

City of Tshwane Municipality hydrological model – a comparison of varying SWMM hydraulic routing complexity on model output

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1. Introduction

In order to develop an integrated catchment management plan for present and future development scenarios, the City of Tshwane Metropolitan Municipality (CTMM) required integrated data on runoff peaks and volumes along all its major watercourses amounting to a total river and tributary length of approximately 1400 km. This is focussed towards improving the planning and management of stormwater drainage systems in all catchments within its area of jurisdiction.

CTMM commissioned SRK Consulting (Pty) Ltd to compile a regional hydrological model of all its major watercourses for the creation of a master drainage plan as well as a river referencing system (RRS) and stormwater management information system (SMIS) to aid in managing the data.

The description of the approach followed in deriving the master drainage plan including data collection, catchment and watercourse delineation, rainfall analysis and the derivation of VisualSWMM CTMM hydrological model (together with calibration and verification), to be used as decision support for Catchment Management is described in Males et al. (in press).

Given the increasing use of SWMM as hydrological/hydraulic model of choice of consultants and municipal organisations for urban stormwater modelling, it is significant to understand the applications and limitations of each of the modules within SWMM. This paper describes a comparison between the different hydraulic routing modules of SWMM and the implications of each module in terms of model generation time, run times and difference in calculated flows. The comparison of hydraulic routing is made between the fully dynamic flow equations of EXTRAN (EXtended TRANsport, Roesner and Dickinson, 1992) and the kinematic flow equations of TRANSPORT (Huber and Dickinson, 1992). This is undertaken for two selected rivers within the Pienaars River basin of the CTMM, the Moreleta and Hartebeesspruits.

2. Hydrological modelling and Catchment Management

Catchment management can be understood on one level as addressing water related concerns within a catchment through an integrated approach based on a understanding of the causes and effects of those concerns. This understanding is obtained through a combination of assessment of available catchment information and hydrological modelling (Görgens et al., 1998).

Hydrological information obtained from regional catchment hydrology for major drainage systems is essential in integrated development planning. It also a further requirement for:

- Reliable flood line determination
- Verification and calibration of minor stormwater drainage system models used for local stormwater master plans
- Assistance in the integrated planning of roads, other infrastructure and urban development.

The choice of which model to utilise is related to the desired level of complexity, with the appropriate level of analysis dependent upon (Yen, 1994):

- Objective and approach taken – continuous (historical) vs. event-based (design) analysis
- Output information needed and required accuracy – design discharge or runoff hydrographs
- Available data – drainage network (pipes, catchpits, junctions), catchment (topography, impermeability, soil characteristics), rainfall (spatial and temporal)
- Tools available – computer capability and numerical techniques
- Flow conditions – network, catchment properties, roughness, Froude numbers

It is also recognised that many of the parameters and input data for hydrological models are derived from geographically referenced physiographic information (topography, geology, soils etc). The time consuming task of data capture and manipulating can be most easily carried out using a GIS system (Herald, 1991).

GIS can be defined as a computerised system for the creation, storage, analysis and display of data of either a spatial or non-spatial nature (Fisher and Wijers, 1991). It can also be considered as a decision support system involving the integration of spatially referenced data in a problem-solving environment (Cowen, 1988).

The value of GIS thus stems from its relational database facility, which enables the manipulation of both spatial and temporal information (Herald, 1991). This provides a powerful tool for determining model input parameters and for the compiling and managing of input data for the following applications (Fisher and Wijers, 1991):

- input of spatial data (rainfall, topography, catchment and subcatchment boundaries, dams, etc.)
- spatial analyses (through either the preparation of data for input into the model such as calculation of subcatchment areas, subcatchment slopes, determination of overland flow lengths and slopes or the analysis of model output)
- spatial representation (digital maps permitting graphical queries from users and decision-makers)

The key advantages of a GIS-based approach for the generation of the CTMM hydrological model may be summarised as follows:

- Facilitates rapid parameter estimations with increased accuracy
- Facilitates potential for utilising existing public databases
- Facilitates an integrated analysis of the various data sets through the spatial overlay capability
- Facilitates a more realistic representation of data
- Allows thematic representation of data
- Facilitates wide spread diffusion of information as an effective communication medium
- Facilitates spatial analysis for planning through simplified and complex spatial analysis tools

3. Generation of CTMM VisualSWMM model

The City of Tshwane Metropolitan Municipality (CTMM), previously the City of Pretoria Municipality, comprises an area of approximately 2300 km². It has a variety of landuse ranging from dense urban development to rural agricultural and undeveloped. The upper third of the municipal area is bisected by the Magaliesberg mountain range.

