water & sanitation

Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA

PROJECT NUMBER: WK21047

INVESTIGATION OF GROUNDWATER AND SURFACE WATER INTERACTION FOR THE PROTECTION OF WATER RESOURCES IN THE LOWER VAAL CATCHMENT. SURFACE GROUNDWATER INTERACTION REPORT (WP11380)

DATE: September 2023

REPORT VERSION: V2.0

WP11380

DWS REPORT NUMBER: RDM/WMA05/00/GWSW/0423

INVESTIGATION OF GROUNDWATER AND SURFACE WATER INTERACTION FOR THE PROTECTION OF WATER RESOURCES IN THE LOWER VAAL CATCHMENT
WP13380

SURFACE-GROUNDWATER INTERACTION REPORT

SEPTEMBER 2023
FINAL

water & sanitation

Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA

Published by

Department of Water and Sanitation

Private Bag X313

PRETORIA, 0001

Republic of South Africa

Tel: +27 (12) 336 7500

Fax: +27 (12) 323 0321

This report should be cited as:

Department of Water and Sanitation (DWS), South Africa. 2022. Investigation of Groundwater and Surface Water Interaction for the Protection of Water Resources in the Lower Vaal Catchment: Surface-Groundwater Interaction Report. Prepared by WSM Leshika Consulting (Pty) Ltd. Report No. RDM/WMA05/00/GWSW/0423

Compiled by:

WSM Leshika Consulting

Postnet Suite No.8

Private Bag X9676

Polokwane 0700

DOCUMENT INDEX

Report name	**Report number**
Inception Report	RDM/WMA05/00/GWSW/0122
Literature Review and Data Gathering Report	RDM/WMA05/00/GWSW/0222
Gap Analysis Report	RDM/WMA05/00/GWSW/0322
Hydrocensus Report	RDM/WMA05/00/GWSW/0422
Water Resources Assessment Report	RDM/WMA05/00/GWSW/0522
Quantified Recharge and Baseflow Report	RDM/WMA05/00/GWSW/0123
Groundwater Quality Categorization Report	RDM/WMA05/00/GWSW/0223
Protection Zones Report	RDM/WMA05/00/GWSW/0323
Surface-Groundwater Interaction Report	**RDM/WMA05/00/GWSW/0423**
External Reviewer Report	RDM/WMA05/00/GWSW/0523
Capacity Building and Training Report	RDM/WMA05/00/GWSW/0623
Main Report on Surface-Subsurface Interactions	RDM/WMA05/00/GWSW/0723
Close-out Report	RDM/WMA05/00/GWSW/0823

Bold indicates this report

APPROVAL

TITLE:	Surface-Groundwater Interaction Report
DATE:	September 2023
AUTHORS:	Project Team
EDITOR:	Fourie I.
REVIEWERS:	Sami. K; Project Management Team
LEAD CONSULTANT:	WSM Leshika Consulting
REPORT NO:	RDM/WMA05/00/GWSW/0123
FORMAT:	MSWord and PDF
WEB ADDRESS:	http://www.dws.gov.za

Approved for WSM Leshika Consulting by:

____

Mr. K. Sami

Study Leader

Approved for the Department of Water and Sanitation by:

____

Ms L. Molokomme

Project Manager

Mr K. Majola

Scientific Manager: Groundwater Reserve Determination

____

Mr Y. Atwaru

Director: Reserve Determination

ACKNOWLEDGEMENTS

The following persons contributed to this project.

Project Management Committee

Atwaru, Yakeen	DWS
Baloyi, Lucky.	DWS
Biyela, Mfundi.	DWS
Boniwe, Nobubele.	DWS
Fourie, Fanus.	DWS
Khoza, Philani.	DWS
Mahlahlane, Kgotso.	DWS
Majola, Kwazikwakhe	DWS
Mazibuko, Molefe Jacob.	DWS
Mokgatle, Tumelo.	DWS
Mokoena, Portia.	DWS
Molokomme, Lerato.	DWS – Project Manager
Mulangaphuma, Lawrence.	DWS
Ngilande, Terrence.	DWS
Okonkwo, Adaora.	DWS
Thebe, Olebogeng.	DWS
Sami, Karim.	WSM Leshika (Pty) Ltd – Study Leader
Mare, Manie	WRP Consulting Engineers (Pty) Ltd
Leshika, Danny	WSM Leshika (Pty) Ltd

AUTHORS

The following persons contributed to this report:

Author	Company
Sami, K	WSM Leshika (Pty) Ltd
Mare, M	WRP Consulting Engineers (Pty) Ltd

REPORT SCHEDULE

Version	Date
First draft	July 2023
Second draft	
Final V1	September 2023
Revised Final V2	September 2023

TABLE OF CONTENTS

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Study Context

The purpose of the NWA (1998) is to ensure that the nation's water resources are protected, used, developed, conserved, managed and controlled in ways which take into account amongst other factors: promoting equitable access to water; redressing the results of past racial and gender discrimination; promoting the efficient, sustainable and beneficial use of water in the public interest; facilitating social and economic development; protecting aquatic and associated ecosystems and their biological diversity and; meeting international obligations (NWA, 1998). Chapter 3 introduces a series of measures which together are intended to protect all water resources.

The Chief Directorate: Water Ecosystems Management (CD: WEM) is tasked with the responsibility to coordinate all Reserve determination studies which have priority over other uses in terms of the NWA.

This study intends to determine and quantify groundwater and surface water interactions and identify protection zoning to prevent the disturbance of the ecological integrity of ecosystems where such interactions occur. A feasibility study undertaken by the Department of Water and Sanitation (DWS) in 2007 and the National Water Resource Strategy II identified the need for surface-subsurface interaction studies in the lower Vaal. The purpose of such studies would be understanding subsurface processes when determining the Reserve.

1.2 Aims and Objectives of the Project

The need to undertake significant groundwater-surface water interaction studies became apparent to the DWS due to the need to understand the groundwater balance when determining the Reserve. Groundwater not only provides for dispersed water supply needs, but also make significant contributions to the ecological reserve, as well as to Basic Human Needs for future water supply. The main objectives of the study are:

- Review existing water resource information;
- Conduct a hydrocensus on an institutional level;
- Conduct a water resource assessment of surface water, groundwater, baseflow, abstraction, surface and groundwater balance, present status category;
- Quantify aquifer parameters and describe aquifer types;
- Determine groundwater-surface water interactions both in terms of quality and quantity to determine protection zones;
- Capacity building and skills transfer to DWS staff.

The project timeframe is 24 months, starting from November 2021-November 2023.

1.3 Purpose of Report

This report is submitted to Department of Water and Sanitation (DWS) by WSM Leshika Consulting to categorise surface-groundwater interactions in terms of simulated channel losses, recharge and baseflow from revisions to the WRSM Pitman network and subsequent calibration

Chapter 2 describes the study area. **Chapter 3** describes the WRSM modelling procedure by which interactions were quantified, **Chapter 4** quantifies the surface-groundwater interactions under natural and present-day conditions, and **Chapter 5** presents the conclusions.

1.4 Surface-Groundwater Interactions

Surface-Groundwater interaction takes place via exfiltration from or infiltrating into the saturated zone (or a combination of both), as well as by lateral subsurface movement through the unsaturated zone. The chemical and physical seepage fluxes generated by these interactions play a significant role in the hydrologic cycle. Regional hydrogeological environments such as climate, geology, and surface topography impact of these interactions. Climatic factors primarily influence the rates of hydrological processes, which in turn affect the groundwater level and surface water stage. Topography influences the groundwater flow systems. The geology exerts significant control over the extent of hydraulic conductivity and connectivity within the rocks and between water resources. The nature of these interactions can be modified by groundwater abstraction, treated and untreated wastewater discharge, land-use modifications, dams, and water transfer schemes, which change the water level of both rivers and aquifers.

Effluent conditions associated with the subsurface water discharging into surface water (gaining stream, baseflow); and influent conditions associated with the subsurface receiving recharge from surface water (losing stream, channel losses). Over-pumping of groundwater results in decreased subsurface discharge to surface water bodies. At high pumping rates, the decreased groundwater level induces influent conditions on the surface water body, known as induced recharge.

Channel losses occur in hard rock areas where river channels often follow lines of structural weakness and surface fracturing, and alluvial environments, where unconsolidated alluvial material underlies the river channel. Transmission losses in alluvial environments can be substantial during both low flows and during the early phases of flood events.

Interactions with the regional aquifer can be classified into 4 broad types (**Figure 1-1).**

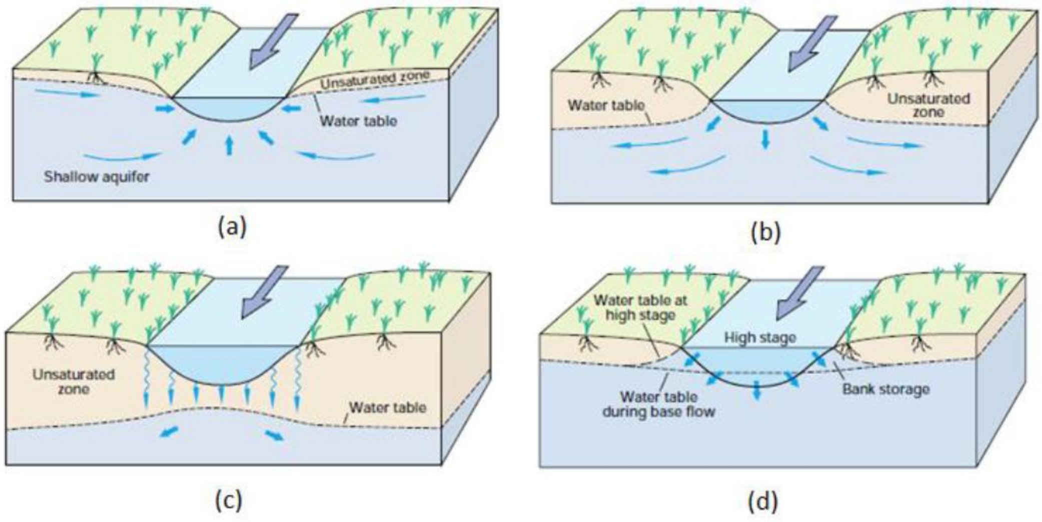


Figure 1-1 Types of interaction

(a) Effluent channels that gain water - affected by abstraction

(b) Influent channels that lose water - affected by abstraction

(c) Disconnected channels that lose water - not affected by abstraction

(d) Composite channels that gain water in the dry season and lose water in the wet season

1.4.1 Processes

The WRSM Pitman model simulates the following surface water and groundwater interactions:

<u>BASEFLOW</u>

- Interflow occurring from the unsaturated zone contributing to hydrograph recession following a large storm event, or discharge from perched water tables via temporary or perennial springs located above low permeability layers, which may cause prolonged baseflow following rain events, even when the regional water table is below the stream channel
- Groundwater baseflow discharged from the regional aquifer to surface water as baseflow to river channels, either to perennial effluent or intermittent streams.

