

Modelling Flood Inundation in the Mlazi River under uncertainty

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ABSTRACT

The paper highlights some of the techniques employed for the Mlazi River in the context of flood analysis and flood forecasting. These techniques are applicable to an environment where there is uncertainty due to lack of historical data for input, calibration and validation purposes. This study was carried out through the application and integration of various modelling techniques. The process involved the integration of GIS technology, a physically based hydrological model for flood analysis, the conceptual forecasting model for real time forecasting and the hydraulic model for computation of inundation levels. The integration of modelling techniques can better be explained by categorizing the process into three phases:

Phase 1 Desktop flood analysis: A continuous physically based model (HEC-HMS Model) was set up using GIS technology. The model applied the SCS-UH method for the estimation of peak discharges. Synthetic hyetographs created from the mean rainfall depths distributed hourly, using appropriate distribution types, were used as input to the model. A sensitivity analysis was implemented and subsequently the HEC-HMS model was calibrated and peak discharges simulated. The peak discharges from the calibrated model were used as input to the hydraulic model and also used for validation of the Mlazi Meta Model (MMM) used for real time flood forecasting. The confidence in the applicability of the HEC-HMS model is based on the intensive efforts applied in setting it up so that it is representation of the Mlazi catchment. Furthermore the output results from the calibrated HEC-HMS model have been compared with other reliable methods of computing peak discharges and also validated with frequency analysis conducted on one of the subcatchments.

Phase 2 Implementation of the Inundation Model: The hydraulic model (HEC-RAS) was created using the Digital Elevation Model (DEM) to define the terrain cross-section along the streams, and hydraulic structures were incorporated into the model. The roughness coefficients and boundary conditions were added to the program manually after having conducted field surveys to determine the appropriate values to be used. Flow data for the computation of levels of inundation were obtained from the HEC-HMS model. The levels of inundation for the natural channel of Mlazi River were simulated under the one dimensional steady state analysis whereas the levels of inundation for the canal were simulated under unsteady state.

Phase 3 Creation of the Mlazi Meta Model (MMM): The creation of the Mlazi Meta Model (MMM) used for real time flood forecasting in the context of Mlazi is the linear catchment model which consists of a semi-distributed three reservoir cell model (Pegram and Sinclair, 2002). This required parameters to be fitted so that it became representative of the Mlazi catchment. The validation of this model required use of design storms together with output time series hydrographs from the HEC-HMS. The synthetic storms were input into the model and the parameters were manipulated so that the output stream flows from the model were approximate to the output from the calibrated physically based model (HEC-HMS). This approach might seem unreasonable because a model is being validated by another model but it should be noted that this approach gives the best initial estimate of the parameters rather than trial and error. The meta-model would further be updated using radar and streamflow data once all structures have been put in place.

INTRODUCTION

Background

Natural watercourses have been modified for centuries at times with the intention of improving the environment in question whereas also at times due to the lack of a full understanding of the natural phenomena, causing severe negative impact. Canalising natural stream channel, thereby changing the course of the river was done for the Mlazi river in the mid 1950 by the Department of Transport, with the intention of deviating the river away from the Durban Airport. What was not properly considered were the hydrological side effects, which have resulted in flooding. The 1987 national floods and the current floods in the Eastern Cape in South Africa are evidence that floods are costly natural disasters in terms of human hardship, loss of lives and economic loss. The 1987 floods, which occurred on the Mlazi River of Durban in South Africa, caused the closure of Mondi Paper industry and the SAPREF refinery for ten days resulting in severe economic loss. Universities and other concerned organisations have involved themselves in flood studies. The studies include flood warnings, floodline delineation; river streamflow forecast and display of levels of inundation in GIS so as to reduce flood damage.

This paper presents the extension of the research (funded by WRC) on river flow nowcasting using radar aimed to include levels of inundation, whose benefit is to be displayed on GIS in the eThekwin Metro Disaster Management Center. This was made possible through the integration of the Mlazi flood study process being conducted by Arcus Gibb Engineering Consultants and the forecasting system developed by Sinclair (Pegram and Sinclair, 2002) as shown in figure 1. The main objective in the study was to deliver an operational system that would produce flood forecasting in real time using real time data and produce levels of inundation for the Mlazi catchment.

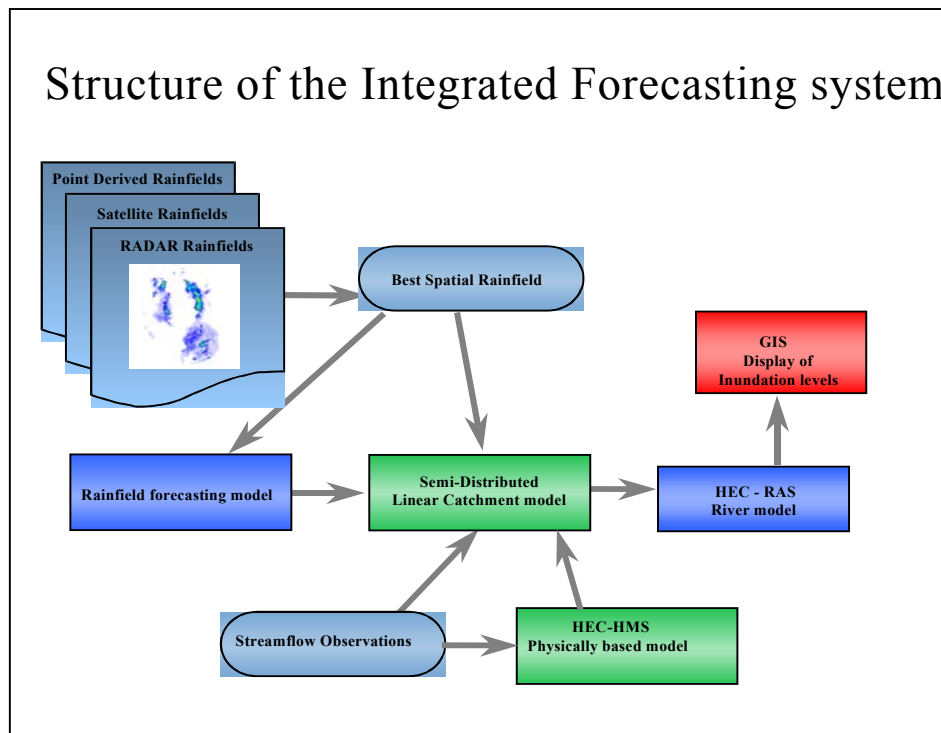


Figure 1.; Structure of the Integrated forecasting System

The most appropriate approach would have involved the direct use of the real time forecasting model created by Pegram and Sinclair (2002) in the context of the Mlazi catchment. This was to be conducted through the acquisition of historical stream data with correlating radar rainfall data, to calibrate and validate the Mlazi Meta Model.

However since the study was conducted in an environment where there is uncertainty due to lack of historical data for input calibration and validation purposes it was necessary to overcome these difficulties. The approach to this study was therefore based on integration of modeling techniques intended to address the uncertainty. A strategy was determined to address the difficulties by introducing a physically based model into the real time forecasting system.

