TWO RIVERS URBAN PARK

SPECIALIST STUDY:

MODELLING OF FLOOD MITIGATION OPTIONS ON THE SALT RIVER

TASK 1 REPORT: SET UP MODEL

FINAL REPORT

Prepared for:

Western Cape Government in partnership with The City of Cape Town

September 2016

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PROJECT NAME:

TWO RIVERS URBAN PARK (TRUP)

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SYNOPSIS:

The report responds to the TRUP ToR outlined on pages 67-68 of the tender requirements. This report is part of a specialist flood modelling study intended to prepare a 2D model of the flooding in the Two Rivers Urban Park (TRUP) area and to propose and model various interventions aimed at reducing flooding. This report deals with the first task, which includes model setup and calibration and proposing flood mitigation options.

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Executive Summary

Purpose of Study

This report is part of a specialist flood modelling study intended to prepare a 2D model of the flooding in the Two Rivers Urban Park (TRUP) area and to propose and model various interventions aimed at reducing flooding. This report deals with the first task, which includes model setup and calibration and proposing flood mitigation options.

Methodology

A one-dimensional model of the rivers and bulk stormwater network was set up based on previous models by SRK (2012). The geometry of the river channel and structures was refined using topographic survey undertaken as part of the model development. A two-dimensional (2D) representation of overland floodplain flow was added based on LiDAR levels.

The bulk stormwater network was included in the model, including areas within the floodplain but outside of the normal catchment. Although the consultant did not consider this of high importance for the urban design questions of the overall project, it was a requirement in the Terms of Reference.

The software specified in the Terms of Reference is PCSWMM, which is designed primarily for the modelling of stormwater networks. Its numerical set up is a quasi 2D model, representing flows between cells as if they would flow through canals. For the urban design challenge and river 2D modelling in general, the consultant recommended other software, but Personal Computer Storm Water Management Model was nonetheless preferred by the City of Cape Town, as this is the software which they currently use.

The sea level modelled is a combination of the 90th percentile high and low tides, a best estimate of sea level rise to 2060, and the 1:50 year storm surge and wave setup for the 1:100 year flood and the 1:20 year storm surge and wave setup for all other floods. The timing of the tide had a marginal effect on flood extents.

Existing catchment and river models, rainfall data and limited stream flow data were made available. The intention of this project was to model the TRUP area, as well as downstream areas affecting flow. None of the available flow data were suitable for calibration of flows or levels in this area.

Findings

A long-section along the lowest point of the river / canal bed produced from the survey shows that the bottom of the Salt canal is more than a meter higher than the bottom of the wetland at the junction of the Liesbeek and Black Rivers adjacent to the PRASA yard, which is below sea level.

Main conclusions for the purposes of advising the TRUP professional design team from this Task 1 report are:

Attenuation of the 1:100 year inflows within TRUP is predicted to be 24%, from a total inflow peak of 317 m^3/s to approximately 241 m^3/s. Attenuation of inflows for the 1:10 year flood is estimated to be 9% from a peak total inflow of 193 m^3/s to a peak outflow of 175 m^3/s.

Local flooding due to capacity of the bulk stormwater network being exceeded by the 1:10 year flood is shown in Northern parts of Maitland Garden Village, in the area around Eastman Road and between Berkley Road and Frere Road and at the soccer stadium.

Most of the sports fields to the west of Liesbeek Parkway are not predicted to be flooded, which is a significant difference from previous which were modelled in 2012. However, after completion of the draft report, we received a report on a floodline study undertaken by African Environmental Development (2016) which indicates surveyed levels which differ from those in our survey. A concern was raised that the exclusion of the sports field from the flood line may be due to the survey differences and the resulting raising of the LiDAR. The City of Cape Town have undertaken to do a further survey comparison in the area.

According to the 2D model, the river water only leaves the TRUP area through the Salt River Canal. The water flooding the PRASA depot is basically coming from the bulk stormwater network further to the west, except for direct flooding of a narrow strip along the bank of the Liesbeek.

The open area of the M5 / N2 interchange is mainly predicted to be flooded in the 1:20 year flood, but not in the 1:10 year flood. This area could therefore be used to provide flood attenuation storage.

Way Forward

Initial scenarios to be run in Task 2 of the flood modelling study are to use a 1:100 year design flood which would change the base scenario already modelled by:

- Widening of the canal and bridges within and downstream of TRUP;
- Adding the planned development footprint as an obstruction;
- Floodplain storage along the Liesbeek area and Black rivers; and

  Alternative flood peaks in the Liesbeek and Elsieskraal assuming upstream storage capacity.

Glossary of Terms:

D	Dimensional
GIS	Geographic Information System
HEC-RAS	Hydrological Research Centre River Analysis System
LiDAR	Light Detection and Ranging
NM&A	NM & Associates Planners and Designers
PCSWMM	Personal Computer Storm Water Management Model
PRASA	Passenger Rail Agency South Africa
TIN	Triangulated Irregular Network
TRUP	Two Rivers Urban Park

1. Introduction

The Two Rivers Urban Park (TRUP) is an area along the Liesbeek and Black Rivers between the N2 freeway up to and including the junction where these rivers join to form the Salt River. Development of TRUP is being planned using the Package of Plans approach as part of the Western Cape Government Regeneration Programme. Nisa Mammon & Associates (NM&A) was appointed by the Western Cape Government who is working in partnership with the City of Cape Town to provide professional services as part of this project. Royal HaskoningDHV were appointed by NM&A to provide various specialist services, one of which is the modelling of flood mitigation options.

As per the terms of reference (ToR), the "aim of this specialist study is to prepare a two dimensional (2D) model of the flooding of the area and to propose and model various interventions aimed at reducing flooding." The specialist study was divided into two tasks. Task 1 includes the model setup and calibration and proposing flood mitigation options. Task 2 was to use the model set up in Task 1 to "model creative flood reduction interventions". While the Client of NM&A is the Western Cape Government, who is working in partnership with City of Cape Town. The technical guidance of this Task was delegated to Mr Ben de Wet, from the Stormwater and Sustainability branch of the City of Cape Town.

2. Report Structure

This report covers Task 1. The input data will be described in section 3. The model development and checking will be described in sections 4 and 5 respectively. Results will be presented in section 6. Proposed scenarios and flood mitigation options to be modelled in Task 2 will be described in section 7.

3. Input Data

3.1 Existing models

Existing catchment and river models were made available by the City of Cape Town. These models were prepared by the SRK consulting (2012) as part of a "*high level stormwater master plan for the Salt River catchment*".

These included:

- Models of the bulk stormwater network (including rivers) in each primary sub-catchment of the Salt River using Personal Computer Storm Water Management Model (PCSWMM) software. Figure 1 shows primary sub-catchments for which PCSWMM models were available. The Jakkalsvlei and Kalksteenfontein catchments were combined in a single model, but all other primary sub-catchments were modelled separately. The models included a rainfall-runoff analysis to determine the runoff hydrograph from smaller secondary sub-catchments and a hydraulic component for routing the flow along the network. Predicted hydrographs at the downstream end of each upstream primary sub-catchment were used as inflow hydrographs to downstream sub-catchments. Overland or street flow was represented by rectangular channels.

- A single steady hydraulic model using Hydrologic Engineering Centre – River Analysis System (HEC-RAS) software of all the main rivers in the catchment, including the Salt River, Black River and Liesbeek. This model was used to predict flood levels along each river for 1:10, 1:20, 1:50 and 1:100 year return periods. Flows used in this model were the peak flows predicted by the PCSWMM bulk stormwater model. The model is based on cross-sections representing the channel and bridge geometry, which were developed using a combination of Light Detection and Ranging (LiDAR) data, site measurements and estimates. No survey was undertaken.

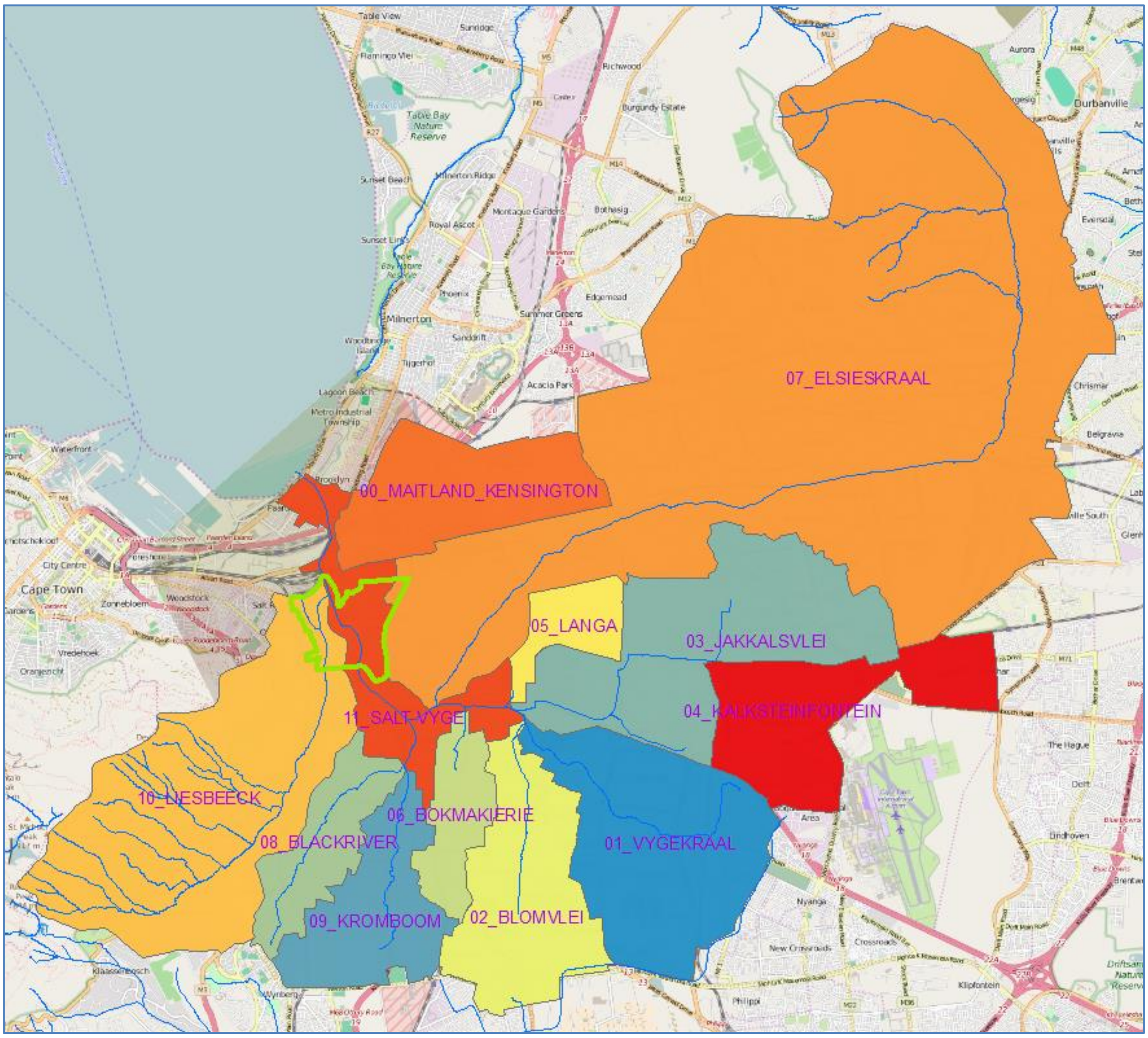

Figure 1: Salt River primary sub-catchments with TRUP boundary in Green (Background: Open Street Map and contributors)

3.2 Data provided by the City of Cape Town

3.2.1 Rainfall and stream flow data

Extracts of the rainfall and stream flow records for gauges in and around the Salt River catchment were provided. The relevant stations are shown in Figure 2 and Figure 3 respectively. The following sets of data were provided:

- 15 minute interval flow data for the stations and over the period listed in Table 1.

