DEVELOPMENT AND ASSESSMENT OF A DYNAMICALLY CALIBRATED FLOW ROUTING MODEL FOR THE VAAL-ORANGE RIVER SYSTEM

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Submitted in partial fulfilment of the requirements for the degree of PhD

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September 2015
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ABSTRACT

A flood forecasting system based on real-time data and continuous hydrological flood routing for the Vaal Orange River System (VORS) in South Africa has been in operation since 1980's, however, the quality of the flood routing results from the muskingum based routing application are affected by non operational telemetry systems, existence of various structures such as dams, tributaries hydro-power stations and bridges which limits the performance of the model. The proof of success of flood routing as part of a flood warning system in reducing impacts of flood damage is well documented and a number of approaches aimed at getting more accurate results have been investigated. This literature review aims to review research studies that have investigated flood routing models. Based on the literature review a proposal for the study is developed that seek to provide an assessment of data requirements, availability, costs, institutional requirements, to recommend a routing modelling approach to implement in the VORS.

Sources of literature such as research journals, articles, conference proceedings, books, research and technical reports, were reviewed to understand different approaches. Hydrological, and dynamic flood routing methods and their role in flood forecasting were identified by the author, and these techniques will be discussed throughout this literature review. Literature revealed that dynamic flood routing models are widely recommended for simulating complex river systems such as VORS compared to hydrological based techniques because they are much more accurate, even though they are more computationally complex and require a lot of detailed field information. Three-parameter Muskingum method may provide better results close to hydraulic models but it still exhibit some limitations of hydrological models. 2-D dynamic routing models provides realistic forecasts better than 1D models but they not suitable for real-time systems as they requires more computational time.

It is postulated that dynamic flood routing can increase flood forecasting lead times, improve the accuracy of flood forecasting and provide currently unavailable flood inundation information in the VORS. These potential gains could contribute towards an improvement in early flood warning and flood control which would result in a significant reduction in flood related losses such as human lives and property.
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<th>Description</th>
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<td>Department of Water Affairs</td>
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<td>DWS</td>
<td>Department of Water and Sanitation</td>
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<td>DEM</td>
<td>Digital Elevation Model</td>
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<tr>
<td>CD</td>
<td>Coefficient of Determination</td>
</tr>
<tr>
<td>HEC-RAS</td>
<td>Hydrologic Engineering Centre's River Analysis System</td>
</tr>
<tr>
<td>QR</td>
<td>Qualifying Rates</td>
</tr>
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<td>VORS</td>
<td>Vaal Orange River System</td>
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1 INTRODUCTION

Flooding is a natural occurrence caused mostly by heavy rainfall, that present a threat to human lives, infrastructure and ecosystems in most parts of the world (Andjelkovic, 2001; Petri, 2002; State of Queensland, 2012; Ghimire, 2013). Floods can also affect people and ecosystems in a positive manner such as when it brings relief from droughts and deposit fertile soils in floodplains. (Ghimire, 2013). The consequences of flooding include loss of livelihood, long lasting psychological impacts, relocation and migration, shortage of food, high cost of goods and services, and economic hardships (Parker et al., 2005).

In the past, South Africa has experienced many major floods, which have led to the loss of many human lives. There has been 25 major flood disasters between 1980 and 2010 (Maswuma, 2011; PreventionWeb, 2014).

Table 1.1. List of Major Historic Flood Disasters in South Africa

<table>
<thead>
<tr>
<th>Year</th>
<th>Place</th>
<th>Reference</th>
<th>Year</th>
<th>Place</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>Montagu floods</td>
<td>Van Bladeren et al., 2007</td>
<td>2000</td>
<td>LIM, MPU</td>
<td>Smithers JC et al., 2000</td>
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Flooding of the Vaal-Orange River System (VORS) is a major concern in South Africa as the system covers nearly half (49%) of the country and supplies water to agricultural, industrial, urban and mining developments, mostly in the Gauteng Province which is the economic heartland of the country (Hattingh, 2008).
The flood prone areas in the Vaal River System, as shown in Figure 1.1, include irrigation schemes, settlements and towns such as Standerton, Vereeniging and Parys downstream of the Grootdraai and Vaal Dams (Hattingh, 2008). The towns of Aliwal North, Hopetown, Christiana and Wepener and some irrigation schemes are the flood prone areas in the Upper Orange System (Hattingh, 2008; International Federation of Red Cross and Red Crescent Societies, 2011). In the Lower Orange River System, flooding frequently affects towns like Prieska, Upington, Keimoes and Kakamasand and many irrigation schemes adjacent to the main river (Hattingh, 2008).

![Figure 1.1 Human settlements prone to flooding in the Vaal Orange River System (after Latting, 2008)](image)

The impacts of flooding can be minimised by "keeping the flood away from people" through construction of flood control structures such as dams dykes and leaves; "keeping people away from floods" through flood forecasting and warning services, emergency response and by "accepting flood and cleaning afterwards" to promote a quick return to normality after the flood has occurred (Myers and Passerimi, 2000; Petri, 2002; Prevention Web, 2014).
In spite of the success of structural control measures in numerous applications over the history of humanity, they can never provide full protection (Lyle, 1998). Structural control measures only reduce the risk of flood damage, while the risk of human settlement in the flood plain remains unchanged after structural measures have been built. The World Meteorological Organization (WMO) emphasizes that the most critical aspect of a flood-loss reduction strategy lies in emergency preparedness and response, which rely on flood monitoring, forecasting and warning systems (Du Plessis, 2002; WMO, 2011).

Forecasting of floods enables warnings to be given to the people likely to be affected by them and timely civil defence measures to be organized (Adams, et al., 1994; Parker et al., 2005; Rao et al., 2011). Flood forecasting uses real-time precipitation and streamflow data in rainfall-runoff modelling and streamflow 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 catchment (Srikanthan, et al., 1994; APFM, 2009; Wiesenegger, 2011). Flood routing is important in that it provides time-series flooding information about the onset, duration and passing of a flood and is useful for flood risk assessment. (Wilson, 1990; Fread, 1992; Balaz et al., 2010; Ghimire, 2013).

Flood routing procedures may be classified as either hydrological or hydraulic (Choudhury et al., 2002) A combination of hydrological and hydraulic models are used in flood level inundation assessments (Blackburn and Hicks, 2001). A flood hydrograph generated from a flood routing model is input to a hydraulic model in order to estimate the flood levels at a downstream location (Blackburn and Hicks, 2001). Such a combination of models can predict flooding at precise locations, for example, housing areas or critical infrastructure such as power stations and road or rail bridges (Fread, 1992; APFM, 2009).

The attractiveness of hydrological flow routing is its relative computational simplicity, however, accuracy considerations can restrict the range of applicability as compared to hydraulic flow routing (Fread, 1992; Haktanir and Ozmen, 1997; Saleh, et al., 2004). The hydraulic flow routing methods are generally more accurate compared to hydrologic techniques because they describe the dynamics of the water or flood wave movement more accurately (Rehnman, et al., 2003). However, their practical applicability is more restricted because of the high demand on computing technology, as well as on quantity and quality of
According to France (1985), hydraulic flow routing methods are more complex and often difficult to implement. Hydraulic flow routing methods involve the numerical solutions of either the convective diffusion equations or the one-dimensional Saint-Venant equations of varied unsteady flow in open channels (France, 1985; Sameer, 2008). With the advancements in technology, the advent of high speed computers, and increasing availability and affordability of data for setting-up and running more complex models, the complete solution of Saint Venant equations is becoming more feasible for addressing various unsteady flow problems (Patowary and Sarma, 2013).

