CHAPTER II

LITERATURE REVIEW

This chapter focuses on reviewing hydrologic modelling, particularly with regards to the hydrologic cycle, watershed hydrology, watershed modeling, and watershed models. However, the review on watershed models is more exhaustive because this is the main topic of this research project.

2.1 HYDROLOGIC CYCLE

Hydrological cycle is the perpetual movement of water throughout the various component of the global Earth’s system (Labat, 2006). The water cycle has no beginning or end, however it includes precipitation falls upon the Earth‘s surface as rain, snow, sleet or hail. The schematic diagram of the hydrologic cycle processes is presented in Figure 2.1. Water that reaches the ground surface will be absorbed, stored in small depressions, or flow downslope over the surface. The absorbed water that has infiltrated into the soil becomes soil moisture. This soil moisture may remain in place, flow downslope toward a stream as runoff, or percolate vertically to become groundwater. Some of the water temporarily stored in the soil may evaporate from the soil surface or be taken up by plant roots and transpire from the plant’s leaves (Shilling et al., 2005; Schwab et al., 1993).

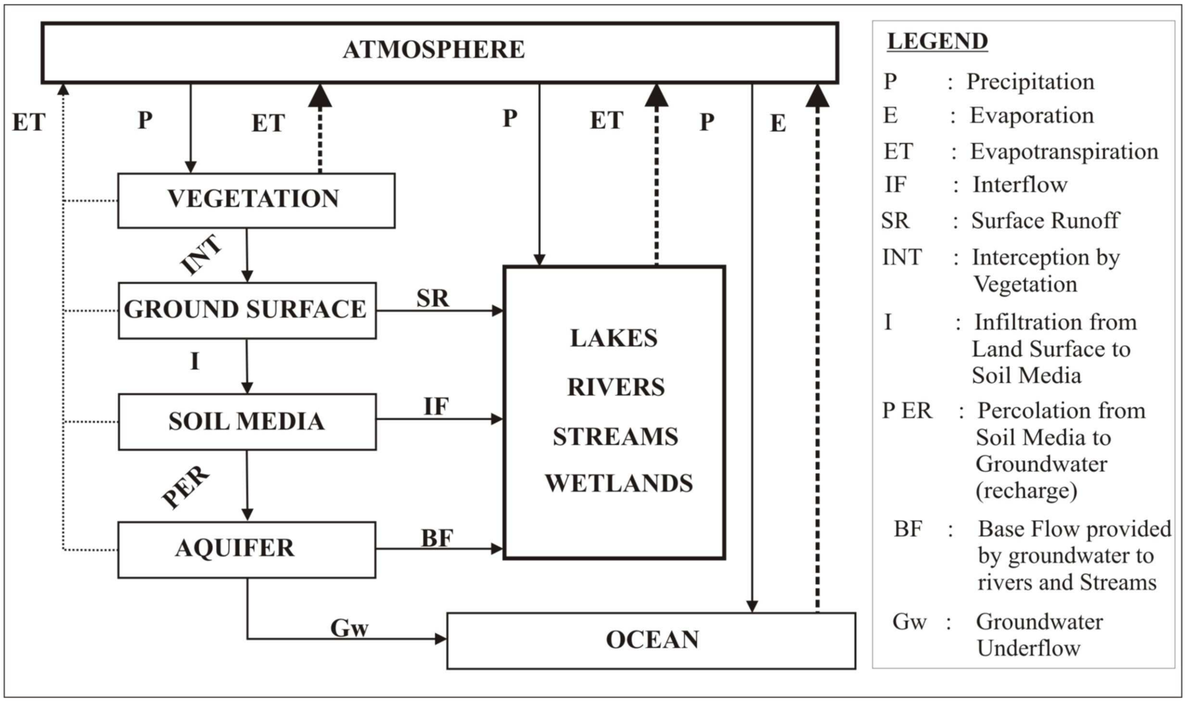

FIGURE 2.1
A System Representation of the Hydrologic Cycle

2.2 WATERSHED HYDROLOGY

Watershed which is delineated by a topographic or groundwater divide is an up-slope area that generates flow to a certain down-slope location (Warren and Gary, 2003). Traditionally, the main aims of hydrological research have been to provide an understanding of the water balance operating in forested catchments or watersheds, the physical processes that control water movement and the impacts on water quantity and quality (Mungai et al., 2004). Vast forests in many upland watersheds of mainland Southeast Asia have now been replaced by fragmented landscapes consisting of remnant forest patches and various human-disturbed land covers (Ziegler et al., 2004).

Figure 2.2 illustrates all the components of land phase of the hydrologic cylce which are required for water balance in a watershed.

