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Water Quality Modelling Report for the Crocodile (West) River Catchment

Department of Water and Sanitation
Branch: Water Resources Management
Chief Directorate: National Water Resource Information Management

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APPROVAL

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1 Introduction

1.1 Background

South African water resource quality is deteriorating, with the main challenges being eutrophication and salinity. The *Upper Vaal Catchment* and *Upper Crocodile Catchment* have been identified in the National State of Water Report 2022, as the areas facing water quality challenges and need continuous monitoring and intervention measures. The Department of Water and Sanitation has, in the financial year 2021/22, begun to conduct a study in the Crocodile (West) Catchment. To develop / configure and apply a catchment-based hydrological water quality model to determine the impacts of various land use or water use activities on the water quantity and quality in the Crocodile catchment. The following deliverables were achieved in the previous year:

- Conceptualization of the Crocodile (West) River Catchment or System
- Literature review of water studies and applicable catchment models
- Configuration of the WQSAM model

The WQSAM model for the Crocodile (west) River Catchment was configured, with the setup, calibration, and simulations still pending pre-processing of hydrological input data.

1.2 Aim of Study

This study aims to develop through model configurations, a water quality model for the Crocodile (west) River Catchment to determine the impacts of various land use or water use activities on the water quantity and quality in the Crocodile catchment. This model application will allow for statistical analysis and correlation of water resource indicators to land use activities.

1.3 Scope of work

The scope of the work is to:

- Pre-process hydrological data for input into the WQSAM
- Calibrate and simulate the Water Temperature
- Calibrate and simulate the nutrients and salinity water quality variables.
- Derive frequency exceedance curves for each variable per quaternary catchment

2 Study Design

2.1 Modelling Framework

The Water Quality Systems Assessment Model (WQSAM) was selected for application for simulation of water quality. WQSAM was driven by simulated modified flows from the Water Resource Yield Model (WRYM) and Natural Daily flows from the Water Resource Simulation Model (WRSM) Daily version (Bailey and Pitman, 2016).

The following are the advantages of the WQSAM Model

- WQSAM is based on a simple structure of applying water quality signatures to flows and return flows;
- Driven by flows from other existing water resource models

The process flow diagram of methods applied for the configuration and setup of the WQSAM for is presented in **Error! Reference source not found.**.

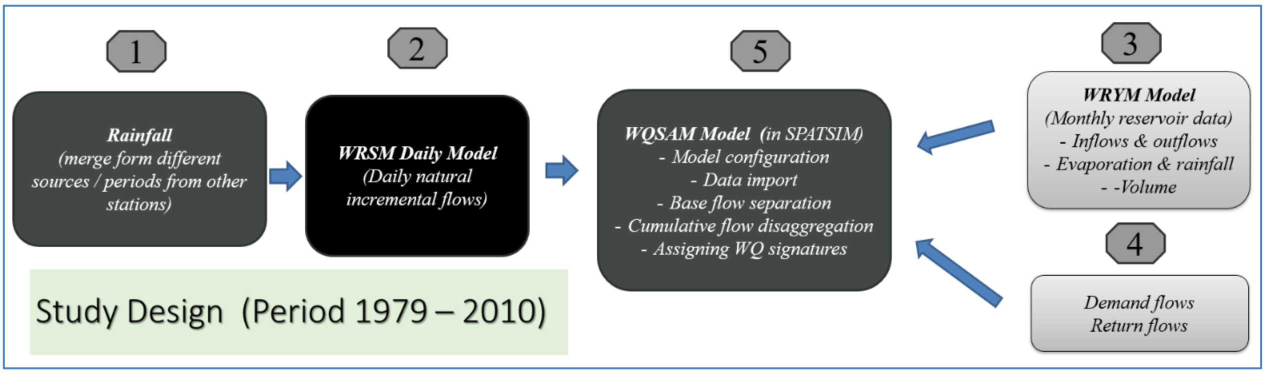


Figure 2.1 Study Design

The WQSAM setup processes are presented in (Figure 2.2)

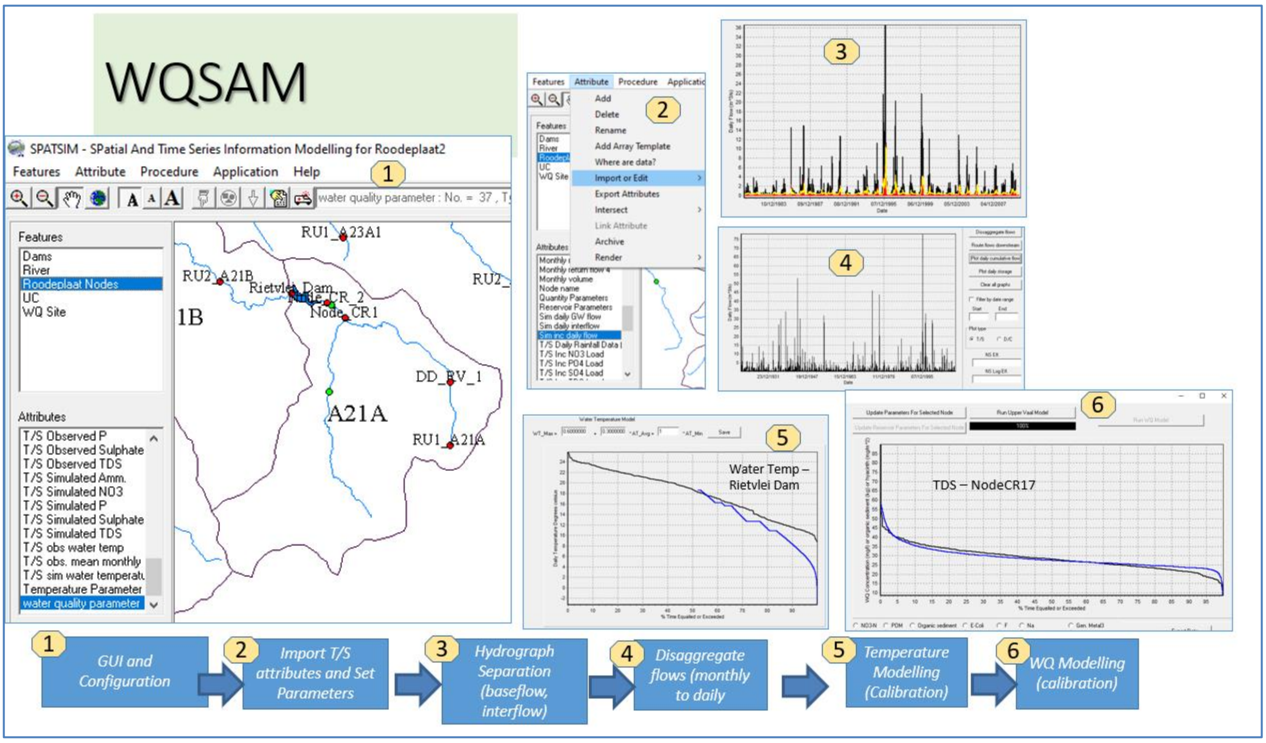


Figure 2.2 Model Setup Process

2.2 Hydrological Pre-Processing

WQSAM is a model designed to be run within the Spatial Time Series and Information Model (SPATSIM) (Hughes, 2004). SPATSIM is a modeling platform from which various hydrological models can be run, includes a simple geographical representation of study catchments, and facilitates the storage of data such as observed and simulated time series data and model parameters.

The nodal structure used in the WRSM and WRYM applications is also replicated in WQSAM. Due to memory constraints, WQSAM has been broken up into two executable programs. The first program deals with all hydrological (flow) components of the water quality model, including linking yield model nodes with the SPATSIM nodes, inputting monthly flow data from the yield model to SPATSIM, disaggregating monthly incremental flow to daily, baseflow separation of incremental flows and disaggregation of monthly cumulative flows to daily. This program is referred to as WQSAM-HYDRO. The second program deals with all water quality modelling, and includes water temperature modelling, salinity modelling and nutrient modelling. This program will be referred to as WQSAM-WQ.

All hydrological pre-processing of flow data, including monthly-daily flow disaggregation and the generation of flow fractions is performed within WQSAM-HYDRO. The WQSAM model is designed to take flows from the WReMP by Stephen Mallory. However, there was no existing WReMP Model setup for the Crocodile (west) River Catchment. Therefore, the following two options could be explored to pre-process hydrological data required and run WQSAM*. (i) Use of scripts to import and pre-process WRYM outputs of flows from the existing WRYM model for the Crocodile (West) Catchment* or (ii). *Use a daily model such as WRSM daily to simulate daily incremental flows and import into WQSAM.*

Option (ii) is an approach that was used, which allowed for elimination of some uncertainties by not applying some scaling and disaggregation of monthly incremental flows to daily flows based on rainfall and observed flow data.

A procedure for pre-processing hydrological data using option (ii) was developed.

2.3 Natural Incremental flows from WRSM Daily

The WRSM/Pitman daily version is a mathematical model for generating daily river flows from meteorological data in South Africa, and the methodology is described in the Hydrological Research Unit report HRU 2/76. The options to generate naturalized daily flows from the runoff module were used to set up and generate daily timestep flows. An example of the generated daily flows from **Oct 1920 – Sept 2010** for one of the runoff modules in the Roodeplaat Dam Catchment is presented in Figure 2.3.

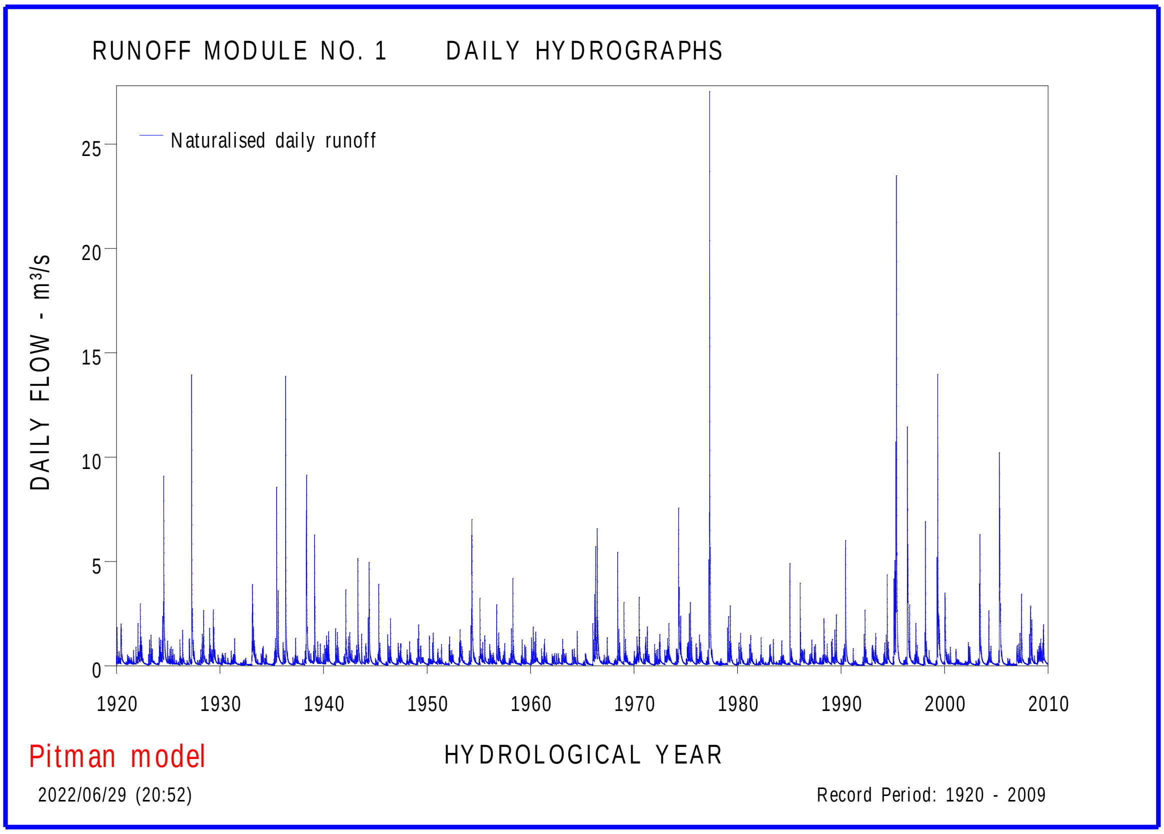


Figure 2.3 Runoff Module generated daily flows

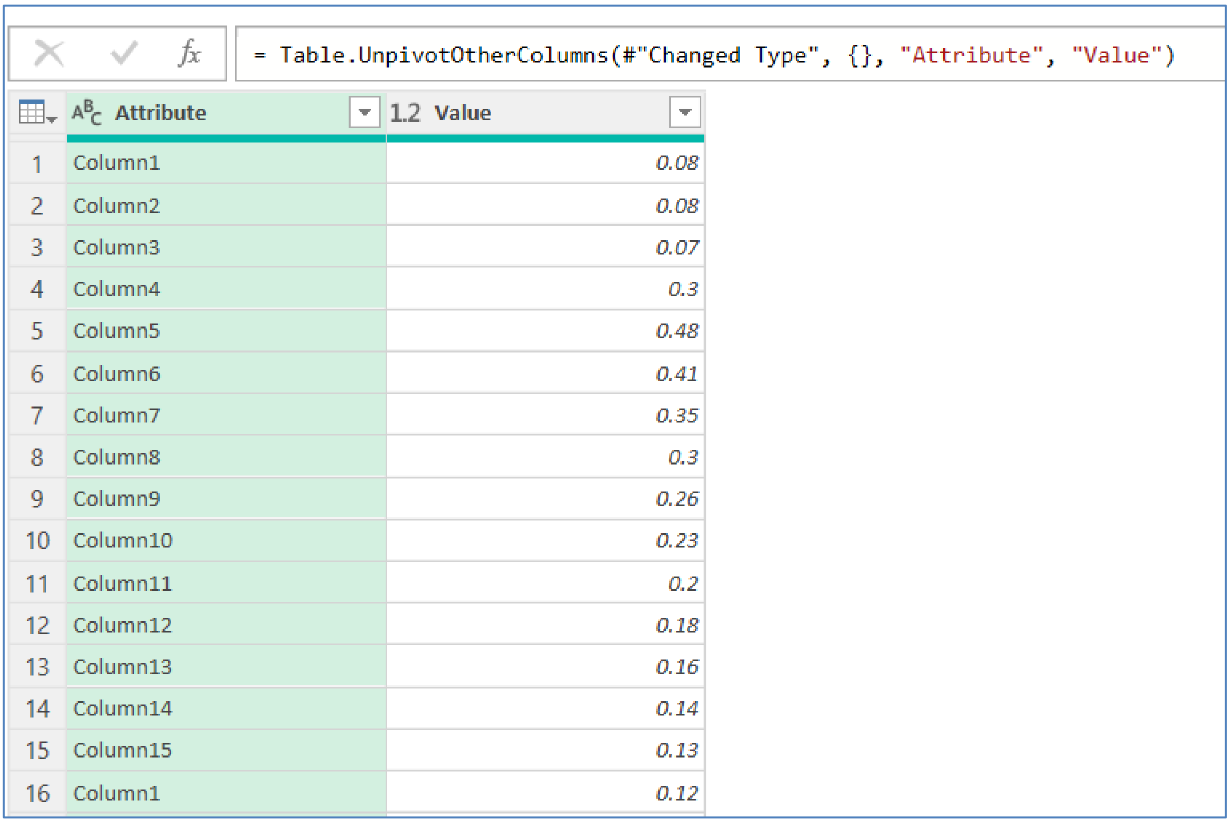
Limitations of the WRSM daily version:

- Only the Pitman method can be used for groundwater and surface water interactions.
- No child or alien vegetation modeling
- Daily flows can only be extracted for runoff modules (i.e., not for routes)

2.4 Import Daily natural incremental flows

The generated daily flows are then processed in excel to create continuous flow format that can be imported in SPATIM, the following steps are followed:

- The “-1” for the 29,30, or 31st day of the months are replaced with space
- Data > get and transform data (from table range)
- Select all columns and “unpivot columns”



```
= Table.UnpivotOtherColumns(#"Changed Type", {}, "Attribute", "Value")
```

	Attribute	Value
1	Column1	0.08
2	Column2	0.08
3	Column3	0.07
4	Column4	0.3
5	Column5	0.48
6	Column6	0.41
7	Column7	0.35
8	Column8	0.3
9	Column9	0.26
10	Column10	0.23
11	Column11	0.2
12	Column12	0.18
13	Column13	0.16
14	Column14	0.14
15	Column15	0.13
16	Column1	0.12

Figure 2.4 Query setting in excel (applied steps)

The daily incremental flows can now be imported as attribute into the configured WQSAM network – attribute for “sim inc. daily flow”. An example of the network configuration is given in Figure 2.5. The time series on the simulated incremental daily flow is presented in Figure 2.6.

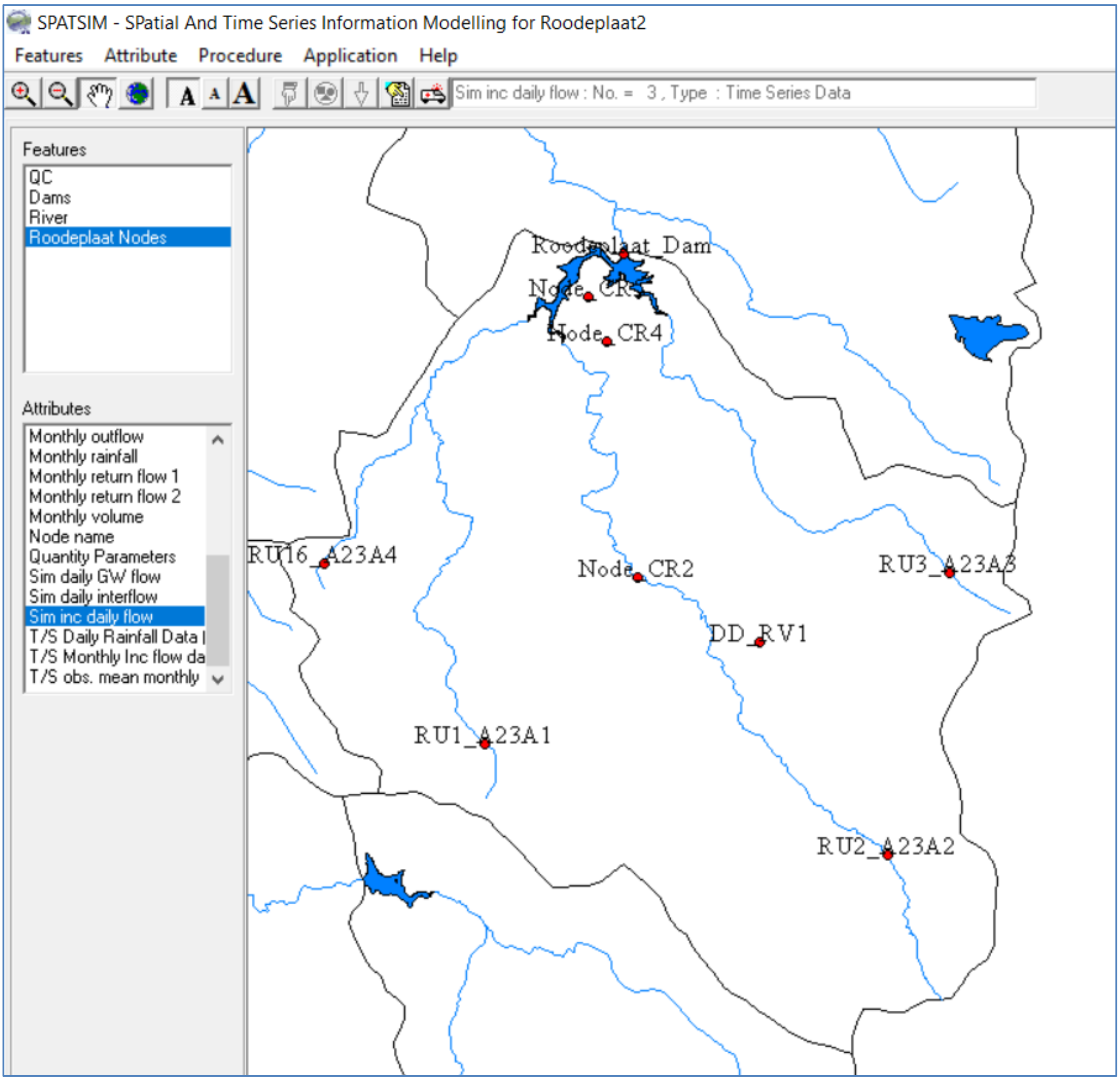
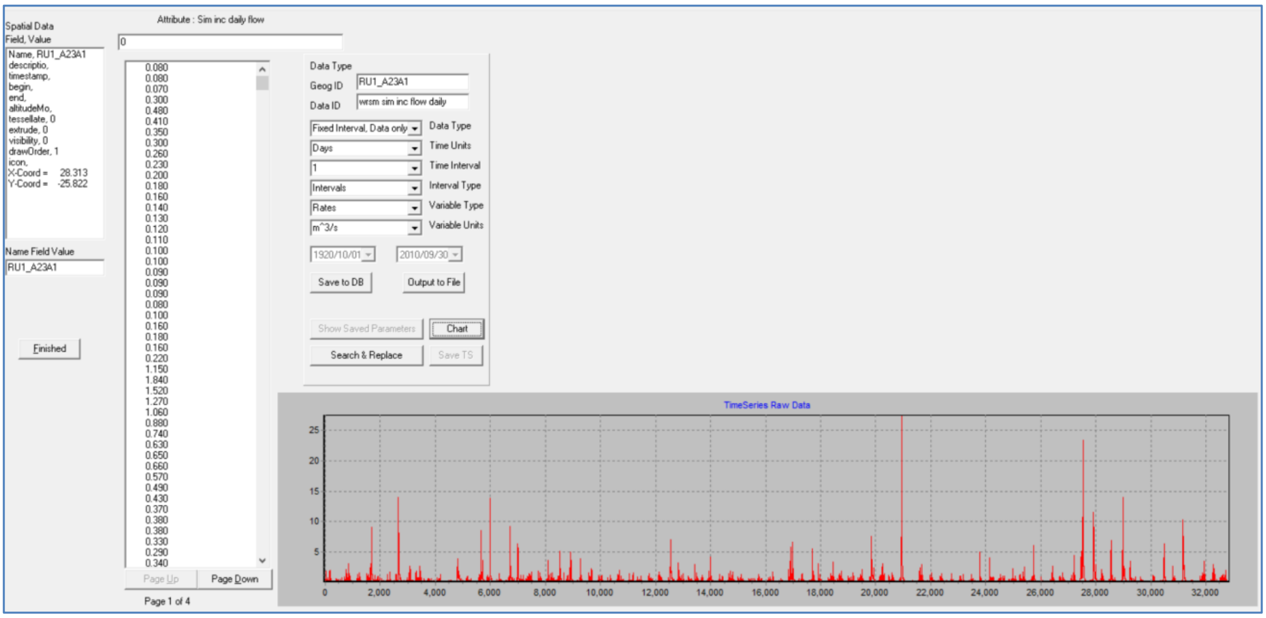


Figure 2.5 WQSAM Network


Attribute : Sim inc daily flow

Spatial Data
Field, Value

```
Name, RU1_A23A1
descriptio,
timestamp,
begin,
end,
altitudeMo,
tessellate, 0
extrude, 0
visibility, 0
drawOrder, 1
icon,
X-Coord =    28.313
Y-Coord =   -25.822
```

Name Field Value: RU1_A23A1

```
0
0.080
0.080
0.070
0.300
0.480
0.410
0.350
0.300
0.260
0.230
0.200
0.180
0.160
0.140
0.130
0.120
0.110
0.100
0.100
0.090
0.090
0.090
0.080
0.100
0.160
0.180
0.160
0.220
1.150
1.840
1.520
1.270
1.060
0.880
0.740
0.630
0.650
0.660
0.570
0.490
0.430
0.370
0.380
0.380
0.330
0.290
0.340
```

Page 1 of 4

Data Type
Geog ID: RU1_A23A1
Data ID: wrsm sim inc flow daily
Data Type: Fixed Interval, Data only
Time Units: Days
Time Interval: 1
Interval Type: Intervals
Variable Type: Rates
Variable Units: m^3/s
1920/10/01 – 2010/09/30

Figure 2.6 Time series attribute for simulated incremental daily flow for a node

2.5 Channel flows

The monthly channel flows are imported from the existing monthly WRSM version or the WRYM.

- **Demand** or extractions (upto 6 per node) – m^3/s
- **Return flows** (upto 4 per node) – m^3/s
- Transfers in or out (upto 3) – m^3/s

All the monthly channel flows are imported into attributes as **"spreadsheet > continuous > monthly"**

2.6 Reservoir

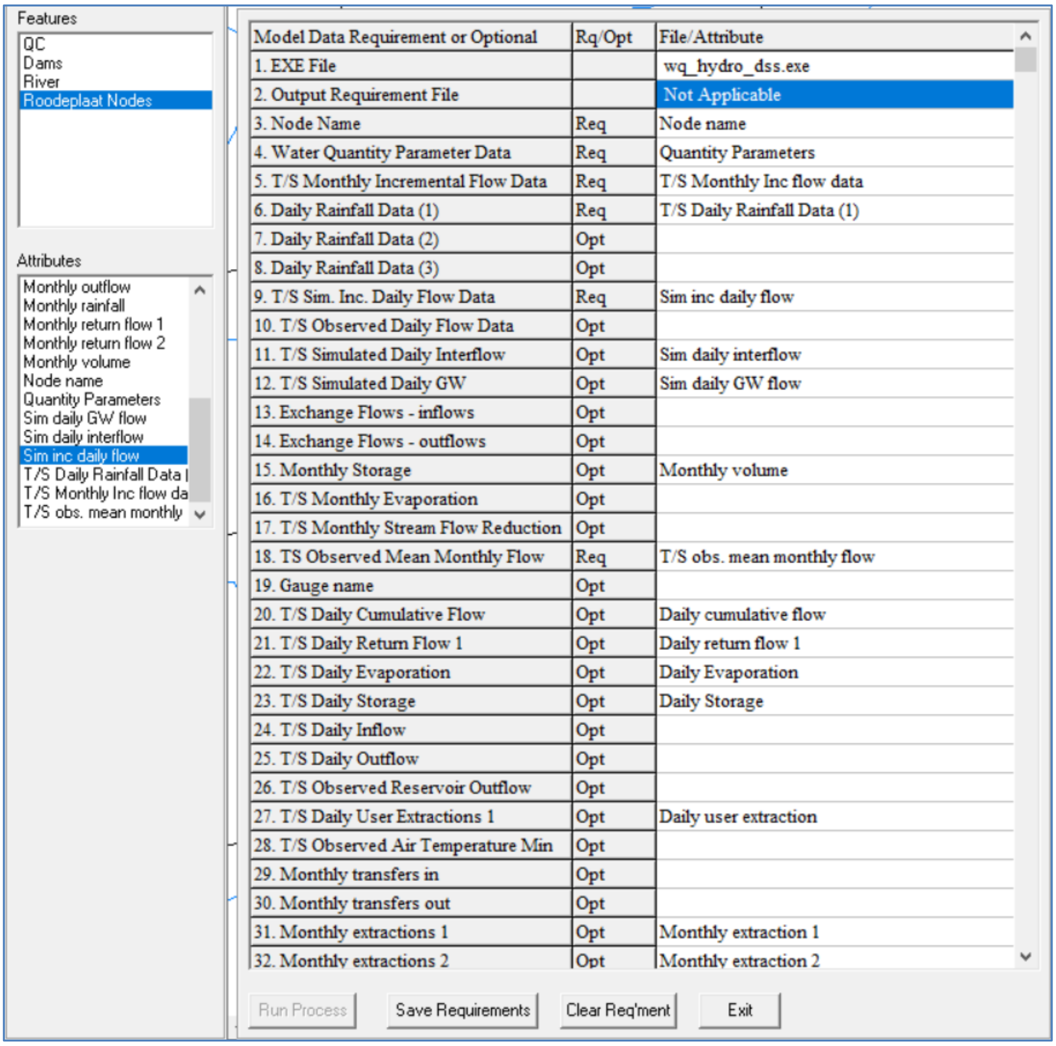
Reservoirs includes both **real dams and dummy dams**. The following monthly reservoir associated attributes are imported from the WRYM.

- Monthly evaporation – m^3/s
- Monthly rainfall – m^3/s
- Monthly Reservoir outflow or releases – m^3/s
- Monthly volume - (M m^3)

All the monthly channel flows are imported into attributes as **"spreadsheet > continuous > monthly"**

2.7 Baseflow Separation

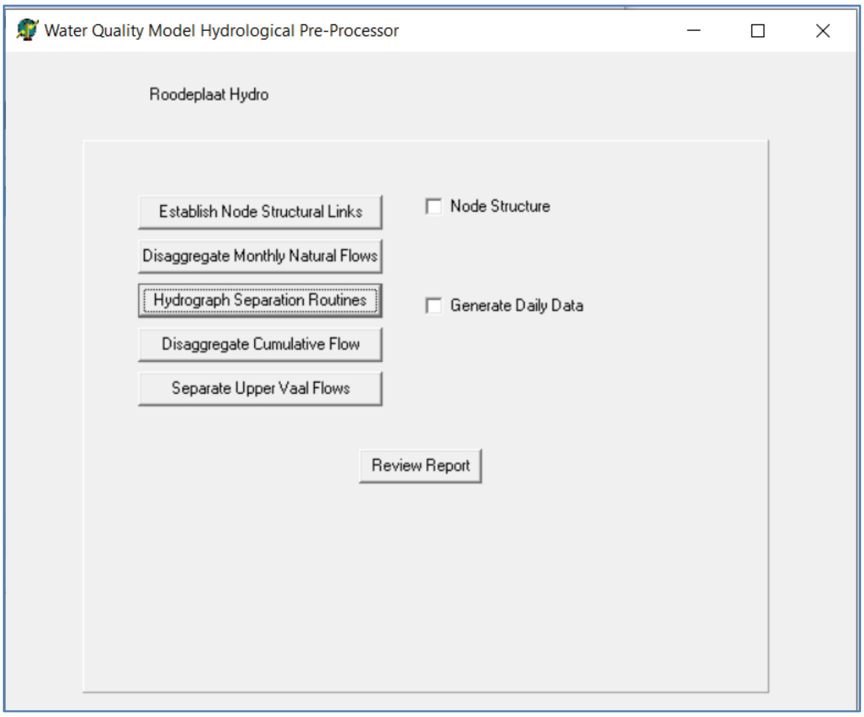
A process run is setup to execute *WQSAM-HYDRO pre-processing* to allow for separation of incremental natural daily flows into “sim daily GW” and “sim daily interflow”, the requirements are depicted in Figure 2.7, the **“Hydrograph Separation Routines”** tab is shown in Figure 2.8.



Model Data Requirement or Optional	Rq/Opt	File/Attribute
1. EXE File		wq_hydro_dss.exe
2. Output Requirement File		Not Applicable
3. Node Name	Req	Node name
4. Water Quantity Parameter Data	Req	Quantity Parameters
5. T/S Monthly Incremental Flow Data	Req	T/S Monthly Inc flow data
6. Daily Rainfall Data (1)	Req	T/S Daily Rainfall Data (1)
7. Daily Rainfall Data (2)	Opt	
8. Daily Rainfall Data (3)	Opt	
9. T/S Sim. Inc. Daily Flow Data	Req	Sim inc daily flow
10. T/S Observed Daily Flow Data	Opt	
11. T/S Simulated Daily Interflow	Opt	Sim daily interflow
12. T/S Simulated Daily GW	Opt	Sim daily GW flow
13. Exchange Flows - inflows	Opt	
14. Exchange Flows - outflows	Opt	
15. Monthly Storage	Opt	Monthly volume
16. T/S Monthly Evaporation	Opt	
17. T/S Monthly Stream Flow Reduction	Opt	
18. TS Observed Mean Monthly Flow	Req	T/S obs. mean monthly flow
19. Gauge name	Opt	
20. T/S Daily Cumulative Flow	Opt	Daily cumulative flow
21. T/S Daily Return Flow 1	Opt	Daily return flow 1
22. T/S Daily Evaporation	Opt	Daily Evaporation
23. T/S Daily Storage	Opt	Daily Storage
24. T/S Daily Inflow	Opt	
25. T/S Daily Outflow	Opt	
26. T/S Observed Reservoir Outflow	Opt	
27. T/S Daily User Extractions 1	Opt	Daily user extraction
28. T/S Observed Air Temperature Min	Opt	
29. Monthly transfers in	Opt	
30. Monthly transfers out	Opt	
31. Monthly extractions 1	Opt	Monthly extraction 1
32. Monthly extractions 2	Opt	Monthly extraction 2

Figure 2.7 WQ-HYDRO pre-process run requirements

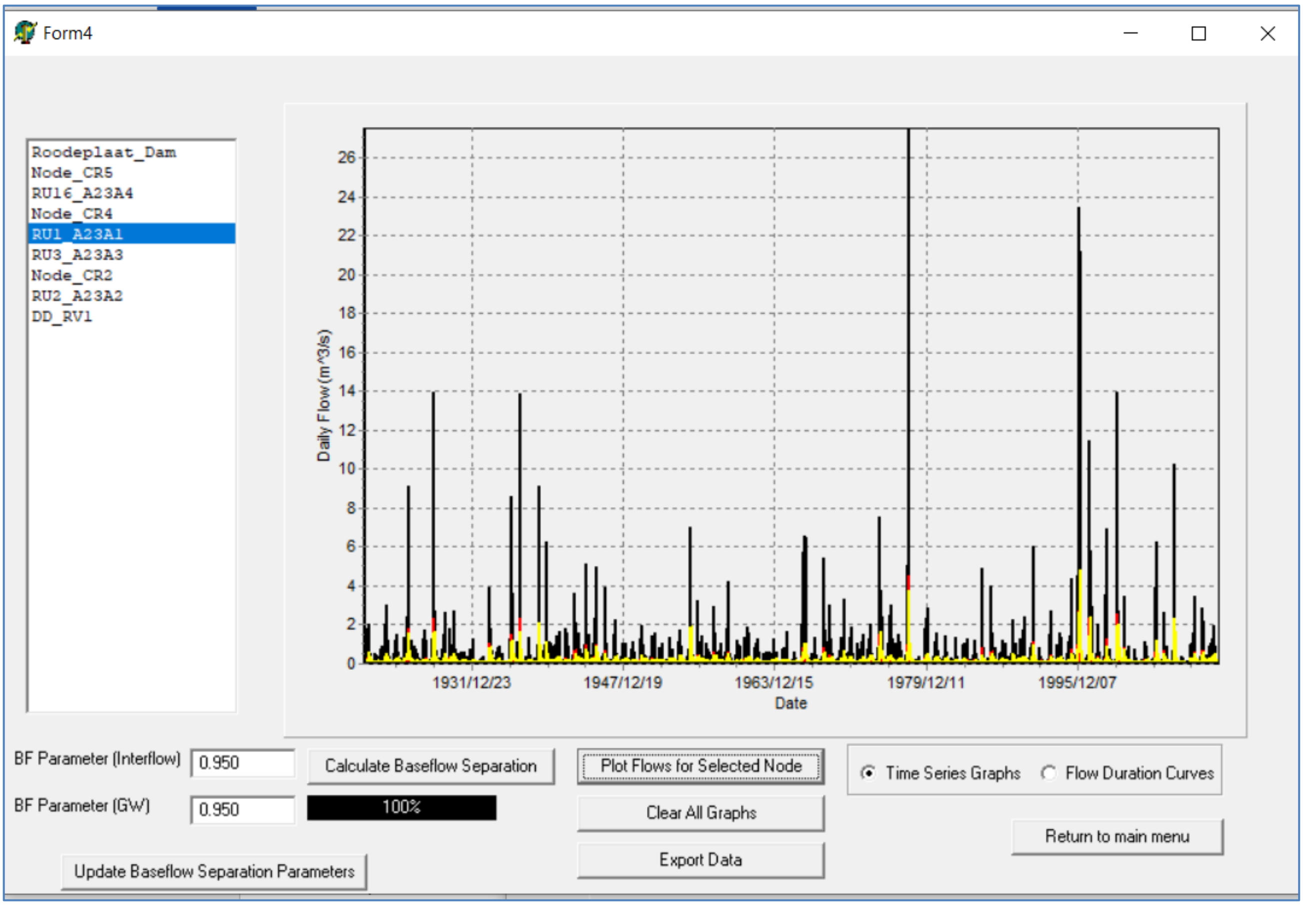
The attribute for T/S monthly Daily Rainfall (1); T/S Monthly Inc flow data; and T/S obs. Mean monthly flow are added even though used, but their time series data are also not imported when using option (ii) as the daily flows will no longer require further processing.



