WATER RESOURCES OF SOUTH AFRICA, 2012 STUDY (WR2012)

Volume 6: SALMOD: Salinity modelling of the Upper Vaal, Middle Vaal and Lower Vaal sub-Water management Areas (new Vaal Water Managmeent Area)

CE Herold & AK Bailey

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WATER RESOURCES OF SOUTH AFRICA, 2012 STUDY (WR2012)

WR2012 SALMOD: Salinity Modelling of the Upper Vaal, Middle Vaal and Lower Vaal sub-Water Management Areas (new Vaal Water Management Area)

Report to the
Water Research Commission

by

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This report forms part of a series of nine reports. The reports are:

1. WR2012 Executive Summary (WRC Report No. TT 683/16)
2. WR2012 User Guide (WRC Report No. TT 684/16)
3. WR2012 Book of Maps (WRC Report No. TT 685/16)
4. WR2012 Calibration Accuracy (WRC Report No TT 686/16)
5. WR2012 SAMI Groundwater module: Verification Studies, Default Parameters and Calibration Guide (WRC Report No. TT 687/16)
6. **WR2012 SALMOD: Salinity Modelling of the Upper Vaal, Middle Vaal and Lower Vaal sub-Water Management Areas (new Vaal Water Management Area) (WRC Report No. TT 688/16 – this report)**
7. WRSM/Pitman User Manual (WRC Report No. TT 689/16)
8. WRSM/Pitman Theory Manual (WRC Report No. TT 690/16)
9. WRSM/Pitman Programmer's Code Manual WRC Report No. TT 691/16)

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Acronym List

CR	Channel reach module in SALMOD
C2H066	Flow and water quality gauging station at a weir with letter H (example of)
C9R001	Flow and water quality gauging station at a dam with letter R (example of)
FIR	Irrigation return flow factor
MCM	Million cubic metres
mg/ℓ	milligram/litre
N	number of samples
PWV	Pretoria, Witwatersrand and Vereeniging
RR	Irrigation module in SALMOD
RV	Reservoir module in SALMOD
SALMOD	Salinity Model
Sub-WMA	The old Upper Vaal WMA is now called the Upper Vaal sub-WMA as it now forms part of the new Vaal WMA. Similarly for the Middle Vaal and Lower Vaal
SW	Salt washoff module in SALMOD
t	tons
TDS	Total Dissolved Solids
VRSAU	Vaal River System Analysis Update Study
WMA	Water Management Area
WR2005	Water Resources of South Africa, 2005 Study
WRSM/Pitman	Water Resources Simulation Model (Pitman model)

Statistical parameters are described in detail in section 4.2

Executive Summary

In the WR2005 study, certain key catchments were analysed in the Upper Vaal WMA with a model called SALMOD which was developed by Dr Chris Herold. In this WR2012 study, it was decided that due to the intense level of development in the Vaal River catchment, it would be very valuable to analyse the entire Upper Vaal, Middle Vaal and Lower Vaal sub- Water Management areas (sub-WMAs) which have now been combined into the Vaal WMA. This would help in further improving the implementation of the Integrated Water Quality Management Plan for the Vaal River System (Zitholele et al, 2009).

SALMOD uses the WRSM/Pitman model output files together with other information that is required to analyse flow, Total Dissolved Solids (TDS) concentration and TDS load. Calibration is done by means of three parameters and by varying the growth or decline in return flow. The SALMOD model produces both statistical indicators of flow, TDS concentration and TDS load as well as graphs of these parameters to aid the user in achieving a successful calibration. Observed TDS concentration was obtained up to September 2010 from the Institute of Water Quality Studies.

This report gives a detailed analysis of flow, TDS concentration and TDS load at all the relevant water quality stations throughout the Upper, Middle and Lower Vaal sub-WMAs. It includes insights gained from many years of experience in analysing water quality in the Vaal River catchment in comments about each tertiary catchment.

Maps and schematic diagrams of each WMA have been provided in the main report. In addition the SALMOD network diagrams for each tertiary catchment have been provided in the appendices.

In some catchments it was extremely difficult to obtain an accurate calibration. This was due to the fact that there was limited data readily available on mine and industrial effluent return in particular and also due to unknown riverbed seepage and changes in irrigation. Therefore some of it has had to be estimated. There is also a greater level of detail required for these catchments which would have to be incorporated into WRSM/Pitman in order to get greater insight into water quality issues. Both of these issues were beyond the limited scope of budget for this study.

The final results at key stations were compared with the Vaal River System Analysis Update Study which used a record period of 1975 to 1994 (see Table below).

Comparison of flow, TDS and load at key points in the Vaal catchment for this study and the VRSAU study.

WMA	Key point	WR2012 Start-End	VRSAU Start-End	Flow (million m³/month)		TDS Concentration (mg/ℓ)		TDS Load (tons/month)	
				WR2012	VRSAU	***WR2012***	VRSAU	***WR2012***	VRSAU
Upper Vaal	Grootdraai Dam (C1R002/ C1H019)	1995/2009 (C1H019)	1975-1994 (C1R002)	***47.1*** ***41.0***	19.2 19.5	***178.0*** ***176.9***	164.1 159.5	***7 985.0*** ***7 770.0***	3 410.4 3 331.4
Upper Vaal	Vaal Dam (C1R001/ C2H122)	1975-2009 (C2H122)	1975-1994 (C1R001)	***101.5*** ***119.0***	120.4 121.5	***149.3*** ***174.1***	140.8 142.7	***16 248.0*** ***22 100.0***	16 367.8 16 360.2
Upper Vaal	Vaal Barrage (C2R008/ C2H018)	1975-2009 (C2H018)	1975-1994 (C2R008)	***136.5*** ***126.9***	88.6 87.5	***490.4*** ***492.5***	476.4 519.2	***39 983.0*** ***37 342.0***	26 735.1 26 720.5
Middle Vaal	C2H018/ C2H007	1978-2009 (C2H007)	1975-1994 (C2H018)	***136.5*** ***139.5***	90.6 92.3	***553.1*** ***535.4***	501.2 508.3	***46 581.0*** ***44 389.0***	28 562.6 28 786.5
Middle Vaal	C4H004	1977-2009	1985-1994	***17.89*** ***17.07***	24.47 24.8	***300.8*** ***397.5***	276.6 277.8	***5 080.0*** ***4 816.0***	6 128.4 7 077.3
Middle Vaal	Bloemhof Dam (C9R002)	1977-2007	1975-1994	***141.89*** ***139.40***	137.5 139.1	***387.4*** ***392.3***	381.8 482.2	***42 208*** ***41 188***	44 661.9 45 585.0
Lower Vaal	Vaalharts Weir (C9H009)	1975-2006	1974-1994	***116.07*** ***112.24***	134.9 147.2	***393.5*** ***384.5***	387.2 397.3	***30 380*** ***28 428***	37 959.2 45 888.9
Lower Vaal	Douglas Weir (C9R003)	1977-2009	1974-1994	***109.74*** ***130.35***	27.6 150.9	***501.4*** ***347.0***	570.2 603.3	***37 540.0*** ***42 269.0***	9 317.2 44 407.1

Note: **Red** is observed and **blue** is simulated.

The differences between the VRSAU study and the WR2012 study are discussed in this report. The differences are attributable to the period 1994 to 2010 being wetter than the 1980's, the changed operation by Rand Water of the Vaal supply scheme, the introduction of dilution management and increased irrigation in the Vaalharts scheme.

Although SALMOD analyses are less detailed than the WQT model, the analyses described in this report as modelled by SALMOD are extremely useful for assessing incremental catchment salt export. As with all models, greater accuracy would be obtained with the SALMOD analyses with a more detailed investigation into some land use aspects such as return flow, irrigation, riverbed seepage and channel surface evaporation to improve on this data. These SALMOD analyses also showed consistent results with what was expected based on Dr Chris Herold's experience with water quality of the Vaal catchment. The report does not only discuss the set up of the model and its calibration for the Vaal sub-catchments, it also adds value in that it is a reflection of the experience with salinity in the Vaal catchments, particularly the experience of Dr Chris Herold.

This report and model can therefore be of key importance in the evaluation, monitoring and further improvement of the Vaal Quality Management Strategy for the Vaal catchments.

1 Introduction

In contrast to other deliverables of the Water Resources 2012 study, this water quality study does not cover the whole of South Africa, Swaziland and Lesotho, but only the Vaal River System. The Vaal River system is considered to be the most important water resource system in South Africa as it provides water to more than an estimated 40% of the country's inhabitants and, with numerous industries and mines in the supply area, the management of these water resources is vital. Water quality is a major concern in the Vaal River system owing to the high number of inhabitants and developments with regard to industrial and/or mining activities. In this study of water quality modelling the focus has been on salinity, i.e. the simulation of TDS, as this has been recognised as the most serious water quality problem facing the Vaal river system owing to development.

Objective
This report updates and improves the salt modelling of the Vaal WMA, combining hydrology with salt modelling up to 2009. As a follow up, this model can provide very useful insights that can serve to improve the implementation of the Integrated Water Quality Management Plan for the Vaal River System.

The water quality modelling was done with SALMOD which is a monthly time step quaternary scale TDS model, which was developed for "what if" scenarios by simply changing default input parameter values. This is regarded as sufficiently accurate and simple for the needs of the national scale Water Resources series reports. SALMOD is an acronym for SALinity MODelling, which was developed by Dr Chris Herold.[1]

The first salinity model for the Vaal was set up as part of the Vaal River System Analysis Update Study (VRSAU) (DWAF, 1998), with the WQT salinity model, also developed by Dr Chris Herold, which is a more complex and detailed model albeit more difficult to calibrate than the SALMOD model. The WQT model has not been calibrated since the VRSAU Study.

In the study prior to WR2012 (WR2005), some key catchments were analysed using SALMOD. In the Upper Vaal sub-Water Management Area (sub-WMA), only the C21 and C22 tertiaries and a small part of the C12 tertiary were analysed in WR2005. No catchments were analysed in the Middle Vaal and Lower Vaal sub-WMAs in WR2005.

As part of the Development of an Integrated Water Quality Management Plan of the Vaal River System for the Department of Water and Sanitation (then Water Affairs and Forestry), which was finalized in 2009 (Directorate National Water Resources Planning, 2009), using the salt water component of the Water Resources Planning Model (WRPM). The difference with the current WR2012 study is that the record period has been extended to September 2010 and SALMOD does not require extensive calibration.

The objective of this WR2012 study was to extend the analysis of WR2005 to the entire Upper Vaal, Middle Vaal and Lower Vaal sub-WMAs (currently called the Vaal WMA, see Figure 1) and add an additional 5 years onto the calibration period. The total period of calibration is therefore from 1974 to 2009 hydrological years, taking into account all new catchment developments that may have affected the water quality in the study area and to compare this against recorded data.

[1] This model is not to be confused with the model with the same name SALMOD, which is the Salinity and Leaching Model for Optimal irrigation Development, also developed for the Water Research Commission (R. J. Armour & M. F. Viljoen, 2002) and also applied in the Vaal catchment.

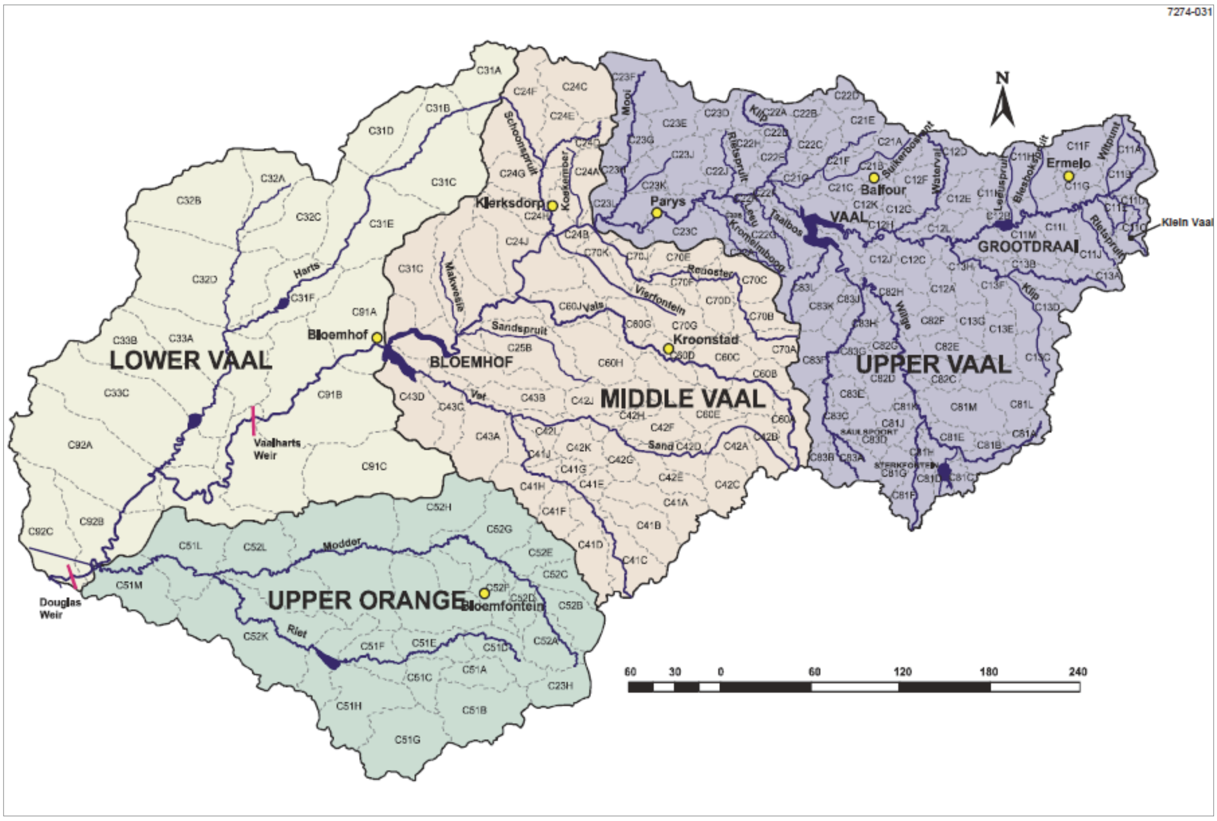

Figure 1.1: Vaal (and Upper Orange) catchment overview of quaternary catchments (Ref. Zitholele et al, 2009, P RSA C000/00/2305/3)

As can be seen from Figure 1.1, the C51 and C52 tertiaries provide inflow to the downstream end of the Lower Vaal sub-WMA, however, SALMOD modelling of these tertiaries was beyond the scope of this study.

SALMOD provides WR2012 with a means of simulating monthly time series of flow, TDS concentrations and load at water quality gauging stations. In WR2005 Mr Grant Nyland produced a version of SALMOD that provided enhanced graphics features which has now been used in this WR2012 study. This version of the model is particularly useful in plotting graphs and has features for zooming, panning, copying into reports, etc.

2 Model Description

The hydrology of the study area was simulated using the WRSM/Pitman monthly time step hydrological model as part of the WR2012 study up to the 2009 hydrological year.

SALMOD is comprised of system nodes connected by routes, which have a similar structure to that of the WRSM/Pitman hydrological model. Information regarding the model structure, algorithms, data requirements and operating instructions are detailed in the salt balance model manual (Herold, 2011). All linkages, the solution order, the inflow and outflow routes and time series input data files are defined via the system nodes. The nodes are numbered by the user. This model includes the following nodes:

Salt Washoff (SW) module:	this node contains algorithms to generate a monthly TDS time series using flow time series input files;
Channel Reach (CR) module:	this node serves to combine upstream inflows and routes them to downstream nodes (includes channel bed losses, wetland storage/bed losses, mining and industrial effluent, inflow from upstream catchments;
Irrigation (RR) module:	this node simulates the TDS outflow as a proportion of TDS inflow of the total irrigated area;
Reservoir (RV) module:	this node simulates the TDS outflow as a proportion of the TDS stored in the reservoirs of the catchment.

Thus the model system configuration is defined as a set of nodes (i.e. SW, CR, RR and RV defined above) linked by the flow links called routes.

3 Scope of the Report

The catchments and the respective monitoring gauging stations are listed in Table 3.1.

Table 3.1: Catchments and gauging stations

Tertiary Catchment	Main River	Gauging Station
Upper Vaal		
C11	Vaal	C1H007
	Blesbokspruit	C1H006
	Vaal	C1R002
	Vaal	C1H019
C12	Klipspruit	C1H004
	Vaal	C1H012
	Vaal	C1R001
	Vaal	C2H122
C13	Klip	C1H002
C81	Oubergspruit	C8H010
	Klerkspruit	C8H006
	Elands	C8H011
	Vaalbankspruit	C8H012
C82	Cornelis	C8H003
	Wilge	C8H014
	Wilge	C8H027
C83	Liebenbergsvlei	C8H007
	Liebenbergsvlei	C8H004
	Liebenbergsvlei	C8H026
	Wilge	C8H022
C21	Rand Water weir	B10
	Suikerbosrand	C2H070
	Suikerbosrand	C2H004
C22	Klip	C2H021
	Klip	C2H141
	Vaal	BAROUT
C23	Wonderfonteinspruit	C2H069 (not used)
	Loopspruit	C2R005
	Mooi	C2R003 (not used)
	Mooi	C2R001 (not used)
	Mooi	C2H085
	Vaal	C2H008/C2H140
	Vaal	C2H018

Tertiary Catchment	Main River	Gauging Station
Middle Vaal		
C70	Rhenoster	C7R001
	Rhenoster	C7H006
C24	Rietspruit	C2R007
	Vaal	C2H007 (not used)
	Rietspruit	C2R006 (not used)
	Skoonspruit	C2H073
C60	Vals	C6H007 (Serfontein Dam)
	Vals	C6H001
	Vals	C6H003
C41	Vet	C4R002 (Erfenis Dam)
C42	Sand	C4R001 (Allemanskraal Dam)
C43	Sand	C4H004
C25	Vaal	C2H061
	Vaal	C2H066 (not used)
	Vaal	C2H067(not used)
Lower Vaal		
C31	Harts	C3R001 (Wentzel Dam)
		C3H003
C32	Dry Harts	None
C33	Harts	C3H007
		C3H013 (d/s Spitskop Dam)
C91	Vaal	C9H021 (d/s Bloemhof Dam)
		C9R001 (d/s Vaalharts Weir)
		C9H009
C92	Vaal	C9R003 (Douglas Weir)

4 SALMOD Calibration Assumptions and Procedures

The WRSM/Pitman model set up was taken for each tertiary catchment and modified to use in SALMOD. Modifications related mainly to the inclusion of salt. Simulated flows from WRSM/Pitman were used in SALMOD for each Salt Washoff module. The following had to be done:

- ***Creating Salt Washoff modules*** - Runoff modules were converted to Salt Washoff modules;
- ***Creating new network diagrams*** - The networks of catchments in WRSM/Pitman, were modified to show to show outflows from Runoff modules in dotted lines without a route number as these are not required in SALMOD;
- ***Creating flow and TDS files*** - Both flow and TDS files needed to be created at observation points as text (*.txt) files from the models. The naming configuration used is the tertiary (e.g. C32) and related channel reach (e.g. 004) and CQ for flow files (Mm³/month) or CC for concentration files (TDS in mg/ℓ) which gives C32004CQ.TXT or C32004CC.TXT. Note that in WRSM/Pitman flow is calibrated on the inflow record to a dam. In SALMOD one needs to analyse the outflow from the dam as this is where TDS concentration is measured and with load obtained by multiplying the two, it is important to measure flow and TDS from the dam outflow. Observation points need both the flow and TDS files at those points;
- ***Creating abstraction points*** - In the case of an abstraction, SALMOD needs to have a dummy Reservoir node with zero storage – as if it is a channel. The supply file from WRSM/Pitman gives the actual abstraction and should therefore be used and not the demand file (which may not be met). In some cases a WRSM/Pitman channel reach had to be changed to a dummy dam to facilitate the abstraction;
- ***Taking account of riverbed seepage*** - In some cases there are riverbed seepages from channel reaches due to water losses. In the Vaal River catchment this occurs in dolomitic areas. They have been shown in the SALMOD network diagrams with a green fill. There are two methods of allowing for riverbed seepage, either as channel seepage (as was done for the WR2005 study with channel riverbed seepage – the modelling term for riverbed seepage) or by changing to a reservoir module and determining from WRSM/Pitman what was abstracted as a riverbed seepage. At a reservoir module, WRSM/Pitman input files that give the inflow are added and files that give the outflow are added, and outflow and inflow are subtracted to get the balance at the node. These are taken into account in SALMOD using time series outflow files. The maximum river bed seepages in Table 4.1 were derived in WRSM/Pitman. In the outflow file WRSM/Pitman will only provide the flow that is available, therefore the flow that it provides in each month of the record period is then used in SALMOD;

Table 4.1: Catchments and riverbed seepage and wetlands storage volume

Tertiary Catchment	**Main River**	**Quaternary Catchment**	**WRSM/Pitman maximum river bed seepage** (million m³/month)	**Wetland storage volume** (million m³)
<u>Upper Vaal</u>				
C21		C21D	0.73	1.80
		C21E	0.18	9.35
		C21F		0.10
C22	Klip	C22A		5.40
		C22B	0.13	3.95
C23	Mooi	C23B	1.16	
		C23C	2.30	
		C23L	2.08	

Tertiary Catchment	Main River	Quaternary Catchment	**WRSM/Pitman maximum river bed seepage** (million m³/month)	**Wetland storage volume** (million m³)
Middle Vaal				
C24	Rietspruit	C24B	1.83	
		C24J	3.42	
C25	Vaal	C25C	6.67	
Lower Vaal				
C91	Vaal	C91B	4.83	
		C91D	3.17	
		C91E	0.18	
C92	Vaal	C92A	2.17	
		C92B	2.17	
		C92C	0.50	

- ***Estimating wetlands storage volumes*** - Wetlands storage volumes were estimated for the Upper Vaal as presented in Table 4.1. These wetlands were taken into account in SALMOD using Channel Reach Storage datafiles. They are also shown on the network diagrams in green with the wetland file name next to the relevant channel;
- ***Creating inputs for flow and TDS*** - TDS files were compiled for the inflow points. Water quality (TDS) data was obtained from the Department of Water and Sanitation (IWQS, Ms Marica Erasmus). An in-house model called AVEMON was used to extract the TDS data for the appropriate station into a monthly time series. Where TDS files are used as observed stations, missing values were left at -1.00. The same applies to missing streamflow values in the observed streamflow files. If the missing values are set at -1.0, then the statistics are unaffected by these values. If TDS and streamflow datafiles are used as input to a node, then the missing values must be patched and the -1.00's replaced. The in-house program TDSPAT was used to patch TDS inflow files. The streamflow datafiles were patched during the hydrological analysis. Inflows required both flow and TDS files whereas abstractions only require a flow file since the TDS is calculated;
- ***Creating inputs for abstraction, return flow and storage time series*** - Reservoir storage time series (e.g. "C24RV2.ANS"), irrigation supply (e.g. "C24RQ1.ANS") and return flow time series (e.g. "C24RQ2.ANS") and simulated flow (with land use included) time series were taken from WRSM2000 (e.g. "C24RQ1.MTS") and used as input to SALMOD, i.e. SALMOD works with data already determined by WRSM2000 for flow;
- ***WMA 13 inclusion*** - The C51 catchment was beyond the scope of this study as it is in the Upper Orange WMA. Accordingly, flow from C51 into C92 was taken from the WR2012 study and TDS was taken from combining water quality stations C5H016 and C5H048 which are in close proximity to each other just upstream of Douglas Weir. All other inflows from upstream systems are simulated flow and TDS from SALMOD; and
- ***Creating SALMOD set-up files and calibration*** - SALMOD set-up files were determined for each tertiary (C11.TXT for example). The output file in all cases was set as "TEMP.TXT". The order of defining nodes and the node details has to be the same and must be in a practical order of solution. When the TDS of incoming flows is unknown, a default value for effluent flows was assigned for every month (generally 320 mg/ℓ, based on knowledge of the study area). Where the average return flow concentration was known, this value was put in. The start year for analysis was taken as 1974 as this is about the time that TDS data became generally available. The end year was 2009 in line with the WRSM2000 analysis. The minimum and maximum starting TDS values were given for all Salt Washoff modules and were adjusted (along with a parameter that affects growth over time "A") to get a good fit between observed and simulated values. An example of a SALMOD set-up file (C92.TXT) is given in Appendix B.

Even if there is a dam or streamflow gauge at the end of a tertiary, simulated flows and TDS values were used throughout from one tertiary to the next, rather than correcting from the observation point for downstream calibration. In some systems there were slight negative salt loads at some nodes that arose due to the upstream inflow being fractionally less than the outflow. In these cases the abstraction to irrigation was slightly reduced to overcome the negative balance.

Abstractions and return flows that take place at industries, municipalities or mines ideally would require modelling through a feedback loop. A feedback loop can be defined as the water that is abstracted from a tributary and returned to the same tributary as effluent. The effluent returned would normally exhibit higher TDS concentrations due to the effects of the water use. Unfortunately the limited number of routes and files allowed in SALMOD does not allow modelling to the same level of complexity as the real system. SALMOD represents the system by lumping together river reaches and irrigation areas. The disadvantage of lumping the system into a single node is that the model allows underperformances. For example, irrigation nodes could have access to either too much or too little water or the mixing may be misrepresented.

Calibrating was done by manipulating the “cmin”, “cmax” and “A” parameters in each slat washoff module, i.e. in each quaternary catchment and examining the statistics and graphs that are shown for each water quality station later in this report. In some catchments growth factors were also required (as dealt with in the next paragraph) with regard to return flows and these factors affected the calibration. The “cmin” and “cmax” parameters defined an upper and lower limit range for concentration. The “A’ parameter can range from 0.1 to 1.0, the lower the value the more load is moved into the peak values. Further details can be found in Herold and Nyland, 2011 which details the work covered in the R2005 Study.

Table 4.2 shows the values used in the tertiary catchments.

Table 4.2: Calibration parameters “cmin”, “cmax” and “A” values

Tertiary Catchments	Quaternary Catchments	“cmin” (mg/ℓ)	“cmax” (mg/ℓ)	“A”
Upper Vaal				
C11	all SWs	120	600	0.9
C12	all SWs	240	14550	0.9
C13	all SWs	92	325	0.3
C21	all SWs	10	50	0.5
C22	C22A to C22D	150	200	0.5
	C22E to C22F and C22H, C22K	200	300	0.5
	C22G and C22J	100	200	0.5
C23	C22A to C22C	20	500	0.9
	C23D and C23E, C23G	210	500	0.2
	C23F	110	400	0.2
	C23H to C23L	170	700	0.2
C81	C81A to C81D	65	300	0.5
	C81E	120	400	0.5
	C81F, C81H	140	500	0.5
	C81G	70	120	0.2
	C81J	200	500	0.9
	C981K	200	400	0.5

Tertiary Catchments	Quaternary Catchments	"cmin" (mg/ℓ)	"cmax" (mg/ℓ)	"A"
	C81L	100	400	0.5
	C81M	200	500	0.5
C82	C81A	180	600	0.9
	C81B	50	400	0.9
	C81C	30	500	0.9
	C81D to C82H	200	900	0.9
C83	C83A	150	500	0.9
	C83B	160	700	0.9
	C83C to A83F	170	700	0.9
	C83G to C83M	190	800	0.9
Middle Vaal				
C24	C24A and C24B	300	1550	0.9
	C24C to C24J	210	2000	0.9
C25	C25A to C25C	120	500	0.9
	C25D to C25F	140	620	0.9
C41	all SWs	100	200	0.9
C42	C42A to C42H and C42L	100	300	0.9
	C42J	1400	1500	0.1
	C42K	750	800	0.1
C43	C43A to C43B	100	150	0.9
	C43C to C43D	100	300	0.9
C60	C60A to C60D	200	300	0.9
	C60E to C60H	240	1550	0.5
C70	C70A to C70C	85	400	0.5
	C70D to C70K	170	400	0.2
Lower Vaal				
C31	C31A to C31E	140	600	0.5
	C31F	300	900	0.5
C32	all SWs	140	900	0.9
C33	all SWs	200	800	0.2
C91	C91A and C91B	300	500	0.2
	C91C to C91E	500	600	0.2
C92	all SWs	100	800	0.5

The growth in diffuse source salt generation has a significant effect on input TDS concentration in the study area due to the growth in urban and industrial development. The reliability in the prediction of diffuse salt generation depends on reasonable estimation of the historical salt generation rates. Further complications arise from the fact that the catchment areas display very long lag times, thus if there is an increase with regard to the establishment of urbanisation or industry, the full increase in the TDS concentration would only be attained many years later. The catchment's salt recharge is a function of both the calibrated starting recharge rate and the historical annual growth rates. In SALMOD the recharge rates are dependent of the annual growth rate factors. Hence, by changing the annual growth rate factors this will allow the predetermined recharge rates to reflect and implicitly account for a different set of calibrated initial salt recharge rates.

Regarding the SALMOD output, the parameters in the tables have the following meaning:

- Mean : Sample mean (measure of the average of the sample)
- Std Dev : Sample standard deviation (measure of the maximum and minimum deviations from the average)
- N : Sample size
- R : Linear correlation (measure of the deviation of the modelled from the observed).
- E1 : Error between modelled and observed means (%)
- E2 : Error between modelled and observed standard deviations (%)
- SF : Significance factor (measure of how well the observed sample represents the full record. Calculated by comparing the modelled mean and the standard deviation for the sample for which observed values are available).
-

Table 4.3: Example table with descriptions

Route 6CR: C1H007 1976 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	28.26	27.58	198.9	199.6	4605.	4475.
Std.Dev.	49.14	46.19	85.2	66.1	6601.	6411.
R	**.8041**		**.7426**		**.8073**	
E1	**-2.4%**		**.4%**		**-2.8%**	
E2	**-6.0%**		**-22.4%**		**-2.9%**	
N	**408**		**354**		**354**	
SF	**1.000**		**.986**		**.991**	
Mean	**27.6**		**205.6**		**4362.5**	
Std.Dev.	**46.2**		**67.8**		**6345.1**	
N	**408**		**408**		**408**	

Note: In red the observed and modelled statistical values where both values exist
In **blue** the statistical parameters taking observed and modelled into account
In **green** the Significance Factor takes into account the modelled values using the full sample (408 months) and the modelled values using only the available values (354 months) as explained above.
In **orange** the statistical parameters for the modelled over the full period (1976 to 2009, i.e. 408 months)

Note on data:

While every effort was taken in the WRSM2000 hydrological part of the WR2012 study to obtain updated rainfall, observed streamflow, reservoir records, water quality and readily available land use/water use data, in some cases data had to be extended (set equal to previous years) due to lack of data. This is generally the case with mine effluent data and due to this, some catchments were extremely difficult to calibrate and the comparisons between simulated and observed were not as good as was hoped for. There were also a few instances of enhancements to network diagrams for the SALMOD analysis that were too late to include in the hydrological analysis which was completed about a year earlier. These enhancements have been noted and will be made to the hydrological analysis in future analyses. A facility was also developed in WRSM/Pitman to compare the observed and simulated storage in a reservoir but this was only available after the hydrological analysis was completed. For future calibrations using WRSM/Pitman at reservoirs, it will therefore be desirable to use calculated inflow to the reservoir (as calculated from the Reservoir Record) and reservoir storages, rather than only relying only on inflow to the reservoir. For SALMOD calibration however, TDS concentration should be used together with outflow from reservoirs for calibration. Spills for reservoirs were obtained from the DWS website. Water quality considerations also give a good check on the hydrological results.

5 Upper Vaal sub-WMA

For the Upper Vaal sub-WMA, the map shown in Figures 5.1 shows the water quality stations in the catchment.

In the case of C13, C21 and C22, these three tertiaries were previously analysed in the WR2005 study whereas the other tertiaries were analysed for the first time. In this WR2012 study, for C13, C21 and C22, diffuse source growth factors were set for various years, due to the fact that the return flows change considerably over time.

The SALMOD schematic for the Upper Vaal shown in Figure 5.2 indicates how the tertiaries link together and the flow and TDS files used in downstream systems.