<u>CHANNEL LOSSES</u>

- Channel losses of surface water generated within the runoff unit when river stage is above the groundwater table in phreatic aquifers with a water table in contact with the river.
- Groundwater baseflow reduction and induced recharge caused by pumping of aquifer systems in the vicinity of rivers causing a flow reversal.
- Channel losses of total runoff generated upstream in channel modules or in endoreic areas, or in wetland modules

The distinction between the two baseflow components distinguishes that not all subsurface water pathways incur passage through the regional aquifer. Subsurface water which does not flow through the regional aquifer is not available to boreholes in terms of conventional groundwater resource assessment; hence a distinction needs to be made between groundwater baseflow originating from the regional aquifer and baseflow originating from other, more rapid, subsurface pathways (interflow). Baseflow can therefore be considered to consist of the portion of subsurface water which contributes to the low flow of streams. This can originate from either:

i) The regional groundwater body (groundwater baseflow), that portion of the total water resource that can either be abstracted as ground water, be lost as evapotranspiration in shallow groundwater areas, or emerge as baseflow to surface water, or;

ii) Saturated soils, perched aquifers, high lying springs, excess recharge that is not accepted by the aquifer, processes that can be lumped as interflow.

1.4.2 Simulation of processes

Simulating baseflow for the correct reason is significant not only for simulating the hydrograph shape, but for simulating the impacts of abstraction. In catchments with significant relief and geological heterogeneities, a large part of the baseflow fraction originates as interflow and never passes through the regional aquifer, and hence does not form part of the groundwater resources as considered in the concept of the groundwater Harvest Potential. These catchments may have a very high recharge, but very limited groundwater resource potential. Such catchments must be simulated as being primarily interflow driven. In such catchments, baseflow to maintain instream flows is not attributed to discharge from the regional aquifers, since a large fraction originates as interflow. Groundwater abstraction may not impact at all on interflow from high lying springs, seeps, and perched water tables, hence would have no impact on the Ecological Reserve, or on the interflow component of baseflow in the river. Only the portion of recharge re-emerging as groundwater baseflow can be impacted by abstraction. High lying perched springs would remain unaffected unless land use or vegetation changes result in a reduction of interflow.

Many publications note that baseflow during hydrograph recession is not linearly related to hydraulic conductance, and during periods of high recharge, leakage calculated by models using linear means is much greater than occurs in practice. This can be attributed to ignoring increased hydraulic resistance to flow as discharge increases. This suggests linear methods, as used in numerical groundwater flow models, do not provide a suitable avenue for modelling interactions in systems where large flow fluctuations occur, as in South African rivers. A more realistic approach to simulating interactions could be adopted by using non-linear equations whereby rapid increases in baseflow occur for small head changes when the head difference is small, but baseflow approaches some maximum value as the head difference becomes larger. This is the approach adopted in the WRSM Pitman model, where baseflow is calculated using the difference between groundwater storage and streamflow in a non-linear manner.

1.4.3 Impact of groundwater abstraction

Simulation of interactions is relevant under conditions where groundwater abstraction takes place. The decline of water levels around pumping boreholes near surface water bodies creates gradients that capture some of the ambient groundwater that would have discharged as groundwater baseflow. At sufficiently high pumping rates these declines also induce flow out of the surface water body, a process known as induced recharge. Both these processes lead to streamflow depletion, which can significantly impact the ecology and yield of dams. The effect of distance from the river is that the abstraction of groundwater takes more time for the impact on baseflow to be noticed, if at all if that portion of the aquifer does not drain as baseflow.

Under natural conditions, dynamic steady-state conditions exist whereby in wet years recharge exceeds discharge and in dry years the reverse take place. This results in a cycle of rising and falling aquifer water levels. Pumping upsets this principle and new equilibrium conditions are eventually reached by increasing recharge (through induced recharge) or decreasing discharge (baseflow depletion, reduced groundwater outflow from the catchment, or reduced evapotranspiration losses from groundwater due to a lowering of water levels). Once new equilibrium conditions are reached whereby pumping is balanced by baseflow depletion, a water licence to abstract groundwater is equivalent to a right to divert streamflow. In general, the further away the abstraction point is from the river, the longer the time to achieve equilibrium conditions. However, until equilibrium is reached these two volumes are not the same and the difference results in aquifer storage depletion. Therefore, groundwater abstraction MUST consider both aquifer storage depletion and baseflow depletion and abstractions must be allocated in terms of the portion that originates as aquifer storage and that which comes from streamflow depletion.

The length of time required for equilibrium to be reached between the surface water and groundwater flow depends on three factors: aquifer diffusivity, which is expressed as the ratio of aquifer storativity and transmissivity, the distance from the well to stream and the time of pumping. These are the three critical physical parameters affecting the impact of pumping on baseflows. In general, a tenfold increase in distance from a surface water course will result in a hundred-fold increase in response time. Recharge is unimportant in terms of the magnitude of the impact on baseflow; however, it limits the pumping rate since the portion originating from the aquifer cannot exceed recharge.

1.4.4 Channel losses

Both surface runoff and baseflow can be lost downstream of runoff unit in which they are generated. Such a process occurs in catchments where runoff is generated in wet upstream areas and lost further downstream, as occurs in the Kuruman and Molopo rivers.

1.4.5 Differences in simulation of interactions with original Pitman model

The original Pitman model did not have the surface-groundwater interaction routines described above, nor did it simulate recharge. Hence in dry areas a 'nett area' was used instead of the gross catchment area to simulate runoff. The nett area ignored endoreic areas and generated runoff only from the nett area contributing flow to the main river stem, thus avoiding excessive runoff. Such an approach cannot work with groundwater included, as endoreic areas contribute to groundwater recharge and may contribute to baseflow, even if they don't generate runoff to the main river stem. To incorporate groundwater, the gross area is used for all runoff units to provide a groundwater balance. Runoff to endoreic areas can be lost as channel losses or with a wetland module. Baseflow which does not reach the main channel can be lost as treating endoreic areas as groundwater evaporation areas since they are generally shallow groundwater areas. In this way both surface and groundwater balances are preserved and calibrations against surface water gauges is possible.

2 STUDY AREA

2.1 Catchments

The study area has been described in the Water Resources Assessment Report and is only summarized here.

The Lower Vaal catchment (former WMA 10) lies in the north-eastern part of the Northern Cape Province, the western part of Northwest Province, and a part of the northern Free State Province (**Figure 2-1**). It contains the Molopo, Harts, and Vaal (below Bloemhof dam) catchments. The basins are located in a semi-arid to arid region of South Africa. Most of the surface water resources originate upstream of Bloemhof dam. Groundwater is an important water resource, especially in areas located away from surface water bodies. Groundwater use depletes the already meagre surface water resources by inducing losses from river channels or depleting flow from dolomitic eyes and as baseflow. The water in the Lower Vaal region drains to the Lower Orange drainage region before reaching the Atlantic Ocean near the town of Alexander Bay in the western corner of the country.

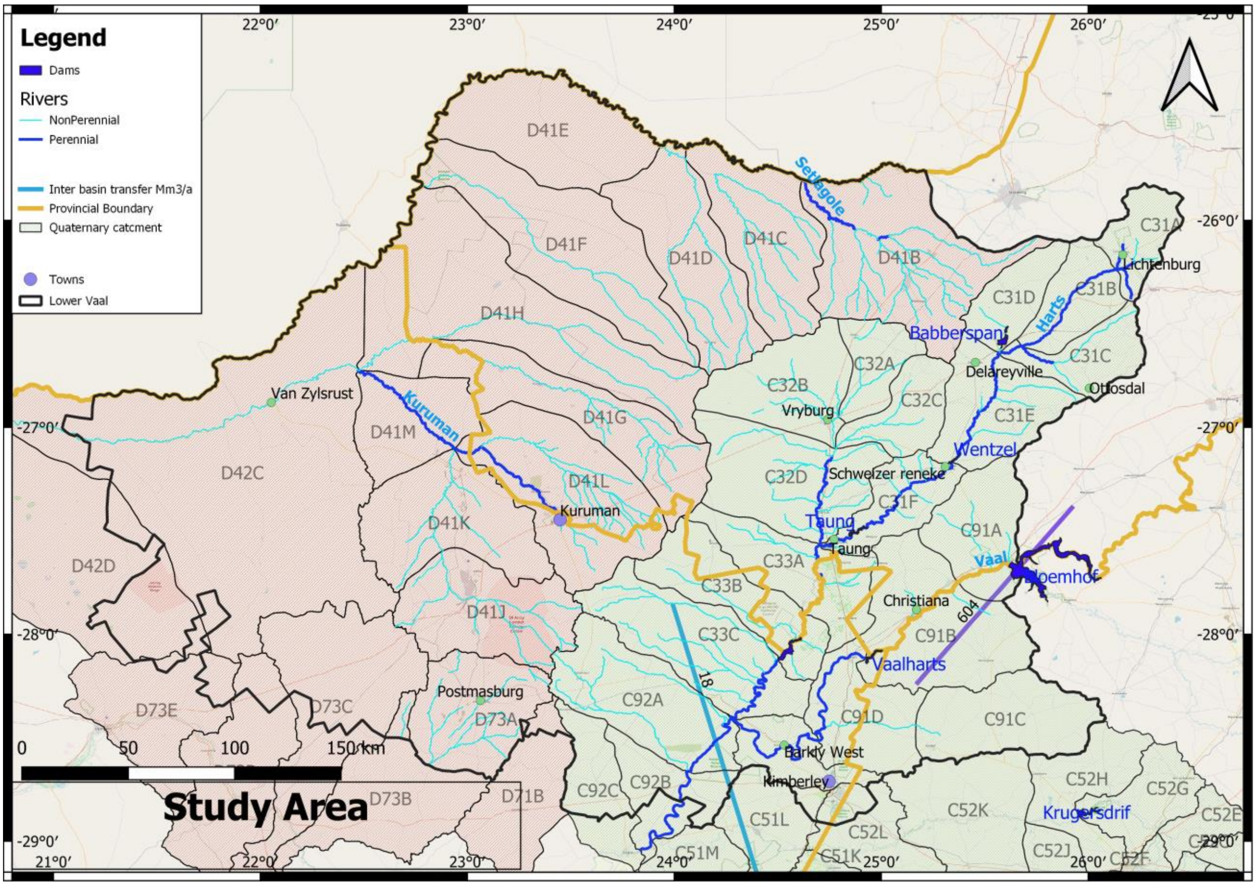


Figure 2-1 Lower Vaal drainage Region

Included in these basins are the Lower Vaal (C9) River, the incremental catchment downstream of Bloemhof Dam and upstream of Douglas weir, the Harts (C3), and Kuruman/Molopo catchments (D4). These catchments include Tertiary catchments C31-C33, C91-92, D41, and Quaternary catchments D73A, D42C-D, D73B-E. These catchments also contain dolomite aquifers, where interaction with surface water can be significant.