The Pienaars River catchment incorporates a number of primary drainage networks including the Pienaars River, Moreletaspruit, Edendalspruit and Hartebeesspruit. For the purposes of this hydraulic routing study, the Moreletaspruit and Hartebeesspruit channels were selected for modelling. The headwaters of the Moreletaspruit are in Moreleta Park in Centurion to the north of Rietvlei Dam. It, then drains northwards through Faerie Glen, Lynwood Ridge and Silverton to the east of the Tshwane CBD, receives the Hartebeesspruit tributary before flowing into the Roodeplaat Dam. The confluence of the Moreleta and Hartebeesspruits is taken as the most downstream point of the hydraulic model. This comprises a total catchment area of approximately 133 km² with a combined total river length of approximately 44km.

These flow paths are indicated in Figure 1 below:

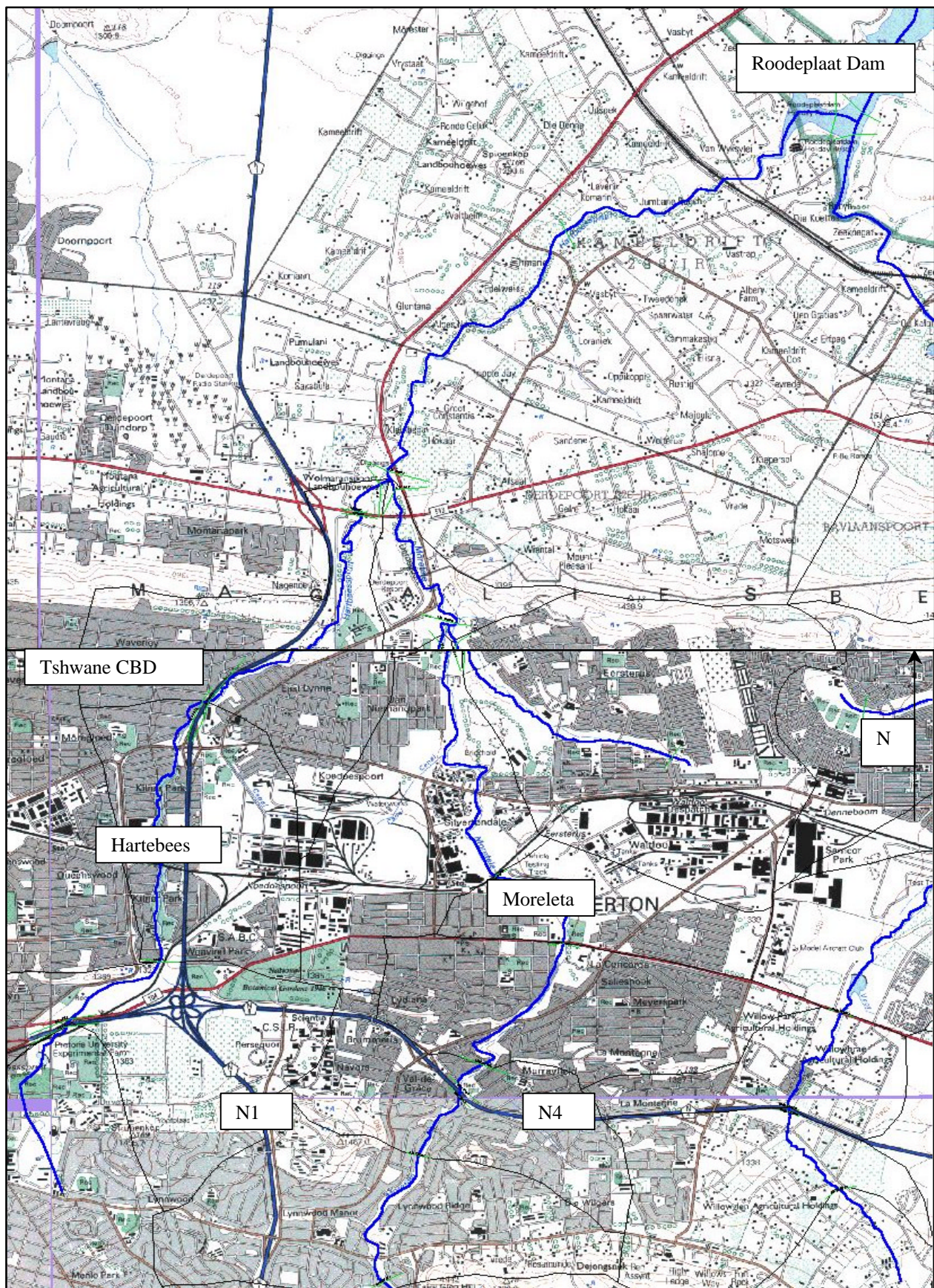


Figure 1: Flow paths of Moreleta and Hartebeesspruits

3.1. Overland flow generation – SWMM RUNOFF module

Flow generation in SWMM originates with overland runoff. Precipitation is read into RUNOFF as input hyetographs, with RUNOFF making a step-by-step accounting of infiltration losses, surface detention, overland flow and channel flow. This leads to the calculation of a number of inlet hydrographs and pollutographs that may be placed on the interfacing file for input into subsequent hydraulic routing modules.