Table 1: Flow data available from before 2011

River	Gauging Station	From	Top
Black	Sybrand Park	20/10/2004	21/10/2004
Salt	Glamis Close	18/03/2004	12/04/2005
Liesbeek	Paradise	20/10/2003	16/09/2005
Liesbeek	Durban Road, Mowbray	19/08/2003	16/09/2005
Elsieskraal	Howard Centre, Pinelands	19/08/2003	16/09/2005

- **Error! Reference source not found.**Design rainfall developed by the University of waZulu-Natal for the City of Cape Town on a 1' x 1' grid for various return periods and durations, which included an additional factor of 15% to account for increases in peak rainfall due to climate change.

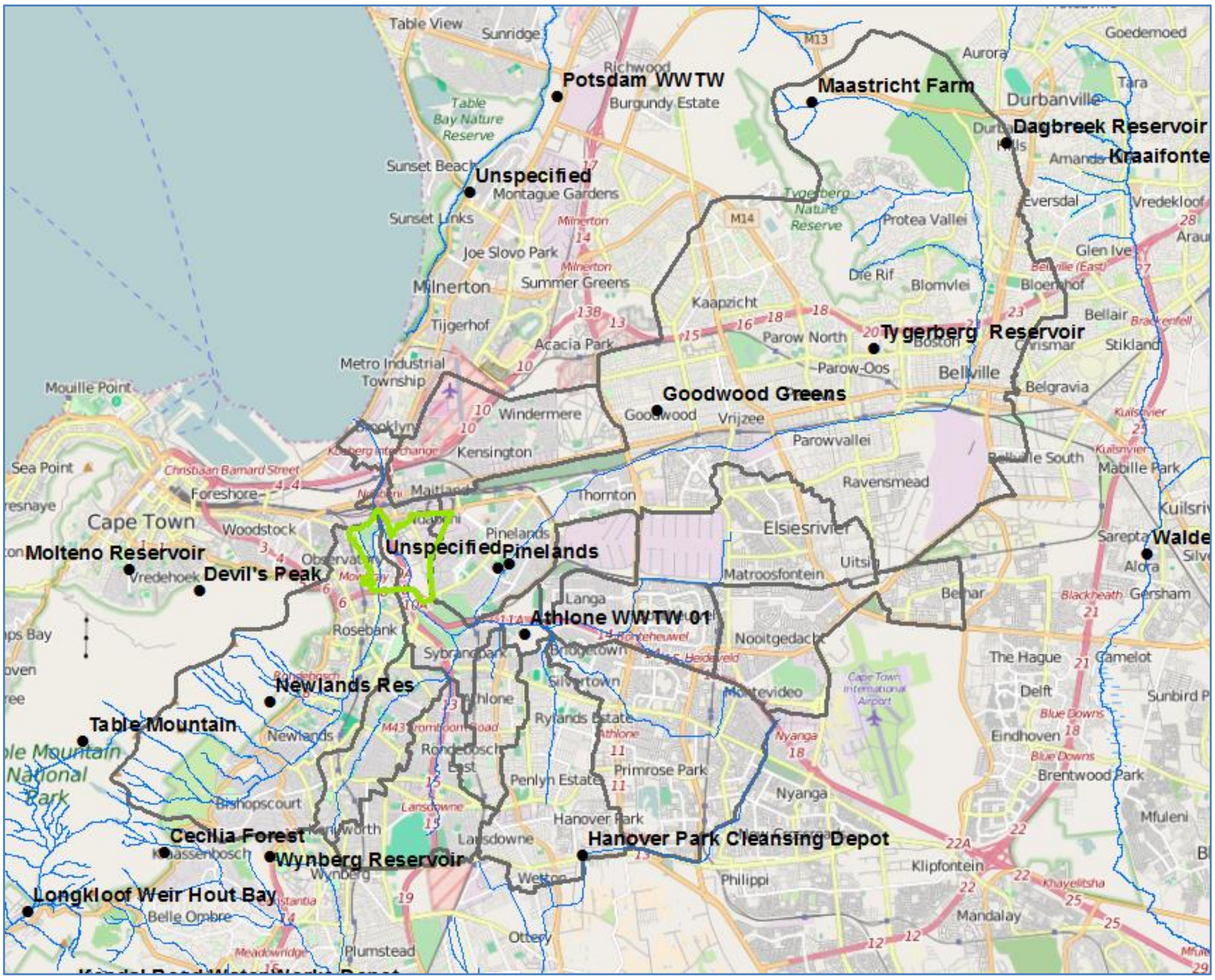

Figure 2: Rainfall stations in and around the Salt River catchment (Background: Open Street Map and contributors)

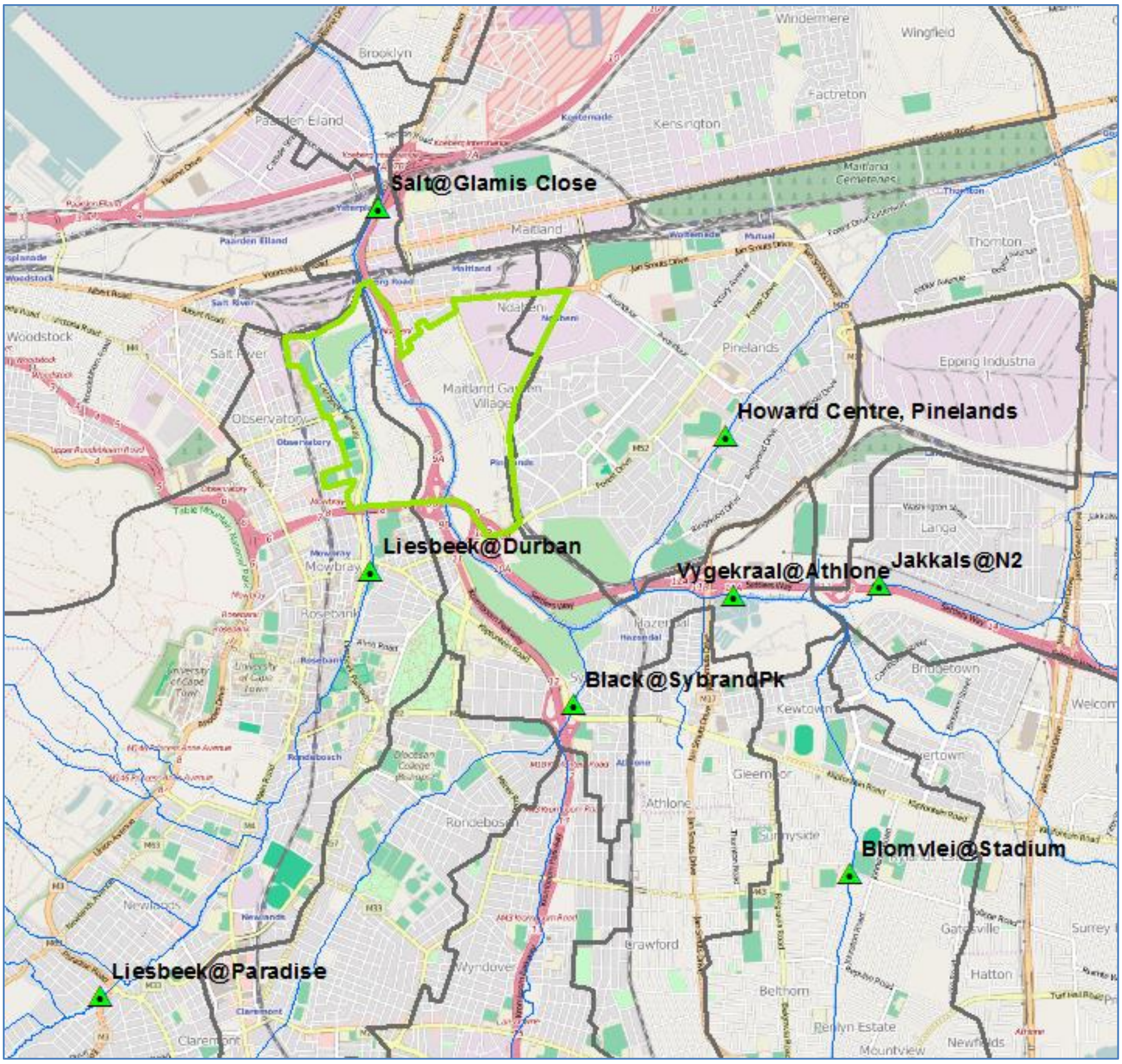

Figure 3: Stream flow gauges in and around the Salt River catchment (Background: Open Street Map and contributors)

3.2.2 Stormwater network and canal data

GIS shape files of the stormwater network were provided by the City of Cape Town, including conduits (i.e. pipes, culverts and open channels), inlets and outlets, junctions (i.e. manholes, junction boxes and other chambers), pump facilities, rivers and open watercourses and storage facilities or storage ponds. Data included conduit sizes and invert levels where available, but as noted by SRK (2012), there was much missing data.

A drawing of the Salt and Black River canals including a long section and cross-sections at various points was provided. The elevation datum of this drawing was, however, not provided.

3.2.3 Elevation data

Both ground and non-ground LiDAR survey points of the area to be modelled were provided. A 50 m x 50 m elevation grid for the remainder of the Salt River catchment was also provided. 2008 Aerial photography was also provided.

3.2.4 Reports of previous investigations

Several reports were obtained from the City of Cape Town, consultants and landowners. Key amongst these for the flood modelling is:

- Final Report: High Level Stormwater Masterplan for the Salt River Catchment (SRK consulting, 2012), which described the previous models; and
- City of Cape Town Climate Change Think Tank Marine/Freshwater Theme: Marine Inputs To Salt River Flood Model (Prestedge Retief Dresner Wijnberg, 2010), which was recommended by the City of Cape Town as the source for sea levels for use in the modelling.

4. Model Setup

4.1 Software and overall approach

The area to be modelled was defined in the terms of reference as shown in Figure 4. In addition to the Liesbeek and Black Rivers within TRUP, the model area includes the Salt River canal, the Zoarvlei (into which overland flow would spill during a flood event) and the suburb of Paarden Eiland and parts of the Salt River suburb and harbour area which may be flooded during extreme floods in the Salt and Liesbeek Rivers.

The model setup was a one dimensional (1D) to two dimensional (2D) approach one-dimensional model of the rivers and bulk stormwater network and a two-dimensional representation of overland floodplain flow. A one-dimensional model assumes flow only in the downstream direction and the same water level at any time across the channel or culvert, which is a reasonable approximation.