The Lower Vaal is located between the Middle Vaal drainage region and the Lower Orange drainage region, with the Upper Orange basin to the southeast, and Botswana to the north. The Lower Vaal has an area of approximately 136 146 km^2. It excludes the Riet-Modder River catchment) (C5), the Molopo River system above its confluence with the Nossob (parts of D42) and portions of the Vaal River catchment below the confluence with the Harts and Douglas weir (parts of C92B and C, and D71B). It is important to note that although the Riet-Modder Catchment forms part of the Vaal River Basin, it is included as part of the Upper Orange River sub-system, mainly because there are several transfers from the Orange River to support water requirements in the Riet-Modder catchment. The only connection between the Vaal and Riet-Modder rivers is the spills from the Riet-Modder catchment into the Vaal River just upstream of Douglas Weir.

The main rivers of the Lower Vaal catchment, the Vaal and Harts, are perennial and most of their tributaries are ephemeral. The main source of surface water is the Vaal River, which flows into the study area below Bloemhof Dam, before its confluence with the Orange River. The main dams are Wentzel, Taung, Spitskop, Vaalharts Weir, Douglas weir and Bloemhof. The largest pan is Babberspan, located in the Harts sub-catchment.

The Kuruman and Molopo Rivers, which drain the Kalahari and northern Lower Orange regions, do not make a meaningful contribution to the surface water resources of the Orange River, and only interact with groundwater via evapotranspiration and losses of flow generated by upstream springs into dry river channels. These dolomitic springs form distinct groundwater ecosystems and are themselves a form of surface-groundwater interaction.

The MAP ranges from 150 to over 600 mm/a, with the highest rainfall in the northeast, declining to the west.

S-pan evaporation increases from 1800 mm/a in the east to 2690 mm/a in the west. Net evaporation losses from open water surfaces can also be significant.

The Lower Vaal catchment area is underlain by diverse lithologies. Several broad lithostratigraphic units fall within the boundaries. A large portion of the central and north-east corner of Lower Vaal is underlain by the Transvaal Supergroup, with much of it consisting of dolomite, chert, and subordinate limestone. The dolomitic area is characterised by a high potential for groundwater development, with relatively high recharge, storage and borehole yields.

2.2 Dolomitic Areas

Dolomitic compartments are a key aspect of surface-groundwater interaction. They have high recharge and little surface runoff, hence are the prime source of baseflow. The large volumes of baseflow generated from dolomitic eyes is typically lost as channel losses downstream **Figure 2-2.**

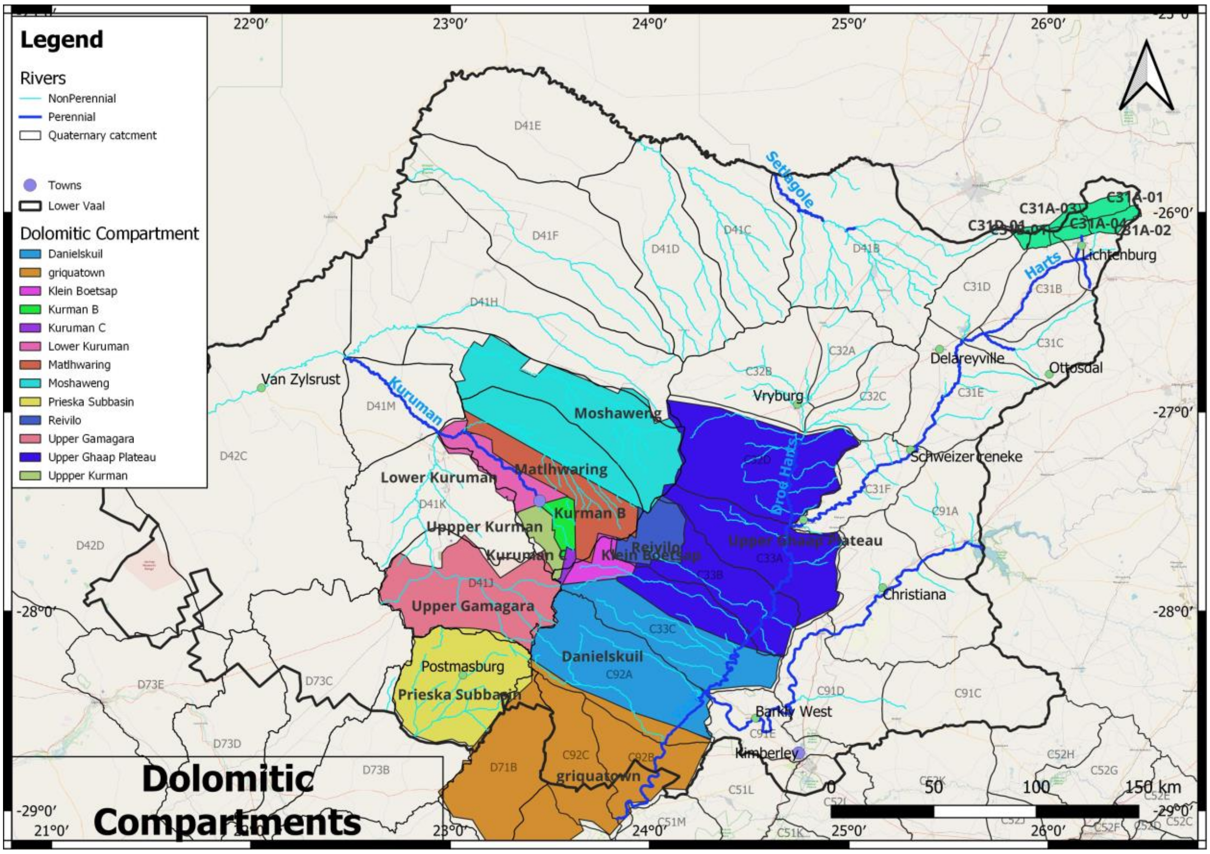


Figure 2-2 Dolomitic Compartments

3 WRSM PITMAN MODELLING

3.1 Summary of Modelling

The simulation of the surface and groundwater-related flows was undertaken through several steps as described in the Recharge and Baseflow Report (DWS, 2023). The WRSM2012 Pitman model setups were used as the basis for the rainfall-runoff simulations. These were modified to include Gross Area and so that each dolomitic compartment in a catchment was treated as a separate runoff unit. Compartment boundaries were selected instead of topographic catchment boundaries.

Networks were based on the main drainage regions. In the Molopo and Kuruman basin (**Figure 3-1)** these were:

- SB network is drainage to the Molopo
- B network is drainage from Botswana into the Molopo
- S network is drainage to the Kuruman