DESKTOP FLOOD ANALYSIS USING CONTINUOUS BASED MODEL

The physically based model was designed for the Mlazi using the hydrologic modelling system program (HEC-HMS) developed by the Hydrologic Engineering Center (HEC) of the U.S Army Corps of Engineers (HEC-HMS manual, 2001). The program as presented by Olivera (2001) uses geographic information systems (GIS) technology to create and set up a Digital Elevation Model (DEM). The GIS was also used to extract relevant information for hydrological modelling of the Mlazi catchment. The extraction of the hydrological information using GIS was carried-out by ML Sultan Town Planning Resource Unit, their application of the GIS technology is presented by Hansen et al (2001). The HEC-HMS constitutes three components called “models”, these are namely;

- The basin model used for managing basin models, which describe the different elements of the hydrologic system such as the reaches, junctions and subcatchments.
- The meteorological model used for managing and editing meteorological models, which describe in time and space the precipitation events to be modelled and optionally an evapotranspiration module.
- The control specification model used for editing and managing control specifications, which define the time frame for the simulation, based on the duration of the storm event.

In addition to the above-mentioned models the HEC-HMS model have the capacity to model loss rate, perform hydrologic routing and cater for the base-flow component. All these are options based on the availability of information and the purpose of the modelling process.

This HEC-HMS configuration was intended to be used for the initial adjustment of the Mlazi Meta Model (MMM to be outlined in the later section) parameters, so that the MMM would be representative of the Mlazi catchment and therefore be suitable for real time flood forecasting once real time data from the Mlazi river was improved and made available. In addition to that, the computed peak discharges were input to the HEC-RAS model used for the delineation of inundation levels. This approach for approximating floodplain limits using continuous-simulation modelling coupled with a hydraulic model with flood-routing capabilities was described by Bradley et al (1996).

The raster based DEM created for the HEC-HMS model was set up using 5m contours that gave a smooth resolution. The smoother resolution would enable precise derivation of hydrological parameter estimates such as the flow length, lag time and time of concentration and SCS curve number estimates. Moglen and Hartman (2001) stated that the estimates of hydrological parameter decreased as the resolution grew coarser. This could result in overestimates of peak discharges. Since the initial parameter estimates for the MMM model were based on the HEC-HMS model it was important that an effort be applied to reduce human error and make sure that the model was a good representation of the Mlazi catchment.

One shortcoming of the project was the lack of correlating rainfall and streamflow data, even for the calibration of the HEC-HMS model. In order to improve the quality of our model in this uncertain environment, it was important to focus on ensuring that the physical parameters to be used to set up the model were precise. A sensitivity analysis conducted for the HEC-HMS model input parameters (based on the SCS curve number method) confirmed that the computed discharges were most sensitive to the variation of the SCS curve number. It was therefore apparent that one should get the best estimates of the CN values for each identified subcatchment so as to obtain realistic peak discharges. This was conducted through the overlaying of physical catchment characteristics such as soil type, and landuse in a GIS environment. The overlay process enabled the computation of weighted CN values and the initial abstraction and lag time. The land use categories identified for the Mlazi catchment based on the landuse maps from the eThekweni Metropolitan Department of Engineering were compared with the SCS land category obtained from Schmidt and Schulze (1978b). The physical parameters were input in each of the subbasin representing the subcatchments shown in figure 2.

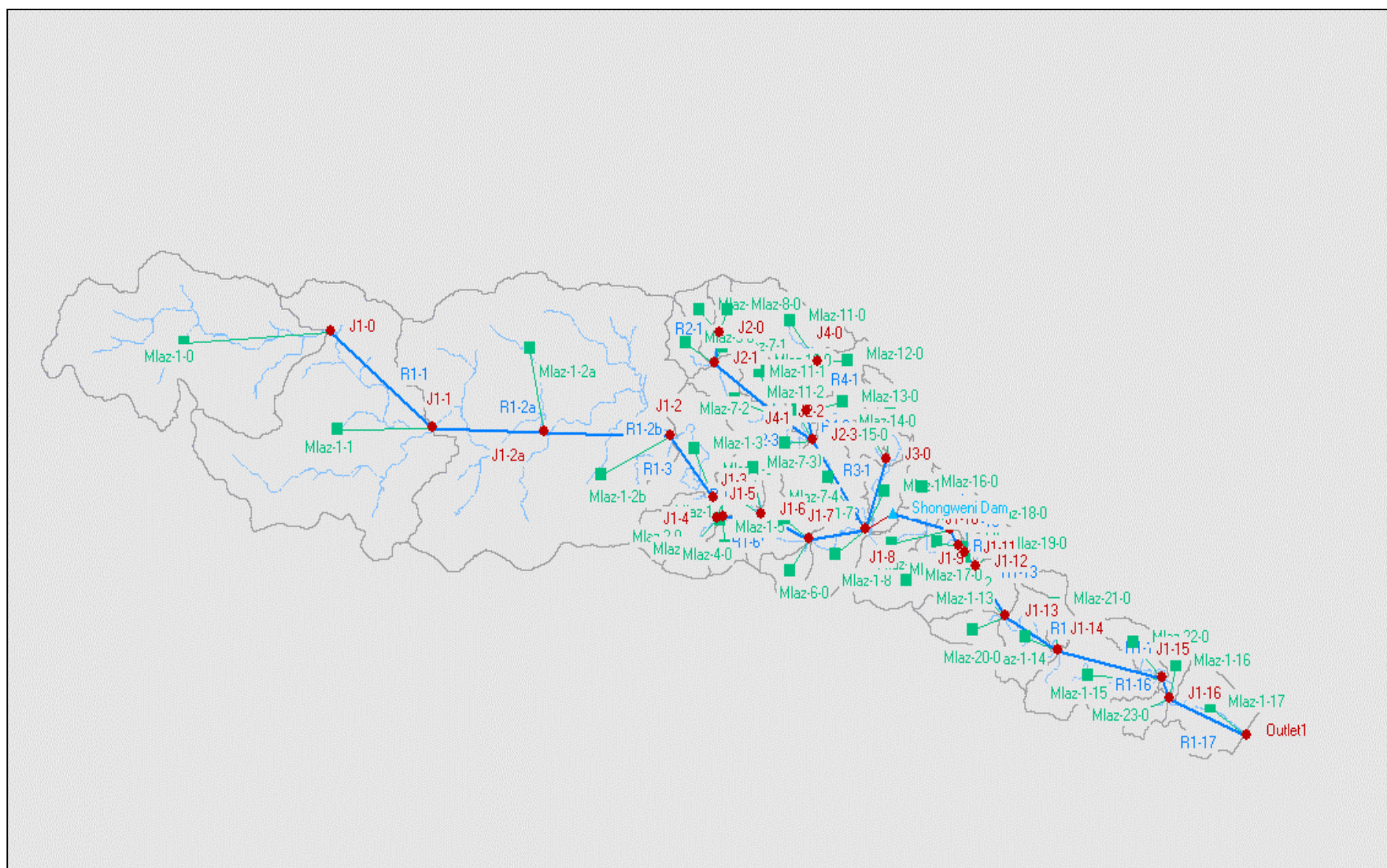


Figure.2; Schematic Layout of the HEC-HMS model for Mlazi catchment

The problem of historical rainfall data was encountered by the use of design synthetic hyetographs based upon the design one day mean rainfall depth and three day mean rainfall depths for various recurrence intervals obtained from Smithers et al (2000). These had to be distributed using suitable temporal storm distributions based on the dimensionless SCS Type 2 synthetic storm distribution created by Schmidt and Schulze (1987) and later revised by applying Adamson's (1982) desegregation scheme to preserve scaling properties which have also been investigated by Menabde et al (1999).