Distributed flow routing known as dynamic routing allows flow rate and water level to be compared as functions of both time and space is based on the complete solution of Saint Venant equations (Fread, 1992). Dynamic flow routing allows for a higher degree of accuracy when modelling flood situations because it includes parameters that other methods neglect. Dynamic routing relies less on previous flood data and more on physical properties of the storm and provides more hydraulic information about the flood event (Fread, 1992).

Many dynamic routing models have been reported in the literature (Cunge 1969; Johnson, 1974; Colon and McMahon, 1985; Schaffranek, 1987; Chang, 1988; Holly et al., 1990; DHI, 2001; Wallingford, 1977; US Army Corps of Engineers, 2001). These include one dimensional (1D) models (flood levels measured in the channel) or 2D models (variable flood depths measured across the extent of a floodplain). 1D flow routing models in software packages such as Mike-11 (DHI, 2001), ISIS (Wallingford, 1997), and HEC-RAS (US Army Corps of Engineers, 2001), based on the Saint-Venant Equations or variations thereof, still form the of majority of numerical hydraulic models used in practical river engineering. The use of coupled hydrological rainfall-runoff model with hydraulic/dynamic (1D) flood routing gives more accurate flood forecasting results and such a system has the ability to extend the lead warning time (Villazon et al., 2009; Henonin et al., 2010; MeiBner, 2011). Although a 1D-2D model would result in more realistic forecasts of the surface flood behaviour, it is usually not suitable for real-time systems as it still requires much more computation time than 1D models (MeiBner, 2011).

Dynamic flood simulation generally consists of construction of a physically-based fully hydrodynamic model, calibration of the model through adjustment of Manning roughness coefficient \( n \) to reproduce historical observations of stage and discharge and interpretation of the model results in a GIS environment (Fread, 1993; Jordanovaet al., 2004; Carrand Smith,
2006; Leandro, 2009; Merwade et al., 2008; Paiva et al., 2011). Calibration ensures that the accuracy of the model is within an acceptable range (Leandro, 2009). According to Ghimire, (2013), factors such as cross section configuration, mesh resolution, and representation of river bathymetry influence the performance of dynamic routing models.

One limitation of dynamic flood outing models is the lack data to parameterize and validate the model. However, the recent advancement in technology, computer, topographic information, has allowed considerable progress in the application of dynamic routing models. Although many studies have been conducted on hydraulic modelling in Southern Africa in the Olifants Basin (Vilanculos et al. 2008) Limpopo Basin (WHO, 2012; Vilanculos et al, 2008) Orange River (Fair et al., 2003; Putterman 2010), Western Cape (Els, 2011) there are still knowledge gaps on its application for continuous simulation on short time scale for flood forecasting and early warning systems in large river basins (WHO, 2011). There is lack of detailed water resources information and flood monitoring systems necessary for collecting data and information, limited data exchange and technical cooperation, lack of technical capacity, lack of funding and computer requirements for implementing appropriate hydrological and/or hydraulic modelling (WHO, 2011).

The objective of this literature review is to review research studies that have investigated flood routing models, data requirements, assessment of available flood related data sources in South Africa and candidate models for assessment to recommend a modelling approach to implement in the VORS. The candidate models will be tested in the Upper Vaal section of the VORS with the most appropriate data sources identified. The Upper Vaal is flood prone and thus presents a suitable test case for the methodology. The river system has a relatively dense hydroclimatic monitoring network and hence has sufficient historical and near real-time data to make the study possible. Finally a brief PhD project proposal is developed based on knowledge gaps identified in the literature review.

Relevant literature was reviewed and is presented in Chapter 2. The relevant literature contained in Chapter 2 includes methods, models and application of hydrological and hydraulic flood routing. Calibration of hydraulic models and evaluation of models suitable for Vaal Orange River System is also presented in Chapter 2. Discussion of the literature review contained in Chapter 2 and recommendations for carrying out the study is presented in Chapter 3. The project proposal for the development and assessment of a dynamically
calibrated routing model for the VORS is presented in Chapter 4. The project proposal covers the problem statement, the objectives of the study that includes the research, aims, hypothesis, and specific objectives, methodology of study, work plan and time schedule.
2 METHODS AND MODELS FOR FLOOD ROUTING

Flood routing is a mathematical method used to predict a hydrograph as it moves down the river (Comet Program, 2006; Seybert, 2006). The method can be used to assess the adequacy of channels and spillways and the extent of floodplain inundation that may take place (Miller and Cunge, 1975; Fread, 1981; Linsley et al., 1982). Detailed descriptions, derivations and examples of flood routing methods are widely documented in the literature (e.g. Cunge, 1975; Weinmaann and Laurenson, 1979; Fread, 1988). This chapter contains a discussion on hydrological and hydraulic modelling techniques, calibration of hydraulic models and assessment of models suitable for the VORS.

2.1 Methods of Flood Routing

Flow routing methods are classified into hydrological and hydraulic flood routing (Arora et al., 2001; Choudhury et al., 2002). According to Shaw (1994), hydrological routing methods are based on the solution of conservation of mass equation and a relationship between storage and discharge in a stream reach or reservoir. The method simulates stage and discharge to account for storage as water moves through stream channels and water control structures (Perumal and Raju, 1998; Moramarco and Singh, 2001; Comet Program, 2006). Hydrological flood routing methods generally consist of two components, the first dealing with conversion of rainfall into runoff and the second with routing of that runoff to the catchment outlet (Rehman, et al., 2003). As noted by Rehman et al. (2003), flood routing methods based on hydrological modelling techniques are limited in their approach in that the catchment parameters are lumped together in a simplified manner resulting in a misrepresentation of the surface profile. Hydrological flow routing methods also neglect backwater effects, and are not accurate for rapidly rising hydrographs routed through mild to flat sloping rivers (Fread, 1992; Salehet al., 2004).

Conversely, hydraulic models are terrain-based models and they can account for the actual physics of water movement in the channel and provide a more accurate representation of the surface runoff as the geometry of the channel and flood plain vary at different points along a watercourse (Fread, 1992; Rehman et al., 2003). Unsteady flow is accurately described as a distributed process because the flow rate, velocity, and depth (stage) vary spatially and
temporally The channel system properties are computed as functions of temporally rather than only dependent on time alone as in the lumped flow routing methods (Fread, 1992). Hydraulic routing methods are based on the solution of the Saint-Venant equations which include: a continuity equation which describes the balance between input, storage and output in a section of a river, and a momentum equation which relates the change in momentum to the applied forces (Liggett, 1975; France, 1985; Barthust, 1988; Becker and Serban, 1990).

The selection of a routing model appropriate for a particular problem requires a thorough evaluation of several factors which, according to the US Army Corps of Engineers (1993), should include backwater effects, floodplains, channel slope, roughness, hydrograph characteristics, flow network, subcritical and supercritical flow. Fread, (1981) include the following additional factors for the purpose of the analysis: accuracy of the model, the type and availability of data, available computational facilities and costs, the extent of flood wave information desired and familiarity of the user with a given model.

In order to obtain a detailed understanding of the hydrological and hydraulic flow routing methods, relevant literature was reviewed and is presented in the following sections. The literature review contained in Section 2.1.1. provides the types and basic description of several hydrological techniques such as the Modified Puls, the Kinematic Wave, the basic Muskingum, the Muskingum-Cunge, the Three Parameter Muskingum, the Non-Linear Muskingum method and the SCS Convex method. Description of the hydraulic and dynamic flow routing methods are provided in Section 2.1.2. Data requirements for configuration of hydraulic and dynamic flow routing models and calibration are provided in Section 23 and 2.4 respectively.