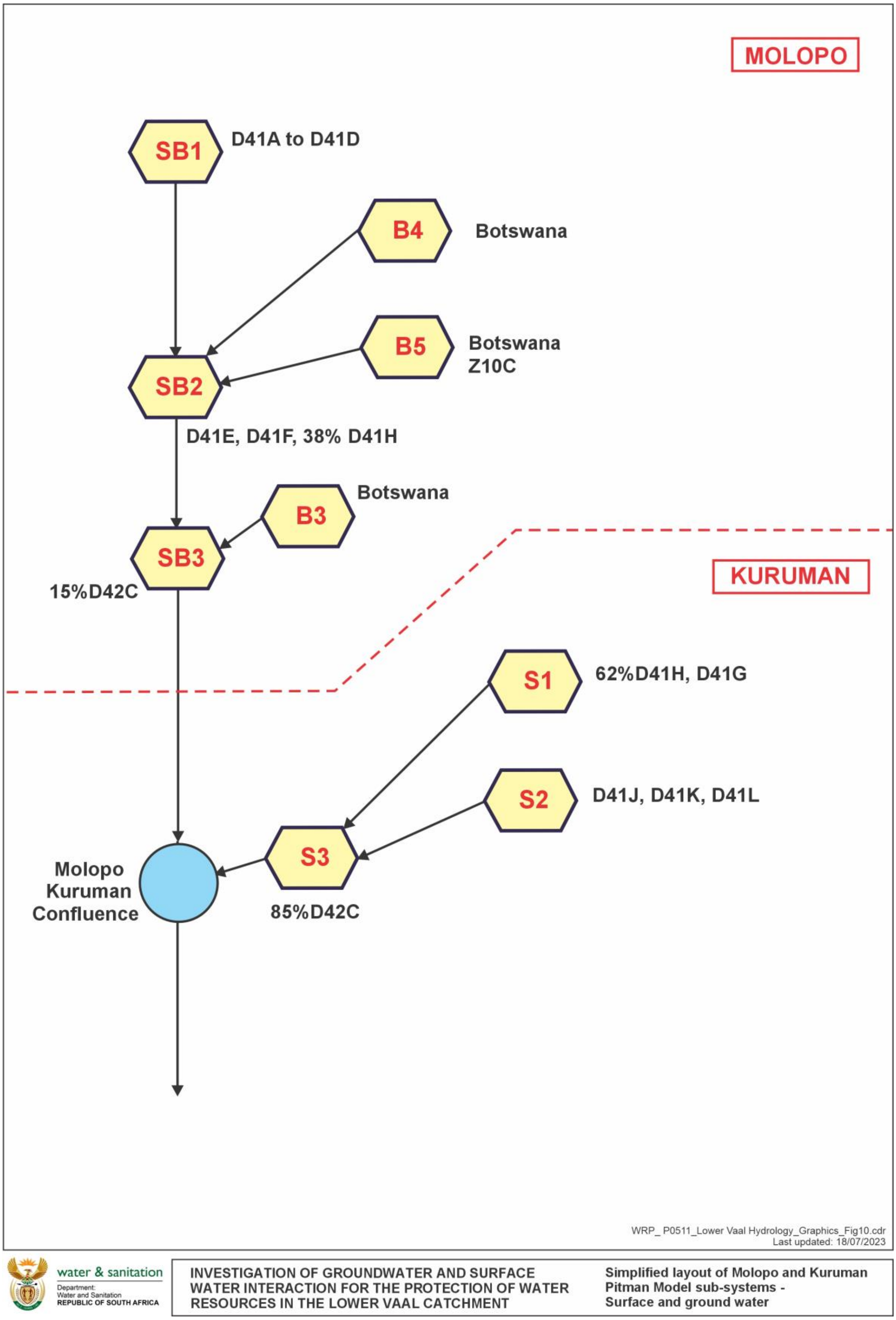


Figure 3-1 Networks in the Kuruman/Molopo system

In the Vaal and Harts systems the following networks were identified **(Figure 3-2)**:

- C31-C33 for the Harts tertiary catchments
- C91 and C92 for drainage directly into the Vaal
- D71 and D73 for drainage into the Lower Orange. Only a small part of these networks is in the Lower Vaal WMA

Each network consists of Quaternary and sub-Quaternary runoff units, split according to the presence of various dolomitic compartments in the catchment, hence each compartment or portion of a compartment in a Quaternary catchment is a separate runoff unit. In addition, channel modules, irrigation modules, reservoir modules, direct abstraction routes, return flows and, transfers from other networks are included. An example for the Vaal networks is shown in **Figure 3-3.** All the network diagrams are in **Appendix 1.**

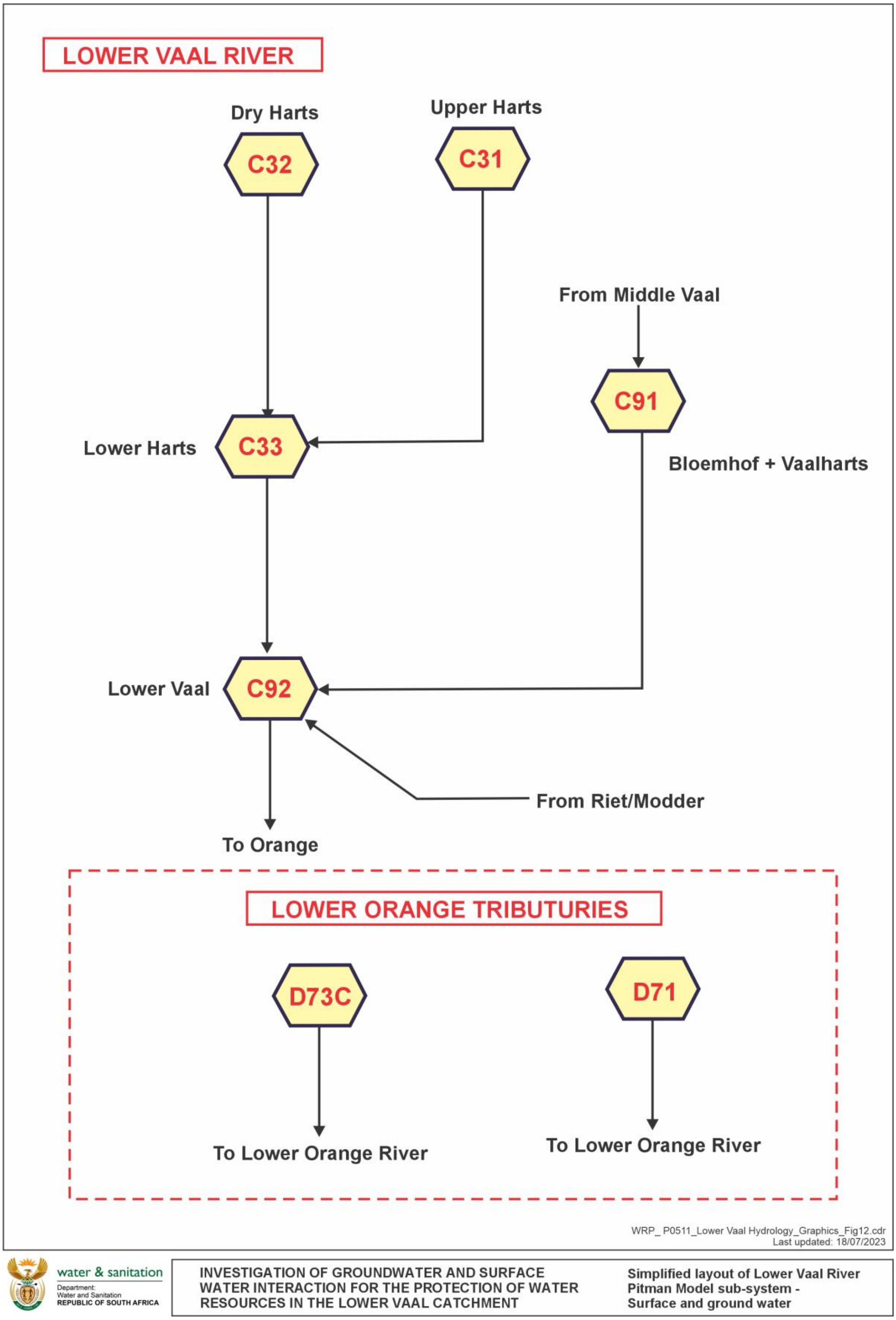


Figure 3-2 Networks in the Vaal

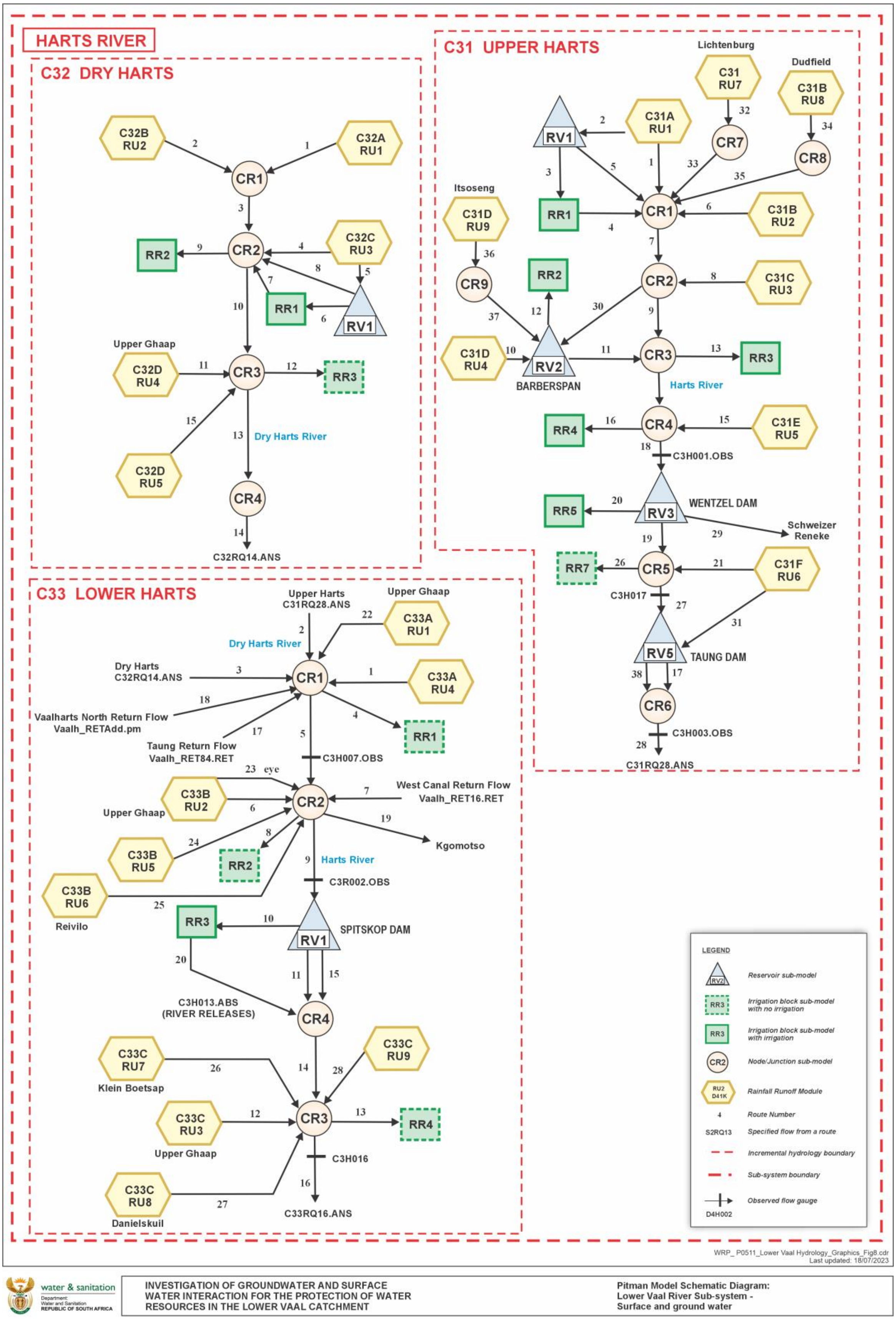


Figure 3-3 Network diagram for the Harts River networks

The following steps were undertaken in the modelling process:

i) Rainfall records were extended to 2021 to generate monthly flows covering the period 1920 to 2021.

ii) Quaternary catchment runoff units were split according to the area underlain by various dolomitic compartments to derive a water balance for each compartment

iii) The Pitman Model was first calibrated by focusing only on the surface water at key points in the system using the extended rainfall and observed runoff. This included checks to ensure that the flow generated from the extended rainfall records does mimic the observed flows well. Based on the available rainfall and observed flow records, the updated hydrology provides flows until the end of the 2021 hydrological year, thus September 2022.

iv) The groundwater component was calibrated to match recharge data and flow at dolomitic eyes and low flows at gauging weirs.