For the purposes of this hydraulic routing study, the EXTRAN and TRANSPORT modules utilised the same RUNOFF interface file. A description of the approach followed in generating the overland flow for the CTMM is provided in Males et al. (in press) and summarised below.

Overland flow was generated using the SCS method given the availability of good soil and land use data and associated curve number information for present and past degrees of urbanisation in the CTMM. Spatially representative design rainfall at various durations and return periods was derived by Smithers and Schulze (2002) for the CTMM using a regional index-flood type approach to frequency analysis based on L-moments termed the Regional L-Moment Algorithm (RLMA) (Smithers and Schulze, 2002). Given a lack of sufficiently long-term, reliable rainfall data in the CTMM, this approach allowed the estimation of events at sites where no rainfall or runoff data exists. 24-hour design rainstorms were generated with a temporal distribution conforming to the SCS Type 2 rainfall distributions.

River centre lines were digitised from the 10 000 scale orthophoto maps. Information from previous reports and CTMM was used to obtain river names. River lengths were obtained using the ArcView extension. River Slope was obtained using the 1085 slope method used by Department of Water Affairs and Forestry Flood Studies division.

Quaternary catchment delineation was undertaken with the use of WR90 (Midgley et al., 1994) to obtain principal river catchment boundaries. These quaternary catchments were subdivided into tertiary subcatchments based on the 5m contour interval and the above identified river delineations.

The average subcatchment slope, assigned to both the pervious and impervious parts of the subcatchment, were obtained using an ArcView extension to generate a slope grid that was reclassified to compute area-weighted slopes per subcatchment.

The Curve Number (CN), as used in the SCS method of runoff generation, is a dimensionless number depending on hydrologic soil group, cover type, treatment, hydrological condition, and antecedent moisture conditions. Curve numbers were obtained through overlaying the soil distribution (in terms of SCS-SA classification) and Landuse shapefiles with spatial analysis generating an area weighted curve number per subcatchment.

The Time of Concentration of overland flow was calculated using the overland flow Tc equation, indicated in equation 1, below:

$$T_c = 0.604 \left(\frac{rL}{S^{0.5}} \right)^{0.467} \dots\dots\dots(1)$$

where Tc = Time of concentration (hrs)
L = Length (km)
S = subcatchment slope (m/m)
r = roughness coefficient

Discretisation of the Moreleta and Hartbeesspruits catchments, a total area of 133 km², resulted in the generation of 26 subcatchments of approximately 5 km² average size and a total length of river of approximately 44km. Design rainfall depths associated with the 1 in 200 year recurrence interval were read into the RUNOFF module allowing the generation of overland flow at each subcatchment outlet for routing in the subsequent hydraulic routing modules of EXTRAN and TRANSPORT. A description of each of these modules is provided below.

3.2. SWMM Hydraulic routing

Both the TRANSPORT and EXTRAN routing modules allow the simulation of complex cross-section shapes including irregular cross sections as determined in HEC-RAS format. This makes them suitable for the modelling of natural river cross-sections. Stored hydrographs generated in the RUNOFF module are input into each module at nodes. Nodes were selected corresponding to the RUNOFF nodes in addition to locations where appreciable changes in channel cross section occur.

The hydraulic system is described as a network of conduits (or channels) joined at elements (manholes or another type of structure) with flow routing proceeding downstream through all the elements during each time interval until the storm hydrographs are routed through the system. Most of the data inputs are thus in terms of that needed to describe the conveyance system being modelled (dimensions, slopes, roughness etc).

Conduit profiles were identified between nodes to derive conduit length, average slope and Manning's "n" roughness. Conduit cross-sections were created using on screen digitising in ArcView GIS. The digitised lines were then converted into 3D sections using the ArcView extension (Profile Extractor). This allowed the selection of a representative cross-section per conduit that was imported into VisualSWMM in HEC2 format as an irregular section based on station – elevation pairs. Where cross-sections included an artificial channel, these channels were inserted in the irregular cross-sections with left and right overbanks and the corresponding change in Manning's roughness "n" coefficient.

Three storage devices within the catchment (Strubens and Valley Dams and Louis Botha Drive) were simulated with standard level-Puls reservoir routing techniques to route hydrographs through the reservoir. A relationship between depth, surface volume and outflow (where required) was inserted for this simulation.

