (2002). "Faecal-indicator concentrations in waters draining lowland pastoral catchments in the UK: Relationships with land use and farming practices." Water Research **36**(7): 1725-1734.

de Brauwere, A., B. De Brye, et al. (2011). "Modelling Escherichia coli concentrations in the tidal Scheldt river and estuary." Water Research **45**(9): 2724-2738.

Debele, B., R. Srinivasan, et al. (2008). "Coupling upland watershed and downstream waterbody hydrodynamic and water quality models (SWAT and CE-QUAL-W2) for better water resources management in complex river basins." Environmental Modeling & Assessment **13**(1): 135-153.

DEFRA (2003). Manure Management Plan - A step by step guide for farmers. Department for Environment, Food and Rural Affairs

DEFRA (2010). Fertiliser Manual (RB209) 8th Edition errata. F. a. R. A. Department for Environment, TSO The Stationery Office.

DEFRA. (2013). "DEFRA Statistics Food Farm Land Use Livestock June Results " Retrieved 30/07, 2015, from https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs/about/statistics.

Di Luzio, M., R. Srinivasan, et al. (2002). "Integration of watershed tools and SWAT model into BASINS." Journal of the American Water Resources Association **38**(4): 1127-1141.

DiDonato, G. T., J. R. Stewart, et al. (2009). "Effects of changing land use on the microbial water quality of tidal creeks." Marine Pollution Bulletin **58**(1): 97-106.

Donigian, A. S., B. R. Bicknell, et al. (1995). "Hydrological simulation program - Fortran (HSPF)." Computer Models of Watershed Hydrology: 395-442.

Douglas, J. F., Gasiorek, J. M., Swaffield, J. A. and Jack, L. B., (2011). Fluid Mechanics, Pearson/Prentice Hall.

Dourte, D. R., S. Shukla, et al. (2014). "Agricultural management impacts on groundwater: Simulations of existing and alternative management options in Peninsular India." Hydrological Processes **28**(19): 5021-5033.

Duda, P. B., P. R. Hummel, et al. (2012). "BASINS/HSPF: Model use, calibration, and validation." Transactions of the Asabe **55**(4): 1523-1547.

Dwight, R. H., D. B. Baker, et al. (2004). "Health Effects Associated with Recreational Coastal Water Use: Urban Versus Rural California." American Journal of Public Health **94**(4): 565-567.

EA (2005). The Frome, Piddle and Purbeck Catchment Abstraction Management Strategy**:** 23.

EA (2008). Sediment fluxes and sources in the Dorset Frome ECSFDI priority catchment. P. S. E. Agency, ADAS UK Ltd**:** 99.

Edwards, A. C., D. Kay, et al. (2008). "Farmyards, an overlooked source for highly contaminated runoff." Journal of Environmental Management **87**(4): 551-559.

Elder, J. W. (1959). "The Dispersion of Marked Fluid in Turbulent Shear FLow " Journal of Fluid Mechanics **5**: 644-560.

Elizabeth J. Kendon, N. M. R., Catherine A. Senior and Malcolm J. Roberts, (2012). "Realism of Rainfall in a Very High-Resolution Regional Climate Model." Journal of Climate **25**: 5791-5806.

Elizabeth J. Kendon, N. M. R., Hayley J. Fowler, Malcolm J. Roberts, Steven C. Chan and Catherine A. Senior (2014). "Heavier summer downpours with climate change revealed by weather forecast resolution model." Letters of Nature Climate Change **4**: 570-576.

EPA (2003). Bacterial Water Quality Standards for Recreational Waters (Freshwater and Marine Waters). O. o. W. (4305T). 1200 Pennsylvania Avenue, NW, Washington, DC 20460, USEPA**:** 32.

European Parliament, C. (2006). Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006 concerning the management of bathing water quality and repealing Directive 76/160/EEC. , Journal of the European Union**:** 15.