The resulting simulations and calibration graphs and statistics are documented in (DWS 2023).

3.2 Modifications to Model

After completion of the recharge and baseflow report (DWS, 2023), it was realised flow gauge C3H017 (Harts at Tlapeng), located between Wentzel and Taung dams was a poor record, resulting in parameter and surface-subsurface interaction discrepancies. Consequently, the Harts River system was recalibrated after some of the dubious recorded flows (**Figure 3-4**) removed.

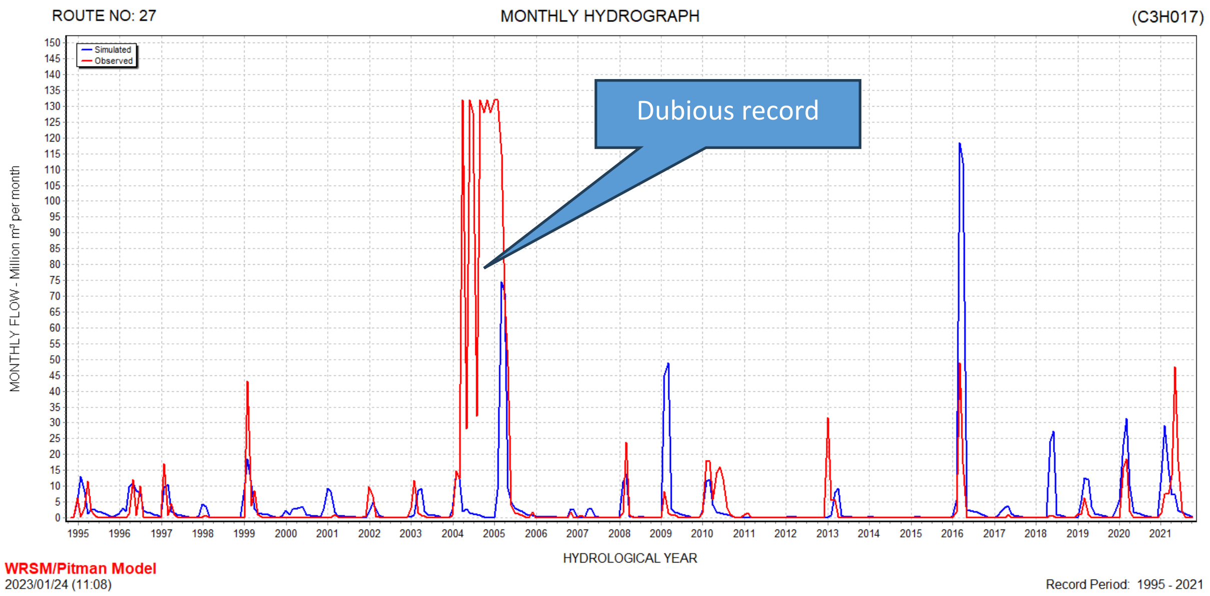


Figure 3-4 Observed versus simulated flows at C3H017.

3.3 WRSM Pitman Parameters

The final WRSM Pitman parameter sets for surface water are given in **Table 3-1,** and the groundwater parameters in **Table 3-2.**

Table 3-1 Surface water parameters for WRSM Pitman model

Quaternary	POW	SL	ST	FT	ZMIN	ZMAX	PI	TL	R
C31A	2	0	150	0	50	985	1.5	0.6	0
C31 Lichtenburg	1.3	0	500	0	999	999	1.5	0.6	0
C31B	2	0	150	0	50	985	1.5	0.6	0
C31B Dudfield	1.3	0	500	0	999	999	1.5	0.6	0
C31C	2	0	150	0	50	985	1.5	0.6	0
C31D	2	0	150	0	50	985	1.5	0.6	0
C31D Itsoseng	1.3	0	500	0	999	999	1.5	0.6	0
C31E	2	0	150	0	50	985	1.5	0.6	0
C31F	2	0	150	0	50	985	1.5	0.6	0
C32A	1.8	0	140	0	30	890	0	0.3	0
C32B	2	0	155	0	30	890	0	0.3	0
C32C	2	0	140	0	30	890	0	0.3	0
C32D Upper Ghaap	1.5	0	500	0	999	999	0	0.3	0
C32D	2	0	140	0	30	890	0	0.3	0
C33A Upper Ghaap	1.8	0	400	0	999	999	0	0.3	0
C33A	2	0	120	0	30	890	0	0.3	0
C33B Reivilo	1.8	0	400	0	999	999	0	0.3	0
C33B Upper Ghaap	1.8	0	400	0	999	999	0	0.3	0
C33B	2	0	120	0	30	890	0	0.3	0
C33C	2	0	120	0	30	890	0	0.3	0
C33C Klein Boetsap	1.8	0	400	0	999	999	0	0.3	0
C33C Upper Ghaap	1.8	0	400	0	999	999	0	0.3	0
C33C Danielskuil	1.8	0	400	0	999	999	0	0.3	0
C91A	2	0	200	0	50	900	1.5	0.25	0.5
C91B	2	0	200	0	50	900	1.5	0.25	0.5
C91C	2.3	0	250	0	50	900	1.5	0.25	0.5
C91D	2.3	0	250	0	50	900	1.5	0.25	0.5
C91E	2.3	0	250	0	50	900	1.5	0.25	0.5
C92A	2	0	140	0	20	900	1.5	0.3	0
C92A Danielskuil	1.5	0	400	0	999	999	1.5	0.3	0
C92B	2	0	140	0	20	900	1.5	0.3	0
C92B Griquatown	1.5	0	400	0	999	999	1.5	0.3	0
C92C	2	0	140	0	20	900	1.5	0.3	0
C92C Griquatown	1.5	0	400	0	999	999	1.5	0.3	0
D41B	2	0	300	0	75	900	1.5	0.25	0
D41C	2	0	300	0	75	900	1.5	0.25	0
D41D	2	0	300	0	75	900	1.5	0.25	0
D41E	2	0	300	0	75	900	1.5	0.25	0
D41F	2	0	300	0	75	900	1.5	0.25	0
D41G	2	0	300	0	75	900	1.5	0.25	0

D41G Moshaweng	2	0	500	0	999	999	1.5	0.25	0
D41Ha	2	0	300	0	75	900	1.5	0.25	0
D41Hb	2	0	300	0	75	900	1.5	0.25	0
D41J Upper Gamgara	1.4	0	500	0	999	999	1.5	0.25	0
D41J	2	0	300	0	75	900	1.5	0.25	0
D41K	2	0	300	0	75	900	1.5	0.25	0
D41L Matlhwaring	3	0	500	0	999	999	1.5	0.25	0
D41L D4H011	2	0	500	0	999	999	1.5	0.25	0
D41L Kuruman A	1.3	0	500	0	999	999	1.5	0.25	0
D41L Kuruman B	1.3	0	500	0	999	999	1.5	0.25	0
D41L Kuruman C	1.3	0	500	0	999	999	1.5	0.25	0
D41L Lower Kuruman	2	0	500	0	999	999	1.5	0.25	0
D41M	2	0	300	0	75	900	1.5	0.25	0
D42Ca	2	0	300	0	75	900	1.5	0.25	0
D73A -Prieska	2.5	0	500	0	999	999	1.5	0.25	0
D73C	2	0	300	0	75	900	1.5	0.25	0

Table 3-2 Groundwater Parameters utilised in WRSM Pitman

Quaternary	GPOW	HGSL	ST	FT	HGGW	ZMIN	Aquifer thickness (mm)	S	SWL (mm)	Max. Discharge rate (mm)	Groundwater Evaporation area (km^2)	Months to average recharge	Unsaturated Storage capacity (mm)
C31A	2	0	140	0	7	50	36	0.0026	75	0.5	195	5	16
C31 Lichtenburg	1.25	0	500	0	12	999	45	0.0256	950	2	150	30	242
C31B	2	0	140	0	7	50	36	0.0026	75	0.5	407	5	16
C31B Dudfield	1.25	0	500	0	12	999	45	0.0256	950	2	20	12	200
C31C	2	0	140	0	7	50	14	0.0023	21	0.5	490	4	14
C31D	2	0	140	0	7	50	32	0.0025	61	0.5	234	5	16
C31D Itsoseng	1.25	0	500	0	12	999	45	0.0256	950	2	20	30	200
C31E	2	0	140	0	7	50	15	0.0022	21	0.5	582	6	14
C31F	2	0	140	0	7	50	11	0.0014	13	0.5	536	7	13
C32A	2	0	155	0	7	30	35	0.0014	29	0.5	210	7	13
C32B	1.75	0	155	0	9	30	76	0.0013	72	0.5	450	7	15
C32C	2	0	155	0	7	30	15	0.0017	16	0.5	270	7	14
C 32D Upper Ghaap	1.5	0	500	0	12	999	59	0.0117	394	2	800	33	93
C32D	2	0	155	0	7	30	59	0.0117	395	0.5	35	33	93
C33A Upper Ghaap	1.75	0	400	0	12	999	48	0.0122	327	1	290	36	81
C33A	2	0	120	0	7	30	11	0.0014	12	0.5	32	7	13
C33B Reivilo	1.75	0	400	0	12	999	65	0.0128	460	2	250	25	66
C33B Upper Ghaap	1.75	0	400	0	12	999	64	0.0128	460	2	225	26	67
C33B	2	0	120	0	7	30	20	0.005	60	0.5	250	6	20
C33C	2	0	120	0	7	30	11	0.0014	12	05	350	6	20
C33C Klein Boetsap	1.75	0	400	0	12	999	65	0.0122	451	2	100	40	82