☐ Node Structure

☐ Generate Daily Data

Figure 2.8 Hydrograph separation routines tab used for baseflow separation



BF Parameter (Interflow) 0.950

BF Parameter (GW) 0.950

● Time Series Graphs ○ Flow Duration Curves

Figure 2.9 Flow separation results

2.8 Disaggregation of cumulative flows

A process run is setup to execute *WQSAM-HYDRO pre-processing* to allow the disaggregation of cumulative flows using an added tab: **"Separate Upper Vaal Flows"** as shown in Figure 2.10, an example of the results in presented in Figure 2.11**.**

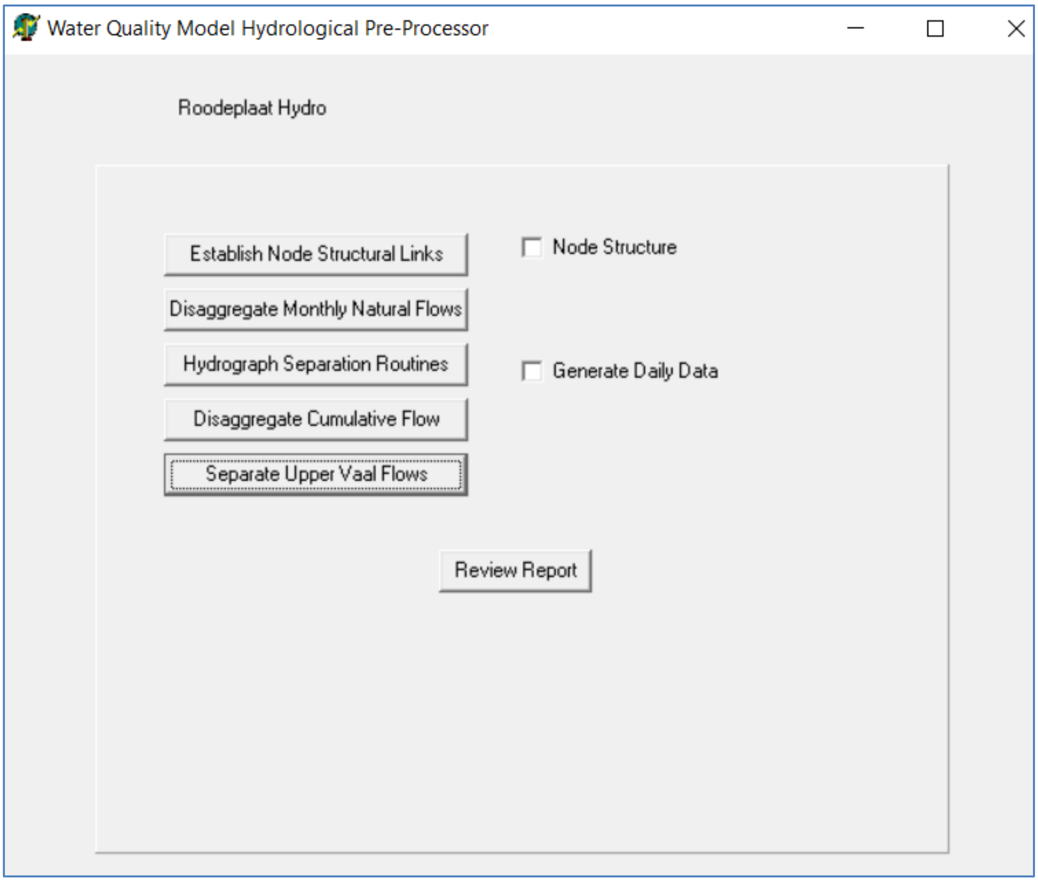
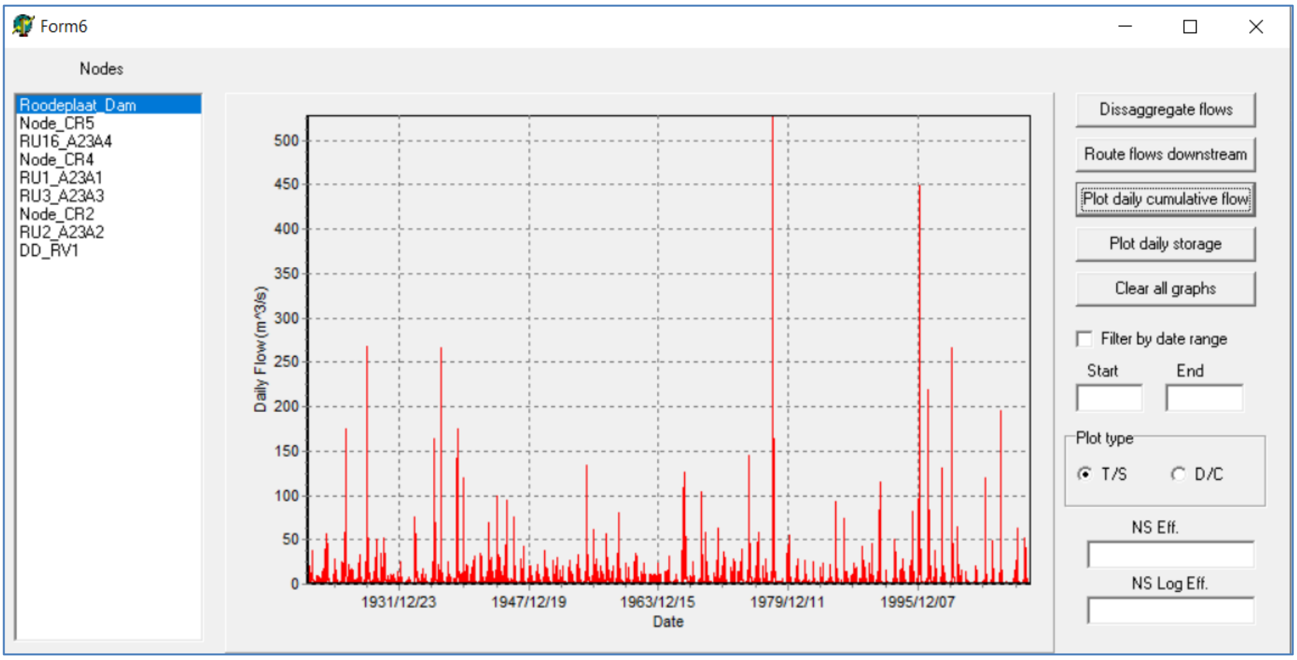


Figure 2.10 cumulative flow disaggregation tab



Roodeplaat_Dam
Node_CR5
RU16_A23A4
Node_CR4
RU1_A23A1
RU3_A23A3
Node_CR2
RU2_A23A2
DD_RV1

☐ Filter by date range

● T/S ○ D/C

Figure 2.11 Monthly cumulative flows disaggregated to daily

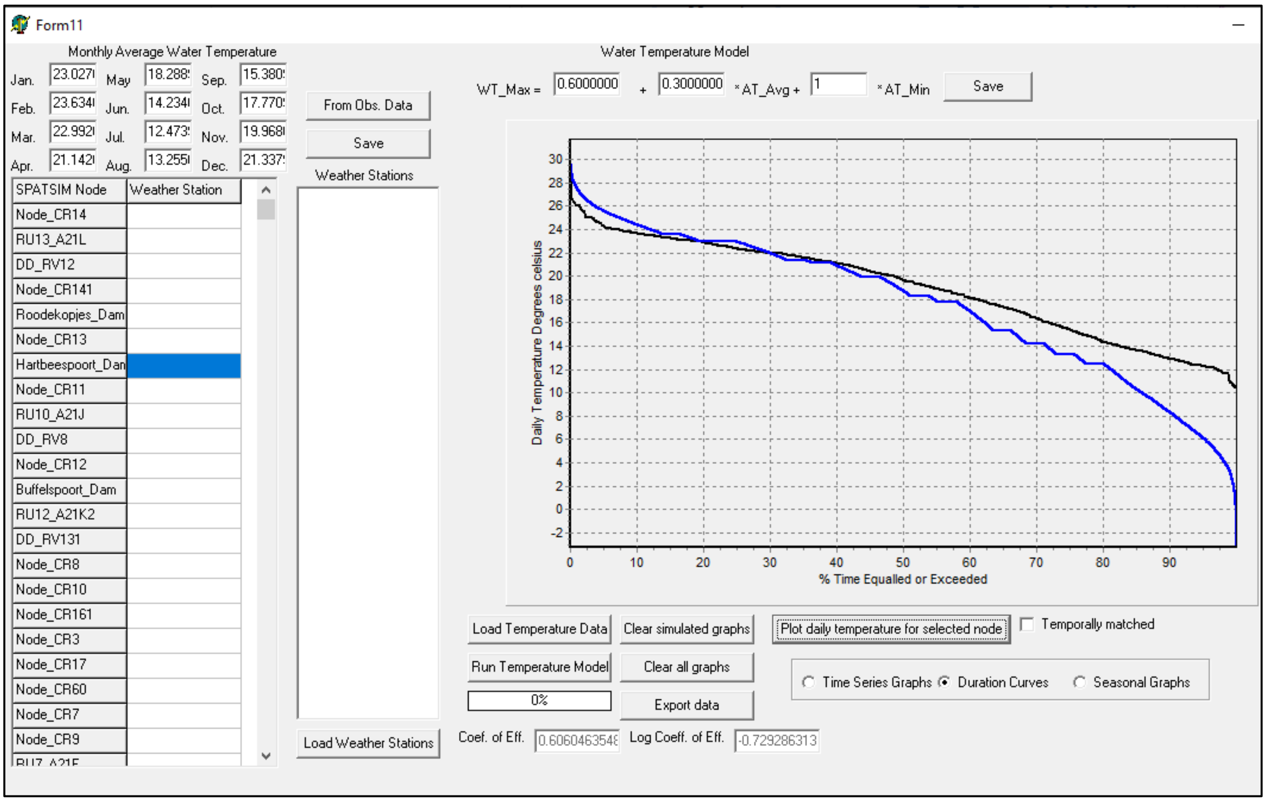
2.9 Other attributes required.

The following attributes should be created and added:

- Sim daily GW flow
- Sim daily interflow
- Daily cumulative flow – ***(for nodes/reaches)***
- Daily evaporation
- Daily return flow 1
- Daily return flow 2 – ***(up to 4 per node)***
- Daily storage
- Daily user extraction 1 only
- Daily reservoir releases
- Quantity parameters – array file

The temperature parameter and water quality parameters files are created.

Next the water temperature and water quality modelling process application are setup for calibrations (see Figure 2.12 and Figure 2.13).



Monthly Average Water Temperature

Jan.	23.027	May	18.288	Sep.	15.380
Feb.	23.634	Jun.	14.234	Oct.	17.770
Mar.	22.992	Jul.	12.473	Nov.	19.968
Apr.	21.142	Aug.	13.255	Dec.	21.337

SPATSIM Node	Weather Station
Node_CR14	
RU13_A21L	
DD_RV12	
Node_CR141	
Roodekopjes_Dam	
Node_CR13	
Hartbeespoort_Dan	
Node_CR11	
RU10_A21J	
DD_RV8	
Node_CR12	
Buffelspoort_Dam	
RU12_A21K2	
DD_RV131	
Node_CR8	
Node_CR10	
Node_CR161	
Node_CR3	
Node_CR17	
Node_CR60	
Node_CR7	
Node_CR9	

Water Temperature Model

WT_Max = 0.6000000 + 0.3000000 *AT_Avg + 1 *AT_Min

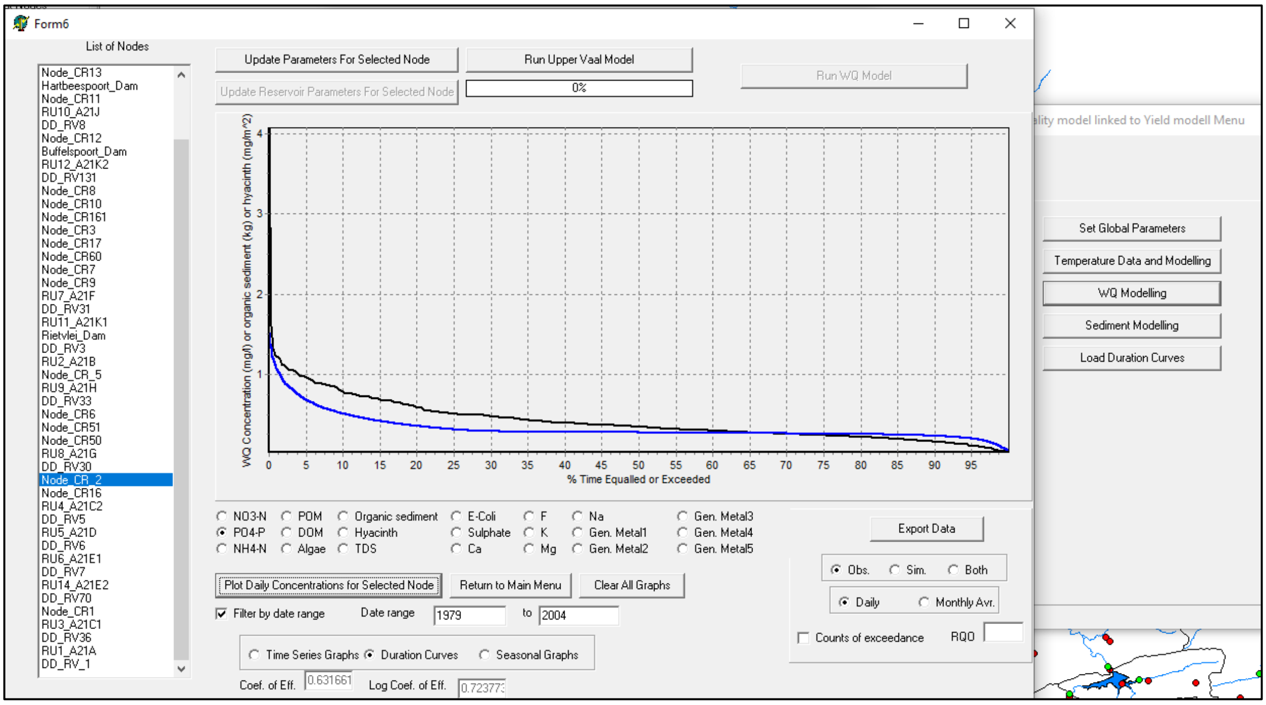
☐ Temporally matched

○ Time Series Graphs ● Duration Curves ○ Seasonal Graphs

0%

Coef. of Eff. 0.606046354 Log Coeff. of Eff. -0.729286313

Figure 2.12 Water Temperature calibrations



List of Nodes

Node_CR13
Hartbeespoort_Dam
Node_CR11
RU10_A21J
DD_RV8
Node_CR12
Buffelspoort_Dam
RU12_A21K2
DD_RV131
Node_CR8
Node_CR10
Node_CR161
Node_CR3
Node_CR17
Node_CR60
Node_CR7
Node_CR9
RU7_A21F
DD_RV31
RU11_A21K1
Rietvlei_Dam
DD_RV3
RU2_A21B
Node_CR_5
RU9_A21H
DD_RV33
Node_CR6
Node_CR51
Node_CR50
RU8_A21G
DD_RV30
Node_CR_2
Node_CR16
RU4_A21C2
DD_RV5
RU5_A21D
DD_RV6
RU6_A21E1
DD_RV7
RU14_A21E2
DD_RV70
Node_CR1
RU3_A21C1
DD_RV36
RU1_A21A
DD_RV_1

0%

○ NO3-N ○ POM ○ Organic sediment ○ E-Coli ○ F ○ Na ○ Gen. Metal3
● PO4-P ○ DOM ○ Hyacinth ○ Sulphate ○ K ○ Gen. Metal1 ○ Gen. Metal4
○ NH4-N ○ Algae ○ TDS ○ Ca ○ Mg ○ Gen. Metal2 ○ Gen. Metal5

☑ Filter by date range Date range 1979 to 2004

○ Time Series Graphs ● Duration Curves ○ Seasonal Graphs

Coef. of Eff. 0.631661 Log Coef. of Eff. 0.723773

● Obs. ○ Sim. ○ Both

● Daily ○ Monthly Avr.

☐ Counts of exceedance RQO

Figure 2.13 Water Quality Modelling calibrations

3 Hartbeespoort Dam Catchment (Upper Crocodile)

The Hartbespoort Dam Catchment in the Upper Crocodile Catchment is a highly modified system characterized by high return flows from wastewater treatment works of water transferred from other catchments. It drains off the two major cities in the Gauteng Province (Johannesburg and Pretoria), and is dominated by Urban, agricultural land uses, and to a lesser extent mining activities (Figure 3.1).

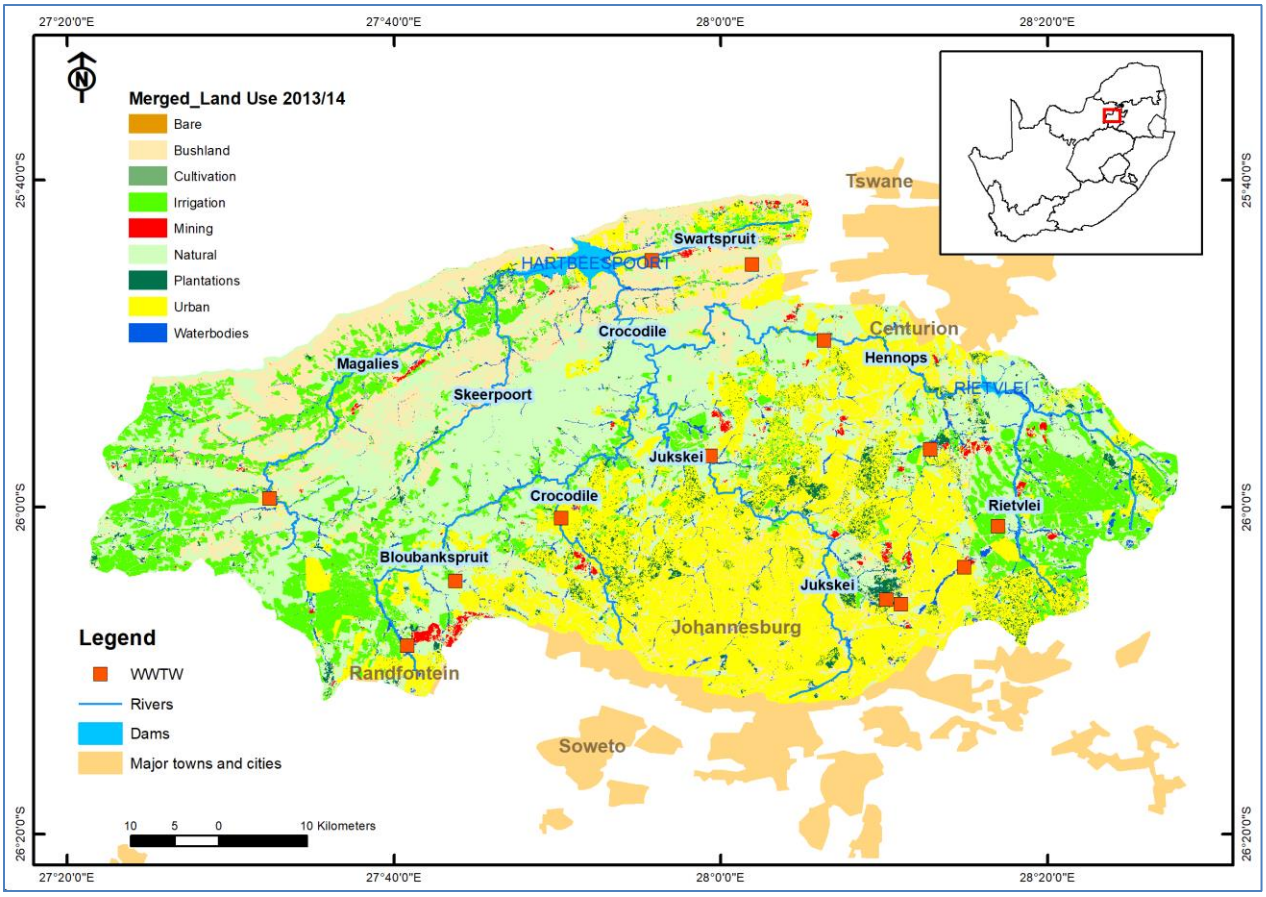


Figure 3.1 Landuse Hartbeespoort Dam catchment

Eutrophication is a looming threat in this catchment especially in the Hartbeespoort Dam Catchment in the upper reaches. This is evident in the hypertrophic condition of the Hartbeespoort Dam. This is considered the most impacted water body in South Africa (Mattews et al., 2015).

3.1 Model Configuration

The water quality data used in the model was obtained from the Department of Water and Sanitation's (DWS) national monitoring programmes with monitoring starting mostly in 1979 (also selected as the study start period). Only water quality data up to 2010 was used as the flow simulations from existing models (WRSM and WRYM) ended in September 2010. The Hartbeespoort Dam Catchment is well covered in terms of the monitoring network, as there are monitoring sites at the outlet of each quaternary catchment, and most water quality sites coincides with flow monitoring sites locations (Figure 3.2).

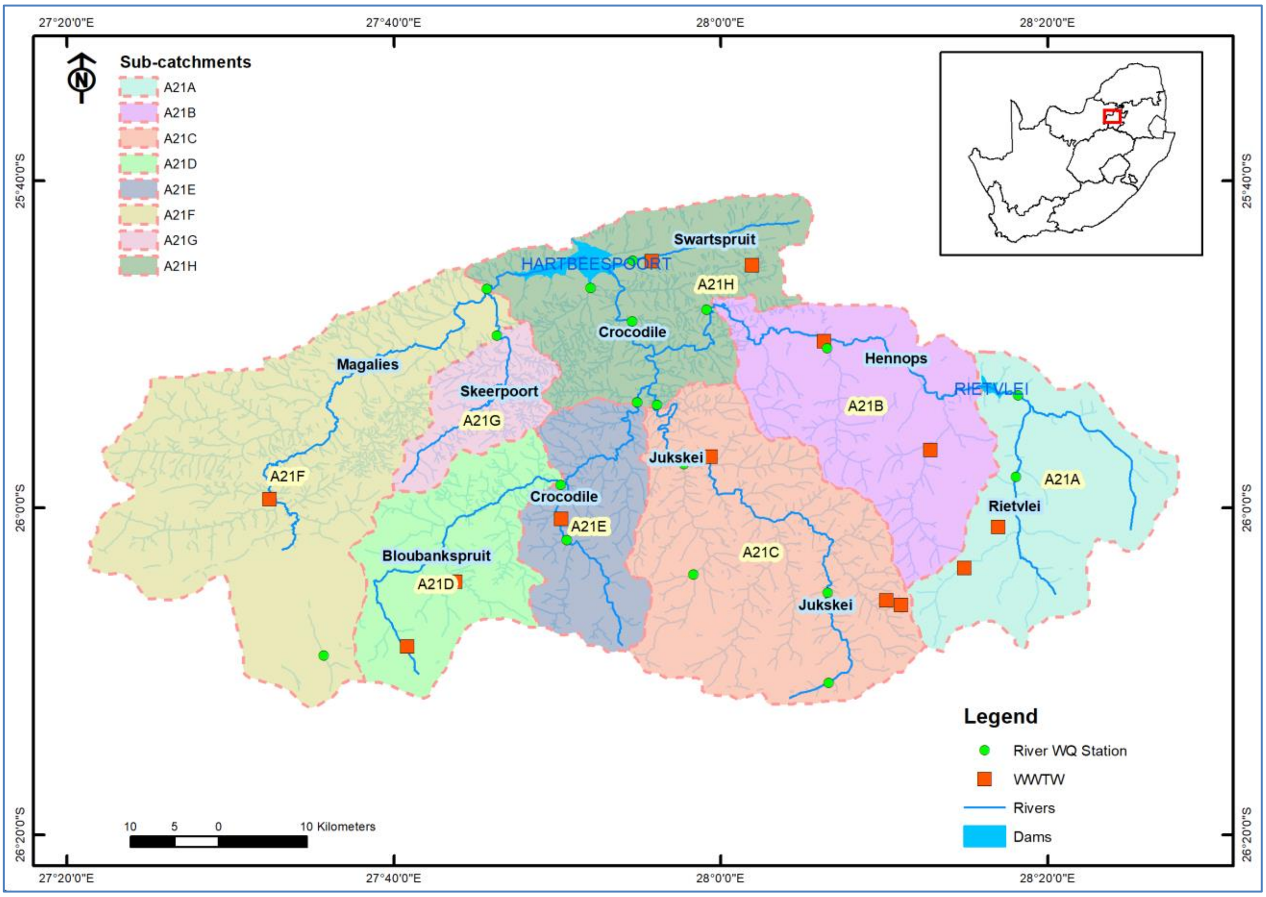


Figure 3.2 Quaternary Catchments and Water Quality Monitoring Points

An example of available data for a station at the confluence of Jukskei River with Crocodile River, is presented in (Figure 3.3). An increasing trend is observed for PO4-N and NH4-N from 2004 – 2010 on Jukskei River.

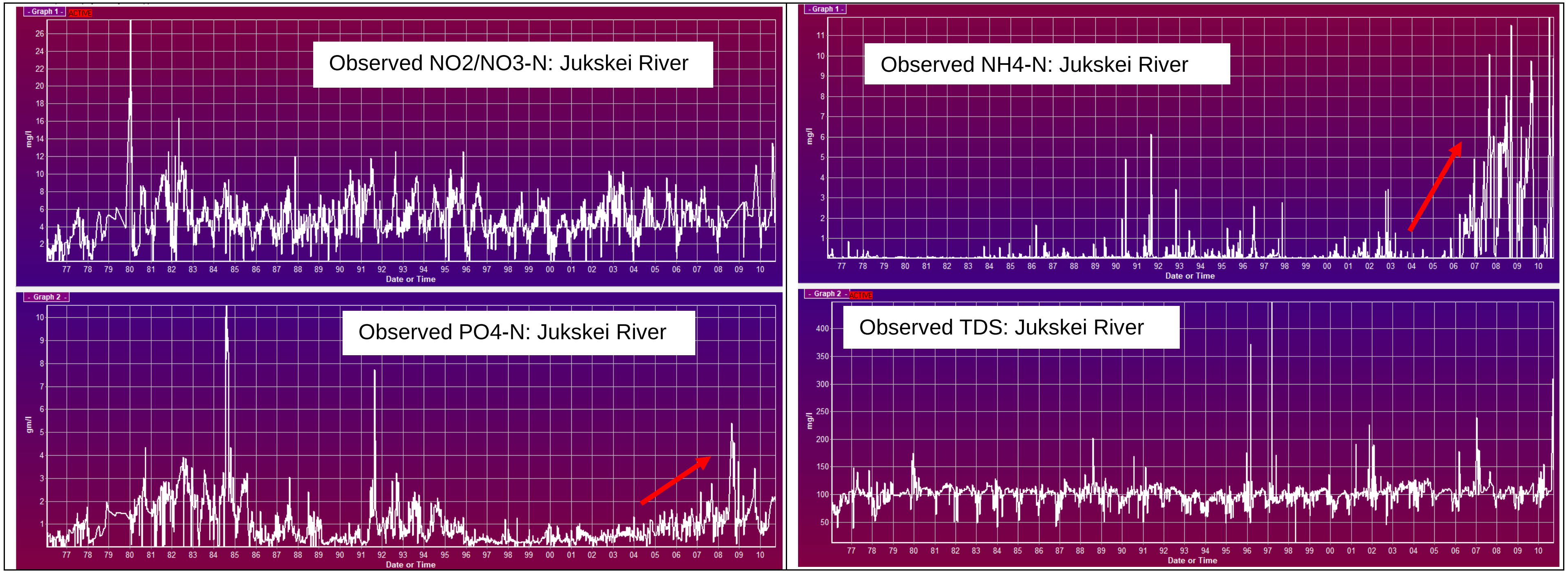
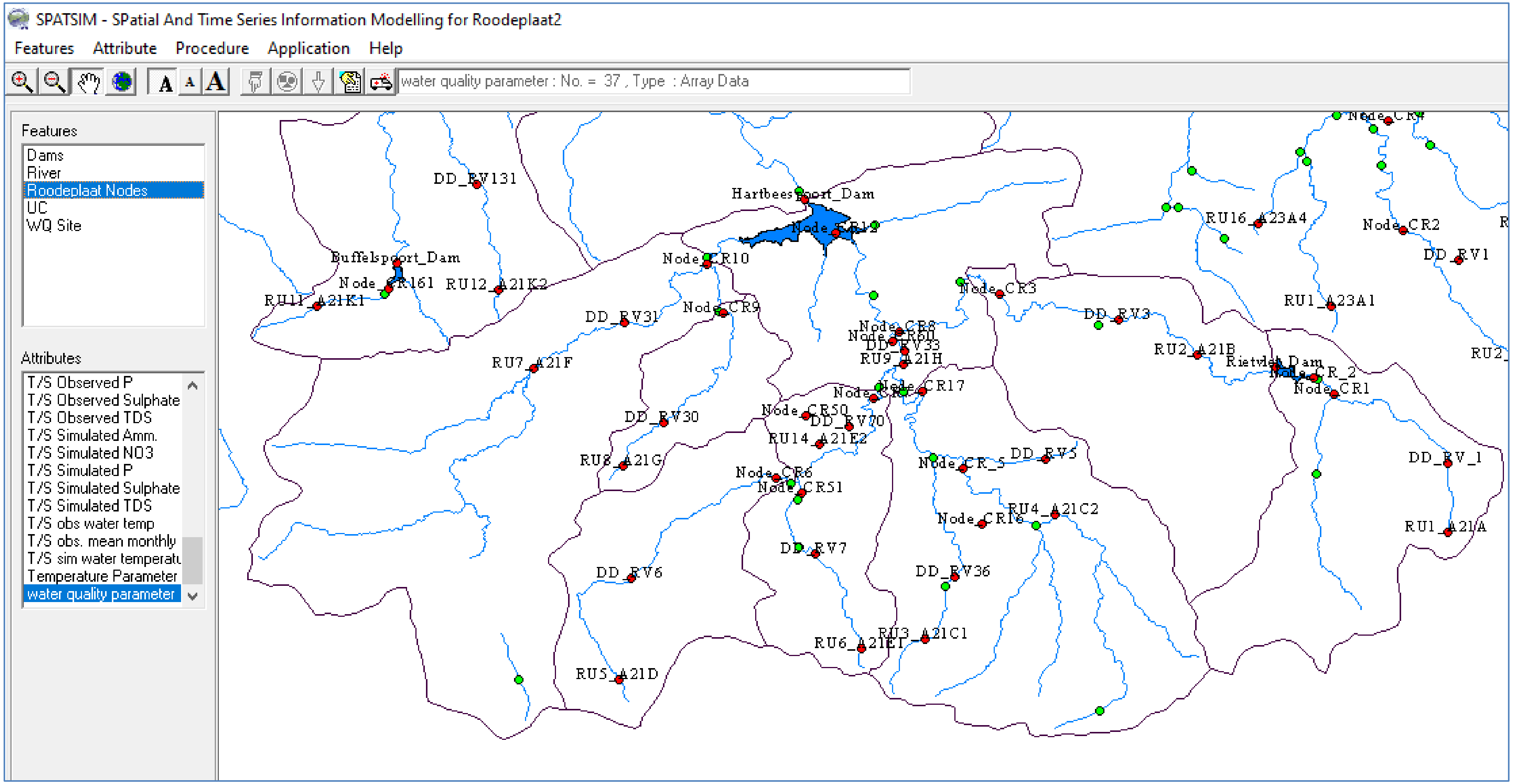


Figure 3.3 Water Quality Observed data

The WQSAM model configuration based on the existing WRSM network is presented in Figure 3.4.