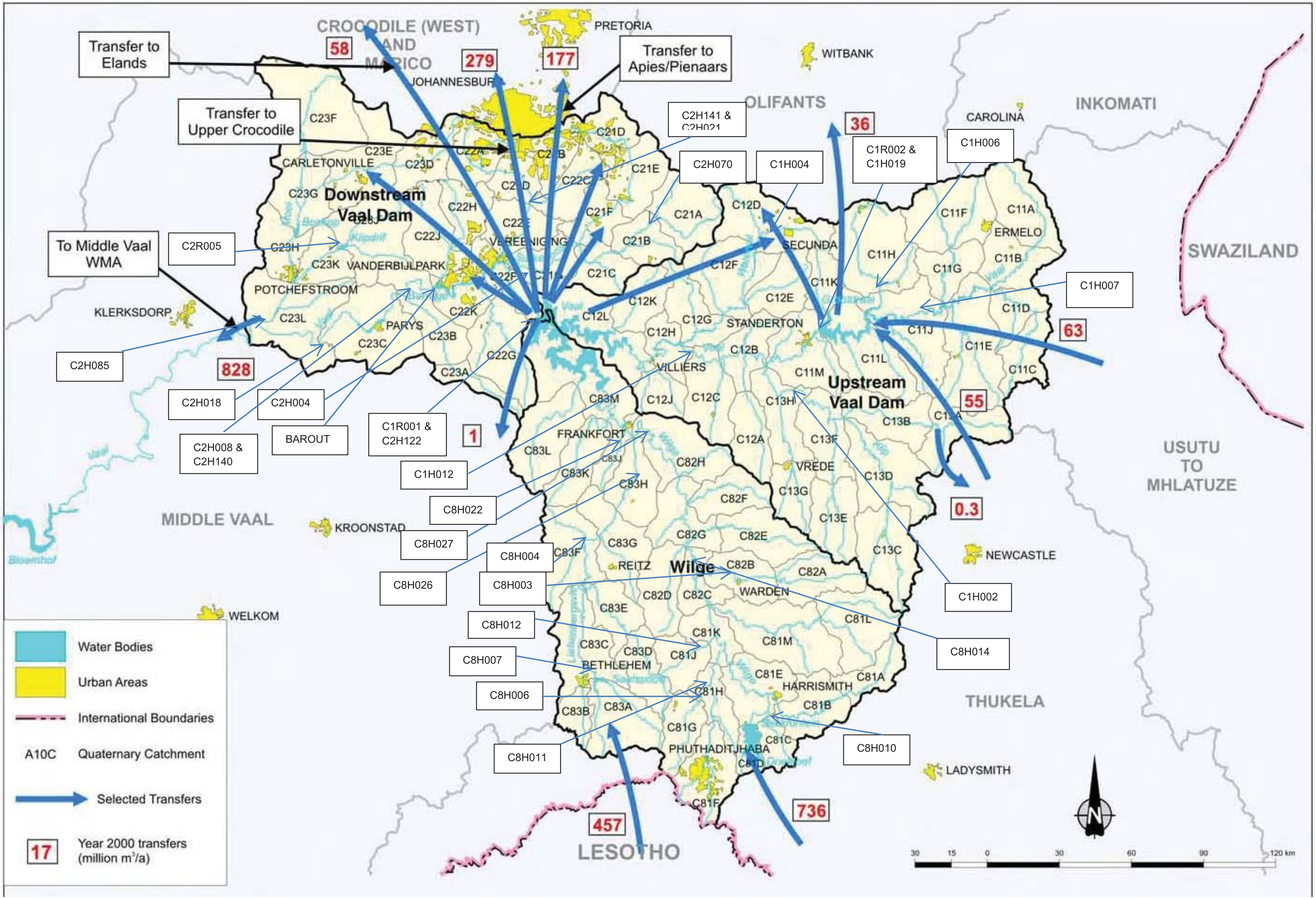

Figure 5.1: Water quality stations in the Upper Vaal sub-WMA. (Ref. BKS, 2003: P WMA 09/000/00/0203 - with water quality stations added)

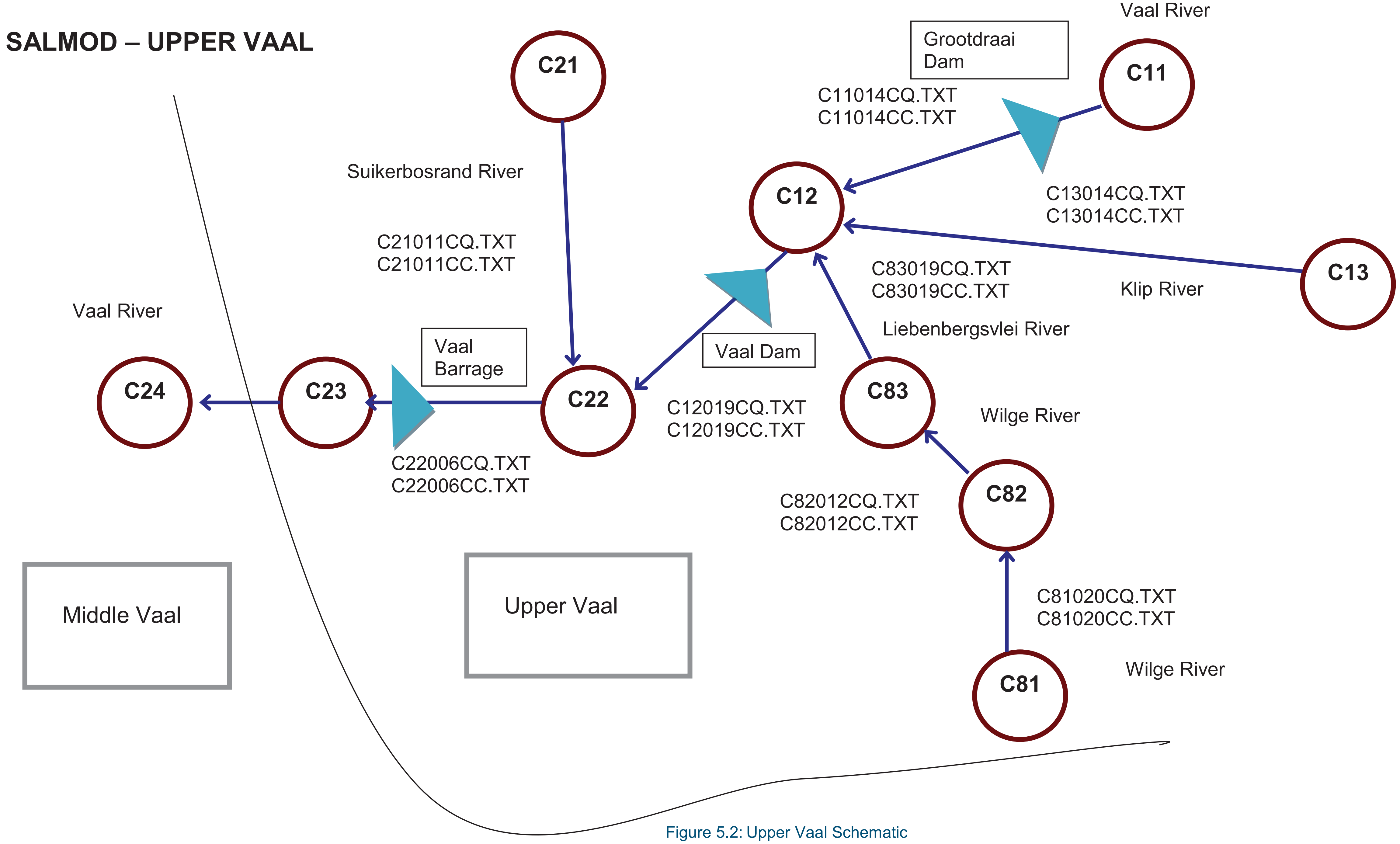

Figure 5.2: Upper Vaal Schematic

5.1 Growth in diffuse source salt generation

The estimated recharge growth rate factors are depicted in the Table 5.1 below. The estimation of the assumed growth rate factors were based on the following:

- 1920 to 1995 growth rate factors as per Table 2.1 of report of PC000/00/18196 Vaal River System Update study (Department of Water Affairs and Forestry, 1998);
- PWV abstractions by Rand Water and industrial users around Vaal Barrage (mainly Eskom, Sasol1 and Iscor) as data used in this study and supplied by those users; and
- 2000 and 2005 projections based on the assumption that growth in diffuse source generation is proportional to industrial water consumption, which is approximately proportional to total water consumption. (This could change as the industrial proportion of municipal use changes. The mix of industries could also change over time).

Table 5.1: Estimated annual salt recharge rate

Year	Growth factor per sub catchment							PWV abstraction (10^6 m³/year)			
	Blesbok	Suiker-bos	Upper Klip	Lower Klip	Riet-spruit	Barrage	Total	Barup	Bard-own	Vdam	Total
1920	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.00	0.00	0.00	0.00
1938	1.091	1.000	1.056	1.085	1.014	1.334	1.101	0.00	67.15	0.00	67.15
1957	1.365	1.000	1.293	1.436	1.213	2.960	1.485	85.86	202.04	0.00	287.90
1970	1.849	1.000	1.546	1.781	1.592	4.004	1.851	89.46	154.07	227.30	470.83
1980	2.282	1.000	1.816	1.884	1.827	4.045	2.066	376.64	203.40	299.10	879.14
1990	2.810	1.000	1.944	2.178	2.068	4.713	2.309	325.25	61.91	624.13	1011.29
1995	3.084	1.000	2.286	2.648	2.594	5.422	2.713	353.88	42.11	731.57	1127.56
2000	3.530	1.000	2.617	3.031	2.969	6.207	3.106	349.52	39.96	901.29	1290.77
2005	3.624	1.000	2.686	3.112	3.048	6.372	3.188	352.96	40.87	931.24	1325.07
2009	4.125	1.000	3.057	3.542	3.469	7.252	3.629	328.73	44.00	1135.35	1508.08

5.2 Effluent return flows

Effluent return flows and effluent discharge from municipal, industrial and the mines were patched to create the respective catchment “EFF.Q” and “EFF.TDS” files (for effluent), MIN.Q and MIN.TDS files (for the mines). Individual effluent discharge flows were combined to form required discharge files. The data was derived from the VRSAU study (1998) and the data from the later years up to 2005 were derived from a Golder Vaal salt balance study. This data was generally extended from 2005 to 2009 as the same values (as for WR2005). The following tables and the graph below give an indication of the effluent discharge for October for the year specified.

Table 5.2: Municipal and Industrial effluent derived from the VRSAU study (DWAF, 1998)

Date	Municipal and industrial effluent (Mm³/month)											
	Klip					Suikerbosrand			Barrage	Riet		Total
Catchment	C22A	C22B	C22C	C22D	C22E	C21D	C21E	C21F	C22FG	Vdblp	C22HJ	
Node	CR1	CR14	CR3	CR2	CR5	CR9	CR10	CR6	CR10	CR12	CR11	
1977/10	7.70	3.44	0.00	0.00	0.03	2.28	0.16	0.06	0.44	0.87	0.00	14.98
1980/10	7.42	3.20	0.60	0.00	0.20	2.29	0.97	0.08	0.66	0.99	0.05	16.46
1990/10	9.72	3.72	1.49	0.00	0.13	2.61	0.54	0.15	0.58	0.74	0.91	20.59
2000/10	14.88	4.69	4.80	0.00	0.28	3.65	1.48	0.17	0.71	0.90	4.54	36.10
2004/10	17.59	4.76	3.02	0.00	0.18	3.39	1.60	0.32	0.68	1.10	6.66	39.30

Table 5.3: Mining effluent derived from the VRSAU study (DWAF, 1998)

Date	Mines effluent (Mm³/month)											
	Klip					Suikerbosrand			Barrage	Riet		Total
Catchment	C22A	C22B	C22C	C22D	C22E	C21D	C21E	C21F	C22FG	Vdblp	C22HJ	
Node	CR1	CR14	CR3	CR2	CR5	CR9	CR10	CR6	CR10	CR12	CR11	
1977/10	0.34	1.24	1.77	0.00	0.00	0.00	0.00	0.47	0.05	0.00	0.15	4.02
1980/10	0.34	1.18	1.21	0.00	0.00	0.00	0.00	0.30	0.06	0.00	0.42	3.51
1990/10	0.42	0.48	0.00	0.00	0.00	0.00	0.00	0.37	0.01	0.00	1.92	3.20
2000/10	0.00	0.65	0.00	0.00	0.00	0.00	0.00	2.38	0.00	0.00	1.12	4.15
2004/10	0.00	0.65	0.00	0.00	0.00	0.00	0.00	2.09	0.00	0.00	1.12	3.86

Table 5.4: Total effluent from the VRSAU study (DWAF, 1998)

Date	Total effluent (Mm³/month)											
	Klip					Suikerbosrand			Barrage	Riet		Total
Catchment	C22A	C22B	C22C	C22D	C22E	C21D	C21E	C21F	C22FG	Vdblp	C22HJ	
Node	CR1	CR14	CR3	CR2	CR5	CR9	CR10	CR6	CR10	CR12	CR11	
1977/10	8.04	4.68	1.77	0.00	0.03	2.28	0.16	0.53	0.49	0.87	0.15	19.00
1980/10	7.76	4.38	1.81	0.00	0.20	2.29	0.97	0.38	0.72	0.99	0.47	19.97
1990/10	10.14	4.20	1.49	0.00	0.13	2.61	0.54	0.52	0.59	0.74	2.83	23.79
2000/10	14.88	5.34	4.80	0.00	0.28	3.65	1.48	2.55	0.71	0.90	5.66	40.25
2004/10	17.59	5.41	3.02	0.00	0.18	3.39	1.60	2.41	0.68	1.10	7.78	43.16

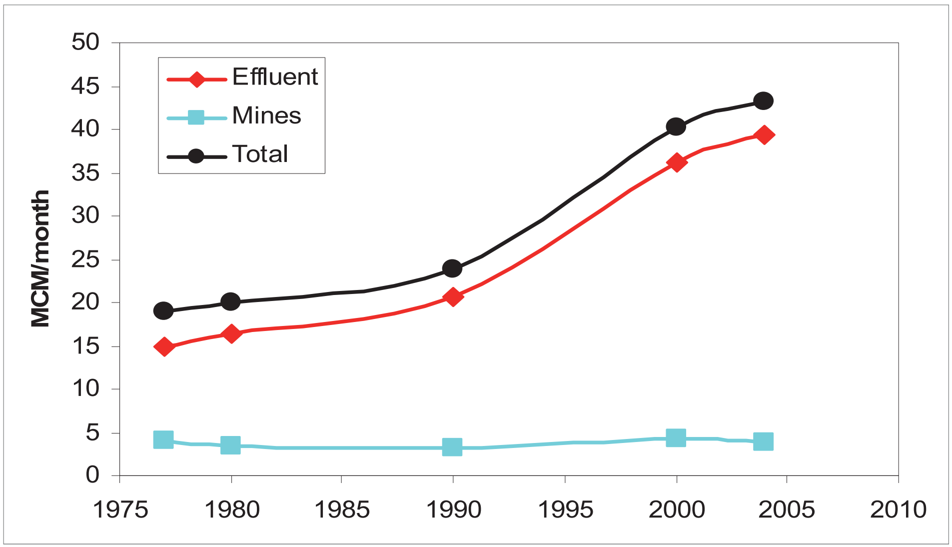

Figure 5.3: Graph depicting the discharge of the effluent from combined municipal, industrial and mines in the Vaal Barrage catchment (million m³/month).

SALMOD was calibrated for each of the following catchments in the Upper Vaal: C11, C12, C13, C81, C82, C83, C21, C22 and C23. The model results are expressed in terms of a table comparing the observed and the modelled data for the specified period. The tertiary catchments are dealt with in the order of flow.

A short discussion of the specific details of each sub-system is provided below. In addition the graphs and statistical comparison of the modelled versus observed flow, TDS and load are given for all the water quality gauges.

5.3 C11 tertiary Catchment

The C11 tertiary catchment is the inflow to the Grootdraai Dam and the reservoir itself. The catchment is characterised by coal mining, especially in the areas north of the Vaal River, and the effect of the Camden, Tutuka and Majuba power stations, Air quality modelling work and measurements reveal high deposition rates, especially in the northern portion of the catchment. Poor surface measurements make it difficult to differentiate between the effects of surface pollution sources and atmospheric deposition. Budget restraints prevented more detailed investigation to determine the loads from each source. Pollution impacts are mitigated by fresh water importation via Heyshope Dam in the Usutu catchment and Zaaihoek Dam in the upper Buffalo River catchment.

5.3.1 **C11: Vaal River at Goedgeluk - C1H007**

The previously mothballed Camden power station is located upstream of C1H007, as are significant coal mining areas. It was necessary to assume growth in diffuse source salt generation in the quaternary catchments upstream of C1H007 to match the observed growth in salt export. The assumption was made that there was no growth before 1950, followed by exponential growth thereafter, reaching an annual growth factor by 2010. This assumption was applied to quaternaries C11A to C11J. Although the growth is expected to be higher in the northern areas than in the southern portion of the catchment, no attempt was made to make this differentiation due to budgetary constraints. It should be noted that the underlying development and deposition effect is expected to be significantly higher than the observed 20% growth in salt export, attributable to the attenuation afforded by the large catchment soil storage resulting in a lag time of two to three decades. The rate at which salts are being deposited onto and generated within the catchment could therefore be considerably greater than what is currently observed in the catchment surface water export.

Figure 5.4 and Table 5.5 indicate that this resulted in a good fit between modelled and observed values.

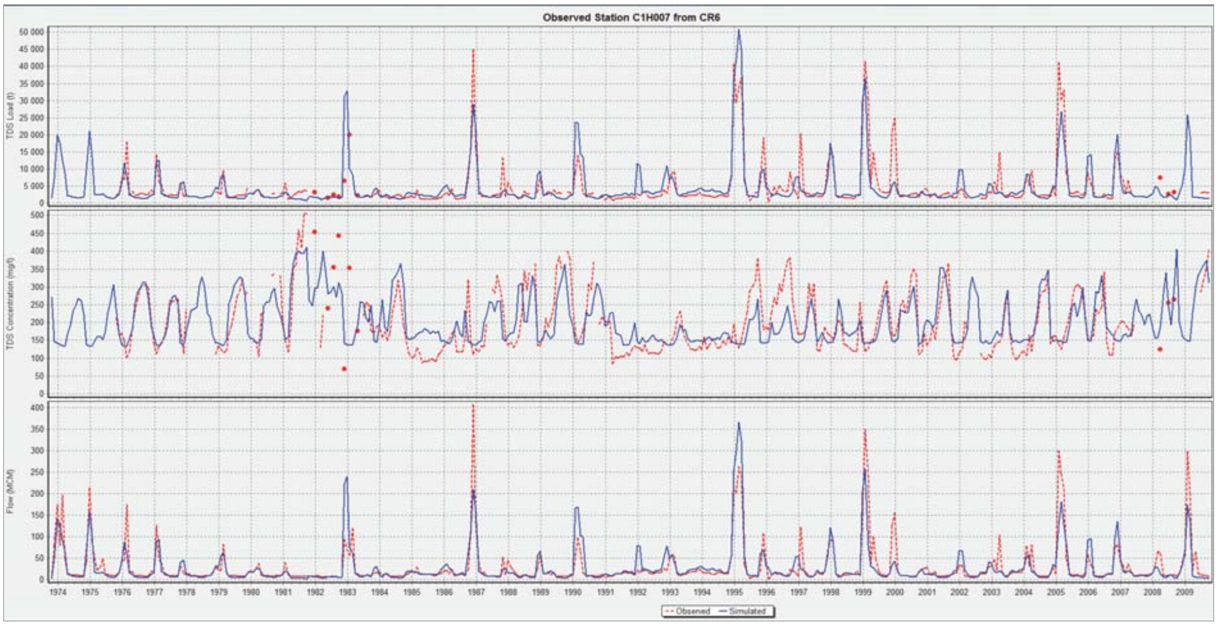

Figure 5.4: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at C1H007

Table 5.5: Comparison between modelled and observed statistical values in the Vaal River at C1H007

Route 6CR: C1H007 1976 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	28.26	27.58	198.9	199.6	4605.	4475.
Std.Dev.	49.14	46.19	85.2	66.1	6601.	6411.
R	.8041		.7426		.8073	
E1	-2.4%		.4%		-2.8%	
E2	-6.0%		-22.4%		-2.9%	
N	408		354		354	
SF	1.000		.986		.991	
Mean	27.6		205.6		4362.5	
Std.Dev.	46.2		67.8		6345.1	
N	408		408		408	

5.3.2 C11: Blesbokspruit at Rietvley - C1H006

Growth in diffuse source salt generation had to be introduced to account for the growth in salt export evident in the plot. In this instance it was necessary to calibrate the diffuse source generation rate doubling between 1950 and 2010. This large increase is consistent with catchment coal mining development and the impact of atmospheric deposition, which is evident from the high deposition rates obtained from air quality modelling.

The results shown in Figure 5.5 and Table 5.6 indicate a good fit between modelled and observed TDS concentrations and a reasonable fit between modelled and observed TDS loads. No attempt was made to force the error between modelled and observed loads to zero, since the modelled flows for this period are 14% low, with consistent large under-estimation of flood peaks.

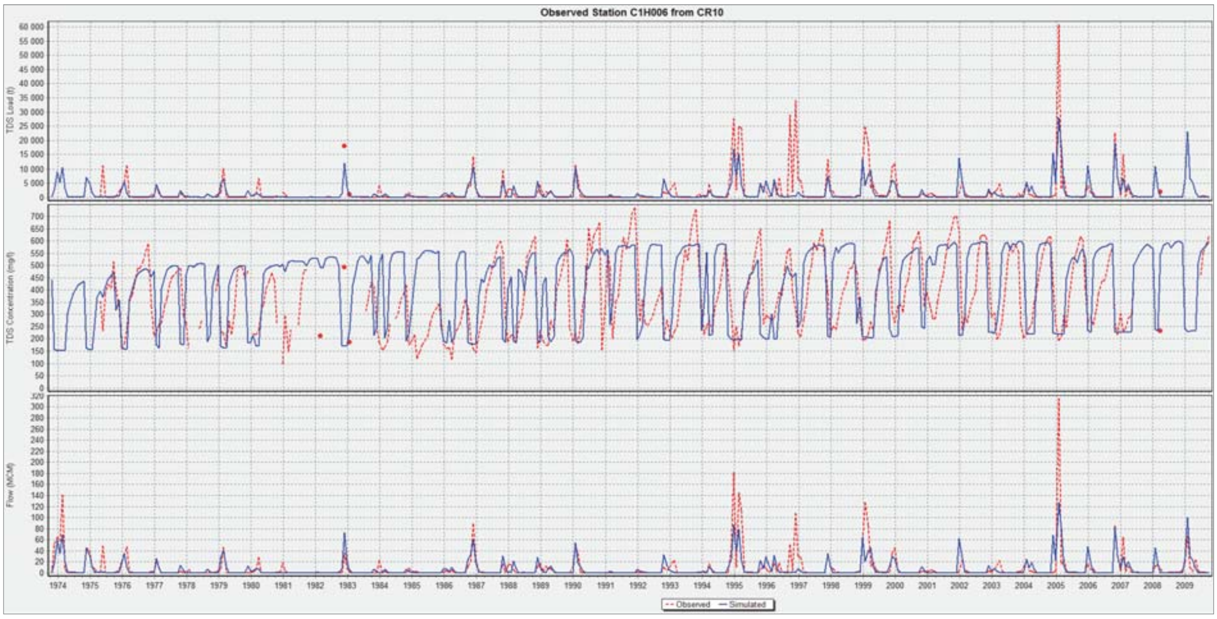

Figure 5.5: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Blesbokspruit at C1H006

Table 5.6: Comparison between modelled and observed statistical values in the Vaal River at C1H006

Route 10CR: C1H006 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	7.74	6.63	374.1	425.8	1928.	1402.
Std.Dev.	24.29	15.59	149.2	153.3	5428.	3140.
R	.7124		.5055		.6911	
E1	-14.3%		13.8%		-27.3%	
E2	-35.8%		2.7%		-42.2%	
N	420		361		370	
SF	1.000		.998		.986	
Mean	6.6		427.9		1442.9	
Std.Dev.	15.6		153.0		3229.0	
N	420		420		420	

5.3.3 C11: Vaal River at Grootdraai Dam - C1R002

The comparison between simulated and observed storage in WRSM/Pitman is shown in Figure 5.6 below (observed storage data was available from October 1979). Figure 5.6 shows that although Grootdraai Dam was down to about 6% in October 1979, the simulated (modelled) storage was higher at about 35%. This is probably due to inaccuracies in the measured abstractions from Grootdraai (SASOL etc.) as the simulated inflow matched up reasonably well against the calculated observed inflow from the Reservoir Record.

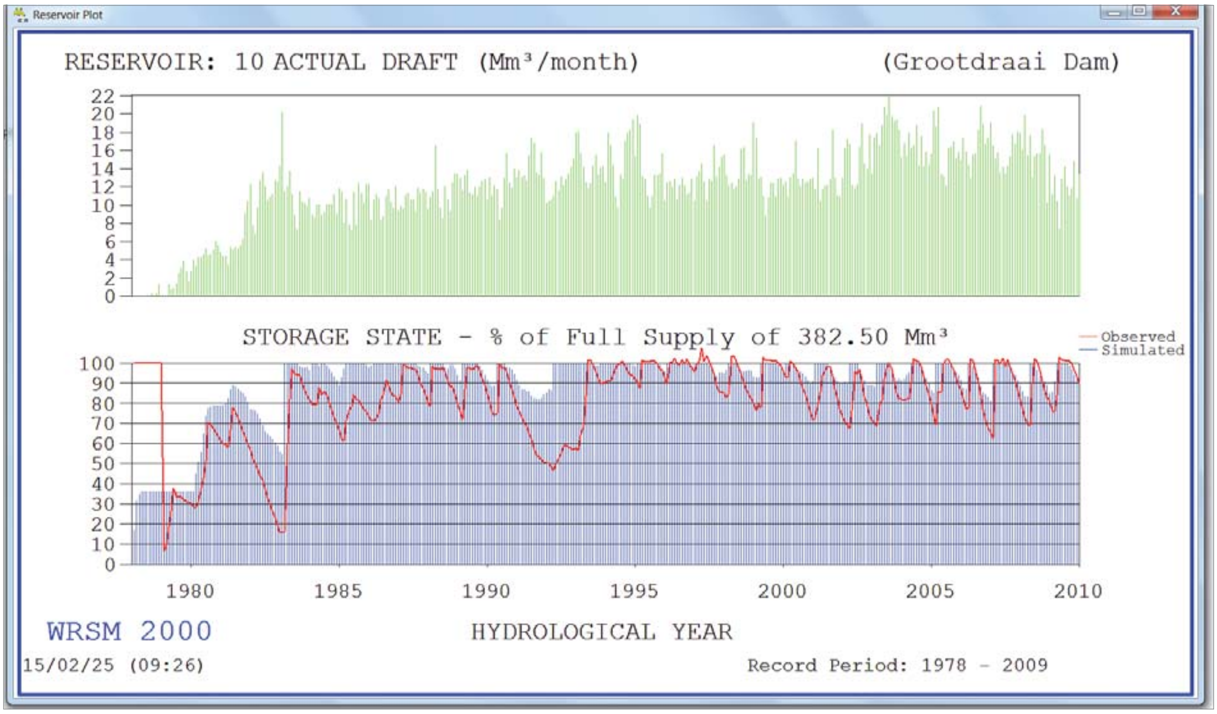

Figure 5.6: Observed and simulated storage in Grootdraai Dam

It is to be noted that the Vaal Dam - Grootdraai Dam emergency weirs scheme that operated for a few months in Sep, Oct and November 1983 should go directly into Grootdraai Dam and not downstream. This is a minor issue since the scheme was discontinued immediately afterwards, however it is to be corrected in a future analysis.

5.3.4 C11:Vaal River at Langverwyl; outflow from Grootdraai dam - C1H019

The weir C1H019 represents the outflow from Grootdraai Dam.

The remainder of the Grootdraai Dam catchment downstream of C1H007 and C1H006 contains the large Tutuka power station and also includes Majuba power station (even bigger than Tutuka). The northern portion of the catchment is also subject to high atmospheric deposition.

Growth in catchment development and atmospheric deposition (especially in the northern part of the catchment) made it necessary to model a doubling of the diffuse source salt generation between 1950 and 2010 in the C11H and C11K quaternaries, with a lower 40% increase in the les developed C11L quaternary.

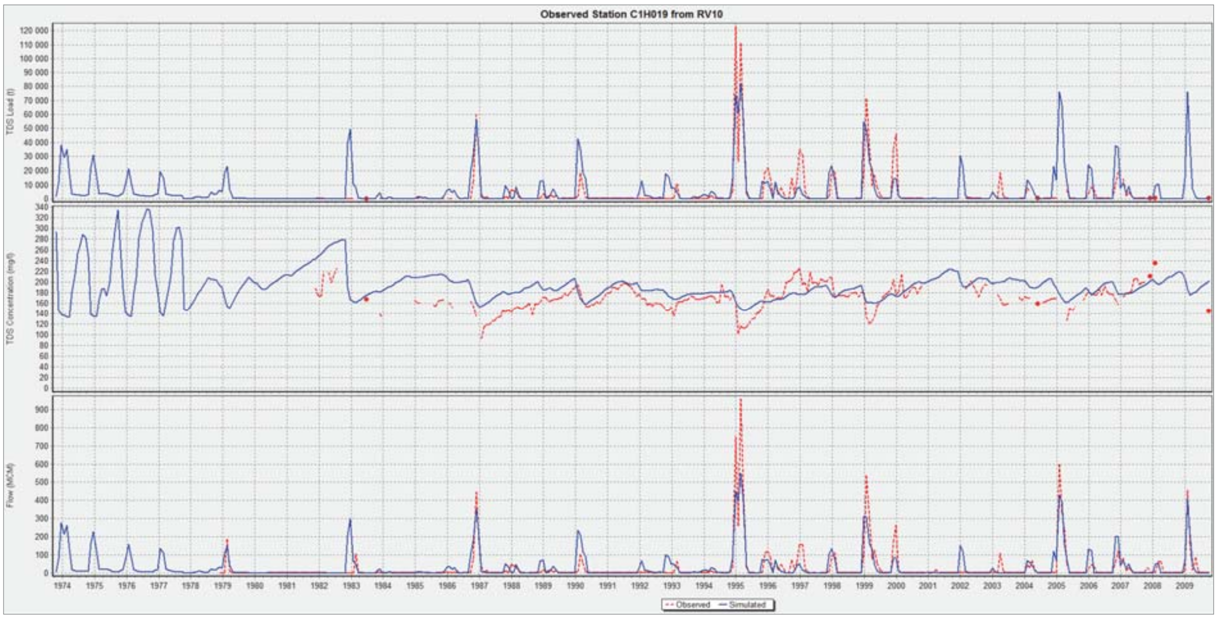

Figure 5.7: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at C1H019

Table 5.7: Comparison between modelled and observed statistical values in the Vaal River at C1H019

Route 16CR: C1H019 1995 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	47.14	41.04	176.9	178.0	7985.	7770.
Std.Dev.	125.84	95.31	25.4	15.4	19140.	16702.
R	.8808		.5337		.8282	
E1	-12.9%		.6%		-2.7%	
E2	-24.3%		-39.3%		-12.7%	
N	180		134		134	
SF	1.000		.987		.962	
Mean	41.0		179.9		7023.9	
Std.Dev.	95.3		14.8		15844.3	
N	180		180		180	

5.4 C13 Tertiary catchment

There was the only water quality station which was analysed in C13. Growth factors were introduced in order to get a reasonable calibration.

5.4.1 **C13: Klip River at Sterkfontein - C1H002**

C1H002 is remarkably devoid of catchment development, yet Figure 5.9 shows a marked increase in salt concentrations. It is particularly significant that the increase in salt concentrations is also evident during times of high discharge. This obviously gives rise to significant growth in salt load export. It is also indicative of diffuse source salt recharge, rather than point source input, which would have been more prominent during low flow periods. The absence of any plausible local development leaves atmospheric deposition as the most probable cause. This contention is greatly strengthened by the results of atmospheric deposition modelling and the very high deposition loads involved, relative to the natural catchment salt generation rates.

This, despite the Klip River catchment being in a region that experiences deposition rates significantly lower than in the northern part of the catchment. This implies that atmospheric deposition already has a very significant impact on salt export. Moreover, the storage in the catchment soils provides a lag of two to three decades (i.e. the time taken before the full impact of an increase in diffuse salt input would materialise). Hence the change that has already been observed is substantially lower than the longer term equilibrium level that can be expected. Three decades may seem a deceptively long time, but this amount of time has already elapsed since the problem was first identified and brought to the attention of researchers. What was the future then is already the present. It will double again well within the lifespan of most of the population of South Africa.

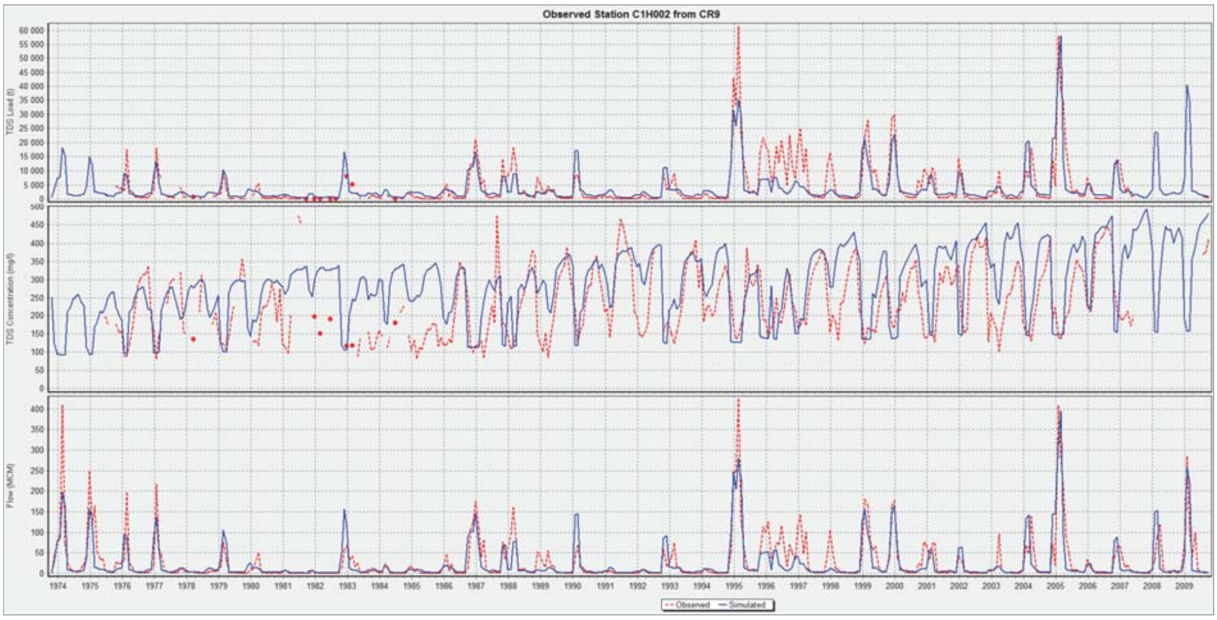

Figure 5.8: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at C1H002

Table 5.8: Comparison between modelled and observed statistical values in the Vaal River at C1H002

Route 9CR: C1H002 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	27.57	23.27	233.6	287.3	4424.	3776.
Std.Dev.	53.65	48.50	93.5	94.1	7905.	6116.
R	.8013		.6560		.8070	
E1	-15.6%		23.0%		-14.7%	
E2	-9.6%		.7%		-22.6%	
N	420		349		354	
SF	1.000		.992		.986	
Mean	23.3		288.9		3839.7	
Std.Dev.	48.5		96.6		6364.3	
N	420		420		420	

5.5 C81 Tertiary Catchment

5.5.1 **C81: Oubergspruit at Frasierspruit – C8H010**

A reasonable fit between modelled and observed TDS concentrations and loads was obtained. There was no obvious need to include growth in diffuse source salt generation.