Falconer, R., E. Harris, et al. (2001). Modelling hydro-environmental processes in riverine systems. Progress in Water Resources.

Falconer, R. A. (1977). Mathematical Modelling of jet-forced circulation in Reservoirs and Harbours. Ph.D., University of London, London, United Kingdom.

Falconer, R. A. (1986). "Water quality simulation study of a natural harbor." Journal of Waterway, Port, Coastal and Ocean Engineering **112**(1): 15-34.

Falconer, R. A. (1991). "Review of Modelling Flow and Pollutant Transport Processes in Hydraulic Basins." Proceedings of First International Conference of Water Pollution = Modelling, Measuring and Prediction.

Falconer, R. A. (1993). "Application of numerical models for water quality studies." Proceedings of the Institution of Civil Engineers: Civil Engineering **97**(4): 163-170.

Falconer, R. A. and B. Lin (1997). "Three-dimensional modelling of water quality in the Humber Estuary." Water Res **31**(5): 1092-1102.

Falconer, R. A. a. L., B., (2001). DIVAST Model Reference Manual Hydro-environmental Research Centre, Cardiff School of Engineering, Cardiff University, The Parade, Cardiff, CF24 3AA.

Ferguson, C. M., B. Croke, et al. (2005). A deterministic model to quantify pathogen loads in drinking water catchments: Pathogen budget for the Wingecarribee. Water Science and Technology. **52:** 191-197.

Ferguson, C. M., B. Croke, et al. (2005). A deterministic model to quantify pathogen loads in drinking water catchments: Pathogen budget for the Wingecarribee. Water Science and Technology. **52:** 191-197.

Foley, J. A., R. DeFries, et al. (2005). "Global consequences of land use." Science **309**(5734): 570-574.

Frey, S. K., E. Topp, et al. (2013). "Using SWAT, Bacteroidales microbial source tracking markers, and fecal indicator bacteria to predict waterborne pathogen occurrence in an agricultural watershed." Water Res **47**(16): 6326-6337.

Frey, S. K., E. Topp, et al. (2013). "Using SWAT, Bacteroidales microbial source tracking markers, and fecal indicator bacteria to predict waterborne pathogen occurrence in an agricultural watershed." Water Res **47**(16): 6326-6337.

Fujioka, R. S., Hashimoto, H. H., Siwak, E. B. and Young, R. H., (1981). "Effect of sunlight on survival of indicator bacteria in seawater." Applied and Environmental Microbiology **41**(3): 690-696.

Galland, J. C., N. Goutal, et al. (1991). "TELEMAC: A new numerical model for solving shallow water equations." Advances in Water Resources **14**(3): 138-148.

Gameson, A. a. S., J., (1967). "Field studies on effect of daylight on mortality of coliform bacteria " 16th International Conference on Microelectronics, Proceedings **4**: 279-295.

Gameson, A. L. H. a. G., D.D., (1975). "Effects of solar radiation on the mortality of some terrestrial bacteria in sea water. In: Discharge of Sewerage from Sea Outfalls " Proceedings of an international Symposium Held at Church House, London.

Gao, G., R. A. Falconer, et al. (2011). "Numerical modelling of sediment-bacteria interaction processes in surface waters." Water Research **45**(5): 1951-1960.

Gao, G., R. A. Falconer, et al. (2013). "Modelling importance of sediment effects on fate and transport of enterococci in the Severn Estuary, UK." Marine Pollution Bulletin **67**(1-2): 45-54.

Garen, D. C. and D. S. Moore (2005). "Curve number hydrology in water quality modeling: Uses, abuses, and future directions." Journal of the American Water Resources Association **41**(2): 377-388.

Gassman, P. W., M. R. Reyes, et al. (2007). "The soil and water assessment tool: Historical development, applications, and future research directions." Transactions of the Asabe **50**(4): 1211-1250.

Gassman, P. W., A. M. Sadeghi, et al. (2014). "Applications of the SWAT Model Special Section: Overview and Insights." J Environ Qual **43**(1): 1-8.