The software specified in the terms of reference is PCSWMM or compatible software. PCSWMM is designed primarily for the modelling of stormwater networks. Its numerical set up is not a real 2D model, but a quasi (or pseudo) 2D model, representing flows between cells as if they would flow through canals, based on hydraulic properties. Bridges are not represented similar to their real physical cross-sections but with openings of the same hydraulic properties. The consultant therefore recommended that another type of software for this urban planning project be used. During the early stages of the modelling, the consultants were requested to provide a quotation for the alternative use of 3D software, but this was not accepted. The consultants also proposed the use of HEC-RAS software, which is designed for river modelling, but PCSWMM was preferred by the City of Cape Town, as this is the software which they currently use.

Figure 4: Modelling area marked in yellow, TRUP project area marked in green

Figure 5 is an example of the model which shows how the two-dimensional component of PCSWMM is quasi-2D in that overland flow is simulated as a network of rectangular channels, with the blue marked connection showing on the right as a canal and its properties.

The basis of the model was the previous models set up by SRK (2012). However, this model was not used by SRK (2012) for the delineation of floodlines. Rather, predicted peak flows were exported from the PCSWMM model to a separate HEC-RAS model for backwater analysis to determine flood levels and plot flood lines.

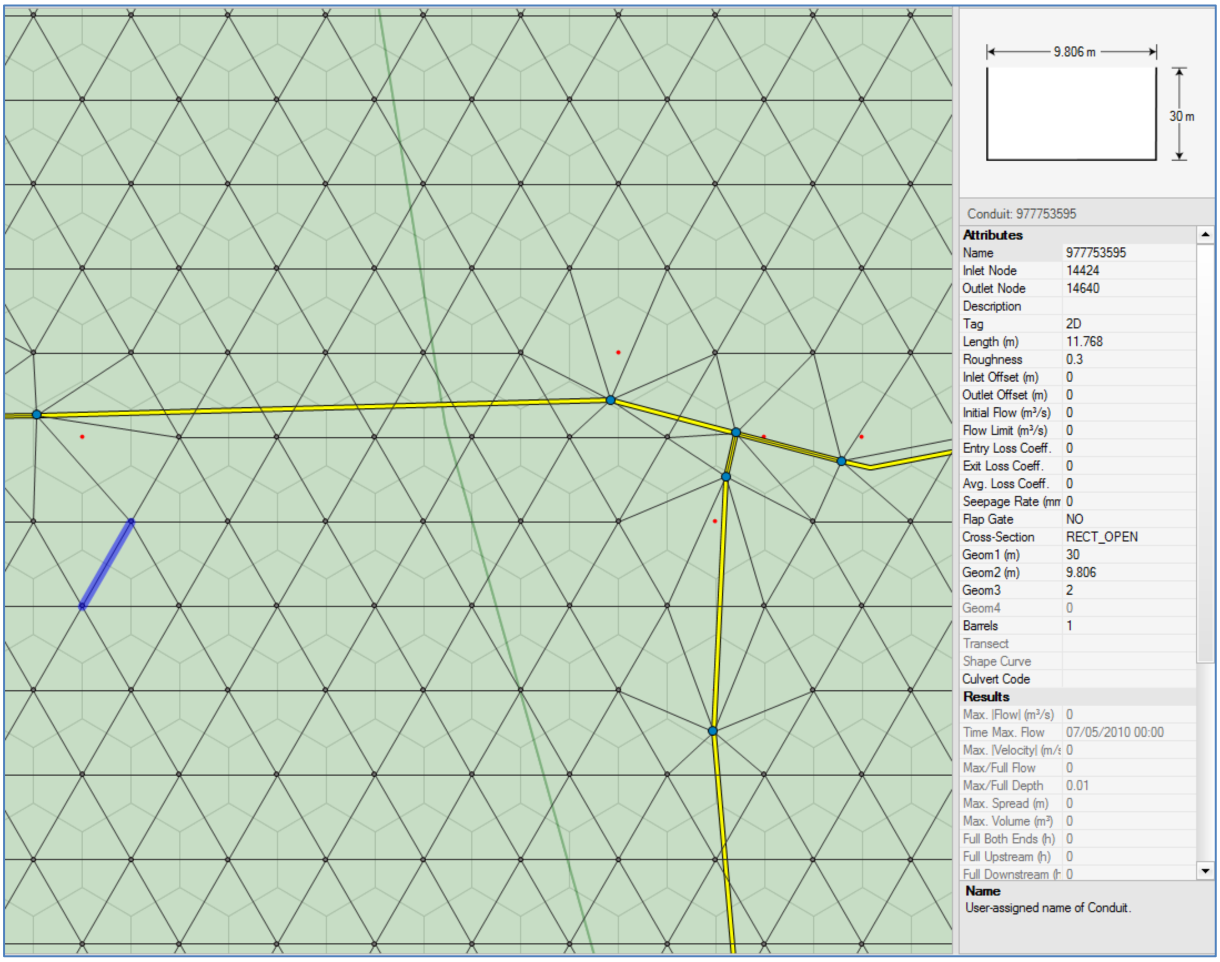

Figure 5: Representation of overland flow as a quasi-2D network in PCSWMM, with on the right the canal representation of the blue marked line

The consultants suggested that the SRK (2012) HEC-RAS model could be used as the basis for the development of a 2D HEC-RAS model, needed for the urban planning advice, in the area of interest. However, 2D HEC-RAS cannot be imported into PCSWMM at the time of writing of this report, and this would therefore not meet the requirement for compatibility with PCSWMM as suggested in the TOR.

The three models set up by SRK (2012) for the three (3) downstream sub-catchments (Liesbeek, Salt-Vyge and Maitland-Kensington) were initially combined into a single model of the bulk stormwater and river network, which was refined as required within the model area.

4.2 Topographic Survey

The necessity for topographic survey as outlined in the terms of reference was reinforced by the fact that previous models did not include any survey, and dimensions and levels were not entirely consistent with site observations.

A survey was conducted along the Liesbeek, Black and Salt rivers from the N2 freeway to the ocean, and included:

- 83 channel cross-sections across each of the rivers;
- 25 bridges;
- Two weirs across the Liesbeek;
- A pipe crossing over the Black River; and
- Pipe sizes and invert levels for stormwater outfalls along the rivers.

Additional survey requirements were initially specified, but the survey specification was later revised due to constraints on the survey budget. Items removed from the specification included:

- River cross-section and structure surveys upstream of the N2.
- Additional cross-sections within TRUP;
- Key points along the stormwater network other than the outfalls; and
- Stormwater attenuation ponds.

A long-section along the lowest point of the river / canal bed produced from the survey is shown in Figure 6. Irregularities in the long-section are explained in Figure 7.

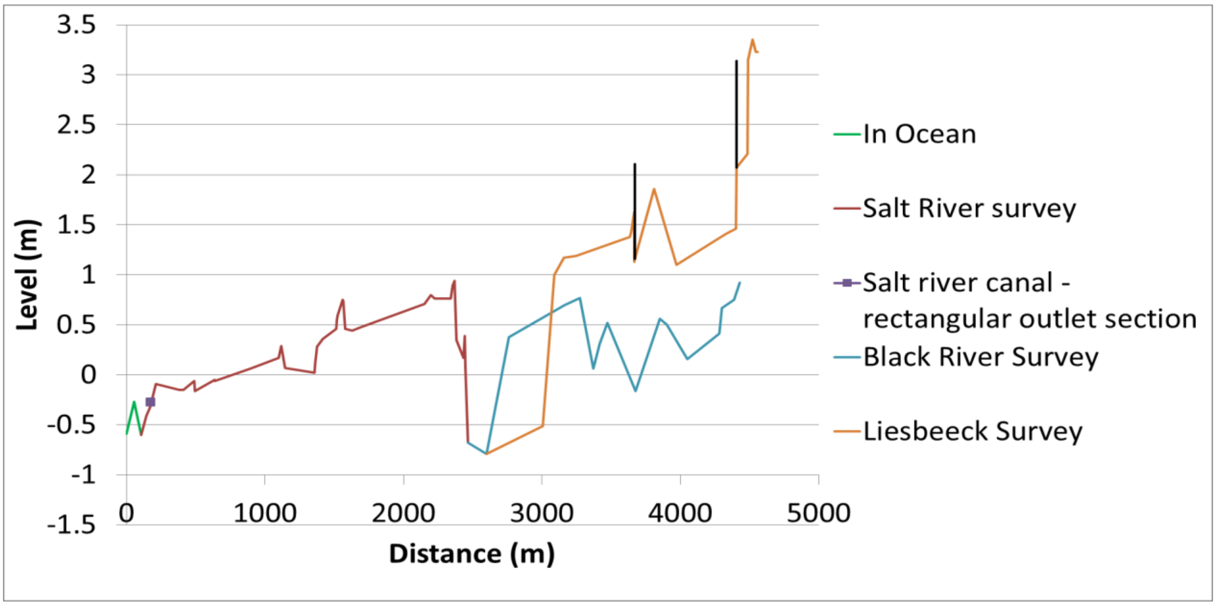

Figure 6: Surveyed long-section along the lowest point along the channel bed

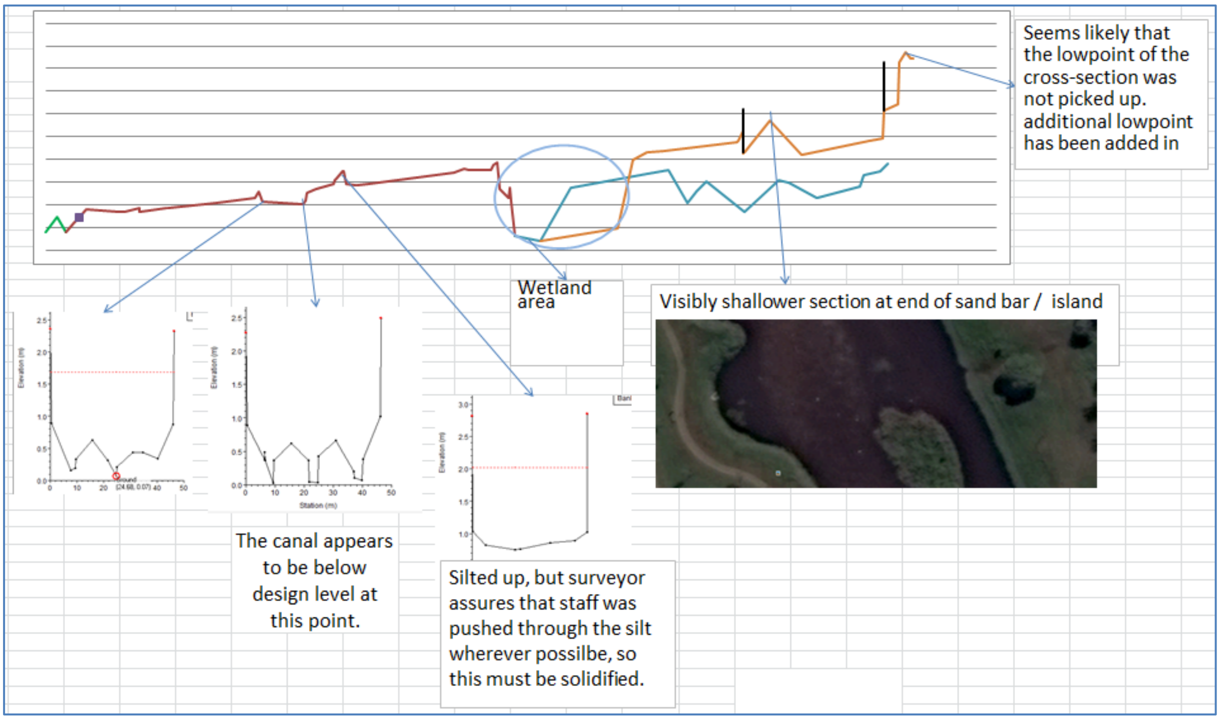

Figure 7: Explanations for irregularities in the surveyed channel long section

Figure 6 shows that the bottom of the Salt canal itself is more than a meter higher than the bottom of the lower end of the TRUP area (1-1.5 m difference). The bottom of the TRUP area is below sea level (-0.7 to -0.8 m).

