Hydrological Forecasting with Radar and the Probability Distributed Hydrological Model (PDM)

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DEDICATION

To my Dad; Pa Joseph Bamidele Adediran

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ABSTRACT

Hydrological measurements from traditional rain and flow gauges are regarded as the true measurement of hydrological occurences on the ground. Data from gauged measurments are however not very effective in real time hydrological forecasting and modern hydrological forecasting system is increseingly based on the use of data generated from weather radar. Furthermore, instead of redering a singular radar based forecast, a more robust probabilistic forecatings system is percieved to be more realistic.

This work therefore accessed the effeciency of weather radar, a Deterministic Now casting System (*DNS*) a Stochastic Now Casting System (*SNS*) and the Probability distributed hydrological model *(PDM)* in measuring and forecasting precipitation and floods at the Brue catchment in south-western England, UK.

The ability of the radar to measure gauged precipitation in 2007 (regarded as the ground truth) was evaluated using Normalized Bias (*NB*) and Normalized Error (*NE*) statistics as the objective funtion of evaluation. Radar overestimated precipitation measurements by average gauges with *NB* value of 0.41 and a considerably low *NE* of 0.68. Furthermore, the effectiveness of a Deterministic nowcasting system (*DNS*) to forecast radar measured precipitation at 132 forecast time series of 6hrs forecast lead time was assessed. The *DNS* overestimated the radar measured precipitation with a *NB* value of 0.87 and recorded an accumulated *NE* of 1.46. Morover, the effeciencies of 10 esemble precipitation forecats generated from a Stochastic nowcasting system (*SNS*) over the singlelar determinisitc forecasts from the *DNS* was evaluated at 3 major hydrological events. Some of the ensembles significantly performed better than the deterministic forecast and brilliantly captured the radar measured precipitation at most of the forecast time series.

Furthermore, the efficiencies of these sources of precipitation measurement to simulate flows with the *PDM* at the Brue catchment were also assessed by integrating the radar based forecasts with measurements from average gauges. The *PDM* performed satisfactorily well in simulating the flows of 17th January 2007 with an average Nash–Sutcliffe Efficiency Index (*NSE*) of 0.65 and the model was judged insensitive to the significantly high precipitation inputs for the hydrological event of 27th of May 2007. However, the *PDM* performed poorly in simulating flows for the historical storms of 20th of July 2007; with the model under estimating flows with bias value of over 250 m^3s^{-1} for an event popular for its devastating flooding in the Southwest of England. The model inadequacies was however associated to poor radar precipitation measurements and forecasts on which flow simulation was based.

This work therefore emphasis the need for developments in hydrological modelling as well as advancement in weather radar technology to effectively correct radar errors due to radar calibration, signal attenuation, clutter and anomalous propagation, vertical variation of reflectivity, range effects, Z-R relationships, variations of drop size distributions, vertical air motions, beam overshooting the shallow precipitation and sampling issues, that has been identified to affect radar measurements.

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List of Abbreviation

PDM- Probability Distributed Model

DNS-Deterministic Nowcasting System

SNS-Stochastic Nowcasting System

NB-Normalized Bias

NE-Normalized Error

RMSE-Root Mean Square of Error

NSE- Nash–Sutcliffe Efficiency Index

Det- Forecast from Deterministic Nowcasting System and ***e1, e2 ...e10.*** **-** Ten ensemble forecasts from the Stochastic Nowcasting System.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Flooding is the most common of all natural hazards and impacts on the greatest number of people across the world. It is an inevitable natural phenomenon occurring from time to time along river plains and natural drainage systems (Ramkumar et al., 2015). A meticulous compilation of natural disasters data that spans from 1980 to 2008, indicates that from the 2,887 flooding events recorded over this period, 2,809,481,489 people were affected with an addition of 195,843 deaths, and an approximated economic damage of (US $ X 1,000) 397,333,885 (EM-DAT, 2009). The reason behind this huge impact simply lies in the attraction of the widely distributed floodplains and low-lying coasts to human settlement worldwide. Three out of every five persons in the world presently lives within 60km of an ocean or major rivers and it has been estimated that by 2010, 80% of the world's population will inhabit a coastal strip hundred kilometres wide; the same area which already holds eight of the world's ten most populated cities (Small and Nicholls, 2003).