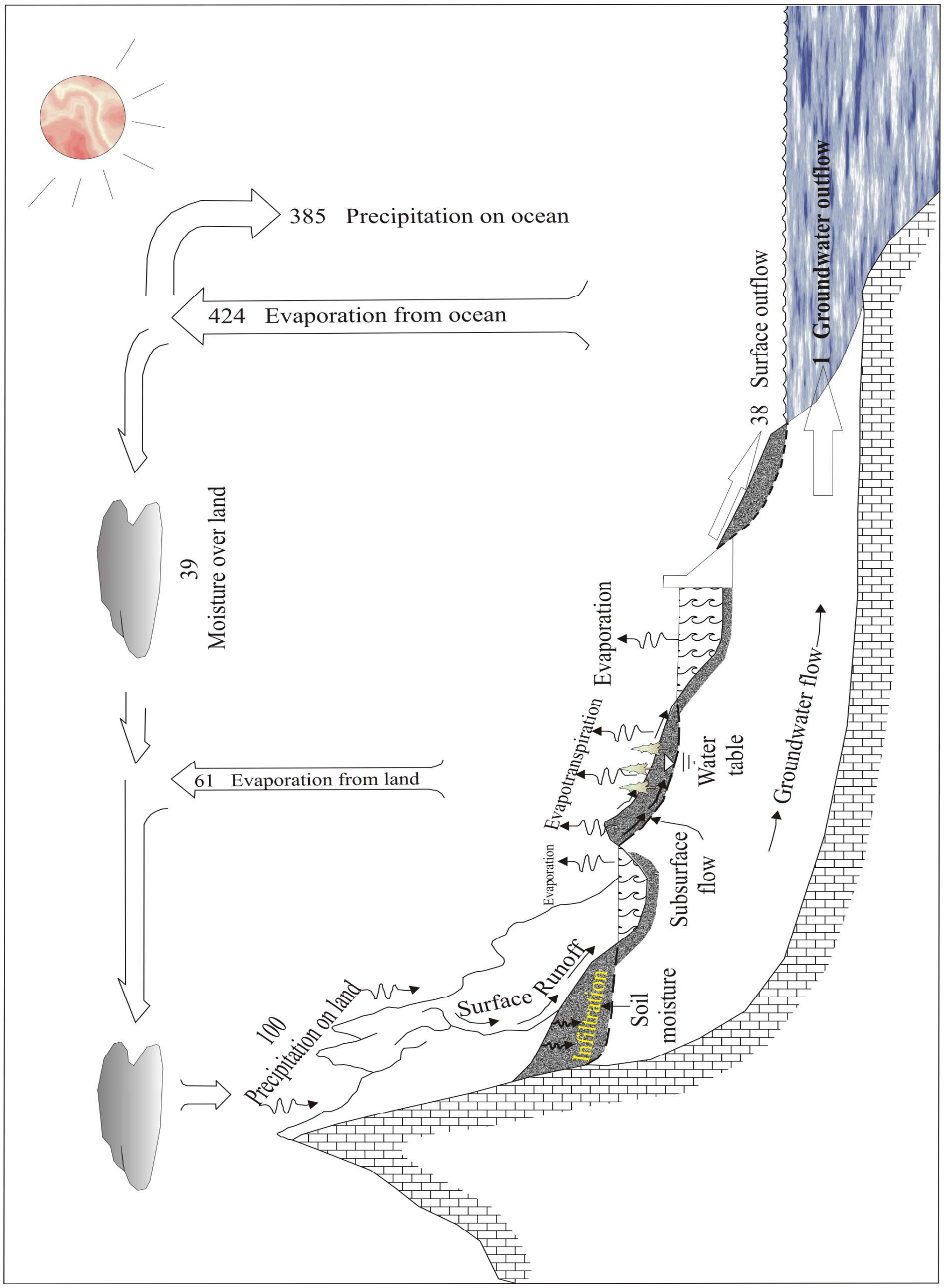

FIGURE 2.2
Hydrologic cylce components with golobal annual average water balance given in units relative to value of 100 for the precitiparion rate on land (Modified after Chow et al., 1988)

One watershed can consists of several sub-watersheds or can be a part of a larger watershed or river basin. The characteristics of a watershed (topography, geology and land cover) play an important role in determining the quantity, quality and timing of stream flow at its outlet as well as of groundwater outflow. Theoretical representation of watershed hydrology is mostly based on physical laws, particularly those of conservation of mass, Newton‘s laws of motion and the law of thermodynamics. The assumption is that the amount of water entering a watershed is equal to the amount of water leaving the watershed plus the net change in storage in the watershed that is:

$$\text{Input} - \text{Output} = \text{Net Change in the storage} \tag{2.1}$$

The water balance of the watershed may be expressed as a mathematical equation showing the relationship among the various hydrologic components as shown in Equation (2.2) is as follows: (Flerchinger and Cooley, 2000).

$$P - Evap - Trans - Int - Ds + Qin + GWin - QWout - Gout \pm \Delta S = 0 \tag{2.2}$$

where,

P: is Precipitation

Evap: is Evaporation

Trans: is Transpiration

Int: is Interception

Ds: is Detention Storage

Qin: is Surface Inflow

Qout: is Surface Outflow

GWin: is Groundwater Inflow

GWout: is Groundwater Outflow

ΔS: is Changes in Storage

While precipitation generates the main input to the cycle, evaporation and transpiration constitute the main losses of water from the groundwater and surface water systems to the atmosphere (Figure 2.2).

2.3 WATER RESOURCE MANAGEMENT PROBLEMS

Integrated Water Resources Management (IWRM) requires planning and management activities to consider a broad set of sectors such as environment, energy, industry, agriculture, and tourism. IWRM is thus characterized by a high level of complexity, because it requires the involvement of numerous decision makers operating at different levels and a large number of stakeholders with conflicting preferences and different value judgments (Giupponi, 2005). It is obvious that water resources management has been an important issue in this century under the specified situation of climate change, regional development and population increase. Moreover, the modern life has become vulnerable to water environment affected by climate change. New water-related technologies may create the additional water consumption or drastic water saving. Freshwater withdrawals by human activities have increased dramatically over the years (Kojiri, 2008). Adequate methodologies and tools are therefore needed, in order to support IWRM, with a leading role to be played by science and research as a support to policy development and implementation (Giupponi, 2005).

Dow et al. (2007) conducted survey of community water systems (CWS) managers in South Carolina and in Pennsylvania's Susquehanna River Basin addresses perceptions of climate vulnerabilities focusing on droughts, lightning strikes, and floods. They found that the water resources sector, in coping with current climate variability and anticipating future vulnerabilities to climate changes, represents an important example of the challenges that come with integrating multiple elements in a vulnerability assessment. Climate and hydrological systems intersect with financial, regulatory, and management systems in the CWS, where knowledge and infrastructure facilitate the mitigation of climate impacts.

2.3.1 Water resource problems in Malaysia

Climate-related events (e.g. droughts or floods) may place stresses on a variety of subsystems (e.g., infrastructure or ecosystems), and interact with other pressures on the system to lead to a diverse set of primary and higher-order impacts (e.g., water rationing, job layoffs, or loss of recreational opportunities) relevant to vulnerability assessment and adaptation efforts (Dow et al., 2007).

Malaysia is rich in terms of water resources, receiving an abundant amount of rain every year. The average annual rainfall is 2,400 mm for Peninsular Malaysia, 3,800 mm for Sarawak and 2,600 mm for Sabah (Ministry of Natural Resources and Environment of Malaysia, 2007). Table 2.1 illustrates the contribution of different water resources in water budget for Malaysia.

Even though, water resources are theoretically abundant in Malaysia, variation over space and time has rendered problems of excess and scarcity at various times and space. The general misconception was that Malaysia has no water shortage until the water crisis hit Selangor, Kuala Lumpur and Penang in 1998 and Melaka in 1991 and again in 2002 (Bahaa-eldin, 2005).

TABLE 2.1
Water Resources in Malaysia

Resources	**Quantity** (billion m^3)
Annual rainfall	990
Surface runoff	566
Evapotraspiration	360
Groundwater recharge	120
Surface artificial storage	25
Groundwater storage	5000

Source: Source: Minerals and Geoscience Department of Malaysia (2003)

The problems are not about having too little water to satisfy Malaysians needs, as in some water-scarce countries, or too much to cope with, rather, it is a problem of not managing water effectively to achieve the desired results. In some river basins, there is already the problem of water shortage especially during periods of prolonged droughts, and conversely, the problem of excessive water and floods during the wet season (Ministry of Natural Resources and Environment of Malaysia, 2007).