4.3 Modelling of River channel and structures

The river channel up to the surveyed top of bank was modelled in one dimension. Cross-section and bridge geometry was set up using HEC-RAS software. Channel cross-sections provided by the surveyor were used directly. In order to allow for connection to the 2D overland flow model between the surveyed cross-sections, additional cross-sections were interpolated between the measured cross-sections at a maximum spacing of 50 m using HEC-RAS. Bridge geometry was also captured using HEC-RAS software using surveyed dimensions. An example is shown in Figure 8.

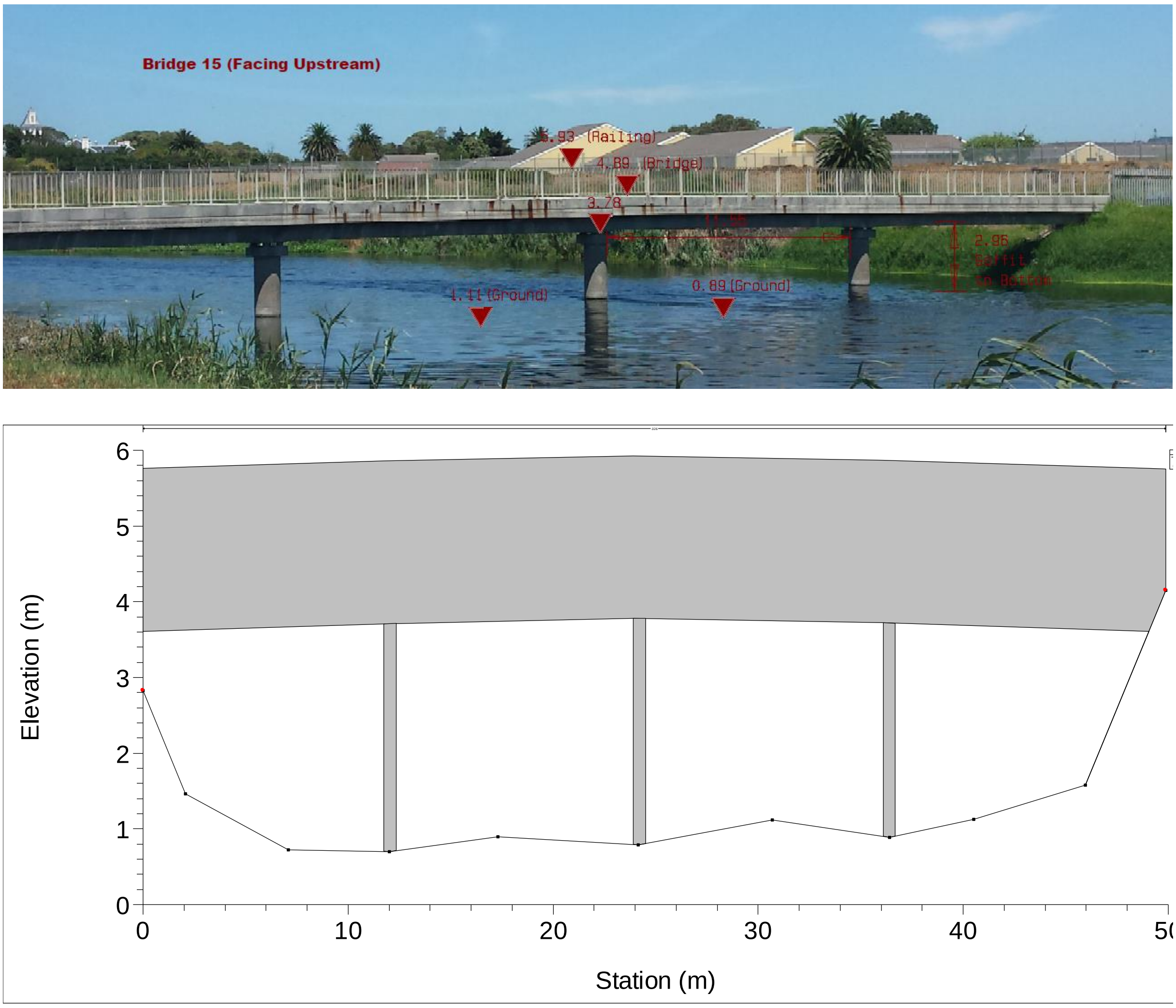

Figure 8: Example of bridge representation in HEC-RAS

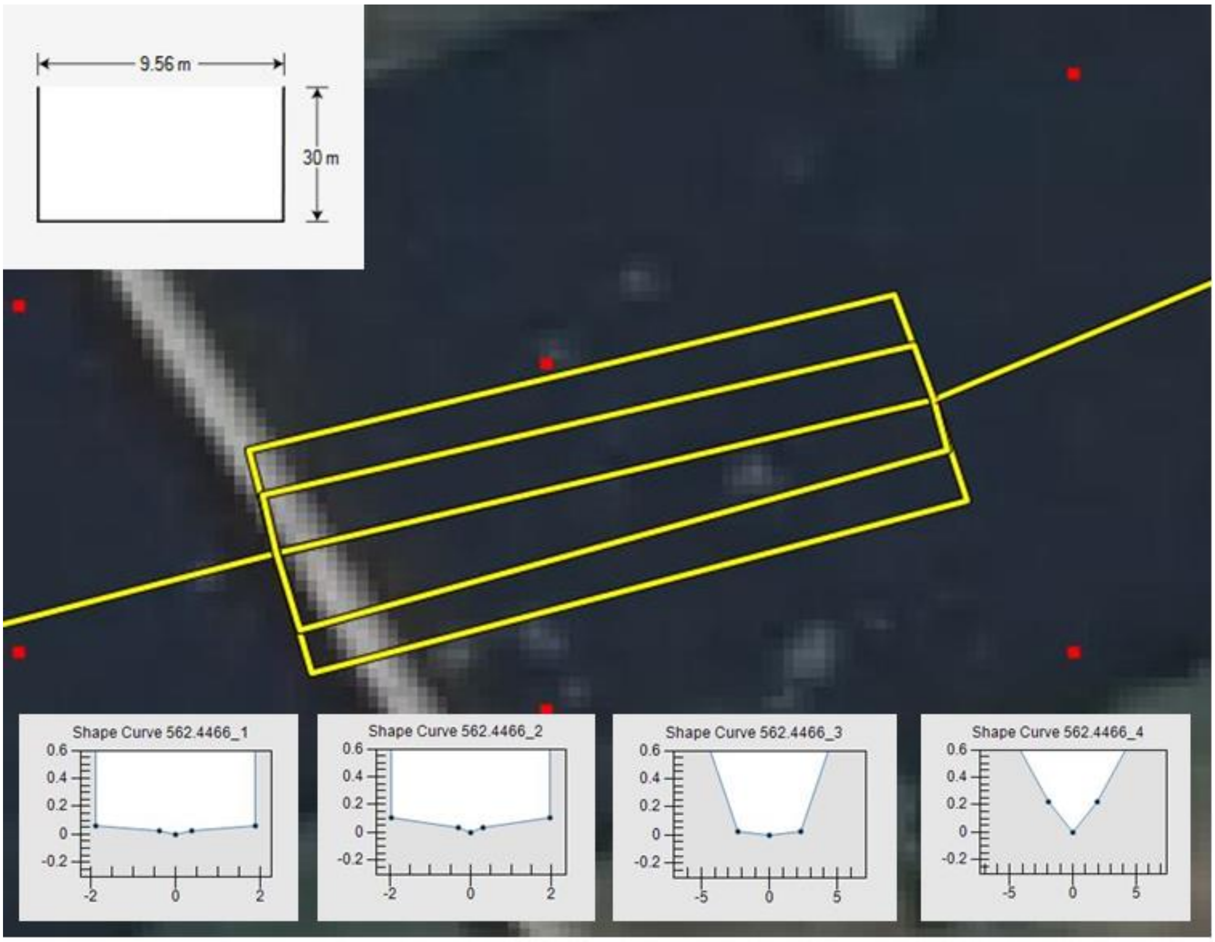

Figure 9: Example of bridge representation in PCSWMM (Same bridge as in Figure 8.)

Since openings are likely to be blocked with debris during a flood, railings, barriers and balustrades were modelled as solid obstacles i.e. assuming that there is no flow through the openings. This is analogous to the situation for guardrails. Any small flow through the openings would be compensated by the energy loss due to the flow expansion and contraction as it passes over the railings.

No debris blocking the openings between piers was assumed, since debris has already been taken into account by assuming no flow through the railings or balustrades.

Cross-sections and bridges were then imported into PCSWMM. The representation of the openings between bridge piers is changed during import into a symmetrical opening with the same flow area for each water level, as shown in Figure 9, which is the PCSWMM representation of the same bridge shown in Figure 8. It is therefore not possible to see the actual opening shape in the PCSWMM model. For this reason, the HEC-RAS model geometry is also being provided electronically.

The river channels (as well as all conduits) were modelled as dry at the start of the simulation. This is not strictly the case in reality where there are known permanent water areas along the channel, most notably the wetlands at the junction of the Liesbeek and Black rivers. An improvement for the Task 2 model runs is to set the initial water level throughout the model as equal to the initial downstream tide level (1.72 m for the 1:100 year flood and 1.64 m for other return periods). This revised initial water level is sufficient to wet all along the river channels. Because the adopted rainfall hyetograph starts at the beginning of the simulation, but only peaks after 12 h, initial runoff allows low points along the river channel to be filled before the peak flow, and flood peaks and extents along the Black River are not affected. However, along the Zoarvlei only, inflows are largely determined from upstream, and the maximum water level and flood extents are affected by the initial water level.

4.4 Bulk stormwater network (culverts and open channels)

Much of the effort of this project was in improving on the bulk stormwater network, in particular in the downstream Paarden Eiland area. Although the consultant did not consider this of high importance for the purpose of advising the TRUP design team, it was a requirement in the Terms of Reference and therefore executed.