Furthermore, floods caused by sea-level rise are expected to affect millions of additional people every year by the end of this century, with small islands and the crowded delta regions around large Asian rivers (such as the Ganges-Brahmaputra) facing the highest risk; and regions of low lying areas of North America, Latin America, Africa and populous coastal cities of Europe, also facing flood risk from both large rivers and ocean storms (IPCC, 2007). The society may still continue to doubt the possibilities of this predicted disaster and the reality of Climate change, but the nightmare of November 2009 where over 1,000 homes were flooded in the town of Cocker -mouth in the UK city of Cumbria, left nobody in doubt that flooding is the number one threat facing the UK. The society must adapt to deal with the climate change induced increasing flooding risk, but it seems highly unlikely that any feasible engineered adaptation mechanism will completely reduce the threat. Therefore, the provision of warnings with sufficient lead time to enable society to mitigate losses will be very important in reducing impacts.

1.2 Justification of the Study

Floods that cause large number of fatalities and costly damages have primarily been associated with developing countries (Wisner et al., 2004) however, even the most developed nations are significantly affected by flash flooding, fluvial and pluvial flooding. For example, the 2002 floods in Europe killed roughly 100 people, affected 450,000 people and left $20 billion worth of damages (Bogardi, 2004). The data of European catastrophic flash flooding since 1950 has been documented (Gaume et al., 2009) and detailed examination of this data revealed that flash floods occured in all the hydro-climatic region of Europe. Building flood defences (Barriers) has been the most popular approach in mitigating flood risks.

However, the magnitude of the present flood risk zones, with the possibilities of future increase in flood risk zones, has made the provision of effective flood defences not only unrealistic but also economically unaffordable. Moreover, the best form of natural disaster defence is not to work against nature (by challenging flood with mechanical barriers) but by working with nature. Therefore, an integrated flood management system that is based on Hydrological forecasting is the most effective method of flood mitigation.

The availability of flood forecasting and warning system ensures timely evacuation and relocation of valuables, alerts rescue workers, enables the possibility of installing flood resilience measures (e.g. Sand Bags and Property barriers), prevent secondary disaster like electrocution and provide the opportunity for effective planning to reduce aftermath impacts. However, at the heart of a flood warning system is hydrological forecasting; a process that uses precipitation and stream flow data in rainfall-runoff and stream flow routing models to forecast flow rates and water levels for periods ranging from few hours to days ahead. The accuracy of forecasted rainfall data, and effective calibration and adoption of the proper flow routing models are therefore the essentials of flood forecasting.

This work therefore attempt to explore the concept of probabilistic hydrological forecasting, by incorporating radar measured rainfall data with that of rain gauges measurement, and using one of the UK-Environmental Agency preferred Model; the Probability Distributed Hydrological Model (PDM), to simulate flows for the Brue catchment in the South west of England. Presently, around 5 million people in 2 million properties live in areas at risk from flooding in England and Wales, with some of these areas along the flood plain of Brue River in Somerset, South-East of England (Defra, 2009). An effective flood forecasting system is therefore the only hope for saving the flood prone areas in poor developing countries that are practically without any defence, as well as for the people in developed country like the UK who are still awaiting a flood defence.

1.3 Research questions

This research attempts to answer the following questions:

- How effective are precipitation forecasts by a Deterministic nowcasting[1] system *(DNS)* in forecasting Radar-measured precipitation?
- Is there any significant difference in precipitation forecasts by ensembles of a stochastic nowcasting system *(SNS)* and a *DNS*?

[1] **Nowcasting-** 'A technique for very short-range forecasting that maps the current weather, then uses an estimate of its speed and direction of movement to forecast the weather a short period ahead — assuming the weather will move without significant changes' (Met-Office, 2010).

- In terms of forecasting flows for the Brue catchment using the *PDM*; are precipitation forecasts from *DNS* better than the ensemble forecasts from *SNS*?
- What are the important hydrological parameters for calibrating the *PDM* for Brue catchment?
- How effective is the *PDM* in forecasting flows for the Brue catchment by incorporating forecast generated from radar data with precipitation data measured by raingauges?
- Does a *SNS* really provide an excellent opportunity for quantifying uncertainties in flow forecasting through the ensemble quantitative precipitation forecasts it generates?