(a) Water shortage - drought

Parallel to the growth in population and the good economic environment over the years which has resulted in extensive industrialization, emphasis was also given to agricultural activities in line with the country's policy to make agriculture the third engine of growth for the economy. Collectively, these have imposed a continuously increasing water demand, and to some extent, caused water stress to certain regions of the country where the demand has exceeded the discharge capacity of the river basins. Given that water is a finite resource, its per capita availability in future will definitely decrease due to these factors (Ministry of Natural Resources and Environment of Malaysia, 2007).

Through the degradation of the natural environments, anthropogenic activities can alter the climate, which can, in turn, cause drought in certain areas. For example, deforestation reduces the on-site rainfall depth, number of rainfall events, and ground water recharge, while concomitantly increasing surface runoff. Many countries, such as Indonesia (1982-1983), the eastern half of Australia, California (1976-1977), India (1982-1983), southern and eastern Africa, and some parts of Europe (1989-1990), have recently faced severe drought problems (Clarke, 1993).

Almost all the water used in this country is extracted from surface water sources with groundwater contributing only about 3 %. Although the annual rainfall is very high (3,000 mm average) there are large variations both in time and in space, and river flows are prone to large fluctuations as well. Hence Malaysia is subject to prolonged dry periods which can easily affect its freshwater supply. This has led to drought occurrences in the past with the most notable one being that of the 1997/98 El Nino related drought which caused extensive impact to the environment, economic and social activities of the whole nation (Ministry of Natural Resources and Environment of Malaysia, 2007).

In many countries, to meet water demands, groundwater is being used for domestic, industrial and irrigation purposes in a non-rational manner, where usage exceeds water replenishment through precipitation and/or groundwater recharge (Clarke, 1993). In some parts of Malaysia such as Selangor, Sarawak and Sabah states, the prolonged drought resulted in a lowering of the groundwater table especially in peat areas, and consequently many cases of extensive forest fires. The local air quality condition became worse because of the thick haze blown from forest fires both locally and from neighbouring countries. Such a situation persisted for months and posed a serious threat to the health of the people. In some places, schools had to close down temporarily and there was poor vision for the traffic including problems to the pilots in landing their aircrafts (Ministry of Natural Resources and Environment of Malaysia, 2007).

(b) Excess water - flooding

Even though Malaysia has seemingly sufficient water resources to meet all our needs for the foreseeable future and not too excessive as compared to other countries like Bangladesh, there are some water-related problems which have raised concerns among water engineers and the public. (Ministry of Natural Resources and Environment of Malaysia, 2007).

Flash-floods have caused countless grievances to the urban folks of Malaysia. In February 2006, a severe flash-flood occurred at the Shah Alam Municipality in the lower Klang River Basin, which caused damages to properties worth approximately 25-million US dollars. The 104 mm rain recorded within 3 hours had caused the water level to rise to a depth of about 1.6 m in some residential and commercial areas, thereby destroying thousands of homes and properties. Despite extensive structural flood-mitigating measures, Malaysia is still frequently hit by severe flash-floods, as indicated by the various events that occurred in 2007 (Wardah et al., 2008).

Rainfall is one of the most difficult variables to forecast; due to its large variability, both in space and in time. Recent advances in radar meteorology have improved the rainfall forecasting process remarkably. Nevertheless, radars can measure the rainfall intensity only after the formation of raindrops. So as to forecast rainfall as early as possible, prediction of the development of convective clouds and the associated precipitation system assumes great significance (Ministry of Natural Resources and Environment of Malaysia, 2007). Numerical weather prediction rainfall forecasts are considered too coarse in their spatial and temporal resolution; hence they are rarely used as direct inputs in rainfall-runoff models for flood forecasting (Nakakita and Uyeda, 2003).

Anthropogenic actions such as deforestation and urban development also greatly influence the flooding events. While deforestation reduces the time taken by the precipitation-derived surface runoff to infiltrate and urbanization reduces the amount of pervious areas available for infiltration, both processes lead to an upward shift in the runoff-rainfall ratio, which in turn, causes greater detachment and carrying of sediment to rivers and lakes (Clarke, 1993). A study carried out in United States showed that urban development in a watershed increases the potential of flooding (Rogers and DeFee, 2005).

2.4 SOIL HYDRAULIC PARAMETERS

The soil surface plays an important role as a boundary between the atmosphere and the unsaturated zone; it separates hydrologic processes (e.g., rainfall and irrigation, into runoff and infiltration). Soil moisture content is of fundamental importance in hydrological processes. How much water infiltrates, evapotranspires, and recharges the subsurface depends on the soil moisture content (Mertens et al., 2004).

Water movement in the unsaturated zone can be modeled mathematically with a combination of Richards's equation and Darcy's law (Nazrul et al., 2006). Surface soil hydraulic properties are key factors controlling the partition of rainfall into runoff and soil water storage, and their knowledge is needed for sound land management (Bodhinayake and Si, 2004). Soil physical properties chiefly determine the value of soil hydraulic function parameters. Clayey soil has more and smaller pores, broader pore size distribution (i.e., range of soil water pressure head is greater) and lower bulk density compared to sandy soil. The clay soil has lower bulk density and hence higher saturated water content, and having more small pores, it retains more water and hence higher residual water content, compared to sandy soil (Nazrul et al., 2006). Soil with broader pore size distribution such as clay soil yields lower porosity, because for the same change in soil water pressure head, the water content change is less than for sand. For clay soil having few, if any, large pores, the bubbling pressure is higher and the reciprocal of bubbling pressure head is low compared to sandy soil (van Genuchten, 1980).

Richards's equation remains the most general method to compute hydrological processes particularly in coupled surface water and groundwater interaction models. These processes include soil moistures and hydrological fluxes such as infiltration, runoff, evapo-transpiration (ET) and groundwater recharge. Soil layering, shallow groundwater table and the effects of soil moisture on infiltration, are all easily incorporated into the Richards's equation model solution (Downer and Ogden, 2004).

The prerequisites for both Richards's and Darcy's equations are parameters in the functional relationships between (1) soil water pressure head h and volumetric water content θ [θ (h)], and (2) soil hydraulic conductivity K and the pressure head or water content [$K(h)$ or $K(\theta)$]. Horizontal and vertical soil heterogeneities make modeling of water movement complex and elusive. Inaccurate estimation of the hydraulic properties, which are input to physically-based hydrologic models, compromises accurate simulation of the water balance variables (Xevi et al., 1997; Christiaens and Feyen, 2001; Vazquez and Feyen, 2003).

2.5 RAMSAR CONVENTION ON WETLANDS

Wetlands are areas where water is the primary factor controlling the environment and the associated plant and animal life. They occur where the water table is at or near the surface of the land, or where the land is covered by shallow water (Ramsar, 2008a).