SPATSIM - SPatial And Time Series Information Modelling for Roodeplaat2

water quality parameter : No. = 37 , Type : Array Data

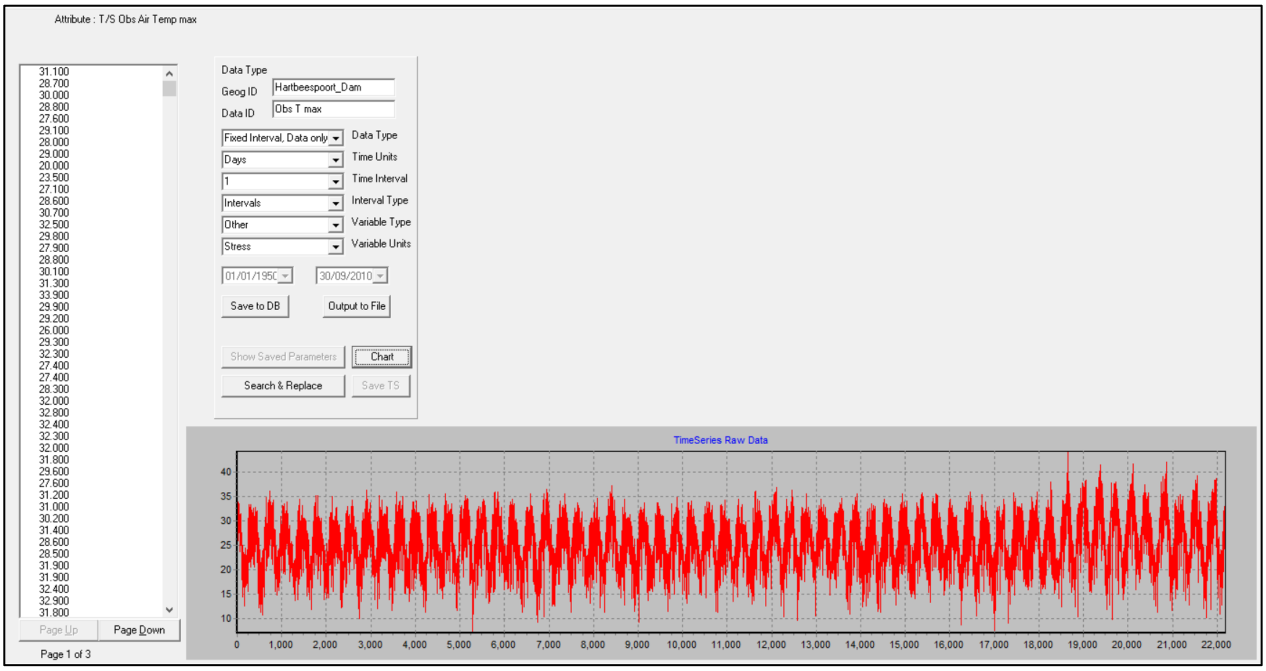
Figure 3.4 Hartbeespoort Dam catchment Model Configuration

3.2 Hartbeespoort Dam Catchment Temperature Model

To run the WQSAM temperature model attributes for a time series of observed min and max air temperature, and water temperature is required. water temperature data was only available for Hartbeespoort Dam and Rietvlei Dam. The following attributes were created:

- Temperature Parameter (Array file)
- T/S obs Air Temp min
- T/S obs Air Temp max
- T/S obs water temp
- T/S sim water temperature

An example of the observed water temperature time series is presented in Figure 3.5 for the Harbeespoort Dam, while the observed water temperature is presented in Figure 3.6. the **water quality model linked to the Yield model** is then executed.



Attribute : T/S Obs Air Temp max

```
31.100
28.700
30.000
28.800
27.600
29.100
28.000
29.000
20.000
23.500
27.100
28.600
30.700
32.500
29.800
27.900
28.800
30.100
31.300
33.900
29.900
29.200
26.000
29.300
32.300
27.400
27.400
28.300
32.000
32.800
32.400
32.300
32.000
31.800
29.600
27.600
31.200
31.000
30.200
31.400
28.600
28.500
31.900
31.900
32.400
32.900
31.800
```

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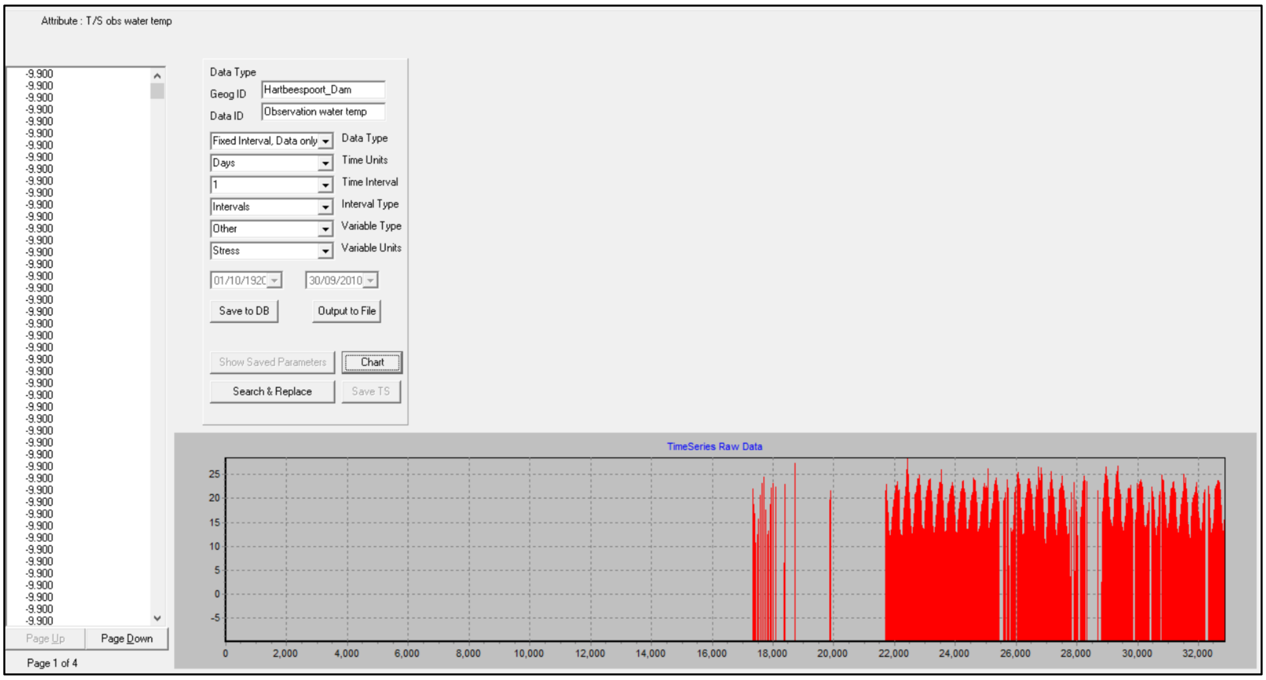
Data Type
Geog ID: Hartbeespoort_Dam
Data ID: Obs T max
Data Type: Fixed Interval, Data only
Time Units: Days
Time Interval: 1
Interval Type: Intervals
Variable Type: Other
Variable Units: Stress
01/01/1950 – 30/09/2010