A number of control sections, represented by bridge and culvert openings of varying sizes, were selected in the Moreleta and Hartebeesspruits. These road crossings were identified in terms of upstream and downstream elevations, culvert shape and dimensions and number of barrels and were included to assess the implications of these structures on backwater flood attenuation. Figure 2 and Figure 3, below, provide an indication of two of the crossings considered. This is followed by a description of the routing differences between TRANSPORT and EXTRAN.



Figure 2: Zambezi Drive crossing – Hartebeesspruit



Figure 3: Atterbury Road crossing – Moreletaspruit

3.2.1. TRANSPORT module

TRANSPORT utilises only the kinematic wave component of the gradually varied, one-dimensional, unsteady flow St. Venant equations for momentum and continuity. Runoff hydrographs are routed under the approximation of steady non-uniform flow conditions with disturbances only allowed to propagate in the downstream direction. No backwater effects are thus modelled and backwater conditions are assumed not to affect upstream computations. Any surcharging is modelled by storing excess flows at the head of the conduit until the capacity exists to accept the stored volume.

The above backwater limitation notwithstanding, the use of TRANSPORT should be considered when the effect of in-channel storage and attenuation on the outfall hydrograph is significant. This is especially the case for large conduits with appreciable lengths and flat grades or if detention storage is implemented in the system.

Output from TRANSPORT takes the form of discharge hydrographs and velocities in selected conduits and junctions in printed and plotted form. No flow depths or water surface elevations are generated and thus TRANSPORT is inappropriate for studies investigating flood depths.

3.2.2. EXTRAN module

EXTRAN utilises the one dimensional fully dynamic flow equations in both open channel and closed conduits to account for conditions where routed flow is non-uniform, unsteady and subject to backwater and surcharge. The basic differential equations for solving unsteady flow problems in EXTRAN are derived from the gradually varied, one-dimensional, unsteady flow St. Venant equations for open channels. They are non-linear hyperbolic partial differential equations and numerical methods must be used to solve the equations since no general analytical solution exists.

The Visual SWMM release of EXTRAN incorporates an updated SWMM solution that is a combination of implicit and explicit methods:

- The flow in conduits is solved implicitly using the full dynamic flow equation (solves for the unknown value at the new time step based on known and unknown information)
- The nodal continuity equation is solved explicitly based on known information of the last time step and value of the last iteration's nodal depth and surface area.
- The boundary conditions are solved based on the last iteration value of flow in the outfall conduits.

Numerical accuracy constraints in the EXTRAN module require that the simulation time step specified be no longer than the time it takes for a dynamic wave to traverse the conduit's computational length. The timestep of the simulation is thus determined by the wave celerity of the shortest conduit with the fastest velocity. Time steps in EXTRAN are thus typically in the range of 1 – 5 seconds. This has considerable implications for the model runtime especially if the model environment is characterised by large catchments with conduits of significantly different lengths.

Output from EXTRAN takes the form of discharge hydrographs and velocities in selected conduits and flow depths and water surface elevations at selected junctions in printed and plotted form.

Table 1, below, summarises the comparison between TRANSPORT and EXTRAN as hydraulic routing modules (James and James, 1997).

	TRANSPORT	EXTRAN
Flow Routing method	Kinematic wave, cascade of conduits	Fully dynamic equations, interactive conduit network
Computational expense for identical networks	Moderate	High
Attenuation of hydrograph peak	Yes	Yes
Time displacement of hydrograph peaks	Yes	Yes
In-conduit storage	Yes	Yes
Backwater of downstream control effects	No	Yes
Surcharge	Weak	Yes
Pressure flow	No	Yes
Branching tree network	Yes	Yes
Flow reversal	No	No
Looped connections	No	No
No. of pre-programmed conduit shapes	16	8
Alternative hydraulic elements	Yes	Yes
Dry weather and base flow	Yes	Yes
Pollutograph routing	Yes	Yes
Solids scour/deposition	Yes	No
Input hydrographs	Yes	Yes

Table 1: Comparison of TRANSPORT and EXTRAN routing properties

Inspection of the Table 1, above reveals that TRANSPORT is superior to EXTRAN in terms of computational expense for identical networks. TRANSPORT can be considered less data and numerically intensive than EXTRAN with corresponding timesavings during data collection and model generation. The assumption of steady flow conditions in TRANSPORT also ensure that TRANSPORT is significantly more numerically stable than EXTRAN with considerably faster model run times.

The principal shortcoming of TRANSPORT in terms of modelling open channels, however, is its inability to account for backwater effects. In order to take advantage of TRANSPORT's enhanced numerical stability and faster model run times, the above backwater limitation is addressed by placing a storage node at each location where backwater effects are expected to be significant. The backwater effect is approximated as a horizontal water surface behind the storage element. This is discussed further in Section 4.2 below.