1.4 Aims and objectives

The broad aim of this research is to develop a framework for probabilistic flood forecasting system for the Brue catchment with the PDM model, using integrated precipitation data from the raingauges, the deterministic nowcasts and the stochastic nowcasts.

The objectives of this research are:

- To evaluate the efficiencies of various precipitation measurements and forecasts methods.
- To understand the principles of Hydrological forecasting with the PDM model
- To evaluate the concepts of probabilistic hydrological forecasting
- To investigate the importance and effects of model parameters in the calibration stage.
- To test different auto calibration methods for parameter estimation
- To investigate the importance of the calibration and validation time series
- To Build an initial PDM to simulate flows for Brue Catchment
- And to investigate the ability of the PDM to forecast runoff and analyse the limits of predictability.

CHAPTER TWO

2.0 LITRATURE REVIEW

2.1 Flood: types, causes and importance

Of all natural disasters, floods impact on the greatest number of people across the world (Moore et al., 2005). A flood is simply an overflow of an expanse of water that submerges land. The EU Flood directives further defines flood as the temporary covering by water of land not normally covered by water (EU, 2007). There are diverse sources or causes of floods. The EU flood directives identifies these to include floods from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas, but may exclude floods from sewerage systems (EU, 2007). Moreover, flooding can be separated into three main categories: flash flooding, river flooding, and coastal flooding (French and Holt, 1989). Flash flooding is defined as a flood that rises and falls quite rapidly, usually as a result of intense rainfall over a small area, in a short amount of time, usually under 6 hours; river flooding is defined as the rise of a river to an elevation such that the river overflows its natural banks causing or threatening damage; and coastal flooding pertains to flooding which occurs from storms where water is driven onto land from an adjacent body of water (Ashley and Ashley, 2008).

Floods are naturally occurring inevitable events that are dependent not only on rainfall amounts and rates, but also on the topography of the area, land use of the region, soil type of the watershed, and antecedent moisture conditions (Funk, 2006). Floods that significantly disrupt or incapacitate a society by causing a large number of fatalities and costly damage have primarily been associated with developing countries, for example, Bangladesh floods (Wisner et al., 2004). However, even the most advanced nations are affected: the 2002 floods in Europe killed roughly 100 people, affected 450,000 people and left $20 billion in damages; the US, which suffered 50 deaths and $50 billion in damage in the Mississippi River flood of 1993, has averaged 25 flood deaths annually since the 1980s (Bogardi, 2004).

A meticulous compilation of natural disasters data that spans from 1980 to 2008, indicates that from the 2,887 flooding events recorded over this period, 2,809,481,489 people were affected with an addition of 195,843 deaths, and an approximated economic damage of (US $ X 1,000) 397,333,885 (EM-DAT, 2009). The reason behind this huge impact simply lies in the attraction of the widely distributed floodplains and low-lying coasts to human settlement all around the world. Since water supply has been a decisive factor in the search for adequate settlement locations throughout history, river banks and lakesides have become preferred living spaces. Most of the cities in the World are located in the valleys and flood plains or on coasts (WMO/GWP, 2008). It has been predicted that pressure to live and work in flood-prone areas, which typically feature attractive rich soils, abundant water supplies and ease of transport, will increase as the world's population continues spiralling upward. The United Nations University Institute for Environment and Human Security (UNU-EHS) therefore warns that unless mitigating efforts are stepped up, the number of people vulnerable to flood disasters worldwide is expected to mushroom to two billion by 2050 as a result of climate change, deforestation, rising sea levels and population growth in flood-prone lands (Bogardi, 2004).

2.2 Principles of Integrated Flood Management

Flood management process has been traditionally problem driven. This usually basically involves the implementation of projects like emergency evacuation, provision of relief materials and compensation for losses. Moreover, inappropriate flood-management strategies pursued over the years have been largely reactive in response to flood threats rather than being proactive (Vijai, 2006).

For example, around 5.2 million properties in England - or one in six properties - are currently at risk of flooding from surface water, rivers and the sea (Defra, 2009). In the recent past, constructing defences has been the main way of dealing with the risks of flooding and coastal erosion. Although physical defences remain a vitally important part of flood management approach, it is however very costly to build and maintain and may not always be the most sustainable option. Latest predictions are that in order to maintain the same level of protection against flooding from rivers and the sea, funding will need to at least double again by 2035 (Defra, 2009).