Gassman, P. W., J. R. Williams, et al. (2010). "The Agricultural Policy/Environmental Extender (Apex) Model: An Emerging Tool for Landscape and Watershed Environmental Analyses." Transactions of the Asabe **53**(3): 711-740.

Ghimire, B. and Z. Deng (2013). "Hydrograph-based approach to modeling bacterial fate and transport in rivers." Water Res **47**(3): 1329-1343.

Graczyk, T. K., B. M. Evans, et al. (2000). "Environmental and geographical factors contributing to watershed contamination with Cryptosporidium parvum oocysts." Environmental Research **82**(3): 263-271.

Green, W. H., and G.A. Ampt (1911). "Studies on soil physics: 1. The flow of air and water through soils." J.Argric.Sci. **4**: 11-24.

Group, P. H. S. (2011). Poole Harbour Aquatic Management Plan 2011. Borough of Poole.

Guse, B., D. E. Reusser, et al. (2014). "How to improve the representation of hydrological processes in SWAT for a lowland catchment - temporal analysis of parameter sensitivity and model performance." Hydrological Processes **28**(4): 2651-2670.

H., C. (1908). "An investigation of the laws of disinfection " Journal of Hyg **8**.

Hampson, D., J. Crowther, et al. (2010). "Predicting microbial pollution concentrations in UK rivers in response to land use change." Water Research **44**(16): 4748-4759.

Hanratty, M. P. and H. G. Stefan (1998). "Simulating climate change effects in a Minnesota agricultural watershed." Journal of Environmental Quality **27**(6): 1524-1532.

Hao, F. H., X. S. Zhang, et al. (2004). "A distributed non-point source pollution model: calibration and validation in the Yellow River basin." Journal of Environmental Sciences-China **16**(4): 646-650.

Harris, E., R. A. Falconer, et al. (2002). "Development of a modelling tool to quantify faecal indicator levels in Cardiff Bay." Proceedings of the Institution of Civil Engineers: Water and Maritime Engineering **154**(2): 129-135.

He, L. M. and Z. L. He (2008). "Water quality prediction of marine recreational beaches receiving watershed baseflow and stormwater runoff in southern California, USA." Water Research **42**(10-11): 2563-2573.

Hoang, L., A. van Griensven, et al. (2014). "Comparison and evaluation of model structures for the simulation of pollution fluxes in a tile-drained river basin." J Environ Qual **43**(1): 86-99.

Holly, F. M. J., and Usseglio-Polatera, J.M. (1984). "Dispersion in Two-Dimensional Flow." ASCE J. Hydraulic Engineering **110**: 902-926.

Howden, N. J. K., M. J. Bowes, et al. (2009). "Water quality, nutrients and the European union's Water Framework Directive in a lowland agricultural region: Suffolk, south-east England." Science of the Total Environment **407**(8): 2966-2979.

Huang, G., R. A. Falconer, et al. (2015). "Cloud to coast: integrated assessment of environmental exposure, health impacts and risk perceptions of faecal organisms in coastal waters." International Journal of River Basin Management **13**(1): 73-86.

Hutchins, M. G. (2010). "How do river nitrate concentrations responds to changes in land use? A modelling case study of headwaters in the river Derwent catchment, North Yorkshire, UK." Environment Mododel Assess **15**: 93-109.

Hutchinson, M. L., Walters, L.D., Avery, S.M., Synge, B.A., Moore, A., (2004). "Levels of zoonotic agents in Bristish livestock manures." Letter of Applied Microbiol **39**: 207-214.

Im, S., K. M. Brannan, et al. (2007). "Comparison of HSPF and SWAT models performance for runoff and sediment yield prediction." J Environ Sci Health A Tox Hazard Subst Environ Eng **42**(11): 1561-1570.

Jamieson, R., R. Gordon, et al. (2004). "Assessing microbial pollution of rural surface waters: A review of current watershed scale modeling approaches." Agricultural Water Management **70**(1): 1-17.