The three day design storm had six random combinations which are equi probable temporal distributions because there is negligible correlation between daily amounts of rain in a sequence of wet days. Zucchini and Adamson, (1984). The scenarios were based on the order in which the magnitude of rainfall depth was selected. LMH represented the order in which the lowest depth L was considered to contribute to the first day of the 3 days followed by the medium M and then the highest H. The worst scenario (LMH) could have been the most favourable to be used for analysis. However it was deduced from the historical flooding of the canal that such a scenario has not really occurred as yet and since the delineation of flood plain was calibrated based on historical flood events the scenario used was the MHL. The synthetic hyetograph was used as input to the HEC-HMS model and also as input to the MMM.

The HEC-HMS model required that a routing method be defined to compute the downstream hydrographs. The most appropriate method selected was the Modified Puls (or storage routing), the method however required storage-flow relationship which were obtained from HEC-RAS. This method had an advantage over the other routing methods available such as kinematic wave, Muskingum-Cunge, and lag method in that it could incorporate the backwater effects caused by downstream conditions, such as bridges and culverts. It should be noted that the initial estimates of the storage-flow relationship were obtained from the Mhlatuzana since it has the same physical characteristics as Mlazi. However these storage-flow relationships were later replaced by the storage-flow relationship computed from the volume storage in the reach calculated in the HEC-RAS river model.

The HEC-HMS model also required the input data for the base-flow, which was assumed to be zero because it was small in magnitude compared with the flood discharges.

The procedure for the calibration process of the HEC-HMS model involved adjusting model parameter values (CN, Initial abstraction and Lag time) until modelled peak discharges matched historical observed peak flows. Due to the unavailability of data for the whole catchment, the calibration process was first applied to two selected subcatchments of Mlazi, which happened to have reasonable historical streamflow and rainfall data. Five storm events were identified and of these five, only one was used for the calibration (2-4 Feb 1999 storm event) because its rainfall data had a good correlation with the stream-flow data. The calibration procedure was carried out in two phases. The first phase involved the use of the 2-4 Feb storm event which had streamflow data correlating to 3-Day total rainfall depths which had to be "stitched" to the radar distribution for the 2-4 Feb 1999 storm event so as to spatially distribute it over the quaternary catchments. Figure 3a and 3b show the HEC-HMS comparison

of the computed and observed hydrographs at the UH6002 streamgauge station (Baynesfield) before and after parameter adjustment respectively.

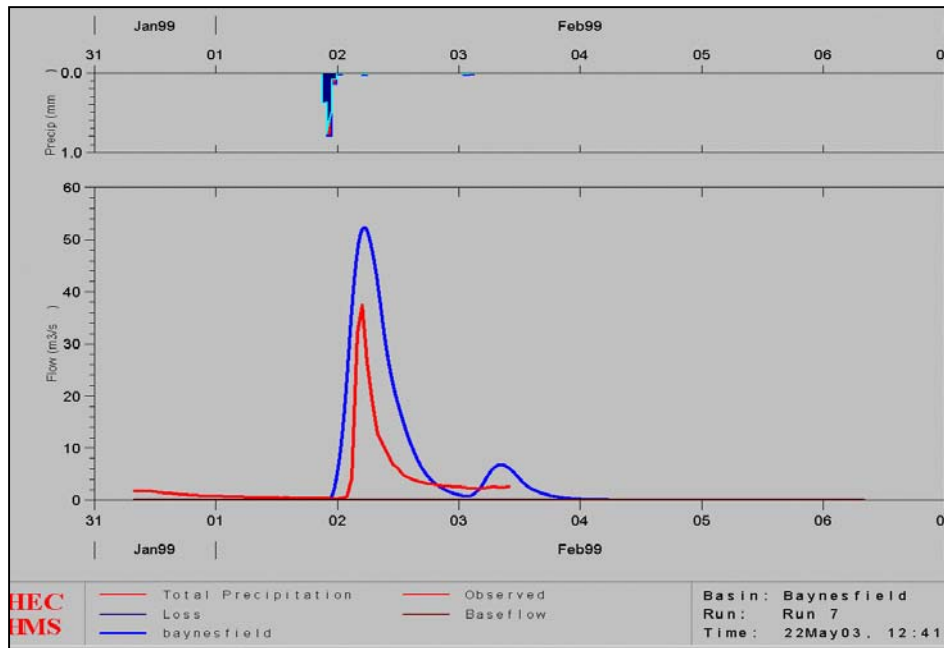


Figure .3a: Gauge U6h002: Observed versus Modelled Hydrographs before parameter adjustment

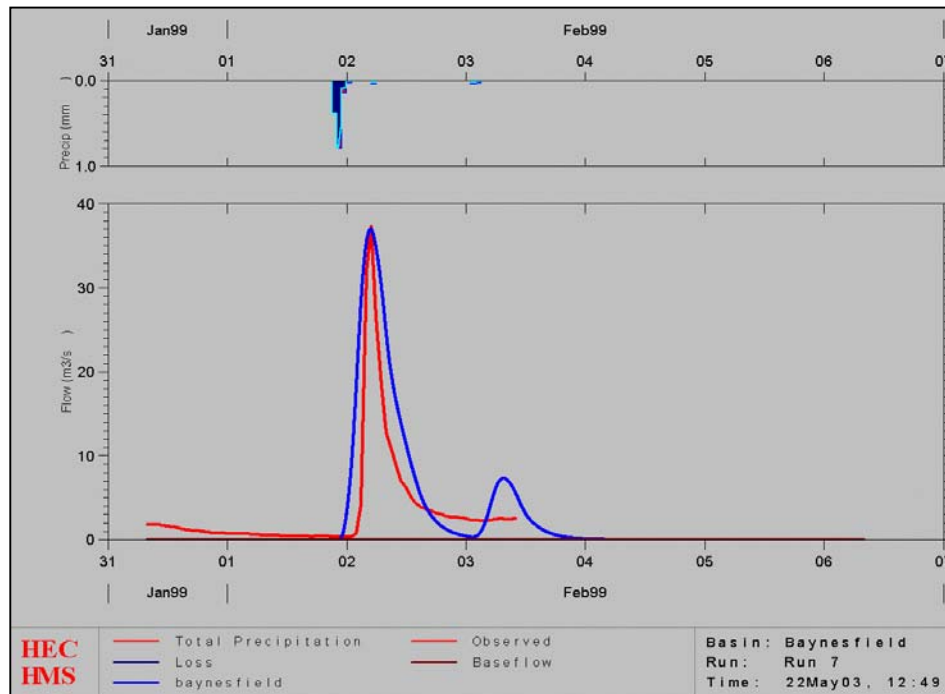


Figure .3b: Gauge U6h002: Observed versus Modelled Hydrographs after parameter adjustment