### 2.1.1 Hydrological Flow Routing

Some of the commonly used hydrological techniques include: the Modified Puls (US Army Corps of Engineers, 1980; Mackenzie et al., 2012; Husna and Halim, 2014), Kinematic Wave (Li et al., 2010), the basic Muskingum (McCarthy 1938; Chow 1964; Bauer, 1975; Linsley et al., 1986, Fread, 1993; Shaw, 1994; US Corps of Engineers, 1993; Choudhury et al., 2002), the Muskingum-Cunge (Chow, 1959; Ponce, 1989;) the Three Parameter Muskingum (O'Donnell, 1985;O'Donnell and Woods, 1988, the Non-Linear Muskingum (Mohan, 1997) and US Conservation Service Convex method (Viessman et al., 1989).
2.1.2 Modified Puls method

The Modified Puls method is generally applied in reservoir routing and its mathematical basis is the conservation of mass with constant density (US Corps of Engineers, 1980; Mackenzie et al., 2012; Husna and Halim, 2014). The method is usually carried out using computer programs such as HEC-HMS (Cunderlik et al. 2004; Mabao and Cabahug, 2014) or TR-20 (City of Springfield, 2007). The key assumption in the Modified Puls method is that there exists a physical relationship between storage and outflow, dependent only upon topography and roughness of the channel (City of Springfield, 2007; Husna and Halim, 2011).

2.1.3 Kinematic Wave method

According to Miller (1984), kinematic wave hydrological routing methods are used mainly for channel and overland-flow routing where lateral inflow is continuously added as a large part of the total flow. The model is usually applied in precipitation-runoff modelling system and in the distributed routing rainfall-runoff models such as HEC-1 (City of Springfield, 2007; Li et al., 2010). The kinematic wave routing method is based on the solution of the continuity equation and uniform flow equation such as Chezy or Manning's equations. Miller (1984) states that kinematic wave models ignore a number of terms in the equation of motion and assume that the friction slope is equal to bed slope and also assumes uniform steady flows conditions (Henderson, 1966). Miller (1984) noted that kinematic wave-models always predict a steeper wave with less dispersion and attenuation than actually occurs. Li et al. (1976) concluded that the applicability of the kinematic wave model to river flood routing is limited because of shock formation, a discontinuity representing a sudden rise in the flow depth. The approximations made in the development of the kinematic-wave equations are not generally justified for most channel-routing applications (Li et al., 1976).

2.1.4 Muskingum method

The Muskingum flood routing model developed by McCarthy (1938) is one of the most frequently used hydrological flood routing method since its introduction in the 1930's because of its simplicity (Chow 1964; Viessmann et al., 1977; Singh and McCann, 1980; Choudhury et al., 2002; Singh and Woolhiser, 2002; Tewolde, 2005). The Muskingum method assumes that
the water surface in the reach is a uniform, unbroken surface profile between upstream and downstream ends of the section. The Muskingum method models the storage volume of flooding in a river channel using a combination of wedge and prism storage (Dooge *et al.*, 1982; Shaw, 1994). The storage equation (Equation 2.1) on which the Muskingum method is based is an expression of continuity. The most common form of the linear Muskingum model is expressed as the discharge/storage equation (Equation 2.2) (Tung, 1985; Fread, 1993):

\[
\frac{dS}{dt} = I_t - Q_t \tag{2.1}
\]

\[
S_t = K[XI_t + (1-X)Q_t] \tag{2.2}
\]

where

- \( S_t \) = temporary channel storage \([m^3]\) at time \( t \),
- \( I_t \) = the rate of inflow \([m^3.s^{-1}]\) at time \( t \),
- \( Q_t \) = outflow \([m^3.s^{-1}]\) at time \( t \),
- \( K \) = the storage time constant for the river reach which has a value close to the wave travel time within the river reach \([s]\),
- \( X \) = a weighing factor varying between 0 and 0.5 [dimensionless], and
- \( t \) = time = \( t \).

The prism storage is the storage beneath a line parallel to the stream bed and is represented by \( KQ \) in the reach (Fread 1992). The wedge storage is the water located beneath the line parallel the stream bed and the actual profile and is represented by \( KX (1-Q) \) (Fread, 1992).

The linear Muskingum routing equation (Equation 2.3) is obtained by combining and solving Equation 2.1 and Equation 2.2.

\[
Q_{j+1}^{t+1} = C_0I_j^t + C_1I_{j+1}^{t+1} + C_2Q_{j+1}^t \tag{2.3}
\]

where

- \( Q_j^t \) = outflow at time \([t]\) of the \( j \) th sub-reach, and
- \( I_j^t \) = inflow at time \([t]\) of the \( j \) th sub-reach.
The following equations are used to determine coefficients $C_0$, $C_1$, and $C_2$.

\[
C_0 = \frac{[(\Delta t - 2KX)]/[2K(1-X) + \Delta t]}{(2.4)}
\]
\[
C_1 = \frac{[(\Delta t + 2KX)]/[2K(1-X) + \Delta t]}{(2.5)}
\]
\[
C_2 = \frac{[(2K(1-X) - \Delta t)/[2K(1-X) + \Delta t]}{(2.6)}
\]

The sum of the routing coefficients $C_1$, $C_2$, and $C_2$ is equal to one and are constant throughout the routing procedures (Fread, 1993).

The key parameters in Muskingum routing are $K$, which describes the storage time constant for the river reach, and $X$, that determines the degree of attenuation of a flood as it passes through the routing reach (US Corps of Engineers, 1993). It assumes that $K$ and $X$ are constant throughout the range of flows (Veissman and Lewis, 2003) The value of $X$ depends on the shape of the wedge storage to be modelled, and the value of $X$ ranges from 0 for reservoir-type storage to 0.5 for full wedge storage. In natural streams, $X$ is between 0 and 0.3 with mean value near 0.2 (Chow et al., 1988). $K$ is the time required for an incremental flood wave to traverse a reach, and it may be estimated as the observed time of travel of peak through the river reach (Chow et al., 1988). Values of $K$ and $X$ are normally determined by calibration from historical flood records if observed inflow and outflow hydrographs are available for a river reach (Gray, 1973; Linsley et al., 1982; Veissman and Lewis, 2003). In determining $X$, a tentative value between 0 and 0.5 is chosen and the historical data are plotted as follows:

\[
S \text{ vs } [IX + (1-X) Q]
\]

The data generally plot in the form of a loop and iteratively varying $X$ will tend to close the loop (Gill, 1978; Fread, 1992). The value of $X$ which causes the width of the loop to be narrow and linear is believed to be the correct value of $X$ (Gill, 1978; Fread, 1992). The main disadvantages of this graphical method is the time required to construct the plots for alternative $X$s, visual subjectivity and the sensitivity of $X$ in short reaches (Heggen, 1984; O’Donnell and Woods, 1988). According to Gill (1978) the least-squares method (LSM) can be used to replace the trial and error method of determining $X$. The slope of the line for the correct value of $X$ determines the value of $K$. Other alternative methods for estimating
Muskingum K and X parameters includes method of moments, method of cumulants, and direct optimization methods (Chatila 2003).