Figure 3.5 T/S observed air temperature max



Attribute : T/S obs water temp

```
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
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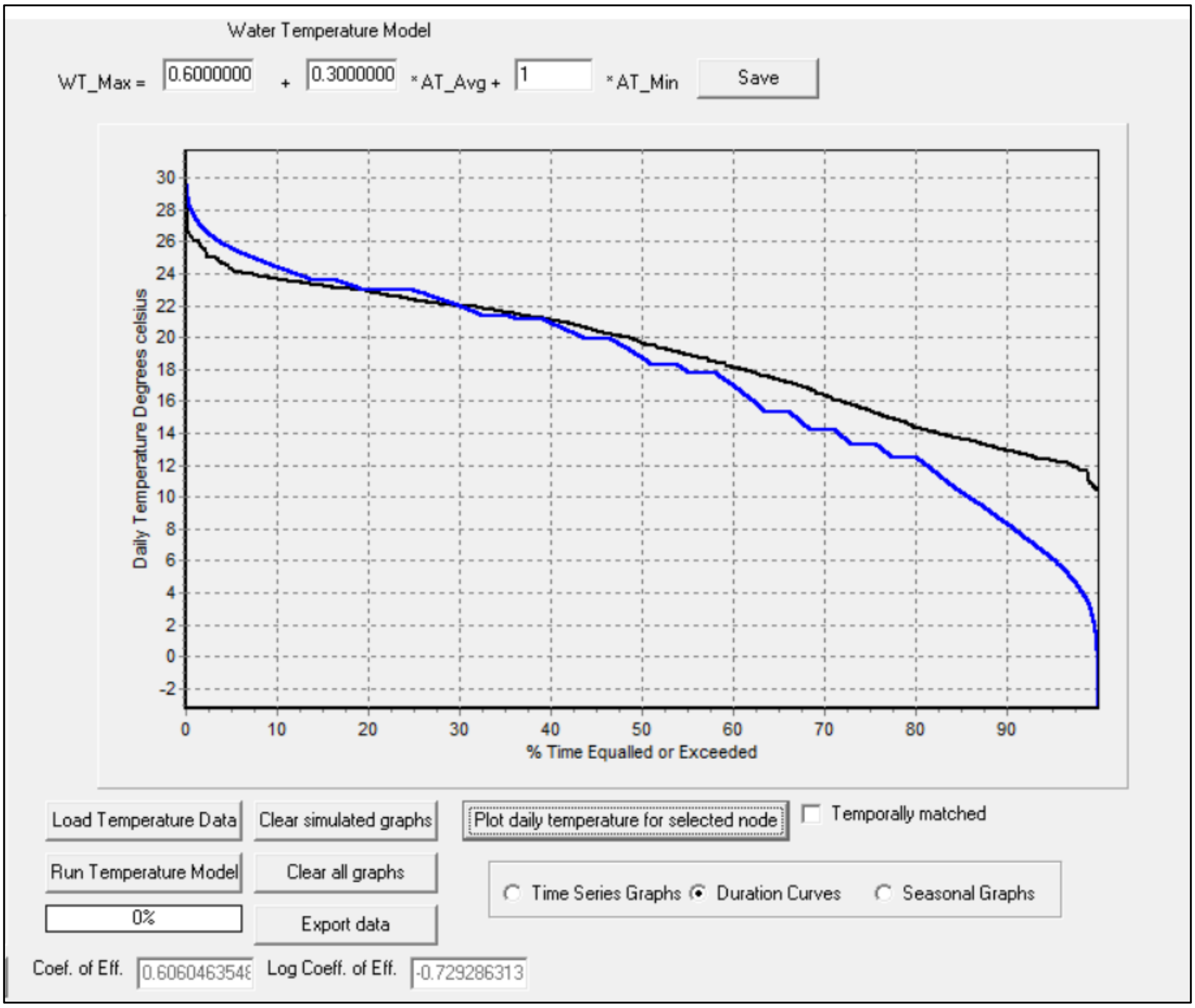
Page 1 of 4

Data Type
Geog ID: Hartbeespoort_Dam
Data ID: Observation water temp
Data Type: Fixed Interval, Data only
Time Units: Days
Time Interval: 1
Interval Type: Intervals
Variable Type: Other
Variable Units: Stress
01/10/1920 – 30/09/2010

Figure 3.6 T/S Observed Water Temeprature

Water Temperature for all notes which did not have observed, were simulated from the air temperature min and max. The calibration of the simulated and observed water temperature for Hartbeespoort Dam is presented in Figure 3.7



WT_Max = 0.6000000 + 0.3000000 *AT_Avg + 1 *AT_Min

☐ Temporally matched

0%

○ Time Series Graphs ● Duration Curves ○ Seasonal Graphs

Coef. of Eff. 0.6060463548 Log Coeff. of Eff. -0.729286313

Figure 3.7 Calibration of the water temperature frequency exceedance curve

3.3 Water Quality Model Calibration Results

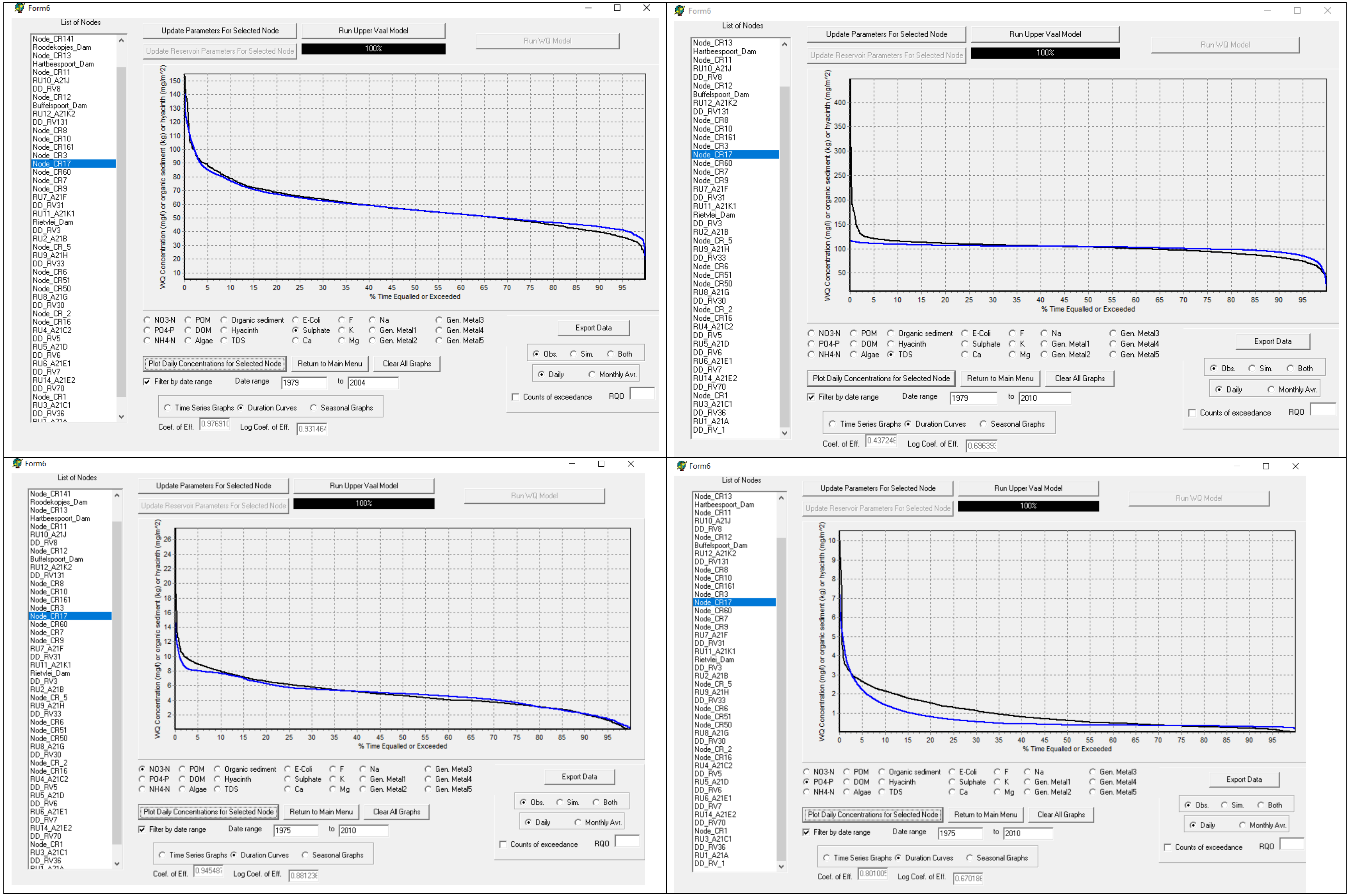
The water quality model linked to the yield model was then setup and calibration carried out at various points with observed data.

3.3.1 Salinity calibrations

The Calibration of Sulphates and TDS at Node CR17 (Outflow from the Jukskei Catchment) frequency exceedance curves are presented in Figure 3.8.

3.3.2 Nutrients Calibration

The nutrient calibration at NodeCR17 – outlet of Jukskei River are also presented in Figure 3.8.



Node_CR17

● Sulphate ● Obs. ● Daily ☑ Filter by date range Date range 1979 to 2004 ● Duration Curves
Coef. of Eff. 0.976910 Log Coef. of Eff. 0.931464

● TDS ● Obs. ● Daily ☑ Filter by date range Date range 1979 to 2010 ● Duration Curves
Coef. of Eff. 0.437246 Log Coef. of Eff. 0.696393

● NO3-N ● Obs. ● Daily ☑ Filter by date range Date range 1975 to 2010 ● Duration Curves
Coef. of Eff. 0.945487 Log Coef. of Eff. 0.881236

● PO4-P ● Obs. ● Daily ☑ Filter by date range Date range 1975 to 2010 ● Duration Curves
Coef. of Eff. 0.801005 Log Coef. of Eff. 0.670186

Figure 3.8 Salinity and Nutrients calibration at outlet of Jukskei River

3.4 Results and Discussions

The WQSAM model was setup and calibrated for a period of 31 years (1979 – 2010) at most. The allocation of water quality signatures to flow fractions was guided by water quality observed data and land use. Salinity was simulated by assigning high values to the groundwater fraction, while high values were assigned to surface flow fraction to simulate nutrients.

The frequency distribution curves were used for calibration and the long-term simulated median (P50) daily concentrations results for PO4, NO3,NH4 and TDS are presented in Figure 3.9.

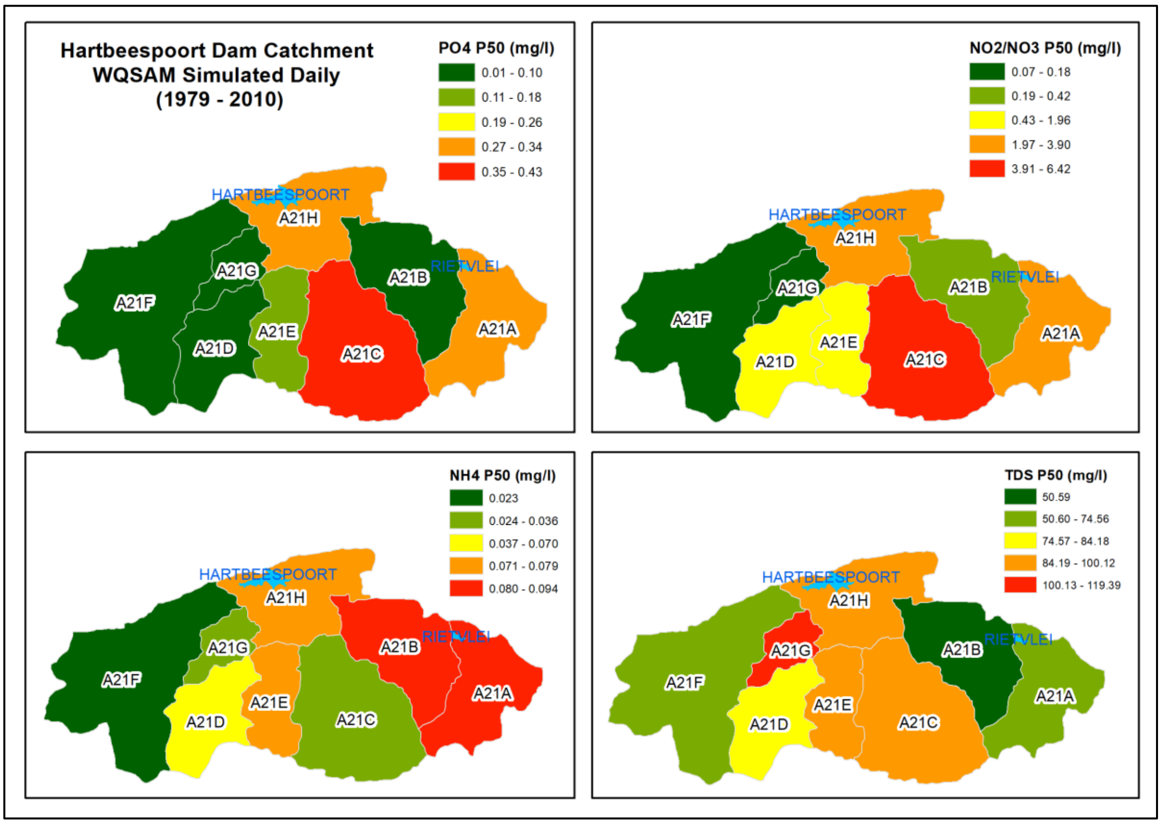


Figure 3.9 Simulated median daily concentrations (mg/l)

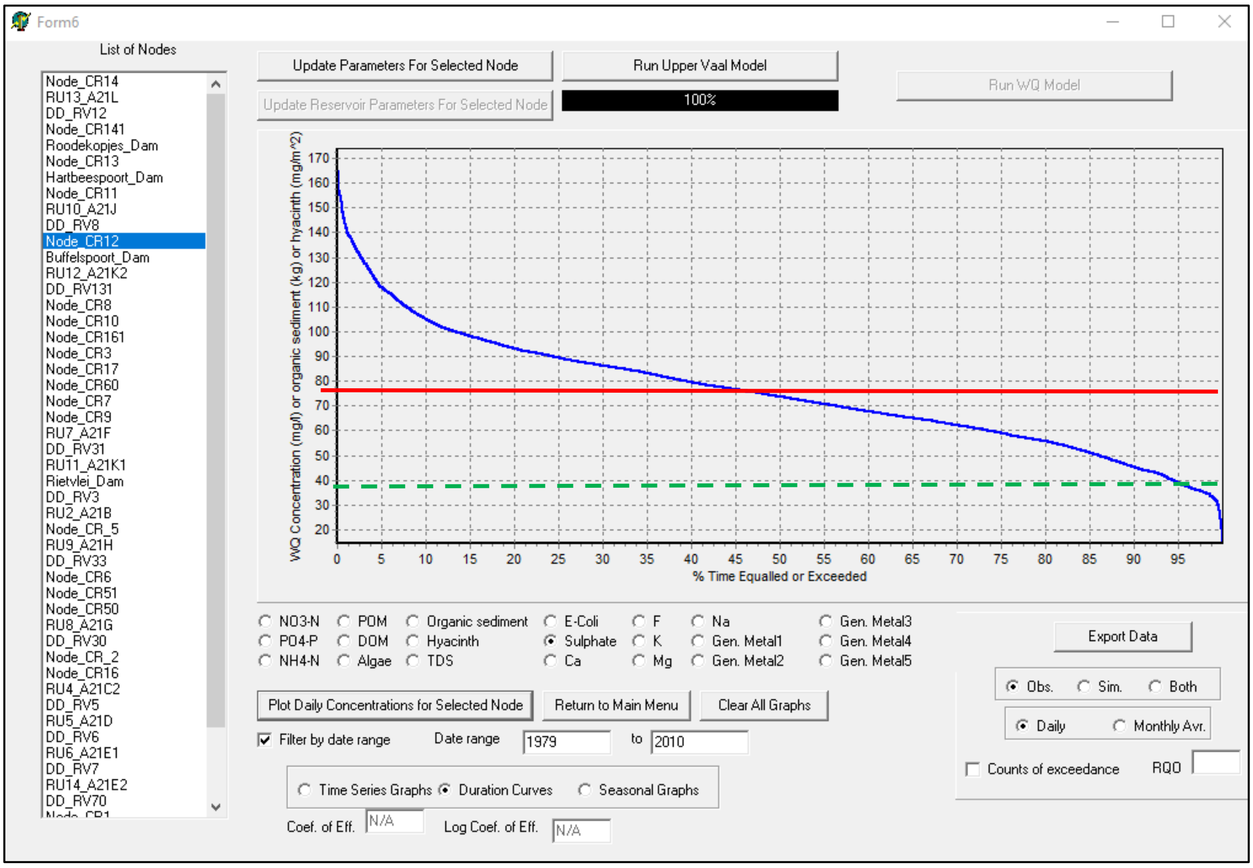
	Rivers
A21A	Rietvlei
A21B	Hennops
A21C	Jukskei
A21D	Bloubankspruit
A21E	Upper Crocodile
A21F	Magalies
A21G	Skeerpoort
A21H	Crocodile

Figure 3.10 Descriptions of River Catchments

The following observations were made:

- An observation was made that the Jukskei River yields high concentrations of Phosphates (PO4) (>0.35 mg/l) and Nitrates (NO3) (> 3.9 mg/l) on a long-term median. Most of the nutrients from the Rietvlei River are retained by the Rietvlei Dam, while phosphates and nitrates from the Jukskei River ends-up at the Hartbeespoort Dam through the Crocodile River.
- High Ammonium (NH4-N) concentrations (>0.08 mg/l) were observed from the Rietvlei River which is dominated by agriculture, and the Hennops River which is dominated by urban settlements.
- High salinity (TDS) concentrations (>100.13 mg/l) were observed on the Skeerpoort River which is mostly natural and bushland, with few patches of irrigation. These could likely be due to the local geology of the area.

The frequency exceedance curves for the Crocodile River inflow into the Hartbeespoort Dam and comparison with the set Resource Quality Objectives (RQOs) is presented in Figure 3.11 to Figure 3.15.



List of Nodes: Node_CR12 (selected)

● Sulphate

☑ Filter by date range Date range 1979 to 2010

● Duration Curves

● Obs. ● Daily

☐ Counts of exceedance RQO

Coef. of Eff. N/A Log Coef. of Eff. N/A

Figure 3.11 SO4 - Inflow to Hartbeespoort Dam (P95 = 34.9 mg/l) RQO < 75 mg/l

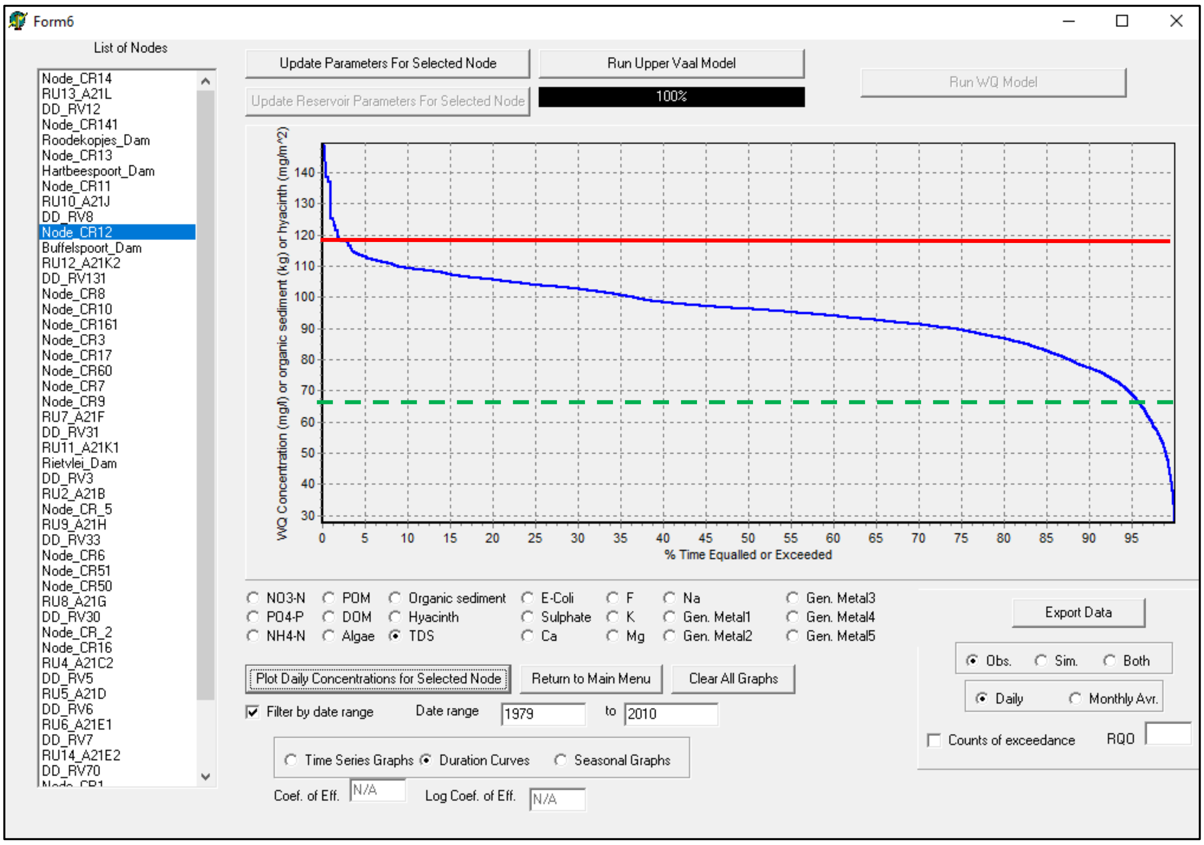


Figure 3.12 TDS inflow into Hartbeespoort Dam (P95 = 68 mg/l) RQO < 117 mg/l

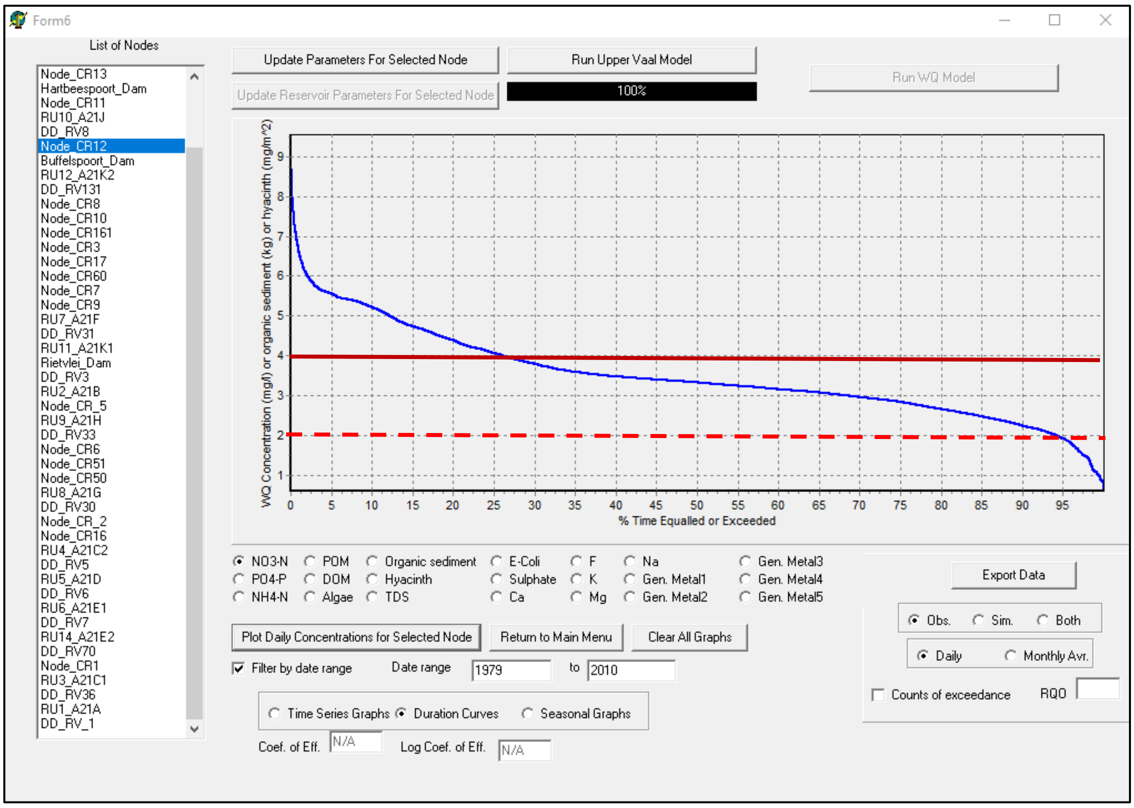


Figure 3.13 NO2/NO3 inflow into Hartbeespoort Dam (P50 = 3.95 mg/l) RQO < 2 mg/l

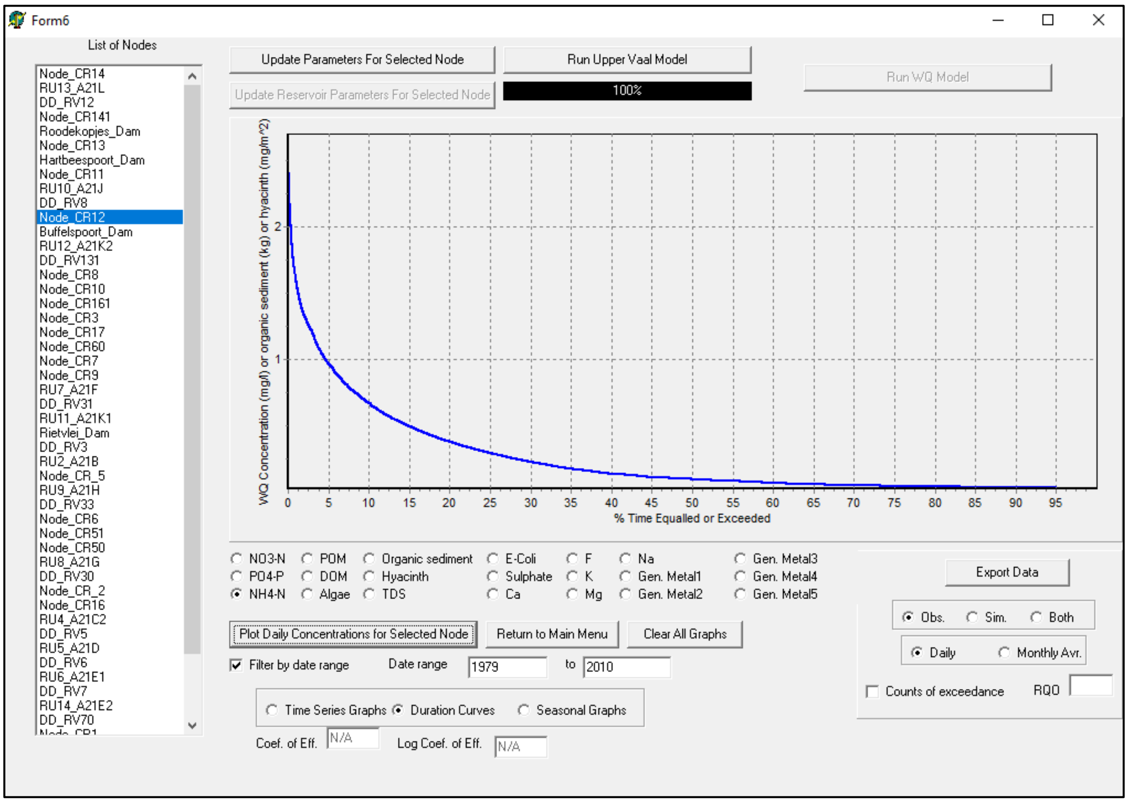


Figure 3.14 Ammonia (NH4) inflow into Hartbeespoort Dam (no set RQO)

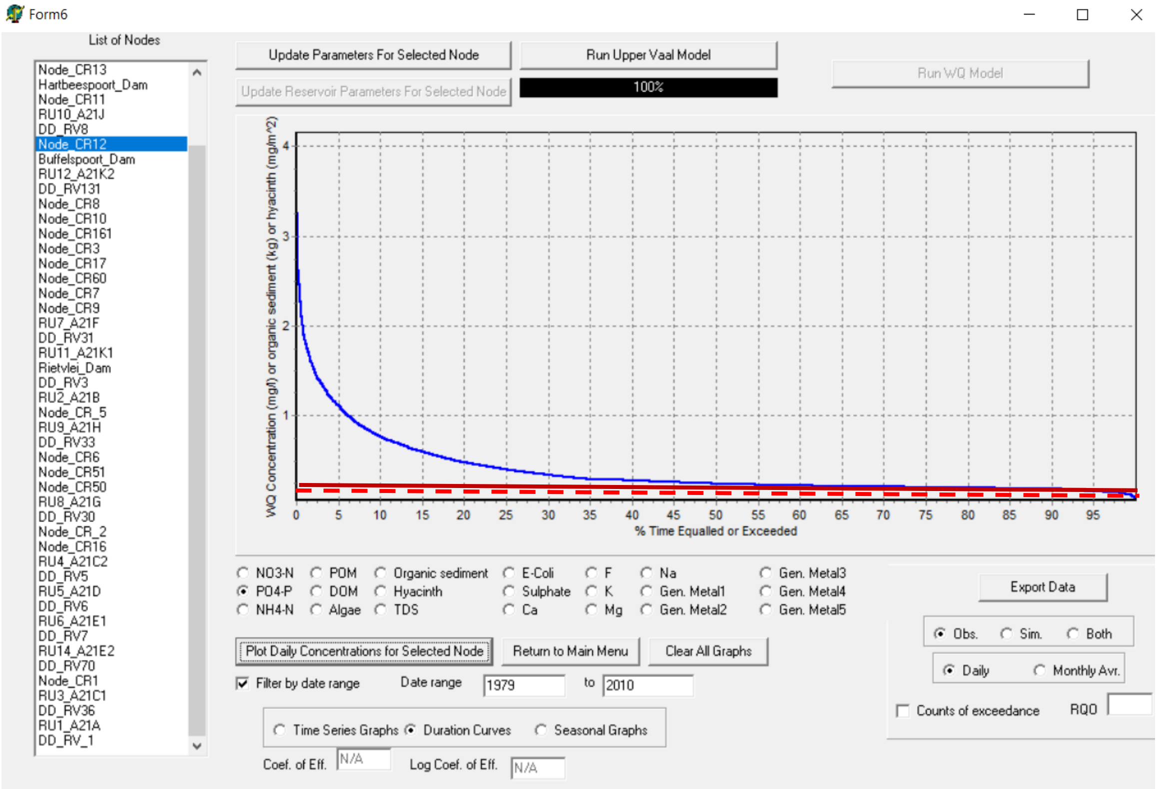


Figure 3.15 Inflow Hartbeespoort Dam Phosphates (limiting to algae and hyacinth) P50 = 0.3 mg/l RQO P50 = 0.2 mg/l

3.5 Summary Conclusions

- The Hartbeespoort Dam is in a hypertrophic state mainly due to high Phosphates and Nitrates concentrations from the **Jukskei River**, and high Ammonium concentrations from the **Hennops River**.
- Sources of Ammonium in the Hennops River is possibly associated with non-agriculture sources (return flows, sewage spills and urban-runoff)
- Mostly, uniform daily return flows were used to drive the model, leading to a limitation in predicting phosphates concentrations peaks and seasonality especially during the dry season.
- Uncertainties associated with input data and model conceptualization complexities need to be explored further.

4 Elands River Sub-Catchment

4.1 Network Configuration

The main function of the network is to specify the order in which the modules must be solved. In addition, the network is used to set the time period for simulation, the data- and result folders to be used and to specify the routes and reservoirs that are to be reported in the summary file. The summary file is an easy-to-check file in which flows in the specified routes or storages in the specified reservoirs are stored on a monthly basis during a simulation run. The Elands sub-catchmnet network diagram is modified from the Water Resource Study (2012) in Figure 4.1 below.

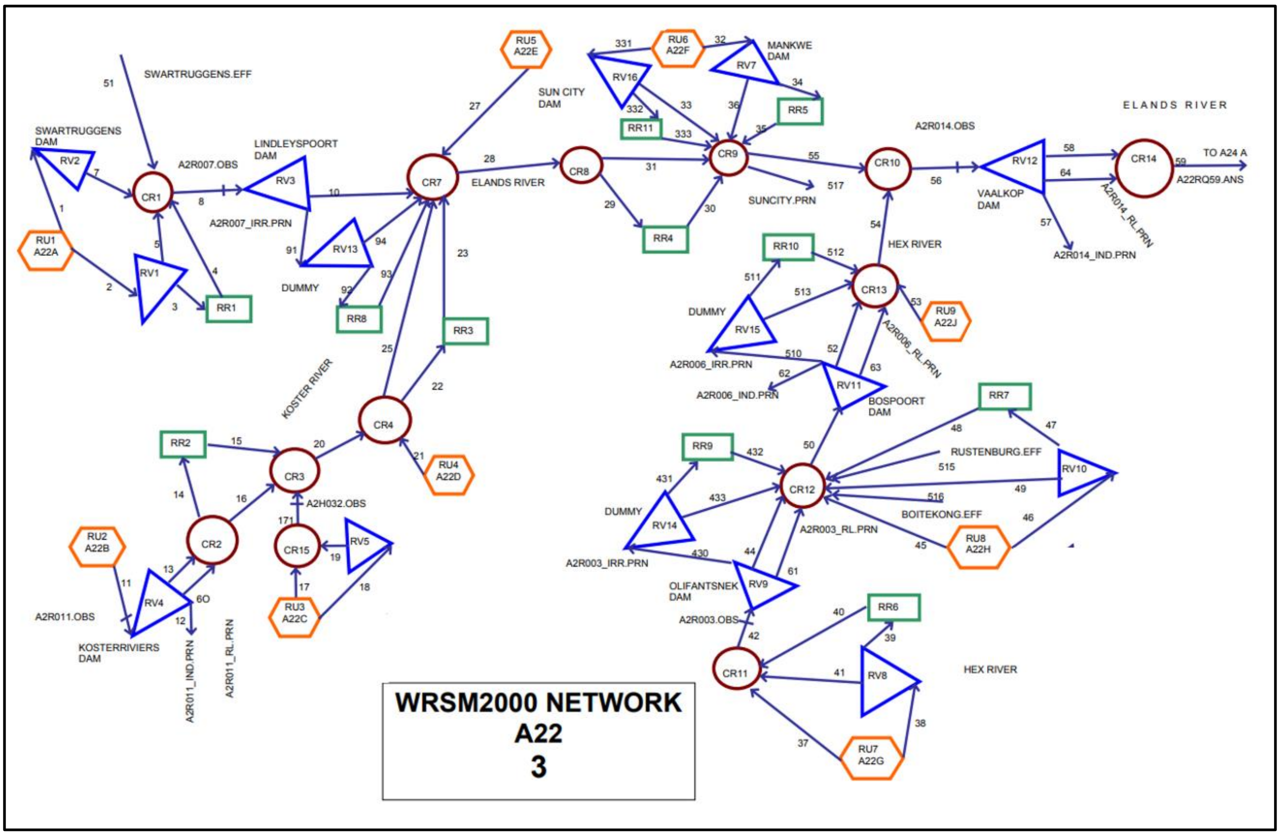


Figure 4.1 Network Diagram Elands Sub-catchments (A22)

4.1.1 Rainfiles

A rainfile is a file that contains a monthly rainfall time series expressed as percentages of MAP for an area or a catchment. Rainfiles should not be confused with raingauge files. A rainfile usually combines the data of multiple raingauges into a single time series and, in addition, the values are expressed as a percentage of the MAP for the area or catchment. Daily rainfall data was extracated from the Daily rainfall data extraction utility from the University of Kwazulu Natal and the data was patched with CFSR daily satellite rainfall data from the year 2000 until 2009 (Table 4-1).

Table 4-1 Daily rainfall file data used for Elands Sub-catchmnet

Sub-catchmnet	**South African Weather Service Patched Rainfall Station (SAWS) Used (1920 - 2000)**	**CFSR Rainfall Station Used to (2000 – 2009)**
A22A	0510308 W	p-258266
A22B	0510712 W	p-258269
A22C	0511084 W	p-258272
A22D	0510817 W	P-254269
A22E	0547526 W	p-254269
A22F	0548165 W	p-254272
A22G	0511469 W	p-258272
A22H	0511524 W	p-258272
A22J	0548747 W	p-254275

4.1.2 Naturalised Daily Flows from Runoff Modules - WRSM Daily

The WRSM/Pitman daily version is a mathematical model for generating daily river flows from meteorological data in South Africa, and the methodology is described in the Hydrological Research Unit report HRU 2/76. The options to generate naturalized daily flows from the runoff module were used to set up and generate daily timestep flows. The generated daily flows from October 1920 – Septemvber 2010 for all nine (9) runoff modules in A22A Catchment are presented in Figure 4.2.

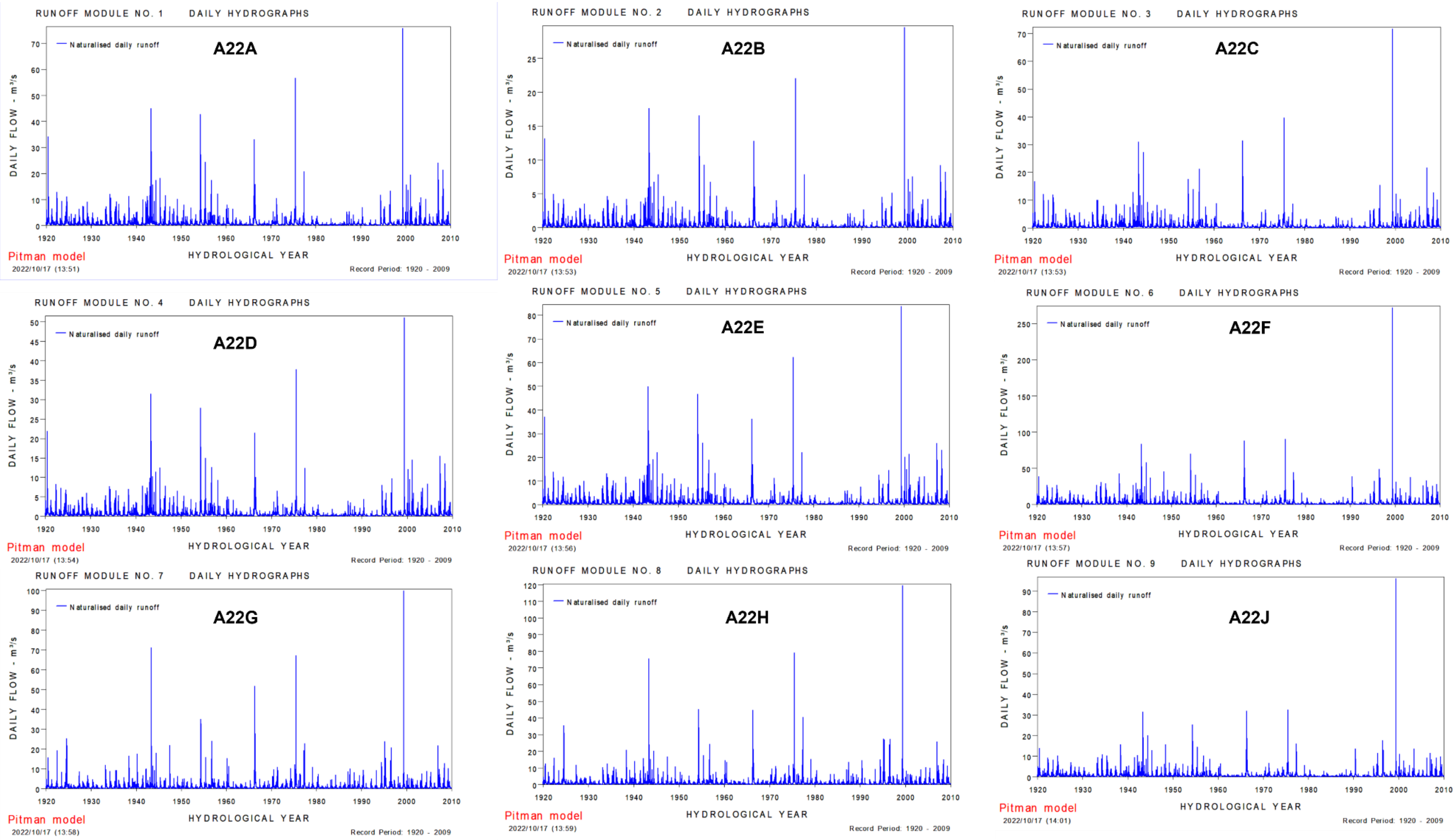


Figure 4.2 Daily Hydrographs for A22 Runoff Modules - October 1920 to September 2010

The Elands Catchment WQSAM Network was modified from the Water Resource Simulation Model (2012). The WQSAM network and nodes are presented in Figure 4.3.

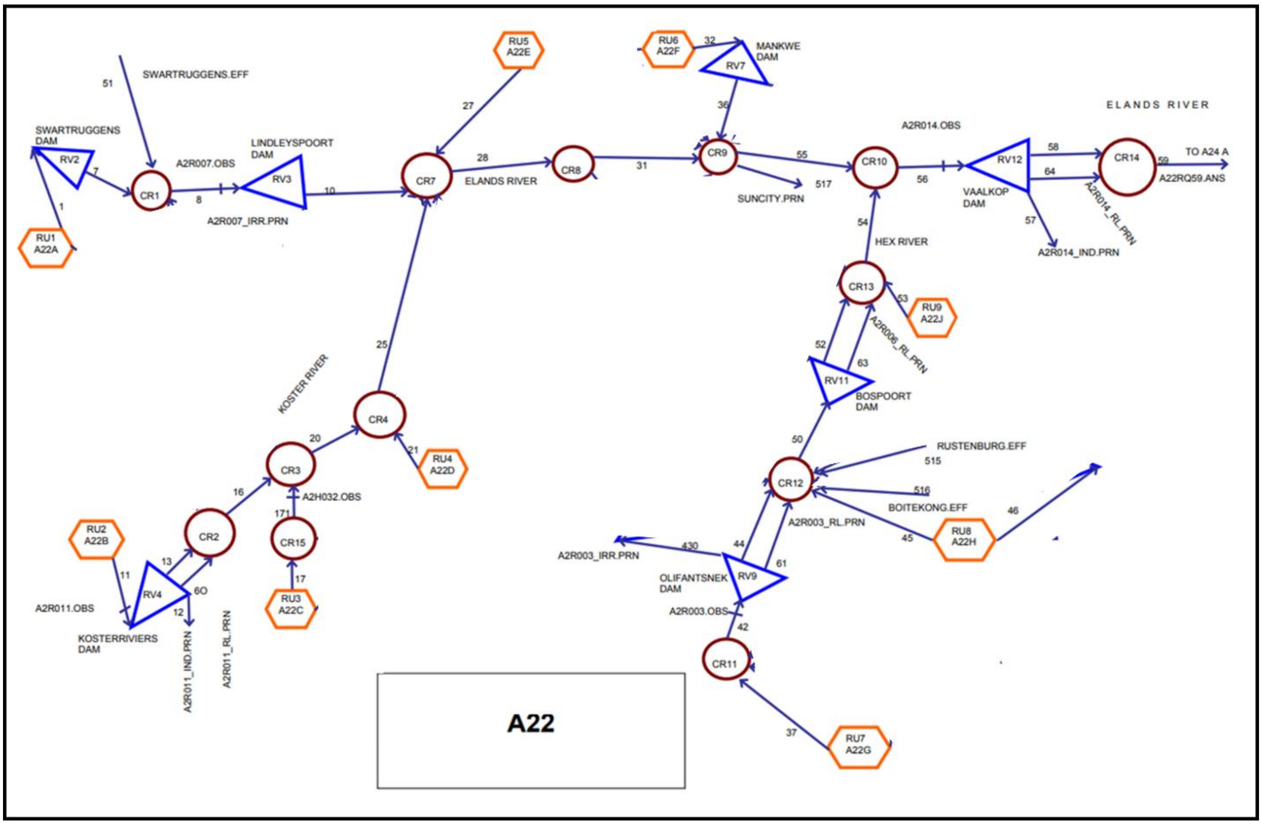


Figure 4.3 Modified Elands Catchment WQSAM Network

4.2 Model Setup

4.2.1 Chanel Flows

WQSAM requires monthly outflows data as well as reservoir storage data such as evaporation. Daily Monthly channel flows are imported from the existing monthly WRSM and imported into time series data of continuous monthly data.

- Demand or extractions (m^3/s) :
  - Bospoort Dam
  - KosterRiver Dam
  - Olifantsnek Dam
  - Vaalkop Dam
- Return flows (m^3/s):

  - Swartruggens return flow
  - Rustenberg return flow
  - Boitkekong return flow
- Transfers in or out (m^3/s)
  - None

4.2.2 Reservoir

Reservoirs are major dams within the catchment. The following monthly reservoir associated attributes are imported from the Water Resource Yield Model for Bospoort Dam, Kosterrivers Dam, Lindelyspoort Dam, Mankwe Dam, Olifantsnek Dam, Swartruggens Dam and Vaalkop Dam:

- Monthly evaporation – m^3/s
- Monthly rainfall – m^3/s
- Monthly Reservoir outflow or releases – m^3/s
- Monthly volume/storage - (M m^3)

4.2.3 Baseflow Separation

A process run is setup to execute *WQSAM-HYDRO pre-processing* to allow for separation of incremental natural daily flows into “sim daily GW” and “sim daily interflow”. The results are presented in Figure 4.4 with the black line representing surface flow, red line representing interflow and yellow line representing groundwater.

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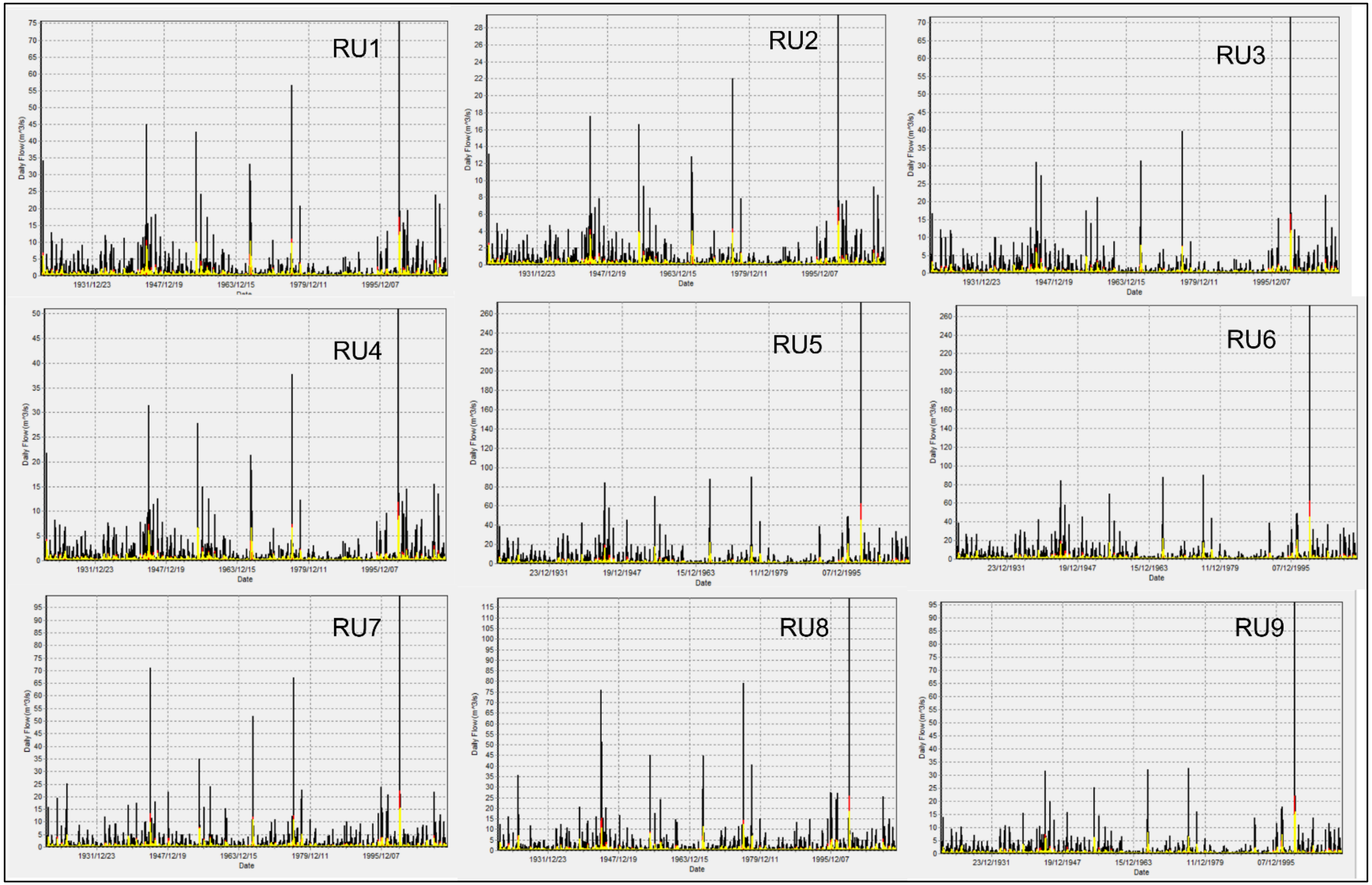
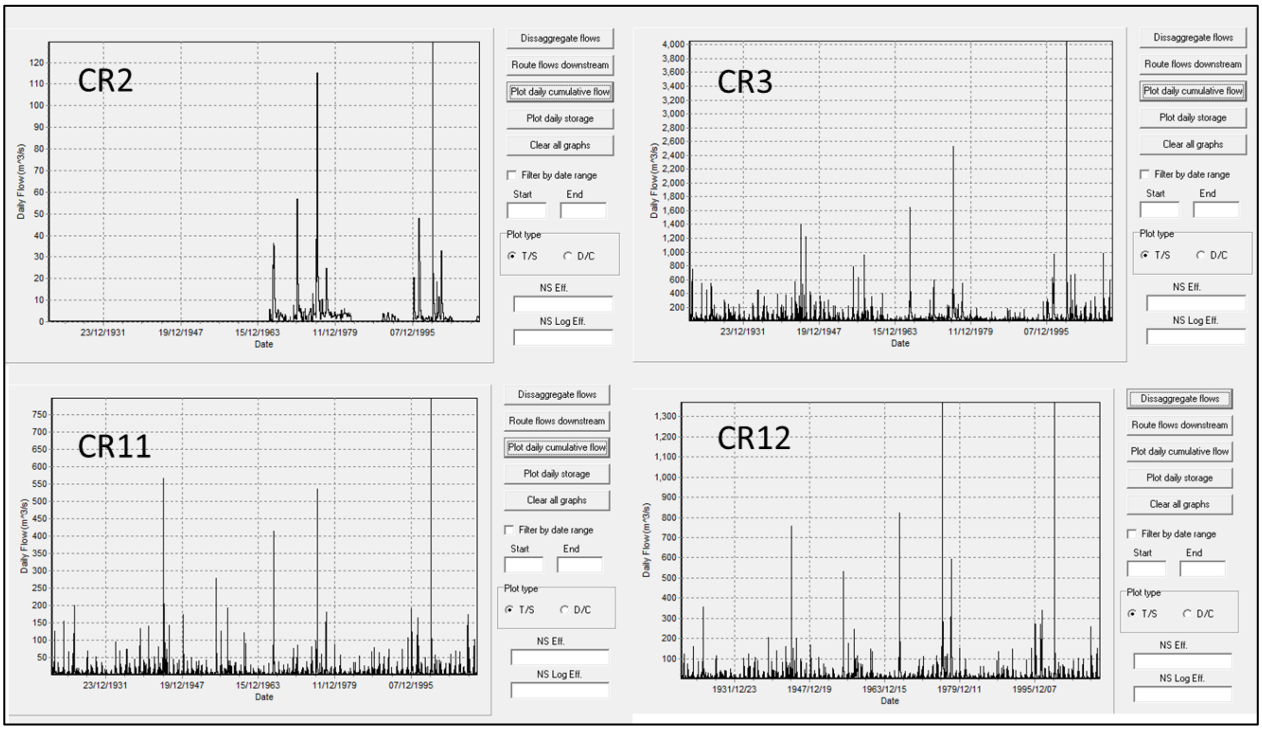


Figure 4.4 Flows Separartion for A22 Catchment

4.2.4 Disaggregation of cumulative flows

A process run is setup to execute *WQSAM-HYDRO pre-processing* to allow the disaggregation of cumulative flows using an added tab*: “Separate Upper Vaal Flows”* , an example of the results in from centre reaches (CR) CR2, CR3, CR11 and CR12 is presented in Figure 4.6



<u>*Figure 4.5 Disaggregated Daily Cumulative flows for centre reaches*</u>

4.2.5 WaterTemperature Sub-model

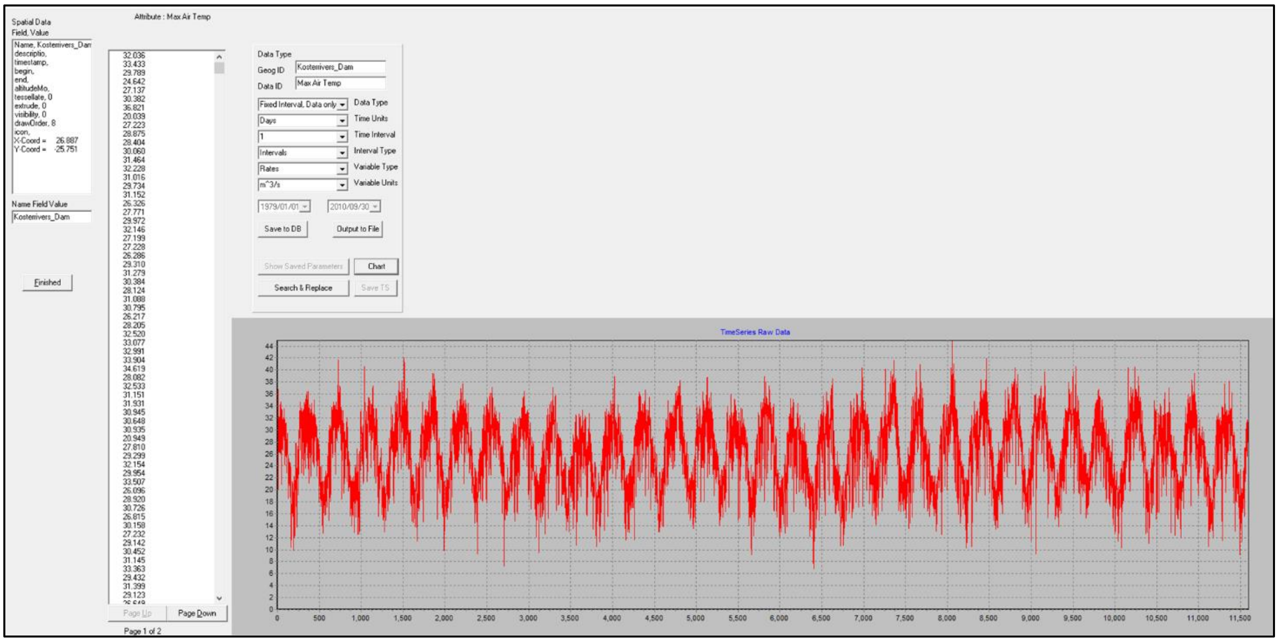
Water temperature is important for water quality modelling. Unfortunately, observed historical data sets are often scarce. WQSAM has adopted the appraoch, which uses air temperature to simulate in-stream water temperature. While there is a consolidated database of air temperature there are only data available for the period 1920–2000, restricting the simulation time periods. From the year 2000 to the end of the simulation period (2009) the average monthly data was used to extend the data set.

To run the WQSAM temperature model attributes for a time series of observed min and max air temperature, and water temperature is required. water temperature data was only available for Bospoort Dam, Lindleyspoort Dam and Olifantsnek Dam. The following attributes were created:

- Temperature Parameter (Array file)
- T/S obs Air Temp min

- T/S obs Air Temp max
- T/S obs water temp
- T/S sim water temperature

An example of the air temperature data for Kosterriver Dam using neighbouring subcatchmnet data (Lindleyspoort Dam) is presented in Figure 4.6.



Spatial Data
Field, Value
Name, Kosterrivers_Dam
descriptio,
timestamp,
begin,
end,
altitudeMo,
tessellate, 0
extrude, 0
visibility, 0
drawOrder, 8
icon,
X-Coord = 26.887
Y-Coord = -25.751

Name Field Value: Kosterrivers_Dam

Attribute : Max Air Temp

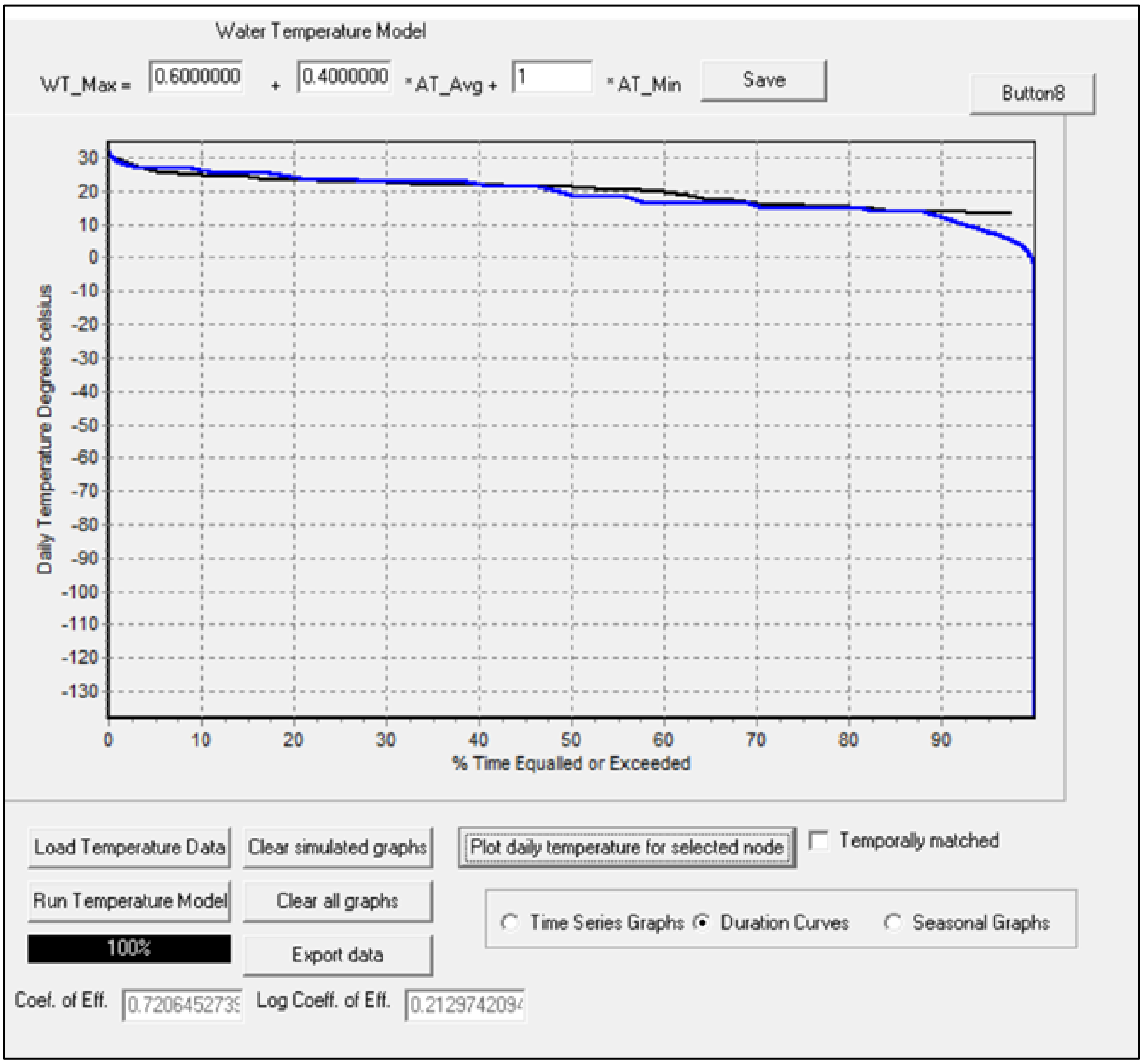
```
32.036
33.433
29.789
24.642
27.137
30.382
36.821
20.039
27.223
28.875
28.404
30.060
31.464
32.228
31.016
29.734
31.152
26.326
27.771
29.972
32.146
27.199
27.228
26.286
29.310
31.279
30.384
28.124
31.088
30.795
26.217
28.205
32.520
33.077
32.991
33.904
34.619
28.082
32.533
31.151
31.931
30.945
30.648
30.935
20.949
27.810
29.299
32.154
29.954
33.507
26.096
28.920
30.726
26.815
30.158
27.232
29.142
30.452
31.145
33.363
29.432
31.399
29.123
```

Page 1 of 2

Data Type
Geog ID: Kosterrivers_Dam
Data ID: Max Air Temp
Data Type: Fixed Interval, Data only
Time Units: Days
Time Interval: 1
Interval Type: Intervals
Variable Type: Rates
Variable Units: m^3/s
1979/01/01
2010/09/30

Figure 4.6 Kosterrivers Maximum air temperature data over the simulation period

Water Temperature for all nodes which did not have observed, were simulated from the air temperature min and max. The calibration of the simulated and observed water temperature for Lindelyesspoort and Olifantsnek Dam are presented in Figure 4.7 and Figure 4.8 respectively. The coefficient of efficiency for both calibrations are good and with of 0.7 Lindleyspoort Dam and 0.8 Olifantsnek Dam. These calibration results are also attributed to good continuous water temperature data.



Water Temperature Model

WT_Max = 0.6000000 + 0.4000000 *AT_Avg + 1 *AT_Min

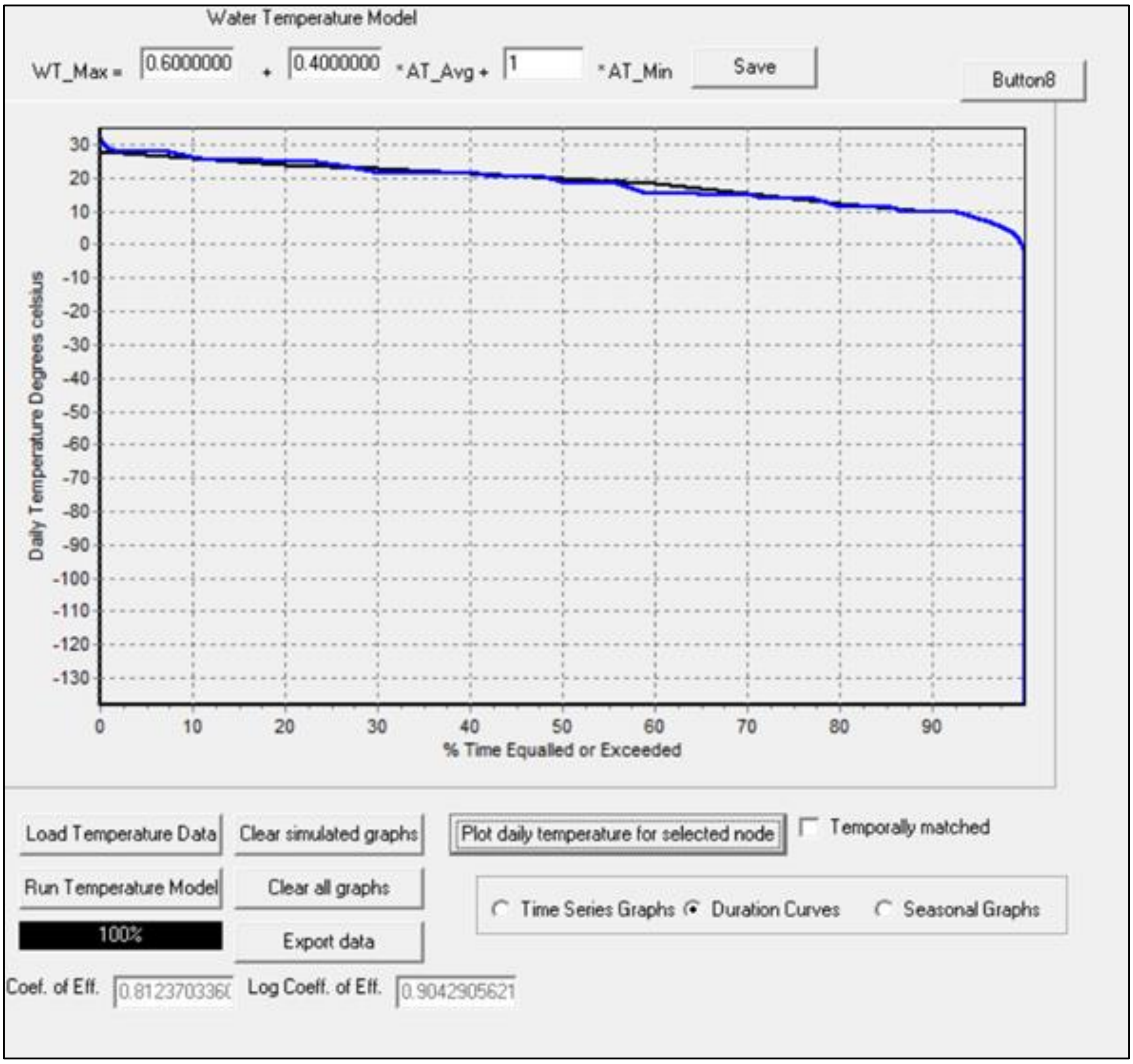
☐ Temporally matched

○ Time Series Graphs ● Duration Curves ○ Seasonal Graphs

Coef. of Eff. 0.720645273

Log Coeff. of Eff. 0.212974209

Figure 4.7 Calibration of the water temperature frequency exceedance curve for Lindleyspoort Dam



Water Temperature Model

WT_Max = 0.6000000 + 0.4000000 *AT_Avg + 1 *AT_Min

☐ Temporally matched

○ Time Series Graphs ● Duration Curves ○ Seasonal Graphs

100%

Coef. of Eff. 0.812370336

Log Coeff. of Eff. 0.9042905621

Figure 4.8 Calibration of the water temperature frequency exceedance curve for Olifantsnek Dam

4.2.6 Water Quality Sub-model

WQSAM currently simulates salinity as total dissolved solids (TDS), nutrients as nitrate plus nitrite, ammonium, sulphate and phosphate, microbial water quality as *Escherichia coli* and water temperature. Long term water quality data is scare for the Elands subcatchmnet. Figure 4.9 presents a case for the sulphate parameter observed values at two different sites.

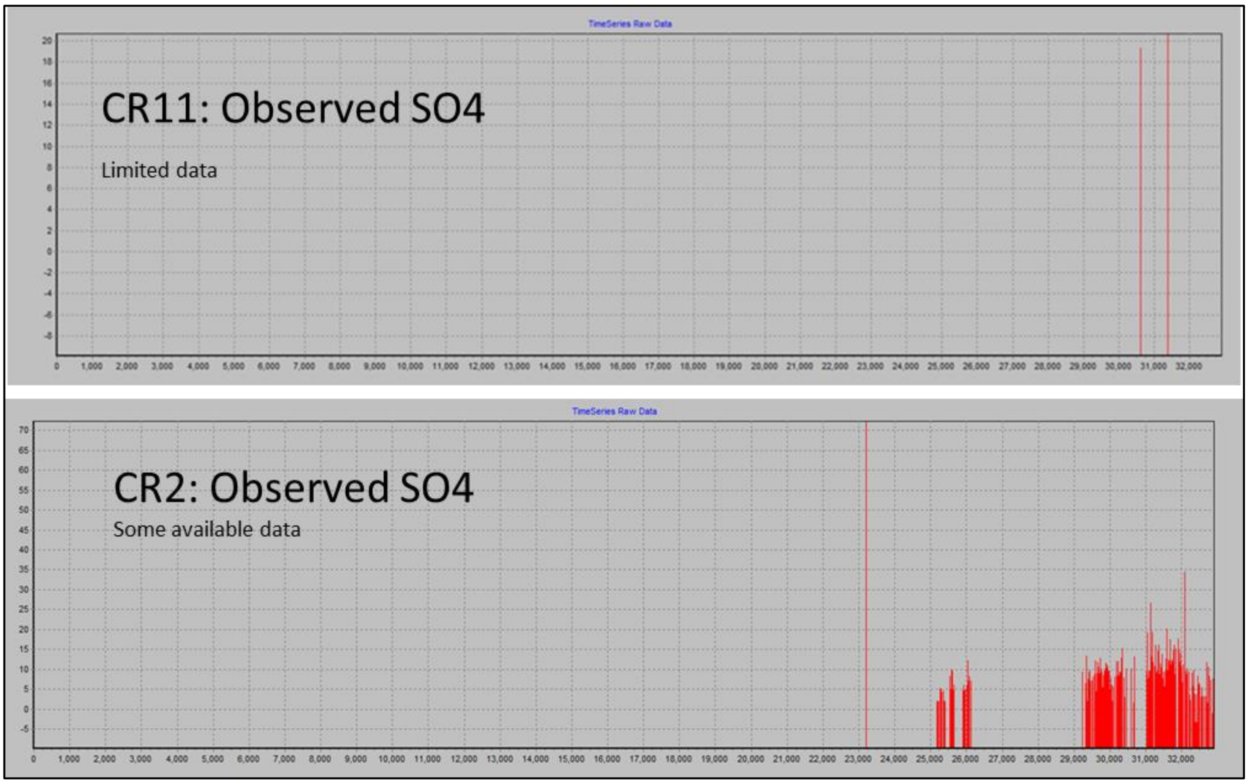


Figure 4.9 Observed SO4 Data Variations at Centre Reaches

At CR11 the is little to no data where as at CR2 there is some data towards the end of the simulated period. Table 4-2 presnts the water quality monitoring sites monitoredd by the Department and monitoring period. However, these sites could not be used and as a result CFSR water quality data was used which was patched on a daily time step to reflect time periods were there was no data.

The model nodes and water quality sites used in the model are presented in Figure 4.10. Nine out of eleven of these water quality sites had data that could be accessed.

Table 4-2 Observed Water Quality Data Sites from the Department forElands Catchment and monitoring period.

Monitoring Point ID	Monitoring Point Name	Latitude	Longitude	Located on Feature Name	Located on Type	Drainage Region Name	Monitoring Active	Monitoring Variable	Measuring Unit	No. of Analyses	First Analyses	Last Analyses
90273	A2R007 LINDLEYSPOORT DAM AT LINDLEYSPOORT 220 JP ON ELANDSRIVIER NEAR DAM WALL	-25.4977	26.69047	A2R007 LINDLEYSPOORT DAM AT LINDLEYSPOORT	Dam / Barrage	A22A	Yes	TEMP-Phys-Water	°C	2023	1968/03/18	2020/02/11
90287	A2R013 SWARTRUGGENS DAM AT BRAKFONTEIN 404 JP ON ELANDSRIVIER NEAR DAM WALL	-25.6618	26.694	A2R013 SWARTRUGGENS DAM AT BRAKFONTEIN	Dam / Barrage	A22A	Yes	TEMP-Phys-Water	°C	22	1980/04/16	1988/05/26
90285	A2R011Q01 KOSTER RIVER DAM ON KOSTER RIVER: NEAR DAM WALL	-25.7	26.905	A2R011 KOSTERRIVIER DAM AT WATERKLOOF	Dam / Barrage	A22B	Yes	TEMP-Phys-Water	°C	1910	1975/03/06	2020/02/11
103092	A2R011A01 KOSTER RIVER @ WATERKLOOF - KOSTERRIVIER DAM	-25.7001	26.90388	A2R011 KOSTERRIVIER DAM AT WATERKLOOF	Dam / Barrage	A22B	No	TEMP-Phys-Water	°C	0		
90259	A2R003 OLIFANTSNEK DAM AT COMMISSIESDRIFT 327 JQ ON HEXRIVIER NEAR DAM WALL	-25.7851	27.25933	A2R003 OLIFANTSNEK DAM AT COMMISSIESDRIFT	Dam / Barrage	A22G	Yes	TEMP-Phys-Water	°C	1753	1975/03/05	2020/02/11
90272	A2R006 BOSPOORT DAM AT TWEEDEPOORT	-25.5628	27.34936	A2R006 BOSPOORT	Dam / Barrage	A22H	Yes	TEMP-Phys-Water	°C	2576	1975/03/06	2020/02/04

	283 JQ ON HEXRIVIER NEAR DAM WALL			DAM AT BOSCHPOORT								
190398	RUSTENBURG CORRECTIONAL SERVICES AT CORRECTIONAL SERVICES DAM	-25.6353	27.25867	RUSTENBURG CORRECTIONAL SERVICES DAM A22H	Dam / Barrage	A22H	Yes	TEMP-Phys-Water	°C	0		
90288	A2R014Q01 BULHOEK 75 JQ - VAALKOP DAM ON ELANDSRIVIER: NEAR DAM WALL	-25.3093	27.475	A2R014 VAALKOP DAM AT BULHOEK	Dam / Barrage	A22J	Yes	TEMP-Phys-Water	°C	1600	1975/03/04	2018/05/16
103095	A2R014A01 BULHOEK 75 JQ - VAALKOP DAM STAGE MONITORING @ VAALKOP DAM WALL	-25.3091	27.47539	A2R014 VAALKOP DAM AT BULHOEK	Dam / Barrage	A22J	No	TEMP-Phys-Water	°C	0		

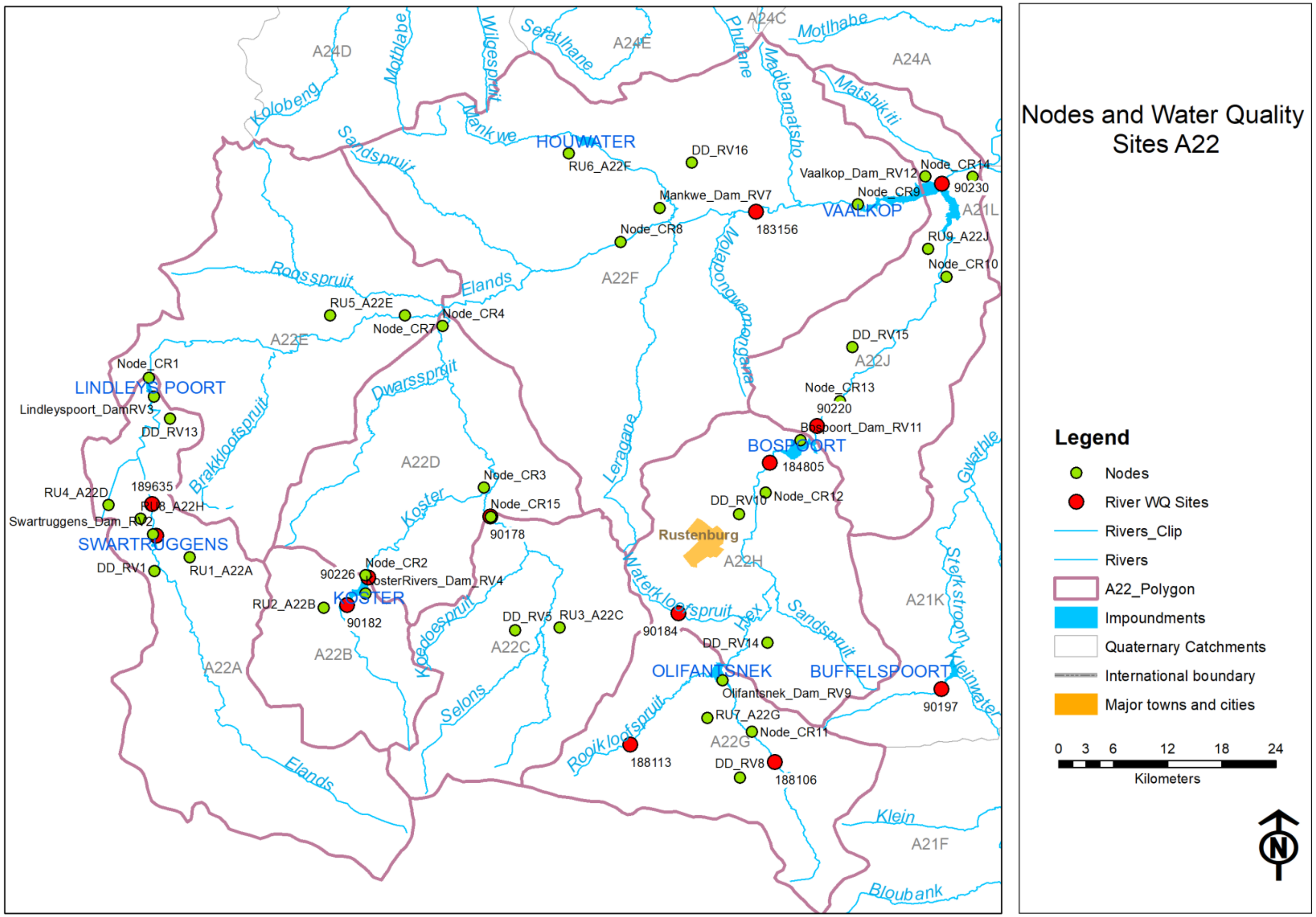


Figure 4.10 Water Quality Monitoring sites and Model Nodes

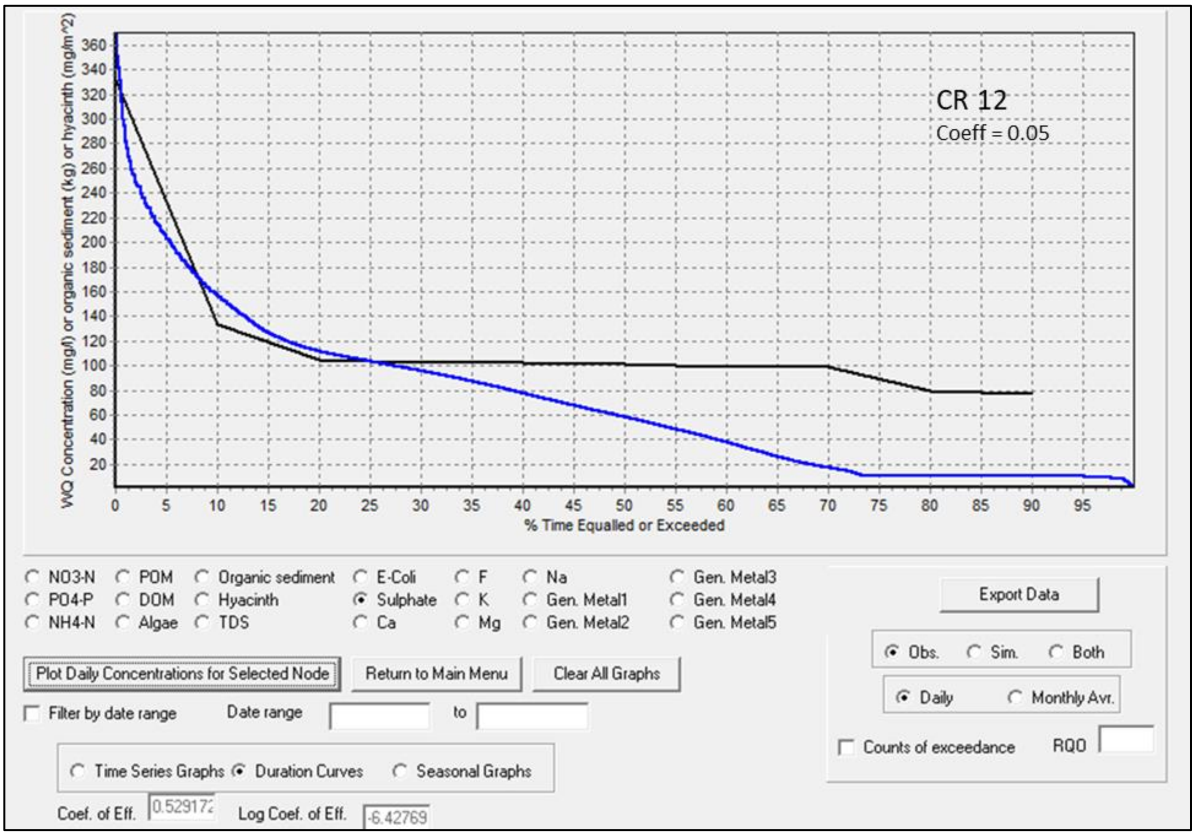
4.2.7 Water Quality Calibration Results

The water quality model simulation period covered the full simulation period by the yield model (i.e. 1920 up to 2000) and was extend until 2009 with the averaged data.The available water quantity data sets covered the period 1920–2000. The modelling procedure comprised calibrating parameters with sufficient water quality data that can be used. Sulphates as opposed to other parameers such as TDS, NH_4, Ammonia, $NO_2 + NO_3$ which had significantly low signatures close to zero or had very limited observed data to calibrate against. This is partly evident for sulphate in Figure 4.9 bove for CR11

The calibration approach is a standard modelling procedure to verify model parameters. Calibration was also used to determine if static water quality parameters could be used in WQSAM and make sense of water quality data gaps where present. The Water Quality calibration results could only be conducted for select sites and these are presented in Figure 4.11 and Figure 4.12.

The calibration results presented are of low confidence with very low coeficient of efficiency. There are relatively few observed water quality data values making calibration difficult to achieve especially for sites with two observation points for the entire simulation period. It should be a standard check to only incorporate data sets which have more than 50 observed data samples for the calibration period for model set up.

The poor curve fit for concentration frequency curves can be caused by a number of factors that are interlinked. These include incorrect flow volumes from the yield model and or inaccurate volumes of baseflow contribution. In addition, lack of observed data make fitting concentration curves difficult. While water quality models can be used to bridge the gaps in water quality datasets, the model is still limited to simulating variables of concern that are well represented in the observed water quality data sets.



● Sulphate

● Obs.

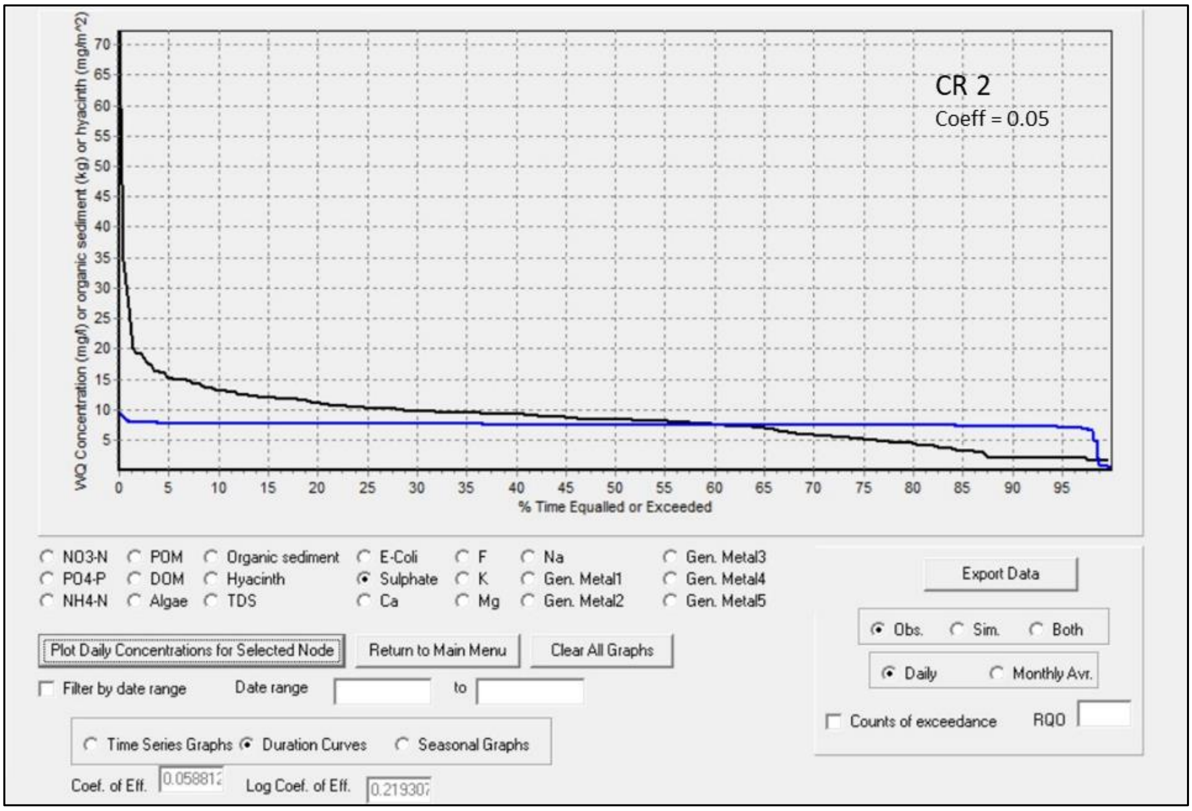
● Daily

● Duration Curves

Coef. of Eff. 0.52917

Log Coef. of Eff. -6.42769

Figure 4.11 Water Quality Calibration Results for CR12



● Sulphate

● Obs.

● Daily

● Duration Curves

Coef. of Eff. 0.05881

Log Coef. of Eff. 0.21930

Figure 4.12 Water Quality Calibation Results CR2

5 Apies-Pienaars River Sub-Catchment

5.1 Model Configuration

The WRSM2000 network structure was used to set up the network. The output data which includes the Simulated daily incremental flows from the WRSM2000, Water Abstraction, Water Demand and reservoir storage data generated by the WRYM were uploaded as inputs into the model.

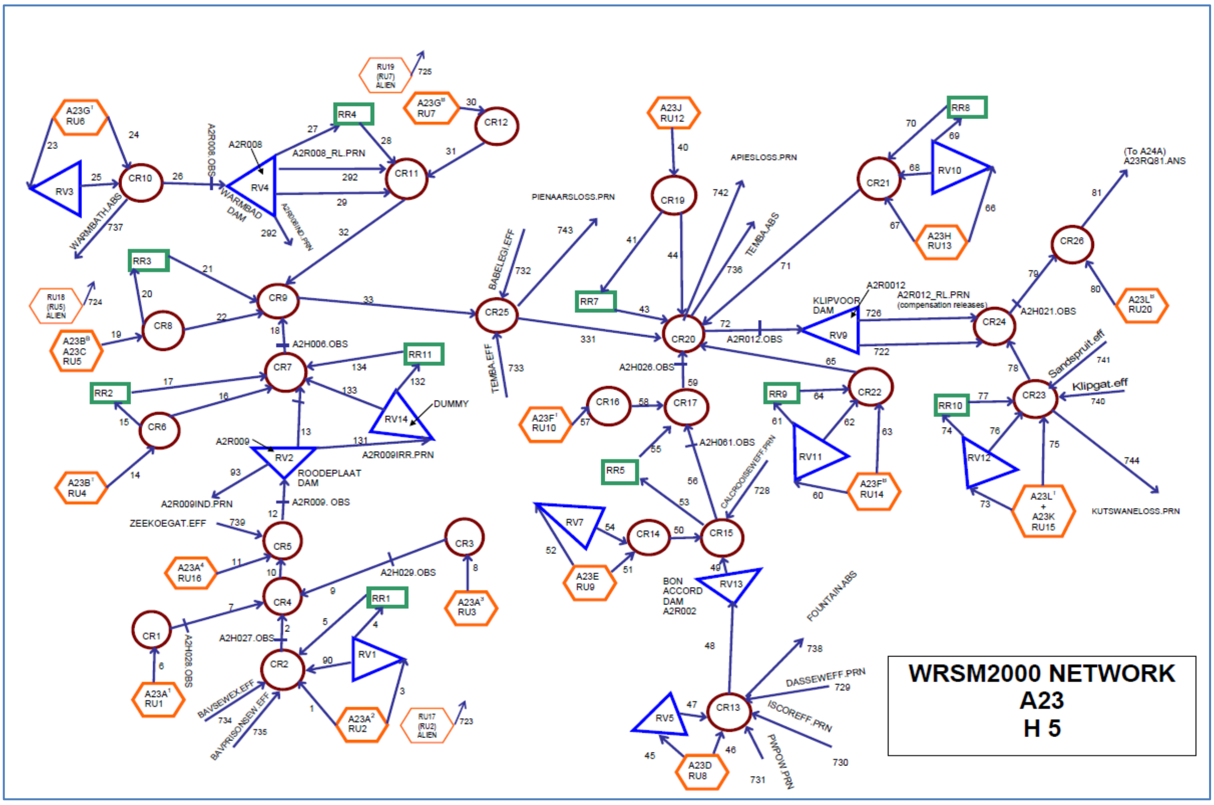


Figure 5.1 WRSM2000 network diagram for A23 quaternary catchment.

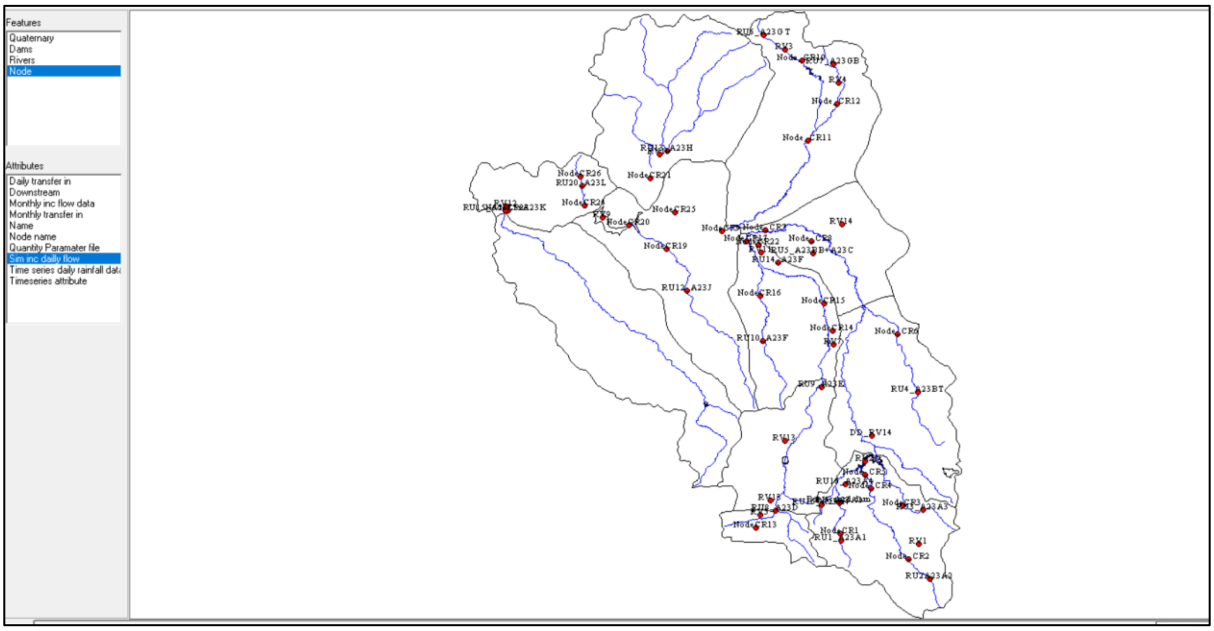


Figure 5.2 Apies-Pienaar Crocodile subcatchment structure created in SPATSIM

5.1.1 Water Quality Hydro processing Model

The *WQSAM-HYDRO* preprocessing model was run in order to separate the natural incremental daily flows into attributes *simulated groundwater* and *simulated interflow.* Figure 5.3 below shows the baseline separation flows time-series plot for different run-off.

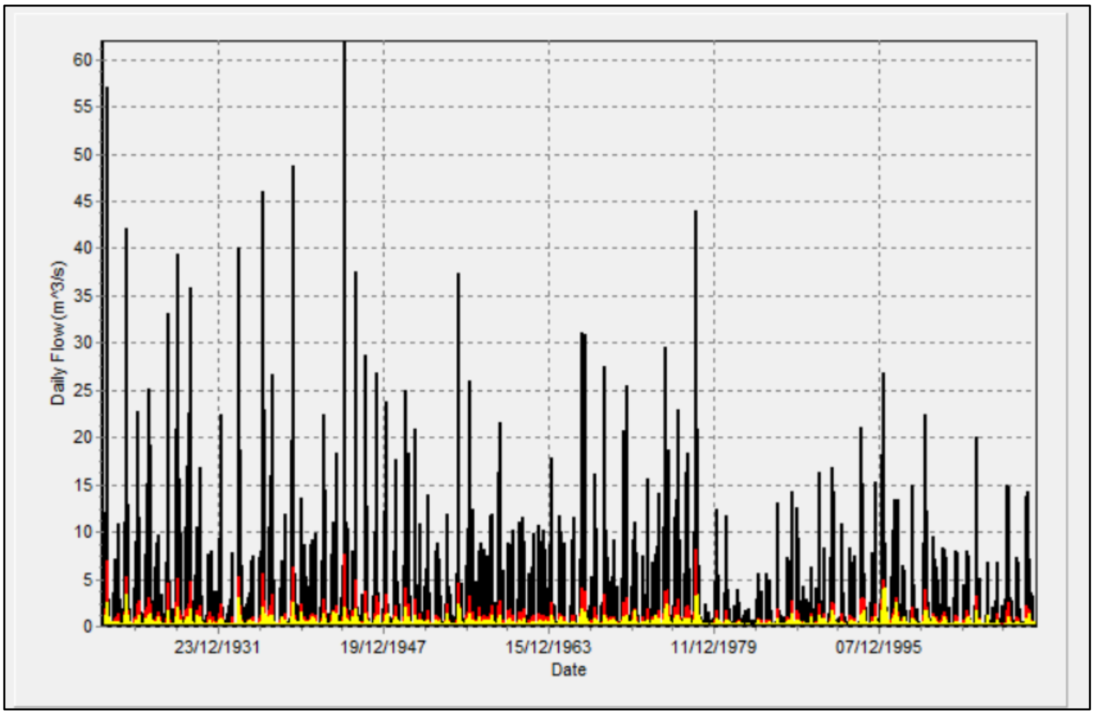


Figure 5.3 Baseflow separation plot for RU1 A23A created in SPATSIM

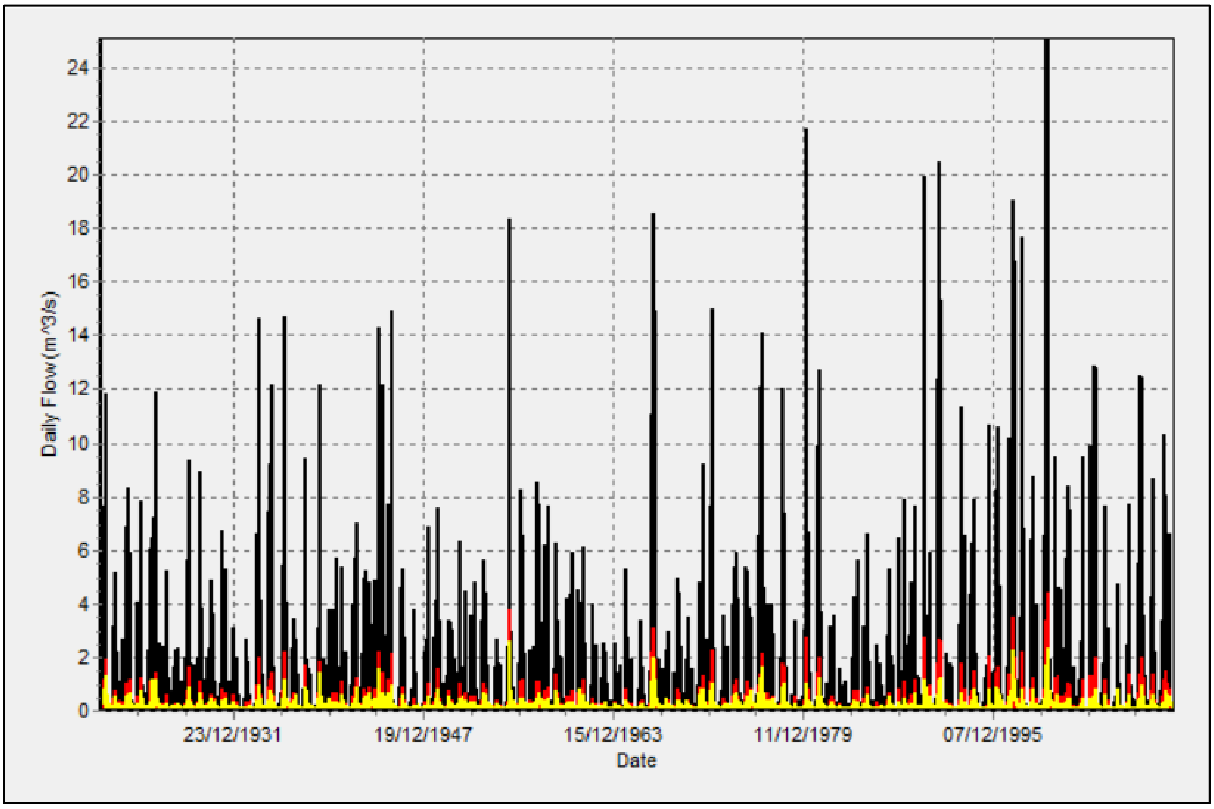


Figure 5.4 Baseflow separation plot for RU6 A23A created in SPATSIM

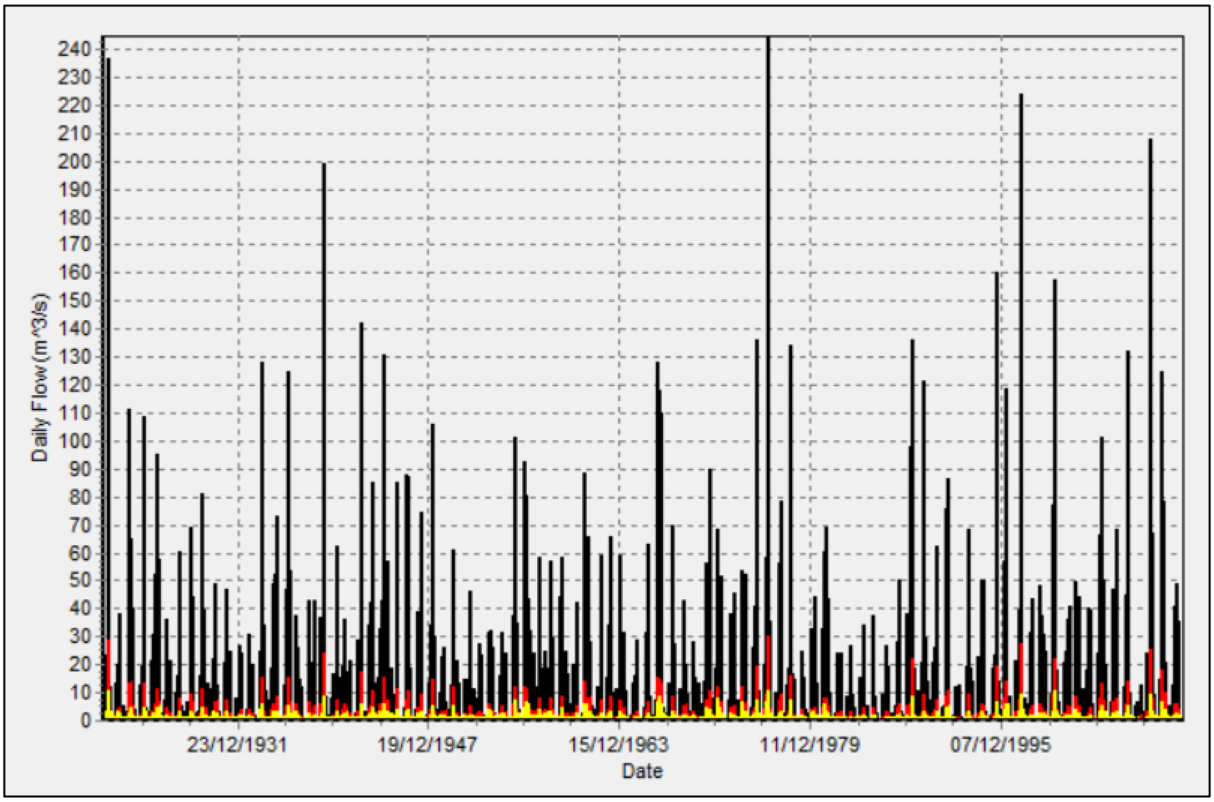
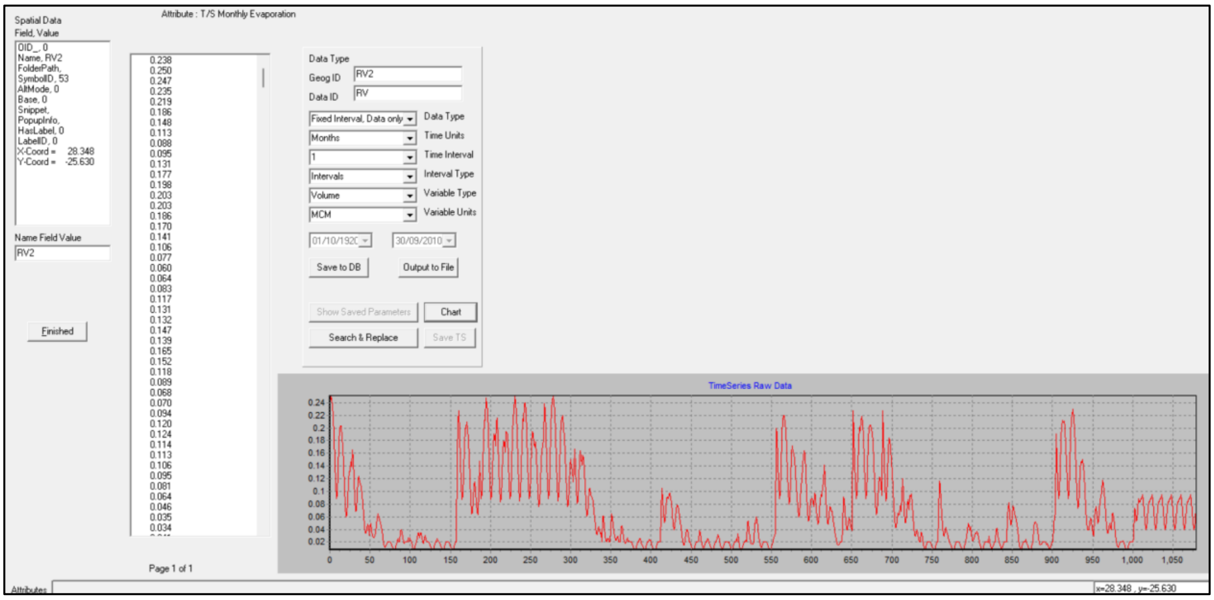


Figure 5.5 Baseflow separation plot for RU9_A23E created in SPATSIM.

(i) Reservoir Parameters

The data exported from the WRYM was used as input into WQSAM in the attributes; *reservoir daily rainfall, monthly storage* and *observed monthly evaporation*. The outflows from the reservoirs were obtained using the route numbers depicted in the WRYM.



Attribute : T/S Monthly Evaporation

Spatial Data
Field, Value
OID_, 0
Name, RV2
FolderPath,
SymbolID, 53
AltMode, 0
Base, 0
Snippet,
PopupInfo,
HasLabel, 0
LabelID, 0
X-Coord = 28.348
Y-Coord = -25.630

Name Field Value: RV2

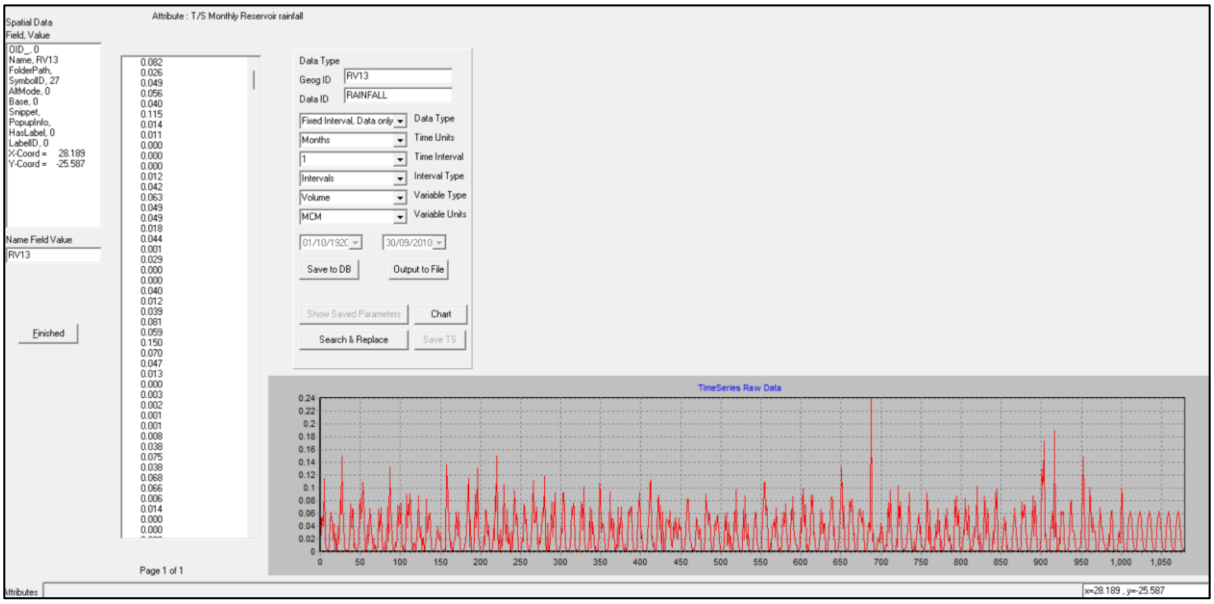
```
0.238
0.250
0.247
0.235
0.219
0.186
0.148
0.113
0.088
0.095
0.131
0.177
0.198
0.203
0.203
0.186
0.170
0.141
0.106
0.077
0.060
0.064
0.083
0.117
0.131
0.132
0.147
0.139
0.165
0.152
0.118
0.089
0.068
0.070
0.094
0.120
0.124
0.114
0.113
0.106
0.095
0.081
0.064
0.046
0.035
0.034
```

Page 1 of 1

Data Type
Geog ID: RV2
Data ID: RV
Data Type: Fixed Interval, Data only
Time Units: Months
Time Interval: 1
Interval Type: Intervals
Variable Type: Volume
Variable Units: MCM
01/10/1920 30/09/2010

x=28.348 , y=-25.630

Figure 5.6 Reservoir Evaporation in Roodeplat extracted from the WRYM



Attribute : T/S Monthly Reservoir rainfall

Spatial Data
Field, Value
OID_, 0
Name, RV13
FolderPath,
SymbolID, 27
AltMode, 0
Base, 0
Snippet,
PopupInfo,
HasLabel, 0
LabelID, 0
X-Coord = 28.189
Y-Coord = -25.587

Name Field Value: RV13