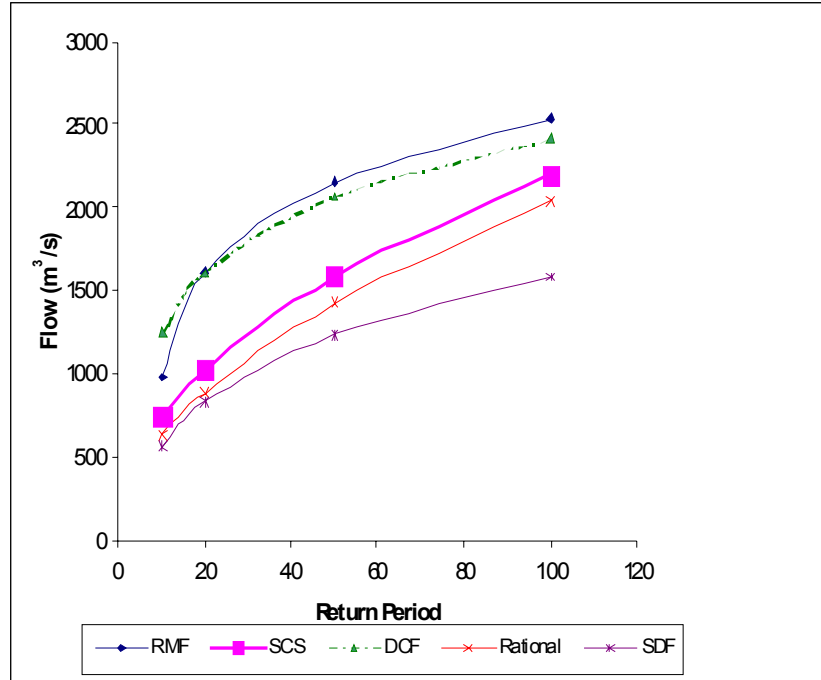


Figure 4; Comparison of HEC-HMS Peak Flow Discharge with other methods

The peak discharge values obtained after conduction of the first phase of the calibration process were compared to those obtained using other methods such as the RMF and rational method as shown by figure 4 above. It was at this point that the values were also compared with the other HEC-HMS peak discharges computed from the previous studies of other catchments within the Durban metropolitan boundary. For instance the Standard Design Formula (SDF) and Durban Corporation formula (DCF) are some of the empirical formulae, which were applied. The later is intended to be replaced by an empirical formula based on the HEC-HMS peak discharges and the catchment size derived to enable an early estimate of the HEC-HMS peak discharges for selected return periods when given the catchment area. The formula is represented as;

$$Q = C(T)A^{0.42}$$

The formula is applied to compute Q for various return periods T. The term C (T) varying for each return period caters for the physical parameters of the catchment.

The second phase was the validation process that involved the use of flood frequency analysis of the 20-year peak discharges from the two stream gauge stations (Baynesfield and Mlaas Road). The observed flows were ranked and assigned a probability value computed by use of the Cunnane (1978) plotting position formula, furthermore the reduced variate y_T was computed based on the computed return period. The observed flows were plotted against y_T . The HEC-HMS computed flows were plotted against the variate y_T (which was computed using the selected return periods of the design rainfall depth). The two plots were compared and the HEC-HMS therefore adjusted to align with the observed through the manipulation of the SCS curve number and the lag time until there was a good match. Figure 5 shows the comparison of the computed peak discharges to the observed peak flows.

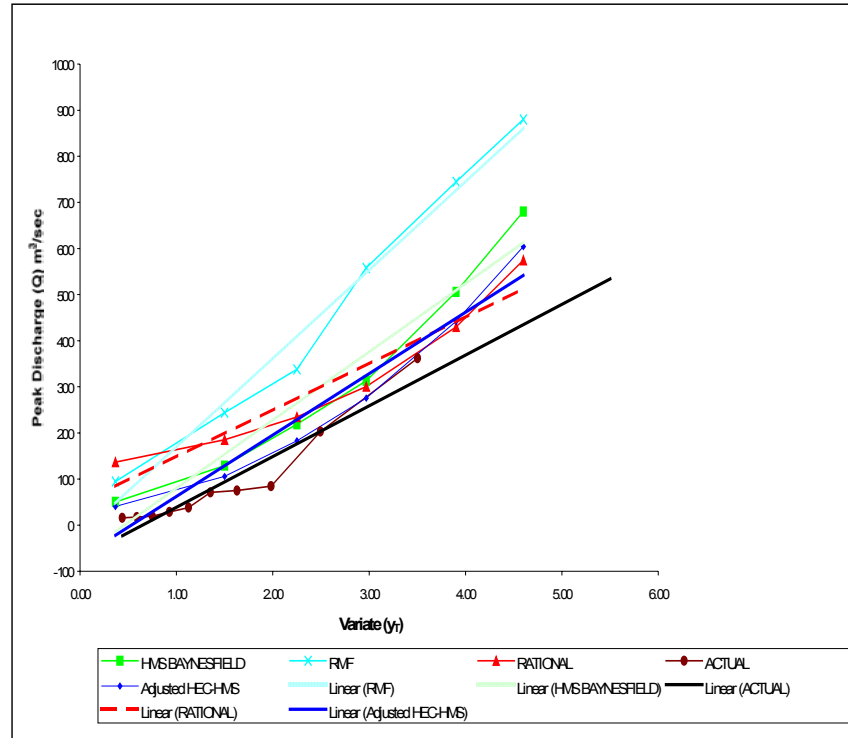


Figure 5; Comparison of Computed Peak Discharges with observed peak flows

Once the HEC-HMS was up and running the HEC-HMS output peak discharges were captured and routed through the HEC-RAS model. The interesting output result was the 100-year hydrograph computed at the junction representing the entrance to the canal shown in figure 6.

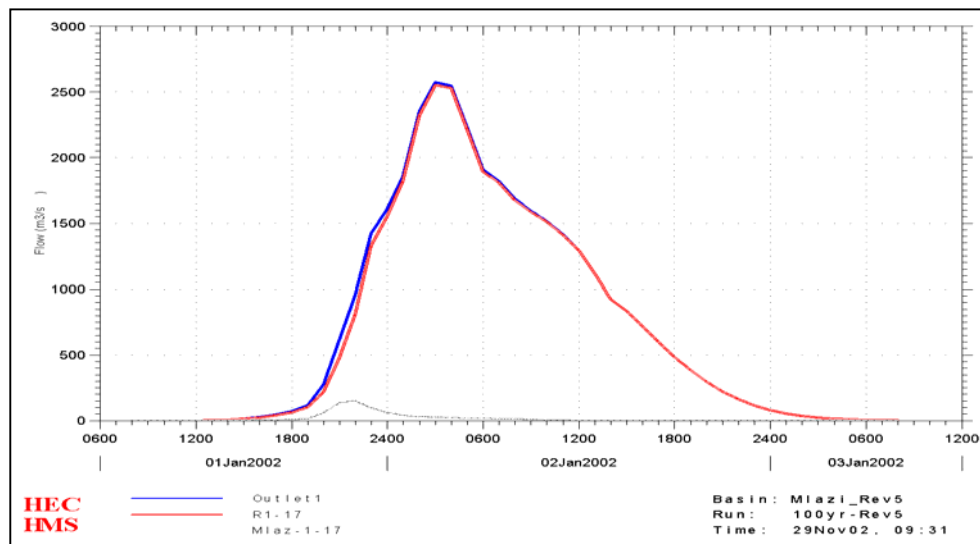


Figure 6; 100yr (One-Day design) flood flow hydrograph at entrance to the canal.