A number of studies have demonstrated limitations of the Muskingum routing method, mainly because of its assumption of a linear relationship between channel storage and weighted flow (Cuneg, 1969; Venetia, 1969; Gill, 1978; Koussis, 1978; Strupczewski, and Kundzewicz, 1980). In reality, a non-linear relationship between storage and discharge exists in most river systems making the use of the linear Muskingum routing method inappropriate. According to Choudhury et al. (2002), the basic Muskingum method is applicable to a single reach having no lateral inflow into the routing reach. For best results the river reaches have to be short, terminating at tributaries and gauged or estimated tributaries inflows added to the main channel flow (O'Donnell, 1985). Where there is lateral inflow in the form of substantial tributaries, the routing reaches should be chosen to terminate at a confluence, augmenting the main channel flow by tributary flow of the next reach (O'Donnell, 1985). This principle is used in the Department of Water and Sanitation (DWS) Muskingum based routing application (Delport, 2010). The NERC (1975) noted that the unique relationship assumed in hydrological routing technique between stage and discharge along the reach is one of the main limitations of the basic Muskingum method.

2.1.5 Muskingum-Cunge method

To overcome the limitations of the basic Muskingum method, Cuneg (1969) proposed a method based on the Muskingum method which use measurable channel properties such as stage-discharge relations and estimated flow cross-sectional data to derive expressions of K and X (Schroeter and Epp, 1988). Though classified as a hydrological method Muskingum-Cunge method gives results comparable with hydraulic methods (Veissman and Lewis, 2003). In the Muskingum-Cunge method, the K parameter is the travel time for a wave to travel the routing reach length and is dependent on the celerity and reach length. The celerity is the velocity with which a variation in flow rate travels along a channel (i.e. the wave speed). In the Muskingum-Cunge method the value for X is also calculated from channel and discharge characteristics, unlike in basic Muskingum method where the parameters are calculated using observed stream flow data (Ponce, 1989). In addition to wave celerity, other variables used to estimate K and X in the Muskingum-Cunge method include the top width of the river, reach cross-section area, reach length and reach slope (Chow, 1959; Fread, 1993). As a result the
values of K and X both change with respect to time and space in the Muskingum-Cunge method.

The Muskingum-Cunge method takes into consideration lateral inflows and the coefficient C₃ in Equation 2.7 is used to add the lateral inflows to the main stream (NERC, 1975):

\[ Q_{j+1}^{t+1} = C_0 I_j^t + C_1 I_j^{t+1} + C_2 Q_j^{t+1} + C_3 \]  

where \( C_3 \) = Averaged lateral inflow [m³.s⁻¹].

According to Weinmann and Laurensen(1979), the Muskingum-Cunge approach improves the computational efficiency and speed, and reduces the amount and detail of field data traditionally needed for hydraulic routing. The Muskingum-Cunge flow routing method is better than other hydrological techniques in that the method is stable with properly selected coefficients (Smith, 1980; Ponce and Theurer 1982; Ponce 1983). According to NERC (1975), the total lateral flow per unit length has an assumed time distribution along the reach and is specified at intervals of ΔL. Backwater effects are ignored and lateral flows are assumed to enter proportionally along the main reach (Fread, 1993).

2.1.6 Three-parameter Muskingum method

In the Muskingum-Cunge method, numerical difficulties are encountered when the ratio of lateral inflow to the main flow is too large and this may solved by increasing the routing length of a specified reach, however, the process becomes tedious. To overcome these limitations, O'Donnell (1985) modified the Muskingum-Cunge method and developed a Three-parameter Muskingum method where the conventional K and X parameters are supplemented by a third parameter (\( \alpha \)) to account for lateral inflows into the reach shown in continuity Equation 2.8 and empirical storage Equation 2.9.

\[ I_t (1+\alpha) = Q_t + \frac{ds}{dt} \]  

\[ S_t = K[X(1+\alpha)I_t + (1+\alpha)Q_t] \]
Application of the three parameter method requires observed inflow and outflow hydrographs to estimate model parameters (K, X and $\alpha$) initially. The K, X and $\alpha$ of a catchment in the three-parameter Muskingum method should be calibrated using different events needing many years of observed inflows and outflows hydrographs since calibrating with specific events might give erroneous parameters for a catchment (O'Donnell et al., 1988). According to O'Donnell (1985), the three-parameter Muskingum method is better than other Muskingum based methods in that it substitutes laborious and subjective trial and error estimation of the K and X parameter values with a direct and best fit solution method. The method avoids the need for multiple routings and multiple parameter determinations over many sub-reaches as the whole river is treated as one (O'Donnell et al., 1988).

### 2.1.7 Non-Linear Muskingum Method

In situations where the storage versus flow relationship is non-linear, Mohan (1997) proposed the Equations 2.10 and 2.11:

\[
S = K[XI_t + (1 - X)Q_t]^n
\]  
\[
S = K[XI_t^m + (1 - X)Q_t^m]
\]

where

- $n$ = exponent parameter [dimensionless], and
- $m$ = exponent parameter [dimensionless].

Equations 2.10 and 2.11 provide a closer fit to the non-linear relationship between storage and discharge and have more degrees of freedom compared to the basic Muskingum equation (Gill, 1978; Mohan, 1997). However, the major limitation to the method is the complex calibration procedure required, owing to the presence of non-linearity in the equation (Gill, 1978; Mohan, 1997).

### 2.1.8 The SCS Convex Method

In situations when limited storage data for a reach is available, the US Soil Conservation Service (SCS) coefficient channel routing technique can be used with success (Viessman et al., 1989). The SCS method can be used to forecast outflow from reach without knowing the concurrent
inflow and can be used to provide flood warning with a lead-time of at least the routing time \( \Delta t \) (Viessman et al., 1989). For example, if the routing interval is one day, today’s inflow and outflow are known and local inflow is known or negligible, then tomorrow’s outflow can be predicted without knowing tomorrow’s inflow. In convex routing method, the peak rate of the outflow hydrograph does not fall on the recession limb of the inflow hydrograph, as in reservoir methods (Mockus, 1967).

\[
Q_2 = (I - C)Q_1 + CI_1
\]

\[
C = \frac{v}{v + 1.7}
\]

where

\[
C = \text{routing coefficient with the range } 0 \leq C \leq 1
\]

The convex method was replaced by att-kin method in 1983 which combines elements from the kinematic method with an attenuation procedure based on storage routing.

2.2 Hydraulic Dynamic Flow Routing

Some of the limitations of hydrological modelling described in Section 2.1 can be addressed by using hydraulic flow routing methods such as the dynamic model (Rehman et al., 2003; Zhang and Bao, 2012; Balica et al., 2013). Earlier studies have confirmed the practical applicability of hydraulic models for flood routing, despite the fact that it is not economically viable to obtain cross-section data over hundreds of kilometres involved in flood routing. According to Fread (1992), hydraulic flow routing models have been applied in the determination of floodplain depths, required heights of structures such as bridges or levees, real-time forecasting of river floods, and inundation maps for dam-break contingency planning.