```
0.082
0.026
0.049
0.056
0.040
0.115
0.014
0.011
0.000
0.000
0.000
0.012
0.042
0.063
0.049
0.049
0.018
0.044
0.001
0.029
0.000
0.000
0.040
0.012
0.039
0.081
0.059
0.150
0.070
0.047
0.013
0.000
0.003
0.002
0.001
0.001
0.008
0.038
0.075
0.038
0.068
0.066
0.006
0.014
0.000
0.000
```

Page 1 of 1

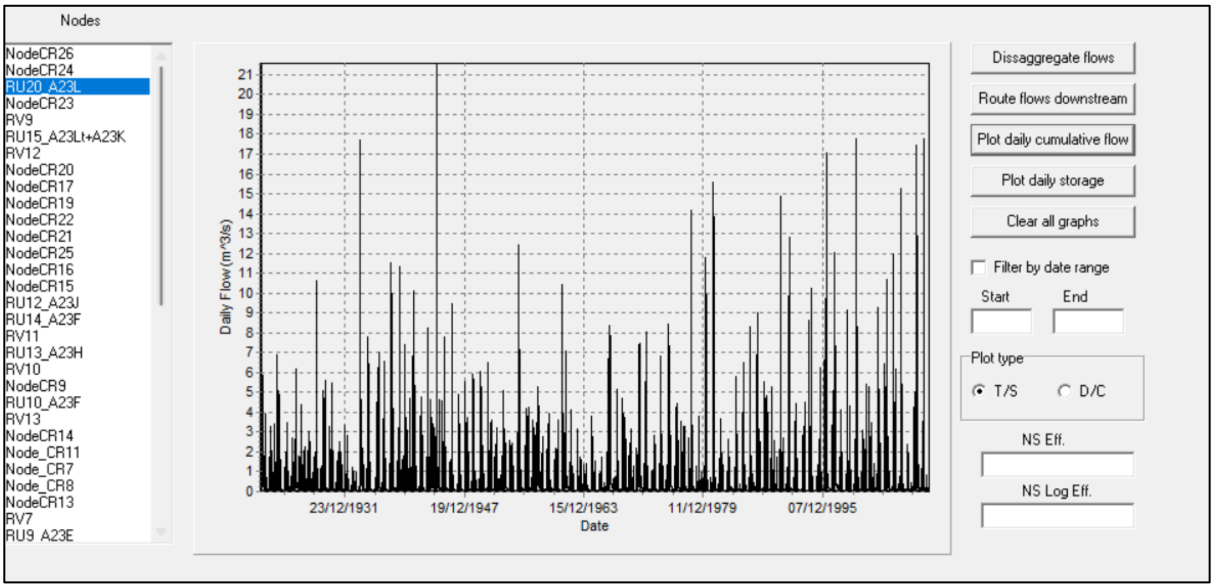
Data Type
Geog ID: RV13
Data ID: RAINFALL
Data Type: Fixed Interval, Data only
Time Units: Months
Time Interval: 1
Interval Type: Intervals
Variable Type: Volume
Variable Units: MCM
01/10/1920 30/09/2010

x=28.189 , y=-25.587

Figure 5.7 Reservoir rainfall extracted in Bon Accord Dam.

(ii) Disaggregation of monthly flows

WQSAM-HYDRO preprocessing model was run to disaggregate cumulative flows from channels (CR) into the entire catchment (RU). The disaggregation window and an example of daily cumulative flow for a RU20_A23L is provided in Figure 5.8



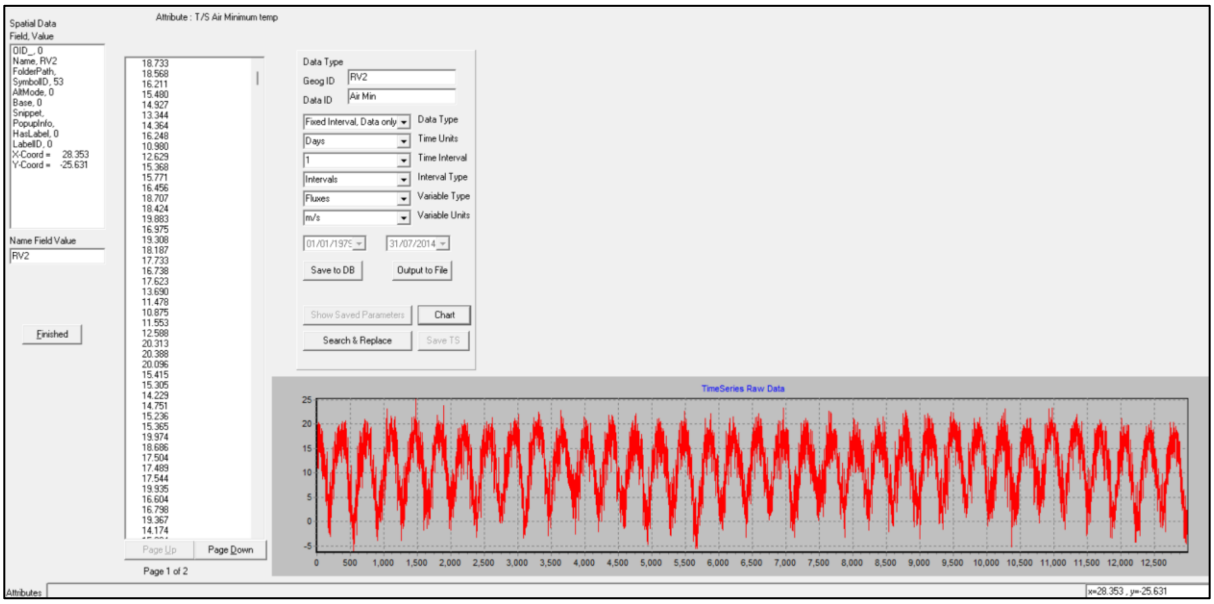
☐ Filter by date range

Plot type
● T/S ○ D/C

Figure 5.8 Disaggregated daily flow for run-off for RU20A23L.

5.1.2 Water Temperature Modelling

The temperature modelling was run through the Water Quality DSS linked to Yield Model interface within SPATSM. Water temperature has a dramatic effect on various processes driving water quality, for example, algal and hyacinth growth, rates of decomposition and nitrification. Observed water temperature data are relatively sparse within the historical monitoring data. Calibration of WQSAM to historical observed data and investigation of future scenarios such as climate change scenarios require WQSAM to provide the facility to simulate water temperatures. The model required the observed air temperature (minimum and maximum) and observed water temperature for input. The air temperature data was obtained from the satellite data using stations within the A23 Catchment. The water temperature data was obtained from the WMS programme. Figure 5.9 to Figure 5.11 shows the Minimum and Maximum temperature, respectively.



Attribute : T/S Air Minimum temp

OID_, 0
Name, RV2
FolderPath,
SymbolID, 53
AltMode, 0
Base, 0
Snippet,
PopupInfo,
HasLabel, 0
LabelID, 0
X-Coord = 28.353
Y-Coord = -25.631

Name Field Value: RV2