Jayakody, P., P. B. Parajuli, et al. (2014). "Evaluating Spatial and Temporal Variability of Fecal Coliform Bacteria Loads at the Pelahatchie Watershed in Mississippi." Human and Ecological Risk Assessment **20**(4): 1023-1041.

Jeong, J., N. Kannan, et al. (2010). "Development and Integration of Sub-hourly Rainfall-Runoff Modeling Capability Within a Watershed Model." Water Resources Management **24**(15): 4505-4527.

Jeong, J., N. Kannan, et al. (2011). "Development of sub-daily erosion and sediment transport algorithms for SWAT." Transactions of the Asabe **54**(5): 1685-1691.

Jha, M. K., P. W. Gassman, et al. (2007). "Water quality modeling for the Raccoon River watershed using SWAT." Transactions of the Asabe **50**(2): 479-493.

Jung Woo Kim, Y. P., Daniel R. Shelton (2009). Sediment Associated Bacteria Release and Settling in SWAT bacteria routing Environmental Microbial and Food Safety Laboratory, Beltsville Agricultural Research Centre USDA-ARS.

Kannan, N., S. M. White, et al. (2007). "Predicting diffuse-source transfers of surfactants to surface waters using SWAT." Chemosphere **66**(7): 1336-1345.

Kannan, N., S. M. White, et al. (2006). "Pesticide modelling for a small catchment using SWAT-2000." J Environ Sci Health B **41**(7): 1049-1070.

Kannan, N., S. M. White, et al. (2007). "Hydrological modelling of a small catchment using SWAT-2000 - Ensuring correct flow partitioning for contaminant modelling." Journal of Hydrology **334**(1-2): 64-72.

Kashefipour, S. M., B. Lin, et al. (2002). "Dynamic modelling of bacterial concentrations in coastal waters: Effects of solar radiation on decay." Advances in Hydraulics and Water Engineering, Vols 1 and 2, Proceedings: 993-998.

Kashefipour, S. M., B. Lin, et al. (2006). "Modelling the fate of faecal indicators in a coastal basin." Water Research **40**(7): 1413-1425.

Kashefipour, S. M., B. Lin, et al. (2002). "Hydro-environmental modelling for bathing water compliance of an estuarine basin." Water Research **36**(7): 1854-1868.

Kay, D., M. Aitken, et al. (2007). "Reducing fluxes of faecal indicator compliance parameters to bathing waters from diffuse agricultural sources: The Brighouse Bay study, Scotland." Environmental Pollution **147**(1): 138-149.

Kay, D., S. Anthony, et al. (2010). "Microbial water pollution: A screening tool for initial catchment-scale assessment and source apportionment." Science of the Total Environment **408**(23): 5649-5656.

Kay, D., J. Crowther, et al. (2008). "Faecal indicator organism concentrations and catchment export coefficients in the UK." Water Research **42**(10-11): 2649-2661.

Kay, D., A. C. Edwards, et al. (2007). "Catchment microbial dynamics: The emergence of a research agenda." Progress in Physical Geography **31**(1): 59-76.

Kay, D., C. M. Stapleton, et al. (2005). "Decay of intestinal enterococci concentrations in high-energy estuarine and coastal waters: towards real-time T90 values for modelling faecal indicators in recreational waters." Water Res **39**(4): 655-667.

Kay, D., M. Wyer, et al. (2005). "Predicting faecal indicator fluxes using digital land use data in the UK's sentinel Water Framework Directive catchment: the Ribble study." Water Res **39**(16): 3967-3981.

Kay, D., M. D. Wyer, et al. (2005). "Sustainable reduction in the flux of microbial compliance parameters from urban and arable land use to coastal bathing waters by a wetland ecosystem produced by a marine flood defence structure." Water Res **39**(14): 3320-3332.