Dynamic flow routing model are based on the complete solution of one-dimensional (ID) or two-dimensional (2D) computational fluid dynamics (Bates and De Roo, 2000; Piotrowski, 2010). The complete solution of Saint Venant equations require many high resolution morphological parameters which allow flow rate and water level to be computed as functions of space and time, rather than time alone (Fread, 1992; Saleh et al., 2004). Equation 2.14 and 2.15 known as the dynamic wave equations or Saint Venant equations are the conservation of...
water volume and conservation of momentum respectively which governs the unsteady flow analysis (Bates and De Roo;2000).

\[ 0 = \frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q_1 \]  
\[ 0 = \frac{1}{A} \frac{\partial Q}{\partial t} + \frac{1}{A} \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) + g \frac{\partial y}{\partial x} g(S_0 - S_f) \]  

(2.14)  
(2.15)

where

\[ Q = \text{discharge [m}^3\text{s}^{-1}], \quad S_0 = \text{bed slope [m/m]}, \]
\[ A = \text{cross sectional area [m}^2\text{]}, \quad S_f = \text{friction slope [m/m]}, \]
\[ Q = \text{discharge [m}^3\text{s}^{-1}], \quad V = \text{velocity [m/s]}, \]
\[ x = \text{distance along longitudinal axes of the channel or flood plain [m]}, \quad y = \text{hydraulic depth [m]}, \]
\[ t = \text{time [s]}, \quad g = \text{acceleration due to gravity = 9.81 [m/s}^2\text{]}, \]
\[ q_1 = \text{lateral inflow per unit length [m}^3\text{s}^{-1}/\text{m}]. \]

2.2.1 One-dimensional (1D) hydraulic flood routing models

One-dimensional solutions of the full Saint-Venant Equations are derived based on the following assumptions: (i) the flow is one-dimensional, in only one of the three coordinate dimensions along the central streamline in the channel (Franzini and Finnermore, 2001; (ii) the water level across the section is horizontal (Dyhouse et al., 2003), (iii) the streamline curvature is small and vertical accelerations are negligible; (iv) the effects of boundary friction and turbulence can be accounted for using resistance laws analogous to those for steady flow conditions, and (v) the average channel bed is small so the cosine of the angle can be replaced by unity (Cunge et al., 1980), (vi) all the points in the in the fluid has the same velocity and direction at a specific time t, and that the velocity components in the other two directions are negligible (Franzini and Finnermore, 2001)

Many 1D hydraulic modelling software packages developed for flow routing are no longer supported by the developers and others have undergone upgrades since early 90’s (Villazon et al., 2009). Some of the models such as InfoWorks, ISIS (Wallingford, 1997), SOBEK, MIKE
11 (DHI, 2005), and HEC-RAS (US Army Corps of Engineers, 2001) are the only hydraulic flow routing models currently supported by their developers. Hence, detailed discussion on 1D modelling packages will be limited to ISIS, MIKE 11, SOBEK and HEC-TAS. ISIS, MIKE 11 and HEC-RAS, which has recently been upgraded to include an unsteady-state module

### 2.2.1.1 ISIS

Integrated Services for Information Systems (ISIS) is one of the leading river modelling software packages used by many consultants, researchers and public bodies (Romanowicz et al., 2014; Ghimire, 2013; . It is a one-dimensional streamflow model based on a finite difference application of the full Saint Venant equations to a series of cross-sections of the river channel and flood plain and any hydraulic conduits that are built in the flow path. The objective is to model the flow of water in a river channel and can, in theory, be used in real-time mode (Wallingford, 2002). This software can also be used to model floodplain and water level in a river culverts, bridges, weirs, sluices, and pumps (Parsa et al., 2013). The costs associated with the model can be prohibitive. The InfoWorks modelling package combines the original ISIS hydraulic model engine with GIS functionality and database storage within a single environment bringing together source data and hydraulic modelling into a single product (Wallingford, 2002). ISIS and other Wallingford commercial software are no longer produced by Wallingford Software because this branch of HR Wallingford was sold to MWH Soft (Gilles and Moore, 2010).

### 2.2.1.2 SOBEK

SOBEK is a one-dimensional hydrodynamic river flow model also based on the Saint Venant equations of unsteady flow (Rehman et al., 2003; Deltares Systems, 2013). The model is developed using the physical description of the geometry of rivers, the continuity equation and a balance of forces governing the flow of water in open channels (Rehman et al., 2003, Zuwen et al., 2003). It can realistically represent the influence of bridges, barrages and dams on the propagation and attenuation of flood waves (Delft hydraulics, 2003). The different roughness values and storage characteristics of a river can be considered (Rehman et al., 2003).
2.2.1.3 MIKE 11

MIKE-11 is a commercial model originating in Europe and is widely used in hydraulic modelling (FEMA, 2009; Butts, 2011; Wiesenegger, 2011; ZAMCOM, 2012; Parsa, 2013; Romanowicz et al, 2014). The software package is based on a finite difference application of the full St Venant’s flow equations to a series of cross-sections of the river channel and flood plain and any hydraulic conduits that are built in the flow path (DHI, 2001). The basic requirements for applying the model are regular cross-sections of the river channel and its flood plains, boundary conditions in the form of upstream and tributary inflow series and certain meteorological time series. Friction loss factors parameters are derived by calibration. The model is useful to assess short-term and long-term downstream water levels and discharges and to examine management options related to localised flow (DHI, 2001). Unsteady uniform flows are simulated under a fully hydrodynamic flow description. It also comes with powerful graphical interfaces (DHI, 2001).

2.2.1.4 HEC-RAS

HEC-RAS is currently among the most popular hydraulic models, if only because it is available free of charge. HEC-RAS has already been widely used by many agencies as it is standard tool for floodplain delineation studies (Hicks and Peacock, 1996; Maidment and Seth, 1999; Els, 2011; Sanjay and Ravindra, 2012; ZAMCOM, 2012; Parsa, 2013; ). HEC-RAS has the capability of simulating one-dimensional steady and unsteady flow and also sediment transport and moveable boundary open flow channel. The primary procedure used by HEC-RAS to compute water surface profiles assumes a steady, gradually varied flow scenario. Energy losses are evaluated by friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilised in situations where water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e. hydraulic jumps), hydraulic bridges, and evaluating profiles at river confluences (stream junctions) (Maidment and Seth, 1999). HEC-RAS is capable of modelling subcritical, supercritical and mixed flow regime water profiles through the use of arbitrary cross-sections. HEC-RAS is comprised of a graphical user
interface, separate computational engines, data storage and management components, graphics, and reporting capabilities.

The main limitation of 1D numerical models is that they are unable to resolve complex floodplain flow fields and require post-processing to produce realistic flood events (Patro et al., 2009).

2.2.2 Two-Dimensional Flood Routing Models

Two-Dimensional flood modelling permits complex interaction of channel and flood flow fields, allowing various complicated modelling scenarios such as flood inundation to be performed (Horritt and Bates, 2002). Complete 2D models are generally used for unsteady flows in estuaries, bays or lakes where environmental pollution concerns require knowledge of flow patterns and velocities dominated by 2D effects (Fread 1992). The depth-averaged Navier-Stokes equations, generally called the Saint-Venant shallow water equations (Equation 2.19 to 2.21), are used in most commercial 2D models (Horritt and Bates, 2002).

Some of the common 2D models includes, DHM 21 and 34 (Hromadka and Yen, 1987), FESWMS 2DH (US Geological Survey, 1995), SOBEK 2D Overland Flow Module (Gilles and Moore, 2010), TABS RMA2 (US Army Corps of Engineers, 2000), FLO 2D (O’Brien, 2009), TUFLOW (Scientific Software Group, 2010), XPSWMM 2D/XPStorm (XP Solutions, 2010), MIKE 21, Adaptive Hydraulics (AdH) (US Army Corps of Engineers, 2012). Two-dimensional numerical models are unable to model structural elements that may produce super-critical or pressurised flow conditions (Patro et al., 2009). Two-dimensional models are generally much more expensive to calibrate and execute on computers than 1D models.