However, the Plan of Implementation of the World Summit on Sustainable Development (WSSD), held in Johannesburg in August/September 2002, highlights the need to "... mitigate the effects of drought and floods through such measures as improved use of climate and weather information and forecasts, early warning systems, land and natural resource management, agricultural practices and ecosystem conservation in order to reverse current trends and minimize degradation of land and water resources …" (APFM, 2004).

Integrated Flood Management is therefore a process promoting an integrated – rather than fragmented approach to flood management. It integrates land and water resources development in a river basin, within the context of IWRM, and aims at maximizing the net benefits from flood plains and minimizing loss to life from flooding (APFM, 2004). It comprises a combination of management methods like Source control to reduce runoff (e.g. permeable pavements, afforestation); Storing runoff (e.g. detention basins, wetlands, reservoirs); Increasing the capacity of the river (e.g. bypass channels, channel deepening or widening); Separating the river and the population (e.g. land use control, dikes, flood-proofing, house raising); Emergency management during the flood (e.g. flood warnings, emergency works to raise or strengthen dikes, flood-proofing, evacuation); and Flood recovery (counselling, compensation or insurance) (APFM, 2004).

2.3 Principles of flood forecasting

It is a matter of fact that good policy and planning can reduce the exposure to flooding through control of land management and housing development, and well-designed flood defence schemes will alleviate the impact of flooding. However, complete protection from flooding is rarely a viable goal (Moore et al., 2005). There is therefore a need for flood forecasting system that is efficient in issuing warning of imminent flooding to allow timely human evacuation and relocation of valuables.

Flood forecasting is the use of real-time precipitation and stream flow data in rainfall-runoff and stream flow routing models to forecast flow rates and water levels for periods ranging from a few hours to days ahead, depending on the size of the watershed or river basin (AMS, 2010). It is a technique which uses the known characteristics of a river basin to predict the timing, discharge, and height of flood peaks resulting from a measured rainfall, usually with the objective of warning populations who may be endangered by the flood (Allaby, 2004). An integrated forecasting system 'chain' with rainfall measurement sources, rainfall displays that provides first-alert and flood-preparedness information, rainfall processing that provides inputs to flood forecasting and modelling systems, and decision-support facilities that trigger dissemination of flood warnings to communities informed on how to respond (Moore et al., 2005) is presented in Figure 1.

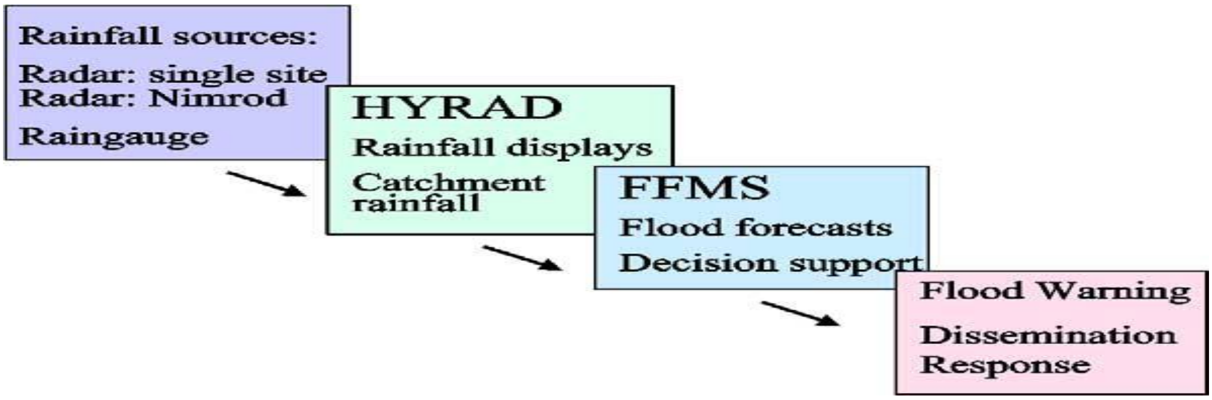

Figure 1: A framework for an integrated flood warning system (Moore et al., 2005)

Moreover, a flood forecast system must provide sufficient lead time for communities to respond. Increasing lead time increases the potential to lower the level of damages and loss of life. Equally, forecasts must be sufficiently accurate to promote confidence so that communities will respond when warned because if forecasts are inaccurate, the credibility of the programme will be questioned and no response actions will occur (UN, 2002).