A map of the bulk stormwater network as modelled is shown in Figure 10. The bulk stormwater network was included in the model as a one-dimensional network. As noted in Table 2, outside or upstream of the modelling area defined in Figure 4, the stormwater network as modelled by SRK (2012) was accepted as provided. Within the model area, the network was checked and refined using available data as indicated in Table 2. Detailed assumptions are included in Appendix F.

Table 2: Assumptions for the modelling of the stormwater network

1	The stormwater network outside of the modelled area will be accepted as modelled by SRK (2012), which was based on the assumptions stated in their report, which generate inflows to the modelled area.
2	Use surveyed levels and conduit sizes where measured at river outfalls
3	Stormwater conduit sizes and levels in the City of Cape Town Geodatabase will be accepted. Where there appears to be an inconsistency, this has been recorded.
4	Where the Geodatabase indicates several parallel conduits of the same size, these are indicated in PCSWMM as a single conduit with a specified number of barrels. This is necessary, since only a single junction is allowed within each 2D cell. Small conduits in parallel with larger conduits are deemed not to be part of the bulk network, and are excluded.
5	Where areas for which there is no data in the Geodatabase have been modelled by SRK (2012), conduit sizes and levels from the SRK (2012) model will be adopted, except where inconsistencies are noted. Sizes from the Geodatabase will, however, take precedence.

6	Open channel cross-sections not previously modelled will be extracted from the LiDAR.
7	Open channel junction rim elevations will be the greater of adjacent ground levels from the LiDAR or the top of the channel, calculated as the invert level plus the channel depth from the extracted cross-section.
8	Where there is no culvert size available, the size was assumed to be the same as that of the upstream and downstream conduits. Where the upstream and downstream conduit sizes differ, the location of the change in size was selected considering the location of inflows. In certain cases, a size in between that of the upstream and downstream culverts was assumed.
9	Where the invert level is missing (as noted by negative or zero values), a level will be approximately interpolated between available levels upstream and downstream. Where there are levels available only upstream or only downstream, available slopes will be approximately projected.
10	Where the manhole rim elevations are incorrect (as can be seen from the fact that the pipe segments/culverts/channels coming into and out of the manhole is clearly larger than the depth), the ground level from the LiDAR survey was used. If this was still too low (i.e. depth is still incorrect), then the rim was assumed to be 0.3 m above the highest soffit of all culverts joining into the manhole.

The bulk stormwater networks in the areas indicated by red ellipses in Figure 10 are outside of the Salt River catchment, and were therefore not modelled by SRK (2012). However, these areas would be connected to the Salt River by overland flows during extreme floods, and were therefore added into the model. These areas, as well as the Zoarvlei, have their own catchments, which were delineated approximately based on stormwater network data and the limited topographic data available in these areas. Catchment parameters affecting runoff were estimated for these catchments.

The most significant changes made to the network are as follows:

- At Northgate Business Park along Section Road just east of the M5, the SRK model showed a series of pipes with diameters 1.65 m, 0.3 m and 0.9 m from upstream to downstream. The diameter of the middle pipe (conduit 260) was changed from 0.3 m to 0.9 m to match the downstream pipes. However, it still seems unusual that a series of 1.65 m diameter pipes would flow into a series of 900mm diameter pipes, and it is suspected that the diameters may still be incorrect.

- Sizes of the main outfall from the canal near the N1 R27 interchange to the harbour were taken by assuming similar dimensions to the upstream canal (conduits 2543 to 2547).
- The diameter of conduit No. 2 along Oude Moulen Road in Ndabeni was changed from 1.0 m to 0.6 m, which was the diameter in the GIS shapefiles received from the City of Cape Town.
- For bridges (except for river bridges, where the river bed may not be picked up), the ground LiDAR usually picks up the ground at the bottom of the bridge opening. However, there were three bridges (N1 over rail at Paarden Eiland, R27 Marine Drive over rail at Lagoon Beach and N1 over the West Coast Busway) where the opening was not picked up. These bridges were therefore represented as rectangular culverts with estimated dimensions. Because the first two of these bridges would allow floodplain flows to pass through towards the sea, a tidal boundary was added downstream of these bridges.

Figure 10: Modelled areas of the bulk stormwater network outside the Salt River catchment

4.5 Two-dimensional modelling of overland flow

4.5.1 Digital elevation model

A digital elevation model was created from the LiDAR ground points.

After the first hydraulic runs, comparison with the survey indicated that the LiDAR was generally lower than the corresponding ground survey, and the level of the LiDAR points had to therefore be raised by 0.25 m. The Lidar levels were therefore raised by 0.25 m throughout the entire model. Since the complete channel section is generally from the survey and not the LiDAR, raising of the LiDAR levels does not affect the channel capacity. At the mouth, where the top of bank was not surveyed, the flow depth is from the surveyed bed level up to the assumed tide level, so the flow area is also not significantly affected by the raising of the LiDAR.

Since the rivers and open stormwater channels below the top of bank level were included in the one-dimensional model, these needed to be excluded from the two-dimensional model. The ground level in the digital elevation model within the rivers and channels was therefore set equal to the level of the top of bank (on the higher side). The full depth of flooding within the channels is therefore not shown in the 2D results.

A Triangulated Irregular Network (TIN) was first generated from the LiDAR points, and then converted to a 1m x 1m elevation grid for use in PCSWMM.

A TIN and 1 m x 1 m elevation grid was also generated including non-ground points, which was useful for understanding the above-ground terrain, but this was not used directly in the model.

A question was raised at the River Study Workgroup meeting of 05 May 2016 whether the openings in the Liesbeek that were recently cut were represented in the LIDAR. These were, in fact picked up in the LiDAR, but in order to better represent the berms in the model, it was decided to:

a) Use a smaller 3 m x 3 m mesh on and around the berms; and
b) To represent the southern break in the berm and the downstream channel as a 1D channel

4.5.2 Area categorisation (roughness)

The two-dimensional model area was divided into polygons representing different land uses, and each was assigned a suitable hydraulic roughness, represented by Manning's n values. The values adopted are shown in Appendix E. Buildings and solid boundary walls (except those modelled as obstructions) were accounted for by increasing the roughness value.

4.5.3 Connection to external catchments and flows

As mentioned in section 0, the storm water network upstream of the modelled area within the Salt River catchment was included from the SRK models. Street or overland flow was represented in these models as rectangular channels 30 m wide in parallel with the pipe flow beneath. While the pipe network was connected directly to the pipe network within the model area, street or pipe flow was connected to a few of the nearby 2D nodes, so as to spread the overland flow. The last conduit upstream of the modelled area was duplicated (with a reduced width) as required in order to connect to several 2D nodes.

Catchments in PCSWMM can only be connected to a single node. Where external catchments were added, except along the Zoarvlei, these were connected directly to the nearest node of the storm water network. Should the capacity of the stormwater network be exceeded, these nodes would overflow into the 2D network. Since the Zoarvlei was represented only by the 2D network, catchments draining to the Zoarvlei were connected directly to a 2D node. The entry point for distributed catchment inflows to the river network (including the Zoarvlei) was generally taken towards the upstream end of the section of river into which that catchment flows, in order to avoid under-estimating the flow along that section of the river.

4.5.4 Obstructions to overland flow

Bridge decks, sections of the traffic barriers (particularly along the M5), as well as certain solid walls were modelled as flow obstructions as indicated in Figure 11. The figure also indicates the 2D flow area outlined in purple, TRUP boundary in green and obstructions in red.

The 2D nodes and mesh needed to be re-generated or manually edited whenever the obstructions were edited.

Figure 11: Obstructions to overland flow included in the model

4.5.5 Overland mesh

An overland mesh was generated by PCSWMM software as described in section 0. An adaptive mesh was used, except for the streets, where a hexagonal mesh was used. The resolution of the mesh in each area was as follows:

- Berms East of the Liesbeek River: 3 m to a maximum of 10m where the change in elevation is less than 0.1 m
- Streets: 10 m

- Above the top of bank of rivers and stormwater channels: 30 m
- All other areas: 50 m, up to a maximum of 200m where the change in elevation is less than 0.1 m

4.5.6 Connection to 1D network

Wherever possible, all 1D nodes within the area of the 2D network were connected to the 2D network. Connections were made using the ‘direct connection’ approach, which moves the relevant 2D nodes to the nearest 1D node.

However, only one 1D node can be connected to each 2D cell. For the bulk stormwater pipes, parallel conduits were combined into single conduits with multiple barrels but single junctions which could be connected to the 2D network. Along the rivers, stormwater nodes to be connected to the 2D network were individually selected in order to ensure that only one node was selected for connection within each cell.

4.6 Tidal boundary condition

In general, in upstream river areas, there is no influence of the ocean downstream, and flood levels are determined entirely by river flow. In this case, the frequency of occurrence of a certain flood level is the same as the frequency of occurrence of the corresponding river flow.

Where the river enters the ocean, the water level is equal to the sea level, and the river flow has no influence on the flood levels. The flood water level is equal to extreme sea levels occurring at a defined frequency.

In between, both sea level and river flow influence flood levels. Moving up the estuary, the influence of the sea level diminishes and the influence of the river flow increases, a defined flood level can be achieved by many combinations of river flow and sea level, each of which has its own probability of occurrence.

The TRUP site is at a location where flood levels across most of the site are primarily determined by river flow. Therefore, it was decided that, in modelling a flood with a defined probability of occurrence, the river flow with the same probability will be adopted.

The sea level modelled is a combination of the tide level, the storm surge (due to wind setup and atmospheric pressure), wave setup and the projected sea level rise. Prestedge Retief Dresner Wijnberg (Pty) Ltd (2010) give estimates of storm surge and wave setup corresponding 1:20 year, 1:50 year and 1:100 year frequencies, as well as best and upper estimates for sea level rise in 2035 and in 2060.

The tidal component is unrelated to weather conditions, and extreme storms can occur at any tide level. Both the timing of the flood peak relative to the twice daily tidal cycle and the tidal range of that particular cycle are important. For the tidal range, the large range from the 10th percentile low tide to the 90th percentile high tide have been adopted, as this gives the full range of tide levels, excluding extremes. The timing of the peak river flow relative to the tidal cycle was also thought to be important, but a sensitivity test proved this did not have much influence on the TRUP area.

It was agreed with the City of Cape Town to use sea level estimates presented by Prestedge Retief Dresner Wijnberg (Pty) Ltd (2010). The initial 1:100 year run used the 2010 sea levels (i.e. without climate change) with the 1:100 year storm surge and wave setup. However, at the workshop on 5 May 2016, it was agreed to use the following estimates, the values for which are presented in Table 3:

- The 2060 best estimate for sea level rise in view of the long-term nature of the TRUP development;
- The 1:50 year storm surge and wave setup for the 1:100 year flood, and the 1:20 year storm surge and wave setup for more frequent floods;
- The 90th percentile high tide; and
- The effect of the timing of the tide would be investigated by modelling both the highest and lowest tide coinciding with the peak inflow to the model area.

The tidal boundaries were more extensive than originally thought. Therefore a new mesh was generated and a tidal boundary was also added in the area near the Northern end of the Zoarvlei where there appears to be some overflow.

Table 3 Extreme tidal ranges and as per Prestedge Retief Dresner Wijnberg (Pty) Ltd Table 6.1

Return period (years)	Low Tide	High Tide
20	0.83	2.45
50	0.90	2.53

Levels include the 90th percentile high tide plus the best estimate sea level rise for 2060.