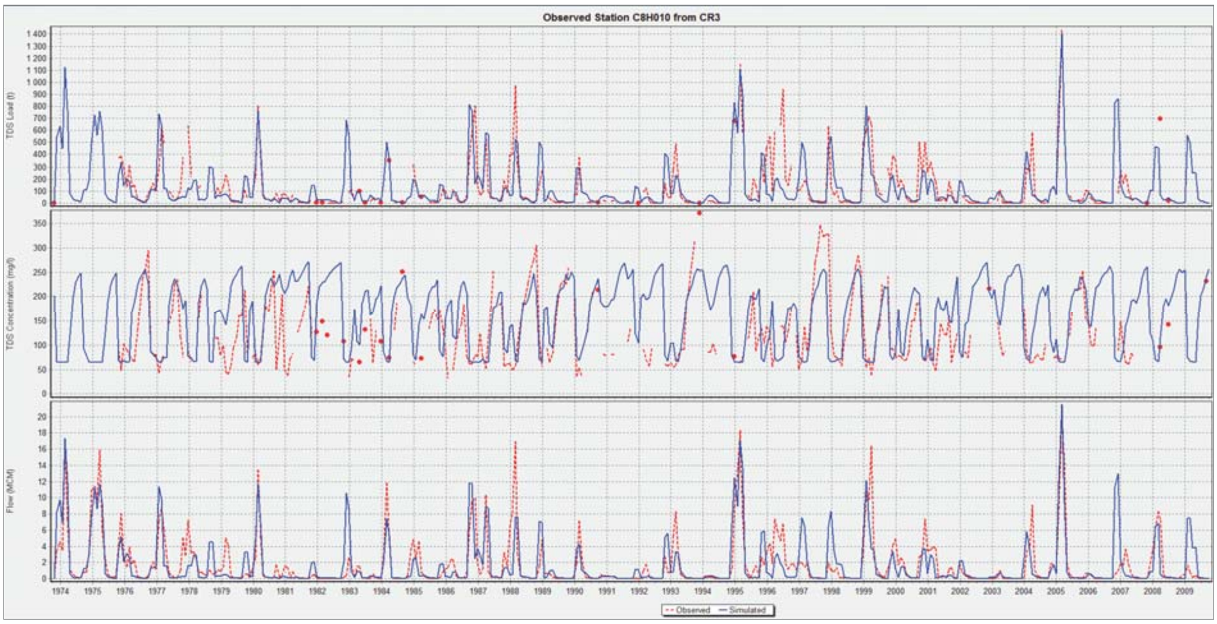

Figure 5.9: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Oubergspruit at C8H010

Table 5.9: Comparison between modelled and observed statistical values in the Oubergspruit at C8H010

Route 3CR: C8H010 1976 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	1.59	1.50	125.6	155.6	126.	114.
Std.Dev.	2.92	2.93	68.5	65.9	204.	192.
R	.6960		.5731		.7006	
E1	-5.4%		23.9%		-10.1%	
E2	.2%		-3.8%		-5.5%	
N	408		289		328	
SF	1.000		.973		.993	
Mean	1.5		165.9		116.0	
Std.Dev.	2.9		68.9		191.2	
N	408		408		408	

5.5.2 **C81: Klerkspruit at Geduld - C8H006**

Flow gauging at C8H006 ceased after the weir was demolished during road renovations. There is no overlap between the periods of observation for flows and TDS concentrations. This makes it impossible to compare modelled and observed TDS loads. Moreover, the TDS sampling is intermittent and ceased entirely after 1999. Although the fit between the observed and modelled mean and standard deviation of the monthly TDS concentrations is good, the correlation coefficient is very poor.

In view of the absence of corroborating flow data and the poor record it was considered inadvisable to try to further refine the calibration fit, but rather to concentrate of downstream gauges where flow data permits the calculation of TDS loads.

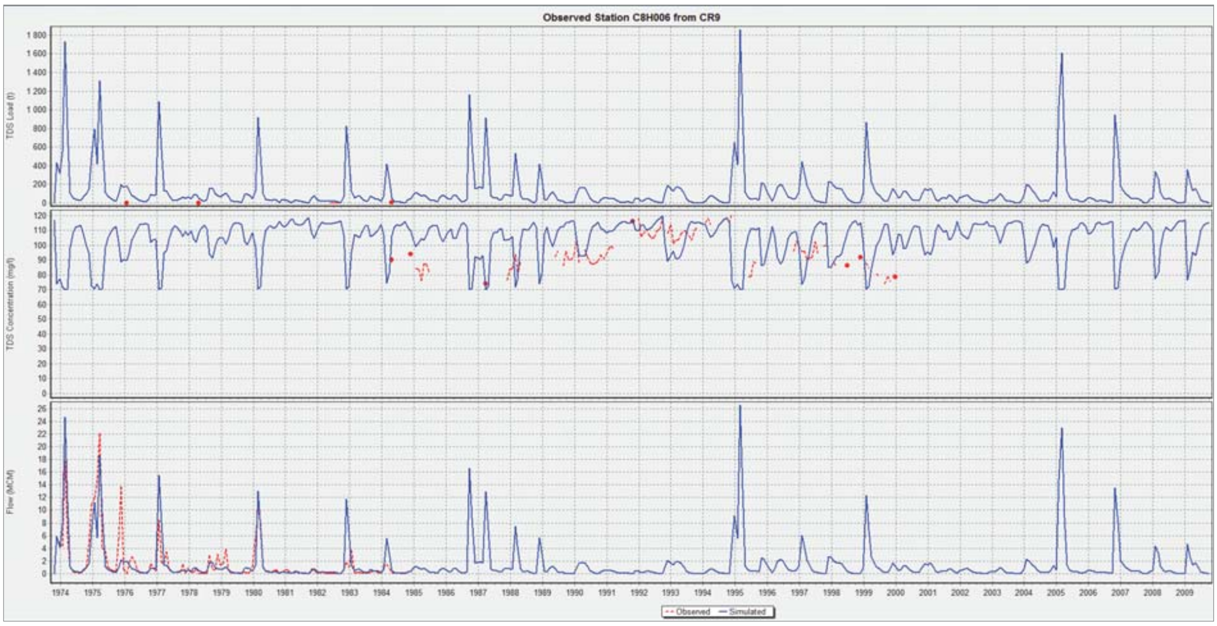

Figure 5.10: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Kleksspruit at C8H006

Table 5.10: Comparison between modelled and observed statistical values in the Klerkspruit at C8H006

Route 9CR: C8H006 1985 - 2000

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	-1.00	-1.00	96.2	104.6	-1.	-1.
Std.Dev.	-1.00	-1.00	12.4	12.3	-1.	-1.
R	-1.0000		.2411		-1.0000	
E1	3.2%		8.8%		-1.0000%	
E2	6.3%		-.6%		-1.0000%	
N	0		94		0	
SF	-1.000		.991		-1.000	
Mean	1.4		103.4		119.1	
Std.Dev.	3.0		12.6		210.5	
N	192		192		192	

5.5.3 C81: Elands River at Killarney - C8H011

During the period of overlap the modelled flows under-estimate the observed mean by 24%, with a similar error in the standard deviation. Hence model calibration (which uses the modelled flows as input) was also reduced so as not to produce unreasonable TDS concentrations. The underlying assumption is that the observed values are correct. It is possible that there is an upward trend in the observed TDS loads (based on the concentrations coinciding with high flow events). However, budget restraints did not permit exploring this possibility.

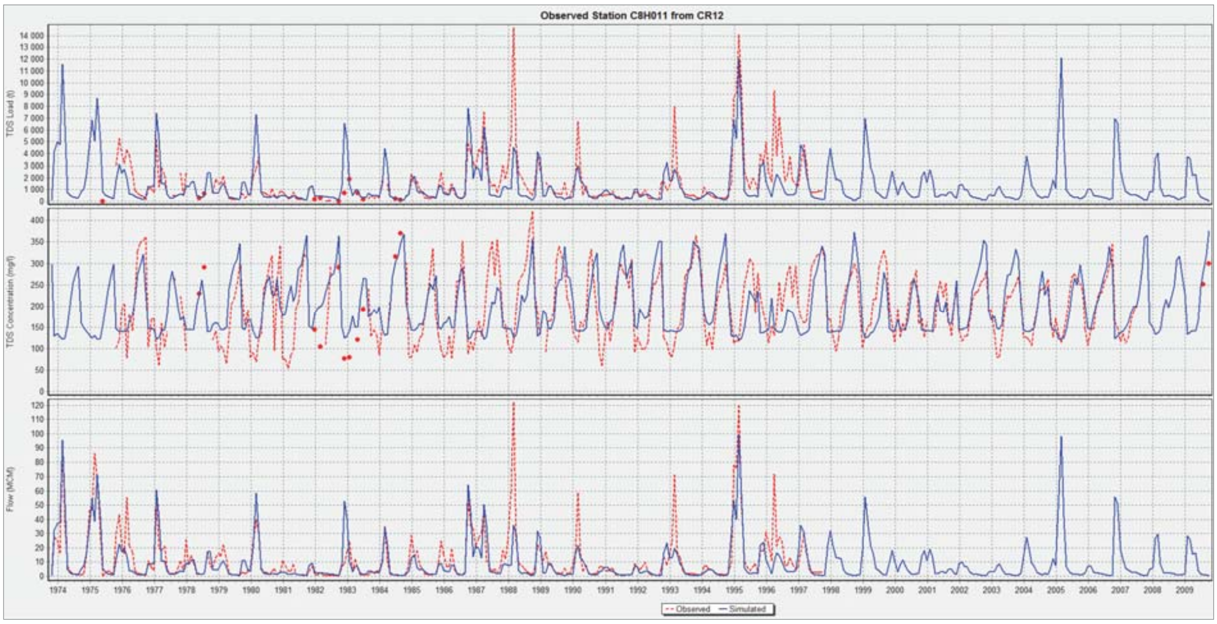

Figure 5.11: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Klerkspruit at C8H011

Table 5.11: Comparison between modelled and observed statistical values in Klerkspruit at C8H011

Route 12CR: C8H011 1976 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	11.08	8.42	195.7	201.4	1623.	1231.
Std.Dev.	16.84	13.08	78.6	66.1	2119.	1647.
R	.7438		.7348		.7301	
E1	-23.9%		2.9%		-24.2%	
E2	-22.3%		-15.9%		-22.3%	
N	264		356		238	
SF	.995		.997		.998	
Mean	8.5		202.4		1228.4	
Std.Dev.	13.2		66.7		1637.5	
N	408		408		408	

5.5.4 **C81: Vaalbankspruit at Voorspoed - C8H012**

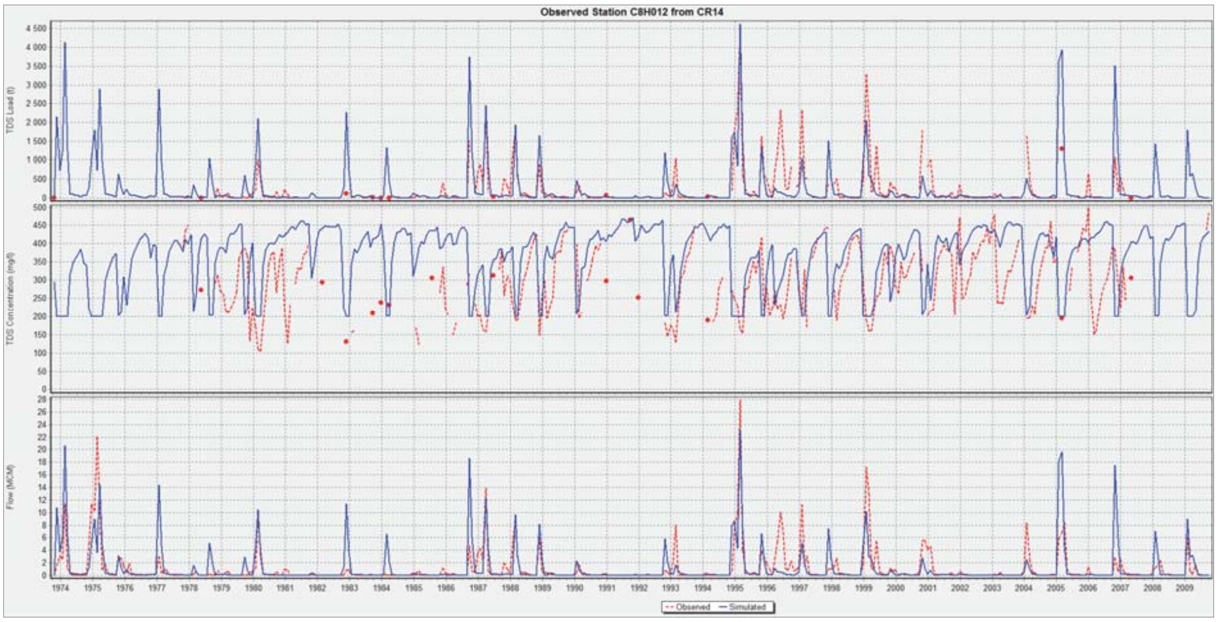

Figure 5.12: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaalbankspruit at C8H012

Table 5.12: Comparison between modelled and observed statistical values in the Vaalbankspruit at C8H012

Route 14CR: C8H012 1978 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	.92	.96	299.2	366.0	213.	196.
Std.Dev.	2.56	2.84	89.7	81.5	518.	573.
R	.6598		.4551		.6837	
E1	4.0%		22.3%		-8.1%	
E2	11.0%		-9.1%		10.5%	
N	384		260		310	
SF	1.000		.992		.985	
Mean	1.0		373.3		205.6	
Std.Dev.	2.8		82.4		567.3	
N	384		384		384	

The absence of monitoring stations on the main stem of the Wilge River meant that comparisons had to be made using stations located in downstream tertiary catchments. This meant having to return to the C81 tertiary iteratively to refine the calibrations.

5.6 C82 Tertiary Catchment

5.6.1 **C82: Cornelis River at Warden - C8H003**

Based on the TDS concentration troughs corresponding to the higher flows shown in Figure 5.14 this may indicate an upward trend in salt load. However, this could be masked by the wetter conditions during the second half of the record (since concentrations tend to drop when the flows increase). This effect was was not explored in this study.

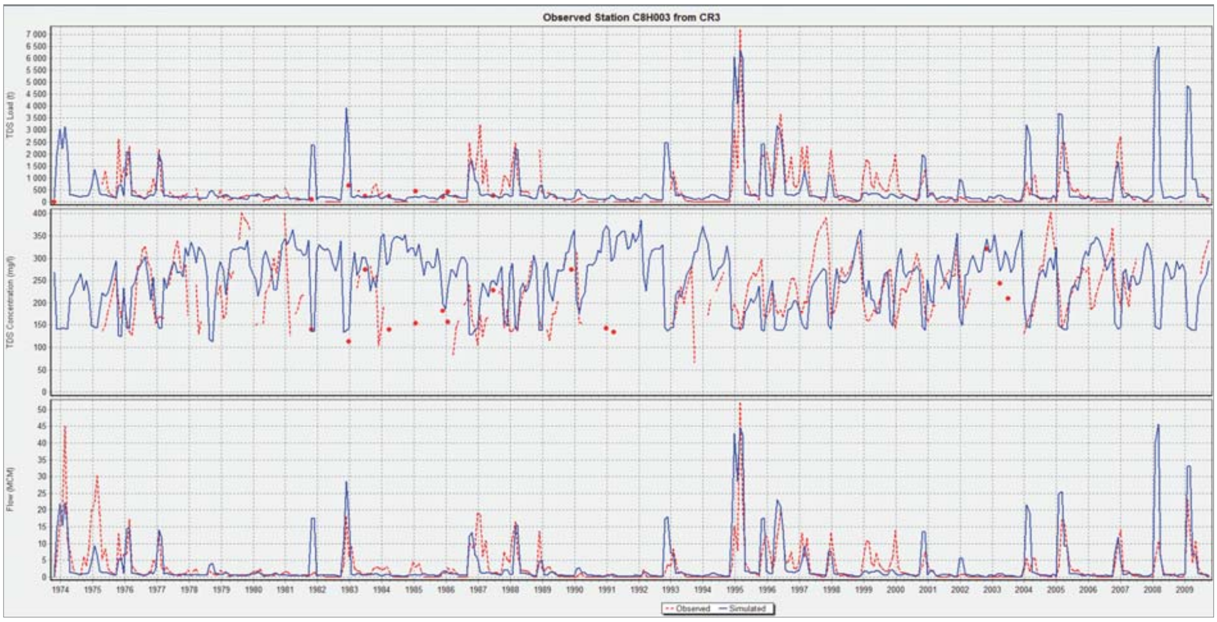

Figure 5.13: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Cornelis River at C8H003

Table 5.13: Comparison between modelled and observed statistical values in the Corenelis River at C8H003

Route 3CR: C8H003 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	2.79	3.01	226.0	242.0	473.	455.
Std.Dev.	5.11	6.72	66.0	61.6	770.	820.
R	.6345		.3826		.6998	
E1	7.6%		7.1%		-3.8%	
E2	31.7%		-6.7%		6.5%	
N	420		274		346	
SF	1.000		.971		.944	
Mean	3.0		256.1		501.2	
Std.Dev.	6.7		65.4		933.6	
N	420		420		420	

5.6.2 C82: Wilge River at Bavaria - C8H014

This is the first monitoring station on the main stem of the Wilge River downstream of the C82 tertiary. However, the water quality record is relatively short, having ceased in 1992 and misses some of the most significant flood events. Hence the results at this station had to be weighed together with those at the downstream Crump weir at C8H027.

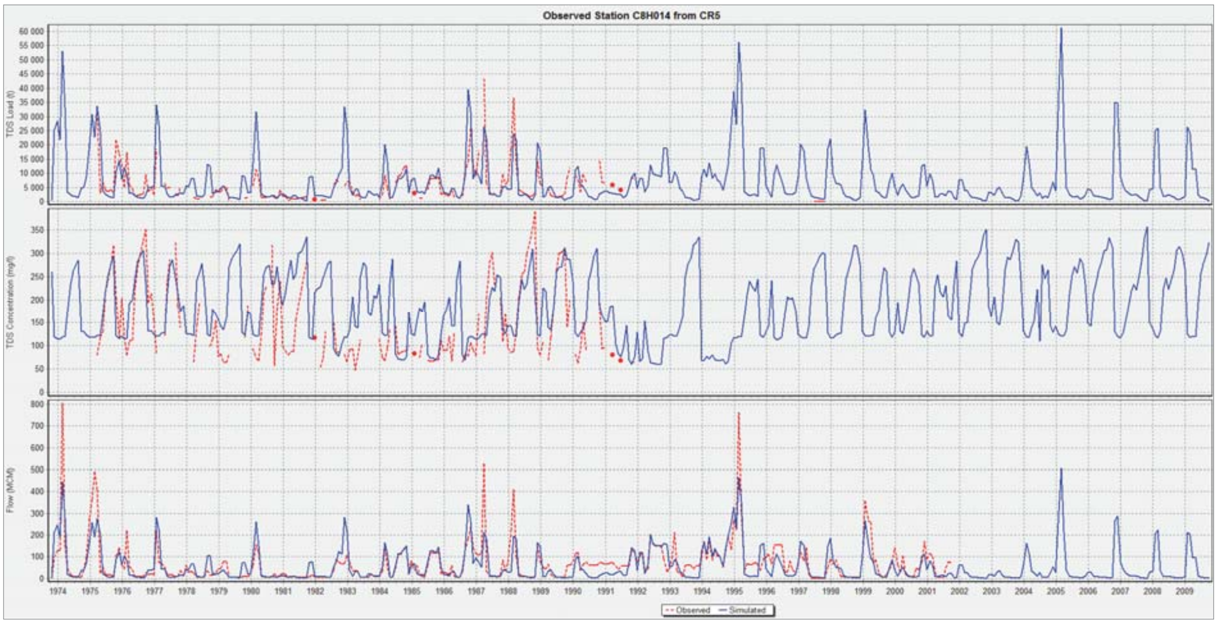

Figure 5.14: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Wilge River at C8H014

Table 5.14: Comparison between modelled and observed statistical values in the Wilge River at C8H014

Route 5CR: C8H014 1975 - 1992

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	59.85	54.62	145.3	176.1	5946.	6744.
Std.Dev.	79.05	68.18	82.4	69.5	6526.	7847.
R	.7287		.6601		.6424	
E1	-8.7%		21.2%		13.4%	
E2	-13.8%		-15.6%		20.2%	
N	216		151		151	
SF	1.000		.989		.971	
Mean	54.6		176.0		6397.3	
Std.Dev.	68.2		72.8		7371.4	
N	216		216		216	

5.6.3 C82: Wilge River at Ballingtomp - C8H027

A good fit was obtained between modelled and observed TDS concentrations and TDS loads at this monitoring station.

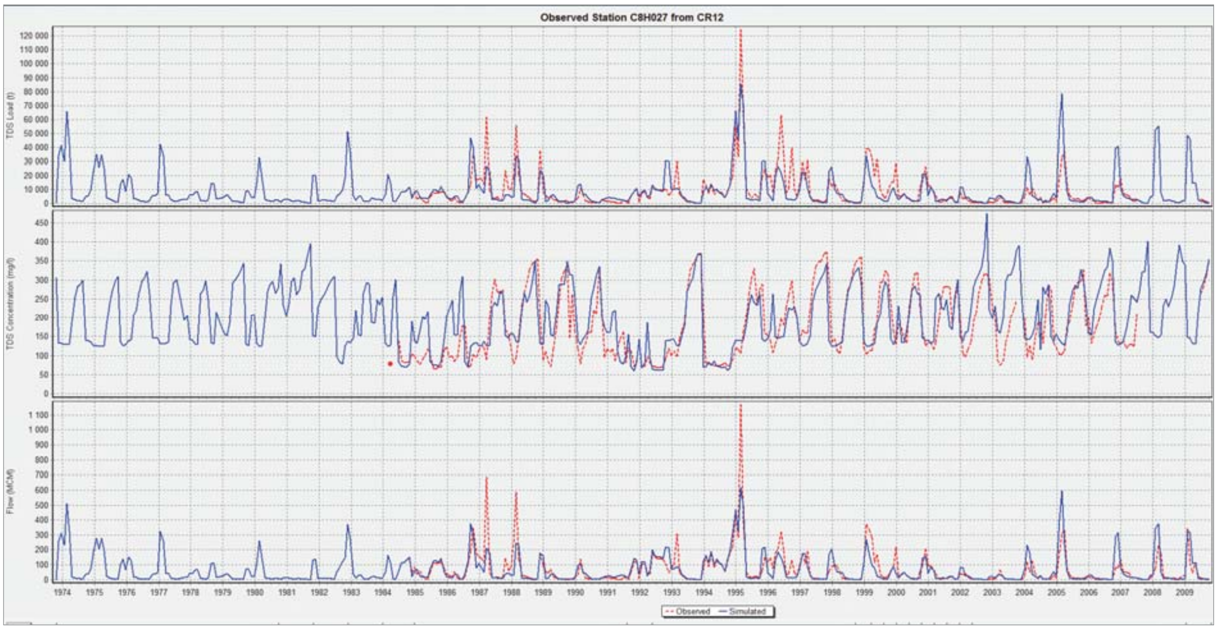

Figure 5.15: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Wilge River at C8H027

Table 5.15: Comparison between modelled and observed statistical values in the Wilge River at C8H027

Route 12CR: C8H027 1984 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	68.75	65.51	179.9	193.4	8728.	8333.
Std.Dev.	112.94	98.29	87.4	83.4	13063.	12358.
R	.7565		.7768		.7555	
E1	-4.7%		7.5%		-4.5%	
E2	-13.0%		-4.6%		-5.4%	
N	300		280		277	
SF	.997		.990		.987	
Mean	65.5		198.4		8524.6	
Std.Dev.	97.0		84.7		12742.1	
N	312		312		312	

5.7 C83 Tertiary Catchment

The C82 tertiary catchment had a gauge at the outlet so C8H027 was used as input to C83 for flow and TDS.

5.7.1 **C83: Liebenbergsvlei at Vogelfontein - C8H007**

Flow data was available for only a short period at the start of the record, which meant that any comparison of loads would be highly misleading. Hence the flow and load values given in Table 5.16 have been ignored.

As this station is just downstream of Saulpoort Dam, the TDS trace distinctly shows the typical effect reservoir storage attenuation. This is especially evident during the first two-thirds of the record. After

1997 this effect is obliterated by the large amounts (relative to the small dam storage) of low TDS water imported from the Lesotho Highlands Water Project (LHWP).

Despite the lack of flow data, the fit between modelled and observed TDS concentrations at station C8H007 follow the observed pattern remarkably well.

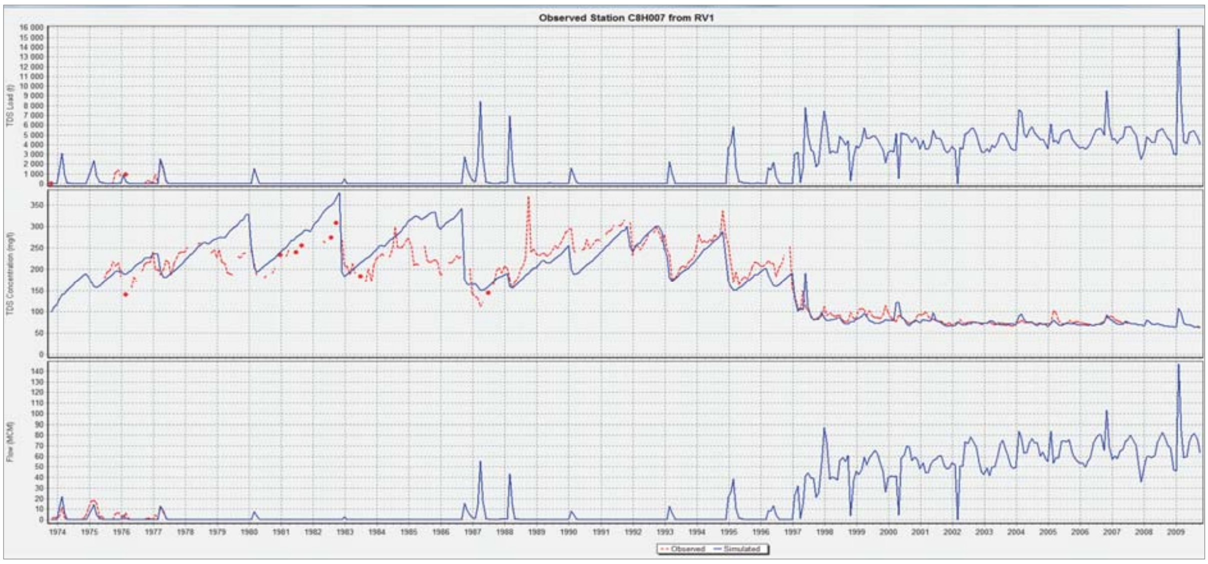

Figure 5.16: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Liebenbergsvlei River at C8H007

Table 5.16: Comparison between modelled and observed statistical values in the Liebenbergsvlei River at C8H007 (C8R004 for TDS)

Route 1RV: C8H007 1975 - 2007

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	3.56	1.81	173.3	175.3	381.	183.
Std.Dev.	5.30	3.78	77.1	84.8	598.	577.
R	.8135		.8932		.7517	
E1	-49.1%		1.2%		-51.9%	
E2	-28.7%		9.9%		-3.6%	
N	36		341		26	
SF	.205		.987		.310	
Mean	19.3		183.4		1594.5	
Std.Dev.	27.8		85.3		2205.1	
N	396		396		396	

5.7.2 C83: Liebenbergsvlei at Demolin - C8H004

The flow record at this station ceased after commencement of the Lesotho Highlands Water Project, possibly due to drowning of the weir. A good fit was obtained between modelled and observed flows and TDS loads up to that point in time. TDS concentrations are also reasonably represented.

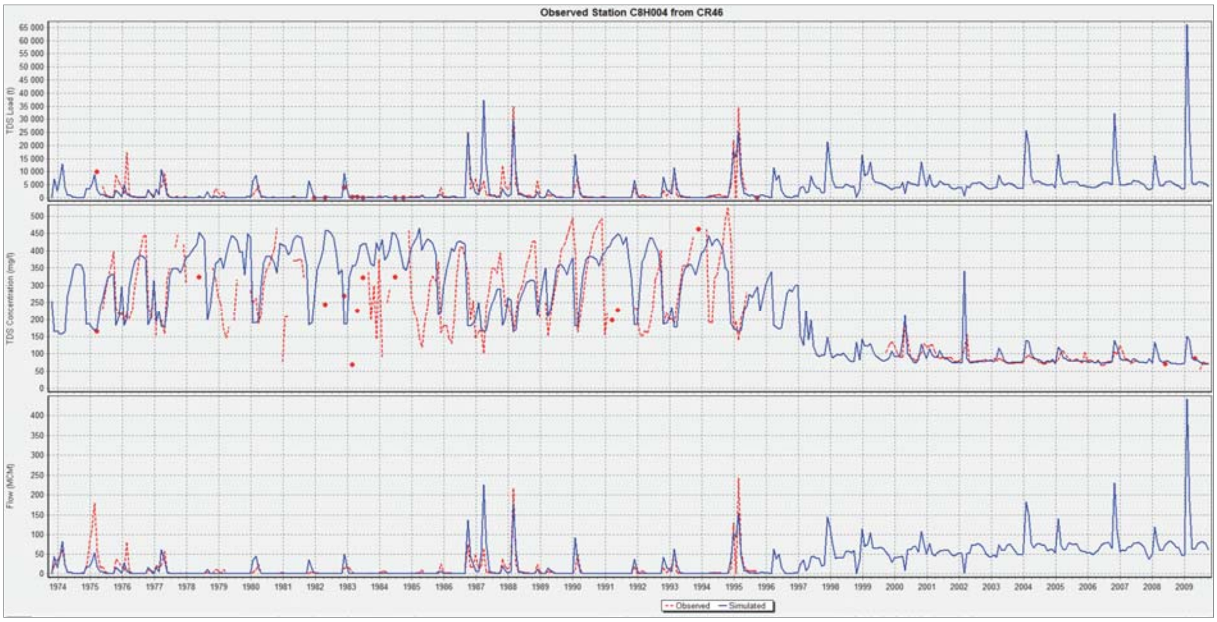

Figure 5.17: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Liebenbergsvlei River at C8H004

Table 5.17: Comparison between modelled and observed statistical values in the Liebenbergsvlei River at C8H004

Route 46CR: C8H004 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	9.91	9.42	217.0	242.5	1940.	1937.
Std.Dev.	28.23	26.63	124.5	134.5	4660.	4939.
R	.6982		.7201		.7349	
E1	-4.9%		11.7%		-.2%	
E2	-5.7%		8.1%		6.0%	
N	252		289		205	
SF	.617		.997		.817	
Mean	30.6		241.1		3498.4	
Std.Dev.	43.2		133.9		5774.9	
N	420		420		420	

5.7.3 C83: Liebenbergsvlei at Vrederiksdal - C8H026

C8H026 is a large well placed Crump weir that was especially constructed a decade ahead of the initial commissioning date of the Lesotho Highlands Water Project to measure water losses in the Liebenbergsvlei River. It is most unfortunate that the flow record at this strategic weir is not available after September 2004, especially given the large scale theft of water by upstream irrigation farmers. TDS concentrations are well represented at this weir.

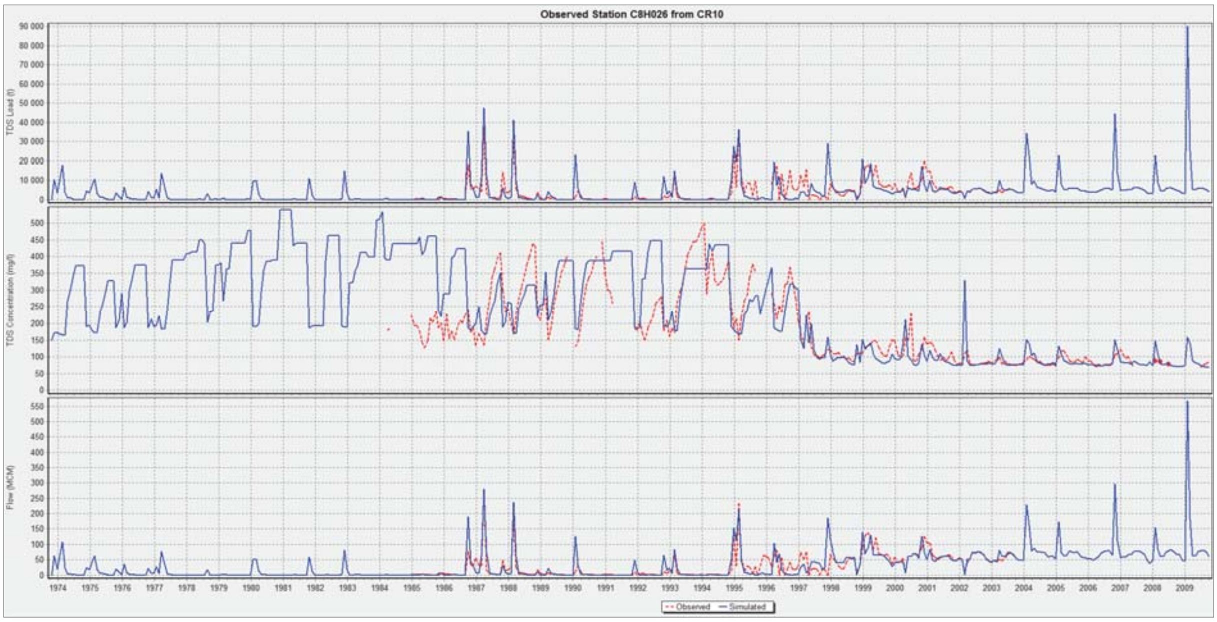

Figure 5.18: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Liebenbergsvlei River at C8H026

Table 5.18: Comparison between modelled and observed statistical values in the Liebenbergsvlei River at C8H026

Route 10CR: C8H026 1984 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	30.27	30.89	184.7	204.6	4212.	4053.
Std.Dev.	39.72	43.73	107.4	129.6	5874.	6873.
R	.8106		.7604		.7380	
E1	2.1%		10.8%		-3.8%	
E2	10.1%		20.7%		17.0%	
N	228		264		224	
SF	.862		.974		.900	
Mean	42.2		213.8		4900.1	
Std.Dev.	56.0		137.7		8476.0	
N	312		312		312	

5.7.4 C83: Wilge River at Wilgers - C8H022

C8H022 combines the inflows from the Wilge River and the Liebenbergsvlei River, just downstream of the confluence of the two rivers. The load fit is about 20% too low, compared with the flow fit. This is contradicted by the good TDS load fit at C8H026 and C8H02. All three weirs have similar lengths of record. The reason for this anomaly would require further detailed investigation.