The Convention on Wetlands signed in Ramsar town (Northern Iran), in February 2nd, 1971; is an intergovernmental treaty for the conservation and sustainable utilization of wetlands which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. There are presently 158 Contracting Parties to the Convention, with 1760 wetland sites, totaling 161 million hectares, designated for inclusion in the Ramsar List of Wetlands of International Importance (Ramsar, 2007a).

The Ramsar List was established in response to Article 2.1 of the Convention on Wetlands, which reads: "Each Contracting Party shall designate suitable wetlands within its territory for inclusion in a List of Wetlands of International Importance, hereinafter referred to as 'the List' which is maintained by the bureau [secretariat of the Convention] established under Article 8" (Ramsar, 2007b). The international criteria for wetlands designation are illustrated in Table A.1 (Appendix A).

2.5.1 Ramsar listed wetlands of Malaysia

Located in the tropics and with a long coastline, Malaysia has an extensive area of wetlands. The Malaysian Wetland Directory lists 105 wetland sites. Mangroves, river system, tropical peat swamp forest constitute the main wetlands ecosystem found in Malaysia (Malaysia Wetlands, 2008).

In 1994, Malaysia signed the Ramsar Convention on Protection of Wetlands. Today, Malaysia has five Ramsar sites. Johor boast the largest with three sites located at Sg. Pulai, Pulau Kukup and Tanjung Piai. The mangrove area north of Kuching is the most recent inclusion into the Ramsar list. While as Tasek Bera was nominated as the country's first Ramsar site. Located in southwest Pahang, Tasik Bera is the largest natural freshwater lake in Peninsula Malaysia. Situated in the saddle of the main and eastern mountain ranges of the Peninsula, it is home to the Semelai community, one of the indigenous communities in Malaysia. Tasik Bera has remained a unique and remote wetland wilderness, which is surrounded by a patchwork of dry lowland forests (Ramsar, 2007b; Malaysia Wetlands 2008). Details about the Ramsar-listed Malaysian Wetlands are shown in Appendix B.

2.6 MODELLING

Model is a representation of a system of the natural or human-constructed world that allows for investigation of the properties of the system, and predicts the future outcomes. It can principally be classified as physical, analog, or mathematical as illustrated (Figure 2.3). The mathematical modelling normally consists of a number of equations and numerical and logical solutions, which converts numerical inputs into numerical outputs. The observations of one process in an analog model are used to forecast another physically analogous natural process. Due to the fast and extensive advances in computer technology mathematical models took over the pioneer place of physical and analog ones (Dingman, 2002; Brooks et al., 1991).

Figure 2.3 illustrates different mathematical models which are further subdivided into several classes. Empirical models derived from field of laboratory experiments or observed input-output relationships, and theoretical (physically-based) models based on physical laws and theoretical principles (Brooks et al., 1991). Governing equations in a deterministic model, count for every parameter, whereas in a stochastic (probabilistic) model, the model parameter or input variables are totally or partially described by probability equations. A distributed model counts for the spatial variability of input parameters in contrast to a lumped model Warren and Gary (2003). Unlike the Event-based and single-event models which compute a particular event or process for a short time period, the continuous model has the capability of forecasting the event for several years. The governing equations are solved mathematically in an analytical model, while as in numerical model; the governing equations are solved approximately using arithmetic operations.

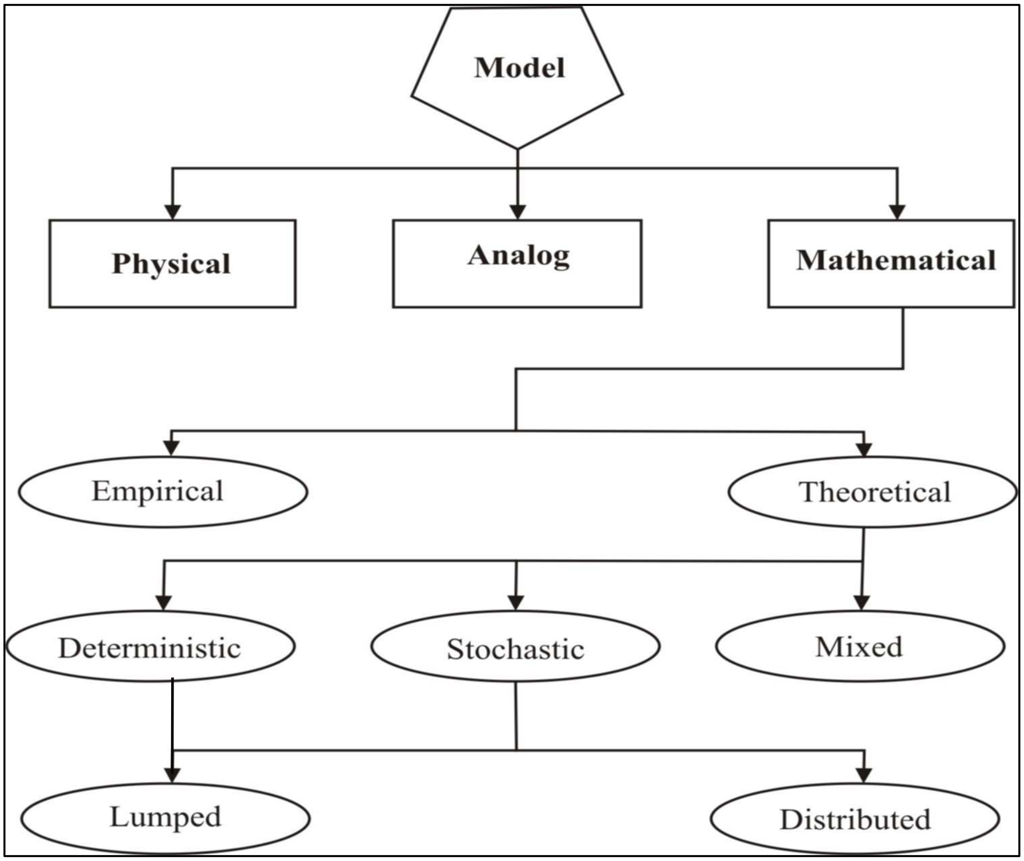

FIGURE 2.3
Classification of hydrologic models (modified after Singh, 1995)

Hydrologic processes and event are better understood by simplifying the actual hydrologic regimes using numerical modelling to predict hydrologic responses and allow one to study the function and interaction of various inputs (Brooks et al., 1991). Figure 2.4 illustrates the modeling protocol that used in the present study.