4.7 Summary of assumptions

The main modelling assumptions and their effect on flood extents are summarised in Table 4.

Table 4: Summary of assumptions and their effect on flood extents

Increase flood extents	Neutral	Decrease flood extents
Peak rainfall preceded by 12h of heavy rain as per SCS-SA type 1 rainfall distribution	Peak rainfall over entire catchment at the same time	No debris blocking bridge openings or weirs
All sub-catchments have peak rainfall of the same return period	Best estimate runoff parameters	No additional blockage by sediment transported during flood
No flow through barriers and balustrades (solid)	Best estimate channel and floodplain roughness	
Existing "solid" sediment remains during flood	Quazi-1D flow	
Sea level: High storm set up with near spring tide	High tide coinciding with peak inflow	
Rainfall includes extra 15% for climate change		
Best estimate sea level rise to 2060 included		

5. Model checking

5.1 Stability and software warnings

As an initial check on the results, PCSWMM software calculates separate flow balances for runoff and flood routing. The runoff loss shows the error in the balance of rainfall, runoff, infiltration and catchment depression storage. The stated runoff error for the final models was -0.1%. The routing error is the error in a balance of inflows, outflow and storage for the flow network. The routing error in the final models was 1.2%. These imbalances are acceptable for a model of this extent, bearing in mind the model objective to test the effect of flood mitigation options.

Model instability appears to be during the initial wetting (and drying) of certain floodplain areas and the corresponding culverts, which is difficult for all 2D models.

The software also presents warning messages for several of the conduits. There are some 1D and 2D conduits where the slope is less than the minimum specified by the software, but these are areas where, according to available information, gradients are indeed flat. The other warning is for 2D conduits where the elevation drop exceeds the culvert length, which is physically impossible. However, this results from the artificial lengths generated by the software for the 2D conduits. The online help of PCSWMM explains this as follows:

"*All 2D junctions are connected to adjacent 2D junctions with 2D links or conduits … The lengths and widths of conduits are adjusted according to a ratio dependent on the number of links connected to the node. This ratio was determined from a large number of tests to give expected wave speeds under a wide range of scenarios*".

In the light of the above, the model setup is accepted.

5.2 Calibration

5.2.1 Aims

Although some upstream areas from the previous SRK models were included, the intention of this project was to model the TRUP area, as well as downstream areas affecting flow through TRUP as indicated in Figure 4. The intention is not to re-model or calibrate upstream models.

Since the model includes both rainfall-runoff analysis and water level analysis, either flows or water levels could be calibrated if suitable data are available.

In terms of flows, calibration could be used to correctly predict the downstream hydrograph for given river inflow hydrographs to the TRUP area. Adjustments could be made to:

- Runoff coefficients for local stormwater catchments within or draining into TRUP; and
- Channel and floodplain roughness, which would affect the attenuation of flows within the area.

In terms of levels, channel and floodplain roughness could be adjusted to give known water levels for a measured flow hydrograph.

5.2.2 Assessment of flow data

Out of the available flow data described in section 0, flood events were investigated for possible use in model calibration. From newspaper cuttings / internet, recent flooding of the River Club area has occurred on August 2004, 6&7 July 2012 and 30 August 2013. From information received from PRASA on another project, the Salt River Depot of PRASA, which is at a higher elevation than the River Club, experienced flooding problems on 9 August 2009 and 12 April 2012.

For the flood events of 12 April 2012, 6&7 July 2012 and 30 August 2013, no flows were recorded at the Salt River gauge, as indicated by zero values throughout the flow record. The flood of 9 August 2009 was completely outside of the time period for which data were provided.

Records for the flood of August 2004 included the Salt River (at Glamis, downstream of TRUP), the Liesbeek River (at Durban Road, upstream of TRUP) and the Elsieskraal River (at Pinelands). However, no record was available for the Black River, which is the tributary with the largest catchment area. This introduces an uncertainty which is compounded by the unknown inflows between the gauges on the Liesbeek and Elsieskraal rivers and TRUP.

Figure 16 shows that inflows within TRUP are very small in comparison to river inflows to the area. Furthermore, the predicted timing of the local inflows relative to the peak river flows means that local inflows add only 3.8% to the flood peak. As this change is less than the uncertainty of the unmeasured flow from the Black River and other catchments between the flow gauges and TRUP, calibration based on those flows which are known flows would be meaningless. It was therefore concluded that no calibration for flows was possible.

5.2.3 Assessment of water level data

In order to calibrate using water levels, predicted and measured water levels should be compared for a known flow. The only information on historical water levels within the model area is:

- The known flooding of the River Club and PRASA sites mentioned above; and
- Gauge records for the Salt River flow gauge at Glamis already mentioned.

Model predictions do indeed show extensive flooding of the River Club. The PRASA site is shown to be just at the edge of the 1:100 year floodplain, and local stormwater runoff likely contributes to flooding of the site when river levels are high. As mentioned previously, flow data are not available for any of these events.

Available records for the Salt River gauge at Glamis are in terms of flow rather than water level, but water levels could be back-calculated using the gauge rating curve. The levels so calculated should be the original recorded levels. The rating curve (and therefore the 'measured' flow) was itself derived using a hydraulic model of the study reach. The alignment of the Salt River canal, in the vicinity of the Glamis Close monitoring point, was modified when the M5/Koeberg Road intersection was upgraded in around 2010. It is unclear whether this had any effect on the gauge rating curve.

It would be possible to compare water levels derived from the TRUP model at the gauge position with measured water levels for the gauged flows. However, this would essentially be comparing the TRUP model with the model used to derive the rating curve, since flows from the rating curve model would be fed into the TRUP model to get back to the water levels. This was not seen a useful means of calibration, since the TRUP model already includes recent survey and floodplain details which were absent from the rating curve model and is therefore already expected to be the more accurate of the two models.

It was therefore concluded that no calibration could be done. While calibration would improve model confidence, we are confident that the un-calibrated model provides a sufficient basis for assessing the effect of flood mitigation options, which is its main purpose.

Nonetheless, further information on the August 2004 flood is provided below for information.

5.2.4 August 2004 flood record

For the August 2004 flood event, recorded flows are plotted in Figure 12. The relative timing of the flood peaks appears to be unrealistic in that the downstream Salt River gauge peaks before both upstream gauges. By the time of the peak flow in the Elsieskraal, the downstream flow in the Salt River has already reduced to less than the Elsieskraal peak, which is clearly not possible.

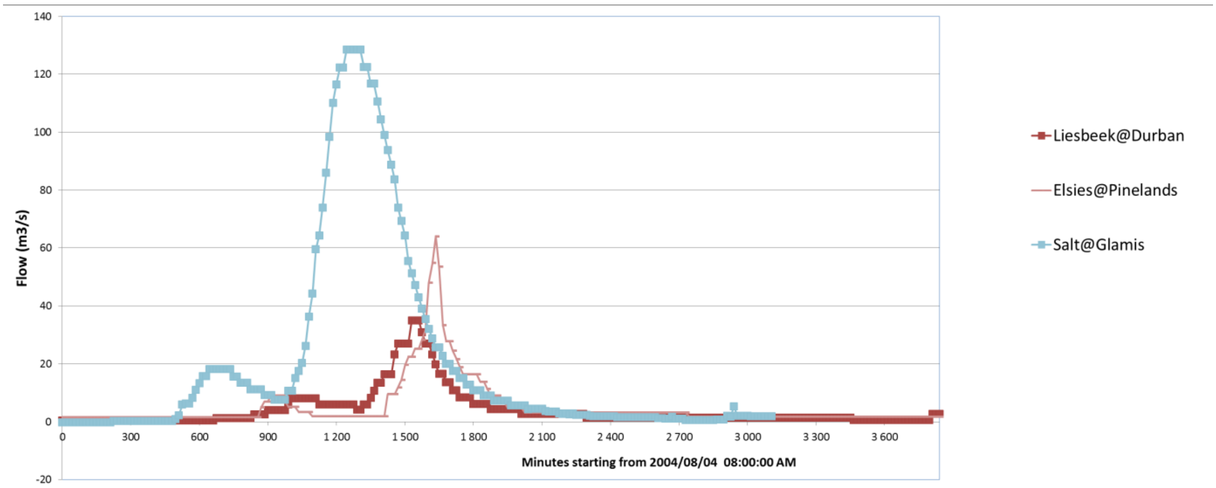

Figure 12: Peak flows recorded for the August 2004 flood

Peak flows and runoff volumes for this flood, as well as catchment areas based on sub-catchments delineated by SRK (2012) are compared in Table 5. Volumes are based on the sum of flows from 08:00 on 04 August 2004 to 24:00 on 06 August 2004, which is the same period plotted in Figure 12. In view of the relative catchment sizes, the increase in peak flow between the Elsieskraal River and the Salt River is more than would be expected, given the likely flood attenuation due to the small slope of the watercourses and wide floodplain.

Table 5: Summary of flow data for the flood of 02 to 05 Aug 2004

Gauge		Liesbeek @Durban	Elsieskraal @Pinelands	Salt @Glamis	Additional catchment between upstream flow gauges and Salt@Glamis
Catchment Area	km^2	22	90	204	91
Peak flow	m^3/s	35	64	128	
Runoff volume	Mm^3	0.94	1.16	3.72	1.62
Runoff volume relative to catchment area	mm	42	13	18	18

Daily and 5-minute interval cumulative rainfall on 5 August 2004 for various rainfall stations in the catchment are shown in Table 6. Pinelands rainfall station is very close to the flow gauge on the Elsieskraal River, so it is expected that this rainfall would contribute both the measured flood in the Elsieskraal River and to the downstream flood in the Salt River. The 5-minute interval data show that there is indeed a higher rainfall event measured in Pinelands compared to other stations, which could explain the higher peak and flood volume in the Salt River, although not the relative timing.

Pinelands is the only rainfall station for which both daily and 5-minute interval rainfall data are available. However, there is a major inconsistency between the two data sets. For Pinelands, the 5-minute dataset gives a total rainfall of 61 mm on 05 August 2004, whereas the daily data gives less than 12 mm.

Table 6: Summary of rainfall data for the flood of Aug 2004

		2004/08/03	2004/08/04	2004/08/05	2004/08/06	2004/08/07
Daily data						
For Black River						
	Athlone	0	10.8	60.6	3.6	24
	Observatory	0	46	40.5	0	0
	Pinelands	0.2	15.4	11.6	5	19.2
	Groenvlei	0	47.4	22.4	9	70.4
For Liesbeek						
	Newlands	1.2	66	36	18.8	90.8
	Cape Town	0	53.3	29.8	0	0
	Kirstenbosch	0.8	102.5	24.5	16	0
5 min interval data						
For Black River						
	Pinelands			61.2		
	Tygerberg			17.2		
	Dagbreek			20.2		
	Maastricht			14		

5.3 Sensitivity to timing tide relative to inflow

As explained in section 0, the effect of the timing of the tide was investigated by modelling both the highest and lowest tide coinciding with the peak inflow to the model area. The respective hydrographs for outflow from the Salt River canal to the sea for the 1:100 year flood are compared to the tide levels in Figure 13 and Figure 15. Note that the outflows plotted are only those through the Salt River Canal, and not through stormwater outfalls.