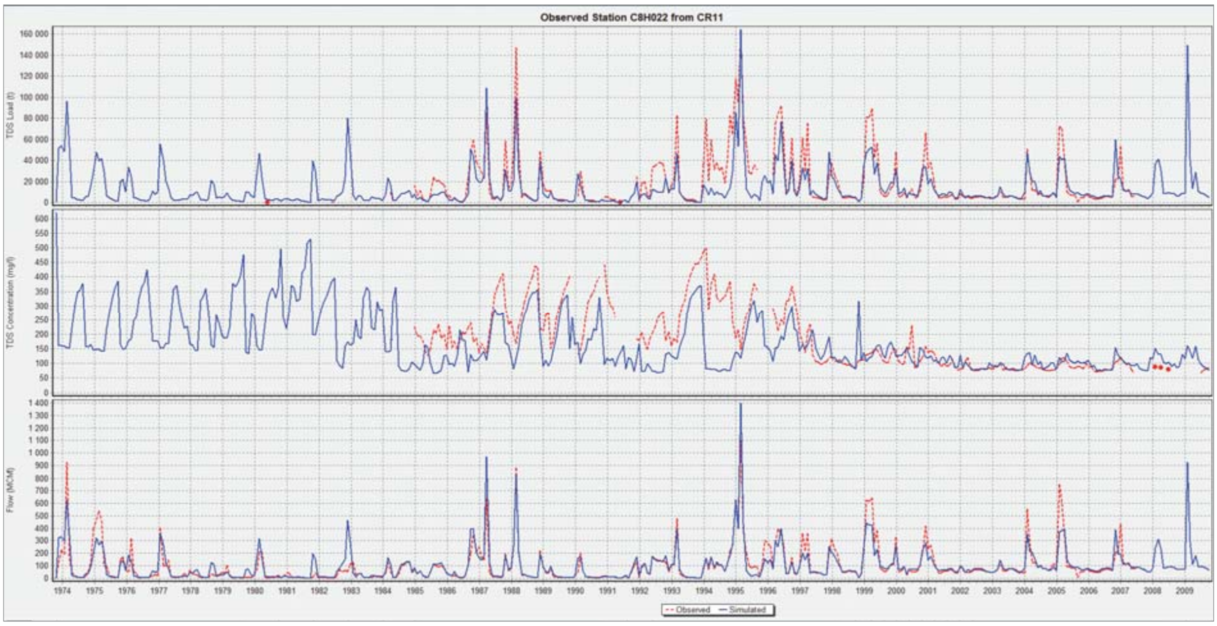

Figure 5.19: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Wilge River at C8H022

Table 5.19: Comparison between modelled and observed statistical values in the Wilge River at C8H022

Route 11CR: C8H022 1984 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	112.88	103.14	184.7	146.0	19526.	13527.
Std.Dev.	148.72	122.88	107.4	67.3	25747.	18356.
R	.8098		.6242		.7278	
E1	-8.6%		-21.0%		-30.7%	
E2	-17.4%		-37.4%		-28.7%	
N	288		264		258	
SF	.969		.996		.986	
Mean	108.3		143.8		13544.7	
Std.Dev.	132.4		67.2		19394.9	
N	312		312		312	

5.8 C12 Tertiary Catchment

The C12 tertiary catchment receives inputs from the C11, C13 and C83 tertiary catchments and terminates in Vaal Dam.

5.8.1 **C12: Waterval River at Brandrift - C1H004**

C1H004 commands the surface water export for the highly developed upper Waterval River catchment, which includes the massive Sasol/Secunda oil from coal complex and its associated coal mines, the EGM gold mines and residential effluent sources.

Although this catchment receives heavy atmospheric deposition, the impact of this on water quality is masked by the severe surface pollution from all the industrial and mining developments. This is further complicated by the very success of pollution abatement measures that have succeeded in reducing industrial pollution discharges, leading to a reduction in overall pollution loads, as is evident from Figure 5.20 .

A sharp reduction in the TDS concentration also ensued from the issuing of a permit for Sasol 2 and 3 to discharge some 25 Ml/d of relatively low TDS blow-down water. This was done because Sasol had developed a positive water balance that necessitated building ever more containment dams, which also received large tonnages of much more saline effluent that could not under any circumstances be released. It makes much more sense to simply discharge the blow-down water and reserve the evaporation dams for disposing of the saline mining and industrial effluent. This blow-down water exerts a pronounced diluting effect on the polluted catchment runoff.

The man-made reductions in surface pollution and the marked changes in effluent point source discharges make it necessary to carry out a detailed investigation to separate out the impact of atmospheric deposition from that of the surface pollution sources. Important as it is, this is clearly beyond the scope of this study. Hence growth in diffuse sources was not included. Instead this is implicitly accounted for in the calibrated diffuse source salt recharge, which is higher than would be expected for a virgin catchment.

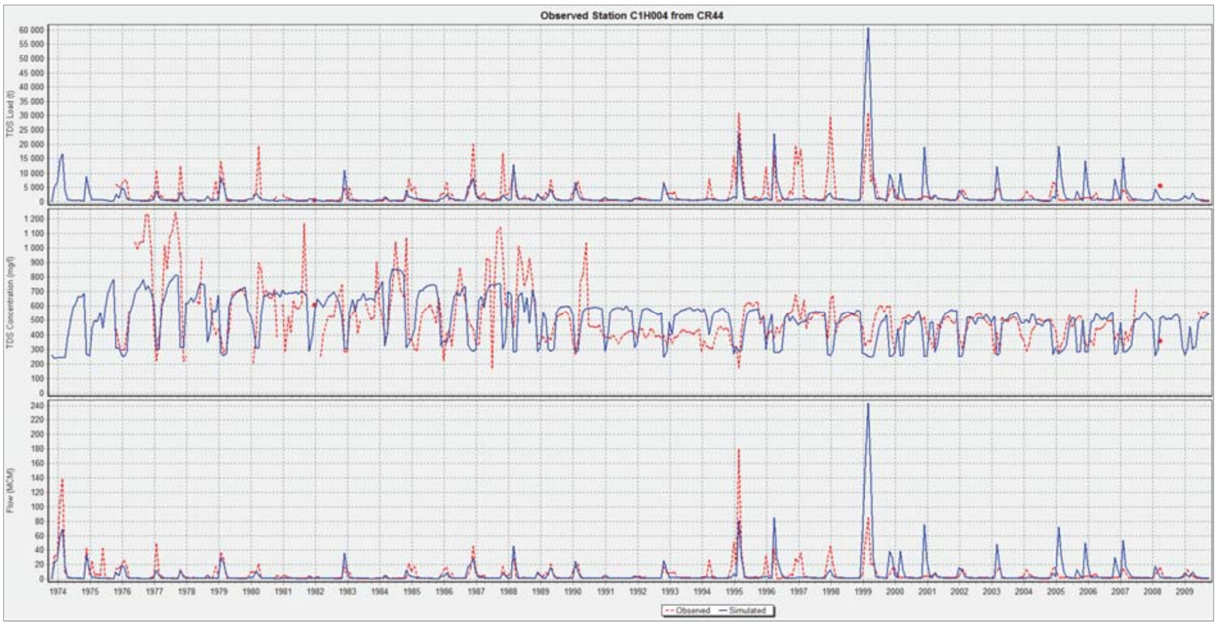

Figure 5.20: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Waterval River C1H004

Table 5.20: Comparison between modelled and observed statistical values in the Waterval River C1H004

Route 44CR: C1H004 1976 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	5.49	6.29	520.8	515.3	2345.	2041.
Std.Dev.	12.56	19.17	192.5	152.8	4226.	5120.
R	.5597		.5203		.5403	
E1	14.6%		-1.1%		-12.9%	
E2	52.6%		-20.6%		21.2%	
N	408		375		375	
SF	1.000		.997		.980	
Mean	6.3		513.1		1962.3	
Std.Dev.	19.2		151.7		4921.8	
N	408		408		408	

5.8.2 C12: Vaal River at Nooitgedacht - C1H012

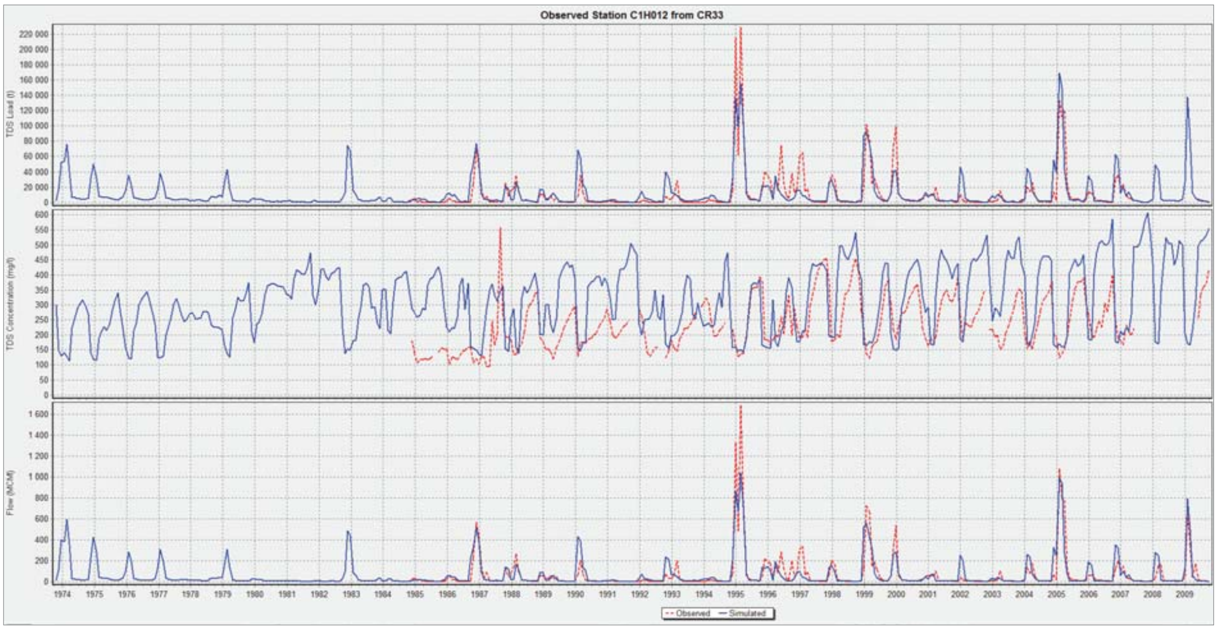

Figure 5.21: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River C1H012

Table 5.21: Comparison between modelled and observed statistical values in the Vaal River C1H012

Route 33CR: C1H012 1985 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	70.51	70.84	235.0	319.6	11589.	12397.
Std.Dev.	184.46	158.21	85.7	116.3	27192.	24212.
R	.8668		.6110		.8334	
E1	.5%		36.0%		7.0%	
E2	-14.2%		35.7%		-11.0%	
N	300		266		277	
SF	1.000		.983		.985	
Mean	70.8		329.1		12769.4	
Std.Dev.	158.2		121.1		24971.1	
N	300		300		300	

5.8.3 **C12: Vaal River at Vaal Dam - C1R001**

The comparison between observed and simulated storage in Vaal Dam showed up worse than at Grootdraai, however the simulated inflow to Vaal Dam compares well to the observed calculated inflow from the Reservoir Record. This again points to inaccuracies with abstractions from the dam. Due to a significant change in storage, the observed storage has only been shown back to 1988.

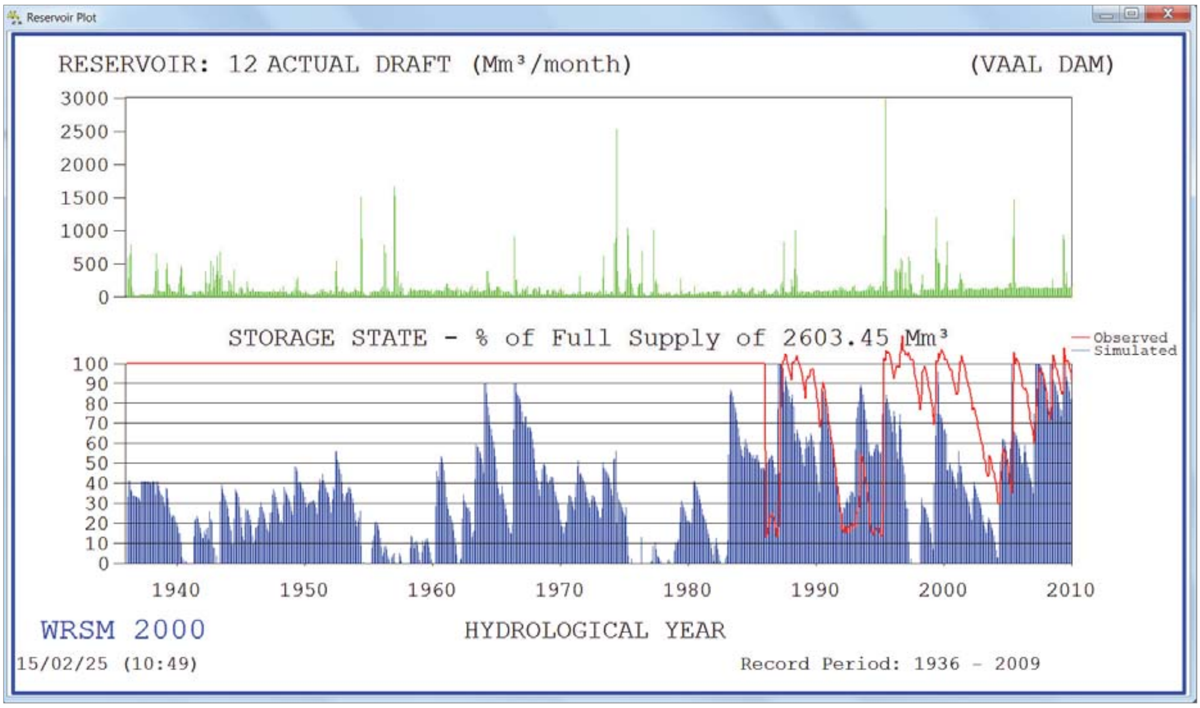

Figure 5.22: Observed and simulated storage in Vaal Dam

5.8.4 **C12: Vaal River in discharge from Vaal Dam – C2H122**

The outflow from Vaal Dam is represented by the observations at weir C2H122. While this weir is strictly located in the C22 tertiary catchment, it actually monitors the discharge from Vaal Dam.

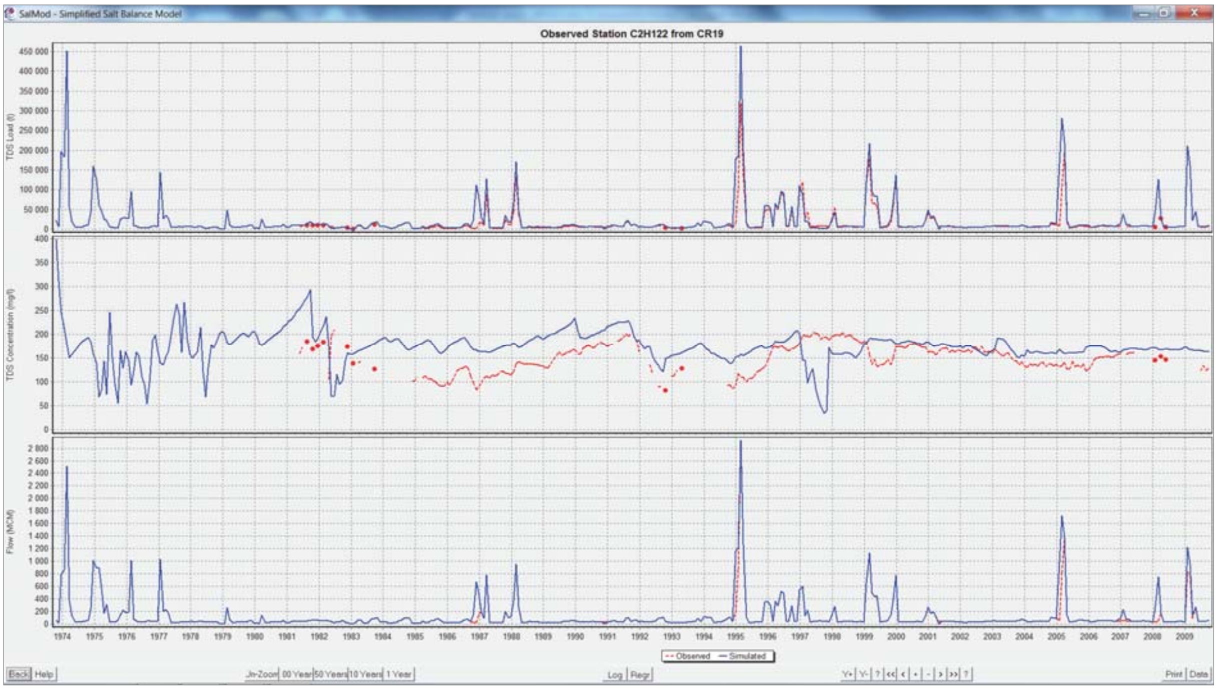

Figure 5.23: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at C2H122

Table 5.22: Comparison between modelled and observed statistical values in the Vaal River at C2H122

Route 19CR: C2H122 1981 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	101.52	119.02	149.3	174.1	16248.	22100.
Std.Dev.	234.24	271.37	29.9	28.8	33599.	48115.
R	.9200		.0413		.9090	
E1	17.2%		16.6%		36.0%	
E2	15.8%		-3.9%		43.2%	
N	348		265		265	
SF	1.000		.995		.961	
Mean	119.0		174.9		20320.6	
Std.Dev.	271.4		29.3		44704.2	
N	348		348		348	

5.9 C21 Tertiary Catchment

5.9.1 C21: Rand Water Weir B10

B10 is a Rand Water weir on the Blesbokspruit at Heidelberg. This station is strategically located downstream of most of the development in the Blesbokspruit / Suikerbosrand C21 system. The diffuse source salt generation rate has been estimated to grow 3.6 times by 2010.

The accuracy of flow gauging at B10 is limited by the modular range of the weir and the short range of the level recording mechanism. Later in the record the first 1 m gauge plate was incorrectly moved in line with the weir plate, thereby rendering the flow record all but useless. Hence little weight can be placed on the TDS load calibration.

The large increase in TDS loads in the second half of the period is attributable to the resumption of pumping from Grootvlei gold mine at a higher discharge rate than before and starting at a substantially higher TDS concentration. The TDS concentration of the mine pumpage has declined from close to 4000 mg/ℓ to about 2000 mg/ℓ over the last 15 years. This is attributable to short circuiting within the mining void after inundation together with a reduction in the rate of sulphate formation in the inundated areas due to oxygen starvation.

Diffuse source pollution plays a major role in the export of salts in the catchment runoff.

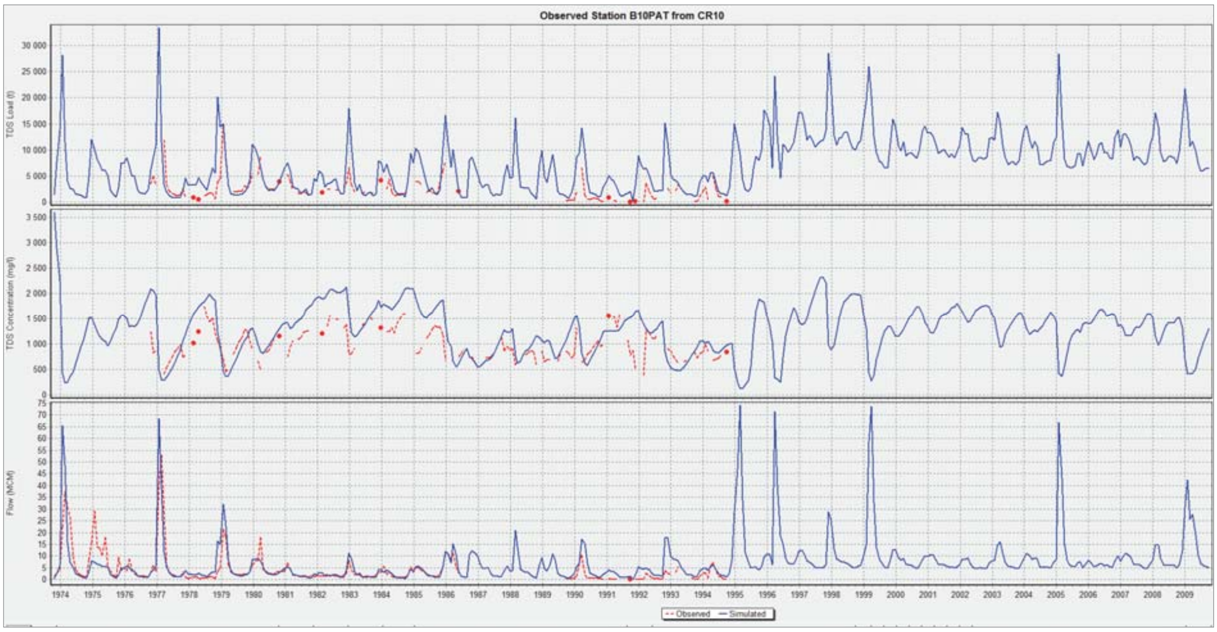

Figure 5.24: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Blesbokspruit RW station B10

Table 5.23: Comparison between modelled and observed statistical values in the Blesbokspruit RW station B10

Route 10CR: 1977 - 1994

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	3.51	4.75	980.1	1205.9	2473.	4453.
Std.Dev.	6.15	7.20	297.4	472.0	2251.	3847.
R	.8291		.7088		.6071	
E1	35.5%		23.0%		80.0%	
E2	17.0%		58.7%		70.9%	
N	166		155		122	
SF	.977		.995		.978	
Mean	4.7		1217.1		4569.7	
Std.Dev.	6.6		477.2		4095.9	
N	216		216		216	

5.9.2 **C21 : Suikerbosrand at Platkoppie - C2H070**

C2H070 is a flood recording station where the base flows are very inaccurate. The recording mechanism was washed away during a flood in 1995 and was never replaced, leaving C2H004 as the only viable gauging weir in the entire C21 tertiary.

The remainder of the Suikerbosrand River below station B10 at Heidelberg is relatively undeveloped. Hence most of the pollution observed at C2H070 is derived from the upper part of the Blesbokspruit above Heidelberg.

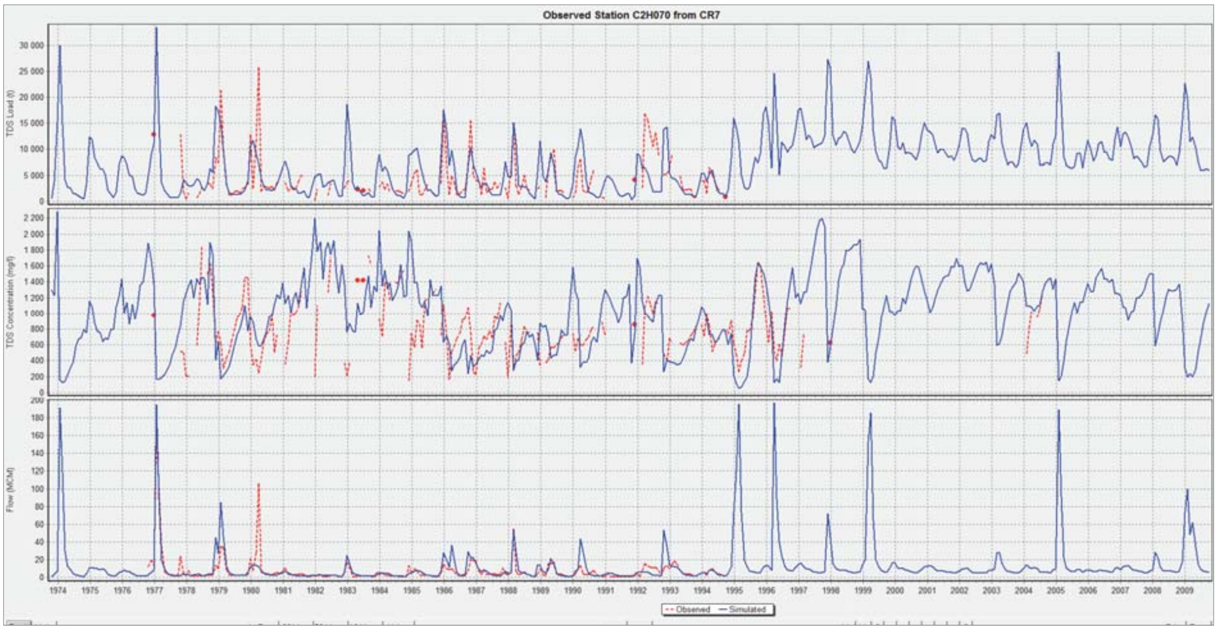

Figure 5.25: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Suikerbosrand River at station C2H070

Table 5.24: Comparison between modelled and observed statistical values in the Suikerbosrand River at station C2H070

Route 7CR: 1977 - 1996

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	7.23	8.08	798.8	874.8	4259.	4985.
Std.Dev.	15.85	17.48	362.0	457.2	4156.	4115.
R	.8144		.4781		.4497	
E1	11.7%		9.5%		17.0%	
E2	10.3%		26.3%		-1.0%	
N	216		178		154	
SF	.819		.980		.959	
Mean	11.3		924.2		5072.3	
Std.Dev.	26.1		468.1		4762.1	
N	240		240		240	

5.9.3 **C21 : Suikerbosrand at Uitvlugt – C2H004**

C2H004 has a limited modular limit and is also subject to backwater effects during high discharges from Vaal Dam. Hence there are several gaps in the flow record during floods. Hence it can be seen that flow gauging in the Suikerbosrand River catchment leaves much to be desired.

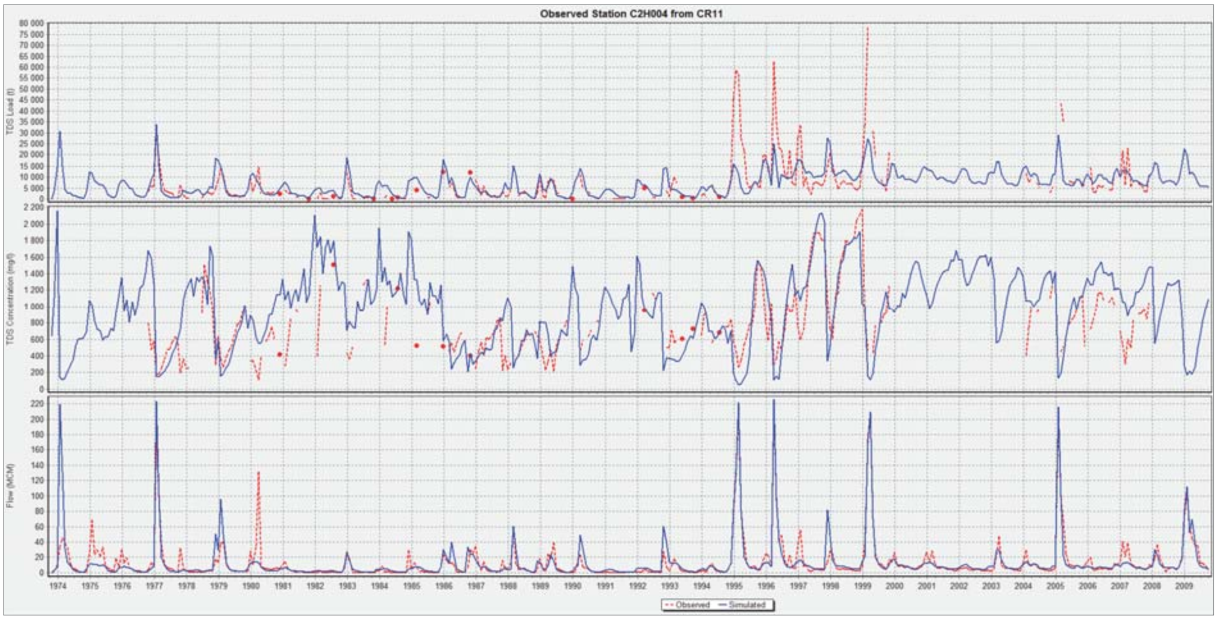

Figure 5.26: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Suikerbosrand River at station C2H004

Table 5.25: Comparison between modelled and observed statistical values in the Suikerbosrand River at station C2H004

Route 11CR: 1977 - 2008

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	13.00	13.20	785.2	897.9	7543.	6990.
Std.Dev.	28.69	29.83	415.8	478.9	10874.	5754.
R	.9276		.7140		.6767	
E1	1.5%		14.3%		-7.3%	
E2	4.0%		15.2%		-47.1%	
N	382		220		238	
SF	.998		.960		.981	
Mean	13.1		997.9		7130.7	
Std.Dev.	29.8		453.3		5446.4	
N	384		384		384	

5.10 C22 Tertiary Catchment

5.10.1 **C22: Klip River at Witkop - C2H021**

The Klip River is the most important source of saline pollution load entering the Vaal River. The usptream catchment is the most highly developed in South Africa. Station C2H021 was discontinued in

1994/5 and replaced by the new station C2H141. The two stations are located very close to one another.

Salt concentrations show a decline from the mid-1980s. This is attributable to three factors:

a) The decline and cessation of mine pumpage (although this has resumed from Grootvlei mine).
b) The implementation of the Rand Water blending scheme, followed by the Vaal Barrage dilution option. This has resulted in a marked improvement in the salt concentration of effluent return flows.
c) The more rapid growth of domestic sewage discharge (which has a substantially lower increase in salt concentration per cycle of reuse), relative to industrial discharge.

A good fit was obtained between modelled and observed TDS concentrations and salt loads at C2H021.

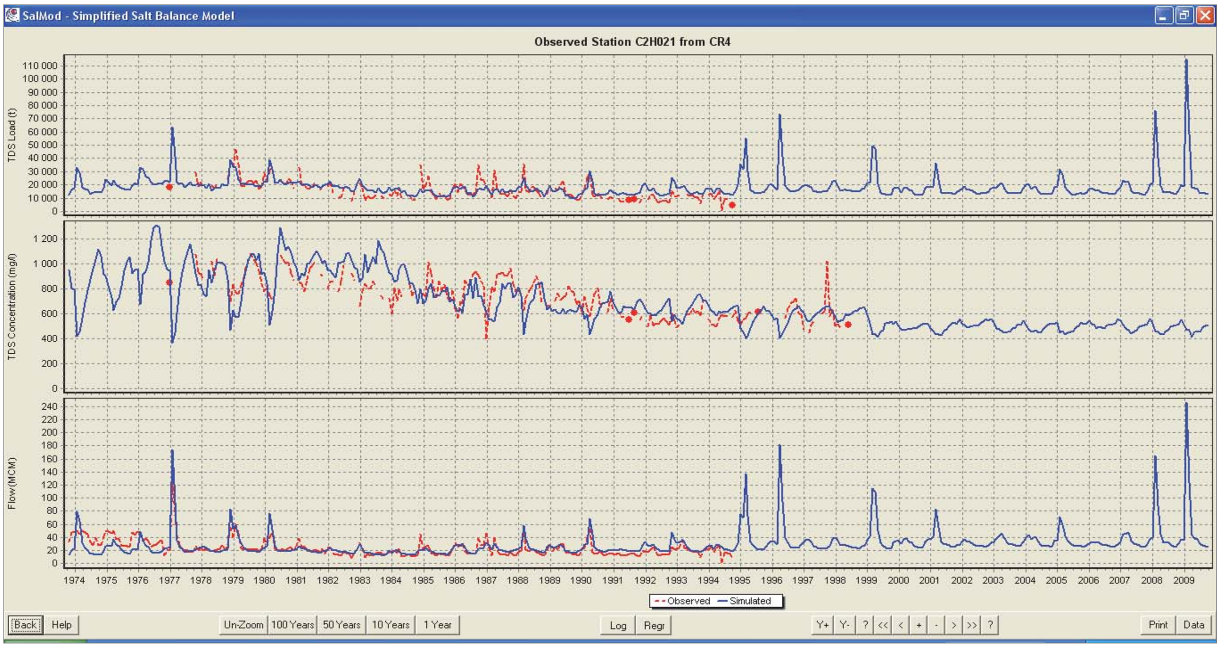

Figure 5.27: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Klip River at station C2H021

Table 5.26: Comparison between modelled and observed statistical values in the Klip River at station C2H021

Route 4CR: C2H021 1977 - 1998

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	21.44	24.02	739.3	744.8	16026.	17116.
Std.Dev.	12.05	14.80	155.5	178.5	7387.	4774.
R	.8696		.7152		.7442	
E1	12.0%		.8%		6.8%	
E2	22.8%		14.8%		-35.4%	
N	216		202		174	
SF	.910		.985		.889	
Mean	26.5		749.1		18083.2	
Std.Dev.	19.2		188.4		7092.5	
N	264		264		264	

5.10.2 **C22: Klip River at Witkop - C2H141**

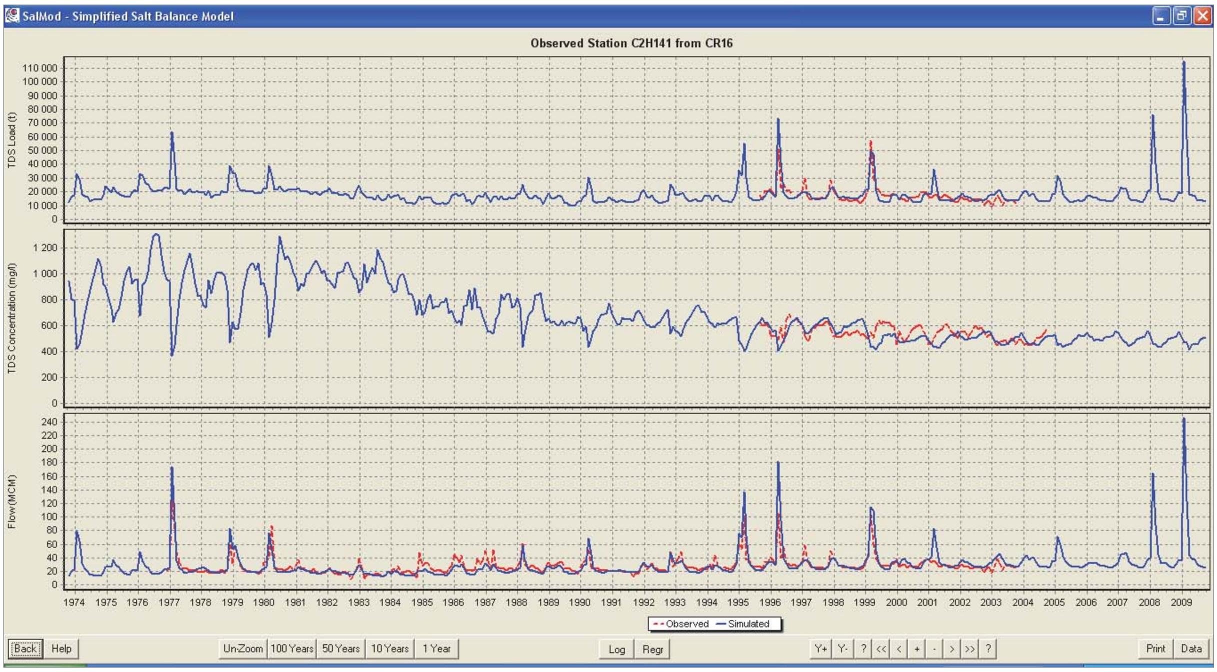

Figure 5.28: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Klip River at station C2H141

Table 5.27: Comparison between modelled and observed statistical values in the Klip River at station C2H141

Route 16CR: C2H141 1995 - 2003

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	32.80	36.53	551.6	533.6	17356.	18055.
Std.Dev.	14.42	23.63	54.9	66.5	6632.	8408.
R	.8643		.4036		.7911	
E1	11.4%		-3.3%		4.0%	
E2	63.9%		21.0%		26.8%	
N	108		97		97	
SF	1.000		.989		.972	
Mean	36.5		534.1		18642.6	
Std.Dev.	23.6		69.5		9099.4	
N	108		108		108	

5.10.3 **C22: Downstream of Vaal Barrage "BAROUT"**

It is noteworthy that the large increase in salt input to the Blesbokspruit due to the resumption of pumping from Grootvlei gold mine (see Figure 4) has had little impact on the salt concentrations at Vaal Barrage. This is indicative of the effect of the Vaal Barrage dilution option and the increasing diluting effect of the growing domestic effluent discharges. This is partially offset by increasing diffuse runoff from the Vaal Barrage catchment.