```
18.733
18.568
16.211
15.480
14.927
13.344
14.364
16.248
10.980
12.629
15.368
15.771
16.456
18.707
18.424
19.883
16.975
19.308
18.187
17.733
16.738
17.623
13.690
11.478
10.875
11.553
12.588
20.313
20.388
20.096
15.415
15.305
14.229
14.751
15.236
15.365
19.974
18.686
17.504
17.489
17.544
19.935
16.604
16.798
19.367
14.174
```

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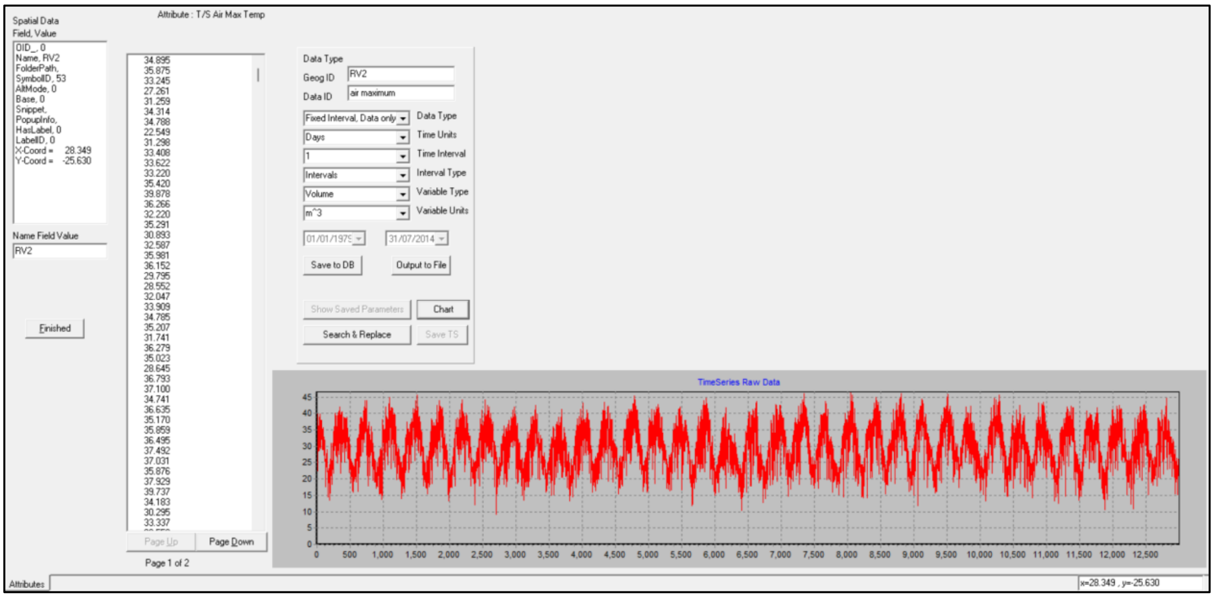
Geog ID: RV2
Data ID: Air Min
Fixed Interval, Data only — Data Type
Days — Time Units
1 — Time Interval
Intervals — Interval Type
Fluxes — Variable Type
m/s — Variable Units
01/01/1979 — 31/07/2014

x=28.353 , y=-25.631

Figure 5.9 Minimum Air Temperature from the satellite for Roodeplaat(RV2).



Attribute : T/S Air Max Temp

OID_, 0
Name, RV2
FolderPath,
SymbolID, 53
AltMode, 0
Base, 0
Snippet,
PopupInfo,
HasLabel, 0
LabelID, 0
X-Coord = 28.349
Y-Coord = -25.630

Name Field Value: RV2

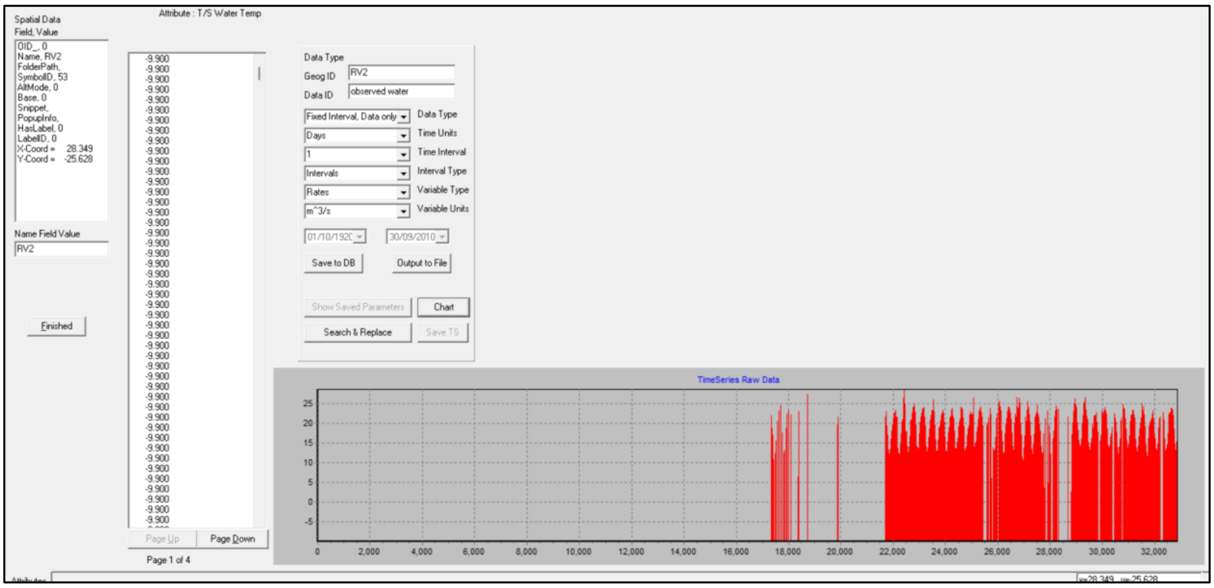
```
34.895
35.875
33.245
27.261
31.259
34.314
34.788
22.549
31.298
33.408
33.622
33.220
35.420
39.878
36.266
32.220
35.291
30.893
32.587
35.981
36.152
29.795
28.552
32.047
33.909
34.785
35.207
31.741
36.279
35.023
28.645
36.793
37.100
34.741
36.635
35.170
35.859
36.495
37.492
37.031
35.876
37.929
39.737
34.183
30.295
33.337
```

Page 1 of 2

Geog ID: RV2
Data ID: air maximum
Fixed Interval, Data only — Data Type
Days — Time Units
1 — Time Interval
Intervals — Interval Type
Volume — Variable Type
m^3 — Variable Units
01/01/1979 — 31/07/2014

x=28.349 , y=-25.630

Figure 5.10 Maximum Air Temperature from the satellite for Roodeplaat(RV2



Spatial Data
Field, Value

```
OID_, 0
Name, RV2
FolderPath,
SymbolID, 53
AltMode, 0
Base, 0
Snippet,
PopupInfo,
HasLabel, 0
LabelID, 0
X-Coord =    28.349
Y-Coord =   -25.628
```

Name Field Value: RV2

Attribute : T/S Water Temp