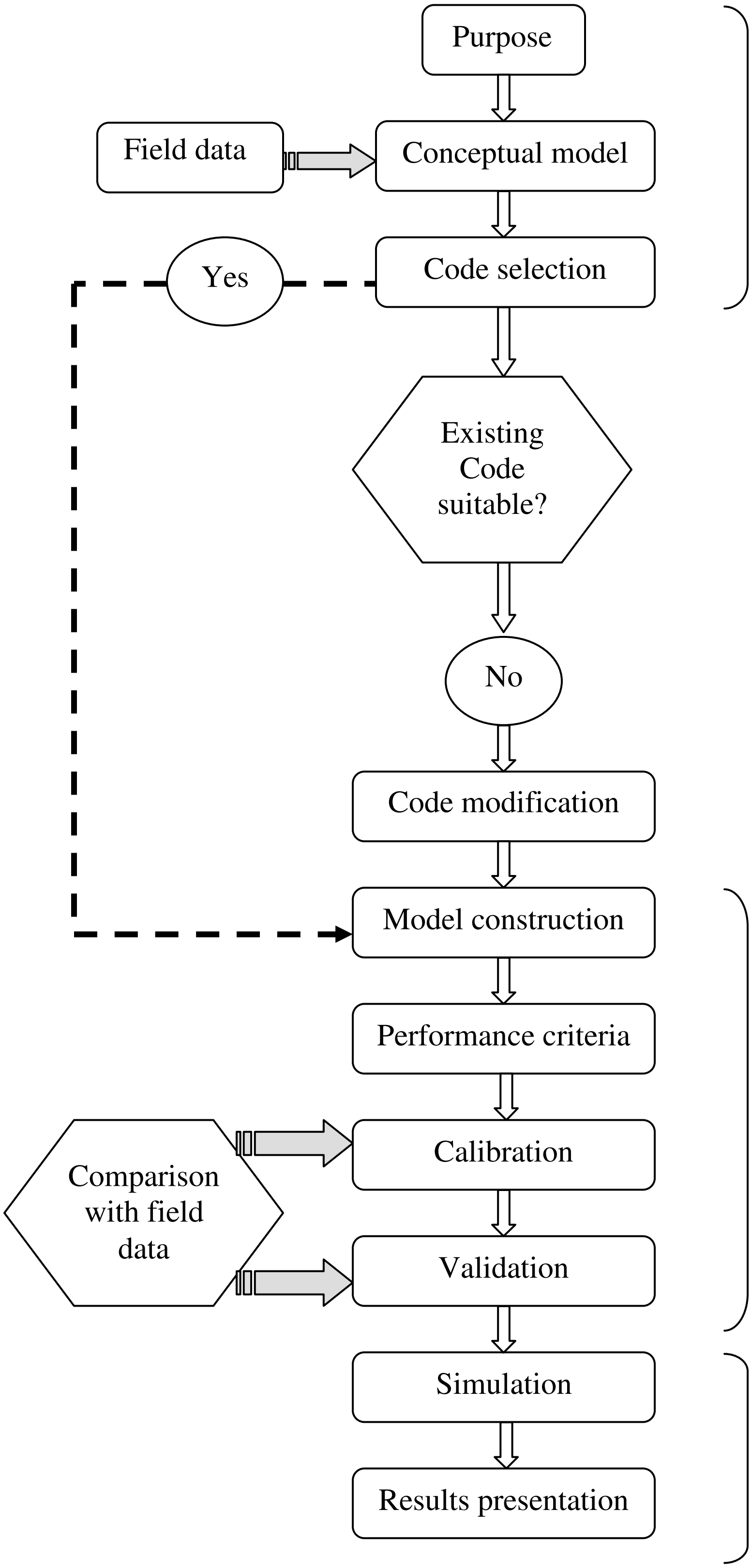

FIGURE 2.4
The modelling protocol and schedule proposed for the present study

The primary objective of hydrologic models is to account for the distribution and movement of water over land, underground, and in stream, as well as the quantity of water stored in the soil and in natural bodies of water and their exchange. These can also account for changes in rates and quantities over time. In recent decades hydrologic models have been developed and extensively applied due to the variability, complications and limited and non-availability that normally associated with the tempo-spatial-distributed climatic, hydrological, soil and landuse data (Dingman, 2002). Singh (1995) classified the watershed numerical models into 5 main categories as follows:

(i) geometry of the model
(ii) Input
(iii) governing equations
(iv) initial and boundary conditions
(v) output.

2.6.1 Watershed models

The first watershed model was the Stanford Watershed Model which was developed in 1966 by Crawford and Linsley (Singh, 1995). Unlike many hydrologic models which simulate hydrological processes mostly at local, relatively small and/or field-scale, watershed models can simulate these processes in regional and/or watershed-scales. Recently, numerous watershed models have become sophisticated and able to address different hydrological issues. Currently there are so many well-known watershed models which include for instance, AnnAGNPS, ANSWER-2000, CREAMS, EPIC, HEC-1, HSPF, MIKE SHE and SWAT (Parsons, 2004; Singh, 1995).

(a) AnnAGNPS Model - ANNualized AGricultural Non-Point Source model

This model is an updated version of AGNPS which considers only daily input data, however the model can produce outputs on an event, monthly, or annual basis. It was first developed in 1980 by the U.S. Department of Agriculture, Agricultural Research Service, U.S. Soil Conservation Service and Minnesota Pollution Control Agency. It was designed to assess storm water quality from agricultural catchments of areas ranging from a few hectares up to three hundreds thousand hectares. According to Bosch et al. (2001) and Young et al. (1995) this model can perform risk and cost-benefit analysis, and handle problems that are associated with managing storm water, erosion and nutrient movement. It is semi-empirical, distributed-parameter, continuous simulation, and watershed-scale model. The rate and volume of storm water are calculated using the TR-55 and SCS-Curve number methods respectively, in that the simulation of overland flow is due to storm events only.

Unlike adequacy of long-term monthly and annual runoff prediction, AnnAGNPS performance encountered some deficiency when it comes to prediction of overland flow. Suttles et al. (2003) and Yuan et al. (2001) found that AnnAGNPS did not properly represent the overland flow in the riparian areas; some more over-predict nutrients and sediment loads. Those researchers suggested improvement of the grid discretization of the model in order to estimate runoff properly. Similarly, in a study conducted in Nepal by Shrestha et al. (2005) the model over-estimated event-based peak flows. In contrast the model performed satisfactorily with an acceptable accuracy when predicted overland event flow under Australian and Canadian conditions (Das et al., 2008; Baginska et al., 2003). The AnnAGNPS neither simulates baseflow nor accounts for spatially distribution of rainfall over the catchment. Accordingly the calculation of water inflow and outflow water balance is not included for the model processor. Apart from that, the overland prediction is not fully based on physical equations.