The HEC-HMS output result shown in figure 6 represents the hydrographs at the entrance to the canal. The hydrograph in red represents the outflow from the Shongweni whereas the small grey peak represents the hydrograph due to the incremented subcatchments (Mlaz-1-17) downstream of Shongweni dam. The hydrograph in blue is the sum of the red and grey hydrographs. The sum is approximately equal to the red hydrograph indicating that there is insignificant contribution of runoff by the subcatchments downstream of Shongweni. This

observation implies that the outflow hydrograph at the outlet of Shongweni is a good estimate of the magnitude of the hydrograph at the entrance to the canal. This observation is a justification for the proposed location of the streamgauge and forecasting system at the outlet of Shongweni dam for the flood warning of the industries such as SAPREF and Mondi located at the flood plain around the canal.

IMPLEMENTATION OF THE INUNDATION MODEL USING HEC-RAS

The Mlazi river model was set up using the HEC-RAS program. The model was used for the determination of the levels of inundation for the Mlazi to be displayed at the disaster management center of the eThekweni Metro municipality using GIS. The HEC-RAS program required a DEM but of a high resolution than HEC-HMS since this model was to be used for producing levels of inundation. The Triangular Irregular Network (TIN's) based DEM was applied. During the modelling process, Mlazi river was split into three component, namely; Upper Mlazi, Lower Mlazi and the Mlazi canalised section. The assumptions with regard to the analysis were based on the channel characteristics of the three portions. For instance steady state analysis was applied for the Upper and Lower Mlazi where the river is characterised by steep, well-defined channels with supercritical flows. The canalised (concrete lining) reach susceptible to overtopping of the canal resulting in inundation of low-lying areas was modelled assuming unsteady flow conditions. The hydraulic assumptions applicable to the Mlazi HEC-RAS model based on guidelines from Chow (1956), and Henderson (1987) and the HEC-RAS manual (1997).

The HEC-RAS program required data input such as the flow data (steady flow/or unsteady flow data) and the geometric data (which define a geometric representation of the river system) including Mannings's coefficients and the bridge and culvert structures.

An interesting aspect of the study was the fieldwork conducted to capture the Manning's roughness coefficient and structural data. The Manning's coefficient values determined during fieldwork were based on a consensus of a consortium of four field researchers who walked along the Lower Mlazi and the Mlazi canal (for a period of a month in July 2002). They assessed the vegetation cover and streambed condition in terms of bedding and water depth thereby assigned Manning's 'n' values based on roughness coefficients table from Chow (1956). A desk top evaluation of the values was also carried out using the photographs shot on site and comparing them with published guides for selecting Manning's roughness coefficients for natural and flood plains produced by the United States Geological Survey and Water supply (U.S.G.S, 2001). Figure 7a and b shows some of the photographs captured and compared to the U.S.G.S pictures.



Maximum; n=0.045		Description	
Site	Vegetation Cover	Stone Size and Sand	Channel Description
Main Channel	No vegetation in channel	gravel bed with some stone and few boulders. $d_{84}=285\text{mm}$	Winding with some pools
Flood Plain	weedy	Trees and bush along banks submerged at high stages	

Figure 7a; Manning's Roughness Coefficients Estimated from Photos (Photos on Left are USGS, on Right are from Mlazi)



Maximum ; n=0.05		Description	
Site	Vegetation Cover	Stone Size and Sand	Channel Description
Main Channel	More weed	gravel bed with more stones, gravel bed with boulders. $d_{50}=175\text{mm}$ and $d_{84}=375\text{mm}$	Winding with some pools
Flood Plain	Thick weed, scattered bush		

Figure 7b; Manning's Roughness Coefficients Estimated from Photos (Photos on Left are USGS, on Right are from Mlazi)

The steady state computation procedure to determine water surfaces from one cross section to the next was carried out by solving the energy equation with an iterative procedure called the standard step method. The computation were carried out as recommended by Chow (1956), i.e. the computation was carried out in an upstream direction for the subcritical flow and in a downstream direction for the supercritical flow.

The Mlazi canal hydrodynamic analysis was carried out under unsteady state conditions using HEC-RAS program. Back ground information pertaining to the purpose and capacity and dimensions of the Mlazi canal was gathered from previous reports. The canal was constructed in the mid 1950's by the Department of Transport, its purpose was to deviate the Mlazi river away from the site of the Botha Airport (Durban Airport). Apart from the airport the Mlazi lagoon attracted industries such as the SAPREF oil refinery (in the early 1960's) and the Mondi paper factory (in the early 1970's). These were constructed in the south and north of the canal respectively, subsequently each is built below the level of the canal and is therefore susceptible to flooding as evidenced during the 1987 floods.

The purpose of the investigation into the flood of the Mlazi canal was to delineate the inundation levels for the 20-, 50- and 100 year return period floods. The methodology as applied involved a one dimensional unsteady flow analysis whereby input hydrographs of a one-hour time series representing an inflow to the canal were input at the upstream part of the modelled canal. Off-channel storage were introduced to monitor the lateral flow spilling over the canal during over-topping. A typical cross-section of the HEC-RAS model of the canal shown in figure 8 indicates that the lateral flow into off-channel storage was monitored by lateral weirs connected to the off-storage areas.

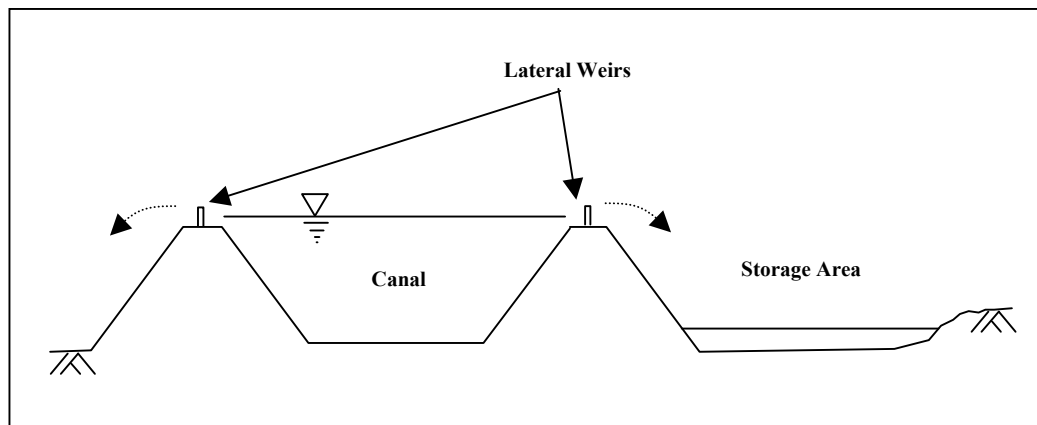


Figure 8; Canal modelling using Lateral Weirs and Storage Areas

It was observed that the quantity of water that flow over the lateral weirs depended on the shape and peak of the flow hydrograph that was being routed through the canal. The total volume of the water that flowed over the lateral weirs into the storage areas as well as the actual storage volume available determined the level to which the overspill water rises. This level thus defined the inundation levels for the floodplain in the canal section.