The modelled TDS concentrations during dry periods in the last third of the plot are significantly lower than in the first two third of the plot. During such conditions the flows are dominated by effluent point discharges. It is therefore unreasonable and ineffective to attempt to rectify this by calibrating increased diffuse source salt generation. The error is most likely attributable to problems with the effluent flow and salinity records. It would require a large scale study to identify and rectify the causes. It is very important to do so, since the Vaal Barrage dilution option requires the release of large quantities of water from Vaal Dam to dilute the TDS concentration in Vaal Barrage to below 600 mg/ℓ. The observed TDS concentrations during this period can be seen to attain this (as expected, since this is the operating rule). The salinity regime of the Vaal river has not been evaluated since the Vaal River System Analysis Update study, which considered data only until September 1995, leaving a gap of over 20 years, which also incorporates over half of the available water quality record. Clearly planning decisions based on such outdated information are extremely dangerous and can jeopardise the water security of the economic heartland of South Africa.

The absence of water quality data in the DWS's WMS system for so critically important a locality as the Vaal Barrage outlet since 2004 (a period of over 10 years) is cause for grave concern. Presumably the information must be available somewhere to support the operation of Vaal Barrage dilution option but it has not been entered into the DWS's database. This serious omission needs to be rectified with immediate effect.

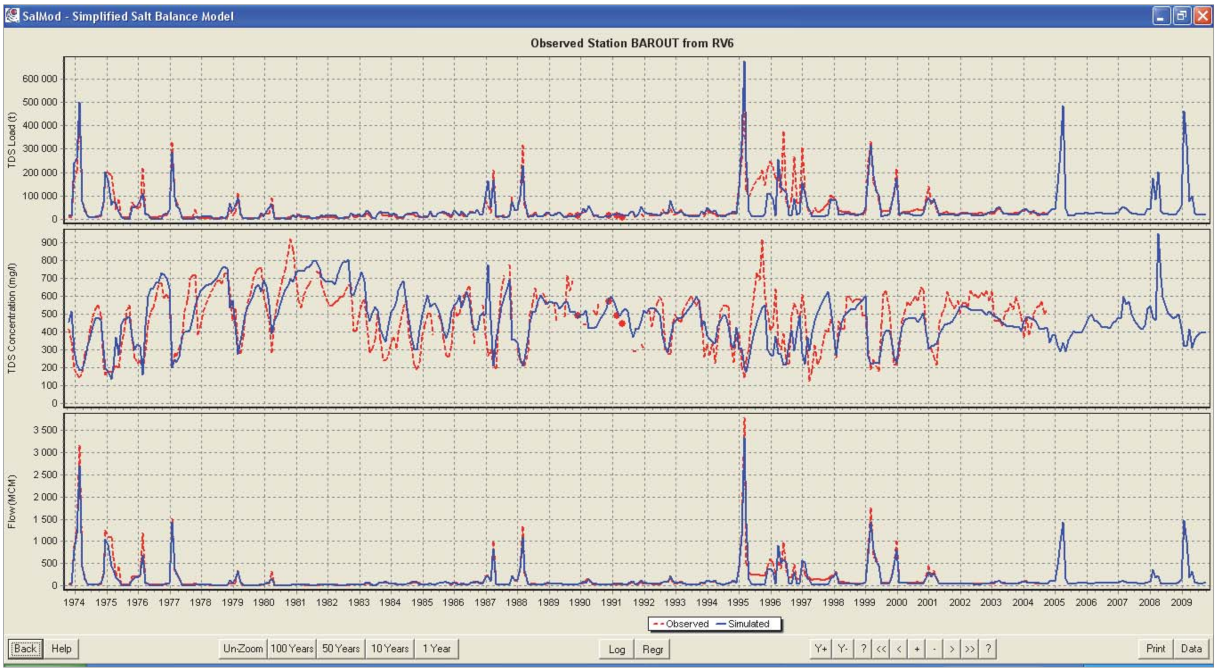

Figure 5.29: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station Barrage outlet

Table 5.28: Comparison between modelled and observed statistical values in the Vaal River at Barrage outlet

Route 6RV: BAROUT 1974 - 2004

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	146.05	127.65	468.4	477.4	46373.	39989.
Std.Dev.	344.42	304.29	159.4	144.3	70135.	65250.
R	.9634		.7055		.8494	
E1	-12.6%		1.9%		-13.8%	
E2	-11.7%		-9.5%		-7.0%	
N	372		347		347	
SF	1.000		.994		.984	
Mean	127.6		480.0		38720.9	
Std.Dev.	304.3		141.6		63269.1	
N	372		372		372	

5.11 C23 Tertiary Catchment

A few enhancements were made to the WRSM2000 hydrological analysis for C23 as follows:

- The C2H069 and C2H008/C2H140 gauges were added to the Wonderfonteinspruit and Vaal River respectively. C2H140 replaced C2H008. The C2H069 gauge was not used for reasons given on the next page;
- The Mine effluent was moved from CR8 to upstream of the C2H069 gauge on the Wonderfonteinspruit; and
- The inflow from the C22 tertiary catchment as well as the SASOL effluent return flow was moved to off-channel of both C23A and C23B quaternary catchments.

Due to a number of problems with obtaining data on return flows, water losses due to riverbed seepage in the dolomitic areas and general complexity (which is beyond the scope of this study), the stations at Klerkskraal Dam (C2R003) and Boskop Dam (C2R001) were not used in the final analysis although attempts were made to calibrate both stations. Therefore the final calibration focus on the C23 tertiary catchment was on the Mooi River at C2H085, the Loopspruit at C2R005 and the Vaal at C2H008/C2H140 and C2H018.

5.11.1 C23: Mooirivierloop at Blaauwbank - C2H069

Although an attempt was made to use the strategically placed C2H069 weir on the lower Mooirivierloop, the attempt had to be abandoned due to lack of adequate information on the complex upstream catchment. This region is characterised by substantial mining activities, complicated by dewatered dolomitic compartments and a pipeline to convey upstream mine pumpage and effluent discharges over the dewatered compartments before discharge back into the Mooirivierloop upstream of C2H069. However, only a fraction of the point discharge actually appears in the surface runoff at this weir since much of it discharges into the dolomitic compartment only to appear at dolomitic eyes downstream of C2H069.

Since modelling these effects successfully would have to be preceded by extensive data gathering and evaluation, the more simplified approach of calibrating on Boskop Dam was adopted. The rationale was that all of the temporarily “lost” upstream point inputs would eventually report to Boskop Dam.

5.11.2 **C23: Loopspruit at Klipdrif Dam - C2R005**

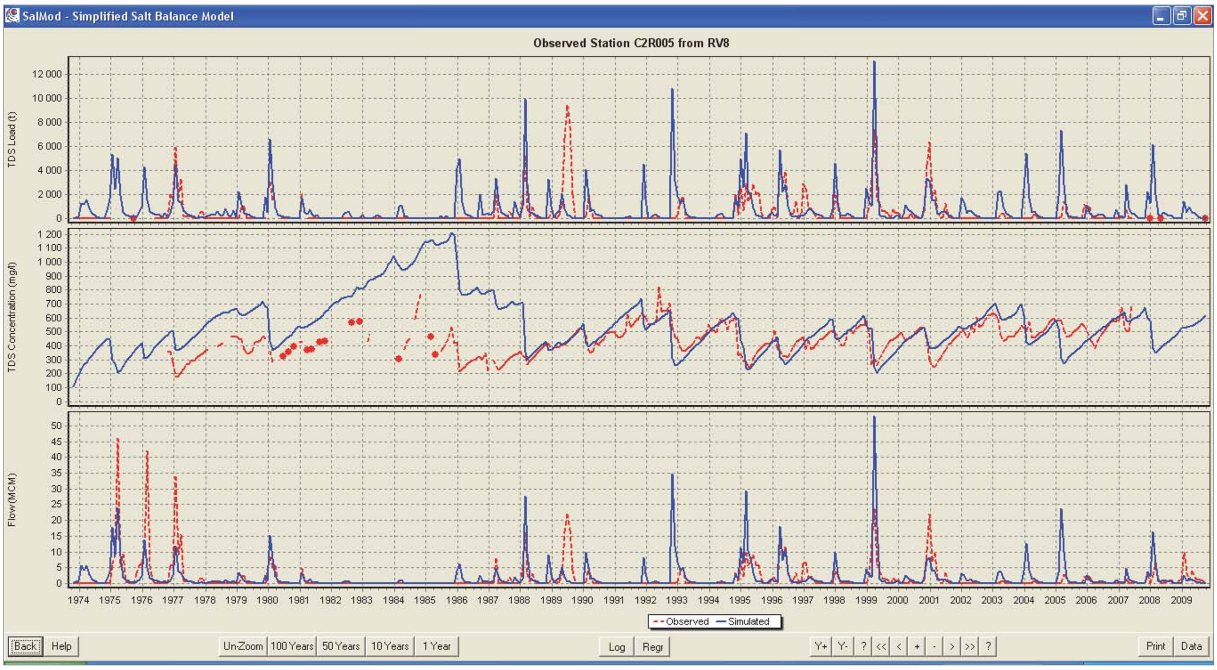

Figure 5.30: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Mooi River at station C2R005

Table 5.29: Comparison between modelled and observed statistical values in the Mooi River at station C2R005

Route 8RV: C2R005 1977 - 2007

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	1.33	1.76	441.6	539.7	445.	703.
Std.Dev.	3.71	4.73	108.3	183.1	1181.	1492.
R	.5223		.1937		.4800	
E1	32.0%		22.2%		58.0%	
E2	27.5%		69.1%		26.4%	
N	372		320		366	
SF	1.000		.963		.997	
Mean	1.8		569.8		698.6	
Std.Dev.	4.7		201.0		1481.0	
N	372		372		372	

The poor fit between modelled and observed flows at Klipdrif Dam inevitably caused deterioration in salinity which affected the calibration. In particular, TDS concentrations during the severe 1980s drought are poorly represented. The comparison between modelled and observed TDS concentrations from 1989 onward is much better, although this is not reflected in the statistics for the entire period.

5.11.3 **C23: Mooi River at Klerkskraal Dam – C2R003**

Klerkskraal Dam is located on the unpolluted upper reaches of the Mooi River, upstream of its confluence with the Mooirivierloop. Interaction with dolomitic aquifers results in a natural salinity of about 400 mg/ℓ.

Despite attempts to calibrate, this station was not used due to problems with the hydrology.

5.11.4 **C23: Mooi River at Boskop Dam - C2R001**

Boskop Dam is located downstream of the upper reaches of the Mooi and the Wonderfonteinspruit. Despite attempts to calibrate, this station was not used for reasons similar to C2H069.

5.11.5 **C23: Mooi River at Hoogekraal - C2H085**

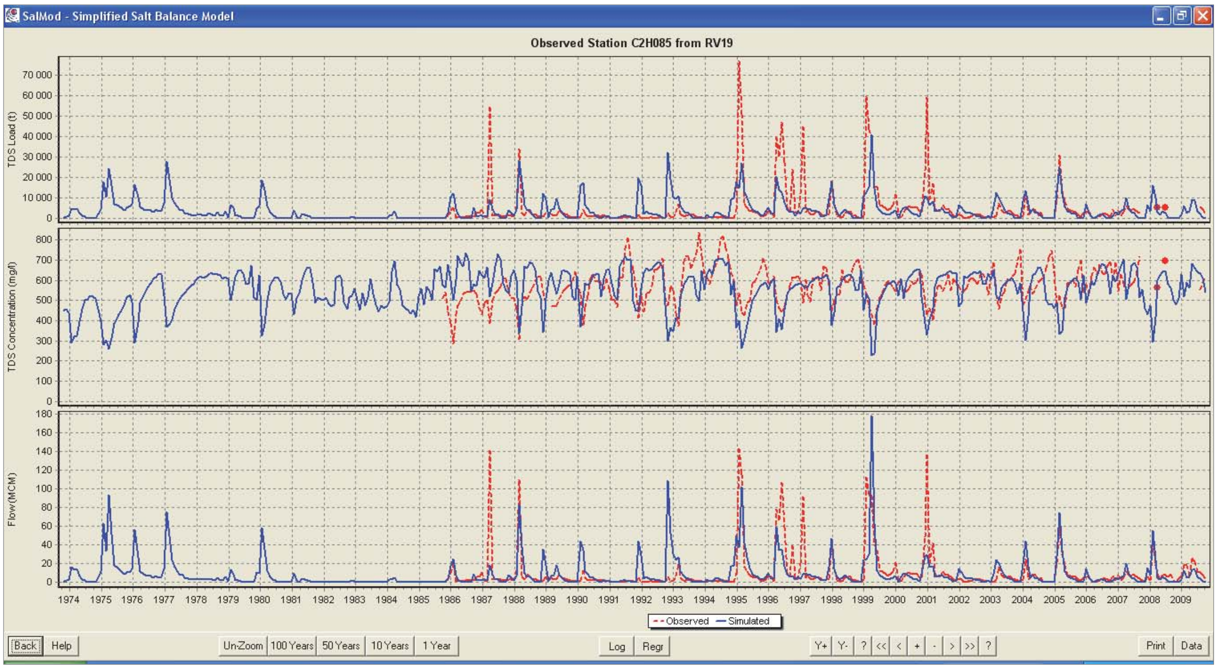

Figure 5.31: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Mooi River at station C2H085

Table 5.30: Comparison between modelled and observed statistical values in the Mooi River at station C2H085

Route 19RV: C2H085 1986 - 2007

MONTHLY STATISTICS	Flow (MCM) Observed	Flow (MCM) Modelled	Concentration (mg/ℓ) Observed	Concentration (mg/ℓ) Modelled	Load (t) Observed	Load (t) Modelled
Mean	10.16	9.90	572.4	570.1	4990.	4373.
Std.Dev.	23.31	18.51	87.9	98.1	10657.	5753.
R	.5630		.4388		.5431	
E1	-2.6%		-.4%		-12.4%	
E2	-20.6%		11.6%		-46.0%	
N	264		262		262	
SF	1.000		.999		.998	
Mean	9.9		570.2		4341.7	
Std.Dev.	18.5		97.7		5742.6	
N	264		264		264	

Due to the unresolved complexities of the upstream system, the correlation between modelled and observed flows as less than desirable. This is reflected in the salinity modelling.

5.11.6 C23: Vaal River at De Vaal - C2H008/C2H140

The inflow from the upstream quaternary C22K (outflow from the Vaal Barrage) enters the upstream end of the C23 tertiary catchment, along with the return flow from SASOL and Vanderbijl Park. In the Vaal River, downstream of C23A and C23B there is a riverbed seepage of 1.16 million m³/a. Downstream of this is the C2H008 station which was in use up to 1995 and was then replaced by C2H140. These two records have been joined to form one observation point.

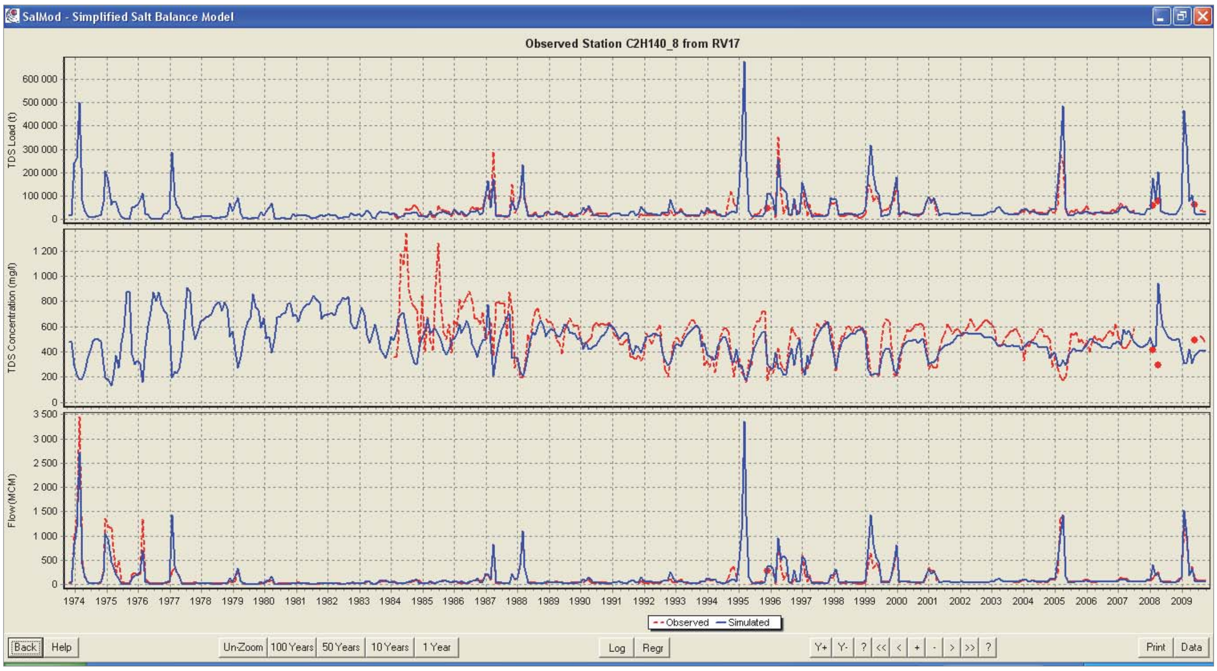

Figure 5.32: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station C2H008/140

Table 5.31: Comparison between modelled and observed statistical values in the Mooi River at station C2H008/C2H140

Route 17RV: C2H008/C2H140 1984 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	111.87	129.45	515.9	458.8	39679.	43100.
Std.Dev.	192.29	226.47	175.2	111.2	44203.	55436.
R	.9205		.6277		.8138	
E1	15.7%		-11.1%		8.6%	
E2	17.8%		-36.5%		25.4%	
N	266		287		241	
SF	.917		.997		.920	
Mean	138.7		459.4		46428.9	
Std.Dev.	295.4		109.9		70831.5	
N	312		312		312	

5.11.7 **C23: Vaal River at De Vaal - C2H018**

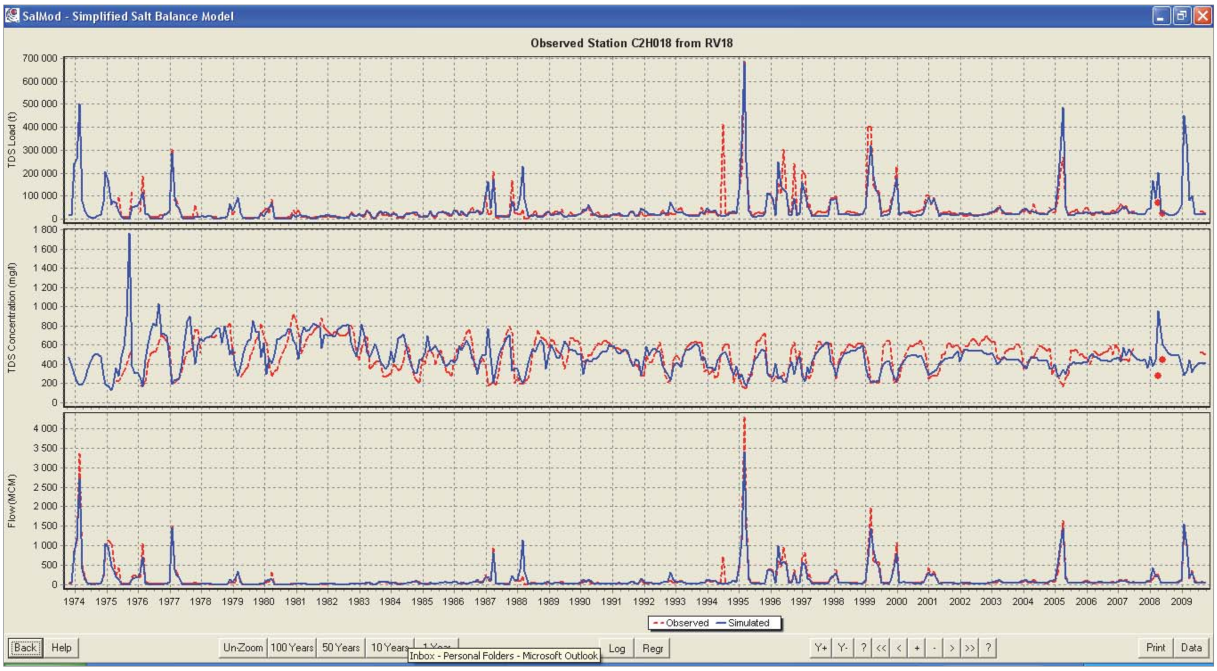

Figure 5.33: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station C2H018

Table 5.32: Comparison between modelled and observed statistical values in the Vaal River at station C2H018

Route 18RV: C2H018 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	136.50	126.87	490.4	492.5	39983.	37342.
Std.Dev.	326.27	282.00	165.3	163.2	64414.	61731.
R	.9522		.5695		.8312	
E1	-7.1%		.4%		-6.6%	
E2	-13.6%		-1.3%		-4.2%	
N	420		383		383	
SF	1.000		.997		.968	
Mean	126.9		488.0		40038.5	
Std.Dev.	282.0		163.8		65473.4	
N	420		420		420	

C2H018 is the last, and reliable, flow gauging weir on the Vaal River in the Upper Vaal sub-WMA. The modelled representation of observed flows and salinity is good.

6 Middle Vaal sub-WMA

For the Middle Vaal WMA, the map shown in Figure 6.1 shows the water quality stations in the catchment and the schematic shown on the next page in Figure 6.2 indicates how the tertiaries link together and the flow and TDS files used in downstream systems. There are no stations at outlets from tertiary catchments in the whole Middle Vaal WMA so all inflows to tertiary catchments from upstream were simulated flow and TDS.

In the Middle Vaal WMA there were quite a number of dams where it was desirable to compare simulated and observed TDS just downstream. With the 2014 version of SALMOD it was noticed that some stations gave enormous simulated TDS which was happening at times where there was no flow. A change was made to SALMOD to check where flow downstream of a dam was zero and if so to define the TDS value as missing value. This was also done for channels. The underlying problem is not actually caused by the simulated zero outflows, but rather stems from the hydrology when the simulated dam storage is too low, resulting in abnormally high calculated salt concentrations. This model change confines the stats and plots to non-zero flows and eliminates the spurious high simulated TDS values.

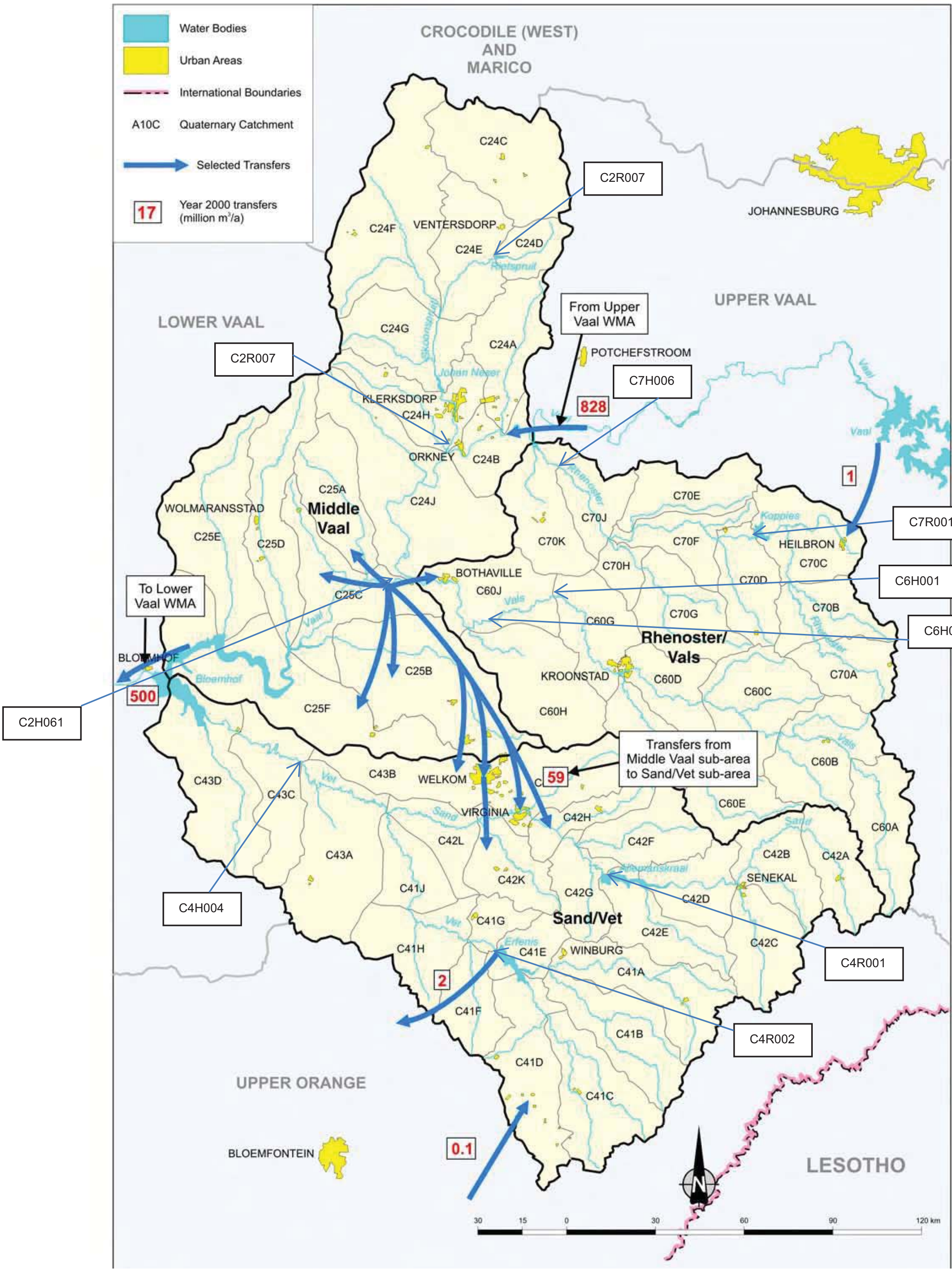

Figure 6.1: Water quality stations: Middle Vaal WMA. (Ref. BKS, 2003 - with water quality stations added)

SALMOD – MIDDLE VAAL

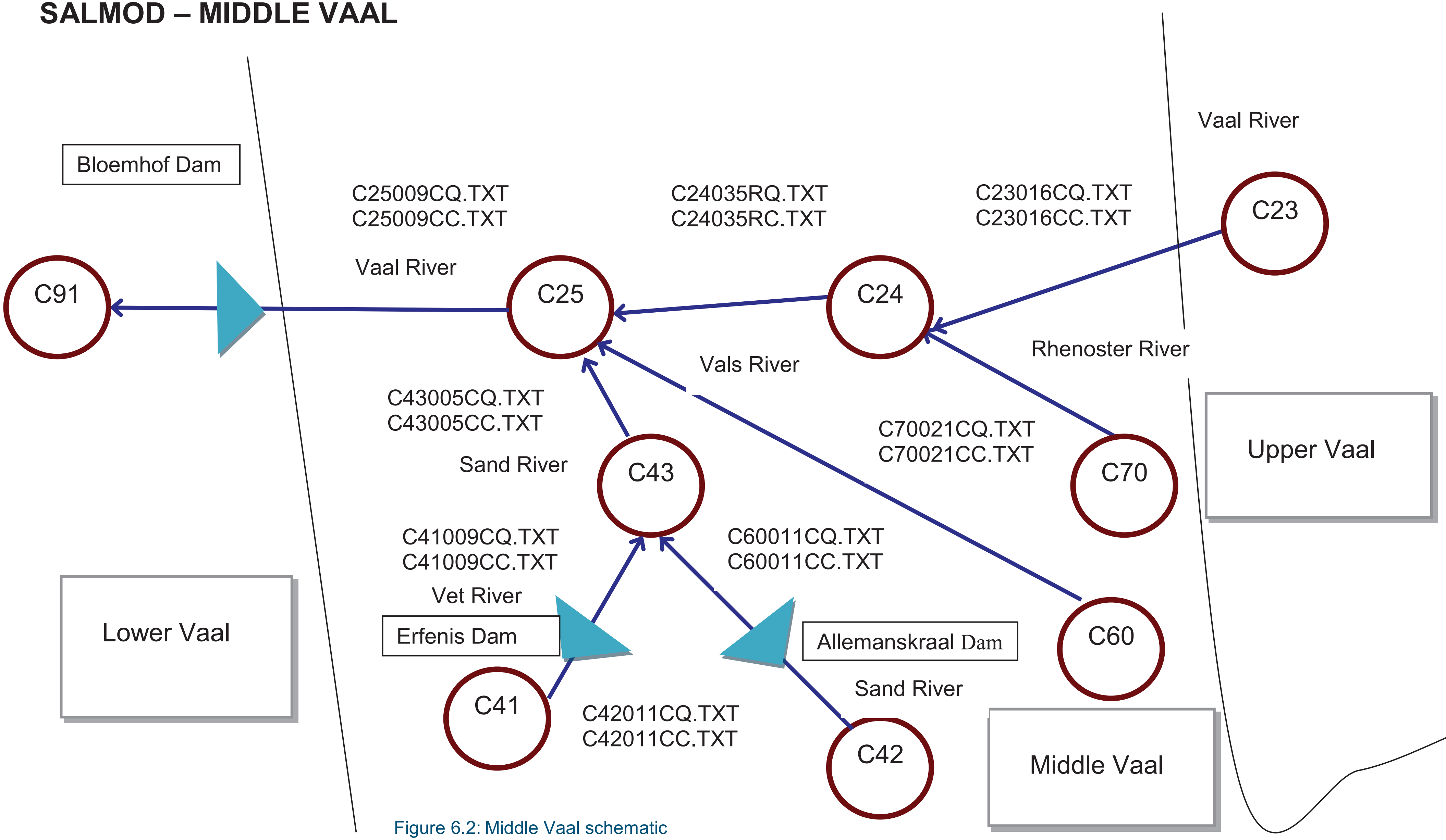

Figure 6.2: Middle Vaal schematic

Note:
From this point on in the analysis a revised version of the SALMOD model was used for some tertiaries which produced a different style of plot. It was not possible to recompile the Delphi plotting version of SALMOD which produced the original plot.

6.1 C70 Tertiary Catchment

6.1.1 C70: Rhenoster River at Koppies Dam – C7R001

For the C7R001 station, spills from Koppies Dam were used together with TDS data for the dam.

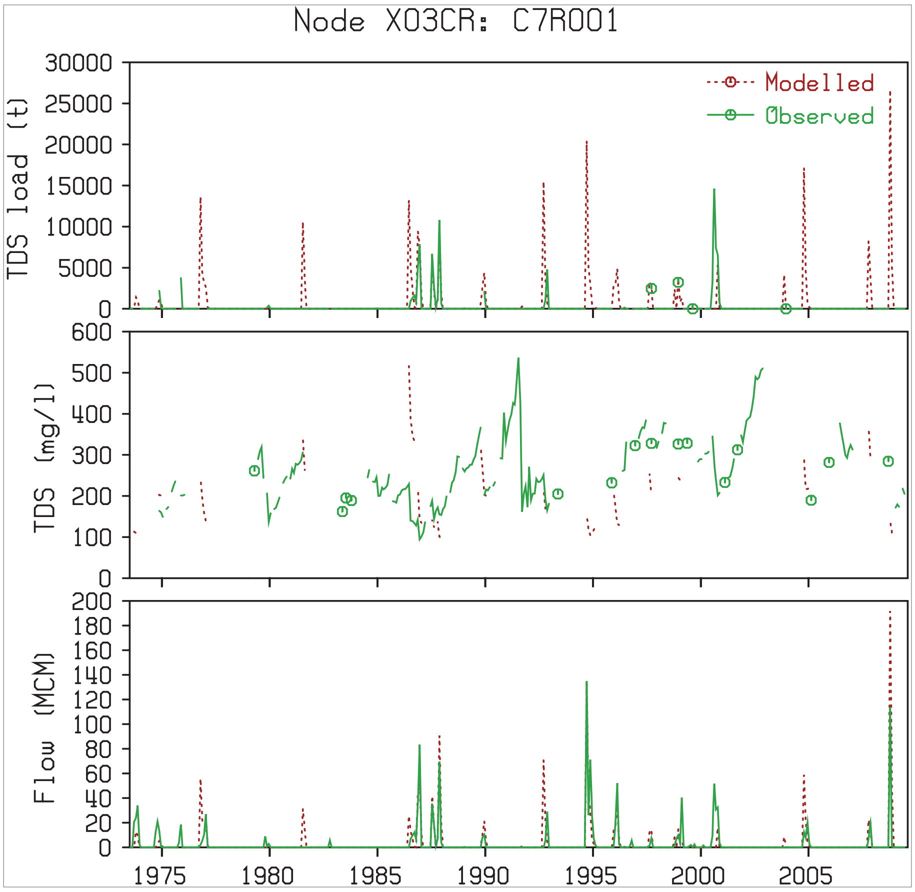

Figure 6.3: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Rhenoster River at station C7R001

Table 6.1: Comparison between modelled and observed statistical values in Rhenoster River at station C7R001

Route 3RV: C7R001 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	2.90	3.27	193.2	232.2	247.	304.
Std.Dev.	12.28	14.69	71.8	104.1	1294.	1555.
R	.7931		.2878		.4083	
E1	13.0%		20.2%		23.0%	
E2	19.6%		45.0%		20.2%	
N	420		25		375	
SF	1.000		.955		.710	
Mean	3.3		214.8		621.0	
Std.Dev.	14.7		94.0		2525.3	
N	420		57		420	

The water quality sample size covering only 25 of the 420 months is much too small to reliably represent salt loads. This is confirmed by the low SF factor - for example, the modelled mean load during the sampled period (304 t/month) is less than half of the modelled mean for the entire period (621 t/month). This implies that many of the most significant flood events were not sampled. Hence it is not reasonable to force the calibrated modelled load to fit the inadequate sampled loads, especially since doing so would have caused significant deterioration in the salinity fit at the downstream gauging station at C7H006, where the sampling is much more representative.