The difference in flood extent is as indicated in Figure 14. There is a very marginal increase in flood extent when the peak inflow to the modelled area coincides with the lowest tide, most likely because the travel time from upstream of TRUP to the ocean is of the same order of magnitude as the 6h required for the tide to rise. The extended duration of the peak outflow limits the impact of the timing of the tide, and the timing of the peak outflow is itself influenced by the timing of the tide. Based on these findings, it was decided to time the tide peak at 9 h and 21 h after the start of the simulation, i.e. so that the low tide coincides approximately with the inflow to the modelled area for all further modelling. The final 1:100 year flood model was therefore the same as that presented in Figure 15, except that the time step was subsequently reduced from 0.3 s to 0.2 s to improve model stability.

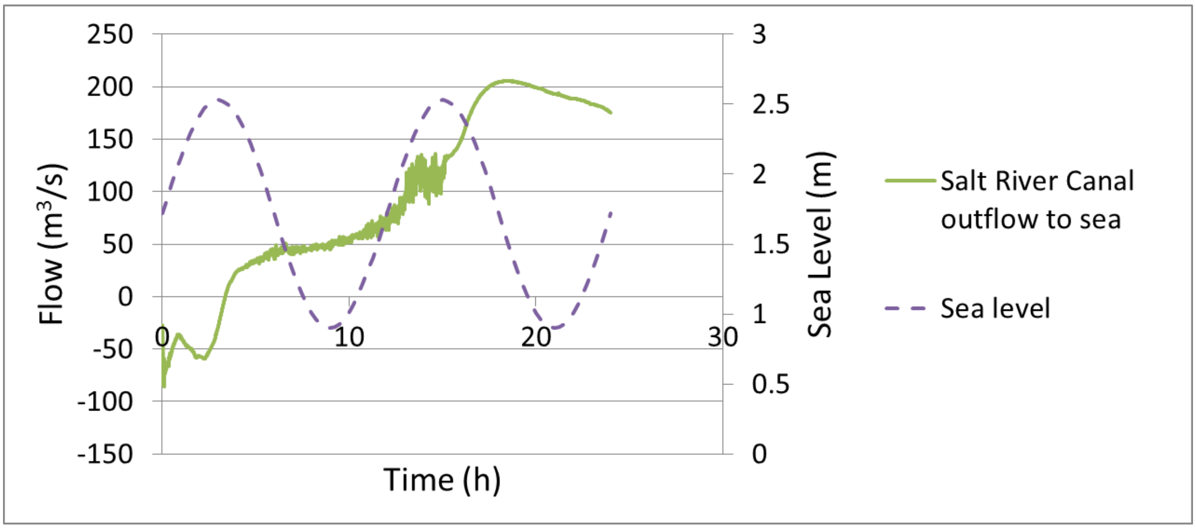

Figure 13: Predicted 1:100 year outflow to sea from the Salt River Canal for highest tide coinciding with peak inflow

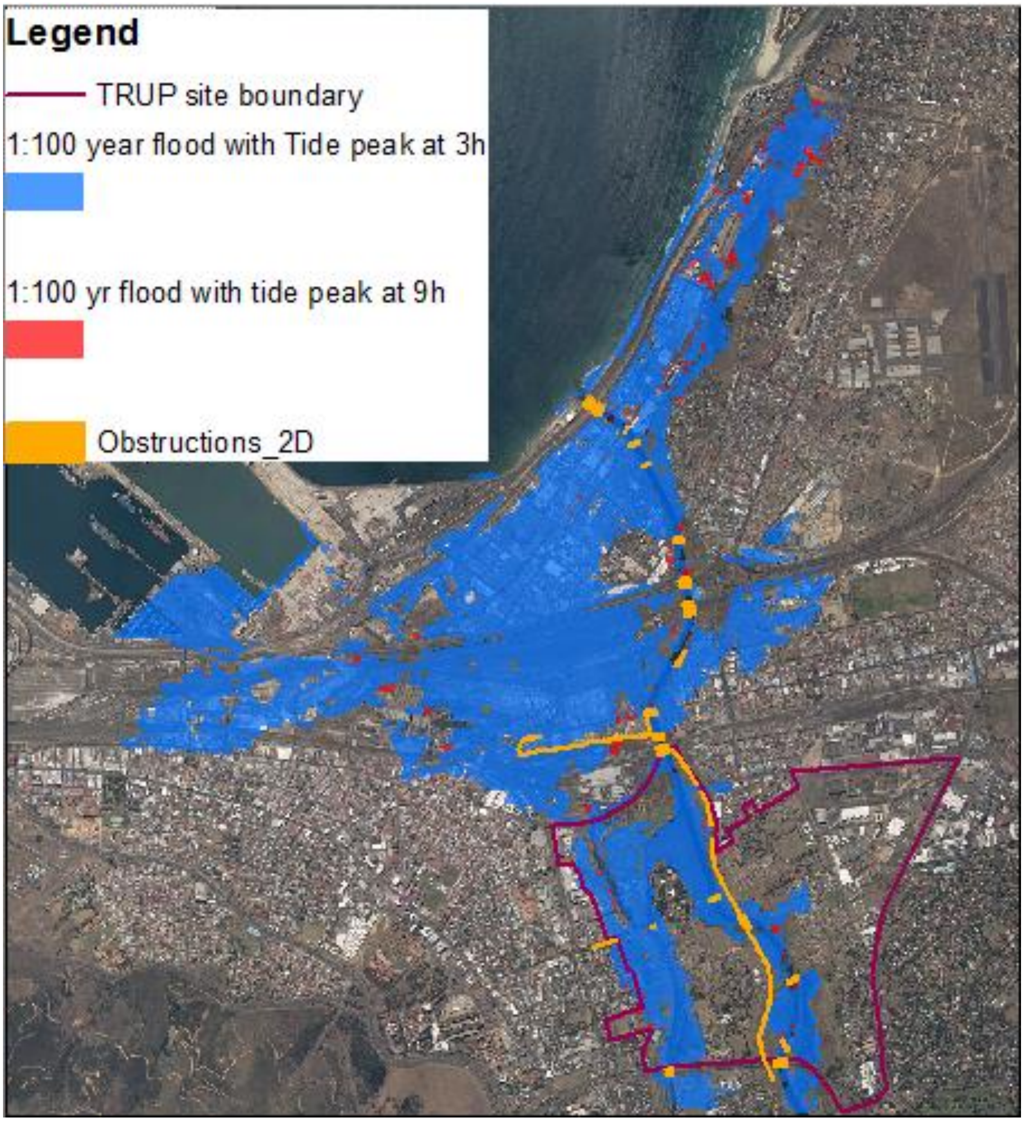

Figure 14: Effect of timing of tide on 1:100 year flood extents

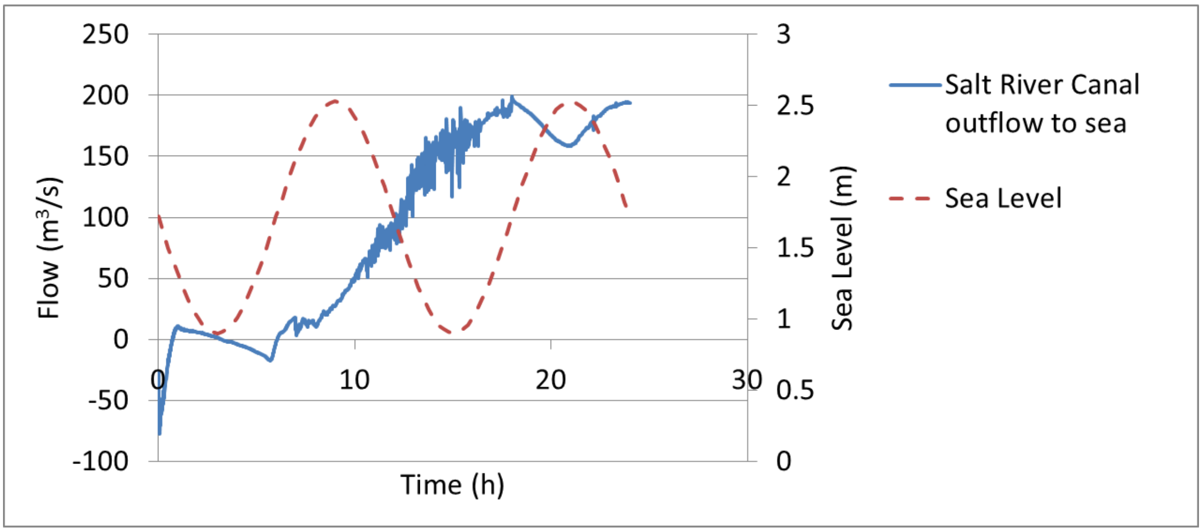

Figure 15: Predicted 1:100 year outflow to sea from the Salt River Canal for lowest tide coinciding with peak inflow

5.4 Sensitivity to upstream cross-sections

During preliminary runs, the Raapenberg Road was backing up floods from the Black River. This was investigated, and it was discovered that higher river bed levels in this area, taken from the cross-sections of SRK's original model, caused the backing up. The first surveyed cross-section was immediately upstream of the N2 Bridge, while the higher bed levels were several metres upstream of this. Knowing that these bed levels had not been surveyed, and seeing no reason why there would be higher bed levels in this area, these bed levels were lowered to an interpolated minimum level between that in the SRK model further upstream and the surveyed levels adjacent to the N2 bridge. This removed the backing up in this area.

6. Results

Predicted flood extents for the 1:10, 1:20, 1:50 and 1:100 years are included as Appendix A.

The following maps are included in Appendix A. Note that the maps are in pairs – one termed "*Modelled*" showing the entire area within which the model was revised and a larger scale map of *TRUP* only.

Map 1: Modelled flood extents for various return periods – with outline of proposed development - Scenario 6 superimposed (but not used in the model)

Map 2: TRUP flood extents for various return periods – with outline of proposed development – Scenario 6 superimposed (but not used in the model)

Map 3: Modelled flood extents for various return periods

Map 4: TRUP flood extents for various return periods

Map 5: Modelled flood extents for 1:10 year flood

Map 6: TRUP flood extents for 1:10 year flood

Map 7: Modelled flood extents for 1:20 year flood

Map 8: TRUP flood extents for 1:20 year flood

Map 9: Modelled flood extents for 1:50 year flood

Map 10: TRUP flood extents for 1:50 year flood

Map 11: Modelled flood extents for 1:100 year flood

Map 12: TRUP flood extents for 1:100 year flood

Flood extents within the TRUP area are essentially similar, but slightly less than those predicted by SRK (2012), except for the following areas which are now predicted to be flooded during the 1:10 year storm (see maps 5 and 6). Additional flooding in the following areas appears to be due to the capacity of the bulk stormwater network in this area being exceeded:

- Northern parts of Maitland Garden Village;
- The area around Eastman Road and between Berkley Road and Frere Road; and
- Hartleyvale Stadium along Liesbeek Parkway.

Note that in the first two of these areas, the upstream extent of the flooding is beyond the area which was modelled for 2D overland flow. The area modelled was as per the terms of reference only. The flooding along these paths is therefore not shown further upstream.