2.4 Historical trends of Hydrological Modelling

Historically, the Rational Method proposed by the Irish Engineer, Thomas James Mulvaney, (Mulvany, 1850) has been widely recognized as the beginning of hydrological modelling (Beven, 2002). The Mulvaney's Rational Method concepts provided a clear exposition of the concept of time of concentration and its relation to maximum runoff; it estimates peak flow but not floods volume and is physically meaningful only in small impervious catchments in which flow is effectively a purely kinematic process (Todini, 2007).

The Mulvaney's model is described by a simple mathematical equation:

$$Q_p = CAR. \quad (1)$$

The equation does not attempt to predict the whole hydrograph but only the hydrograph peak Q_p, with input variable, *A*, the catchment area, *R*, the maximum average rainfall intensity and *C*, an empirical coefficient (Beven, 2002). This model was applied to the design of sewers around the 19th century (Kuichling, 1889, Lloyd-Davies, 1906).

Furthermore, (Sherman, 1932) introduced the concept of the unit hydrograph (UH). This was based on the principle of superposition of effects, allowing the complete flood hydrograph to be predicted from rainfall sampled at constant interval (Todini, 2007). After the introduction of the system theory, the unit hydrograph was later interpreted as the response of a linear, causative, dynamic stationary system into two forms of hydrograph units; the instantaneous unit hydrograph (IUH) and the finite period unit hydrograph (TUH) (O'Donnell, 1966) as described by Todini, 2007). In other to achieve a better physical interpretation of catchment response, the 1960s saw the development of models in which individual components in the hydrological cycle were represented by interconnected conceptual elements each of which represented a particular subsystem (Todini, 2007). Some of these models were described in (Dawdy and O'Donnell, 1965), and (Crowford and Linsley, 1996).

Moreover, a new type of lumped model was introduced at the end of the 1970s. These were based on the concept that the rainfall runoff process is mainly dominated by the dynamics of saturated areas which can be related to the soil moisture storage, based on the Dunne assumption that all precipitation enters the soil and that surface runoffs originates by saturation of the upper soil layer (Todini, 2007). Examples of these models are the Xinanjiang soil moisture distributed model (Zhao, 1977) and the Probability Distribution Model (PDM) (Moore and Clarke, 1981). (Beven and Kirkby, 1979) developed a better distribution function model called the TOPMODEL, based on the assumption that accumulation of soil moisture can be approximated by successive steady states of the water table originating in the upper soil layer (Todini, 2007).

Conclusively, the advances in remote sensing technology that provides detailed variety of information like soil types and land use, and especially the availability of weather radar technology, have recently led to the development of hydrological models that are used in real time probabilistic hydrological forecasting.

2.5 Basic Classification of Hydrological Models

There are different ways of classifying the numerous hydrological models. However, hydrological models can basically be classified into two broad classes, but of four types. These are the Lumped or Distributed Hydrological Models, and the Deterministic Models or the Stochastic Models.

The lumped models treat the catchment as a single unit, with state variables that represent averages over the catchment area, as average storage in the saturated zone (Beven, 2002). The GR2M model (Makhlouf and Michel, 1994) and the Probability distributed hydrological model (PDM) More (Moore, 2007) are examples of lumped model. This model is capable of simulating monthly discharge using estimations of average rainfall in a basin. It provides a simplified representation of the rainfall–discharge process and is characterised by a small number of parameters which do not correspond to specific physical attributes (Niel et al., 2003). On the other hand, Distributed hydrological models make prediction that are distributed in space, by discretizing the catchment into a large numbers of elements or grids squares and solving the equations for the state variables associated with every element grid square (Beven, 2002). Distributed model sometimes have a routing component of the main river(s) within a catchment which however requires detailed information of cross-sectioning in the river(s).

The HRCDHM model (Hydrology Research Canter Distributed Hydrologic Model) is an example of a distributed model. The HRCDHM is a sub catchment based model which uses the Sacramento model for runoff generation within each sub catchment (Carpenter and Georgakakos, 2006). It is a 'data hungry' model with potential difficulties in providing enough data to ensure optimum model functioning. It also includes components for temporal distribution of runoff at the sub catchment outlet and kinematic channel routing between sub catchments and to the watershed outlet (Carpenter et al., 2001, Carpenter and Georgakakos, 2004).