```
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
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-9.900
-9.900
-9.900
-9.900
-9.900
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-9.900
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-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
```

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Data Type
Geog ID: RV2
Data ID: observed water
Data Type: Fixed Interval, Data only
Time Units: Days
Time Interval: 1
Interval Type: Intervals
Variable Type: Rates
Variable Units: m^3/s
01/10/1920 – 30/09/2010

Figure 5.11 Observed Water Temperature for the Roodeplaat Dam(RV2).

5.2 Calibration of Water Temperature Model

The model calibration was performed for water temperature using observed temperature data (air and water) displayed in Table 6-2. A multiple regression approach was used to simulate and calibrate water temperature as given by Equation 1 below:

$$WTmax = C + (A \times ATavr) + (B \times ATmin) \quad \text{………. Equation 1}$$

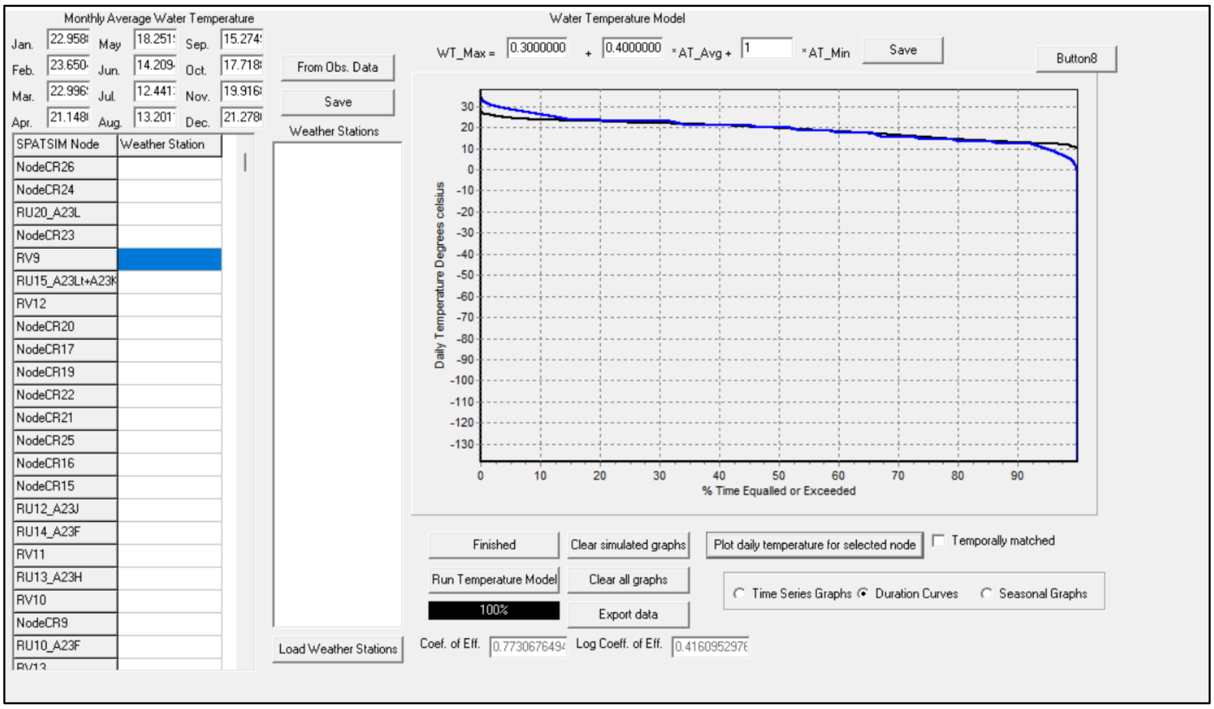
Where:

WTmax is the maximum water temperature for that day;

ATavr is the average air temperature for that day; and

ATmin is the minimum air temperature for that day.

The calibration involved adjusting A, B and C model parameters (Equation 1). The model calibration was considered satisfactory when the Co-efficient of Efficiency was greater than **0.5.** The calibration exercise for water temperature is shown in Figure 5.12.



Monthly Average Water Temperature

Jan.	22.958	May	18.251	Sep.	15.274
Feb.	23.650	Jun.	14.209	Oct.	17.718
Mar.	22.996	Jul.	12.441	Nov.	19.916
Apr.	21.148	Aug.	13.201	Dec.	21.278

SPATSIM Node	Weather Station
NodeCR26	
NodeCR24	
RU20_A23L	
NodeCR23	
RV9	
RU15_A23Lt+A23K	
RV12	
NodeCR20	
NodeCR17	
NodeCR19	
NodeCR22	
NodeCR21	
NodeCR25	
NodeCR16	
NodeCR15	
RU12_A23J	
RU14_A23F	
RV11	
RU13_A23H	
RV10	
NodeCR9	
RU10_A23F	
RV13	

Water Temperature Model

WT_Max = 0.3000000 + 0.4000000 * AT_Avg + 1 * AT_Min

☐ Temporally matched

○ Time Series Graphs ● Duration Curves ○ Seasonal Graphs

Coef. of Eff. 0.773067649

Log Coeff. of Eff. 0.416095297

Figure 5.12 Calibration process for water temperature for Klipvoor Dam (RV9).

6 Lower Crocodile Sub-Catchment

6.1 Catchment Description

The Lower Crocodile sub-catchment is one of four sub-catchments that make up the Crocodile West Catchment. The sub-catchment has 9 quaternaries A24A-A24J (Figure 6.1), which fall within two provinces, quaternaries A24D and A24E are within the North West Province while the rest of quaternaries are within the Limpopo Province. The Crocodile River flows out of the Lower Crocodile sub-catchment into the Limpopo River which discharges into the Indian Ocean in Mozambique. The Lower Crocodile is characterised by large-scale irrigation activities along the mainstem of the Crocodile River while the rest of the sub-catchment's activities comprise of cattle farming, game farming and mining (DWAF, 2004).

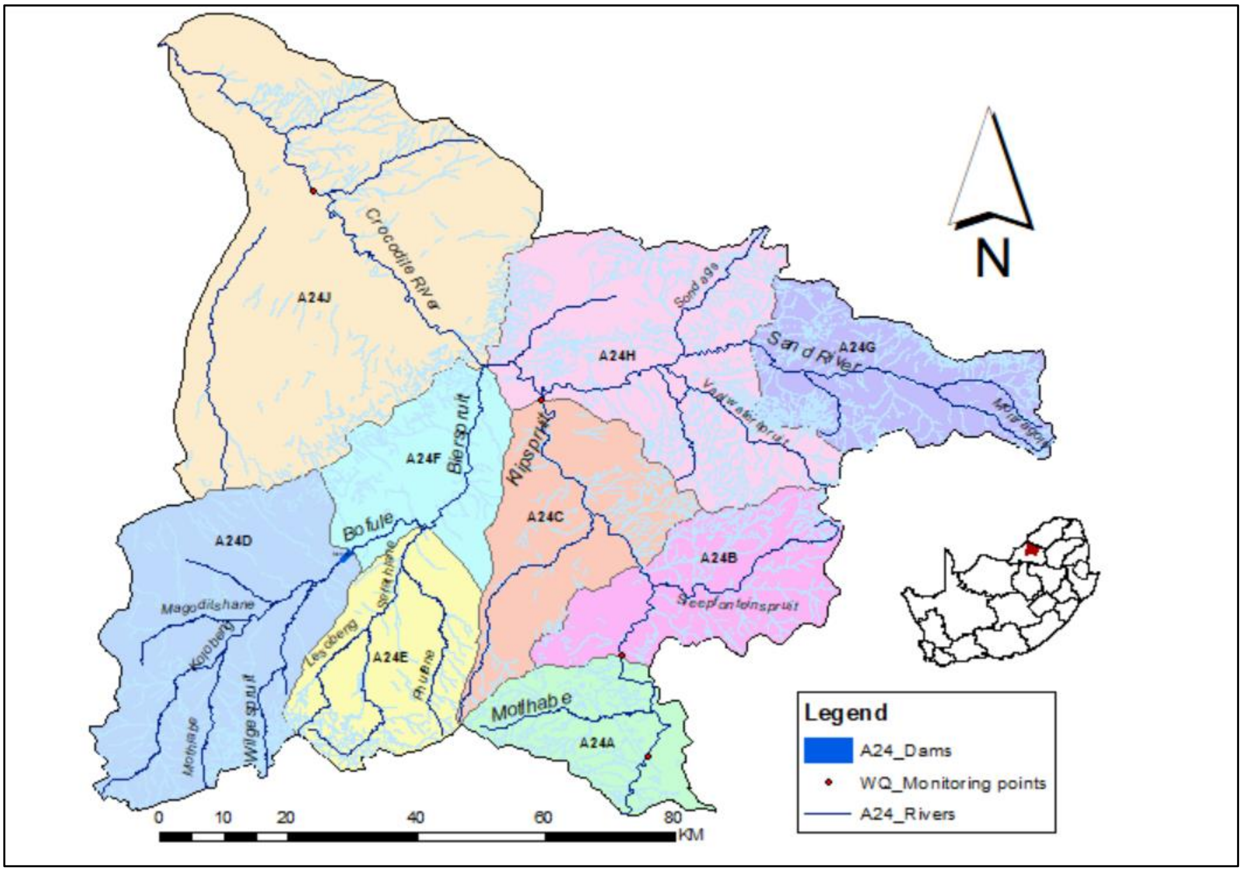


Figure 6.1: The Lower Crocodile sub-catchment (A24).

6.2 Methodology

The study used 3 models which comprised a rainfall-runoff model, yield model and a water quality model to achieve its objectives namely;

(i) **WRSM2000** was used to simulate daily natural flows;
(ii) **WRYM** was used to simulate monthly reservoir data and impacted flows; and
(iii) **WQSAM** was used to simulate water quality in the lower Crocodile sub-catchment.

The outputs from the WRSM2000 and WRYM were used as inputs in the WQSAM model.

6.2.1 WRSM2000/Pitman Model Configuration

The WRSM2000/Pitman model was used to simulate naturalised daily flows (which are flows without any man-made effects such as reservoirs, industry, towns, irrigation schemes, mines etc) from the South African meteorological data. The catchment under investigation was presented as a network (Figure 6.2) in the Pitman Model. The network had routes and various modules (Channel, Runoff, Mine Irrigation and Reservoir Modules). The current study obtained data for all modules from the detailed WR2012 study. However, the data used in the runoff module, which is referred to as rainfile/s were created from different sources of meteorological data. The rainfiles contained monthly rainfall data for each quaternary in the catchment.

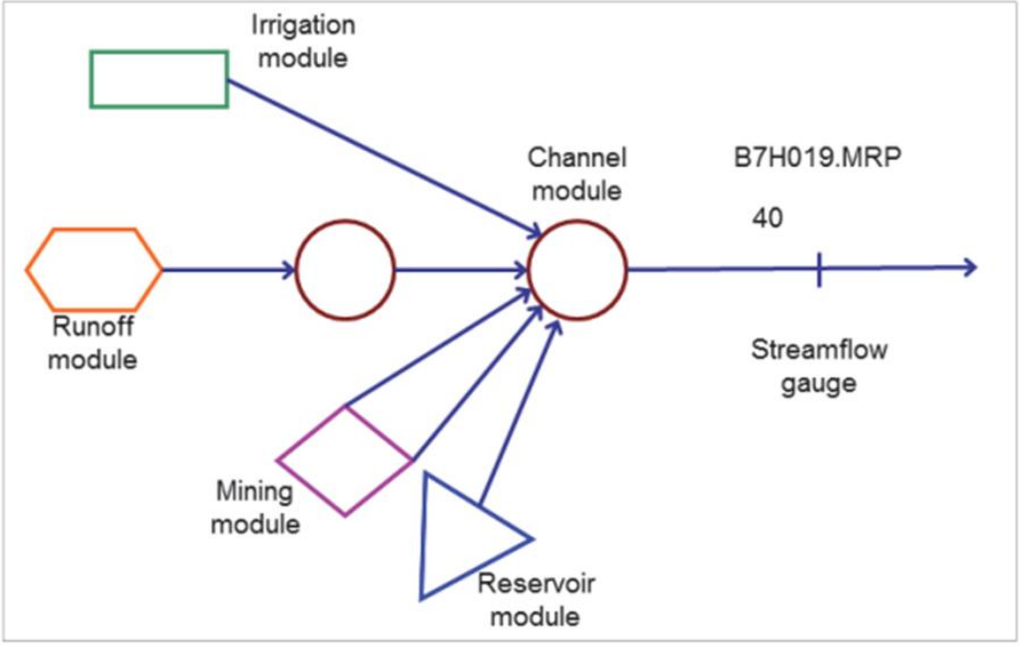


Figure 6.2: Example of a catchment represented as a network in WRSM (Source: Bailey and Pitman, 2016).

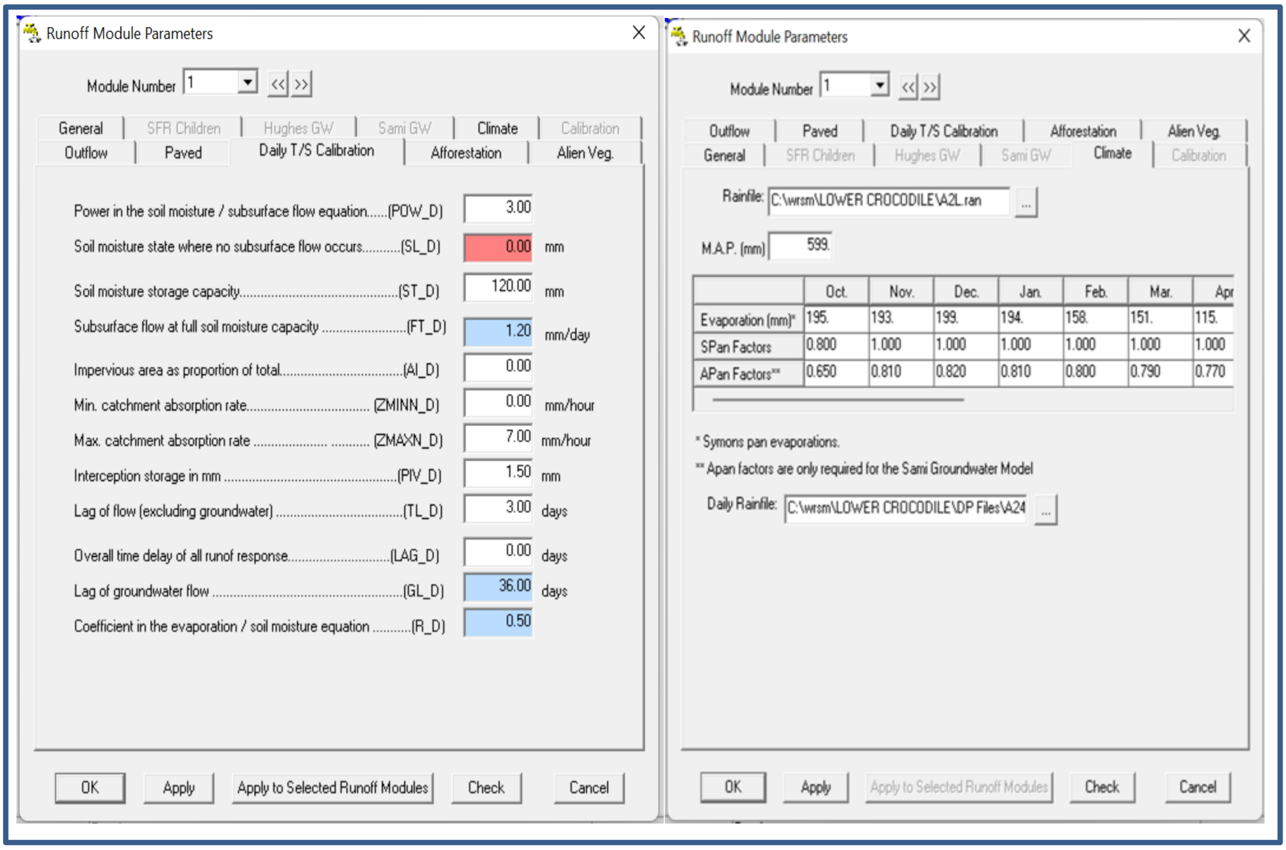
(i) *Runoff module data processing*

The runoff module included meteorological parameters such as rainfall, Mean Annual Precipitation as well as monthly evaporation with corresponding S-Pan factors as per WR2012 study. The record of historical rainfall data used was October 1920 – September 2010.The SAWS rainfall record used in this study was 1920- 2000, this record was supplemented using CFSR satellite daily rainfall data with records from 2000- 2010. The SAWS and CFSR station numbers used per quaternary catchments are shown in Figure *6.3.*

Table 6-1, a snapshot of WRSM2000/Pitman runoff module inputs and calibration parameters are shown in Figure 6.3.

Table 6-1 Daily rainfall file data used for Lower Crocodile Sub-catchment.

Quartenary Catchment	Runoff Unit	SAWS Rainfall Station	CFSR Rainfall Station
A24A	RU1	0548165 W	p-251275
A24B	RU2	0588385 W	p-245275
A24C	RU3	0588385 W	p-248275
A24D	RU4	0547526 W	p-251269
A24E	RU5	0548483 W	p-251272
A24F	RU6	0548483 W	p-248272
A24G	RU7	0588406 W	p-245278
A24H	RU8	0588385 W	p-245278
A24J	RU9	0587668 W	p-245272



Module Number 1

Power in the soil moisture / subsurface flow equation......(POW_D) 3.00
Soil moisture state where no subsurface flow occurs...........(SL_D) 0.00 mm
Soil moisture storage capacity..(ST_D) 120.00 mm
Subsurface flow at full soil moisture capacity ....(FT_D) 1.20 mm/day
Impervious area as proportion of total..................................(AI_D) 0.00
Min. catchment absorption rate.................................. (ZMINN_D) 0.00 mm/hour
Max. catchment absorption rate .... (ZMAXN_D) 7.00 mm/hour
Interception storage in mm ....(PIV_D) 1.50 mm
Lag of flow (excluding groundwater) ....(TL_D) 3.00 days
Overall time delay of all runof response...........................(LAG_D) 0.00 days
Lag of groundwater flow ....(GL_D) 36.00 days
Coefficient in the evaporation / soil moisture equation ....(R_D) 0.50

Module Number 1

Rainfile: C:\wrsm\LOWER CROCODILE\A2L.ran

M.A.P. (mm) 599.

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr
Evaporation (mm)*	195.	193.	199.	194.	158.	151.	115.
SPan Factors	0.800	1.000	1.000	1.000	1.000	1.000	1.000
APan Factors**	0.650	0.810	0.820	0.810	0.800	0.790	0.770

* Symons pan evaporations.
** Apan factors are only required for the Sami Groundwater Model

Daily Rainfile: C:\wrsm\LOWER CROCODILE\DP Files\A24

Figure 6.3: Example of WRSM inputs for quaternary A24A.

The WRSM2000 generated naturalised daily flows from the runoff module for each quaternary, an example of hydrograph generated from WRSM2000 for quaternary A24A is provided in *Figure 6.4*. The naturalised daily flows from WRSM2000 were transformed in Microsoft Excel in order to have a continuous flow data that is compatible with WQSAM model. It should be noted that WRSM2000 model generates a (-1) value for flows on the last days of the month (29, 30 and 31), for the purpose of WQSAM modelling, these values were removed.

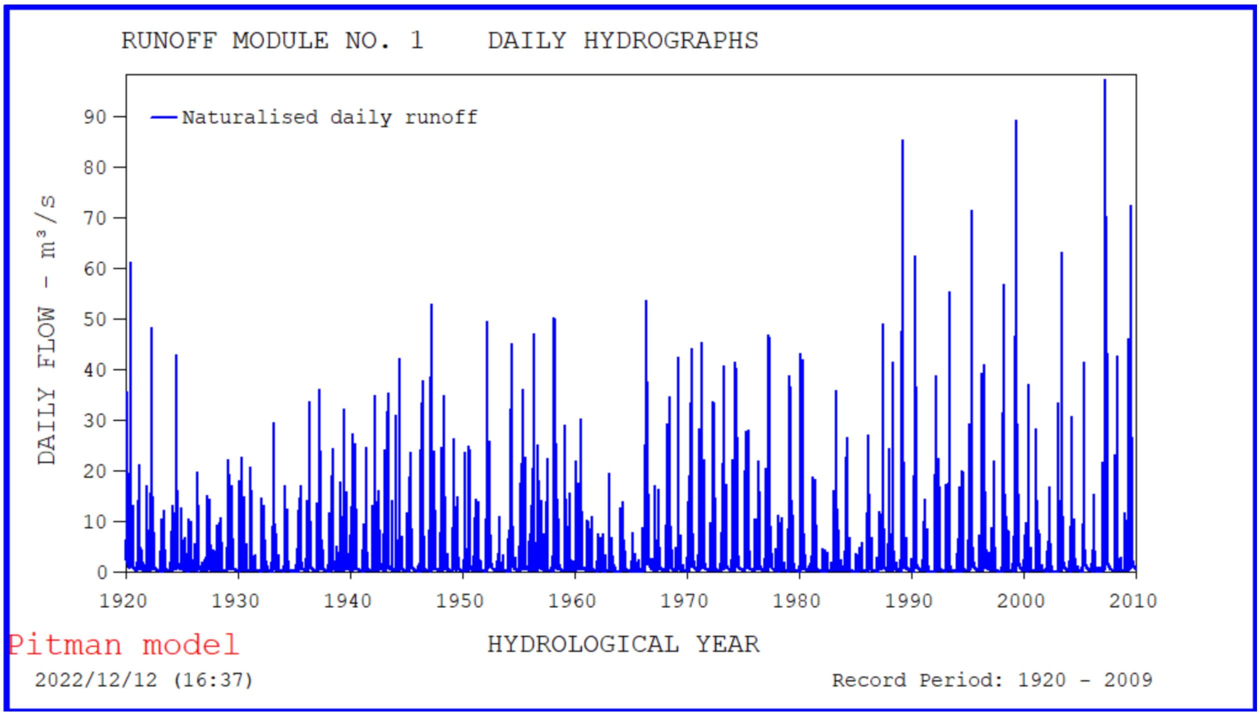


Figure 6.4: Hydrograph generated by WRSM2000 for A24A quaternary catchment.

6.2.2 WQSAM Configuration

WQSAM was designed to run through SPATSIM, which is a modelling platform where several other hydrological models are run. The main goal for using WQSAM in the current study was to develop water quality model for the Crocodile West Catchment, the model configuration is detailed in this section.

(iii) Network/System set-up

The initial step in WQSAM was to set up a network that replicates the WRSM2000 network structure, which links the nodes and routes as per the WRSM2000 network shown in Figure 6.5. Features and corresponding attributes for nodes were created as shown in Figure 6.6. The data which includes the daily incremental flows from the WRSM2000 as well as reservoir storage data generated by the WRYM were used as input into the model. It is important to note that the Lower Crocodile sub-catchment is an inlet of the three upstream Crocodile West Sub-catchments, and therefore receives flows Elands and Apies-Pienaars sub-catchments. The outflows (boundary conditions) from the said sub-catchments were used as inflows in the Lower Crocodile and uploaded under the attributes “Daily Transfer in”, “Monthly Transfer in” (Figure 6.6).

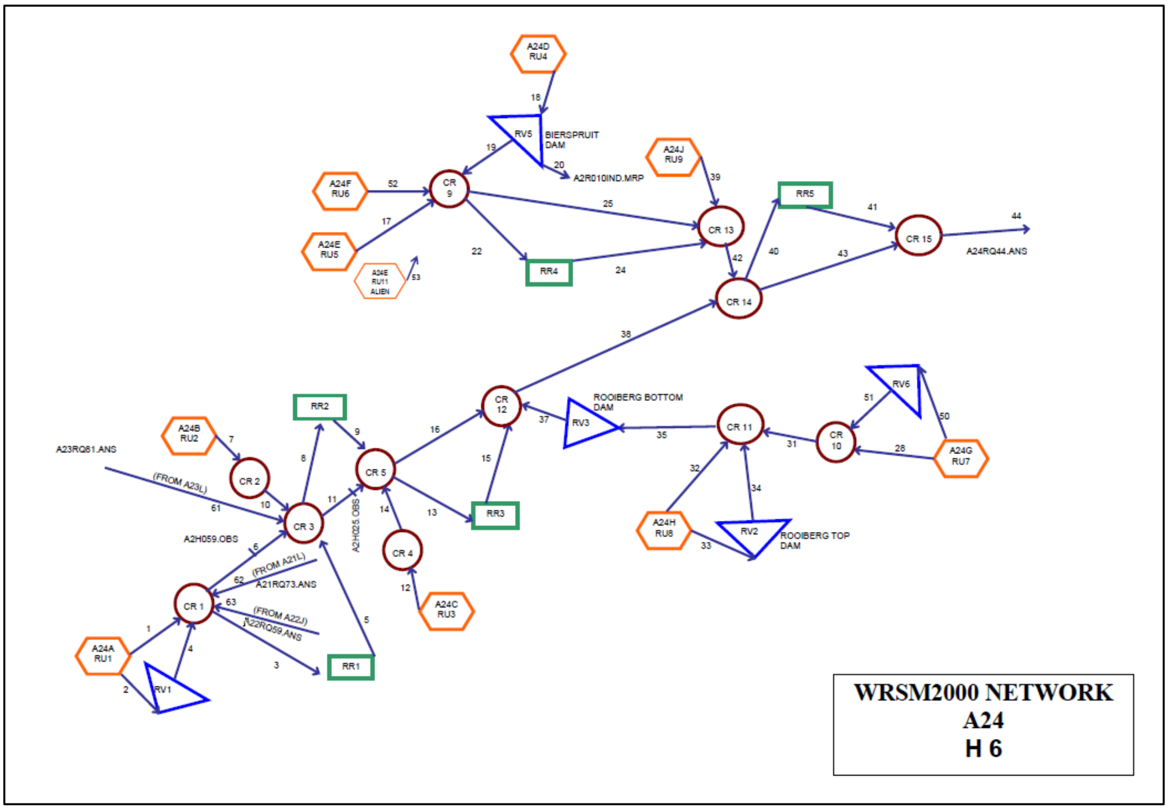


Figure 6.5: WRSM2000 network diagram for A24A quaternary catchment.

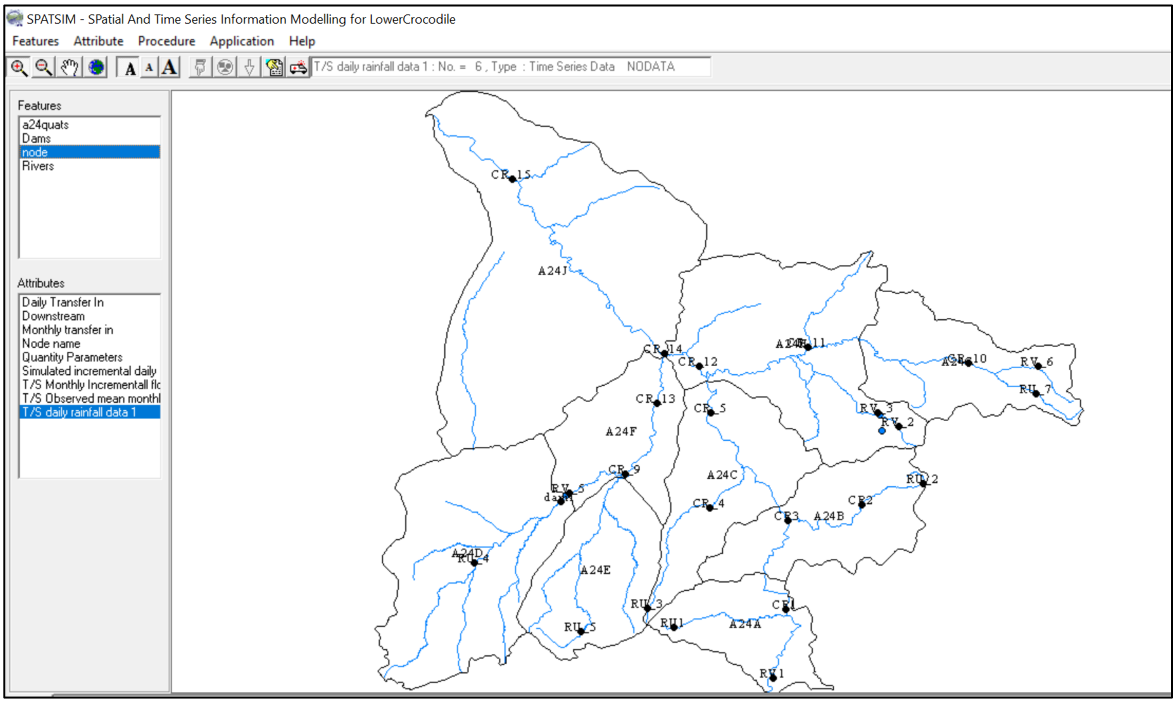
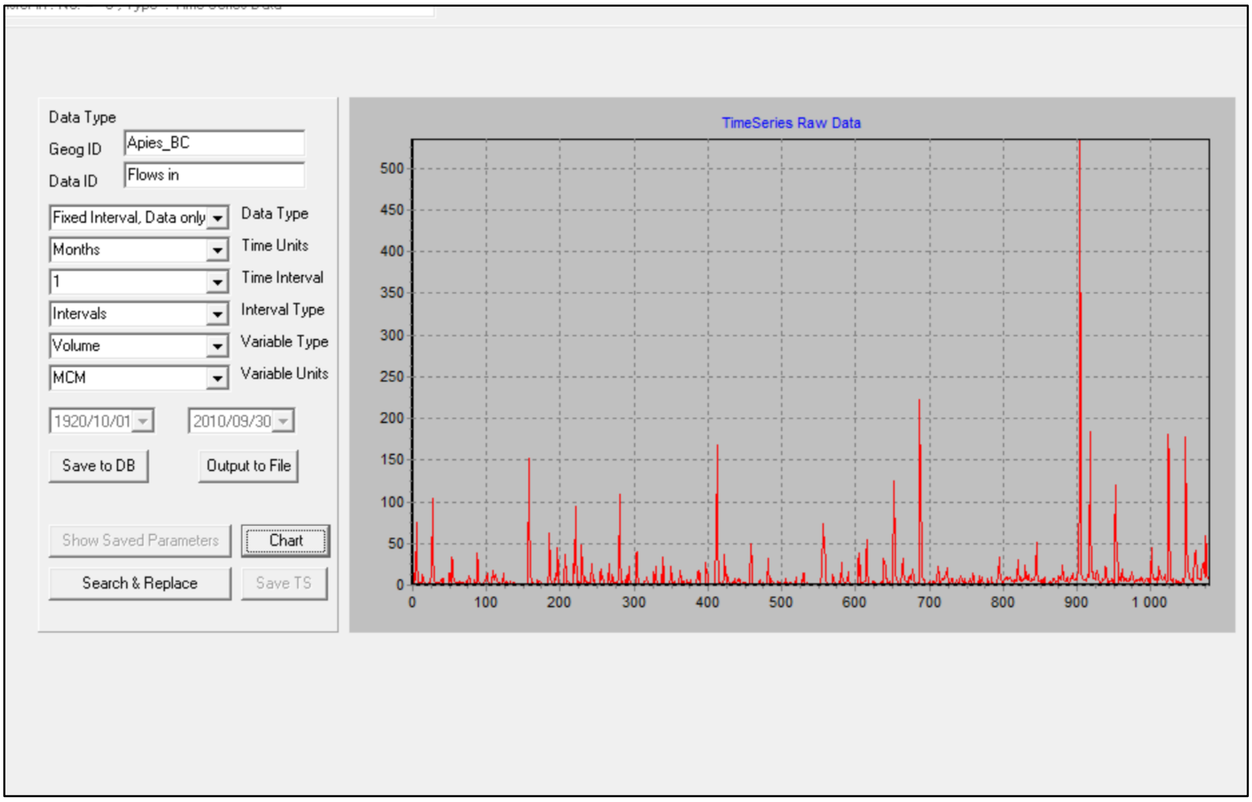


Figure 6.6: Lower Crocodile subcatchment structure created in SPATSIM.

(iv) Boundary conditions

The Lower Crocodile sub-catchment is located at the outlet of the Crocodile West Catchment, it is therefore subject to boundary conditions as it receives water from the upstream sub-catchments. The inflow into the catchment was accounted for using the “monthly transfer in” attribute, where the volume of water flowing in from Apies, Elands and Crocodile was stored. *Figure 6.7* shows the volume of water that flows into the catchment from the Apies-Pienaars sub-catchment (Quart_A23) monthly.

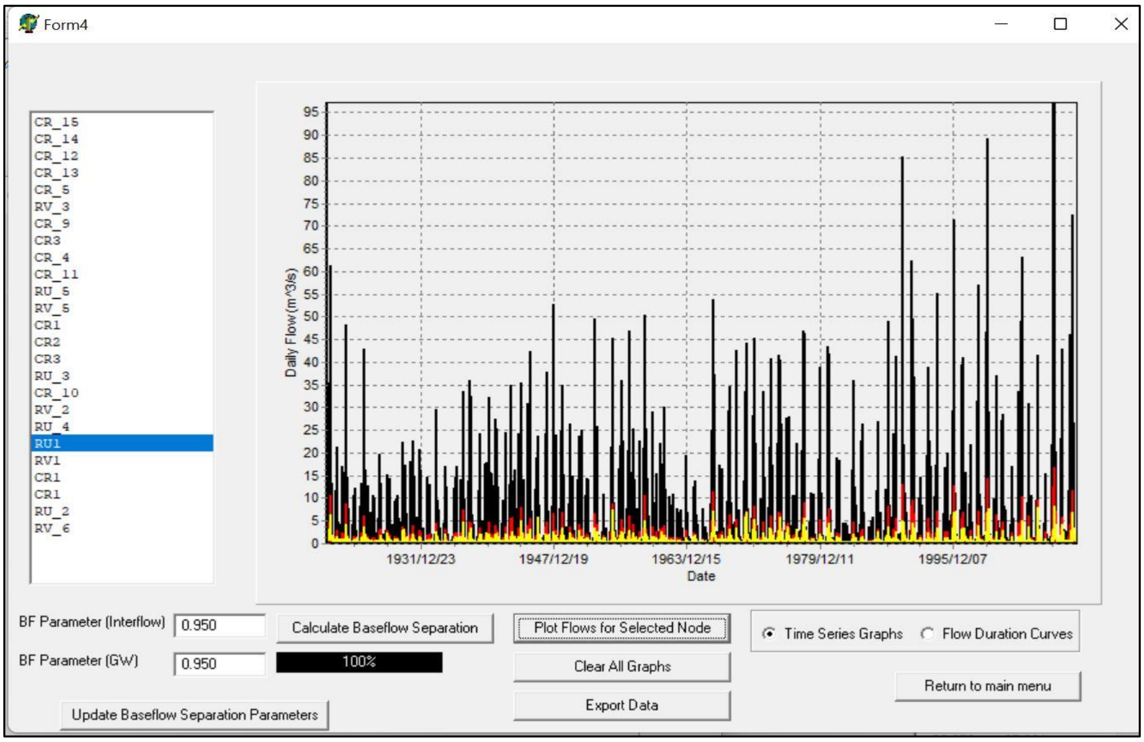


Data Type
Geog ID: Apies_BC
Data ID: Flows in
Data Type: Fixed Interval, Data only
Time Units: Months
Time Interval: 1
Interval Type: Intervals
Variable Type: Volume
Variable Units: MCM
1920/10/01
2010/09/30

Figure 6.7: Apies Monthly Transfers into the Lower Crocodile sub-catchment.

(v) Baseflow separation

The *WQSAM-HYDRO* preprocessing model was run in order to separate the natural incremental daily flows into attributes *simulated groundwater* and *simulated interflow.* Figure 6.7 below shows the separated flows time-series plot for run-off unit 1 (RU1).



BF Parameter (Interflow) 0.950

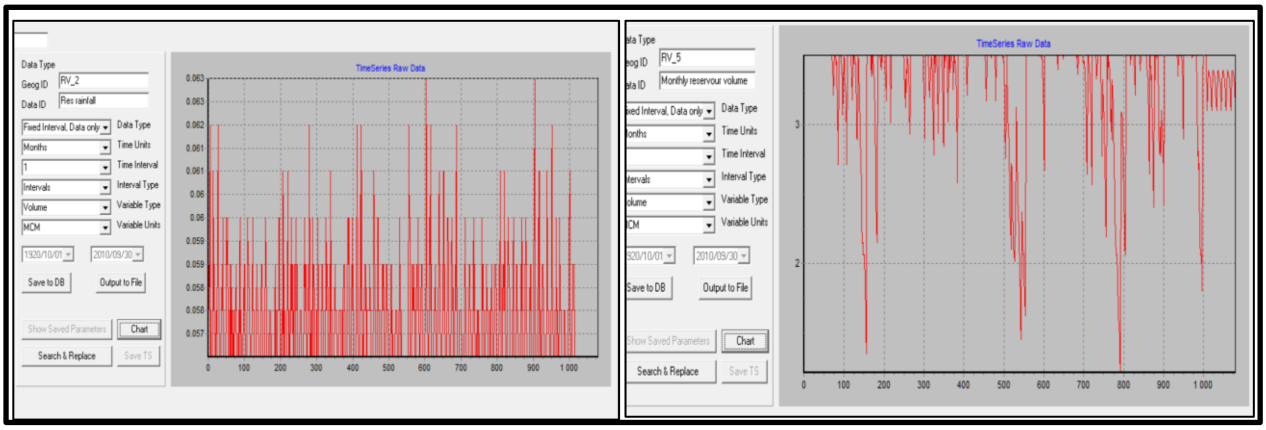
BF Parameter (GW) 0.950

● Time Series Graphs ○ Flow Duration Curves

Figure 6.8: Baseflow separation plot for RU_1 created in SPATSIM.

(vi) Reservoir Parameters

The data exported from the WRYM was used as input into WQSAM in the attributes; *reservoir daily rainfall (Figure 6.9a), monthly storage (Figure 6.9b)* and *observed monthly evaporation*. The outflows from the reservoirs were obtained using the route numbers depicted in the WRYM, However the Lower Crocodile routes from the dams had no data and outflow routes data from WRSM2000 were utilised. The outflows record was up to 2003 and was extended to 2009 using monthly averages. The data was uploaded into WQSAM under attribute *Monthly Reservoir Releases*.



Geog ID RV_2; Data ID Res rainfall; Fixed Interval, Data only; Months; 1; Intervals; Volume; MCM; 1920/10/01; 2010/09/30

Geog ID RV_5; Data ID Monthly reservoir volume; Fixed Interval, Data only; Months; Intervals; Volume; MCM; 1920/10/01; 2010/09/30

Figure 6.9: (a) Reservoir rainfall extracted from the WRYM, (b) Monthly volume of Bierspruit Dam.

(vii) Cumulative Flows Disaggregation

WQSAM-HYDRO preprocessing model was run to disaggregate cumulative flows from the channels (CR) into the entire catchment (RU). The disaggregation window and an example of daily cumulative flow for RU_2 is provided in *Figure 6.10*.

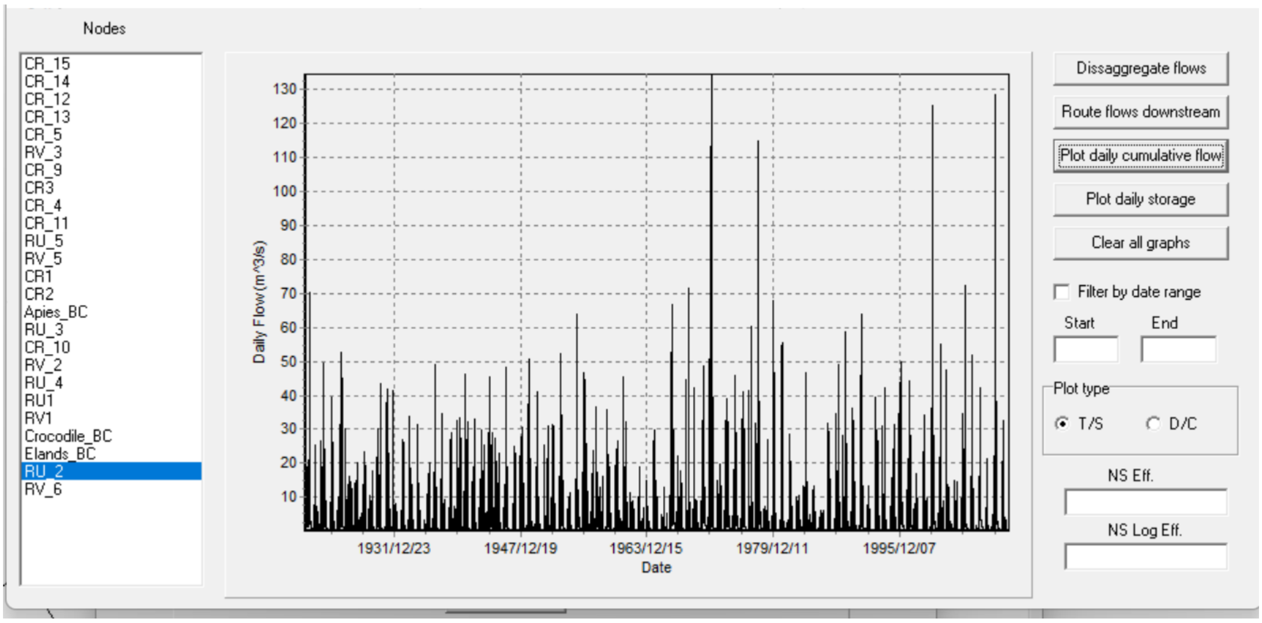


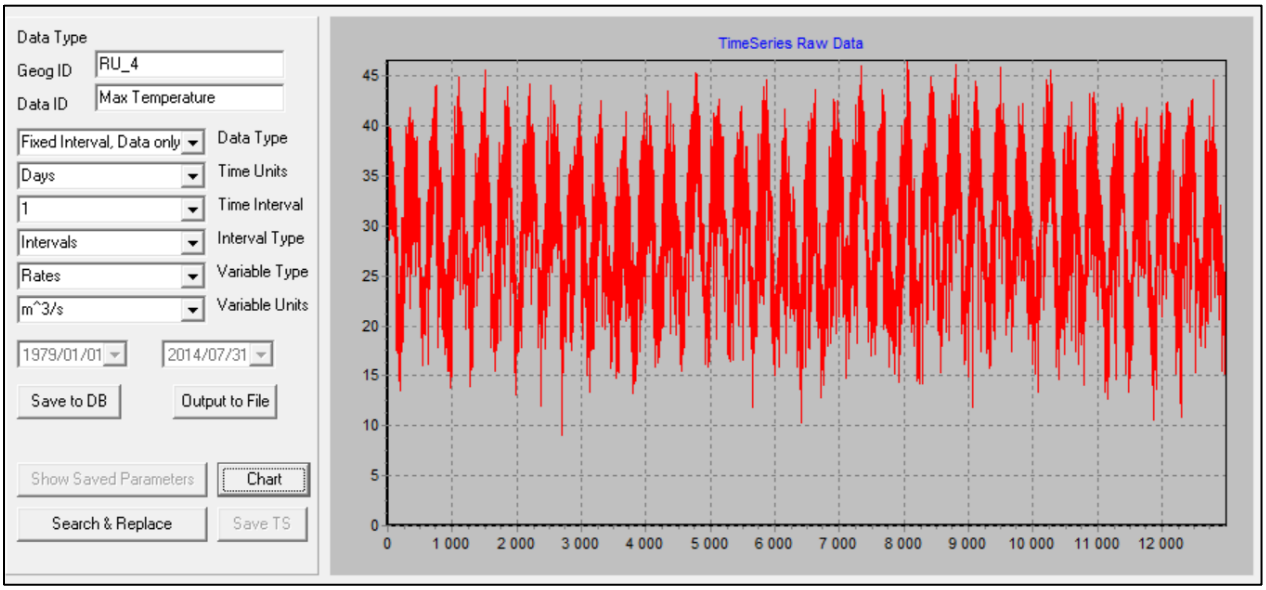
Figure 6.10: Dissagregated daily flow for run-off unit 2.

6.2.3 Water Temperature Modelling

The temperature modelling was run through the Water Quality DSS linked to Yield Model interface within SPATSM. The model required observed air temperature (minimum and maximum) and observed water temperature for input. The air temperature data was obtained from the satellite data using stations presented in *Table 6-1* for flow data, the water temperature data was obtained from the Department's water quality monitoring programme. The programme monitors water quality daily at an hourly-timestep, the data was then averaged out to one value per day and patched using a data patching utility inserting (-9.9) in the gaps. A list of attributes created in water temperature modelling is displayed in Table 6-2 and the maximum temperature for RU_4 is displayed in *Figure 6.11*.

Table 6-2: List of attributes created for water temperature modelling.

Attribute	File type	Data entry
Maximum air temperature	text	Maximum air temp data from satellite stations
Minimum air temperature	text	Minimum air temp data from satellite stations
Observed water temperature	t/s	Observed data from dams collected by DWS
Simulated water temperature	t/s	Water temperature data simulated by the model
Temperature parameters	Array	Water temperature model parameters and monthly water temperature data



Data Type
Geog ID: RU_4
Data ID: Max Temperature
Data Type: Fixed Interval, Data only
Time Units: Days
Time Interval: 1
Interval Type: Intervals
Variable Type: Rates
Variable Units: m^3/s
1979/01/01
2014/07/31

Figure 6.11: maximum air temperature for the R_U 4.

(i) Calibration of Water Temperature Model

The model calibration was performed for water temperature using observed temperature data (air and water) displayed in Table 6-2. A multiple regression approach was used to simulate and calibrate water temperature as given by Equation 1 below:

$$\mathit{WTmax} = C + (A \times \mathit{ATavr}) + (B \times \mathit{ATmin}) \ldots\ldots\ldots \quad \mathit{Equation\ 1}$$

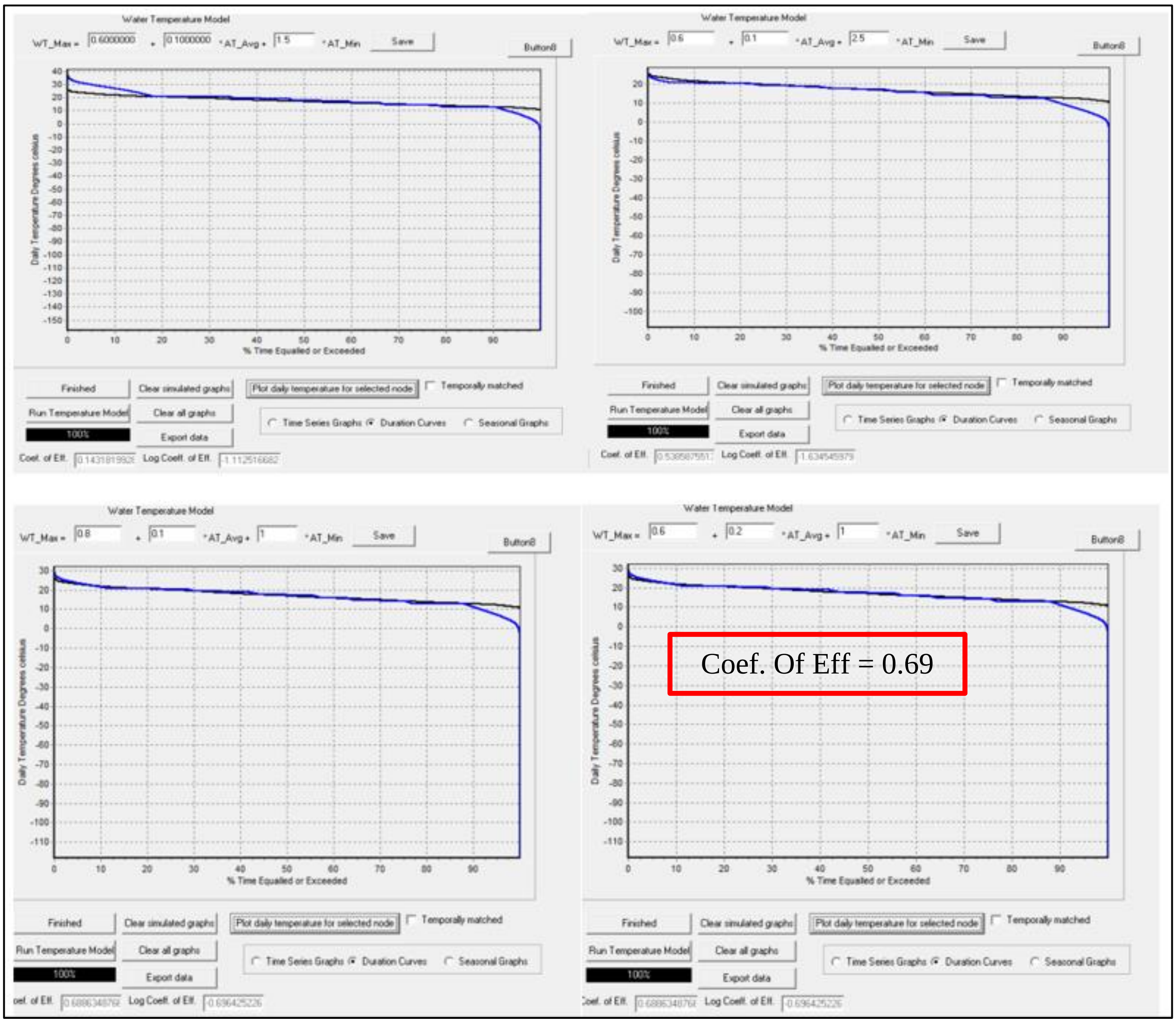
Where:

WTmax is the maximum water temperature for that day;

ATavr is the average air temperature for that day; and

ATmin is the minimum air temperature for that day.

The calibration involved adjusting A, B and C model parameters (Equation 1). The model calibration was considered satisfactory when the Co-efficient of Efficiency was greater than **0.5.** The calibration exercise for water temperature is shown in Figure 6.12



WT_Max = 0.6000000 + 0.1000000 *AT_Avg + 1.5 *AT_Min
Coef. of Eff. 0.143181992 Log Coeff. of Eff. -1.112516682

WT_Max = 0.6 + 0.1 *AT_Avg + 2.5 *AT_Min
Coef. of Eff. 0.53858755 Log Coeff. of Eff. 1.634545979

WT_Max = 0.8 + 0.1 *AT_Avg + 1 *AT_Min
Coef. of Eff. 0.688634876 Log Coeff. of Eff. 0.696425226

WT_Max = 0.6 + 0.2 *AT_Avg + 1 *AT_Min
Coef. of Eff. 0.688634876 Log Coeff. of Eff. 0.696425226

Figure 6.12 Calibration process for water temperature and obtained co-efficients of efficiency

6.3 Water Quality Modelling

Observed water quality data was obtained from the Departmental water quality monitoring program. There were 3 monitoring stations within the A24 quaternary catchment, these stations were linked to the closest channel routes (CR) for allocation of observed water quality data. In calibration of the water quality model, the non-point sources were calibrated at a catchment level (RU), while the point sources were calibrated at the channel routes (CR). Table 6-3 shows the observed data that was used for water quality assessment and calibration. Model calibration was undertaken for only one (1) water quality parameter (Sulphates). Calibration for other parameters (TDS,PO4, Ammonia and NO3) was limited by water quality data availability. Water quality concentrations compliance was assessed using the Resource Quality Objectives (RQOs) gazzeted by the Department of Water and Sanitation for Crocodile west Catchment in 2017 (**Gazzette No. 41310**).

Table 6-3: Attributes created in water quality modelling.

Attribute	**File type**
Observed PO_4 Simulated PO_4	text
Observed NH_4 Simulated NH_4	text
Observed SO_4 Simulated SO_4	T/S
Observed NO_2NO_3 Simulated NO_2NO_3	T/S
Observed TDS Simulated TDS	T/S
Water quality parameters	Array

6.3.1 Model Calibration results for Channel Route 1 (CR_1)

Channel Route 1 is located in the uppermost parts of A24 sub-catchment (*Figure 6.5*), the nearest water quality monitoring site was Station No. 90203 (Figure 6.1). This route was calibrated at the nearest run-off unit 1. The goodness of fit between observed and simulated data was assessed using the graphical and statistical approaches. The latter included using the Co-efficient of Efficiency, the co-efficient of >0.50 is considered to be good while the co-efficient of 0.75 is rated as very good (Moriasi *et al*., 2007). A good fit between simulated and observed was obtained with signatures presented in *Table* with a co-efficient efficiency = 0.80. The calibration exercise and duration curves are shown in (*Figure 6.13*). The model simulated sulphates well at low and high flow and undersimulated sulphates at medium flows. The RQO at this site is 100 mg/l, Figure 6.13 shows that this concentration is exceeded 25% of the time during high-medium flows.

Table 6-4: Flow signatures used for calibrating CR1.

PARAMETERS	**SURFACE FLOW**	**INTERFLOW**	**GROUNDWATER**	**RETURN FLOW**
FLOW SIGNATURES (MG/L)	160	30	80	3
Co-Efficient of Efficiency	0.80			

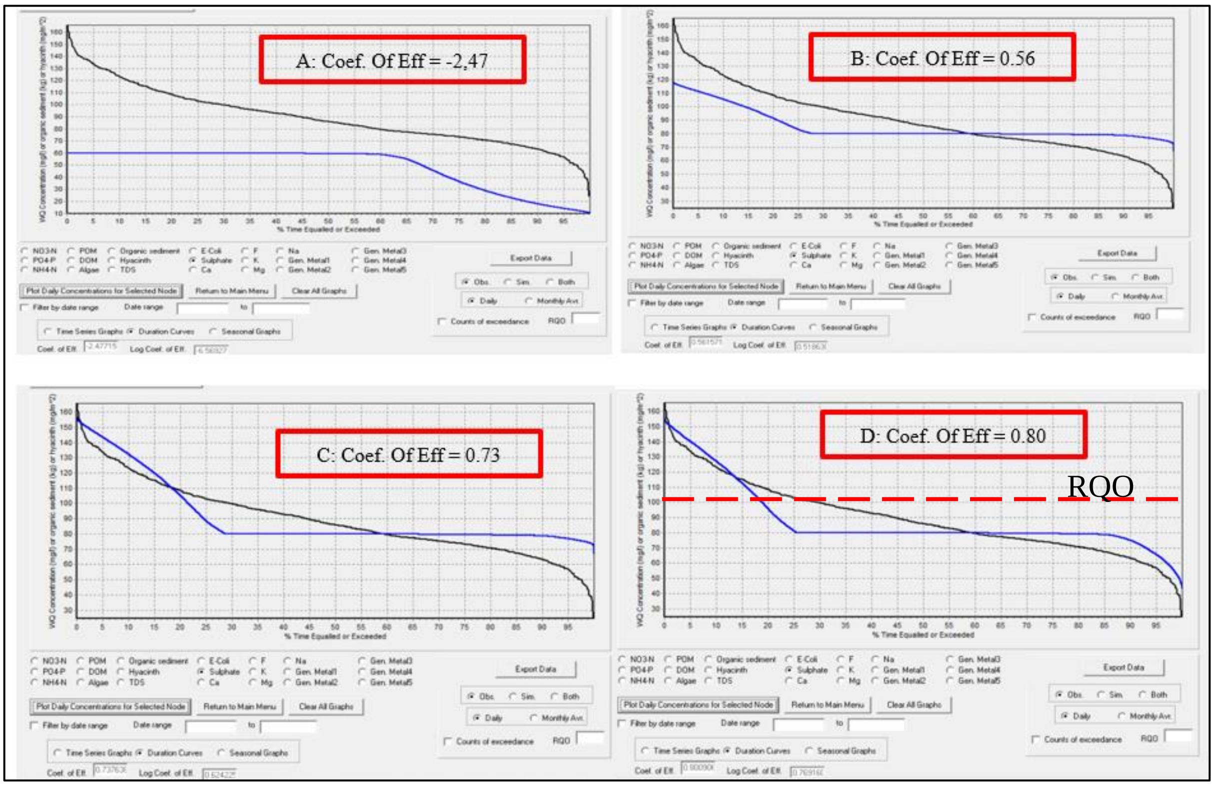


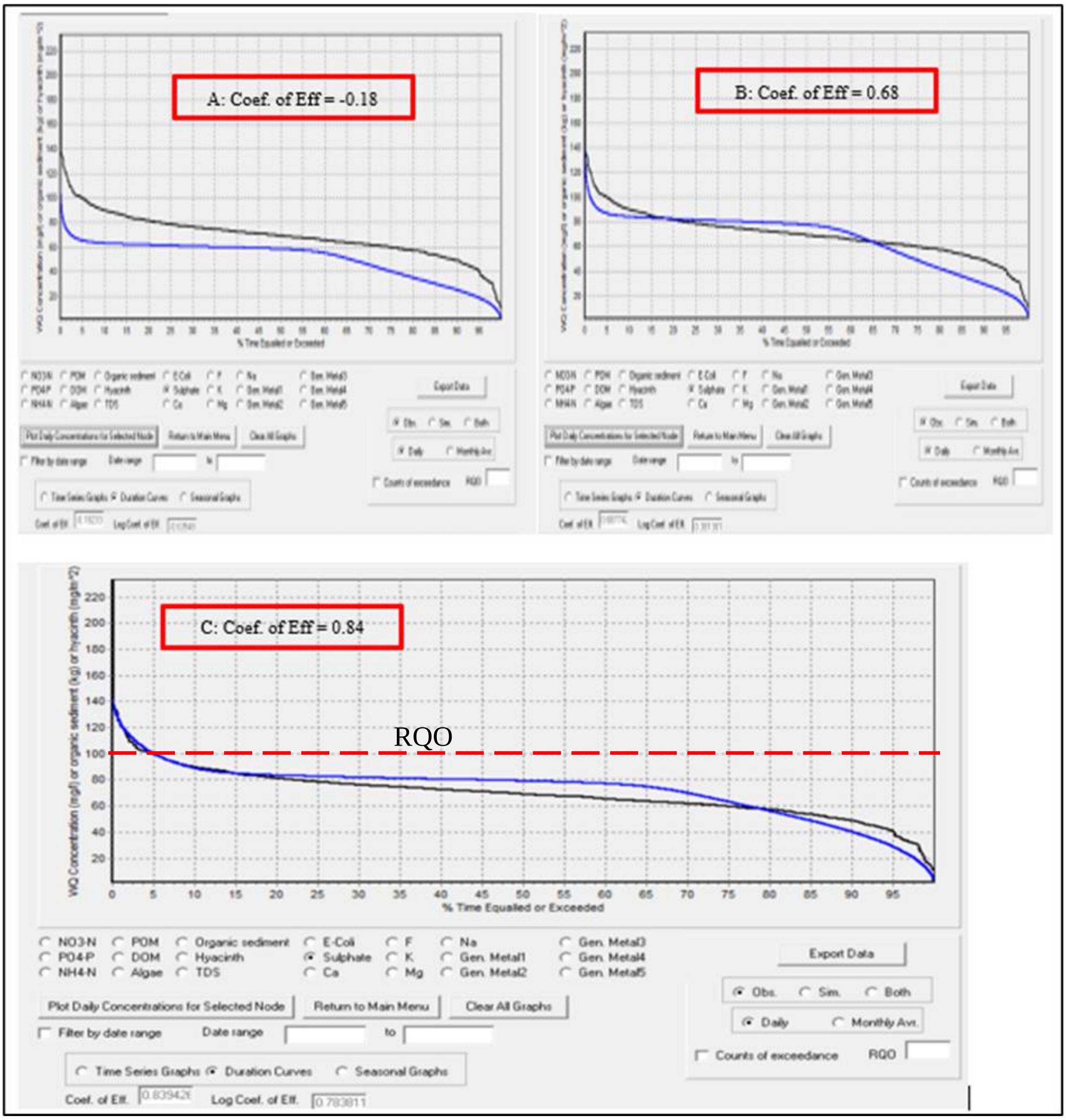
Figure 6.13: Sulphates calibration for CR1.

6.3.2 Model Calibration results for Channel Route 3 (CR_3)

Channel Route 3 is located immediately below CR_3 (*Figure 6.5*), the nearest water quality monitoring site was Station No. 90204 (Figure 6.1). This route was also calibrated at the nearest run-off unit 1. The goodness of fit between observed and simulated data was assessed using the graphical and statistical approaches. A good fit between simulated and observed was obtained with signatures presented in *Table* with a co-efficient efficiency = 0.84. The calibration exercise and duration curves are shown in (*Figure 6.14*). A good calibration at this route was achieved by giving allocating more signature to the groundwater component. The RQO at this site is 100 mg/l, this concentration is only exceeded during high flows less than 5% of the time.

Table 6-5: Flow signatures used for calibrating CR3.

Parameters	**Surface Flow**	**Interflow**	**Groundwater**
Flow signatures (mg/l)	150	30	200
Co-Efficient of Efficiency	0.84		



Coef. of Eff. 0.83942

Log Coef. of Eff. 0.783811

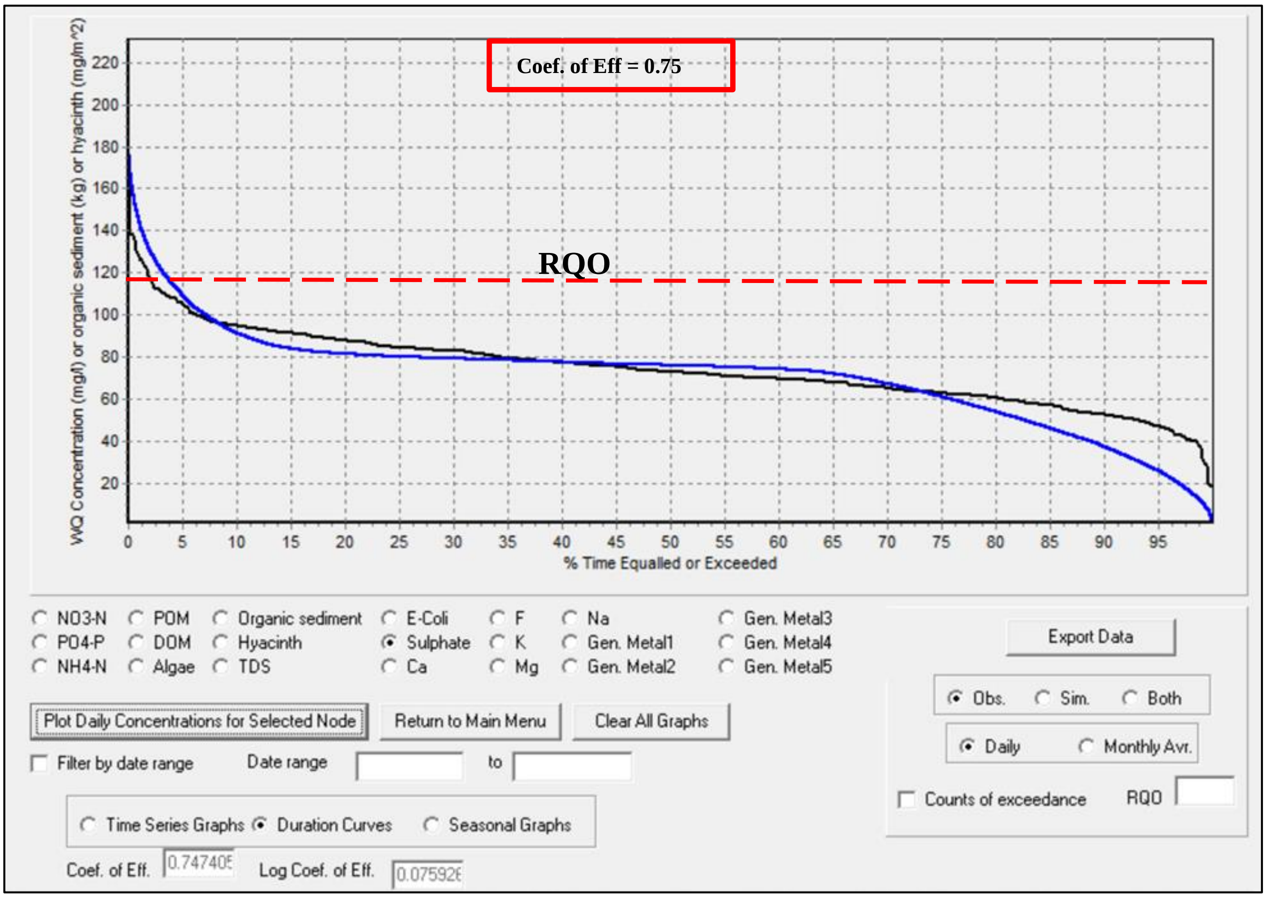
Figure 6.14: Sulphates calibration for CR3.

6.3.3 Model Calibration results for Channel Route 12 (CR_12)

Channel Route 12 is located immediately below CR_5 (*Figure 6.1*) on the Crocodile River channel, the nearest water quality monitoring site was Station No. 90204 (Figure 6.1). This route was also calibrated at RU_1 as it is the only RU_along the main channel closer to the route. The goodness of fit between observed and simulated data was assessed using the graphical and statistical approaches. A good fit between simulated and observed was obtained with signatures presented in Table 6-6 with a co-efficient efficiency = 0.75. the duration curve is shown in *Figure 6.15*. The model under simulated water quality at low flows while it was well simulated at high flows.The RQO at this site is 100 mg/l, this concentration is only exceeded during high flows 5% of the time.

Table 6-6: Flow signatures used for calibrating CR12.

Parameters	**Surface Flow**	**Interflow**	**Groundwater**
Flow signatures (mg/l)	190	130	320
Co-Efficient of Efficiency	0.75		



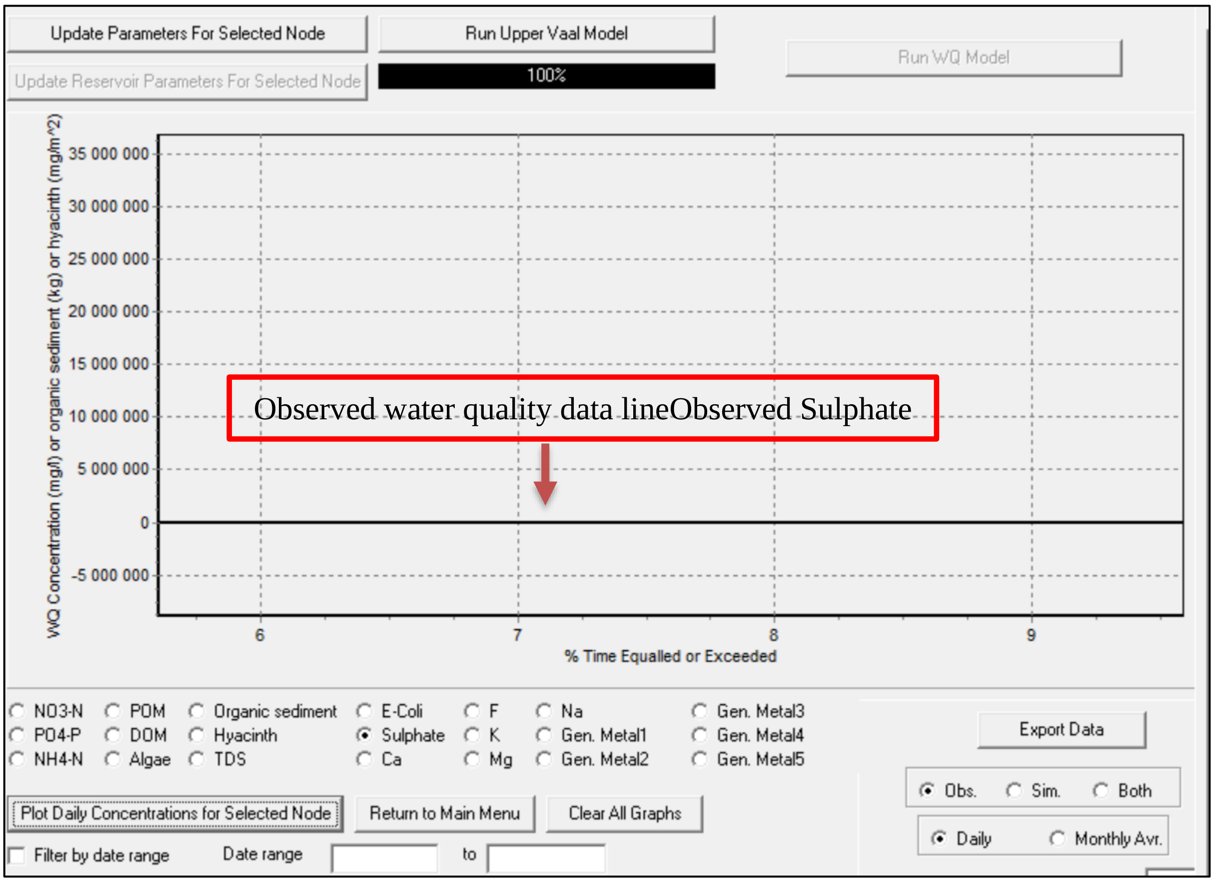
Coef. of Eff. 0.74740

Log Coef. of Eff. 0.07592

Figure 6.15: Sulphates calibration for CR12.

6.3.4 Model Calibration results for Channel Route 15 (CR_15)

Channel Route 15 is is the last channel route in the A24, the Crocodile River flows out of the sub-catchment at this route. This route could not be calibrated due to data availability limitations for sulphates at Station No. 188062. The attempts to filter by date range for each year (1920-2010) also yielded the same results. Figure 6.16 shows the observed water quality data line and Figure ()Figure 6.17 shows the data statistics.



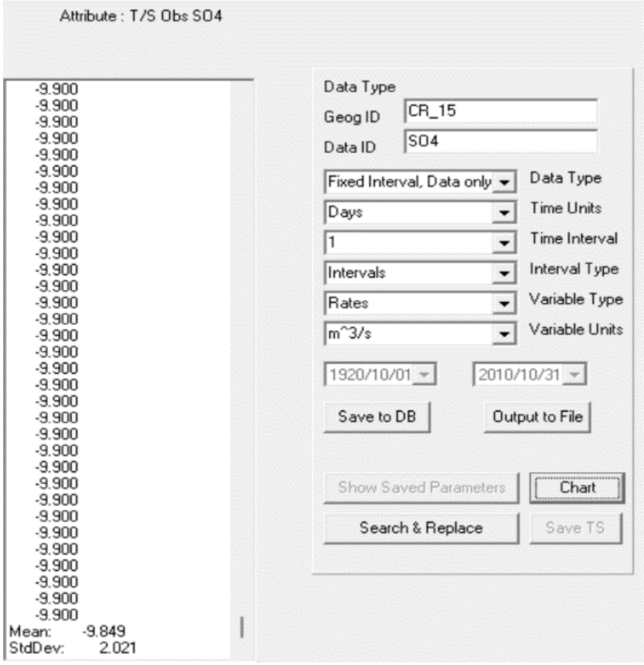
● Sulphate

● Obs.

● Daily

☐ Filter by date range

Figure 6.16: Sulphates calibration for CR15.


Attribute : T/S Obs SO4