4. Hydraulic routing results of Moreletaspruit with EXTRAN and TRANSPORT

Given the use of the same RUNOFF interface file and identical conduit configurations, the results of each module simulation will allow direct comparison of the kinematic versus fully dynamic approaches in terms of model runtime, continuity error and peak flow.

4.1. Hydraulic routing with no backwater effects considered

Table 1, above, indicates that TRANSPORT, whilst providing much of the functionality of EXTRAN, does not allow simulation of backwater conditions. A comparison is thus initially undertaken of the

two routing approaches for the design rainfall depths associated with the 1 in 200 year recurrence interval storm with no backwater inducing structures simulated, apart from the three storage reservoirs (Strubens and Valley Dams and Louis Botha Drive), in order to assess the similarity in performance of each approach. This model simplification is achieved though ignoring the road crossing control sections described in Section 3.2 above.

The results of each simulation are depicted in Figure 4, below.

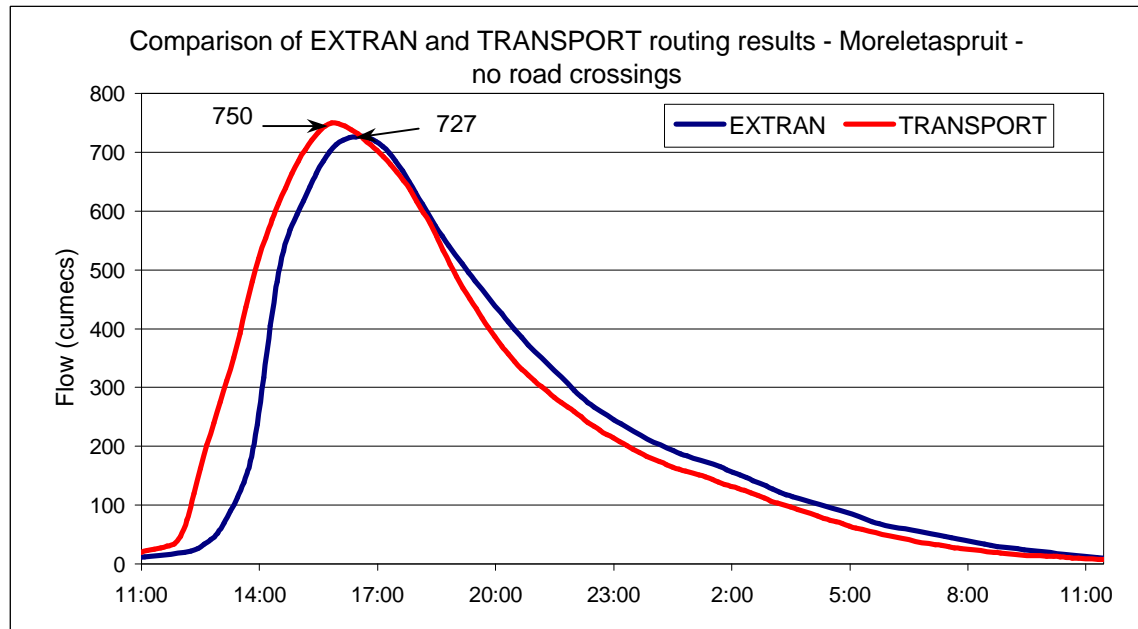


Figure 4: Comparison between EXTRAN and TRANSPORT modules with road crossings ignored

Figure 4 indicates that the kinematic method of TRANSPORT provides comparable results with the fully dynamic approach of EXTRAN with a similar hydrograph shape (25 minute lag) and 3% difference in peak flows in the Moreletaspruit downstream of the confluence with the Hartebeesspruit. The results of the model runs are indicated in Table 2 below,

	TRANSPORT	EXTRAN
Peak flow (m^3/s)	750	727
Continuity error	0.9%	-1.8%
Model run time (s)	12	305
Simulation efficiency	-	3.1 (Good)

Table 2: Comparison of results of TRANSPORT vs. EXTRAN simulations – No backwater conditions

A comparison of the model runs for each module (undertaken on Pentium III, 600 MHz, 128Mb RAM) reveals that TRANSPORT provided comparable results to EXTRAN with a dramatically faster simulation time under simplified no backwater conditions.

4.2. Hydraulic routing with backwater effects considered

In order to accurately represent the natural river systems associated with the urban environment, however, backwater flow attenuation must be considered. This is expected to occur most significantly at road crossings where flow is channelled through narrowed culvert and bridge openings. Low crossings with small culvert openings were ignored given the small impact on the 1 in 200 year recurrence interval storm.