Moreover, Deterministic models are models in which the processes are modelled based on definite physical laws and no uncertainties in prediction are admitted (Seth, 2009). Deterministic models permits only one outcome from a simulation with one set of inputs and parameters values (Beven, 2002). The water and environmental consultants — catchment (WEC-C) model is an example of a distributed, deterministic model of numerical form, that is capable of simulating both water and solute movement within a catchment (Croton and Bari, 2001). Other examples include the SHE (Système Hydrologique Européen) Model (Abbott et al., 1986, Jain et al., 1992), the TOPOG (Terrain Analysis *Hydrologic Model)*(O'Loughlin, 1986, Vertessy et al., 1993) and IHDM *(Institute of* Hydrology *Distributed* Mode)(Calver and Wood, 1995).

In contrast to the Deterministic hydrological models, the stochastic models allow for some randomness or uncertainty in the possible outcomes, due to uncertainty in input variables, boundary conditions or model parameters (Beven, 2002). The Autoregressive moving average (ARMA) model has been the stochastic model of choice to generate synthetic sequences, however, recent advances in the understanding of the inter-annual and multi-decadal variability in hydrological time series caused by the nonlinear climate dynamics recent research has advocated for more complex stochastic models (Thyer et al., 2006).

The lag-one autoregressive (AR(1)) model (Grayson et al., 1996) and the two-state hidden Markov model (HMM) are examples of complex stochastic models (Thyer et al., 2006).

2.6 Rainfall-runoff models in the UK

The Environmental Agency (EA) in the UK adopts a range of both locally and internationally developed models for flood forecasting. They range in type from transfer function (empirical black box), through lumped conceptual to more physically-based distributed models (Moore and Bell, 2001) Some of the models used by the EA include the Thames Catchment Model (TCM), Midlands Catchment Runoff Model (MCRM), Probability Distributed Moisture model (PDM), Isolated Event Model (IEM), US National Weather Service (Sacramento) model (NWS), Transfer Function model (TF), Physically Realisable Transfer Function model (PRTF) and the Grid Model (Developed by IH for the NRA) (Moore and Bell, 2001). All these models are capable of transforming rainfall and evaporation time series of total catchment flow. The Thames Catchment Model (TCM), the Midlands Catchment Runoff Model (MCRM), the Probability Distributed Moisture model (PDM), and the US National Weather Service Sacramento model (NWS) are all lumped conceptual models with continuous water accounting procedures, and each model is associated with an updating procedure whereby recent measurements of flow are incorporated into the model so as to improve forecast performance in real-time (Moore and Bell, 2001).

The result of a comprehensive comparison of these models suggests that no model consistently out-performs all others across a number of catchments. The TCM was identified as one of the best performing models when judged using the R^2 statistics whilst the PDM was more successful while judged according to the Threshold CSI criterion (relevant to the issuing of flood alerts) and in forecasting flood peaks (Moore and Bell, 2001).

The results of the 2001 Model comparison also indicates that Operationally, the TCM, PDM and IEM models appear to be the most appropriate flood forecasting models to use, of those assessed, the choice depending on the complexity of catchment response whilst all models have value in the right situation (Moore and Bell, 2001).

2.7 The Probability Moisture Distributed Model (PDM)

(i) Principles

The hydrological Probability Distributed Moisture (PDM) model; developed at the Centre for Ecology and Hydrology is a fairly conceptual rainfall-runoff model which uses a distribution of soil moisture storage capacities for soil moisture accounting (Moore, 1985, Moore, 1999, Moore, 2007) production of runoff along the gradient of a catchment is mainly controlled by the soils water absorption capacity which can be conceptualised as a simple store of a storage capacity. Based on the principle that different points in a catchment have differing storage capacities and that the spatial variation of a capacity can be described by a probability distribution, the PDM was therefore developed to integrates the point runoffs to yield the catchment surface runoff into surface storage (Moore and Bell, 2001). A schematic representation of the PDM (Moore, 2007) and a conceptual description of the PDM (Cabus, 2008a) are presented in Fig. 2 and Fig. 3 respectively.