C33C Upper Ghaap	1.75	0	400	0	12	999	65	0.0122	451	2	200	41	82
C33C Danielskuil	1.75	0	400	0	12	999	65	0.0122	451	2	480	45	82
C91A	2	0	200	0	7	50	14	0.0019	19	0.5	174	7	14
C91B	2	0	200	0	7	50	12	0.0046	34	0.5	328	20	40
C91C	2.25	0	250	0	6	50	16	0.0054	52	0.2	940	28	39
C91D	2.25	0	250	0	6	50	13	0.0048	38	0.2	440	28	40
C91E	2.25	0	250	0	6	50	18	0.0017	21	0.2	320	11	14
C92A	2	0	140	0	7	20	18	0.0017	21	0.2	150	11	14
C92A Danielskuil	1.5	0	400	0	12	999	67	0.0119	453	2	580	53	91
C92B	2	0	140	0	7	20	18	0.0017	21	0.2	450	11	14
C92B Griquatown	1.5	0	400	0	12	999	53	0.0112	342	2	140	81	103
C92C	2	0	140	0	7	20	18	0.0017	21	0.2	185	11	14
C92C Griquatown	1.5	0	400	0	12	999	70	0.0121	486	2	275	55	87
D41B	2	0	300	0	6	75	127	0.0016	121	0.1	200	16	26
D41C	2	0	300	0	6	75	120	0.0011	79	0.1	500	30	31
D41D	2	0	300	0	6	75	131	0.0014	107	0.1	550	22	28
D41E	2	0	300	0	6	75	141	0.0004	50	0.1	90	35	27
D41F	2	0	300	0	6	75	126	0.0007	60	0.1	300	36	30
D41G	2	0	300	0	6	75	134	0.0005	54	0.1	30	35	28
D41G Moshaweng	2	0	500	0	12	999	151	0.0014	151	2	2300	80	34
D41Ha	2	0	300	0	6	75	134	0.0005	54	0.1	170	39	28
D41Hb	2	0	300	0	6	75	134	0.0005	54	0.1	170	39	28
D41J Upper Gamgara	1.4	0	500	0	12	999	80	0.0016	73	0.1	600	22	25
D41J	2	0	300	0	6	75	80	0.0016	74	0.1	80	22	25
D41K	2	0	300	0	6	75	125	0.0014	110	0.1	250	28	31

D41L Matlhwaring	1.25	0	500	0	12	999	141	0.0017	165	2	280	120	28
D41L D4H011	2	0	500	0	12	999	141	0.0017	165	2	400	120	28
D41L Kuruman A	1.25	0	500	0	12	999	141	0.0017	165	5	0	24	28
D41L Kuruman B	1.25	0	500	0	12	999	141	0.0017	165	5	33	50	28
D41L Kuruman C	1.25	0	500	0	12	999	141	0.0017	165	4	1	24	28
D41L Lower Kuruman	2	0	500	0	12	999	141	0.0017	165	2	200	120	28
D41M	2	0	300	0	6	75	145	0.0009	94	0.1	85	45	34
D42Ca	2	0	300	0	6	75	202	0.0008	155	0.1	19	305	67
D73A	2.5	0	500	0	12	999	100	0.0016	57	1	900	50	24
D73C	2	0	300	0	6	75	138	0.0011	135	0.1	150	102	59

4 SURFACE-GROUNDWATER INTERACTIONS

To determine interactions under natural and present-day conditions, the simulations undertaken were:

- Calibration against observed flow records with a time series of varying surface and groundwater abstraction, varying irrigation area, the construction of reservoirs over time (DWS 2023)
- Naturalisation of the hydrology by removing all anthropogenic effects to quantify the surface and groundwater resources and interactions (DWS 2023)
- Present day hydrology by including present day anthropogenic effects from 1920-2021 to determine the impact of present-day water use on the runoff and interactions.

4.1 Natural Runoff, Recharge and Baseflow

The final naturalised runoff, baseflow, recharge and channel losses per runoff unit under natural conditions are shown in **Table 4-1**.

4.2 Present Day Runoff, Recharge and Baseflow

To determine impacts of land and water use on the hydrology, present day flows were calculated and compared to natural flows. This was done by extending present-day groundwater abstraction, irrigation areas, and reservoir volumes from 1920 to 2021. The final present-day runoff, baseflow, recharge and channel losses for each runoff unit are shown in **Table 4-2**. The MAR is shown as incremental MAR down channel because of the effect of abstractions and return flows between runoff units from channel modules.

Table 4-1 Simulated naturalised MAR, recharge and baseflow

Quaternary	Gross Area	Subarea area/ Nett area	MAP	MAR	GRAII Baseflow	Simulated Baseflow	Channel losses	GRAII Recharge	Simulated Recharge		Recharge (% of rainfall)
	Km^2	Km^2	mm/a	Mm^3/a	Mm^3/a	Mm^3/a	Mm^3/a	mm/a	mm/a	Mm^3/a	
C31A	1 402	649	577	5.39	0.95	0.02		24.89	9.55	6.20	1.66
C31A Lichtenburg		753	577	9.32		9.32		24.89	34.14	25.70	5.92
C31B	1 743	1 358	553	8.64	0.90	0.03		22.01	8.83	14.49	1.60
C31B Dudfield		102	553	1.19		1.19			32.23	3.27	5.83
C31C	1 635	1 635	566	11.85	0.95	0.17		21.59	8.83	14.44	1.56
C31D	1 494	780	530	3.83	0.56	0.01		21.91	8.12	11.36	1.53
C31D Itsoseng		96	530	1.02		1.02			30.43	2.91	5.74
C31E	2 960	1 941	506	11.93	0.79	0.07		17.13	7.18	21.25	1.42
C31F	1 789	1 789	477	7.05	0.35	0.32		12.59	6.10	10.91	1.28
C32A	1 405	681	449	7.00	0.53	0.00		12.35	6.09	8.56	1.36
C32B	3 002	1 587	434	13.64	1.26	0.05		13.62	6.09	18.28	1.40
C32C	1 658	916	460	10.26	0.87	0.02		13.74	6.36	10.54	1.38
C32D Upper Ghaap		2 943	442	22.75		22.75			18.16	53.44	4.11
C32D	4 140	1 197	442	10.52	1.84	0.20		17.10	5.92	7.09	1.34
C33A Upper Ghaap	2 859	1 317	432	4.34	1.36	4.34			14.38	18.94	3.33
C33A		1 542	432	21.12		1.85	12.30	14.01	6.28	9.68	1.45
C33B Reivilo	2 835	881	422	4.61		4.61			12.84	11.31	3.04
C33B Upper Ghaap		1 075	422	6.42		6.42			12.84	13.80	3.04
C33B		879	422	9.98	1.23	0.06	14.89	15.64	5.58	4.90	1.32
C33C	4 149	1 118	397	9.31		0.10	25.92		4.74	5.30	1.19
C33C Klein Boetsap		469	397	2.30		2.30			11.02	5.17	2.78
C33C Upper Ghaap		972	397	4.83	1.41	4.83		12.09	11.02	10.71	2.78

Quaternary	Gross Area	Subarea area/ Nett area	MAP	MAR	GRAII Baseflow	Simulated Baseflow	Channel losses	GRAII Recharge	Simulated Recharge		Recharge (% of rainfall)
	Km²	Km²	mm/a	Mm³/a	Mm³/a	Mm³/a	Mm³/a	mm/a	mm/a	Mm³/a	
C33C Danielskuil		1 590	397	6.36		6.36			11.02	17.52	2.78
C91A	2 546	2 546	464	4.04	0	0.03		12.73	12.12	30.86	2.61
C91B	4 679	4 679	433	5.73	0	0.06	45.00	12.56	11.25	52.64	2.60
C91C	3 135	3 135	430	11.09	0	0.05		8.61	7.52	23.58	1.75
C91D	2 697	2 697	397	3.79	0	0.00	2.40	8.94	6.90	18.61	1.74
C91E	1 509	1 509	371	2.07	0	0.00	49.00	8.37	6.42	9.69	1.73
C92A		554	367	3.66		0.01			2.92	29.82	0.80
C92A Danielskuil	3 923	2 873	367	12.63	0	12.62		10.29	10.38	3.53	2.83
C92B		1 482	331	6.66		0.02			2.38	5.96	0.72
C92B Griquatown	1 979	677	331	2.09	0	2.09		7.67	8.81	1.46	2.66
C92C		623	326	2.64		0.01			2.35	11.73	0.72
C92C Griquatown	1 959	1 335	326	5.13	0	5.13		9.54	8.79	29.82	2.70
D41B	6 164	971	476	2.63	0.00	0.05	18.41	10.25	4.98	30.70	1.05
D41C	3 919	2 995	416	11.08	0.00	0.09	7.30	6.28	4.11	16.11	0.99
D41D	4 380	2 744	380	6.95	0.00	0.08	5.23	7.90	3.4	14.89	0.89
D41E	4 497	467	346	0.77	0.00	0		4.63	2.33	10.48	0.67
D41F	6 011	1 498	338	2.26	0.00	0	9.19	5.06	2.22	13.34	0.66
D41G	4 312	471	361	1.28		0	2.51	7.91	2.91	1.37	0.81
D41G Moshaweng		3 841	361	0.23	0.00	0.23			5.44	20.90	1.51
D41Ha	8 657	850	307	1.14	0.00	0		4.42	1.99	6.55	0.65
D41Hb		1 388	316	2.13		0.01	2.13		2.78	14.92	0.88
D41J Upper Gamagara	3 878	3 314	323	3.05	0.00	3.05	3.01		10.14	33.60	3.14
D41J		564	323	1.21		0.01		7.13	2.08	1.17	0.64
D41K	4 216	1 552	330	3.63	0.00	0.02	4.3	6.92	2.18	9.19	0.66

Quaternary	Gross Area	Subarea area/ Nett area	MAP	MAR	GRAII Baseflow	Simulated Baseflow	Channel losses	GRAII Recharge	Simulated Recharge		Recharge (% of rainfall)
	Km²	Km²	mm/a	Mm³/a	Mm³/a	Mm³/a	Mm³/a	mm/a	mm/a	Mm³/a	
D41L Matlhwaring	5 383	1 408	403	3.6	0.00	3.55	3.33		18.55	26.12	4.60
D41L D4H011		1 982	403	1.96		1.87	2.18		6.76	13.40	1.68
D41L Kuruman A		461	403	8.43		8.43	7.54		18.55	8.55	4.60
D41L Kuruman B		334	403	3.01		3	2.98		18.55	6.19	4.60
D41L Kuruman C		84	403	1.38		1.28	1.38		18.55	1.55	4.60
D41L Lower Kuruman		972	403	0.94		0.9	1.77	11.50	6.76	36.39	1.68
D41M	2 628	471	322	0.78	0.00	0	1.02	4.70	1.95	5.12	0.61
D42Ca		190	225	0.10	0.00	0.00			0.73	1.98	0.32
D42Cb	18 112	1075	258	0.97	0	0	1.46	1.32	0.97	14.93	0.38
D73A Prieska	3 238	3 440	323	0.31	0.00	0.33	0.31	8.61	1.52	5.23	0.47
D73C	6 221	978	230	0.3	0.00	0.00		3.50	1.15	7.15	0.50