6.1.2 C70: Rhenoster River at Arriesrust – C7H006

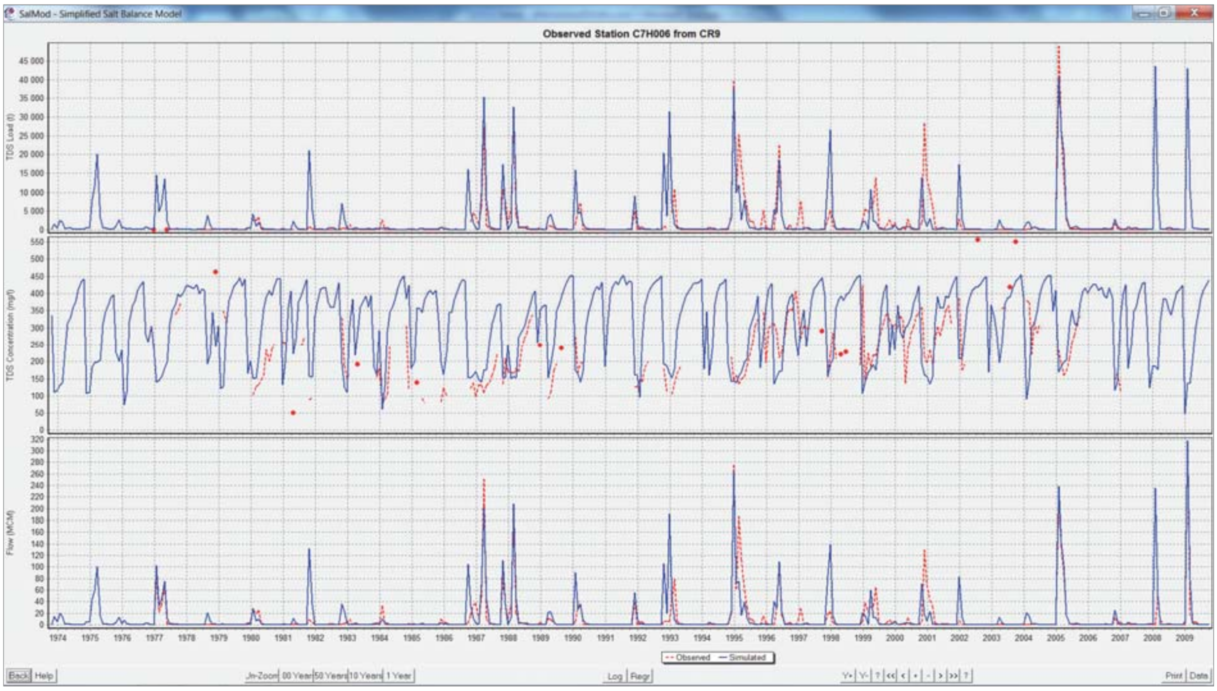

Figure 6.4: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Rhenoster River at station C7H006

Table 6.2: Comparison between modelled and observed statistical values in the Rhenoster River at station C7H006

Route 9CR: C7H006 1977 - 2007

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	9.46	11.32	231.8	270.5	1650.	1894.
Std.Dev.	30.87	33.21	93.6	88.3	5258.	5194.
R	.7731		.4172		.7799	
E1	19.6%		16.7%		14.8%	
E2	7.6%		-5.7%		-1.2%	
N	372		183		345	
SF	1.000		.962		.967	
Mean	11.3		308.7		2040.0	
Std.Dev.	33.2		86.6		5499.3	
N	372		372		372	

A good fit was obtained between modelled and observed salt loads, as per the stats and the plot. The modelled mean load was deliberately calibrated above the observed mean load to allow for the fact that the mean modelled flow was 20% lower than the mean observed flow during this period. The statistical fit between modelled and observed TDS concentrations was not as good, but the plot shows that the representation was generally reasonable.

6.2 C24 Tertiary Catchment

C24 receives inflow from the Upper Vaal tertiary catchment C23 and from the Middle Vaal tertiary C70.

6.2.1 **C24: Vaal River at Pilgrim's Estate Dam – C2H007**

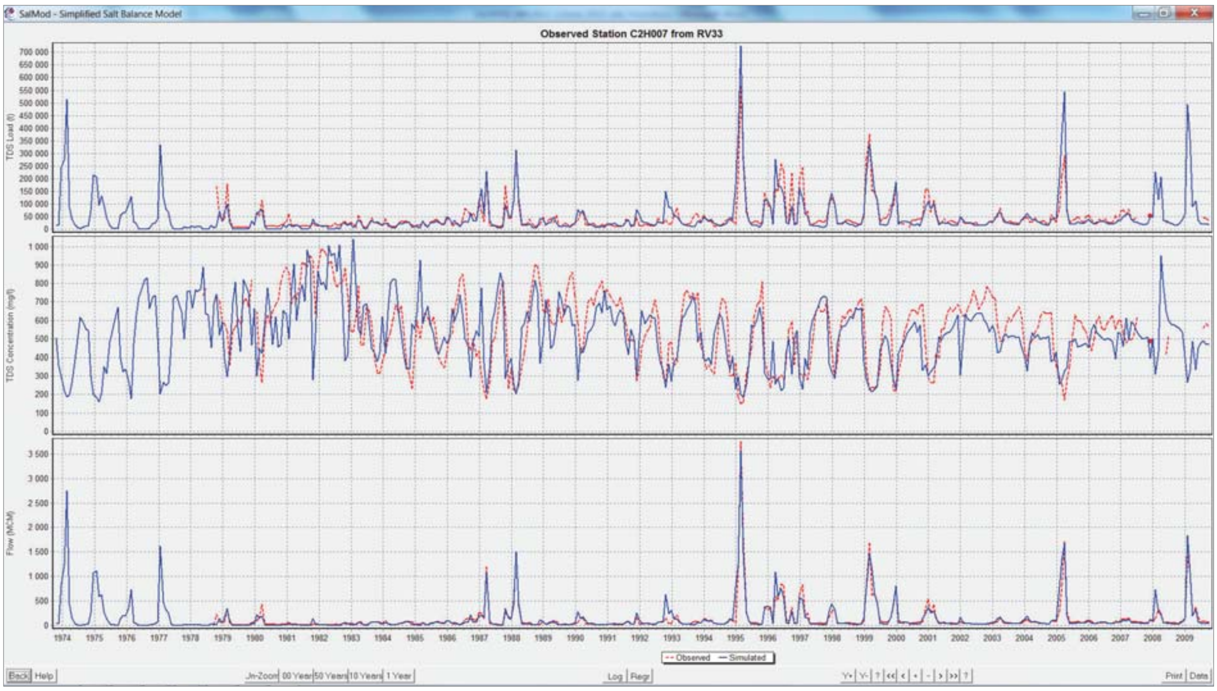

Figure 6.5: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station C2H007

Table 6.3: Comparison between modelled and observed statistical values in the Vaal River at station C2H007

Node 33RV: C2H007 1978 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	136.49	139.52	561.8	530.0	46581.	44187.
Std.Dev.	307.60	314.05	179.8	164.4	60062.	70649.
R	0.9530		0.6784		0.8802	
E1	2.2%		-5.7%		-5.1%	
E2	2.1%		-8.6%		17.6%	
N	372		352		348	
SF	0.990		0.998		0.979	
Mean	135.6		532.5		45650.4	
Std.Dev.	309.9		164.1		74502.4	
N	384		384		384	

The flow fit at this station is good, as is that for concentration and salt load.

6.2.2 C24: Rietspruit at Rietspruit Dam – C2R007

It was not possible to get a reasonable correlation between observed and simulated flow and TDS at this station due to inaccurate return flow data.

6.2.3 C24: Swartleegte River at Elandskuil Dam – C2R006

It was not possible to get a reasonable correlation between observed and simulated flow and TDS at this station due to inaccurate return flow data.

6.2.4 C24: Skoonspruit at Goodgenoeg – C2H073

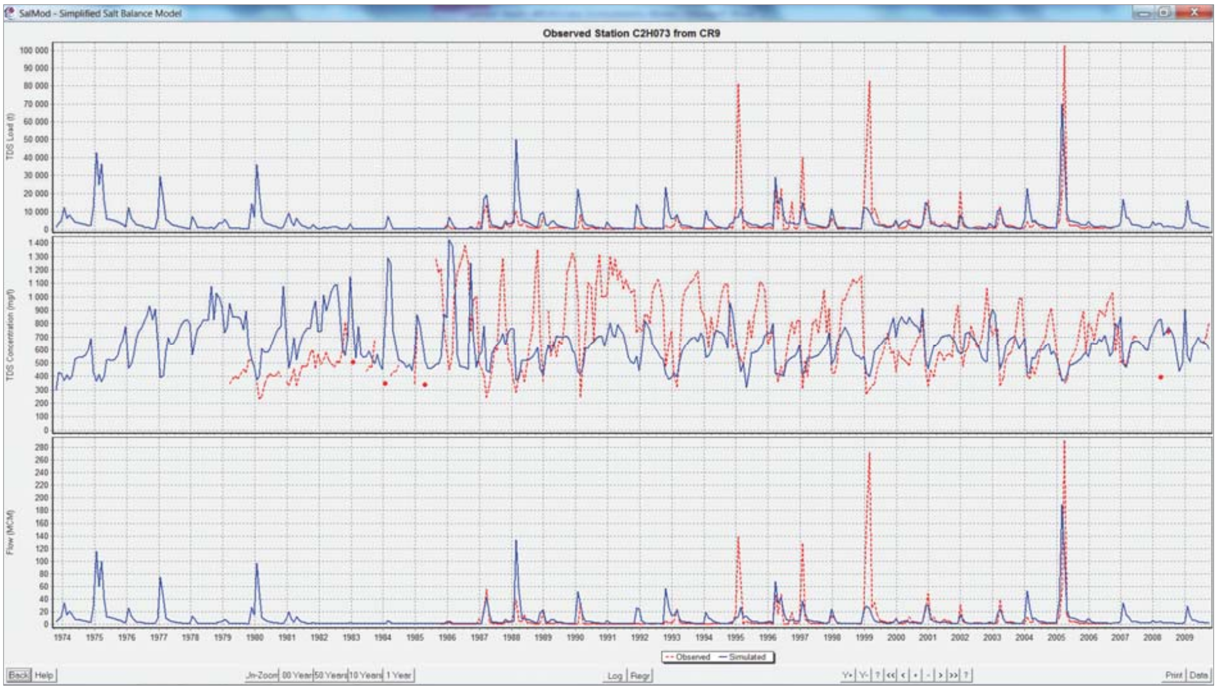

Figure 6.6: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station C2H073

Table 6.4: Comparison between modelled and observed statistical values in the Skoonspruit River at station C2H073

Route 9CR: C2H073 1978 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	8.80	8.85	695.7	755.3	3777.	3845.
Std.Dev.	30.41	18.80	270.3	263.6	10928.	5182.
R	.4761		.3336		.4402	
E1	.6%		8.6%		1.8%	
E2	-38.2%		-2.5%		-52.6%	
N	252		323		251	
SF	.922		.987		.945	
Mean	7.4		777.1		3404.6	
Std.Dev.	16.6		257.6		4697.7	
N	384		384		384	

35% gaps in the flow record and the poor hydrological fit resulted in a correspondingly poor load correlation. Nevertheless it was possible to get a good match between modelled and observed mean loads. The good correspondence between the modelled and observed mean and standard deviation of the TDS concentrations is belied by the poor correlation coefficient, as shown in the plot. The poor correlation is in keeping with the hydrological inaccuracy.

6.3 C60 Tertiary Catchment

6.3.1 **C60: Vals River at Kroonstad – C6H007**

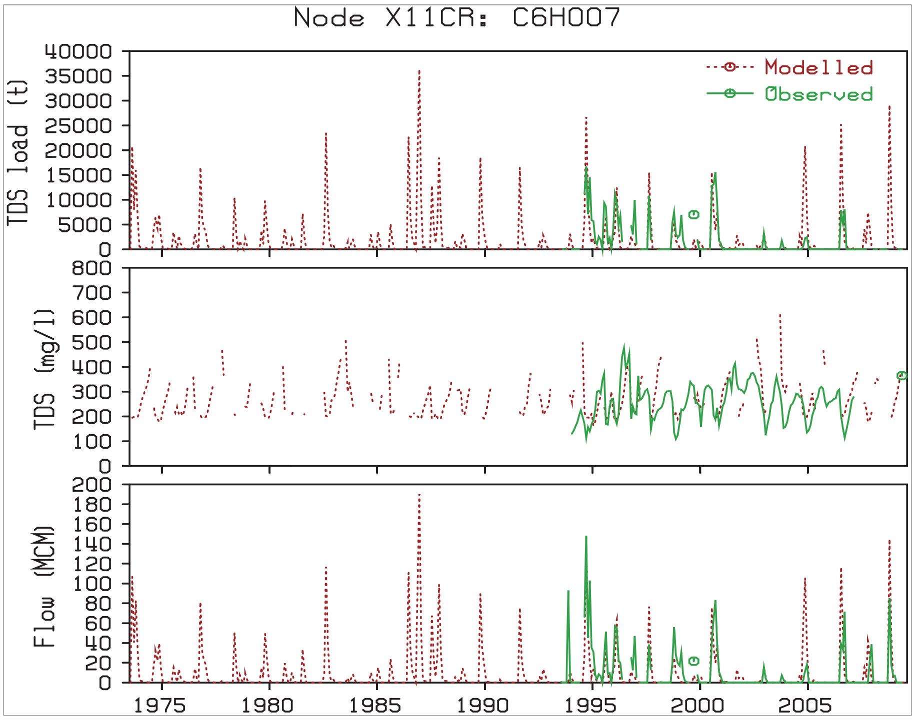

Figure 6.7: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vals River at station C6H007

Table 6.5: Comparison between modelled and observed statistical values in the Vals River at station C6H007

Route 11RV: C6H007 1994 - 2007

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	10.57	8.56	238.3	272.0	1897.	1800.
Std.Dev.	22.57	21.17	78.6	84.8	3649.	4301.
R	.6154		.4222		.6355	
E1	-19.0%		14.2%		-5.1%	
E2	-6.2%		7.8%		17.9%	
N	154		103		151	
SF	.970		.982		.967	
Mean	7.9		276.7		1648.5	
Std.Dev.	20.4		89.4		4108.0	
N	168		107		168	

A moderate salinity calibration was obtained at this station.

6.3.2 **C60: Vals River at Roodewal – C6H001**

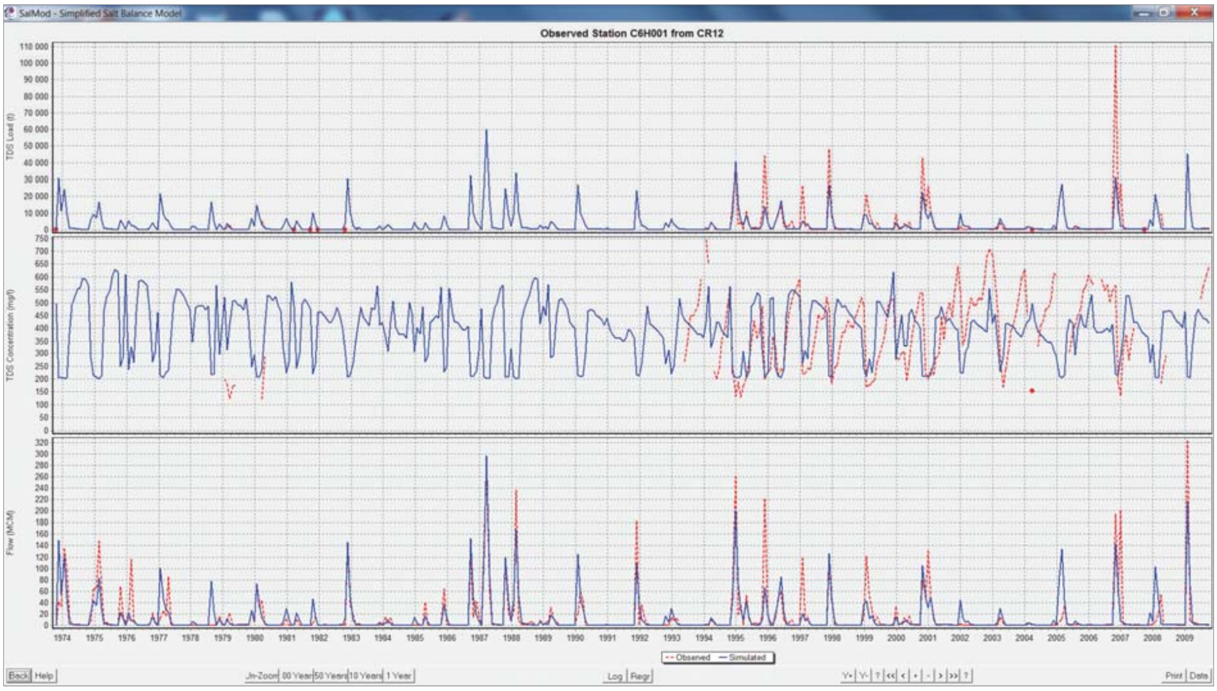

Figure 6.7: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vals River at station C6H001

Table 6.5: Comparison between modelled and observed statistical values in the Vals River at station C6H001

Route 12CR: C6H001 1993 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	14.10	12.62	399.8	434.8	3687.	2746.
Std.Dev.	42.01	30.95	144.4	124.4	11325.	5907.
R	.7542		.3464		.8092	
E1	-10.5%		8.8%		-25.5%	
E2	-26.3%		-13.8%		-47.8%	
N	204		166		169	
SF	1.000		.988		.917	
Mean	12.6		426.0		3275.2	
Std.Dev.	30.9		121.1		6920.0	
N	204		204		204	

A moderate salinity calibration was obtained at this station.

6.3.3 **C60: Vals River at Mooifontein – C6H003**

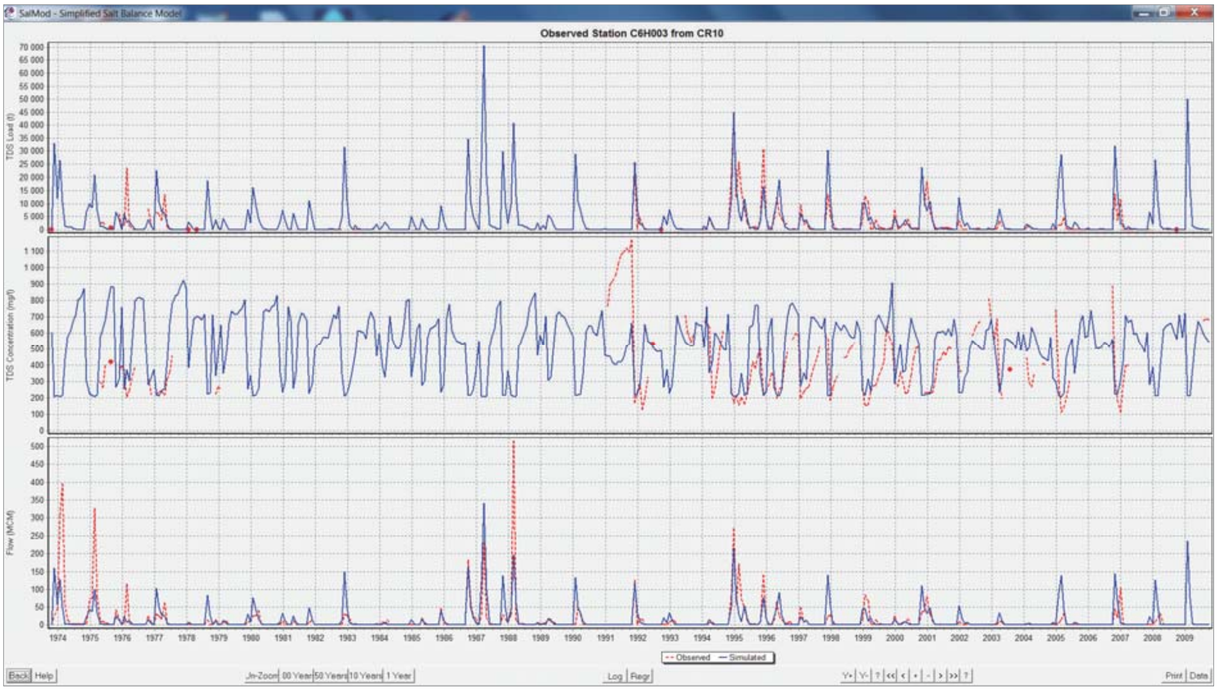

Figure 6.8: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vals River at station C6H003

Table 6.6: Comparison between modelled and observed statistical values in the Vals River at station C6H003

Route 10CR: C6H003 1991 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	10.60	12.51	425.7	541.1	2315.	3307.
Std.Dev.	29.94	30.23	221.9	195.8	5670.	6904.
R	.6470		.3599		.7354	
E1	18.0%		27.1%		42.9%	
E2	1.0%		-11.8%		21.8%	
N	208		139		186	
SF	.973		.891		.963	
Mean	12.8		577.4		3468.8	
Std.Dev.	32.9		284.7		7634.0	
N	228		222		228	

Although the correlation was good, the modelled load was very low. However, the load error is only 2% of the observed load in the Vaal at station C2H007. The sample size was too small to adequately represent TDS concentrations.

6.4 C41 Tertiary Catchment

In C41 and C42 there is just one station in each WMA at the major dams Erfenis and Allemanskraal dams respectively. There are large irrigation releases at both dams into irrigation canals as well as spills. There are also end of canal releases into the river for farmers located in the C43 quaternary who don't have access to the canals. In order to model the flow, TDS and load correctly, in the model a dummy channel reach and a dummy reservoir were used downstream of the dam. Canal releases, spills and river releases were accumulated into the dummy channel reach. Downstream of this dummy channel reach the observed flow, TDS and load were analysed. The observed flow was taken to be the spill file (from the DWS website) added to the observed release (from the Reservoir Record). At the dummy reservoir, the canal releases were taken out of the system, and the remaining flow returned to the downstream channel reach. These details are shown in the network diagrams.

6.4.1 **C41: Vet River at Erfenis Dam – C4R002**

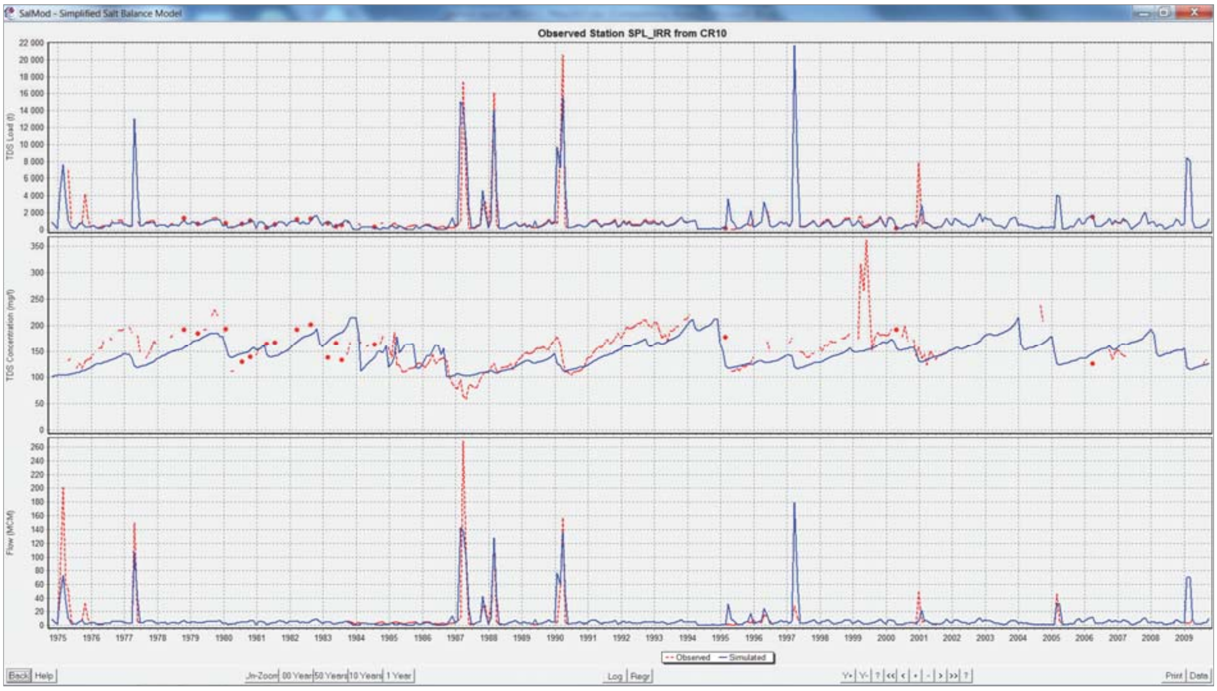

Figure 6.9: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vet River at station C4R002

Table 6.7: Comparison between modelled and observed statistical values in the Vet River at station C4R002

Node 10CR: C4R002 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	7.58	8.16	154.4	140.7	1046.	1040.
Std.Dev.	21.40	19.08	38.2	23.0	2166.	2124.
R	0.6966		0.6250		0.7640	
E1	7.8%		-8.9%		-0.6%	
E2	-10.8%		-39.7%		-1.9%	
N	420		240		240	
SF	1.000		0.965		0.991	
Mean	8.2		147.2		1064.6	
Std.Dev.	19.1		25.3		2149.9	
N	420		420		420	

A good fit was obtained between modelled and observed salt loads. That for TDS concentrations was also good, except for the peak concentration shown in the plot during 1999.

6.5 C42 Tertiary Catchment

6.5.1 **C42: Sand River at Allemanskraal Dam – C4R001**

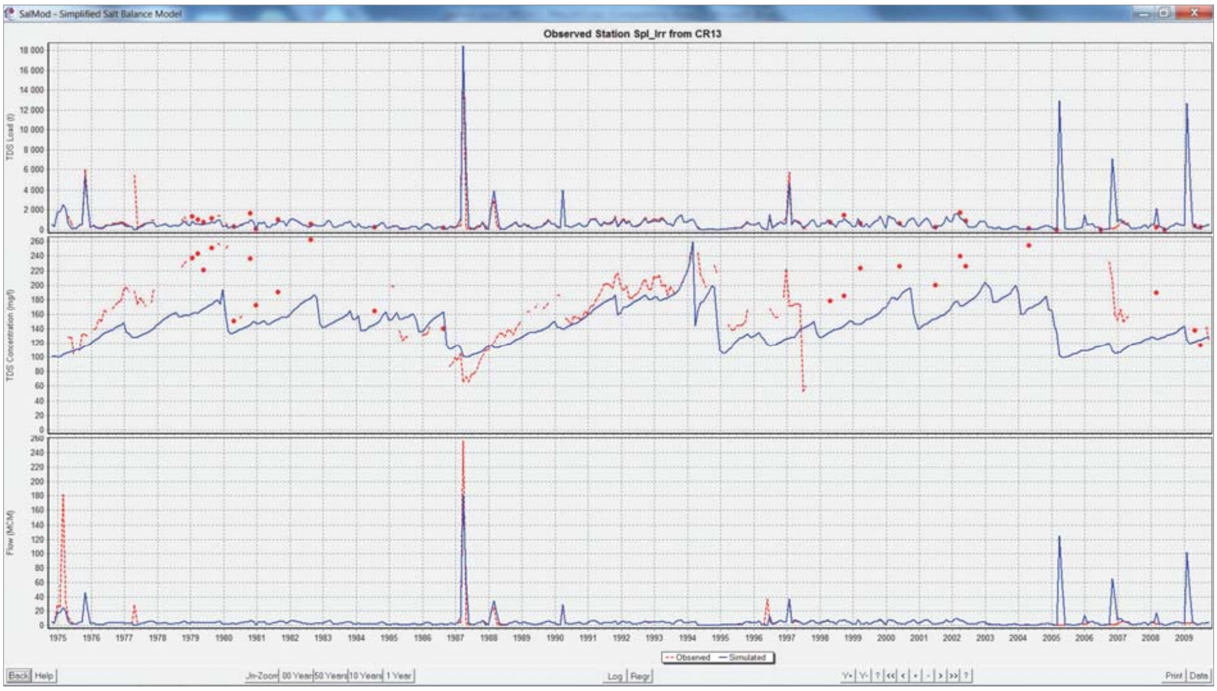

Figure 6.10: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Sand River at station C4R001

Table 6.8: Comparison between modelled and observed statistical values in the Sand River at station C4R001

Node 13CR: C4R001 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	4.90	5.47	169.0	144.2	770.	781.
Std.Dev.	15.82	13.34	43.7	27.7	1420.	1586.
R	0.6078		0.6936		0.8413	
E1	11.6%		-14.7%		1.5%	
E2	-15.7%		-36.6%		11.7%	
N	420		186		189	
SF	1.000		0.984		0.956	
Mean	5.5		147.0		726.3	
Std.Dev.	13.3		26.5		1430.6	
N	420		420		420	

The flow correlation is less than desired. Although that for loads is much higher, this cannot be construed as significant as it is likely to include fortuitous compensating errors, since the load correlation is usually dominated by that of the flows. (This is because the variance of the salt loads is dominated by the flow peaks.) TDS concentrations are under-estimated for most events.

6.6 C43 Tertiary Catchment

It is very clear that the load rises dramatically in C43 during big floods that cause mining containment structures to spill. This is the opposite of what we normally see (reducing TDS with increasing flow). In the last decade or two the salinity concentration increase has been triggered by even smaller floods. This is due to closure of the mines north of the Sand River draining towards Witpan. In the past the northern mines pumped water from Witpan for use in their reduction plants. This no longer happens since the mines have closed. However, there is still a lot of runoff to Witpan from mine dumps, etc. Witpan also receives a substantial sewage effluent inflow from Welkom. Since Welkom receives high TDS water supply from the Vaal River, then adds salt to this, the Welkom effluent would enter Witpan at close to 1000 mg/ℓ. Evaporative concentration in this erstwhile natural evaporation pan increases the salt concentration. Since the mining of this water has been reduced, it doesn't take much to cause Witpan to spill during flood events, with an ensuing increase in the salt load during such events.

6.6.1 **C43: Vet River at Fizantkraal – C4H004**

This WMA receives inflow from C41 and C42 and has only one station at C4H004.

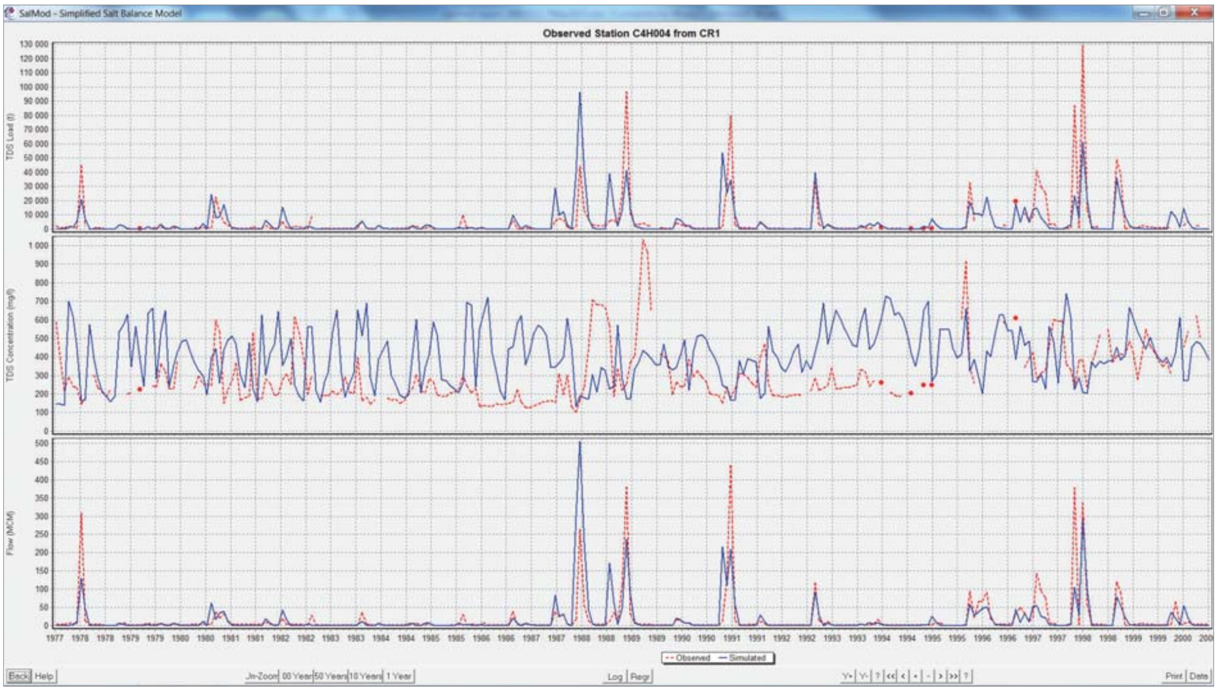

Figure 6.11: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vet River at station C4H004

Table 6.9: Comparison between modelled and observed statistical values in the Vet River at station C4H004

Node 1CR: C4H004 1977 - 1999

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	17.89	17.07	300.8	397.5	5080.	4816.
Std.Dev.	55.17	51.13	155.5	152.5	14783.	11240.
R	0.6950		0.0027		0.6752	
E1	-4.6%		32.2%		-5.2%	
E2	-7.3%		-2.0%		-24.0%	
N	276		235		236	
SF	1.000		0.991		0.965	
Mean	17.1		406.6		4463.6	
Std.Dev.	51.1		150.6		10562.7	
N	276		276		276	

C4H004 is a hydro-flume designed to pass the excessive sediment load. However, this reduces the accuracy of the flow gauging. A reasonable fit was obtained between modelled and observed salt loads. However, the TDS concentration fit is very poor since it is impossible to model salt concentrations without detailed information on the water and salt balance of Witpan.

6.7 C25 Tertiary Catchment

6.7.1 **C25: Vaal River at Klipplaatdrif – C2H061**

The only gauge worth analysing in this catchment is C2H061. C2H066 and C2H067 are miniscule (0.005 of the observed load at C2H061).