(b) ANSWERS-2000 Model - Areal Non-point Source Watershed Environment Response Simulation

This model is a physically-based, distributed parameter, continuous simulation, watershed-scale model which was developed in the 70s by Beasley and Huggins (Dillaha et al., 2004). Its design aims at simulating flow in ungauged catchments where calibration is very hard to be achieved. Furthermore it can be used to assess the efficiency of agricultural and urban catchments best management practices in decreasing sediment and nutrient transport to streams during surface storm events. Data manipulation can be performed via the Arc-Info link, thus allows easy input and output. Generally the applicability the ANSWERS-2000 is bound to medium-size watersheds of areas ranging between 500 and 3000 hectares which are dominated by surface hydrologic processes. Depending on the management practices and the homogeneity of soil characteristics, slopes, landuse, types of crops, and nutrients the modelled catchment can be divided into unique grid squares of maximum1 ha. The ANSWERS-2000 uses breakpoint rainfall. Generally it uses very short time-steps (30 second) when simulating overland flow during storm events otherwise a 24-hour time step is adopted in between storm events. Furthermore it counts for all the hydrological processes in both the surface unsaturated zone including ET, interception, surface retention and detention, infiltration, percolation, overland flow, and channel flow (Dillaha et al., 2004; Ward and Benaman, 1999).).

The efficiency of the model performance was examined and found reasonably accurate at simulating different vegetation cover conditions at a catchment outlet (Connolly et al., 1979). However, the same researchers found that the model was rather inaccurate than for high intensity events when it comes to prediction of overland flow and channel flow for less rainfall event during dry seasons. Thus they recommended that this model to be used for complex watersheds, without calibration.

ANSWERS-2000 is unable to simulate interflow and groundwater contributions to base flow. Therefore, the model is considered unsuitable for wetlands and areas where vadose zone controls the lateral and vertical flow of water between saturated and unsaturated zone.

(c) CREAMS Model – Chemicals, Runoff, and Erosion from Agricultural Management Systems

According to Knisel and Williams (1995).This model was developed in the year 1978 by the United States. Department of Agriculture - Agricultural Research Service. The model design was aimed mainly at assessing non-point source pollutant loadings under different management scenarios. Like ANSWERS-2000, The CREAMS model counts for the hydrologic processes that control overland and channel flows such as precipitation, infiltration, distribution soil water, percolation, evaporation, transpiration, overland flow and channel flow. CREAMS Model counts for surface runoff using the SCS curve number method which uses daily rainfall data to estimates instantaneous peak runoff rates. Otherwise a modified Green and Ampt infiltration method, however this method requires either a breakpoint or hourly rainfall input data. When the infiltration method is applied, the volume and rate of runoff are computed by summing the runoff at each time interval and routed to the field outlet. Potential evaporation is estimated using the Priestly-Taylor method, while evaporation and transpiration are estimated using Retch's method (Knisel and Williams 1995).

CREAM-WT is a modified version of CREAMS considered temporal variability in soil hydraulic conductivity and soil erosion. Rudra et al. (1985) used the modified version to evaluate the water quantity and quality under southern Ontario conditions. They found that the performance of the modified version was satisfactory as compared to the original version. CREAM -WT was also applied to simulate shallow groundwater table in a coastal catchment in Florida where it predicted overland flow, ET, infiltration and soil moisture content reasonably good relative to the original version (Heatwole et al., 1987).

The CREAM model does not account for baseflow. Also, the model is lumped based on homogeneous soil, a single crop cover and management practice, and uniform rainfall over the entire watershed area. Thus it does not have the integration nature to be capable of modelling wetlands.

(d) EPIC Model - Erosion-Productivity Impact Calculator

This is a continuous simulation model, was developed to study the impact of soil erosion on soil productivity (Williams, 1995). According to Williams and Arnold (1997) the model is considered an agricultural management tool which composed of many simulation components including weather, hydrology, sedimentation, erosion, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics and plant environmental control. In order to forecast the weather conditions EPIC requires set of hydro-meteorological parameters including rainfall, air temperature and solar radiation. The SCS curve number method is used for the determination of surface runoff volume. In contrast to calculate the peak runoff rate the EPIC processor can pick the SCS TR-55; or otherwise alternatively the modified rational formula can be used. While infiltration, overland flow, channels flow, lateral subsurface flow, ET, and dynamics of water table can be computed by the hydrology component. Vertical interlayer's flow is simulated by the percolation component of the model using a storage routing technique, that is to say, the flow occurs when soil water content exceeds field capacity. The potential evaporation is calculated by several methods including (i) - Penman-Monteith, (ii) - Penman, (iii) - Hargreaves and Samani, and (vi) - Priestley-Taylor. Generally EPIC is capable of calculating crop yield reduction caused by the excess soil moisture it can also be used in setting-up irrigation planning based on the level of plant water stress (Williams, 2002).

EPIC was efficiently applied to rank different soil water systems using the daily soil moisture content which were computed by the model. The EPIC model has also been used as multi-disciplinary approach by coupling to other models in order to assist in decision-making and irrigation management for water release policies in a watershed in Oklahoma, United States (Costantini et al., 2002; Evers et al., 1998). Nonetheless EPIC model showed some considerable limitations which include:

- Inability of baseflow simulation
- Assumption of homogeneity of weather, soil, and management systems
- Simulation of runoff using empirical equations
- Being limited for catchments of maximally 100 hectares area

(e) HEC-1 Model

This is deterministic semi-distributed and single-event rainfall-runoff model which was developed in 1968 by the United States Corps of Engineers. The abbreviation HEC stands for the Hydrologic Engineering Center model (Feldman, 1995). It was developed from a series of small programs that simulate some parts of the rainfall-runoff process. The model can minimally run on 1-minute time-step and model catchments, of areas ranging between 1 km^2 and 100,000 km^2. Hydrographs for gauged and hypothetical rainfall events can be produced by the HEC-1 at one or more positions within the modelled catchment. The model has the ability to simulate rainfall, rainfall losses (due to interception and infiltration), baseflow, runoff transformation and routing for each sub-basin (Feldman, 1995; Kobold and susnik, 2000). HEC-1 model use a simplified method to model the baseflow which requires initiating flow, a recession threshold, and a logarithmic decay recession rate. The loss component includes the detention storage, infiltration, and interception. The HEC-1 model counts for the runoff using i)- the unit hydrograph / SCS curve number method, and ii)- kinematic wave. The Incorporated Muskingum-Cunge flood routing, reservoir releases input over time, and improved numerical solution of kinematic wave equations represent improvement and expansions to the hydrologic simulation capabilities together with interfaces to the HEC Data Storage System, DSS. The Muskingum- Cunge routing may also be used for the collector and main channels in a kinematic wave land surface runoff calculation (Hydrologic Engineering Center, 1998; Feldman, 2000). The model can, therefore, be either physically-based or empirical, based on the adopted procedure of simulation.