Kay, D. P., A. L. Blankenship, et al. (2005). "Differential accumulation of polychlorinated biphenyl congeners in the aquatic food web at the Kalamazoo River Superfund site, Michigan." Environmental Science & Technology **39**(16): 5964-5974.

Kim, J. W., Y. A. Pachepsky, et al. (2010). "Effect of streambed bacteria release on E. coli concentrations: Monitoring and modeling with the modified SWAT." Ecological Modelling **221**(12): 1592-1604.

King, K. W., J. G. Arnold, et al. (1999). "Comparison of Green-Ampt and curve number methods on Goodwin Creek Watershed using SWAT." Transactions of the American Society of Agricultural Engineers **42**(4): 919-925.

Lee, C. M., T. Y. Lin, et al. (2006). "Persistence of fecal indicator bacteria in Santa Monica Bay beach sediments." Water Research **40**(14): 2593-2602.

Lee, D. Y., H. Lee, et al. (2014). "Characterization of sources and loadings of fecal pollutants using microbial source tracking assays in urban and rural areas of the Grand River Watershed, Southwestern Ontario." Water Research **53**: 121-131.

Liang D., F. A. R., Lin B., (2003). "Improved Numerical Modelling of Estuarine Flows."

Liang D., F. A. R., Lin B., (2007). "Linking one- and two- dimensional models for free surface flows." Proceedings of the ICE - Water Management **160**(3): 145 - 151.

Lin, B. and R. A. Falconer (1995). "Modelling sediment fluxes in estuarine waters using a curvilinear coordinate grid system." Estuarine, Coastal and Shelf Science **41**(4): 413-428.

Lin, B., S. M. Kashefipour, et al. (2003). Predicting near-shore coliform bacteria concentrations using ANNS. Water Science and Technology. **48:** 225-232.

Lin, B., M. Syed, et al. (2008). "Predicting faecal indicator levels in estuarine receiving waters - An integrated hydrodynamic and ANN modelling approach." Environmental Modelling and Software **23**(6): 729-740.

Liu, M. B., D. P. Chen, et al. (2013). "[Coupling SWAT and CE-QUAL-W2 models to simulate water quantity and quality in Shanmei Reservoir watershed]." Ying Yong Sheng Tai Xue Bao **24**(12): 3574-3580.

Liu, Z. and S. T. Y. Tong (2011). "Using HSPF to model the hydrologic and water quality impacts of riparian land-use change in a small watershed." Journal of Environmental Informatics **17**(1): 1-14.

Lu, S., N. Kayastha, et al. (2014). "Multiobjective calibration for comparing channel sediment routing models in the soil and water assessment tool." Journal of Environmental Quality **43**(1): 110-120.

Ludicello, J. J. C., David A. (2013). "Multimodel, multiple watershed examination of in-stream bacteria modeling." Environmental Engineering ASCE **139**(5): 8.

Maharjan, G. R., Y. S. Park, et al. (2013). "Evaluation of SWAT sub-daily runoff estimation at small agricultural watershed in Korea." Frontiers of Environmental Science and Engineering in China **7**(1): 109-119.

Mallin, M. A., S. H. Ensign, et al. (2001). "Demographic, landscape, and meteorological factors controlling the microbial pollution of coastal waters." Hydrobiologia **460**: 185-193.

Mancini, J. L. (1978). "Numerical estimates of coliform mortality rates under various conditions." Water Pollution Control Federation **50**(11): 2477-2484.

McElroy, A. D., S. Y. Chiu, et al. (1976). "Loading functions for assessment of water pollution from nonpoint sources." Loading Functions for Assessment of Water Pollution from Nonpoint Sources.

McEvoy, J. M., G. Duffy, et al. (2005). "The prevalence and characterisation of Cryptosporidium spp. in beef abattoir water supplies." Water Res **39**(15): 3697-3703.

Mezrioui, N., B. Oudra, et al. (1994). "Effect of microalgae growing on wastewater batch culture on Escherichia coli and Vibrio cholerae survival." Water Science and Technology **30**(8 pt 8): 295-302.