Remainder of a Quaternary catchment that is non-dolomitic

Dolomitic

Table 4-2 Present day runoff, baseflow and groundwater use

Quaternary	Subarea area/ Nett area	Gross Area	Simulated Recharge		Incremental MAR	Channel losses	Baseflow	Use	Stress Index
	Km²	Km²	mm/a	Mm³/a	Mm³/a	Mm³/a	Mm³/a	Mm³/a	
C31A	649	1 402	9.55	6.20	9.00	0.96	0.00	5.00	0.81
C31 Lichtenburg	753		34.14	25.70			8.40	19.36	0.75
C31B	1 358	1 743	8.83	14.49	16.22		0.00	12.00	0.83
C31B Dudfield	102		32.23	3.27			1.06	2.59	0.79
C31C	1 635	1 635	8.83	14.44	27.56		0.00	8.17	0.57
C31D	780	1 494	8.12	11.36	**3.8**		0.01	1.93	0.17

C31D Itsoseng	96		30.43	2.91			0.92	2.00	0.69
C31E	1 941	2 960	7.18	21.25	36.47		0.00	15.19	0.71
C31F	1 789	1 789	6.10	10.91	30.40		0.00	7.70	0.71
C32A	681	1 405	6.09	8.56	5.78		0.00	7.62	0.89
C32B	1 587	3 002	6.09	18.28	10.74		0.00	38.46	2.10
C32C	916	1 658	6.36	10.54	6.16		0.00	5.78	0.55
C32D Upper Ghaap	2 943	4 140	18.16	53.44			21.88	14.99	0.28
C32D	1 197		5.92	7.09	**58.08**		0.20	0.00	0.00
C33A Upper Ghaap	1 317	2 859	14.38	18.94			4.16	3.68	0.19
C33A	1 542		6.28	9.68	154.28	12.00	1.85	0.00	0.00
C33B Reivilo	881	2 835	12.84	11.31			4.61		0.00
C33B Upper Ghaap	1 075		12.84	13.80			6.33	1.82	0.13
C33B	879		5.58	4.90	120.35	8.40	0.06		0.00
C33C	1 118	4 149	4.74	5.30	**140.05**	6.00	0.10		0.00
C33C Klein Boetsap	469		11.02	5.17			2.30		0.00
C33C Upper Ghaap	972		11.02	10.71			4.83		0.00
C33C Danielskuil	1 590		11.02	17.52			6.25	1.90	0.11
C91A	2 546	2 546	12.12	30.86	1940.17		0.01	5.72	0.19
C91B	4 679	4 679	11.25	52.64	1595.42	20.40	0.00	19.95	0.38
C91C	3 135	3 135	7.52	23.58	11.04		0.00	3.18	0.13
C91D	2 697	2 697	6.90	18.61	1588.88	2.40	0.00	1.26	0.07
C91E	1 509	1 509	6.42	9.69	**1513.30**	36.00	0.00	0.73	0.08
C92A	554	3 923	2.92	11.46	1636.72		0.01		0.00
C92A Danielskuil	2 873		10.38	29.82			12.33	4.56	0.15
C92B	1 482	1 979	2.38	3.53	1792.02	26.04	0.02		0.00
C92B Griquatown	677		8.81	5.96			2.05	0.68	0.11
C92C	623	1 959	2.35	1.46	**1794.04**	6.00	0.01		0.00
C92C Griquatown	1 335		8.79	11.73			4.78	5.60	0.48

D41B	971	6 164	4.98	30.70			0.00	7.90	0.26
D41C	2 995	3 919	4.11	16.11			0.00	4.10	0.25
D41D	2 744	4 380	3.4	14.89	4.12	23.70	0.00	14.44	0.97
D41E	467	4 497	2.33	10.48			0.00	0.94	0.09
D41F	1 498	6 011	2.22	13.34			0.00	0.43	0.03
D41Ha	850		1.99	6.55	4.70	8.91	0.00	3.70	0.57
D41G	471	4 312	2.91	1.37			0.00	0.00	0.00
D411G Moshaweng	3 841		5.44	20.90			0.03	5.38	0.26
D41Hb	1 388	8 657	2.78	14.92	0.12	2.99	0.00	7.00	0.47
D41J Upper Gamgara	3 314		10.14	33.60	0.00	0.27	0.47	30.08	0.90
D41J	564	3 878	2.08	1.17			0.01	0.00	0.00
D41K	1 552	4 216	2.18	9.19	0.57	3.86	0.00	8.18	0.89
D41L Matlhwaring	1 408	5 383	18.55	26.12	0.16		2.66	3.00	0.11
D41L D4H011	1 982		6.76	13.40	0.77		0.98	4.00	0.30
D41L Kuruman A	461		18.55	8.55	0.82		8.17	1.00	0.12
D41L Kuruman B	334		18.55	6.19	0.00		0.94	4.00	0.65
D41L Kuruman C	84		20.01	1.67	0.00		0.92	2.00	1.20
D41L Lower Kuruman	972	5 383	6.76	36.39	0.08	12.34	0.46	2.00	0.05
D41M	471	2 628	1.95	5.12	**0.42**	0.86	0	1.92	0.37
D42Ca	190	18 112	0.73	1.98	**2.91**	1.92	0.00	0.42	0.21
D42Cb	1 075		0.97	14.93	**0.21**	1.18	0.00	2.34	0.16
D73A	3 440	3 238	1.52	5.23	**0.06**		0.28	47.52	9.09
D73C	978	6 221	1.15	7.15	**0.29**		0.00	0.61	0.09

4.3 Comparison of Natural and Present-Day Flows

4.3.1 Natural flows

The naturalised water balance is shown in **Table 4-3.** The difference with the original WR2012 naturalised data is that WR2012 does not include runoff from endoreic areas, many of which contain discharge from dolomitic eyes which never reaches main river stems. WR2012 also generates permanent flow from the Molopo River, which is unrealistic. This project included the endoreic areas as they contribute to groundwater recharge. The runoff and baseflow they generate was accounted for with evaporation losses and channel losses. By using only nett area, excluding endoreic area, a groundwater balance cannot be established. This project also directly simulated the dolomitic compartments and recharge from the eyes, resulting in baseflow which is not expressed in WR2012 not GRAII. This discharge was lost downstream as channel losses.

The entire catchment generates 805.09 Mm^3/a of recharge, of which 109.06 Mm^3/a emerges as baseflow. 105.39 Mm^3/a of the baseflow is from dolomites. Channel losses are 223.57 Mm^3/a, of which 96.4 Mm^3/a are in the Vaal and consist of runoff generated upstream and released from the Bloemhof dam. The remaining 127.17 Mm^3/a are channel losses of the baseflow generated largely from dolomites, and of surface runoff from non-dolomitic areas lost as channel losses downstream, largely in the Kuruman, Molopo and Harts rivers. The nett runoff generated in the Lower Vaal after accounting for channel losses is 87.76 Mm^3/a. The Gross runoff from the Lower Vaal when upstream inflows and channel losses are included is 2068.49 Mm^3/a.

Table 4-3 Natural Runoff, Recharge and baseflow

	Area (km^2)	MAR (Mm^3/a)	WR2012 MAR (Mm^3/a)	Baseflow (Mm^3/a)	Recharge (Mm^3/a)	Channel Losses
Harts						
C31	9102	60.22	57.90	12.15	110.53	0.00
C32	7324	64.17	35.43	23.02	97.91	0.00
C33	9843	69.27	29.93	30.87	97.34	53.11
Total	**26269**	**193.66**	**123.26**	**66.04**	**305.79**	**53.11**
Vaal						
C91	14566	26.72	26.37	0.14	135.37	96.40
C92	7544	32.81	16.17	19.88	63.97	0.00
Total	22110	59.53	42.54	20.02	199.34	96.40
Upstream inflow from Bloemhof dam		1964.81				
Molopo						
D41 Molopo	9525	24.83	17.86	0.22	92.06	40.13
D42 Molopo	190	0.10	2.22	0.00	1.98	1.46
Upstream inflow from D41A		14.27				
Inflow from Botswana		5.64				
Kuruman						

D41 Kuruman	16841	31.63	101.83	22.45	178.60	31.16
D42 Kuruman	1075	0.97	3.23	0.00	14.93	0.00
Total Molopo and Kuruman	**27631**	**57.53**	**125.14**	**22.67**	**287.58**	**74.74**
D73	4418	0.61	0.00	0.33	12.38	0.31
Lower Vaal Grand Total	**80428**	**311.33**	**290.94**	**109.06**	**805.09**	**223.57**
Grand Total		2281.78				223.57

4.3.2 Present day flows

Present day flows are shown in **Table 4-4** as incremental flows after all abstraction is removed. The discharge from the Vaal is 1794.04 Mm^3/a, while an additional 0.21 Mm^3/a leaves the Lower Vaal from the Kuruman River and 2.91 Mm^3/a from the Molopo River as episodic flow. D73 contributes to the Orange River below the Vaal confluence.