For EXTRAN, the selected road crossing control sections were modelled as rectangular conduits with the number of barrels related to the number of openings. The road deck was modelled as a broad

crested weir with crest level related to road level. Flood flows exceeding the discharge capacity of the culvert would back up against the road crossing until the levels exceeded the road deck level. At this point the road crossing would be overtopped with flows rejoining the downstream river channel.

For TRANSPORT, each selected road crossing was modelled as a storage element with a horizontal water surface upstream of the crossing approximating the backwater attenuation. Hydraulic analysis of the multi-barrelled culvert openings and associated upstream and downstream cross-sections determined the flow capacity of the crossing and obtained a relationship between depth and outflow through the culvert and weir overflow over the road deck. A stage volume relationship upstream of the control section was obtained from channel invert to above road deck through extraction from digitised contour maps in ArcView interpolated to 1 m intervals.

Figure 5, below, provides a comparison of flows through the Zambezi Road crossing indicated in Figure 2, above. This road crossing of the Hartebeesspruit consists of three rectangular box culverts 3.7m deep and 5.5 m wide. In order to increase the attenuation effect of the structure, the structure was modelled in both TRANSPORT and EXTRAN with one of the culvert openings considered blocked. The results are compared for each routing module for the “No bridge crossing” condition as described in Section 4.1, above, in addition to consideration of the crossing.

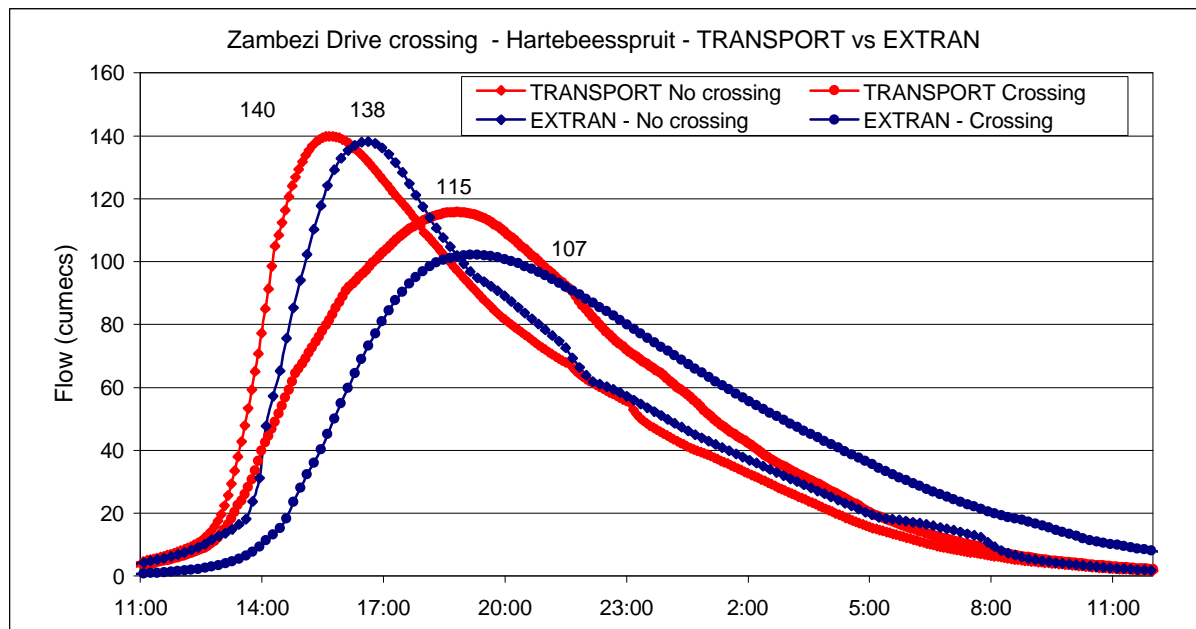


Figure 5: Comparison of EXTRAN and TRANSPORT with backwater conditions – Hartebeesspruit

Analysis of Figure 5, reveals that the use of a storage device in TRANSPORT to approximate the backwater attenuation of the Zambezi Road crossing not only attenuates the flood peak comparably well with the unsteady flow conditions simulated in EXTRAN but also decreases the lag between peak flows when compared to the “No crossing” condition.

Figure 6, below, provides a flow comparison between TRANSPORT and EXTRAN at the Garsfontein Road crossing of the Moreletaspruit. This crossing is composed of two rectangular barrels 2.6 m deep and 3 m wide. Again, one of the culverts was modelled as being completely blocked to enhance the backwater effects due to the structure.