Milne, D. P., J. C. Curran, et al. (1986). "Effects of Sedimentation on Removal of Fecal-Coliform Bacteria from Effluents in Estuarine Water." Water Research **20**(12): 1493-1496.

Moore, J. A., J. D. Smyth, et al. (1989). "Modeling bacteria movement in livestock manure systems." Transactions of the American Society of Agricultural Engineers **32**(3): 1049-1053.

Moriasi, D. N., J. G. Arnold, et al. (2007). "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations." Transactions of the Asabe **50**(3): 885-900.

Nash, J. E., and J.V. Sutcliffe. (1970). "River flow forecasting through conceptual models: Part I. A discussion of principles." J.Hydrology **10**(3): 282-290.

Nasr, A., M. Bruen, et al. (2007). "A comparison of SWAT, HSPF and SHETRAN/GOPC for modelling phosphorus export from three catchments in Ireland." Water Res **41**(5): 1065-1073.

Neitsch, S. L., J. G. Arnold, et al. (2004). "Soil and water assessment tool, Input/output file documentation, version 2005." Blackland Research Center, Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Temple, TX.

Neitsch, S. L., J. G. Arnold, et al. (2005). "Soil and water assessment tool theoretical documentation." Grassland.

Nelson, R. G., J. C. Ascough, et al. (2006). "Environmental and economic analysis of switchgrass production for water quality improvement in northeast Kansas." Journal of Environmental Management **79**(4): 336-347.

Niazi, M., C. Obropta, et al. (2015). "Pathogen transport and fate modeling in the Upper Salem River Watershed using SWAT model." J Environ Manage **151C**: 167-177.

Ouyang, W., F. Hao, et al. (2010). "Soil erosion and sediment yield and their relationships with vegetation cover in upper stream of the Yellow River." Science of the Total Environment **409**(2): 396-403.

Ouyang, W., F. H. Hao, et al. (2008). "Nonpoint source pollution responses simulation for conversion cropland to forest in mountains by SWAT in China." Environ Manage **41**(1): 79-89.

Parajuli, P. B. (2007). "SWAT bacteria sub-model application and evaluation." SWAT bacteria sub-model evaluation and application.

Parajuli, P. B., K. R. Mankin, et al. (2009). "Source specific fecal bacteria modeling using soil and water assessment tool model." Bioresour Technol **100**(2): 953-963.

Parajuli, P. B., K. R. Mankin, et al. (2007). "Fecal Bacteria Source Characterization and Sensitivity Analysis of SWAT2005." 1-24.

Park, J. Y., G. A. Park, et al. (2013). "Assessment of future climate change impact on water quality of chungju lake, South Korea, Using WASP Coupled with SWAT." Journal of the American Water Resources Association **49**(6): 1225-1238.

Partnership, P. H. C. I. (2014). Poole Harbour Catchment Initiative Catchment Plan 2014. Poole**:** 58.

Preston, R. W. (1985). "Representation of Dispersion in Two-dimensional Water Flow, Report No. TPRD/L/2783/N84." Central Electricity Research Laboratories, Leatherhead, England, 1-13.

Reddy, K. R., R. Khaleel, et al. (1981). "Behavior and transport of microbial pathogens and indicator organisms in soils treated with organic wastes." Journal of Environmental Quality **10**(3): 255-266.

Refsgaard, J. C. and B. Storm (1995). 809-846.

Saleh, A., J. G. Arnold, et al. (2000). "Application of swat for the Upper North Bosque River Watershed." Transactions of the Asae **43**(5): 1077-1087.

Saleh, A. and B. Du (2004). "Evaluation of SWAT and HSPF within BASINS program for the Upper North Bosque River watershed in Central Texas." Transactions of the Asae **47**(4): 1039-1049.

Sanders, B. F., F. Arega, et al. (2005). "Modeling the dry-weather tidal cycling of fecal indicator bacteria in surface waters of an intertidal wetland." Water Research **39**(14): 3394-3408.