The analysis results in the following summary;

- The results indicate that the nominal capacity of the canal is approximately 1200 m³/sec equivalent, to the flow associated with the 20-year return period flood event.
- The risk of overtopping occurring in the next 30 years is 79%.
- For the 100-year design event, nearly 12 million cubic meters of water is spilled from the Mlazi canal.
- The risk of this wide spread inundation occurring within the next 30 years is approximately 26%.
- The sensitivity analysis carried out shows that the inundation levels increase linearly with the Manning's 'n' and that the Manning's 'n' value has a 30% effect on the inundation levels. This observation justifies the need for a selection of a good estimate of the Manning's 'n'.

A flood damage assessment was carried for areas within the Mlazi river system where flooding was problematic, these were identified and subsequent engineering mitigation measures were suggested. The area where severe flooding occurs was in the wide flood plain areas in the lower 3km canalised section of the Mlazi river. The analysis indicates that peak floods of a magnitude equal to a 20-year return period and above, inundate the Mondi and SAPREF sites located within the floodplain. When overtopping occurs, the surrounding areas are inundated to a depth approximately 3m for the 100 year design event. The South Coast road and adjacent areas are also inundated at the entrance to the canal. The 100-year floodplain for the canalised portion of the Mlazi is shown in figure 9, the airport is susceptible to the 1:200 flood event.



Figure 9; 100yr flood maximum water surface profile, Mlazi Canal

Recommended Flood Mitigation Measures

Previous reports suggested the following measures;

- Increase canal wall height
- Increase canal width
- Build a flood relief canal
- Provide SAPREF flood protection berms

Of the above mentioned, the bunding of sensitive areas (such as SAPREF and Mondli) is likely to be the most cost effective and practical solution. In addition the most cost-effective flood damage mitigation would be the implementation of the Mlazi flood forecasting system at the downstream of the Shongweni dam. The early warning would assist in alerting the industries and thereby give them time to close down their machines and ensure that employees and the surrounding residents are evacuated from the area before the flood occurs. This would assist to prevent loss of lives and plant damage due to seizure of machines as a failure caused by improper close down.

Mlazi Meta Model for Real Time Flood Forecasting

The Mlazi flood real time forecasting system was investigated and set up was a linear model. The model consist of a semi –distributed three reservoir cell model applied to each subcatchment and linearly summed to produce the combined catchment output (Pegram and Sinclair, 2002) called the Mlazi Meta Model (MMM). This is a conceptual model, which required parameter adjustments so that it became a representative of the Mlazi catchment.

MMM consists of three main components, which are as follows;

- a) Best Spatial Rainfield:** The best spatial rainfield is a result of the combination of the point rainfield, radar rainfield and (possible in the future) satellite rainfields. The joint use of radar and raingauge data aims at the utilisation of the high point accuracy of the latter and the wide spatial coverage of the former. The merged rainfield is input to the rainfield-forecasting model and also to the linear catchment model.
- b) Rainfield Forecasting Model;** In cases where the catchment response time is short (<2hrs), there is an advantage in taking trouble to forecast the rainfall up to one hour ahead in real time. The rainfall forecast is carried out by the use of the String of Beads model (Pegram and Clothier, 1999). The model manipulates the time and space dependence in rainfields in forecast mode. The forecast rainfield is input to the linear catchment model.
- c) Semi-Distributed Linear Catchment Model;** This model consists of semi-distributed cell models which in turn use a system of three linear reservoirs to conduct rainfall-runoff conversions to compute streamflows for each cell. The response of the arrangement of linear reservoirs is governed by the use of an Auto Regressive Moving Average (ARMA) type equation which is a form of the State-Space equations (Pegram and Sinclair, 2000). The input to the model is the best-observed spatial rainfall field (possible followed by the short-term forecast

rainfield). Functions of the ARMA type are parametrically efficient and are easy to adjust in real time. This means that optimal (Kalman) filtering techniques can be applied to update the state and parameters of the model based on the real flows (also input) available and the current state of the catchment. The outputs from the model are forecasted flows, which are similar to observed flows. The forecasted streamflows are then routed through the river channel model (HEC-RAS) from the Shongweni Dam through the canal to the outlet.

The validation of this model would require a reliable record of rainfall and streamflow historical data so that precise forecast can be conducted. However due to the absence of reliable streamgauges downstream of Shongweni dam together with poor time series of only daily rainfall data, the validation will have to wait until the system is finally integrated. In June 2003, the Shongweni dam was instrumented for high flows by DWAF.

It was this hindering factor which resulted in the introduction of an integration modelling process which involved the use of design storms together with output time series hydrographs from the calibrated physically based model (HEC-HMS). This approach might seem unreasonable because a model is being calibrated by another model but it should be noted that this approach gives better initial estimates of the parameters than guesswork. The MMM would further be updated using recorded radar data and streamflow data once all structures have been put in place.

The confidence in the applicability of the HEC-HMS model was based on the intensive efforts that were applied in setting it up so that it was a representative of the Mlazi catchment. The HEC-HMS itself would not have been a good model for real time forecasting in comparison with the MMM. The advantages of using the MMM for real time forecasting as compared to the use of the HEC-HMS model are as follows;

- The HEC-HMS model is subject to human judgement and requires laborious, time consuming work such as feeding information into ACII files by hand. Furthermore the state and characteristics of the catchment is a snap short based on historical analysis of the system. By contrast the MMM has few parameters, seven at most (usually three or four) and these are calibrated continually on input and output sequences.
- In forecast model it would be difficult to adjust the parameters of the HEC-HMS model at frequent intervals to match the output with observed flows. This is so because the parameter files would have to be altered by hand and it would not be clear how much to alter the parameters such as the SCS curve number and initial abstraction. By contrast, the MMM's few parameters of the model are designed to be optimally adjusted in real time to match the modeled output to the observed flows.
- The philosophy of the MMM is to accomplish the objective of meaningful forecasting. One needs to start with a good estimate of the MMM parameters and this is achieved by calibrating it on the input to and output from the fitted HEC-HMS model to selected flow events.

Calibration Results of the MMM

The results shown below are from the MMM fitting process which involved selecting starting values for the MMM model to ensure that the forecasting process starts suitably close to some observed streamflows. The input and output data set used for the parameter tuning was obtained from the HEC-HMS model.