The limitations of 1D and 2D in floodplain modelling can be overcome by dynamically coupling one-and two-dimensional models to improve hydraulic modelling accuracy and computational efficiency (Frank et al., 2001; Patro et al., 2009).

2.2.3 Coupled 1D/2D flood routing models
1D and 2D coupled modelling has been used in a number of flood forecasting applications and is now available in commercial packages such as MIKE FLOOD (DHI, 2005) INFOWORKS (Wallingford, 2002), ISIS/ISIS2D, ISIS/TUFLOW (Gilles and Moore, 2010; Linet et al., 2006). The flow in the collection system is modelled in 1D but the surface flow is computed with a 2D engine solving the Saint-Venant 2-dimensional flow equations. Although 2D models are far more realistic than 1D models to represent the surface flow behaviour, 1D-2D models still require more computational time than 1D models (MeiBner, 2011). Thus, 1D-2D models are currently not used for real time applications while 1D models can be used online for real-time forecast applications (Henonin, 2010).

2.3 Data availability and requirement for dynamic flood routing in SA

Extensive data is required to provide information for the application of a dynamic routing model (McKay et al, 1996; Birkhead, et al.,2007; Havenga et al., 2007). Basic input data required by dynamic routing model include the channel network connectivity, cross-section geometry, reach lengths, energy loss coefficients, stream junctions information and hydraulic structures data (Birkhead, et al.,2007). Cross-sections are required at representative locations throughout a stream reach and at locations where changes in discharge, slope, shape or roughness occur (Birkhead, et al.,2007).

In hydraulic modelling the spatial variation of topographic and meteorological parameters are taken into account (Raoet al, 2011). Topographic models such as a Digital Elevation Model(DEM) are the main input for topographic parameter extraction (Zhu and Gold, 2005; Martini & Loat 2007). Current DEMs based on LiDAR (Light Detection And Ranging) cause premature flooding due to unknown river characteristics below water surface because the remote sensing techniques applied in their development do not penetrate beneath the water level (Foxgrover and Jaffe, 2005;English, 2009; Athearn et al., 2010).The conventional forms of LiDAR do not penetrate water. Additional bathymetric measurements are necessary to complete any parts of a DEM which were under water when the LiDAR was undertaken (English, 2009; Smart, et al., 2009). Bathymetric data collection is time-consuming, expensive and it requires careful processing to correctly interpolate between sounded points or cross-sections and to seamlessly integrate bathymetric data into a LiDAR- based DEM (English, 2009; Smart, et al., 2009). Various thematic layers that are required for the
topographic model can be prepared in an ArcGIS environment (Rao et al., 2011). Table 2.1 shows some of the input data and their availability in South Africa for dynamic routing. From the table below it is evident that high resolution DEMs of 1m to 10m resolution are only available in small areas in South Africa making dynamic modelling very challenging. Most of the current land cover data set in South Africa are very dated and at small scale. DWS collects water depth and discharge values at various gauging stations within the country. There is a comprehensive data collected in most stations but there are still gaps in other stations. There is no official archive of historical images capturing flood events, or any hazards in South Africa. Historic aerial photography or satellite images are required for calibration and validation purposes where extent of a particular flood event are determined from an image compared with the result of the hydraulic model.
Table 2.1: Data requirements and availability for dynamic routing in South Africa (After Els, 2011)

<table>
<thead>
<tr>
<th>Data requirements</th>
<th>Data specifications</th>
<th>Data availability in South Africa</th>
<th>Coverage</th>
<th>Source</th>
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<tbody>
<tr>
<td><strong>Topographical</strong></td>
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<tr>
<td>Contour DEM</td>
<td>CD: NGI: 1: 10 000 (5m)</td>
<td>SA partial</td>
<td>CD: NGI</td>
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<td>&lt; 5m (Winde and Hoffman 2010)</td>
<td>CD: NGI: 1: 50 000 (20m)</td>
<td>SA</td>
<td>CD: NGI</td>
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<tr>
<td>Between 10X10 and 5x5</td>
<td>CD: NGI: 25m and 50m DEM</td>
<td>SA partial</td>
<td>CD: NGI</td>
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<td>(Martin and loat, 2007)</td>
<td>ASTER GDEM (30m)</td>
<td>SA partial</td>
<td>CD: NGI</td>
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<td></td>
<td>SRTM 90m DEM (90m)</td>
<td>Near global</td>
<td>ERSDAC</td>
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<td>GTTOP30 (1 km)</td>
<td>Near global</td>
<td>ERSDAC</td>
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<td></td>
<td>DWS DEM (1m)</td>
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<td>SA partial</td>
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<td>Upper Vaal</td>
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<tr>
<td>Land cover (land use) vector raster</td>
<td>NLC 1994 (1:250 000)</td>
<td>SA</td>
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<td>NLC 2000 (1:50 000)</td>
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<td>Globcover (300m)</td>
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<td>GLC 2000 (1km)</td>
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<td>FAO, UNEP, JRC</td>
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<td>Historical</td>
<td>Flow, rainfall, water quality, groundwater and water use licenses</td>
<td>SA</td>
<td>DWS hydrological information centre</td>
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<td>dated flood maps and historic reports</td>
<td>Areal imagery</td>
<td>SA</td>
<td>CD: SM and CD: NGI</td>
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<td>water level and velocity photo and Satellite imagery</td>
<td>Areal (1: 20 000-1:150 000)</td>
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<td>CD: NGI</td>
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<td>flood marks</td>
<td>Orthophotos (1: 20 000-1:60 000)</td>
<td>SA</td>
<td>CD: NGI</td>
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<td>newspaper articles</td>
<td>Optical imagery</td>
<td>SA</td>
<td>GLCF</td>
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<td>Landsat 4, 5 MSS</td>
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</table>
2.4 Calibration of Hydraulic Flood Routing Models

The ability of any hydraulic or dynamic model to be sustainably used in a flood forecasting system is if the model is properly updated and calibrated to reproduce historical observations of stage and discharge (Leandro, 2009; Henonin, 2010). Calibration is essential for validating and verifying the accuracy of flood models (Leandro, 2009). The calibration process is used to estimate hydraulic parameters and refine model geometry to optimise model replication of the observed data under a range of flow scenarios. Calibration may be accomplished via either a trial-and-error or an automatic technique (Fread, 1992). A complete calibration requires data for a long period of time, covering a wide range of water levels. In the absence of observed flows and water-surface elevations, selection of Manning n should reflect the influence of depth, seasonal changes, bank and bed materials, channel obstructions, irregularity of the river banks, and especially vegetation (Chow 1959; Koegelenberg et al., 1997). The resistance to flow is mostly represented by the Manning n, Chezy C, or Darcy f coefficients (Chow, 1959;Chow et al., 1988; Linsley et al.,1986; Dyhouse et al., 2003). The Manning n is generally the most applied roughness coefficient.

Several studies including Wasantha (1995),Usul and Turan (2006), Vijay et al. (2007),Patro et al. (2009) and Parhi, 2011;Timbadiya et al. 2011;) have calibrated channel roughness for different rivers for the development of hydraulic models using previous flood data supported with photographs of rivers collected during field visits. The Root Mean Squared Error (RMSE) and Singular Value Decomposition (SDV) methods have been used to assess the performance of the simulation for various values of Manning’s n (Patro, et al., 2009).