Santhi, C., J. G. Arnold, et al. (2001). "Application of a watershed model to evaluate management effects on point and nonpoint source pollution." Transactions of the Asae **44**(6): 1559-1570.

Santhi, C., R. Srinivasan, et al. (2006). "A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas." Environmental Modelling & Software **21**(8): 1141-1157.

Schmalz, B., F. Tavares, et al. (2008). "Modelling hydrological processess in mesoscale lowland river basins with SWAT - Capabilities and challenges." Hydrological Sciences Journal **53**(5): 989-1000.

Schuol, J., K. C. Abbaspour, et al. (2008). "Estimation of freshwater availability in the West African sub-continent using the SWAT hydrologic model." Journal of Hydrology **352**(1-2): 30-49.

SCS (1972). (Soil Conservation Service) National Engineering Handbook, Section 4 Hydrology U.S. Government printing Office: Washington, D.C.

Semenza, J. C., J. S. Caplan, et al. (2012). "Climate change and microbiological water quality at California beaches." EcoHealth **9**(3): 293-297.

Servais, P., G. Billen, et al. (2007). "Modelling microbiological water quality in the Seine river drainage network: past, present and future situations." Hydrology and Earth System Sciences **11**(5): 1581-1592.

Srinivasan, R., T. S. Ramanarayanan, et al. (1998). "Large area hydrologic modeling and assessment - Part II: Model application." Journal of the American Water Resources Association **34**(1): 91-101.

Stewart, G. R., C. L. Munster, et al. (2006). "Simulating water quality improvements in the Upper North Bosque River watershed due to phosphorus export through turfgrass sod." Transactions of the Asabe **49**(2): 357-366.

Stumpf, C. H., M. F. Piehler, et al. (2010). "Loading of fecal indicator bacteria in North Carolina tidal creek headwaters: Hydrographic patterns and terrestrial runoff relationships." Water Research **44**(16): 4704-4715.

Sturdee, A. P., Bodley-Tickell, A.T., Archer,A., Chalmers,R.M., (2003). "Long term study of Cryptosporidium prevalence on a lowland farm in the United Kingdom." Veterinary Parasitology **116**: 97-113.

Svensson, C. and D. A. Jones (2010). "Review of rainfall frequency estimation methods." Journal of Flood Risk Management **3**(4): 296-313.

Tang, J., S. McDonald, et al. (2011). "Modelling Cryptosporidium oocysts transport in small ungauged agricultural catchments." Water Res **45**(12): 3665-3680.

Thomann, R. a. M., J., (1987). Principles of surface water quality modeling and control Harper Collins Publishers Inc.

Timoshenko, S. P. a. G., J. N., (1970). Theory of Elasticity, McGraw-Hill.

Tong, S. T. and S. Naramngam (2007). "Modeling the impacts of farming practices on water quality in the Little Miami River Basin." Environ Manage **39**(6): 853-866.

Vache, K. B., J. M. Eilers, et al. (2002). "Water quality modeling of alternative agricultural scenarios in the US corn belt." Journal of the American Water Resources Association **38**(3): 773-787.

van Griensven, A., T. Meixner, et al. (2006). "A global sensitivity analysis tool for the parameters of multi-variable catchment models." Journal of Hydrology **324**(1-4): 10-23.

Van Liew, M. W., J. G. Arnold, et al. (2003). "Hydrologic simulation on agricultural watersheds: Choosing between two models." Transactions of the American Society of Agricultural Engineers **46**(6): 1539-1551.

Van Liew, M. W. and J. Garbrecht (2003). "Hydrologic simulation of the Little Washita River experimental watershed using SWAT." Journal of the American Water Resources Association **39**(2): 413-426.

Vandenberghe, V., A. van Griensven, et al. (2001). "Sensitivity analysis and calibration of the parameters of ESWAT: application to the River Dender." Water Sci Technol **43**(7): 295-300.