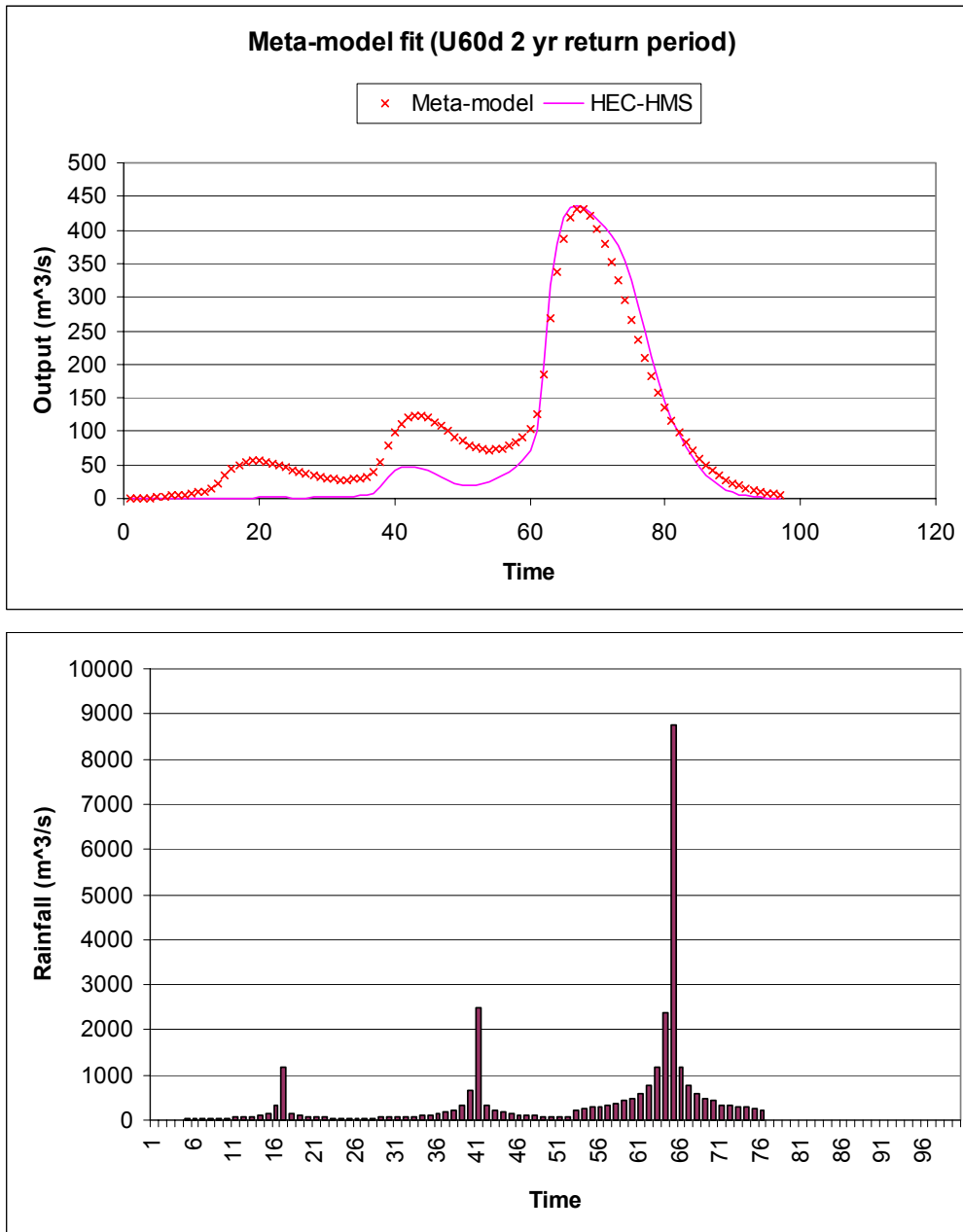


Figure 10; Flow chart for the parameter fitting procedure

The Meta model fit shown in figure 10 is for the downstream outflow to the canal. The 3-Day rainfall design (LMH) was for a 2yr recurrence interval and therefore the output hydrograph was also assumed to be for a 2yr recurrence interval. From the output hydrograph it is observed that a close fit was obtained for the highest peak (due to the third day storm) and the Meta Model produced peak due to the first two-day storms which were slightly higher in magnitude than those obtained from the HEC-HMS model.

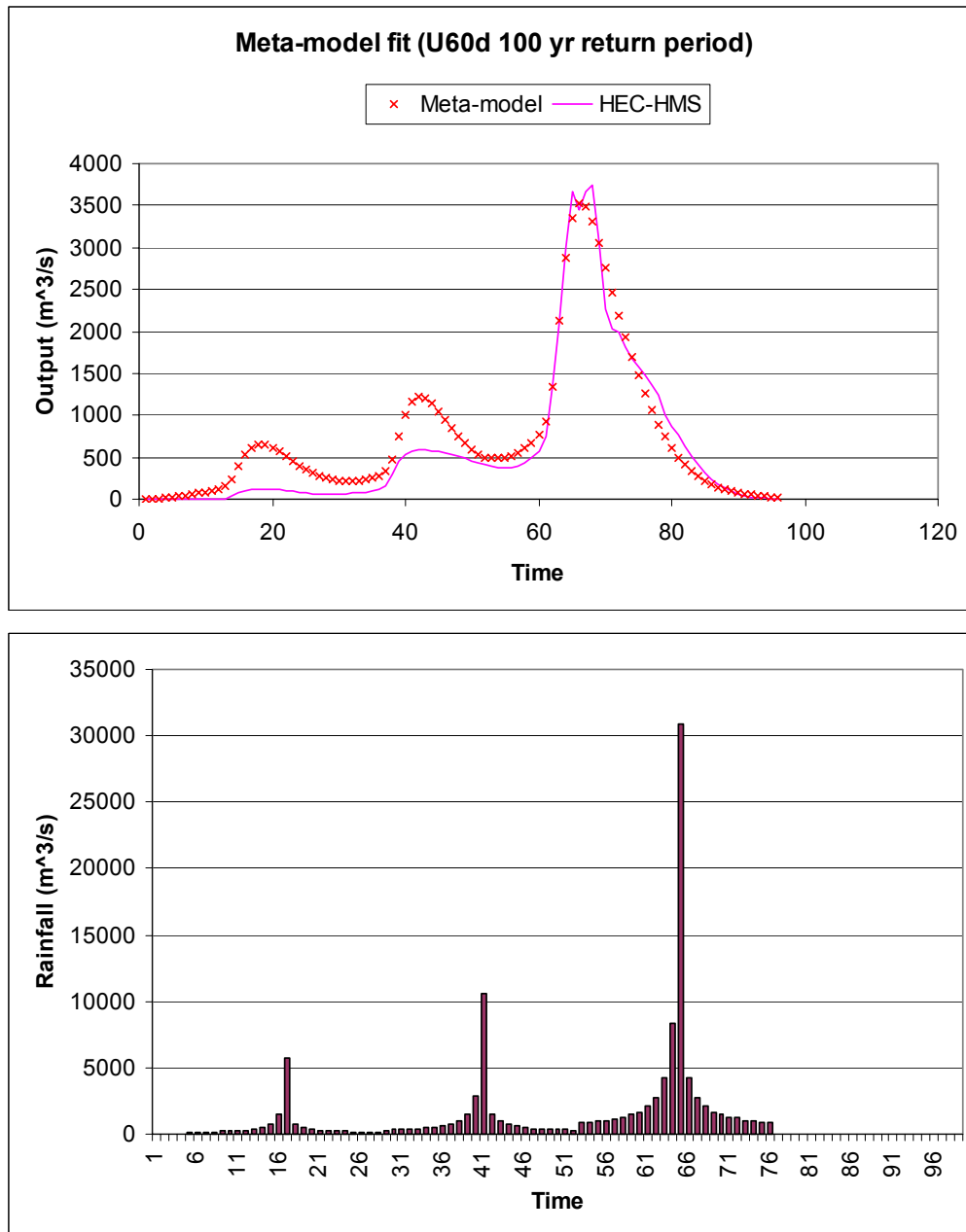


Figure 11; Flow chart for the parameter fitting procedure

The Meta model fit shown in figure 11 is for the downstream outflow to the canal. The 3-Day rainfall design (LMH) was for a 100yr recurrence interval and therefore the output hydrograph was also assumed to be for a 100yr recurrence interval. From the output graph it is observed that a close fit was obtained for the highest peak (due to the third day storm) and the Meta Model produced peak due to the first two-day storms which were slightly higher in magnitude than those obtained from the HEC-HMS model.