```
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
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-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
-9.900
Mean:     -9.849
StdDev:    2.021
```

Data Type

Geog ID: CR_15

Data ID: SO4

Data Type: Fixed Interval, Data only

Time Units: Days

Time Interval: 1

Interval Type: Intervals

Variable Type: Rates

Variable Units: m^3/s

1920/10/01 – 2010/10/31

Figure 6.17: snapshot of observed sulphates data for CR15

6.3.5 Simulation of Sediments, Ammonia and Nutrients

The simulation of sediments (TDS), Ammonia (NH_4) and nutrients (orthophosphates and nitrates+nitrite) was not perfomed due to data availability limitations. The observed data for these constituents demonstrated straight lines for the entire record of data (1920-2010). This made it difficult to calibrate the model for sediments and nutrients in the Lower Crocodile subcatchment. The duration curves for these constituents are shown in Figure 6.18 to Figure 6.20 below.

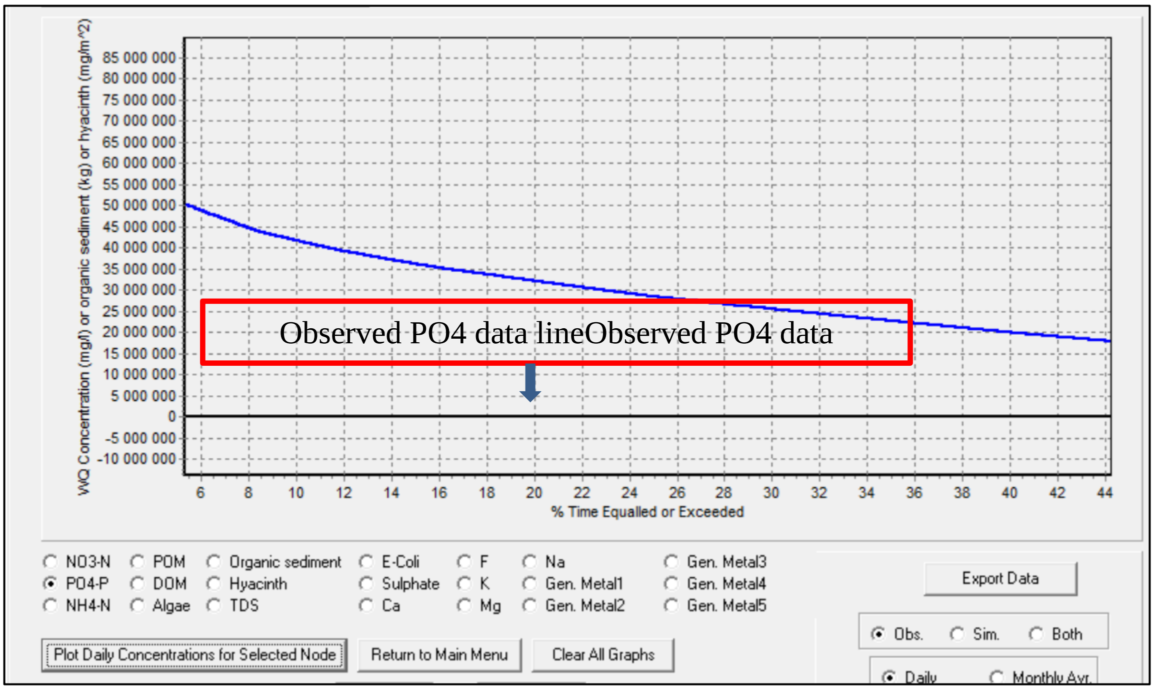
Observed PO4 data lineObserved PO4 data

Figure 6.18: Orthophosphates duration curve showing constant line for observed data.

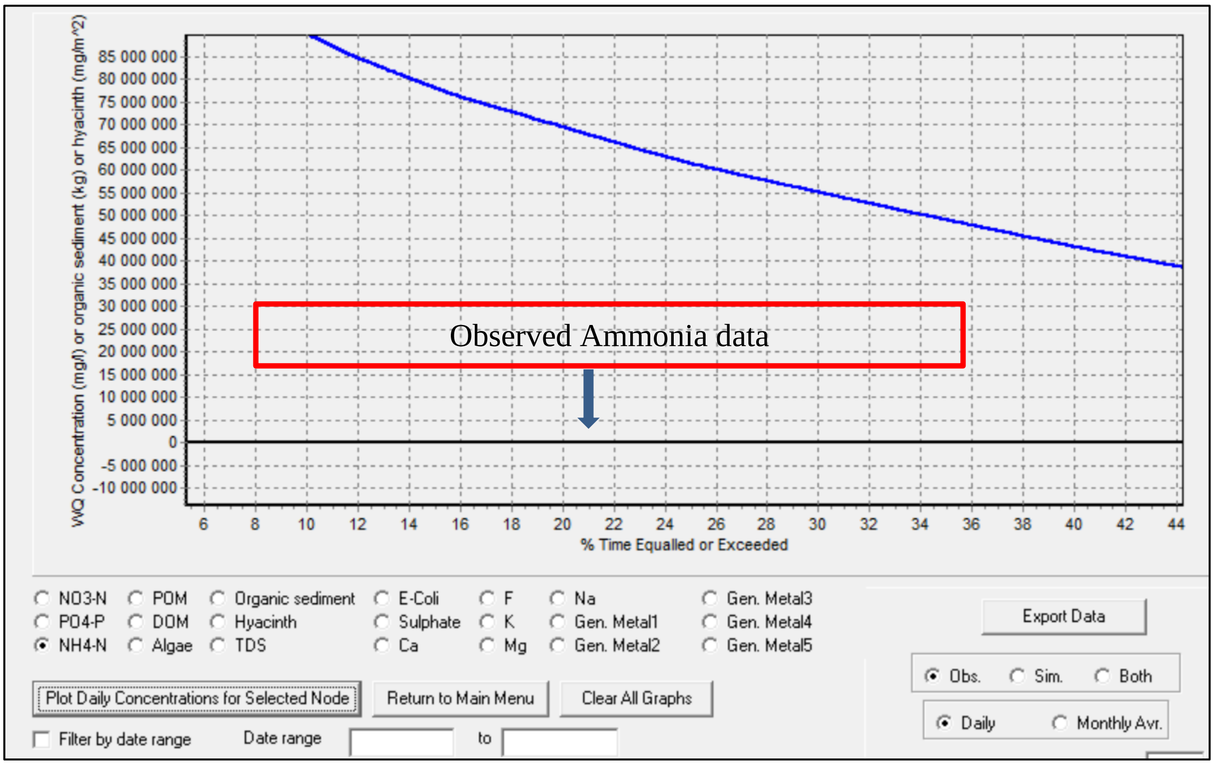
Observed Ammonia data

Figure 6.19: Ammonia duration curve showing constant line for observed data.

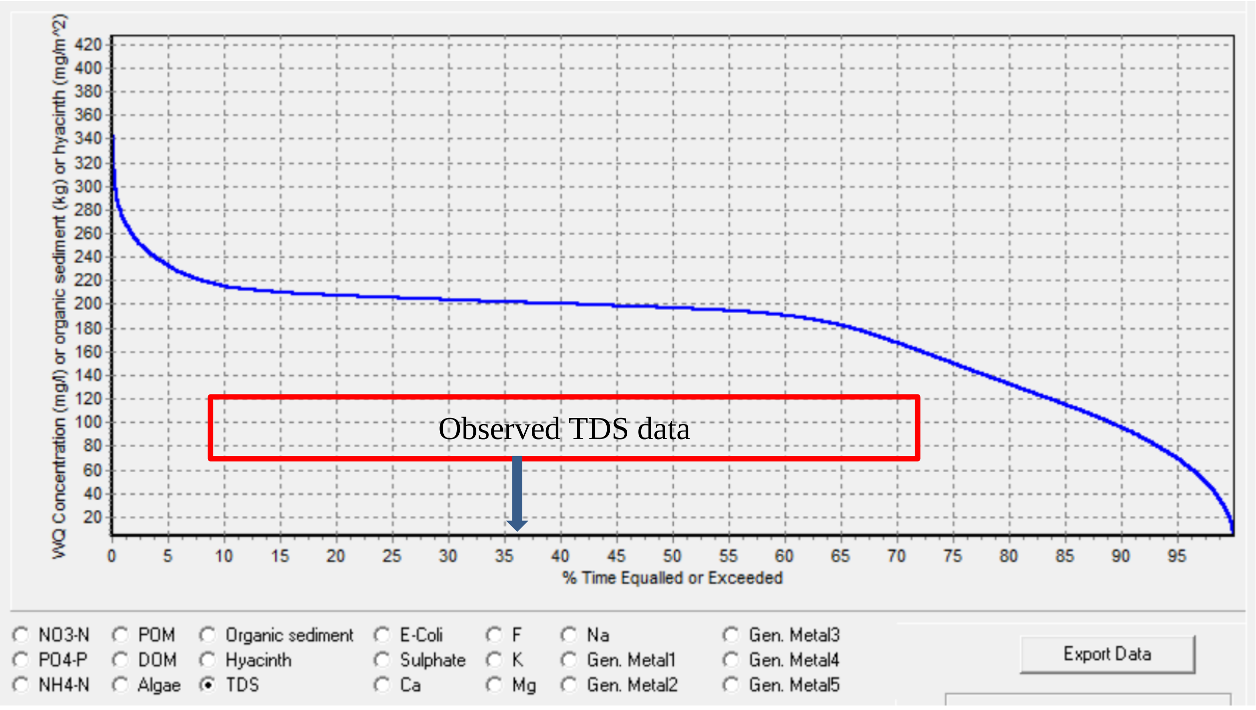

Figure 6.20:TDS duration curve showing constant line for observed data.

6.4 Discussions and Conclusions

Sulphates have demonstrated a uniform seasonal trend throughout the channels, where the concentrations peak during low flow months (highest peak in July), and decrease during the summer months. The increase in concentration during low flow months can be attributed to reduced dilution capacity of the river, and not necessarily increased pollution inputs. Moreover, CR3 and CR12 have shown compliance to the RQO of 100mg/l, the recommended concentration is only exceeded 5% of the time during high flows, which indicates that most pollutants are transported into the channel through run-off. CR1 exceeds the RQO 25% of the time, which could be due to the possibly polluted water that flows in from the from Apies and Elands into this channel. The sulphates simulations obtained in this study can be used for predicting and managing impacts such land-use impacts on water quality in the catchment.

The modelling in data scarce basin has always been a difficult process especially in cases where data inputs, such as water quality cannot be patched. This was demonstrated in the current study where water quality was unavailable, the calibration and modelling became impossible.

7 References

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