Another key difference is that most of the sports fields to the west of Liesbeek Parkway are not predicted to be flooded. However, after completion of the draft report, we received a report on a flood line study undertaken by AED (2016) which indicates surveyed levels which differ from those in our survey. A concern was raised that the exclusion of the sports field from the flood line may be due to the survey differences and the resulting raising of the LiDAR. The City of Cape Town have undertaken to do a further survey comparison in the area.

According to the 2D model, the river water only leaves the TRUP area through the Salt River Canal. The water flooding the PRASA depot is basically coming from the bulk stormwater network further to the west, except for direct flooding of a narrow strip along the bank of the Liesbeek.

The open area of the M5 / N2 interchange is mainly predicted to be flooded in the 1:20 year flood (see maps 7 and 8), but not in the 1:10 year flood (Maps 5 and 6). This area could therefore be used to provide flood attenuation storage.

Comparison with the development proposals for TRUP (as at 15 June 2016, when the modelling was undertaken) shows significant development within the floodplain, along both the Liesbeek and Black rivers.

Modelled flood hydrographs for the 1:10 year and 1:100 year floods are shown in Figure 16 and Figure 17 respectively. (Note that the 1:100 year hydrographs are based on a preliminary model with a time step of 0.3 s rather than the final model where the time step was reduced to 0.2 s.) Attenuation of the 1:100 year inflows within TRUP is predicted to be 24%, from a total inflow peak of 317 m^3/s to approximately 241 m^3/s. (The change in flow across-the TRUP area is a reduction in flood peak of 21%, which is made up of 4% local inflows less 24% attenuation.) Attenuation of inflows for the 1:10 year flood is estimated to be 9% from a peak total inflow of 193m^3/s to a peak outflow of 175 m^3/s. It is somewhat unusual that there is a greater percentage attenuation for the larger flood, but this can be explained by the additional flooded area providing attenuation storage. Instabilities are particularly visible on the outflow hydrographs.

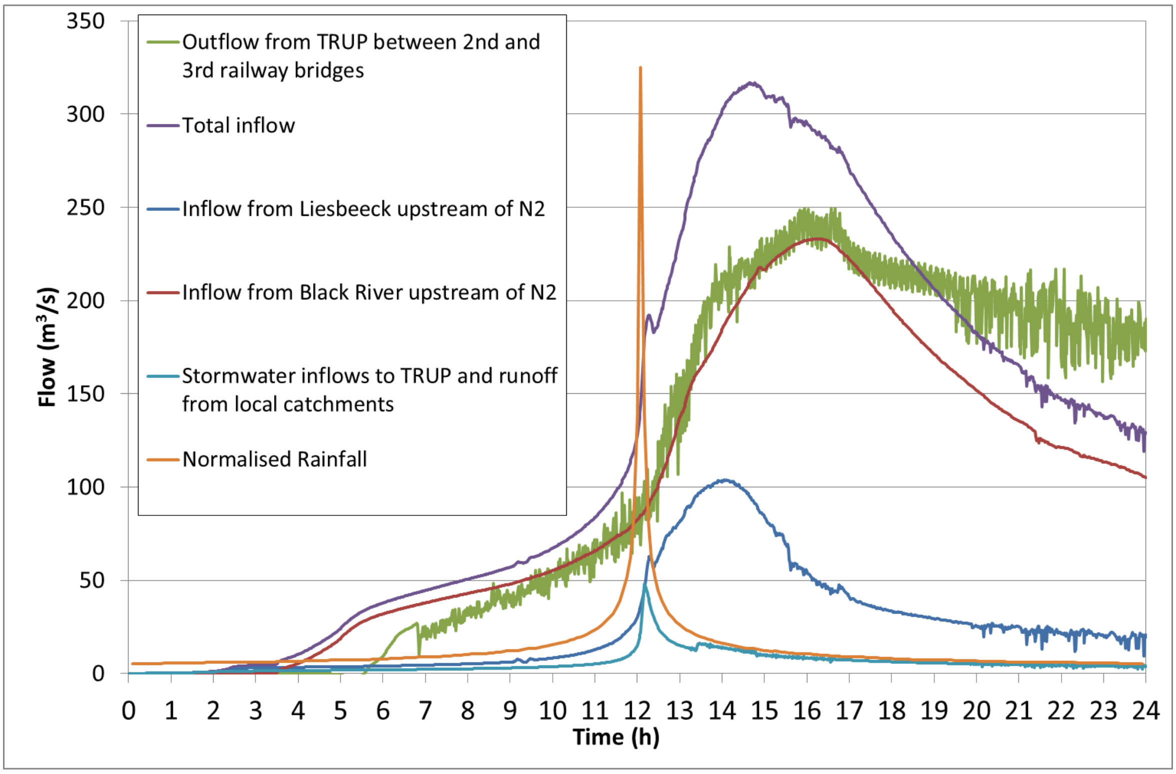

Figure 16: Modelled hydrographs for inflow from and outflow to TRUP for 1:100 year flood

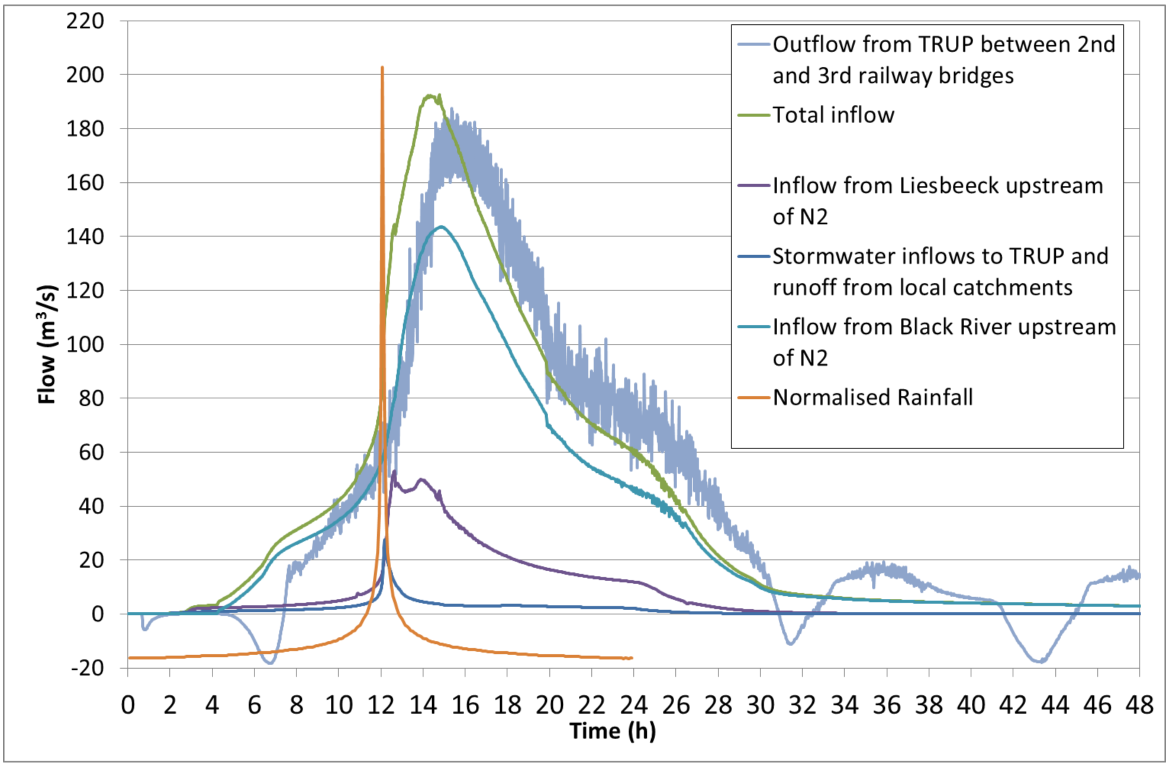

Figure 17: Modelled hydrographs for inflow from and outflow to TRUP for 1:10 year flood

Volumes under the 1:10 year hydrographs are compared in Table 7. Outflow volumes are slightly lower than inflow volumes because of water remaining in storage at the end of the 48 h simulation.

Table 7: Total flood volumes under the modelled 1:10 year hydrographs

Flow	Total Volume (thousand m³)
Liesbeek River Inflow to TRUP	1 357
Black River inflow to TRUP	5 559
Stormwater inflows to TRUP and runoff from local catchments	257
Total Inflow to TRUP	7 173
Total outflow from TRUP along Salt River Canal	6 929
Total outflow to along Salt River Canal to sea	6 499

7. Proposed scenarios for modelling in Task 2

As per the terms of reference, "*the service provider will be required to propose, agree and model further development scenarios in the area of interest, as well as flood mitigation interventions*".

Flood mitigation concepts are presented in Appendix B, and were discussed in detail during a workshop held on 05 May 2016. After a presentation by the flood modelling team, each participant was given the opportunity to rate up to five options as preferred for modelling and up to five options as not preferred. Participant ratings are also included in Appendix B, with the number of participants favouring each option in the green circles and the number of participants not preferring each option in the orange circles. Minutes are included in Appendix B.

The scenario modelled in Task 1 and described in this report was considered to be the base scenario.

It was decided to model the following options for the 1:100 year flood:

- The original request during the workshop of 05 May 2016 was to model widening of the bridges within and downstream of TRUP. However, it was discussed that an alternative which would be simpler to model would be the removal of the bridges, and modelling the removal of bridges was noted in the workshop minutes. However, this was again discussed between Ben de Wet and Peter Hirschowitz on 07 July 2016, and it was decided to go back to the original suggestion of modelling widening of the bridges within and downstream of TRUP, together with widening of the canal between the bridges.
- Planned developments within TRUP proposed by the design team in the drawing *Proposed_Development_TRUP Site 25-5-2016 JP.dwg* layout *Buildable areas floor area estimates* and identified in the drawing layer names as Scenario 6. The areas to be developed would be modelled as obstructions, and surrounding fill slopes would not be considered.
    - The impact of the planned developments would determine new modelled flood levels and the flood modelling team would feed back to the design team an indication of the storage that would be needed to compensate.
- Planned developments within TRUP as modelled above plus storage within the TRUP site in selected areas (still to be defined) adjacent to the Liesbeek and Black Rivers.
- Planned developments within TRUP as modelled above plus an alternative flood peak (still to be defined) in Liesbeek and Elsieskraal rivers assuming upstream storage capacity.

Following these initial runs, the River Study Group would decide on further runs or refinements required.

8. References

African Environmental Development (AED) (2016) *Flood line determination for the Salt and Liesbeek rivers at the Cape Town River Club*, Report Number AED0313/2015 Rev. 02.

SRK consulting (2012) Stormwater Infrastructure Asset Management Plan (Phase 2A) Rainfall Analysis and High Level Masterplanning: Salt River Catchment: Final Report: High Level Masterplanning. Report Number 403343/03, City of Cape Town.

Prestedge Retief Dresner Wijnberg (2010) City of Cape Town Climate Change Think Tank Marine/Freshwater Theme: Marine Inputs To Salt River Flood Model. Report No. 1063/1, City of Cape Town.