The peak flows associated with the 1 in 200 year recurrence interval storm exceeded the capacity of this culvert and flow was partly routed over the road deck to rejoin the downstream channel cross-section. The hydrographs depicted in Figure 6, below, thus provide a summation of culvert flow and weir overtopping flow of the road crossing control section.

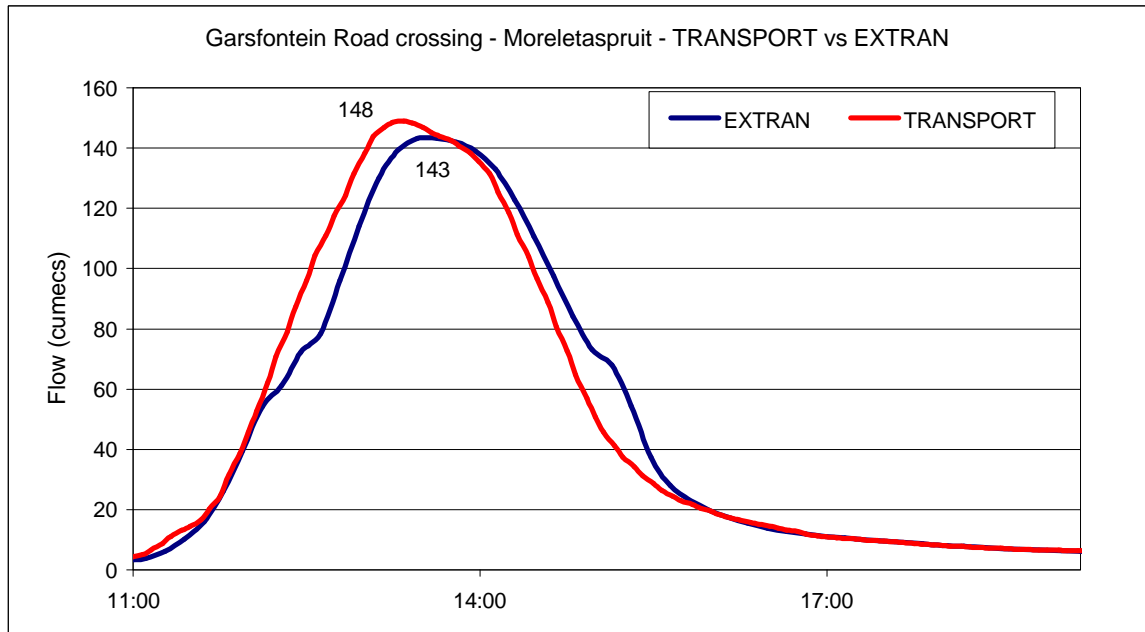


Figure 6: Comparison of EXTRAN and TRANSPORT with backwater conditions – Moreletaspruit

The peak flow indicated in Figure 6, above, calculated with the fully dynamic EXTRAN equations fall within 3.5% of the peak flow calculated using the kinematic TRANSPORT equations when a storage device is utilised within TRANSPORT to simulate the backwater effects experienced at a control section.

Figure 7, below, compares the hydraulic routing approaches at the most downstream point on the Moreletaspruit. This provides an indication of the accumulated peak flow attenuation due to the modelled road crossing control structures.

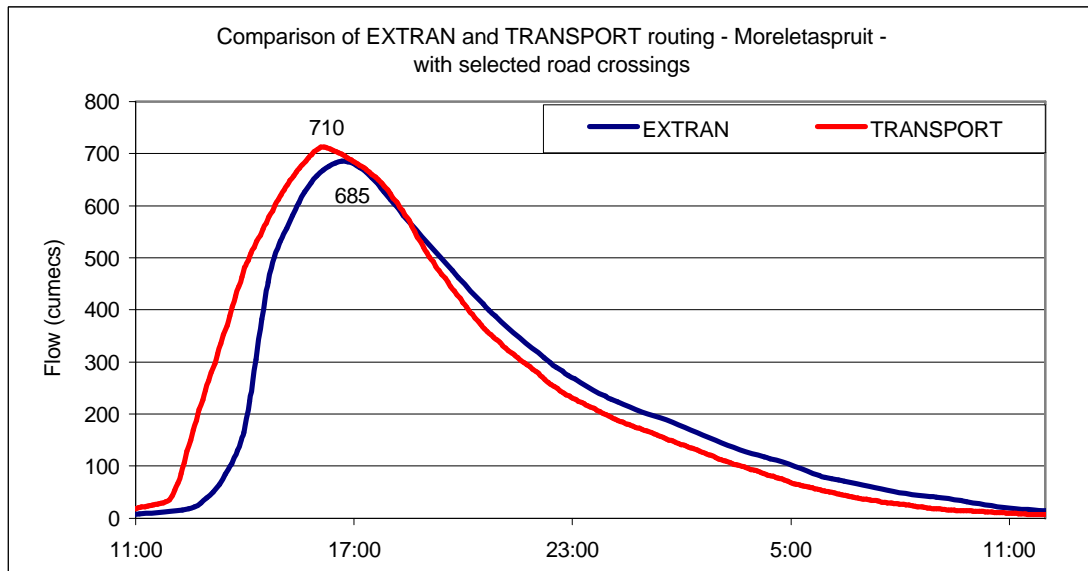


Figure 7: Comparison of EXTRAN and TRANSPORT with backwater conditions – Moreletaspruit