Merz (2011) developed a calibration method where all channel cross sections were identified by a base value and the differing channel and flood plain roughness of the sections were represented in each of the sections relative to the base value. Values of roughness for the channel and floodplain were then raised or lowered based on land use type by using aerial photography of the catchment. During this process it was ensured that the adopted roughness values were consistent with those recommended by Chow (1959). According to Merz(2011), this approach of calibration (a) allows future users to readily see whether one cross section
has a higher degree of roughness, as one section can be compared to the next, (b) it readily enables the use of resistance number interpolation tool which can be used to calibrate one set of cross sections to a variety of past events, as changes to Manning’s n are saved using the same cross section name, but with an additional extension name, and (c) to allow for sensitivity of the model to roughness, or large scale changes to the catchment roughness to be easily assessed, as users simply need to adjust the base Manning's values in the hydrodynamic parameters file. This provides a trail for future model calibrations as well as comparison and identification of sensitive parts, and or potential errors in the model.

2.5 Application of Flood Routing Models

The South African Department of Water and Sanitation (DWS) makes use of a simple in-house developed Muskingum based model for flood forecasting in the VORS to predict peak flow values, expected volumes, time of peak at downstream locations and to optimise the operation of different dams in the systems (Delport, 2010). The model, uses actual real-time flow values obtained from gauging stations to generate hydrographs (Delport, 2010). The model has performed very well over the years and is very useful for quick analysis but the quality of the results are sometimes influenced by the existence of various structures in the VORS, such as large and small dams, large and small tributaries, hydro-power stations, flow gauging stations, and bridges, which may results in backwater effects and which limits the performance of hydrological models (Wessels and Rooseboom, 2008). The quality of the results are also affected by non-operational telemetry systems and gauging stations, as the model is heavily reliant on actual real-time flow. The model does not accurately take into consideration the physical characteristics of the VORS channel, including lateral inflows and this also compromises the quality of the results, particularly when considering the extent and complexity of the VORS.

2.6 Evaluation of Models suitable for VORS

South Africa does not have National Standards for assessing technical performance of hydrologic and hydraulic model that can be used for flood forecasting. Some of the tests that
can be used to assess the applicability of a model are shown in (Crowder et al., 2004; Table 2.2 Marker et al., 2004)

Table 2.2. Some model capabilities and criteria for the selection of flood routing approach for the Vaal Orange River System

<table>
<thead>
<tr>
<th>Model</th>
<th>Data requirements</th>
<th>Institutional, and operational effort</th>
<th>Numerical accuracy to simulate</th>
<th>Software Capability to simulate</th>
<th>Reproducibility to simulate</th>
<th>Support documentation</th>
<th>Licensing and other costs</th>
<th>Public Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>DWS Muskingum based model</td>
<td>Rainfall; River flow</td>
<td>Medium</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Muskingum-Cunge</td>
<td>Rainfall; DEM; Landuse</td>
<td>Medium</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Three-Parameter Muskingum</td>
<td>Rainfall</td>
<td>Medium</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>ISIS</td>
<td>Monthly</td>
<td>High</td>
<td>Y</td>
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<td>HEC-RAS</td>
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<td>FLO-2D</td>
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<tr>
<td>Mike Flood</td>
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3 DISCUSSION AND CONCLUSIONS

This chapter presents discussion and conclusion of the literature review contained in Chapter 2, initially focussing on key points and then providing an insight into the area of study.

The impacts of flooding can be significantly reduced when flood monitoring and warning systems are in place. The flood monitoring and warning systems will vary from simple rainfall forecasts, with or without weather radar utilising rain and water surface gauging stations, to complex systems that incorporates hydrological and dynamic hydraulic models.

Hydrological and hydraulic models offer a wide variety of process options, differing levels of complexity and data requirements and degrees of technical support and training. Their application also depends on the forecasting objective, geographical and environmental factors as well as institutional capabilities.

Some of the common hydrologic routing methods include: Modified Puls, Simple Muskingum, Muskingum-Cunge, Three Parameter Muskingum method and the US Soil Conservation Service (SCS) coefficient channel routing technique. Flood routing methods based on hydrologic modelling techniques are limited in their approach in that the catchment parameters are lumped together in a simplified manner resulting in a misrepresentation of the surface runoff. Some of the limitations of hydrological flood routing have been addressed in the Muskingum-Cunge method and later in the Three-parameter Muskingum method. The Three-parameter Muskingum method presents an improvement compared to other hydrological models in that it has the ability to produce comparable results to hydraulic routing models with reduced amount and detail of field data and with a better computational efficiency.

Dynamic flood routing models, are preferred to hydrological based techniques because they are much more accurate even though they are computational complex and data intensive. Some of the most commonly used dynamic flood routing models include HEC-RAS, MIKE 11, InfoWORKS, SOBEK and ISIS. HEC-RAS is widely used in many studies mainly because it is readily and freely available and that there are no licence fees as compared to MIKE 11, InfoWorks and other hydraulic dynamic models.
The dynamic flood routing models require calibration to ensure that the accuracy of the model is within acceptable range and this is achieved by adjusting the Manning's roughness coefficient to reproduce historical observations of stage and discharge. Such an adjustment process may be accomplished via either a trial-and-error or an automatic technique. Several calibration methods have been applied to these methods, such as locking cross sections into a base value and lowering or raising the value on differing channel and flood plain roughness of cross sections basing on land use type and aerial photography of the catchment.

Based on the literature reviewed, hydraulic based models will be more appealing for flood routing in the VORS since they have the ability to accurately simulate flows in complex basins (Balica et al., 2013). However, it will also be worthwhile to test the applicability and performance of the DWS Muskingum based routing model, Three-parameter Muskingum-Cunge hydrological model against hydraulic models suitable for such a large catchment as the VORS on a continuous basis for flood/flow forecasting. The Three-parameter Muskingum-Cunge is an alternative technique for continuous flood routing due to its comparability, computational efficiency and reduced amount and detail of field data required if for hydraulic routing is not viable.

In the literature that has been reviewed there is evidence of potential for use of dynamic flow routing in large catchment using the available 1D models with real-time data. There is however, the challenge of availability of correct data for setting the models in South Africa (Els, 2011). It is envisaged that after this study the South African Department of Water and Sanitation can move from the current simple Muskingum based hydrological forecasting method, which is dependent on actual gauging stations data, to a physically based method. A dynamic method will be most suitable if the required input data is available, but the Three-parameter Muskingum method may also provide better flood forecasting results for continuous flood forecasting in the VORS.

Several studies have been carried out on the comparison of hydrological versus hydraulic routing methods (Fread, 1992; Rehman et al., 2003; Grilles and Moore, 2010) but these have not been performed in catchments in South Africa. This study will focus on the availability of the required data, computing requirements, numerically stability and accuracy, capability, reproducibility, adaptability, cost, of the hydraulic models with the aim to develop a suitable dynamic flood routing method/model in the Vaal Orange River.
4 PROJECT PROPOSAL

The DWS makes use of a simple in-house developed Muskingum based model for flood forecasting in the VORS (Delport, 2010). The model, uses actual real-time flow values obtained from gauging stations for flood routing (Delport, 2010). The model is very useful for quick analysis but the quality of the results are sometimes influenced by the existence of various structures in the VORS which may results in backwater effects and the non-operational telemetry systems and gauging stations which limits the performance of the model (Wessels and Rooseboom, 2008). The model does not accurately take into consideration the physical characteristics of the VORS channel, including lateral inflows and this also compromises the quality of the results, particularly when considering the extent and complexity of the VORS. A dynamic flow routing model would be ideal for simulating flows in such a complex system.