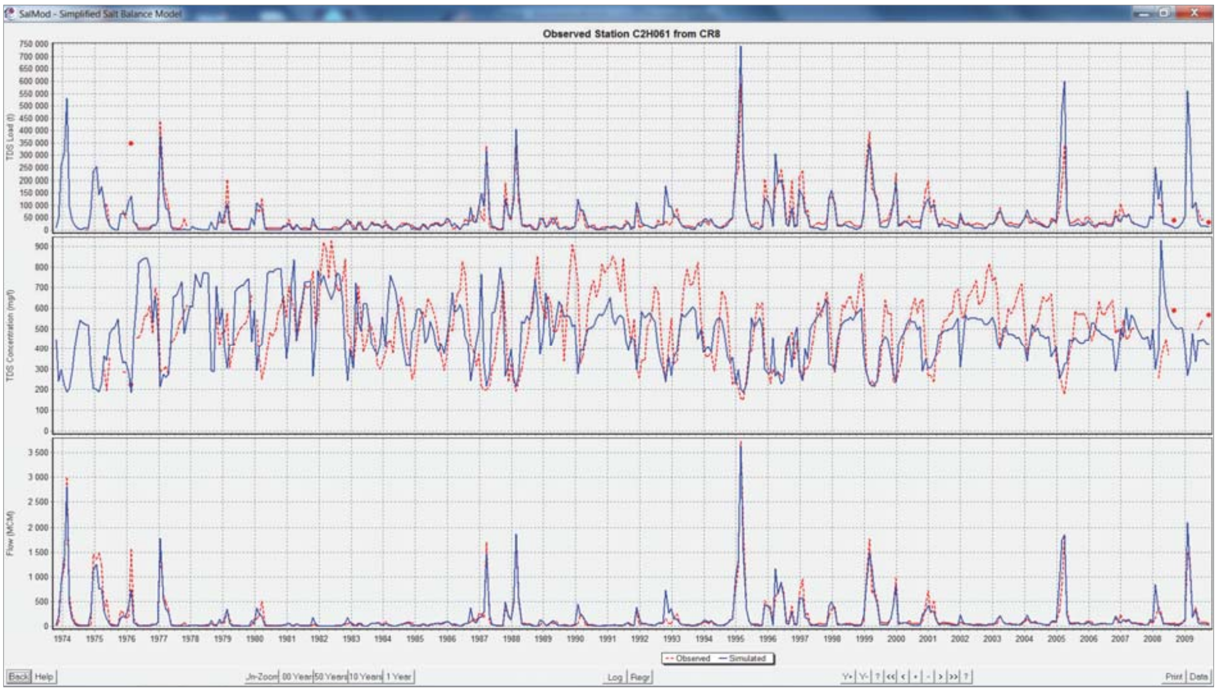

Figure 6.12: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station C2H061

Table 6.10: Comparison between modelled and observed statistical values in the Vaal River at station C2H061

Route 8CR: C2H061 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	160.73	157.21	507.4	488.1	47113.	45381.
Std.Dev.	354.04	349.30	167.9	144.5	69492.	79818.
R	.9344		.4913		.8899	
E1	-2.2%		-3.8%		-3.7%	
E2	-1.3%		-13.9%		14.9%	
N	420		379		380	
SF	1.000		.995		.972	
Mean	157.2		485.9		47995.6	
Std.Dev.	349.3		146.5		84334.5	
N	420		420		420	

The good flow fit enables a correspondingly good salt load fit. Reasonable modelled TDS concentrations were also obtained, although the standard deviation was impaired by over-estimation during low flow conditions.

7 Lower Vaal sub-WMA

The map shown in Figure 7.1 shows the water quality stations in the Lower Vaal sub-WMA. The catchment and the schematic shown on the next page in Figure7.2 indicate how the tertiaries link together and the flow and TDS files used in downstream systems.

The Vaalharts irrigation scheme is the major water user in this WMA. The tertiary C91 needs to be solved before C33 so that the return flow TDS values for the Vaalharts irrigation can be determined which is required as input to the lower part of C33. The Vaalharts irrigation scheme was split into two as there is an area upstream of C3H007 and another smaller area between C3H007 and Spitskop Dam.

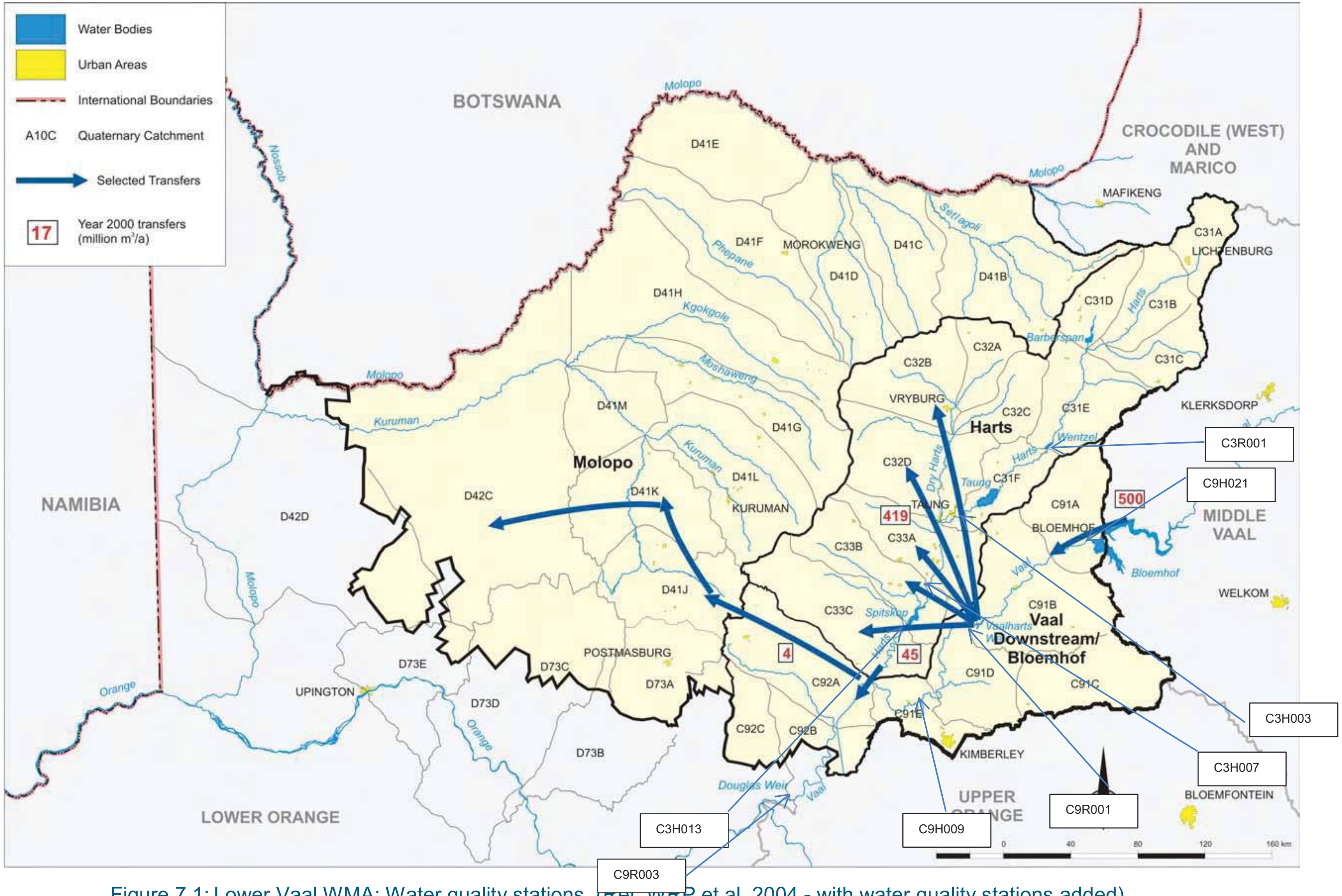

Figure 7.1: Lower Vaal WMA: Water quality stations. (Ref. WRP et al, 2004 - with water quality stations added)

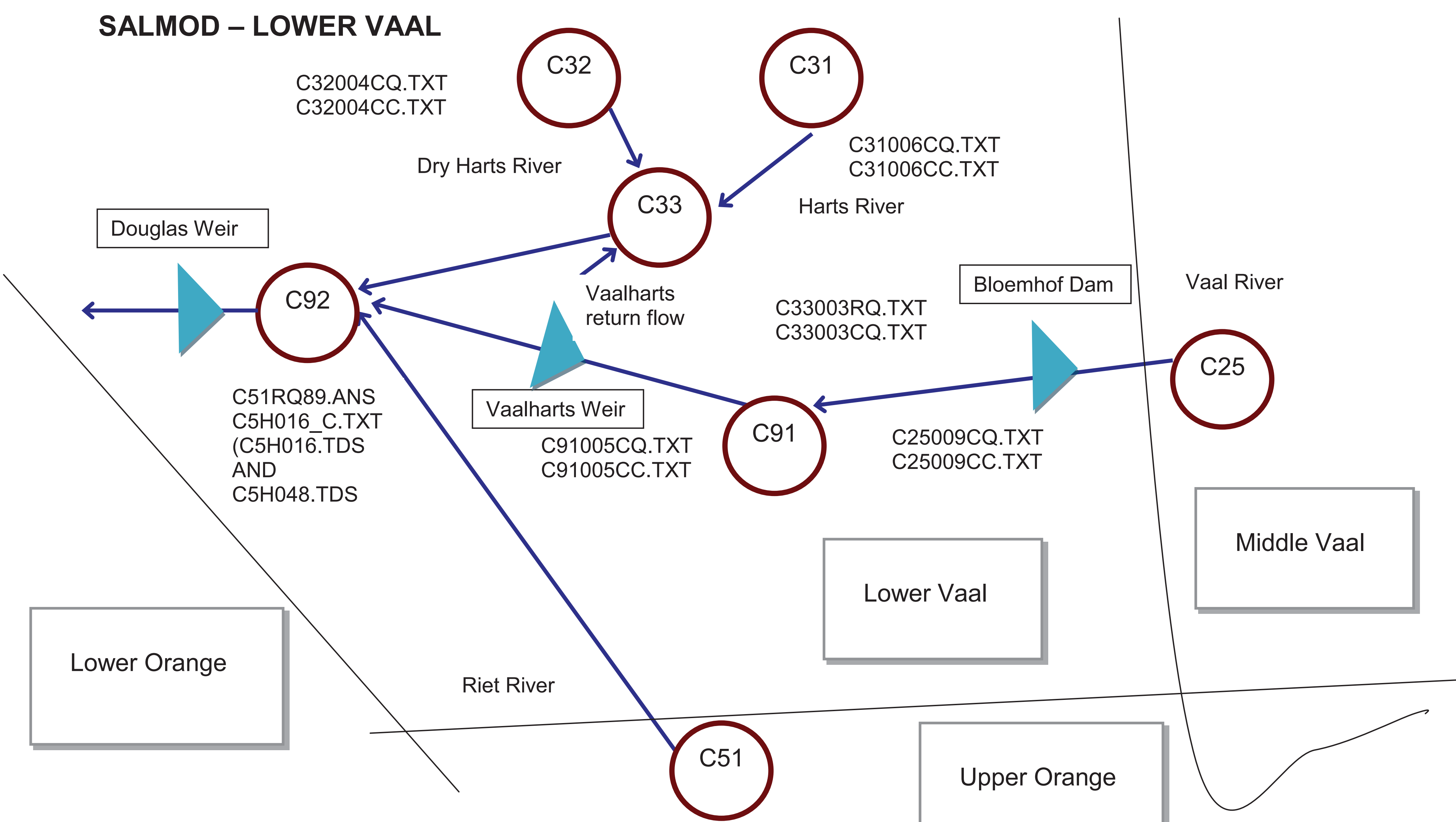

Figure 7.2: Lower Vaal Schematic

7.1 C91 Tertiary Catchment

7.1.1 C91: Vaal River at Port Arlington (downstream of Bloemhof Dam) – C9H021

C91 has Bloemhof Dam and the Vaalharts weir. There is a large abstraction at Vaalharts weir for the Vaalharts irrigation scheme. Therefore the same approach has been used at C9R001 as with Erfenis and Allemanskraal dams to include the irrigation abstraction with the downstream release and spillage from the dam for the purposes of comparing the total TDS and load leaving the dam.

It was discovered that specifying the observed time-series of releases from Bloemhof Dam, namely C9H021 abstractions (taken from the DWS website), resulted in a simulated storage graph for Bloemhof that was completely different from the observed. When the observed trajectory showed a full dam, the simulated trajectory sometimes was at zero. This occurred after passage of flood events that caused spillage of the dam. This occurred for about half of such events, i.e. whenever the modelled flood volume was lower than that observed. Although the error between the two at the hydrological calibration point looked reasonably since in the longer term it was balanced by flood events where the reverse happened, even a good hydrological fit at this point masked the implausible changes taking place in the simulated reservoir storages. This large modelling error obviously played havoc with the salinity simulation. Hence, in order to get the dam release plus spillage to more realistically represent what the model was producing, it was necessary to truncate the specified water release at an estimated maximum to meet downstream water demand and free the model to simulate the spillage whenever the dam fills. This ensured that the dam was always left full after the passage of a major flood, rather than causing an irrational significant reduction in storage level. Consequently a cap of 100 million m³/month was made to this time-series abstraction. This value of 100 million m³/month was established by inspection of the data and it is set at a realistic value to separate the spills from the releases for downstream demands. This approach worked and a far better fit was obtained as is shown in Figure 7.3 below.

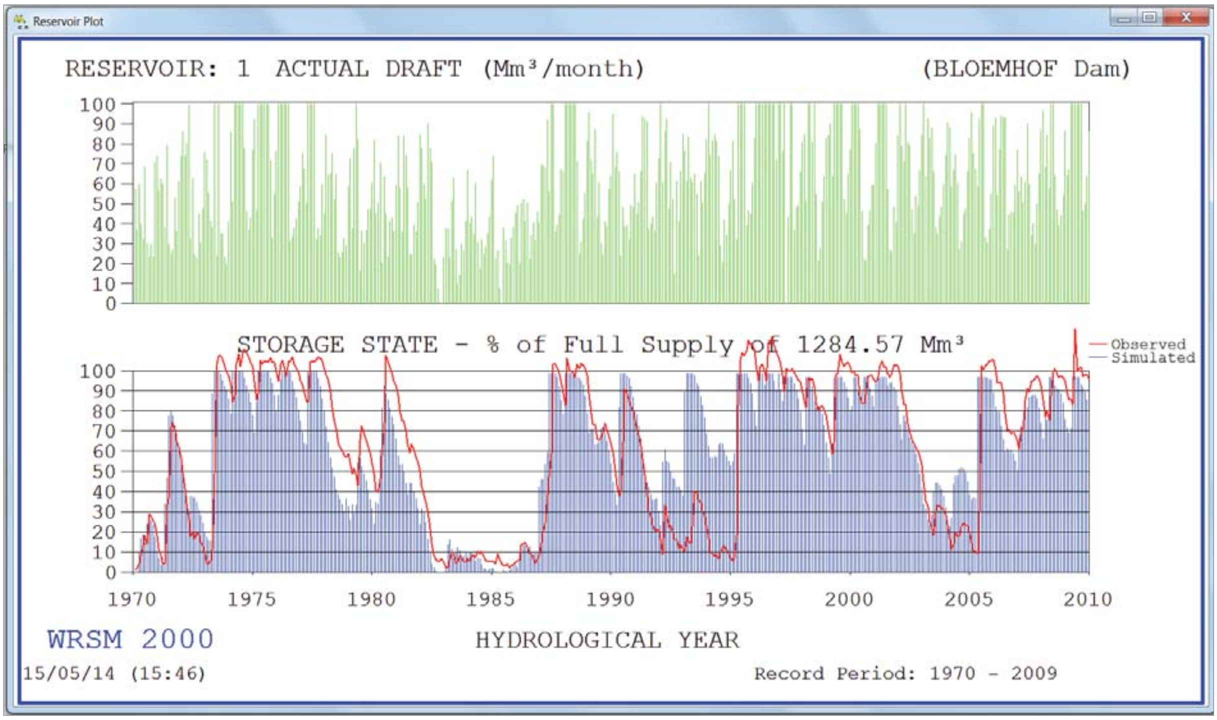

Figure 7.3: Observed and simulated storage in Bloemhof Dam

A similar problem occurred downstream at Vaalharts Weir where the time-series release C9H008 was capped at 10 million m³/month. This value was more difficult to arrive at and was initially taken as 45 million m³/month by inspection of the releases; however the much smaller dam and large abstraction for Vaalharts irrigation canals made the selection of the value to cap more difficult. The smaller storage capacity at Vaalharts also changed quite considerably over time. This graphical option shown above in the WRSM/Pitman model is limited as it can only be based on one storage, therefore the modelling reflected in Figure 7.3 can only be considered as a rough indication.

In both cases (Bloemhof Dam and Vaalharts Weir) better results could have been obtained if the observed reservoir records had separated controlled releases from spillage (then one would know what is released for downstream use).

The SALMOD graph of flow, TDS and load is shown in Figure 7.4 .

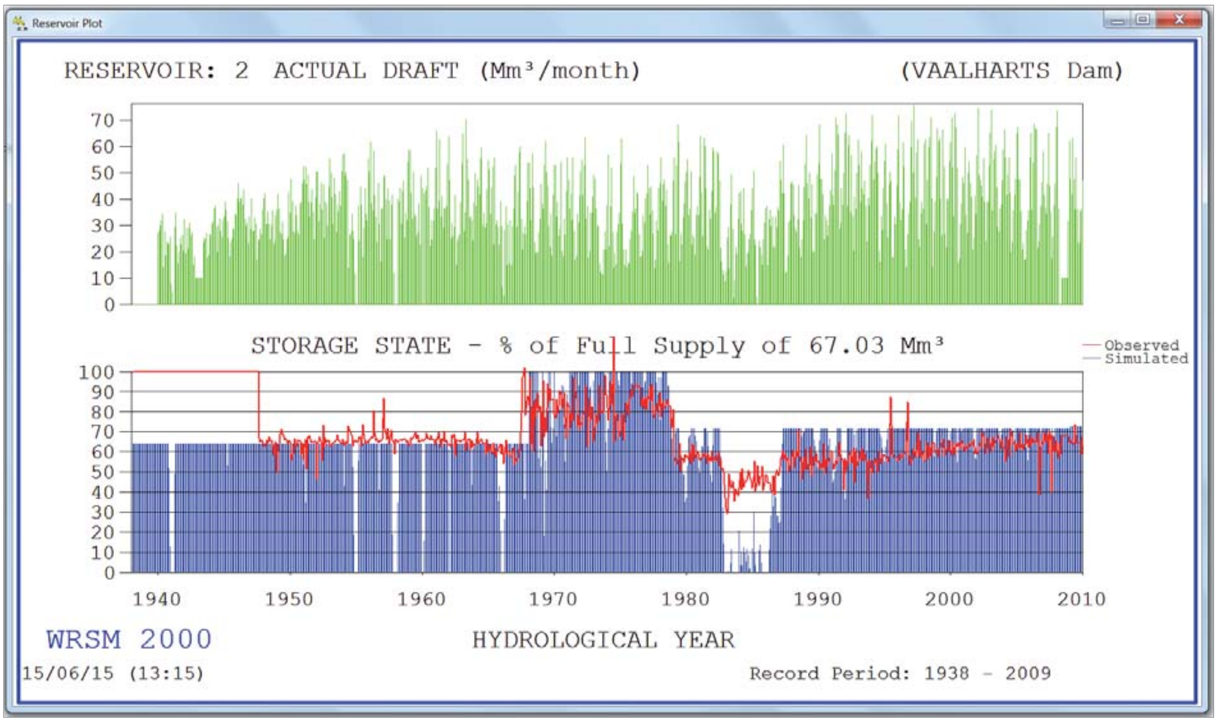

Figure 7.4: Observed and simulated storage in Vaalharts Weir

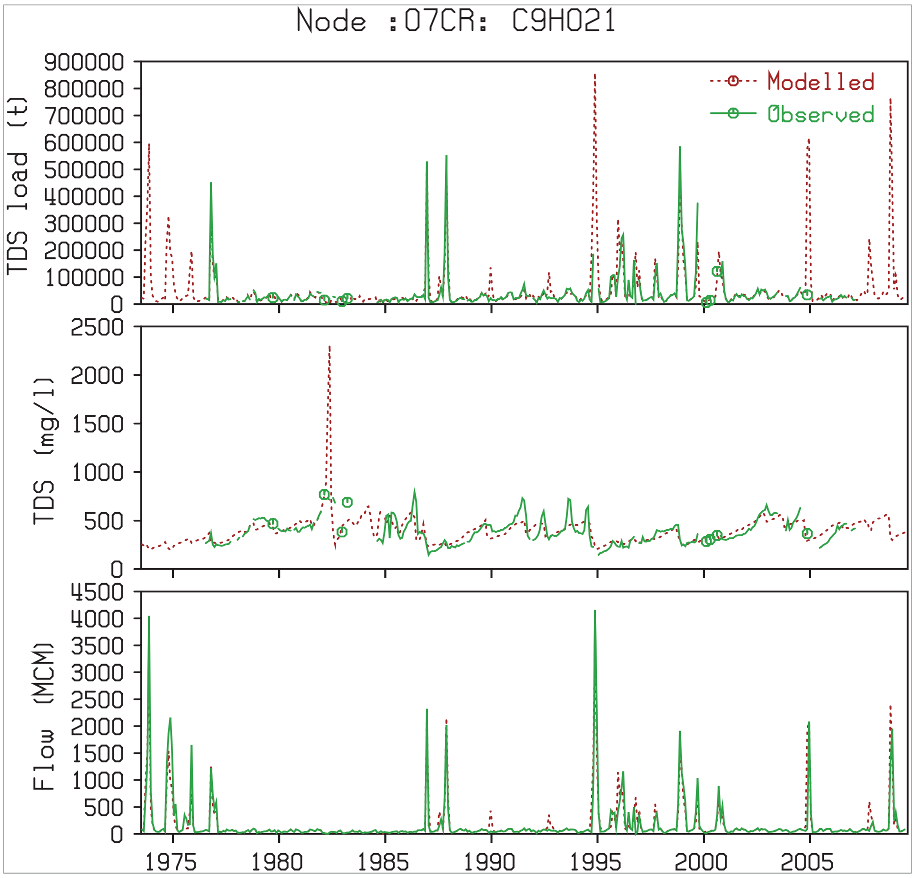

Figure 7.5: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station C9H021.

Table 7.1: Comparison between modelled and observed statistical values in the Vaal River at station C9H021

Route 7CR: C9H021 1977 - 2007

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	141.89	146.54	387.8	400.6	42208.	45126.
Std.Dev.	356.94	339.06	129.3	161.0	72767.	73740.
R	.9151		.5734		.8035	
E1	3.3%		3.3%		6.9%	
E2	-5.0%		24.4%		1.3%	
N	372		303		305	
SF	1.000		.987		.953	
Mean	146.5		405.3		46342.0	
Std.Dev.	339.1		154.6		86515.0	
N	372		371		372	

The fit between modelled and observed flows and salt loads is good. However, it should be cautioned that gaps in the water quality record have left the loads of three biggest floods ungauged, with no data at all for the last two years. TDS concentrations are well modelled, except for one doubtful flood peak corresponding to the 1980s drought when the modelled dam storage nearly empties, while the observed did not (although it did drop to about 5%).

7.1.2 **C91: Vaal River at Schoolplaats (Vaalharts Weir) – C9R001**

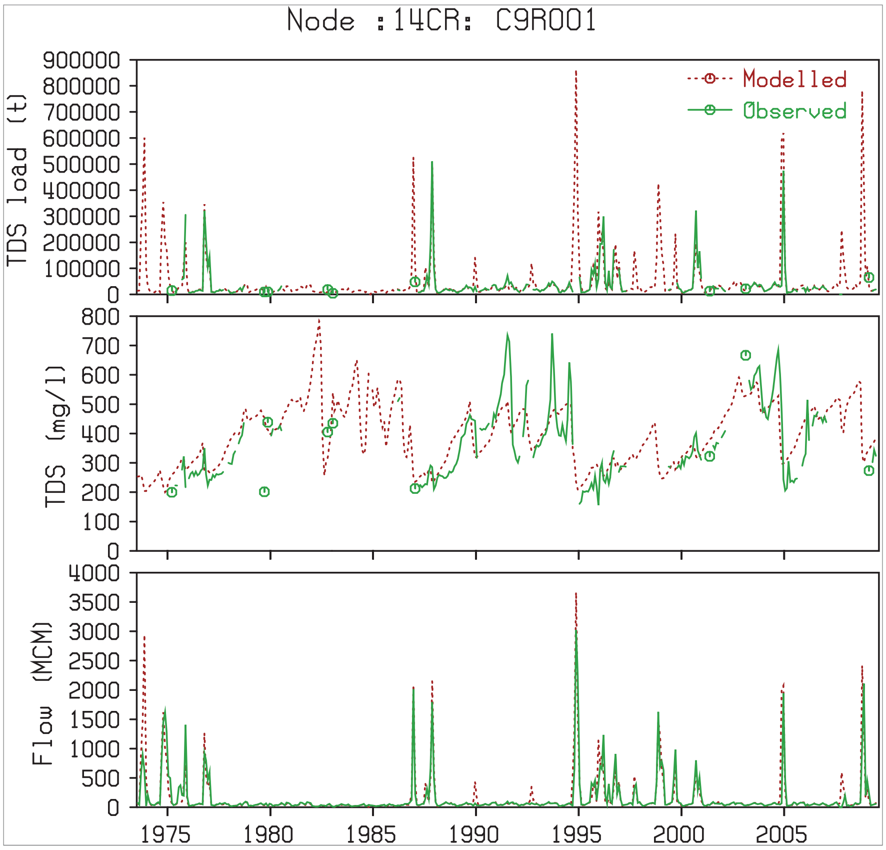

Figure 7.6: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station C9R001.

Table 7.2: Comparison between modelled and observed statistical values in the Vaal River at station C9R001

Route 14CR: C9R001 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	151.69	153.59	363.6	377.8	39152.	43238.
Std.Dev.	336.91	362.17	125.3	89.6	65543.	77668.
R	.8803		.8169		.7572	
E1	1.3%		3.9%		10.4%	
E2	7.5%		-28.5%		18.5%	
N	420		232		234	
SF	1.000		.947		.922	
Mean	153.6		401.4		47945.3	
Std.Dev.	362.2		104.3		95728.2	
N	420		419		420	

A good fit was obtained between modelled and observed flows and salt loads, while that for TDS concentrations was excellent. However, once again it must be warned that 45% of the months have no water quality data, resulting in the three largest floods remaining ungauged. Hence the load comparison is incomplete.

7.1.3 **C91: Vaal River at De Hoop – C9H009**

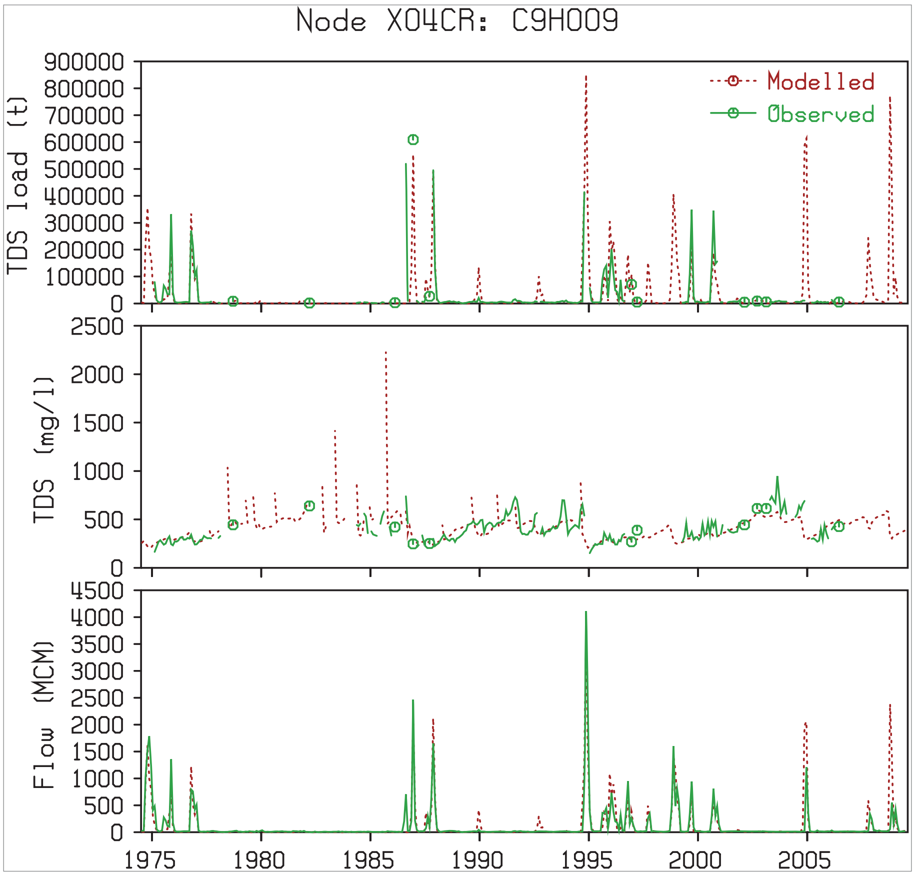

Figure 7.7: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station C9H009

Table 7.3: Comparison between modelled and observed statistical values in the Vaal River at station C9H009

Route 4RV: C9H009 1975 - 2006

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	116.07	112.24	393.5	384.5	30380.	28428.
Std.Dev.	361.80	355.02	134.3	109.6	83520.	81689.
R	.8864		.6586		.7308	
E1	-3.3%		-2.3%		-6.4%	
E2	-1.9%		-18.3%		-2.2%	
N	384		214		229	
SF	1.000		.883		.949	
Mean	112.2		410.5		30926.7	
Std.Dev.	355.0		164.9		91942.8	
N	384		348		384	

A good fit was obtained between modelled and observed flows and salt loads, although there were gaps in the water quality record for the three biggest modelled floods. (The SF value for loads was high, but this could be fortuitous circumstance.) The mean TDS concentration is good, but the plot does show a few abnormally high peaks during dry periods. Most of these peak concentrations remain unchallenged due to excessive gaps in the record, with 38% of the months unmonitored.

7.2 C31 Tertiary Catchment

7.2.1 C31: Harts River at Wentzel Dam – C3R001

This is an extremely dry catchment which makes a hydrological fit very difficult. Wentzel Dam is very small and the record scrappy. It also has a tendency to dry out due to evaporation. The load is relatively very low.

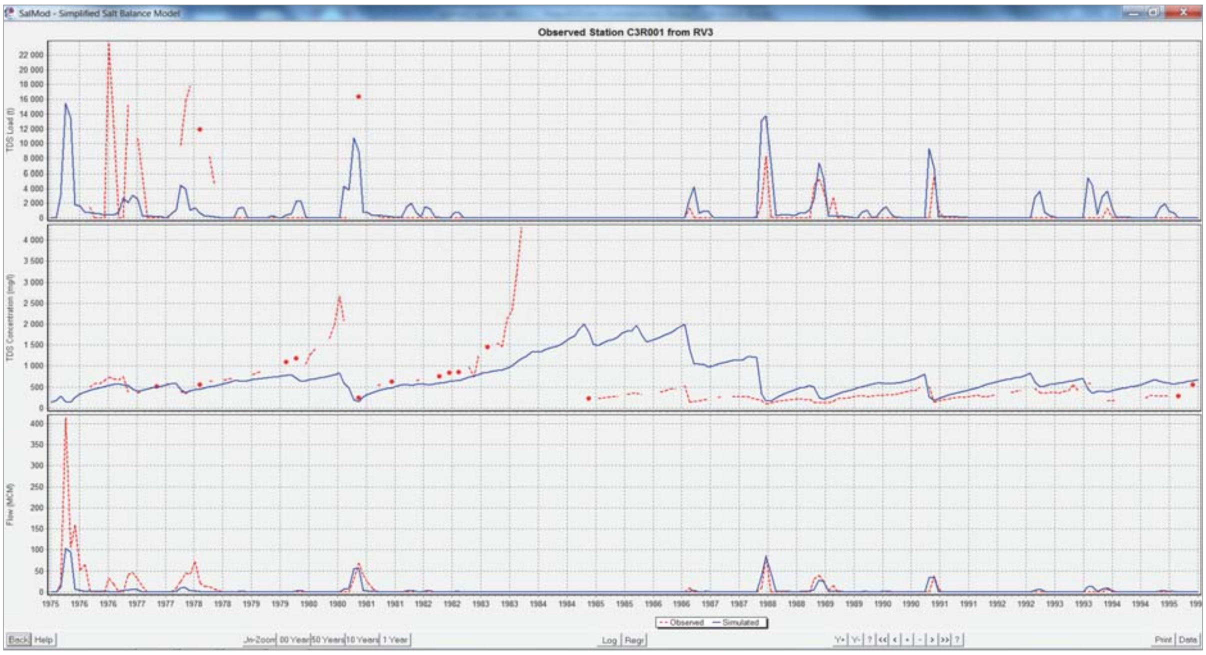

Figure 7.8: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Harts River at station C3R001

Table 7.4: Comparison between modelled and observed statistical values in the Harts River at station C3R001

Node 3RV: C3R001 1975 - 1994

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	7.10	3.55	538.4	706.8	845.	792.
Std.Dev.	31.76	12.70	572.5	412.0	3176.	1929.
R	0.6977		0.1300		0.3387	
E1	-49.9%		31.3%		-6.3%	
E2	-60.0%		-28.0%		-39.3%	
N	240		157		225	
SF	1.000		0.977		0.901	
Mean	3.6		734.7		969.7	
Std.Dev.	12.7		435.2		2345.1	
N	240		240		240	

The extreme aridity renders flood peaks very erratic and flashy, resulting in a poor hydrological fit. This in turn results in a poor salinity fit.

Wentzel Dam is very small and subject to high evaporation. Evaporative concentration can cause extreme peak TDS concentrations. Poor hydrological data makes it impossible to match these events.

7.2.2 C31: Harts River at Taung Dam – C3H003

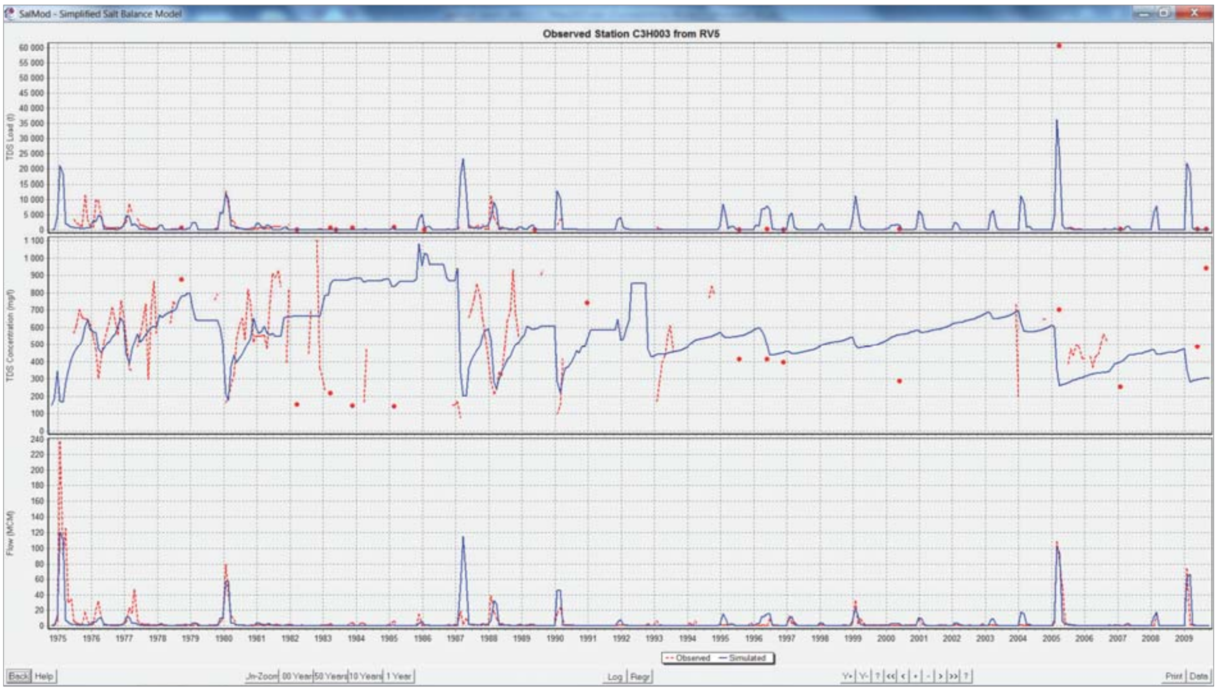

Figure 7.9: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Harts River at station C3H003

Table 7.5: Comparison between modelled and observed statistical values in the Harts River at station C3H003

Node 5RV: C3H003 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	4.08	3.85	531.4	515.6	1365.	1051.
Std.Dev.	17.07	14.31	221.9	157.2	5038.	3065.
R	0.7100		0.0883		0.7043	
E1	-5.7%		-3.0%		-23.0%	
E2	-16.2%		-29.1%		-39.2%	
N	420		136		171	
SF	1.000		0.958		0.895	
Mean	3.9		562.8		1313.6	
Std.Dev.	14.3		170.7		3731.4	
N	420		420		420	

Taung Dam is more substantial than Wentzel Dam and the flow record is more reliable. A reasonable hydrological calibration was obtained at this point. The water quality sampling record is sparse and the many gaps result in poor representation of the salt loads. Hence, although the correlation of the monthly loads was reasonable, it was considered unwise to attempt to increase the modelled mean since this would entail having to apply unusually high salt generation parameters to the incremental catchment between Wentzel Dam and Taung Dam. The correlation for TDS concentrations is poor.