Inspection of Figure 7 reveals that given the use of storage devices to approximate backwater effects at control structures, the kinematic TRANSPORT approach produces a peak flow and hydrograph shape that compares well to the peak and hydrograph generated with the fully dynamic EXTRAN hydraulic approach. The difference in peak flow is less than 4% and the lag between peak flows is less than 30 minutes. Table 3, below, summarises the performance of each simulation

	TRANSPORT	EXTRAN
Peak flow (m ³ /s)		
Hartebeesspruit	115	107
Moreletaspruit	712	685
Continuity error	< 1%	-2.5%
Model time step (s)	300	1.5
Model run time (s)	14	1218
Simulation efficiency	-	2.18 (Excellent)

Table 3: Comparison of results of TRANSPORT vs. EXTRAN simulations – Backwater conditions

Although providing the full functionality required for the modelling of dynamic river systems, the principle limitation of EXTRAN in modelling large regional catchments is its numerical intensity of simulation. This results in frequent model numerical instability due to significant differences in conduit lengths. The introduction of very short time steps of the order of 1 – 5 seconds, depending on the length and flow velocity of the shortest conduit in the model, improves model numerical stability and decreases continuity errors but has the associated disadvantage of increasing the duration of the model simulation. Model debugging to overcome model instability and errors in continuity becomes a time consuming process frustrated by long model runtimes. If the modelling environment is one of generating peak design flows on a regional basis with large catchments and conduits of significantly varying lengths, this renders the use of EXTRAN a time consuming and thus expensive process.

Analysis of Table 3, above, reveals that TRANSPORT is able to deliver similar peak flow results to EXTRAN when backwater conditions are accounted for by the introduction of a storage node at the area of concern. This is with the TRANSPORT simulation taking 1.5% of the duration of the EXTRAN simulation for this particular river system. This is a significant savings in time in model simulation for a relatively small catchment of 133 km². For larger catchments typical of regional flood studies (the CTMM has 2300 km² catchment requiring hydrological modelling for the development of integrated catchment management plans for present and future development scenarios), this time difference is expected to increase further.

5. Conclusions

Distributed hydrological models can play a significant role in Catchment Management through the provision of flow data for the integrated planning of urban development and infrastructure. These models structure knowledge whilst indicating limitations in available data to be rectified for future modelling applications.

The derivation of the model is significantly aided by the use of GIS to allow the effective use of spatial geographic information and the transformation of this information into representative variables for hydrological simulation. This parameter estimation is accomplished with increased accuracy and efficiency through an integrated analysis of the various data sets using spatial overlay capabilities. The ability of GIS to display thematic representations of data also results in it being an effective communication medium for the widespread diffusion of information.

This paper presents a comparison between the increasing complexity of hydraulic routing approaches provided by SWMM in the kinematic approach of TRANSPORT and fully dynamic approach of EXTRAN. The Moreletaspruit and Hartebeesspruits, two rivers within the Pienaars catchment of the CTMM, are modelled using each approach with the peak flows generated by each approach compared.

The principle limitation of EXTRAN is the intensity of numerical simulation. The fully dynamic flow equations allow for backwater effects to be simulated but at the cost of considerable extra complexity and computer time. Short time steps of the order of 1 – 5 seconds are required in order to minimise numerical instability and improve continuity errors. If large regional catchment simulations are required, the resulting model simulation time renders EXTRAN a time consuming and thus expensive process to generate and optimise.

TRANSPORT through ignoring the unsteady term of continuity equation generates peak flows quickly and with enhanced stability. The inability to account for backwater effects caused by road and bridge crossings and other control structures is addressed through the simulation of a horizontal water surface behind a storage device at each of these structures. A relationship between stage, storage and outflow is derived for each storage device through a simple hydraulic investigation.

The results of this study appear to indicate this approach is able to generate comparable results to the fully dynamic approach utilised in EXTRAN at a fraction of the time in model runtime and model generation. This has obvious implications in modelling budget constraints. TRANSPORT with storage devices at control sections thus seems to be more appropriate for regional modelling of urban river systems than EXTRAN when flow hydrographs are required.

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