HEC-1 kinematic wave procedure was used to forecast runoff for ungauged watersheds (Duru and Hjelmfelt, 1994). They found that, despite the limited calibration process, the model performance was good. Furthermore, the landuse impacts on the hydrologic cycle could be assessed accurately. However, Smith and Goodrich (1996) argued against this conclusion in that the infiltration algorithm of the HEC-1 model assumes step function infiltration behavior: after an initial extraction amount, the infiltration rate is assumed to fall suddenly to a constant value. Since this would only happen for a shallow porous layer over an impermeable barrier, both the initial rainfall loss and the constant loss rate are simplifications which must vary with storm characteristics, and thus are not physically based parameters. Another considerable limitation of HEC-1 is that the model simulates flooding using one-dimensional Muskingum-Cunge model which in turn are more inaccurate than the dynamic wave model because acceleration terms are ignored (Merkel, 2002). Thus the HEC-1 is incapable of handling hydrological investigations in watersheds in which integrated surface and subsurface flows feature.

(f) HSPF Model – Hydrological Simulation Program FORTRAN

Hydrological Simulation Program—FORTRAN (HSPF) is a comprehensive numerical model. It was developed in 1974 by United States Environmental Protection Agency (USEPA) as an extension of three models (ARM, NPS and HSP) and based on the original Stanford Watershed Model IV. The key steps in modeling a watershed with HSPF are the mathematical representation of the watershed, the preparation of input meteorological and hydrological time series, the estimation of parameters and the calibration and validation process (Castanedo et al. 2006). HSPF model simulates water movement conceptual in terms of overland flow, interflow and groundwater flow. The overland flow consists of an infiltration-excess mechanism. These processes may include land use changes on water, sediment and contaminant transport. HSP, based on the original Stanford Model IV, can simulate both the land area of watersheds and the water bodies like streams or lakes (Albek et al., 2004; Crawford and Burges, 2004; Johnson et al., 2003).

The semi-distributed model employs HRUs (hydrological response unit) based on uniform climate and storage capacity factors. The flow from each HRU is routed downstream using the storage routing kinematic wave method. The HSPF model has a modular structure and is a lumped parameter model. Pervious land segments over which an appreciable amount of water infiltrates into the ground are modeled with the PERLND module. Impervious land segments, over which infiltration is negligible, such as paved urban surfaces, are simulated with IMPLND module. Processes occurring in water bodies like streams and lakes are treated by the RCHRES module. These modules have several components dealing with the hydrological processes and processes related to water quality (Albek et al., 2004). The model provides a water budget.

In a study carried out by Brun and Band, (2000) the HSPF Model was use to assess the impacts of land use changes on a catchment behavior and analyze the linkage between the runoff ratio baseflow. They found that when the percentage impervious cover exceeds an initial value of approximately 20 %, the observed runoff increases remarkably while at the same time baseflow decreased. However, the HSPF requires a 3-years simulation period in order to initiate transient model before calibration and validation. HSPF was efficiently used by Albek et al. (2004) to model hydrological behavior of an agricultural watershed in Turkey, the Modelling process aimed also at modelling of all the components of the hydrological cycle under different climate and landuse changes scenarios. Nonetheless the HSPF model is considered incapable of addressing wetlands problems due to (i)- being partially-distributed (ii)- being partially physically-based by applying physical and empirical equations for water flow simulation (iii)- lumping the catchment characteristics and climatic parameters into a few units.

(g) MIKE SHE model

MIKE SHE is an integrated, deterministic, fully distributed watershed and physically-based model. It comprises the whole flow modules which can describe the flow within the entire land-based part of the hydrological cycle including evapotranspiration and interception, overland flow and channel flow, unsaturated zone, saturated zone, and river/aquifer exchange. The original MIKE SHE model was developed and became operational in 1982, under the name Systeme Hydrologique European (SHE) (Yan and Zhang, 2005). Later the model was developed for water resources managers who were concerned with rapidly changing landuse practices in agriculture, forestry and wetlands (Danish Hydraulic Institute 1998). The model was sponsored and developed by three European organizations including the Danish Hydraulic Institute (DHI), the British Institute of Hydrology, and the French consulting company SOGREAH. MIKE SHE model is applicable to a wide range of water resources and environmental problems related to surface water and groundwater systems, and the dynamic interaction between the two regimes (Hosseinipour 2005; Ward and Benaman, 1999). The MIKE SHE modeling system consists of a water movement module and several water quality modules. The water movement module simulates the hydrological components including evapotranspiration, soil water movement, overland flow, channel flow, and groundwater flow. The related water quality modules are: (i)- advectiondispersion, (ii)- particle tracking, (iii)- sorption and degradation, (iv)- geochemistry, (v)- biodegradation, and (vi)- crop yield and nitrogen consumption. The most recent model enhancement was the development of an integrated surface water and ground water model by coupling the water movement module of MIKE SHE with the channel flow simulation component of MIKE 11 (Yan and Zhang, 2005). It has a modular structure, which enables data exchange between components as well as addition of new components. The topography along with watershed characteristics (vegetation and soil properties) is included into the model (Abbott et al., 1986a).The model is used mostly at the watershed scale and from a single soil profile to several sub-watersheds with different soil types (Danish Hydraulic Institute, 2004). At each grid point MIKE SHE spatially distributes all the catchment modelling parameters. These include all the hydro-meteorological variables, vegetation input and hydrological responses through an orthogonal grid network and column of horizontal layers (Abbott et al., 1986b). The flexibility of MIKE SHE operating structure allows using any number of components depending on the availability of input data and, for sure, the financial roof for the specific project.

MIKE SHE modelling system has been widely used by water management personnel, scientists and engineers. Thompson et al. (2004) developed a procedure to evaluate evaporation from ditch surfaces using a coupled MIKE SHE / MIKE11 model for a lowland wet grassland in southeast England. They concluded that dynamic calculation of evaporation from ditch water surfaces would enhance the ability of the model to explore alternative water level management and climate change scenarios, thus, the coupled model has the capability to handle wetland situations.

Several studies have been conducted using the MIKE SHE model in different regions and under diverse soil and climatic conditions. Sahoo et al. (2006) modelled the hydrological response of a mountainous-terrain catchment. They found that the model under-estimated the channel flow large storm events; however gave a correlation of 0.7 between observed and simulated channel flow. Demetriou and Punthakey (1999) efficiently used the MIKE SHE to tackle the problem of fluctuations of groundwater table and the subsequent salinity in an Australian catchment of complex hydrogeological system. Their results indicated that the model accurately simulated the spatial and temporal groundwater flow, runoff and water flow from drainage and supply system.