Shown in table 1 and 2 are parameter values for the above plotted graphs. The values are based on the connectivity of elements in the Mlazi represented by figure 12.

Parameter	Value
K_1	4.7
K_2	17.5*
K_3	7.5
K_4	6.7
K_5	272.6*
K_6	7.2
K_7	8.1

Table 1; 2 year Return Period Parameter Values

Parameter	Value
K_1	1.7
K_2	177.3*
K_3	2.1
K_4	6.3
K_5	1102.8*
K_6	9.4
K_7	18.2

Table 2; 100 year Return Period Parameter Values

The parameters are the average residence times of water in the individual storage elements from the point of view of the associated outlet. Thus the larger the k values, the smaller the flow through the corresponding exit. A very large value of k indicates that the exit could be closed off to yield a less complicated model. Thus k_2 and k_5 (in bold and with asteriks) could be set to infinity in both models reducing the general of three tank model to a cascade of 3 tanks as shown in figure 13. Once this happens, the inference is that the total residence time in the system (input to outflow) equal to $k_1+k_3+k_4$, reduces from 19.1 hr for the 2yr flood to 10.2hr for the 100yr flood which makes physical sense. Thus the linear model is adaptable to the data. As expected the starting values of the parameter of MMM can be set with reasonable confidence and will adapt with the application of the Kalman filter once real time flows are available.

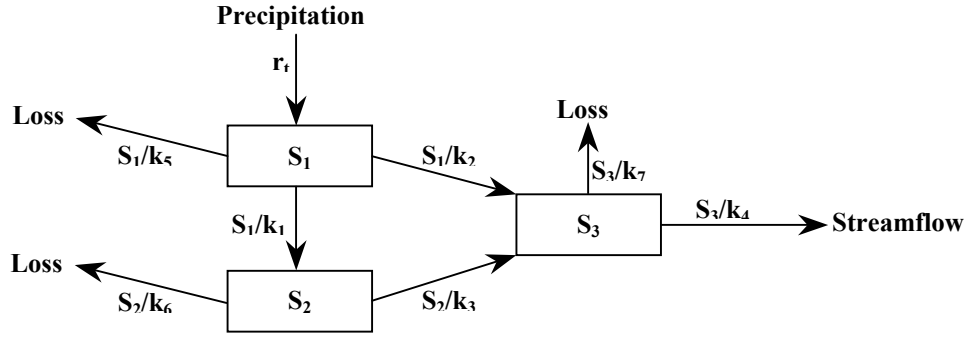


Figure 12: A general linear 3 reservoir feed forward model with (possible) losses from each reservoir.

The (continuous time) State-Space representation for the arrangement in Figure 12 is given by the following set of differential equations

$$\dot{S}_1(t) = -\left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_5}\right)S_1(t) + r(t - \tau)$$

$$\dot{S}_2(t) = \frac{1}{k_1}S_1(t) - \left(\frac{1}{k_3} + \frac{1}{k_6}\right)S_2(t)$$

$$\dot{S}_3(t) = \frac{1}{k_2}S_1(t) + \frac{1}{k_3}S_2(t) - \left(\frac{1}{k_4} + \frac{1}{k_7}\right)S_3(t)$$

where $\dot{S}_i(t)$ is the time derivative of the storage in the i 'th reservoir at time t , $S_i(t)$ is the sequence of storage's in the i 'th reservoir, the k_i 's are the response constants for each of the reservoirs and $r(t - \tau)$ is the lagged (by τ intervals) sequence of precipitation inputs to the system. The resulting streamflow $y(t)$ is

$$y(t) = \frac{1}{k_4}S_3(t)$$

Conclusion and Prognosis

The objective of this study was to apply the linear catchment model for real time flood forecasting to the Mlazi catchment (the MMM) and subsequently produce levels of inundation which were to be displayed at the eThekweni disaster management center. Since the study was conducted in an uncertain environment where there was unavailability of record radar rainfall data and correlating streamflow data for setting up and calibrating the Mlazi Meta Model (MMM) an alternative approach had to be implemented to address the situation. This was achieved by the integration of various modelling techniques such as the use of GIS technology, application of the physical based model for flood analysis, the set up of the forecasting model for real time forecasting and the hydraulic modelling process to produce inundation levels.

The processes conducted in the integration concept are summarised as follows;

- The physically based model (HEC-HEM) was set up using GIS technology, a DEM was created for the Mlazi catchment and subsequently the hydrological information was applied to the model based on the SCS-UH method for the estimation of peak discharges. Synthetic hyetographs were used as input to the calibrated HEC-HMS model, resulting in computation of the peak discharges for various selected recurrence intervals. The HEC-HMS model was calibrated by first calibrating its upstream subcatchments using the 2-4 Feb 1999 storm event captured for the two subcatchments (Baynesfield and Mlaas road) streamgauge stations. The parameter adjustments conducted on the two subcatchments were thereby spread throughout the whole catchment.
- The outflow hydrograph of interest was the 100- year hydrograph at the entrance of the canal, which highlighted a peak discharge approximately equal to the peak discharge computed at the exit junction of the Shongweni dam. The results in that location gave a justification for the proposed location of streamgauge and forecasting system at the outlet of Shongweni since the incremented subcatchment down stream of the Shongweni have a negligible effect to the peak discharge computed at the entrance to the canal.
- The HEC-HMS outflow hydrograph had to be routed through the HEC-RAS river model. The DEM created for the HEC-RAS river model was of a higher resolution than the HEC-HMS. The Mlazi river model (HEC-RAS) was split into three portions namely the Upper Mlazi, Lower Mlazi and the Mlazi Canal based on the channel characteristic. Steady flow conditions were assumed for the Upper and Lower Mlazi whereas unsteady flow condition was assumed for the canalised section where off-channel storage and lateral weirs were incorporated to analysis the lateral flow. Fieldwork was conducted for capturing the roughness coefficients and hydraulic structures in the Mlazi. The computation of the inundation levels was successfully carried out and these are to be displayed using GIS at the eThekweni Disaster Management center.
- The HEC-HMS configuration was used for the initial adjustment of the MMM parameters. The initial adjustment process involved the application of the HEC-HMS input-output data (synthetic hyetograph and HEC-HMS outflow) to MMM thereby adjusting the parameter to such a point that the MMM output matched the

HEC-HMS output. The starting values of the linear model are adaptable to the data and will adapt with application of the Kalman filter once real time data flow is available.

The requirements for application of the model to the Mlazi are;

- A telemetering stream gauges. The DWAF representatives at WRC meeting confirmed that a stream gauge station has been set up at the outlet of the Shongweni dam. The location of the stream gauge was confirmed through the HEC-HMS (physical rainfall -runoff model) model to be the strategic point for the location of the real-time forecasting system for early flood warnings for the industrial areas around the Mlazi canal. This would enable online updating of the streamflow estimates since they would require up to date measurements of streamflow.
- Telemetering rain gauges within the Mlazi Catchment. The eThekwini Municipality and METSYS are installing telemetering raingauges and making their data and the SAWS data available in one database.

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