The load contribution to the downstream system is relatively small.

7.3 C32: No gauges

The dry Harts is extremely arid and therefore contributes little to the downstream system. There are no flow gauging stations in this quaternary. As the load contribution will also be small, this tertiary has not been modelled.

7.4 C33 Tertiary Catchment

7.4.1 **C33: Harts River at Espagsdrif – C3H007**

The C33 tertiary catchment has return flow from the Vaalharts irrigation scheme, both from the North canal and West canal areas. The WRSM/Pitman supply to the abstraction from Vaalharts storage weir in C91 (C9H018.ABS, which is C91RQ12.ANS) was split by area into North and West Canal (240 and 50 km2 respectively) and entered in C33 into the respective irrigation blocks RR6 (North canal) and RR7 (West canal).

The relatively large Vaalharts irrigation return flow prompted a re-think on starting salinity in the input file. This necessitated a modification to the SALMOD model (version May 25th 2015) which is of significance for large return flows. SALMOD now reads in a “starting salt storage” (mg/ℓ) for each irrigation block as an additional parameter. For the North and West canal irrigation areas it was estimated at 1 100 mg/ℓ. This has to be balanced with the return flow factor (FIR) for each irrigated area such that the starting and ending concentrations come out the same. Then both are adjusted up or down by the same factor to obtain a reasonable fit between modelled and observed values. The SALMOD input file (C33.TXT) contains the necessary input with the starting irrigated area salinities balanced and calibrated. Since the North canal irrigation node area required a bigger calibrated percentage return flow; it also needed a bigger FIR value, which is about twice that of the West canal node).

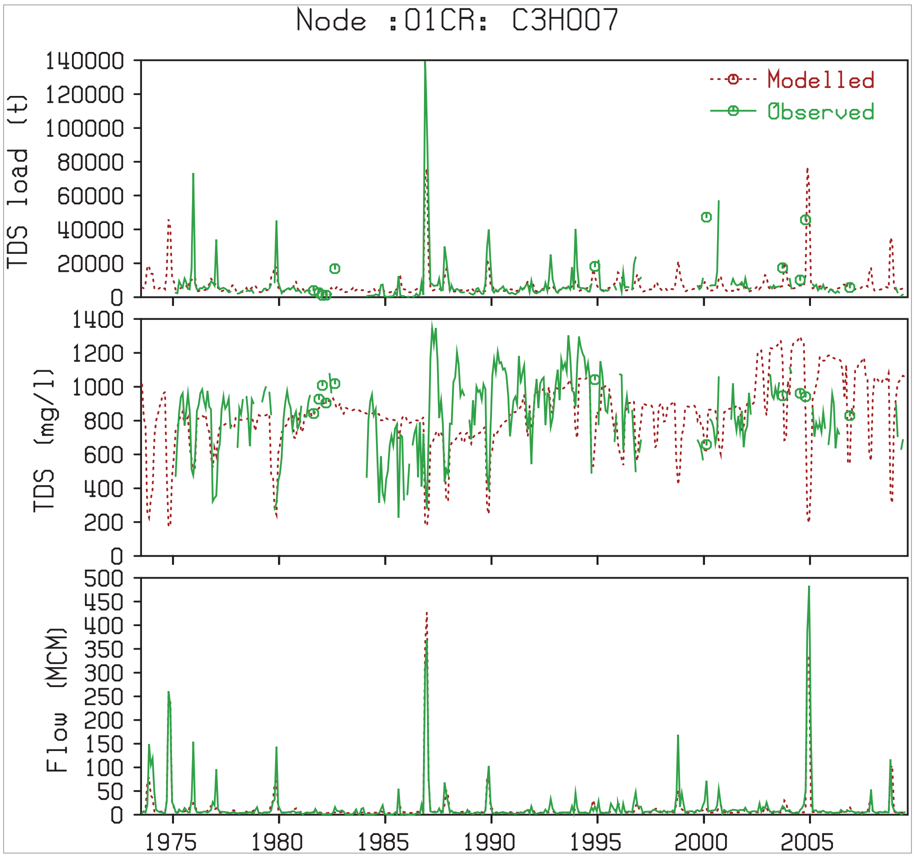

Figure 7.10: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Harts River at station C3H007

Table 7.6: Comparison between modelled and observed statistical values in the Harts River at station C3H007

Route 1CR: C3H007 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	15.59	13.13	838.8	823.0	7939.	6054.
Std.Dev.	44.85	39.97	218.9	185.2	13478.	6465.
R	.9211		.3976		.8379	
E1	-15.7%		-1.9%		-23.7%	
E2	-10.9%		-15.4%		-52.0%	
N	420		272		272	
SF	1.000		.977		.924	
Mean	13.1		835.5		6750.3	
Std.Dev.	40.0		200.3		7860.2	
N	420		420		420	

The correspondence obtained between modelled and observed flows and salt loads is very good. The modelled mean TDS concentration is also good. However, the standard deviation is somewhat damped and the TDS concentration correlation is poor.

7.4.2 **C33: Harts River at Spitskop Dam – C3R002 using C3H013 for streamflow**

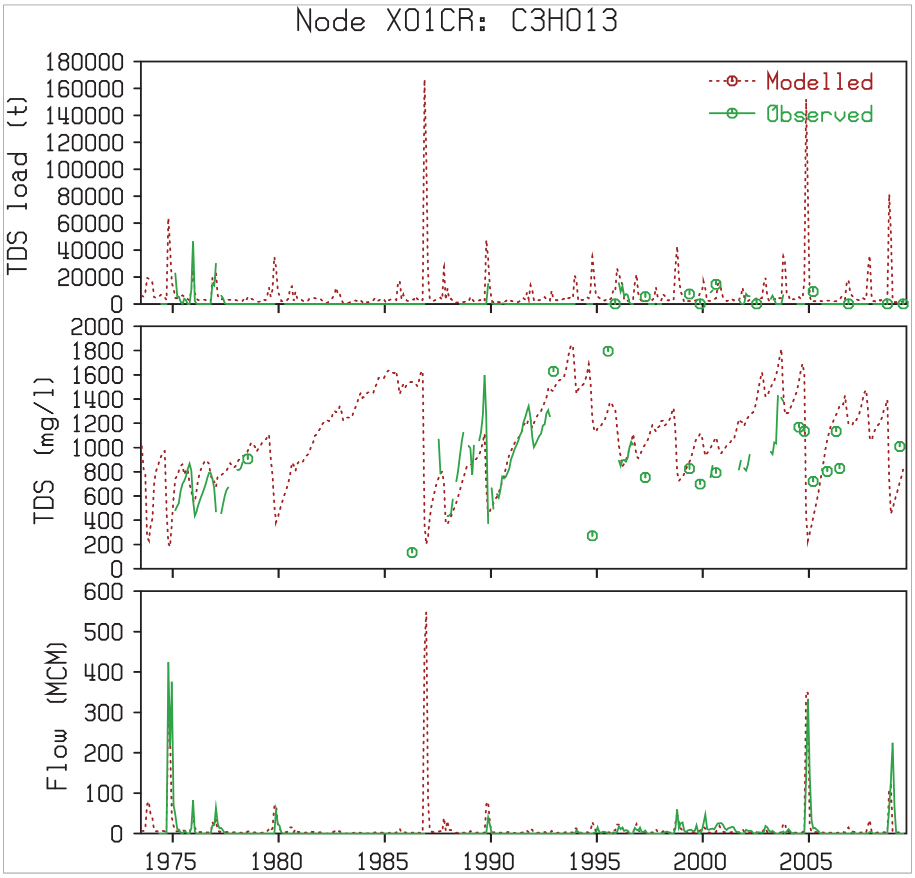

Figure 7.11: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Harts River at station C3R002/C3H013

Table 7.7: Comparison between modelled and observed statistical values in the Harts River at station C3H013

Route 1RV: C3H013 1975 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	9.16	10.49	878.8	975.3	1186.	5399.
Std.Dev.	38.96	39.56	283.3	306.8	4354.	11231.
R	.6076		.6232		.1880	
E1	14.5%		11.0%		355.2%	
E2	1.5%		8.3%		157.9%	
N	401		127		289	
SF	.926		.944		.857	
Mean	11.9		1079.9		7198.0	
Std.Dev.	46.9		347.0		14978.6	
N	420		420		420	

Flow gauging at C3H013 is inaccurate, especially for higher flows. Hence, it is unreasonable to apply unrealistically low salt generation rates to the incremental catchment to try to match the observed salt loads, given the good load fit at C3H007 (in fact, even if the salt load generation were to be set to zero it would be impossible to reduce the salt load at C3H013 sufficiently at C3H013). Moreover, the water quality sampling record is sparse and covers only 36% of the months, resulting in a relatively low SF factor for loads. The TDS concentration fit is reasonable.

7.5 C92 Tertiary Catchment

7.5.1 C92: Vaal River at Douglas Storage Weir – C9R003

The releases from Bloemhof Dam are aimed at just satisfying downstream losses and demands with zero spillage from Douglas Weir into the Orange (except when floods make this impossible). Douglas Weir also receives a transfer from Marksdrift on the Orange River which has a maximum transfer capacity of 6 m³/s. "The volume transferred depends on the water available in the Vaal River and the water level in the Douglas Weir. The volume transferred can therefore vary considerably from year to year, but is in the order of 120 million m³/a, to a maximum of 142 million m³/a (ref. "Development of Reconciliation Strategies for Large Bulk Water Supply Systems: Orange River". P.G. Van Rooyen WRP Consulting Engineers, P RSA D000/00/18312/6).

Gauging error is a distinct possibility at C9R003 given the long Labyrinth spillway, the effective length of which will shortened as the flood peak increases, due to the flow then seeing the labyrinth as one very wide, but shorter, broad crested weir. Hence good flow gauging at higher flows cannot be expected. Simulated flows lower than the observed fit that profile. With Douglas Weir having a very small storage compared with the wet weather inflow, there is no way one could mimic the small fluctuations around full supply to get an accurate graph of observed versus simulated storage. What is important is that the simulated storage is nearly always full, reflecting the actual behaviour.

In the lower flow range the observed TDS concentrations are also unrepresentative since samples are taken at the right hand side of the weir at the low flow notch. On one occasion during a site visit, a very large difference between the TDS concentration at the right and left banks of the weir was observed due to lateral stratification caused by the fresh water inflow via the Orange-Vaal canal discharging on the left hand side of the pool. It was also speculated by locals that irrigation return flows from the Vaal River tend to hug the right bank of the pool.

The record of monthly water transferred from the Orange River to the head of the canal shows a considerable increase in annual discharge from 36 million m³/a in 1992 to 154 million m³/a in 2013. It was also observed during a recent field investigation that there is considerable amount of irrigation direct from the canal remote from Douglas Weir. This, together with the fact that the total amount of water transferred is well in excess of the irrigation requirement from Douglas Weir, made it clear that the amount of water reaching Douglas Weir must be much smaller than the total transfer. In order to improve the best fit between flow, TDS and load, a file of reduced fresh water importation from the Orange River to Douglas Weir was used (D3H019.ADJ) assuming that the 36 million m³/a flow in the first complete year (1992) can be taken as the requirement for irrigation from Douglas Weir and that the rest of the abstraction from Marksdrift was consumed by increasing new irrigation direct from the canal. This is obviously highly inaccurate since it does not take into account the actual growth in irrigation area or the month by month fluctuation pattern of irrigation abstractions. All that is known is that there is a lot of irrigation along the route of the canal and this is remote from the Vaal River, so return flows would be pretty small.

Despite the unknowns and estimations relating to bed losses, irrigation and splitting Douglas Weir into two sections to crudely approximate the abstraction of some irrigation supply from the diluted water near to Douglas Weir with some abstracted from the further reaches of the pool backed up by the Weir where TDS concentration levels are closer to those entering from the Vaal River and Rietspruit, the fit is tenable. Especially so since under dry flow conditions the upstream dams in the Vaal River system are operated so as to minimise the spillage from Douglas Weir into the Orange River. This means the modelled low flows will not be accurate since we are chasing the last dregs of water at the tail end of a long river reach far downstream of the regulation (one or two overcast days will reduce irrigation demands and river evaporation losses, thereby changing the low flows at Douglas Weir). The other way around can result in artificially dropping the modelled storage in the lake at Douglas, resulting is erratic simulated salinity.

Figure 7.12 shows the reservoir plot for Douglas Weir. The modelled storage state dropped to zero for about four years during the 1980s drought. Six other shorter periods when the modelled storage dropped to zero can be seen in the period up to 1990. However, since this occurred during low flow conditions there should be little discernible effect on the salinity of the Orange River since the flow in the Orange River at its confluence with the Vaal River seldom drops below 100 m³/s. Figure 4.59 shows that there is was no water quality sampling in Douglas Weir during this period.

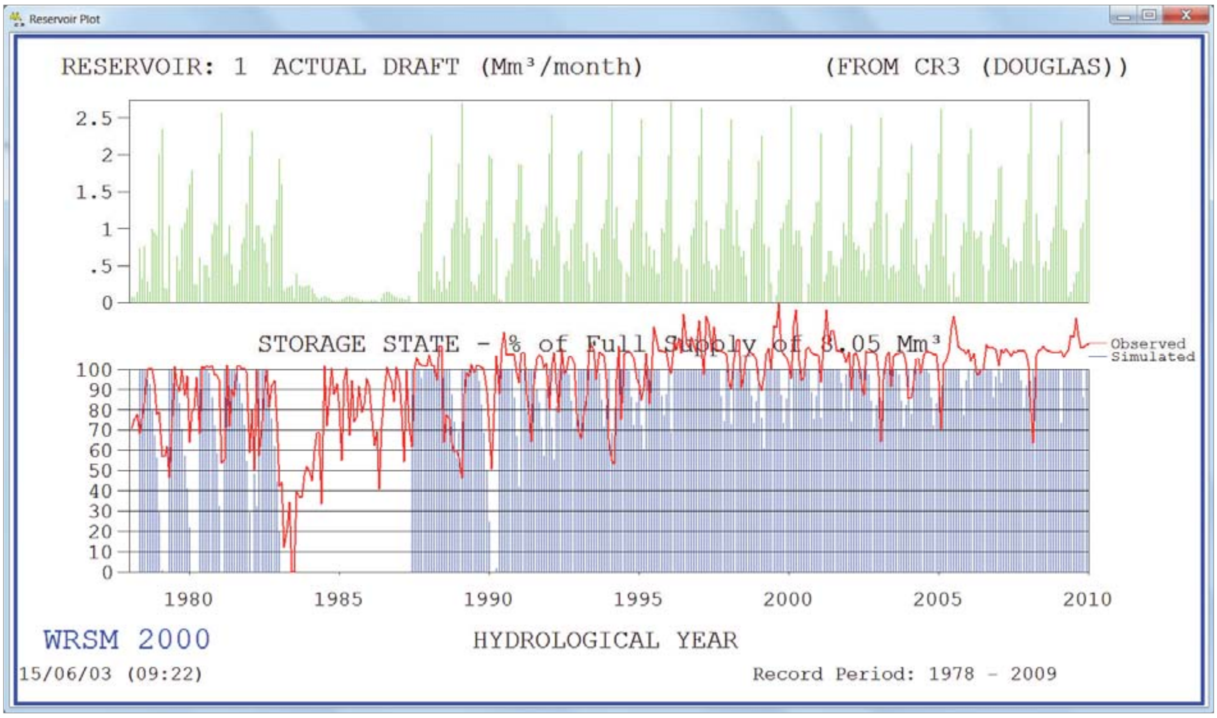

Figure 7.12: Observed and simulated storage in Douglas Weir

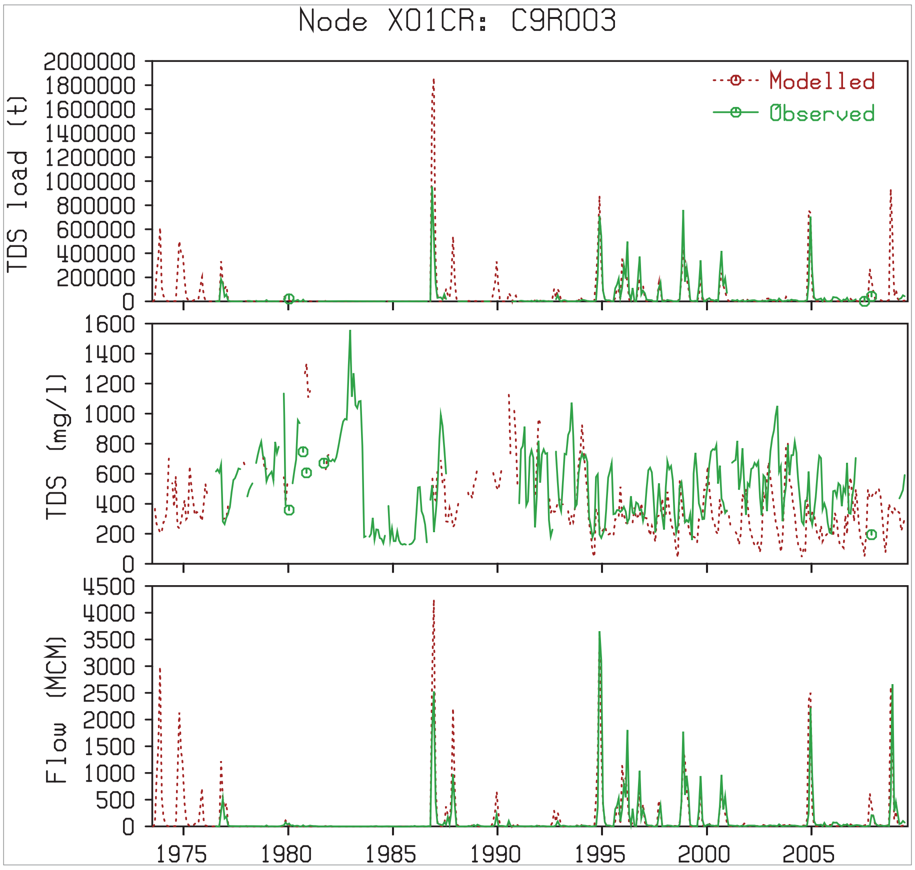

Figure 7.13: Comparison between modelled and observed monthly flows, TDS concentrations and TDS loads in the Vaal River at station C9R003.

Table 7.8: Comparison between modelled and observed statistical values in the Vaal River at station C9R003

Route 1RV: C9R003 1977 - 2009

MONTHLY STATISTICS	Flow (MCM)		Concentration (mg/ℓ)		Load (t)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean	109.74	130.35	501.4	347.0	37540.	42269.
Std.Dev.	383.47	445.51	200.4	189.5	113173.	167780.
R	.8224		.2682		.8013	
E1	18.8%		-30.8%		12.6%	
E2	16.2%		-5.5%		48.3%	
N	396		204		328	
SF	1.000		.936		.978	
Mean	130.3		381.4		45394.7	
Std.Dev.	445.5		222.7		165241.0	
N	396		264		396	

There is a good correlation between modelled and observed flows, however, the modelled mean and standard deviation are higher than the observed. The salt loads follow this same pattern, except that the standard deviation is even higher.

The modelled mean TDS concentration is 30% low and the correlation coefficient is poor. This is mainly attributable to low flow conditions, especially during the period following the commissioning of the Orange-Vaal canal. This strongly suggests that the modelled delivery of the low TDS concentration Orange River water to Douglas Weir is still too large. Therefore there may be justification for assuming that even more of the transfer water was consumed in meeting new irrigation demands along the canal. However, there is little to be gained from making further tests. It would be far more beneficial to obtain accurate information on the historical canal irrigation abstractions, or even the growth in irrigated area.

8 Conclusions and Recommendations

Despite the problems encountered with lack of mining and effluent return flow data, unknown riverbed seepage and limited irrigation data particularly with regard to growth or decline, satisfactory calibrations were achieved.

The Vaal River System Analysis Update Study (VRSAU) was completed in 1999 and was used to compare flow, TDS and load at key points as shown in Table 8.1 below.

Table 8.1: Comparison between monthly modelled and observed flows, TDS concentrations and TDS loads obtained at key points obtained during the WR2012 and VRSAU studies

WMA	Key point	WR2012 Start-End	VRSAU Start-End	Flow (million m³/month)		TDS Concentration (mg/ℓ)		TDS Load (tons/month)	
				WR2012	VRSAU	***WR2012***	VRSAU	***WR2012***	VRSAU
Upper Vaal	Grootdraai Dam (C1R002/ C1H019)	1995/2009 (C1H019)	1975-1994 (C1R002)	***47.1*** ***41.0***	19.2 19.5	***178.0*** ***176.9***	164.1 159.5	***7 985.0*** ***7 770.0***	3 410.4 3 331.4
Upper Vaal	Vaal Dam (C1R001/C2H122)	1975-2009 (C2H122)	1975-1994 (C1R001)	***101.5*** ***119.0***	120.4 121.5	***149.3*** ***174.1***	140.8 142.7	***16 248.0*** ***22 100.0***	16 367.8 16 360.2
Upper Vaal	Vaal Barrage (C2R008/C2H018)	1975-2009 (C2H018)	1975-1994 (C2R008)	***136.5*** ***126.9***	88.6 87.5	***490.4*** ***492.5***	476.4 519.2	***39 983.0*** ***37 342.0***	26 735.1 26 720.5
Middle Vaal	C2H018/ C2H007	1978-2009 (C2H007)	1975-1994 (C2H018)	***136.5*** ***139.5***	90.6 92.3	***553.1*** ***535.4***	501.2 508.3	***46 581.0*** ***44 389.0***	28 562.6 28 786.5
Middle Vaal	C4H004	1977-2009	1985-1994	***17.89*** ***17.07***	24.47 24.8	***300.8*** ***397.5***	276.6 277.8	***5 080.0*** ***4 816.0***	6 128.4 7 077.3
Middle Vaal	Bloemhof Dam (C9R002)	1977-2007	1975-1994	***141.89*** ***139.40***	137.5 139.1	***387.4*** ***392.3***	381.8 482.2	***42 208*** ***41 188***	44 661.9 45 585.0
Lower Vaal	Vaalharts Weir (C9H009)	1975-2006	1974-1994	***116.07*** ***112.24***	134.9 147.2	***393.5*** ***384.5***	387.2 397.3	***30 380*** ***28 428***	37 959.2 45 888.9
Lower Vaal	Douglas Weir (C9R003)	1977-2009	1974-1994	***109.74*** ***130.35***	27.6 150.9	***501.4*** ***347.0***	570.2 603.3	***37 540.0*** ***42 269.0***	9 317.2 44 407.1

Note: **Red** is observed and **blue** is simulated.

Looking at the comparison between observed flow and hence load in the table above, the following comments can be made:

- the drought in the 1980's impacted quite markedly on the flows and hence load in the VRSAU study. There was also no Lesotho Highlands transfer until 1997. This explains why by including an extra 15 years of data for a much wetter period, the WR2012 flows and hence load were more than double those for VRSAU study at Grootdraai Dam;
- Rand Water (RW) changed its operation in the late 1980s to abstract an increasing proportion of its increasing water supply via the Vaal Dam-Zuikerbosch canal, leading to virtually its entire supply being drawn directly from the Vaal Dam in recent years. Thus, despite increased runoff from the Vaal Dam catchment and increasing importation from the Lesotho Highlands Water Project (LHWP), the net result of this big change in operation was a reduction in the outflow from Vaal Dam;
- contrary to superficial expectation from the reduced release from Vaal Barrage, the outflow from the Vaal Barrage increased substantially. This is because the change in the operation brought about by the Vaal Barrage dilution option caused a large proportion of the incremental catchment runoff and the substantial effluent return flow (amounting to about a third of RW's water demand) to spill from Vaal Barrage;
- as expected, the increased WR2012 study runoff persists into the Middle Vaal at C2H018/C2H007 and down through Bloemhof Dam;
- at Vaalharts Weir there is a reduction in flow in the WR2012 study in comparison to the VRSAU study due to increased irrigation abstractions for the Vaalharts irrigation scheme. This reduction in runoff is evident right down to Douglas Weir as indicated by the modelled flows. However, the observed VRSAU study flows at Douglas Weir are much too low. This is thought to be attributable to an error in the observed data. Fortunately the incorrect observed flow data was ignored in favour of the modelled values; and
- the one area where the reason for the reduction in the WR2012 runoff is not as clear is the Vet River at station C4H004, which receives releases from the Allemanskraal and Erfenis dams. This is most likely attributable to the manner in which these two dams were operated and the amount of irrigation water abstracted. For example, it is known that during at least part of the earlier period irrigation water was drawn from these dams, well in excess of their assured yield. This may also have a bearing on the dams outflow during the two periods. However, the quantity is relatively small and some of this regulated flow is also absorbed by scheduled riparian irrigation along the Vet River downstream of the Sand-Vet confluence. The small residual contribution to the Vaal River system did not warrant detailed examination of the records used in the VRSAU study merely for comparative purposes.

Although SALMOD analyses are less detailed than the WQT model, the analyses described in this report as modelled by SALMOD are extremely useful for assessing incremental catchment salt export. As with all models, greater accuracy would be obtained with the SALMOD analyses with a more detailed investigation into some land use aspects such as return flow, irrigation, riverbed seepage and channel surface evaporation to improve on this data. These SALMOD analyses also showed consistent results with what was expected based on Dr Chris Herold's experience with water quality of the Vaal catchment. The report does not only discuss the set up of the model and its calibration for the Vaal sub-catchments, it also adds value in that it is a reflection of the experience with salinity in the Vaal catchments, particularly the experience of Dr Chris Herold.

This report and model can therefore be of key importance in the evaluation, monitoring and further improvement of the Vaal Quality Management Strategy for the Vaal catchments.

9 References

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WRP, PDNA, WMA and Kwezi-V3 . "Internal Strategic Perspective for the Lower Vaal Water Management Area (WMA No. 10)" P WMA 10/000/00/0203.

Appendix A

Network Diagrams

Appendix B

An example of a SALMOD input file C92.TXT

USER INSTRUCTIONS TO RUN PROGRAM SALMOD.FOR

```
C92                                                    <System identifier code>
C:\WR2012\SALMOD\C92\C92-4\OUT                               <Output directory>
y                                                    <Generate debug messages?>
  .02                           <Maximum allowable water balance error (MCM)>
  .02                                            <Minimum node storage (MCM)>
1974 2009                                                           <LYS,LYE>
13                                                                   <NNODE>
 2 'RV'    6 'CR' ''                  <  1:INODE,TNODE,INDS,TNDS,INDES>
 6 'CR'    5 'RV' ''                  <  2:INODE,TNODE,INDS,TNDS,INDES>
 4 'RR'    5 'RV' ''                  <  3:INODE,TNODE,INDS,TNDS,INDES>
 5 'RV'    3 'RV' ''                  <  4:INODE,TNODE,INDS,TNDS,INDES>
 3 'RV'    7 'CR' ''                  <  5:INODE,TNODE,INDS,TNDS,INDES>
11 'RR'    7 'CR' ''                  <  6:INODE,TNODE,INDS,TNDS,INDES>
 7 'CR'    1 'RV' ''                 <  7:INODE,TNODE,INDS,TNDS,INDES>
 1 'RV'    4 'RV' 'C9R003'           <  8:INODE,TNODE,INDS,TNDS,INDES>
 1 'RR'    4 'RV' ''                  <  9:INODE,TNODE,INDS,TNDS,INDES>
 4 'RV'    8 'CR' ''                 < 10:INODE,TNODE,INDS,TNDS,INDES>
 8 'CR'    5 'CR' ''                  < 11:INODE,TNODE,INDS,TNDS,INDES>
 3 'RR'    5 'CR' ''                < 12:INODE,TNODE,INDS,TNDS,INDES>
 5 'CR'    0 '00' ''                  < 13:INODE,TNODE,INDS,TNDS,INDES>
1                                                <Number of observation routes>
1 'RV'                                                         <IOBS(3),TOBS>
C9R003.SPL                                                <Observed FLOW file>
C9R003.TDS                                                 <Observed TDS file>
3                                                                      <NSW>
1             <SALT WASHOFF MODULE   1SW                         - SW number>
C92A                                                         <SW description>
 1612.0                                                      <Catchment area>
  100.    800.    .500                                          <CMIN,CMAX,A>
1                                               <Diffuse source growth control>
1                                                                    <MAXSW>
 2 'RV'   1.000                                              <NSWR,TSWR,PSWR>
C92RU1NC.MTS                                                <Runoff FLOW file>
N                                     <Is there an inflow to SW module   1SW?>
2              <SALT WASHOFF MODULE   2SW                        - SW number>
C92B                                                         <SW description>
  889.0                                                      <Catchment area>
  100.    800.    .500                                          <CMIN,CMAX,A>
1                                               <Diffuse source growth control>
1                                                                    <MAXSW>
 3 'RV'   1.000                                              <NSWR,TSWR,PSWR>
C92RU2NC.MTS                                                <Runoff FLOW file>
N                                     <Is there an inflow to SW module   2SW?>
3              <SALT WASHOFF MODULE   3SW                        - SW number>
C92C                                                         <SW description>
  435.0                                                      <Catchment area>
  100.    800.    .500                                          <CMIN,CMAX,A>
1                                               <Diffuse source growth control>
1                                                                    <MAXSW>
 4 'CR'   1.000                                              <NSWR,TSWR,PSWR>
C92RU3NC.MTS                                                <Runoff FLOW file>
N                                     <Is there an inflow to SW module   3SW?>
2                <RESERVOIR MODULE   2RV           - No. of external sources>
C33003CQ.TXT
C33003CC.TXT
C91013CQ.TXT
C91013CC.TXT
2                          <No. of abstractions (excluding for irrigation)>
GAM_BED.ABS                                                        <bedloss>
N
GAMAGARA.ABS                                                   <abstraction>
N
C92RV2.ANS                                                  <RV storage file>
 100.0                                                <Starting TDS (mg/ℓ)>
C92RQ5.ANS                                                     <Outflow file>
0                <CHANNEL REACH MODULE  6CR       - No. of external sources>
N                                    <Bed seepage from channel reach  6CR?>
N                                                     <Variable CR storage?>
6.63             <IRRIGATION MODULE   4RR                 - Irrigation area>
 1.000                                                   <Storage depth (m)>
 2200.                                             <Start concentration (mg/ℓ)>
  .300                                     <Irrigation return flow factor, FIR>
6 'CR'                                                 <Supply node to  1RR>
C92RQ18.ANS                                              <RR water supply file>
C92RQ19.ANS                                               <RR return flow file>
```

```
1                  <RESERVOIR MODULE   5RV          - No. of external sources>
C51RQ89.ANS
C5H016_c.TXT
1                             <No. of abstractions (excluding for irrigation)>
BDLS_CR3.ABS
N
DUMMY.ZRO                                                     <RV storage file>
 500.0                                                    <Starting TDS (mg/ℓ)>
C92RQ26.ANS                                                      <Outflow file>
0                  <RESERVOIR MODULE   3RV          - No. of external sources>
0                             <No. of abstractions (excluding for irrigation)>
DUMMY.ZRO                                                     <RV storage file>
 500.0                                                    <Starting TDS (mg/ℓ)>
C92RQ21.ANS                                                      <Outflow file>
11.61              <IRRIGATION MODULE   11RR                - Irrigation area>
 1.000                                                      <Storage depth (m)>
 1600.                                             <Start concentration (mg/ℓ)>
  .600                                     <Irrigation return flow factor, FIR>
3 'RV'                                                   <Supply node to  1RR>
C92RQ24.ANS                                              <RR water supply file>
C92RQ224.ANS                                              <RR return flow file>
1                   <CHANNEL REACH MODULE 7CR       - No. of external sources>
D3H019.ADJ
D3H019.TDS
N                                         <Bed seepage from channel reach 7CR?>
N                                                      <Variable CR storage?>
0                <RESERVOIR MODULE   1RV            - No. of external sources>
0                             <No. of abstractions (excluding for irrigation)>
C92RV1.ANS                                                    <RV storage file>
 500.0                                                    <Starting TDS (mg/ℓ)>
C92RQ12.ANS                                                      <Outflow file>
11.61              <IRRIGATION MODULE   1RR                 - Irrigation area>
 1.000                                                      <Storage depth (m)>
 1800.                                             <Start concentration (mg/ℓ)>
  .600                                     <Irrigation return flow factor, FIR>
1 'RV'                                                   <Supply node to  1RR>
C92RQ9.ANS                                               <RR water supply file>
C92RQ209.ANS                                              <RR return flow file>
0                <RESERVOIR MODULE   4RV            - No. of external sources>
1                             <No. of abstractions (excluding for irrigation)>
BDLS_CR4.ABS                                                          <bedloss>
N
C92RV4.ANS                                                    <RV storage file>
 500.0                                                    <Starting TDS (mg/ℓ)>
C92RQ16.ANS                                                      <Outflow file>
0                 <CHANNEL REACH MODULE  8CR        - No. of external sources>
N                                        <Bed seepage from channel reach  8CR?>
N                                                      <Variable CR storage?>
3.32               <IRRIGATION MODULE   3RR                 - Irrigation area>
 1.000                                                      <Storage depth (m)>
  800.                                             <Start concentration (mg/ℓ)>
  .600                                     <Irrigation return flow factor, FIR>
8 'CR'                                                   <Supply node to  3RR>
C92RQ14.ANS                                              <RR water supply file>
C92RQ214.ANS                                              <RR return flow file>
0                 <CHANNEL REACH MODULE  5CR        - No. of external sources>
N                                        <Bed seepage from channel reach  5CR?>
N                                                      <Variable CR storage?>
```

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