Villaret, C., J. M. Hervouet, et al. (2013). "Morphodynamic modeling using the Telemac finite-element system." Computers and Geosciences **53**: 105-113.

Vinten, A. J. A., G. Sym, et al. (2008). "Faecal indicator pollution from a dairy farm in Ayrshire, Scotland: Source apportionment, risk assessment and potential of mitigation measures." Water Research **42**(4-5): 997-1012.

Wade, A. J., P. Durand, et al. (2002). "A nitrogen model for European catchments: INCA, new model structure and equations." Hydrology and Earth System Sciences **6**(3): 559-582.

Webster, L. F., B. C. Thompson, et al. (2004). "Identification of sources of Escherichia coli in South Carolina estuaries using antibiotic resistance analysis." Journal of Experimental Marine Biology and Ecology **298**(2): 179-195.

White, M. J., R. D. Harmel, et al. (2014). "SWAT Check: A Screening Tool to Assist Users in the Identification of Potential Model Application Problems." J Environ Qual **43**(1): 208-214.

Whitehead, P. G., P. J. Johnes, et al. (2002). "Steady state and dynamic modelling of nitrogen in the River Kennet: Impacts of land use change since the 1930s." Science of the Total Environment **282-283**: 417-434.

Wilby, R. L., P. G. Whitehead, et al. (2006). "Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK." Journal of Hydrology **330**(1-2): 204-220.

Wilkinson, J. (2000). Modelling Faecal Coliform Dynamics. Ph.D. Ph.D., University of Wales, Aberystwyth.

Wilkinson, J., A. Jenkins, et al. (1995). "Modelling faecal coliform dynamics in streams and rivers." Water Research **29**(3): 847-855.

Williams, J. R. a. R. W. H. (1978). Optimal operation of large argricultural watershed with water quality constraints Texas Water Resources Institute, Texas A&M University.

Worrall, F., T. P. Burt, et al. (2009). "Fluvial flux of nitrogen from Great Britain 1974-2005 in the context of the terrestrial nitrogen budget of Great Britain." Global Biogeochemical Cycles **23**.

Worrall, F., H. Davies, et al. (2012). "The flux of dissolved nitrogen from the UK - Evaluating the role of soils and land use." Science of the Total Environment **434**: 90-100.

Wu, X. G. and H. S. Tang (2010). "Coupling of CFD model and FVCOM to predict small-scale coastal flows." Journal of Hydrodynamics **22**(5 SUPPL. 1): 284-289.

Yakirevich, A., Y. A. Pachepsky, et al. (2013). "Modeling transport of Escherichia coli in a creek during and after artificial high-flow events: Three-year study and analysis." Water Research **47**(8): 2676-2688.

Yong, S. T. Y. and W. Chen (2002). "Modeling the relationship between land use and surface water quality." Journal of Environmental Management **66**(4): 377-393.

Yuan, D., B. Lin, et al. (2007). "Development of an integrated model for assessing the impact of diffuse and point source pollution on coastal waters." Environmental Modelling and Software **22**(6): 871-879.

Zabaleta, A., M. Meaurio, et al. (2014). "Simulation climate change impact on runoff and sediment yield in a small watershed in the basque country, northern spain." Journal of Environmental Quality **43**(1): 235-245.

Zhang, X., R. Srinivasan, et al. (2007). "Predicting hydrologic response to climate change in the Luohe River basin using the SWAT model." Transactions of the Asabe **50**(3): 901-910.

Zhang, X. S., R. Srinivasan, et al. (2008). "Runoff simulation of the headwaters of the Yellow River using the SWAT model with three snowmelt algorithms." Journal of the American Water Resources Association **44**(1): 48-61.

Zhou, J., R. A. Falconer, et al. (2014). "Refinements to the EFDC model for predicting the hydro-environmental impacts of a barrage across the Severn Estuary." Renewable Energy **62**: 490-505.