Sonnenborg et al. (2003) focused on the problem of how the steady-state system should be conceptualized in order to obtain parameter estimates resulting in consistency between the steady-state and transient models. Their results show that the estimated parameters are highly sensitive to the way that the steady-state model is conceptualized. Furthermore the study suggests how the steady-state model should be conceptualized in order to obtain reliable parameter estimates that produce acceptable transient model results.

MIKE SHE was applied to an urban watershed to addressed extreme overflows due to large groundwater infiltration to the sewer network of Vittskoevle, a village outside the City of Kristianstad, Sweden (Ward and Benaman, 1999). The authors consider MIKE SHE to be verified successfully for the catchment. The model was simulated to assess the impacts from historical measures and alternative future mitigation schemes. The results indicate among others, that the construction of a new alternative drainage scheme would make it possible to reduce the inflow to the plant by as much as 75% without risk of increased groundwater levels.

MIKE HSE performed satisfactorily when applied to model the impact of irrigation on water logging and soil salinity (Punthakey et al., 1993). Singh et al. (1997) applied efficiently the MIKE SHE/MIKE 11 system to an irrigated area in order to simulate its channel system. Their results showed the capability of the MIKE SHE/MIKE 11 coupled model in the planning and operation of vast irrigation projects, and its contribution to greater water use efficiency and improved crop production. Based on water balance Singh et al. (1999) used MIKE SHE to manage crop irrigation requirements. They concluded that the MIKE HSE could effectively be used for irrigation planning and management of water resources for agricultural purposes. Coupled MIKE SHE/MIKE 11 model with an optimization routine was applied by Mishra et al. (2005) to improve irrigation planning water resources management by achieving optimal canal water release with the aid of an integrated optimization simulation model. They concluded that by minimizing the supply-demand gap, and enhancing the spatial distribution of the irrigation water in the canal system, the overall deficit of the irrigated areas could be reduced.

In this research project, the applicability and predictive capacity of the MIKE SHE model was tested under Malaysian climatic conditions. Compared to other watershed models, the MIKE SHE model used the fully-dynamic Saint Venant equations to determine surface runoff, rather than the SCS-CN method. Also, this model simulates all the processes in the hydrologic cycle by fully integrating the surface, subsurface and groundwater flow. Although snowmelt option is also incorporated in the model; however it is not applicable in the tropical climate conditions. Model also includes river flow simulation via the MIKE 11 model. MIKE SHE model was selected to be evaluated in this study, more elaboration in terms of documentation and input data has been discussed comprehensively in the Chapters III and IV of this thesis.

Generally speaking, the literature indicated that the MIKE SHE modelling system has been used effectively and widely in many watersheds studies, where conventional simplified watershed models do not or cannot represent the whole water cycle components. Overall, the unique feature of MIKE SHE hydrology component is the integration of various hydrological processes in the model, at different time scales. Thus, the integration nature and the ability to count for both surface and subsurface flow systems and their interaction make MIKE SHE suited well for wetlands studies. Furthermore, the model is user friendly. To the best of my knowledge, this model has not been applied in Malaysia by local researchers before.

(h) SWAT Model - Soil and Water Assessment Tool

SWAT is a deterministic, physically-based, continuous simulation, watershed model. It was developed in the early 1990s and considered the latest incarnation of a family of watershed models developed by the Agricultural Research Service of USDA extending back to CREAMS and ROTO (Routing Outputs to the Outlet) (Ward and Benaman, 1999; Arnold et al., 1993). The immediate predecessor of SWAT is SWRRB model. The new version of the model, AVSWAT, includes a graphical user interface. The SWAT was developed principally to compute runoff and loadings from rural — especially agriculture dominated — watersheds and predicts long-term impacts of land management practices on water, sediment, pesticide and nutrient yields in watersheds with varying soils and land cover. The basic components of SWAT include precipitation, air temperature, solar radiation, surface runoff, irrigation, percolation, lateral subsurface flow, potential evapotranspiration, soil water evaporation, pond and reservoir storage and routing, sediment yield and channel sedimentation, crop growth, nutrients, pesticides, agricultural management, and stream routing, pond/reservoir routing. This semi-distributed model divides the watershed into multiple subbasins up to ten thousands which is called hydrological response units (HRUs). It operates on a daily time step (Soil and Water Assessment Tool. 1999; Ward and Benaman, 1999).

SWAT computes the volume of surface runoff using the SCS curve number method or Green and Ampt infiltration method; while as the amended Rational Formula or the SCS TR-55 is used to count for the peak runoff rate. The model uses a kinematic storage routine to counts for lateral subsurface flow and percolation. SWAT considers baseflow contribution to total stream flow by routing a shallow aquifer storage component to the stream. SWAT provides three solutions for evapotranspiration computation which include: (i)- Hargreaves, (iii)- Priestley-Taylor or (iii)- Penman-Monteith methods. (Bekoe, 2005; Soil and Water Assessment Tool, 1999; Ward and Benaman, 1999). The model output consists of evapotranspiration, soil water storage and water yield (sum of surface runoff and subsurface flow).

In their study that was conducted on a catchment in the U.S., Bosch et al. (2004) found that the SWAT performance accuracy was rather less on daily basis than monthly one. According to them, some more, the SWAT model could not count for the baseflow adequately. The same finding was obtained by studies of Chu and Shirmohammadi (2004), and Spruill et al. (2000) in that SWAT model failed to give acceptable runoff forecasting on a daily basis. On the contrary, a good agreement between the observed and predicted values was obtained by King et al. (1999) who adopted an approach of using a sub-daily time step for routing stream flow. Nonetheless, those authors concluded that application of sub-daily time steps together with breakpoint rainfall was not advantageous for vast basin predictions. A group of researchers in Canada found that SWAT performance was fairly good (Gebremeskel et al., 2005).

A modified version of the SWAT model was applied by Du et al. (2005) to simulate surface and subsurface flows, water table dynamics, tile flow, potholes, surface tile inlets, and aeration stress on plants, for vast flat landscapes. The obtained results were satisfactory with respect to the patterns and monthly flow rates. AVSWAT, on the other hand, was found applicable for forecasting and assessing the total maximum daily load of total nitrogen, total phosphorus and suspended solid for a small watershed containing rice paddies, located in Korea (Kang et al., 2005).

The mean and variance of water balance components varied with geographic scale, thus exhibiting the scale-dependent water balance uncertainty laws (Muttiah and Wurb, 2002). These mean and variance of water balance components are very sensitive to a wet climate, soil heterogeneity within the watershed, land use, and uniformity of rainfall pattern. In general, the only limitation of the SWAT model is that it is semi-distributed, where it divides the watershed into sub-basins having homogeneous climate, soil, land cover and management practices.