4.1 Introduction

This chapter presents a project proposal to select and develop a suitable dynamic flood routing method/model for the VORS by evaluating candidate hydrological and hydraulic routing methods for the availability of data, computing requirements, numerically stability and accuracy, capability, reproducibility, adaptability, form and function, cost, and model run-time. The project proposal covers the problem statement, the objectives of the study that will include research aims, hypothesis and specific objectives, methodology of study, work plan and time schedule.

4.2 Hypothesis

The project will provide a clear indication of the feasibility and capability of a dynamically calibrated routing model in the VORS which has not been tested before. The calibrated dynamic model will perform better than the current system. It is postulated that such a system can increase flood forecasting lead times, improve the accuracy of flood forecasting and provide currently unavailable flood inundation information. These potential gains would contribute towards an improvement in early flood warning and flood control and result in a significant reduction in flood related losses such as human lives and property.
4.3 Research Aims

The primary aim of the study is to improve the accuracy of flood forecasting and increase flood forecasting lead times thereby reducing the negative impacts of flooding in the VORS. This will be achieved by developing a suitable dynamic flood routing model appropriate for implementation in the VORS.

4.4 Objectives

To achieve the research aims and investigate the hypothesis, the specific objectives are to:

(a) Review literature on different flood routing methods and select suitable flood model for the VORS
(b) Determine the data requirements for dynamic flood routing and carry out an assessment of available data in South Africa
(c) Conduct field surveys/measurements to generate hydraulic river channel and flood plain characteristics,
(d) Develop methods to estimate the below water surface profiles based on the available DEM
(e) Develop dynamic calibration techniques,
(f) Carry out flood modeling for Upper Vaal using available data
(g) Evaluate flood modelling results and make recommendations about modelling approach/system to implement in the VORS

4.5 Methods and Materials

This section discusses the methodology that will be used in this study. The first section describes the study site followed by the methodology. The third part describes the work pan equipment and resources.
4.5.1 Research site

The study area includes the entire VORS but it is envisaged that the pilot dynamic flood modelling will be limited to the Upper Vaal due to the available 1 m DEM that the Department of Water and Sanitation has recently purchased that covers only the Upper Vaal. If successfully the system will be rolled out to the entire VORS. Besides being critical for socio-economic development in the country, the Upper Vaal is flood prone and thus present a suitable test-case for the methodology. The river system has a relatively dense hydroclimatic monitoring network and hence has sufficient historical and near real-time data to make the study possible.

4.5.2 Methodology

A number of candidate dynamically calibrated hydraulic routing flood/flow models and hydrologic models will be reviewed and a selection criteria will be used to select the models for evaluation. It will not be possible to configure all the models due to time, effort and time costs involved. In assessing the models the following criteria will be used; numerically stability and accuracy, technical capability, reproducibility, adaptability, suitability for South African conditions, especially the Orange-Vaal River Basin; capability of running in sub-daily (minimum hourly) time-steps; amenability to coupling; and traceable development and maintenance team, and ease of use.

An assessment of available data sources national and international required for dynamic flood routing will be conducted. The assessment will be based on resolution scale and coverage. The accuracy of the data sources is important as it influences the modelling approach to be followed. Qualitative and quantitative methods for data collection will be used. Field visits, document analysis, visits to data custodians are some of the methods that will be used to gather relevant data. A reliable configuration of most of the popular hydraulic modelling packages, including HEC-RAS and Mike 11, requires large quantities of geometric and spatial information such as river cross-sections, slopes, lengths, surface areas and heights. This information is not readily available; hence dedicated field surveys will be undertaken to calibrate/verify information obtained from the 1 m LiDAR DEM. Field surveyed data will be used to develop methodology for determine water sub-surface which is lacking from LiDAR DEM.
Flood modelling using the Three-Parameter Muskingum method and other selected dynamic routing models will be conducted for the Upper Vaal. The data sourced during the study will be used to configure the models to demonstrate a feasibility of implementing dynamic routing in the VORS. The Mike 11 Flood Model and the HEC-RAS are the preferred dynamic models for this study but their applicability will depend on availability of data. The Three-parameter Muskingum method is also selected for this study as it has the ability to produce comparable results to hydraulic routing models with reduced amount and detail of field data and with better computational efficiency. The evaluation will determine whether the Three-Parameter Muskingum method, the Mike 11 and HEC-RAS can perform similarly or better than the current Muskingum-based flood routing system at the Department of Water and Sanitation. The inputs data and outputs from the selected models such as graphs, tables and map will also be assessed for ease of integration with installed information systems such as the DWA Real Time System, HYDSTRA database and DWA Hydrology website for publishing flow levels at selected sites.

4.6 Work Plan, Time Schedule and Equipment and Resources

Having discussed the methodology, it is paramount that all the research activities be well scheduled. The list of required equipment and resources are included in this section. To complete the methodology approaches in the previous section, the following work plan and related activities are proposed to ultimately achieve the purpose of the study.
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<thead>
<tr>
<th>Task</th>
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<tr>
<td>1</td>
<td>Literature Review &amp; write up</td>
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<td>2</td>
<td>Improve Understanding of Hydraulics</td>
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<td>4</td>
<td>Gather Hydraulic Model Input Data including field surveys</td>
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<td>10.3</td>
<td>Submission of Final Draft of Thesis</td>
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PROPOSED RESEARCH ACTIVITIES, WORK PLAN AND DELIVERABLES

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<td>10.3</td>
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</tr>
</tbody>
</table>
4.7 Equipment and resources

The model input will include data from the Department of Water and Sanitation. This will include real-time data for water levels recorded at various weirs and spillways. The data will be used for the calibration and verification of the model. Topographic hydraulic parameters of the catchment will be determined from a 1 m LiDAR DEM sourced by DWS from Tom Tom Africa. The geometry of cross sections will be obtained from Lidar DEM. Field surveyed data will be used to determine water subsurface. Initial values of Manning’s $n$ will be determined from field visits, photos, aerial imagery, tables of Manning's produced by Chow (1959) and other suitable methods.

The project expenses will be budgeted and paid for under the Hydrological Services Directorate’s of the DWS goods and services budget.

The Department’s procurement procedures present the biggest risk to the project. The success of the project hinges on the use of Digital Elevation Model (DEM) data and timely acquisition of software such as MIKE 11 DWS currently has no licence for MIKE 11. The procurement processes tend to be slow and this may delay critical aspect of the project. The DEM data is only available for a portion of the main stem of the Vaal River only and excludes the Vaal Dam. There are more than 10 Acoustic Doppler Velocity Profilers between the Gauteng and Free State DWS Region available for use for the project. The Gauteng and Free State DWS Regions are responsible for maintaining flow gauging stations in the Upper Vaal River System.

4.8 Intellectual Considerations

The official documentation of the University of KwaZulu-Natal related to intellectual property titled: Intellectual Property and Proprietary Information Agreement (Form IP2), was signed and submitted to the School of on the 1st on 29 January 2014.

4.9 Expected Outcomes and Deliverables

The following outcomes and deliverables are envisaged as a final product from this study:
Knowledge contributions: The study will provide methodologies for determining bed level below water surface from LiDAR based DEM. The project will also provide information on the feasibility of carrying out continuous dynamic flood routing on VORS considering the size of the basin, and also the data availability to carry out the modelling.

- One Doctor of Philosophy in Agricultural Engineering dissertation;
- Two/more published articles in accredited journals; and
- One/more national and international conference attendance/presentation.
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