Table 4-4 Present day flows

	Area (km^2)	Incremental MAR (Mm^3/a)	Baseflow (Mm^3/a)	Groundwater Use (Mm^3/a)	Channel Losses
Harts					
C31	9102	26.86	10.39	73.94	0.96
C32	7324	58.08	22.08	66.85	0
C33	9843	140.05	30.49	7.40	26.4
Vaal					
Upstream inflow from Bloemhof dam		1964.81			
C91	14566	1513.30	0.01	30.84	58.8
C92	7544	1794.04	19.2	10.84	32.04
Inflow from Riet River		181.93			
Transfer from Orange		17.32			
Molopo					
D41A		14.27			
Botswana		5.64			
D41 Molopo	9525	4.7	0	31.51	32.61
D42 Molopo	190	2.91	0	0.42	1.92
Kuruman					
D41 Kuruman	16841	0.42	14.64	68.55	20.32
D42 Kuruman	1075	0.21	0	2.34	1.18
D73	4418	0.35	0.28	48.13	0.31

4.3.3 Impacts of abstraction on the hydrology

The impact of surface and groundwater use is shown in **Table 4-5.** The total runoff from the Lower Vaal, when inflows from the Riet River and Orange River transfers are included, has been reduced by 474.54 Mm^3/a due to surface and groundwater use. Baseflow has been reduced by 12 Mm^3/a due to a groundwater abstraction of 340.8 Mm^3/a. Much of the large-scale abstraction occurs in catchments with little or no baseflow, hence it does not impact on baseflow and reduces evapotranspiration from groundwater. The remainder of the flow reduction occurs due to surface water abstraction. Channel losses reduce by 49.0 Mm^3/a due to baseflow reduction which reduces discharge from dolomitic eyes.

Table 4-5 Impacts on MAR, baseflow and channel losses under present day abstraction

Catchment	Natural			Present day			
	Incremental MAR (Mm^3/a)	Baseflow (Mm^3/a)	Channel Losses (Mm^3/a)	Incremental MAR (Mm^3/a)	Baseflow (Mm^3/a)	Channel Losses (Mm^3/a)	Groundwater Use (Mm^3/a)
Harts	140.55	66.04	53.11	140.05	62.96	27.36	148.19
Vaal	2068.49	20.02	96.4	1794.04	19.21	90.84	41.69
Kuruman	0.44	22.45	32.16	0.21	14.64	21.5	70.89
Molopo	3.25	0.22	41.59	2.91	0	34.53	31.93
D73	0.61	0.33	0.31	0.35	0.28	0.31	48.13
Total	**2072.8**	**109.1**	**223.6**	**1797.51**	**97.1**	**174.54**	**340.8**
Flow Reduction							
				474.54	**12.0**	**49.0**	

Baseflow reduction is shown in **Figure 4-1.** The largest impact of groundwater abstraction occurs in the dolomites of D41L around Kuruman and in D41J, in the Lichtenburg dolomites of C31A, and in the Ghaap Plateau dolomites of C32D.

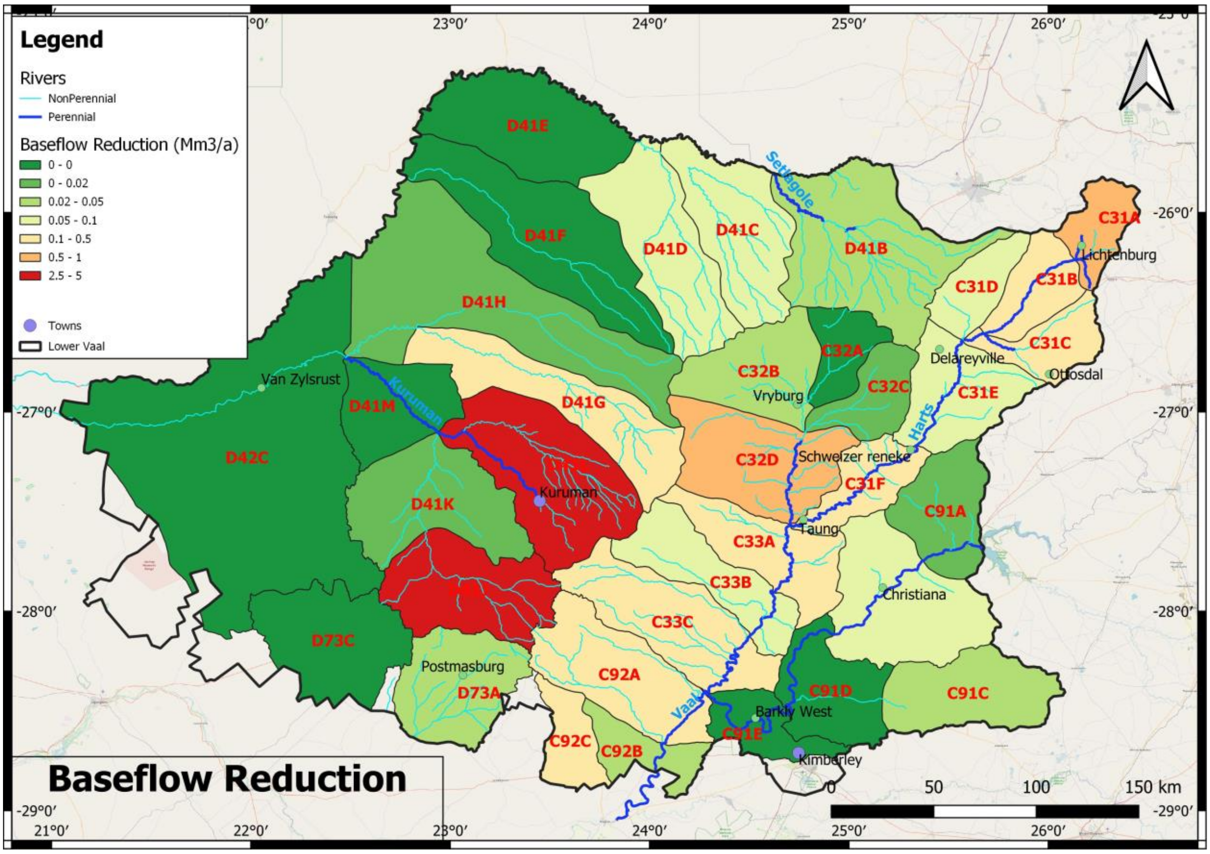


Figure 4-1 Baseflow reduction from present day groundwater abstraction

The impact on surface-groundwater interactions in terms of runoff reduction, baseflow reduction and differences in channel losses is shown in **Figure 4-2.**

4.3.4 Dominant Interaction Type by catchment

The identified runoff units are classified according to the dominant interaction type in **Table 4-6.**

Table 4-6 Surface-Groundwater interaction type

Interaction type (Figure 7-1)	Catchment
a	C31A-F, C92A-C
b	C91D-E, D41 dolomites of Kuruman catchment
c	D41E-G, D42
d	C32A-D, C33A-D, C91A-C, D41B-D

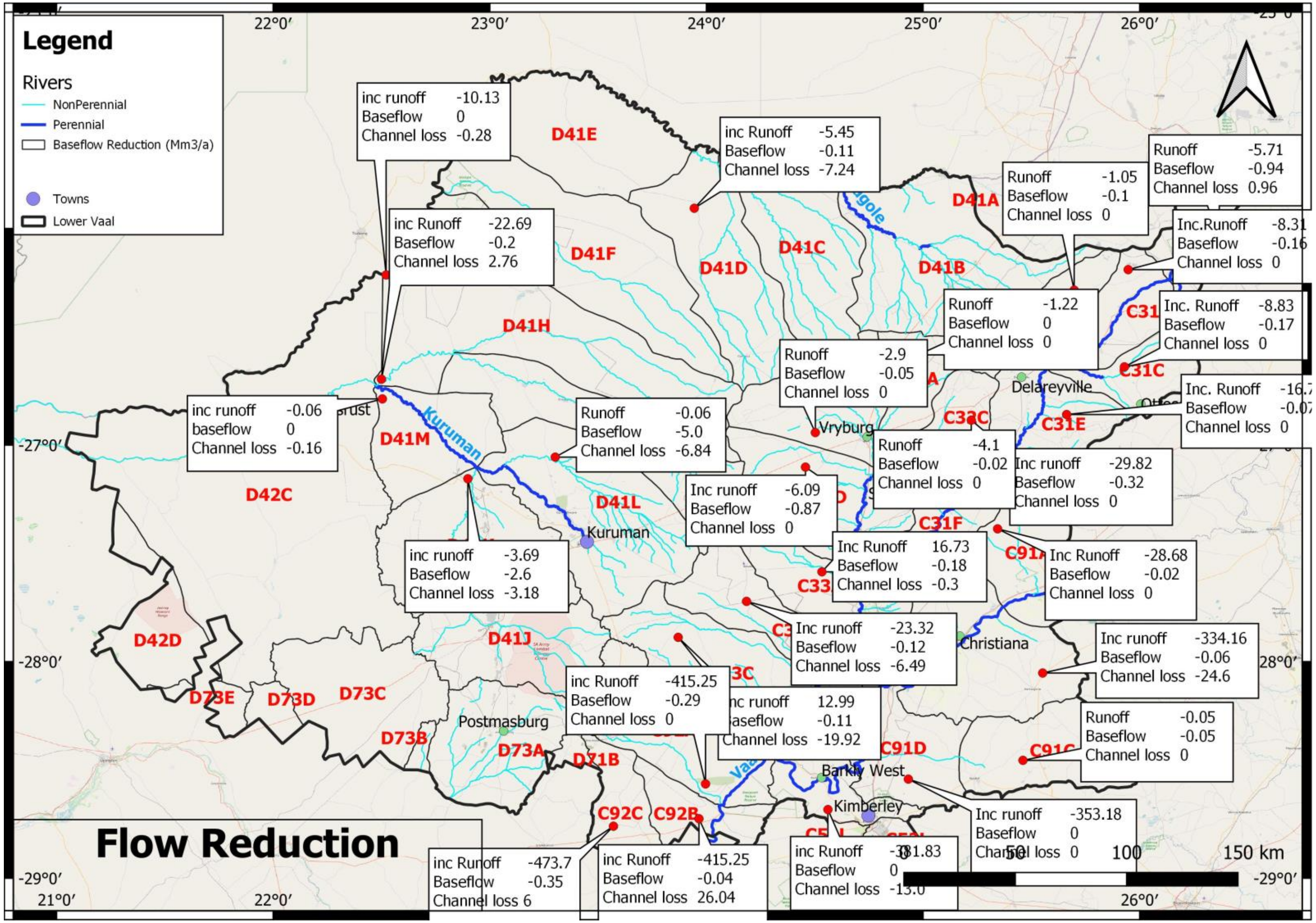


Figure 4-2 Groundwater-surface water interactions

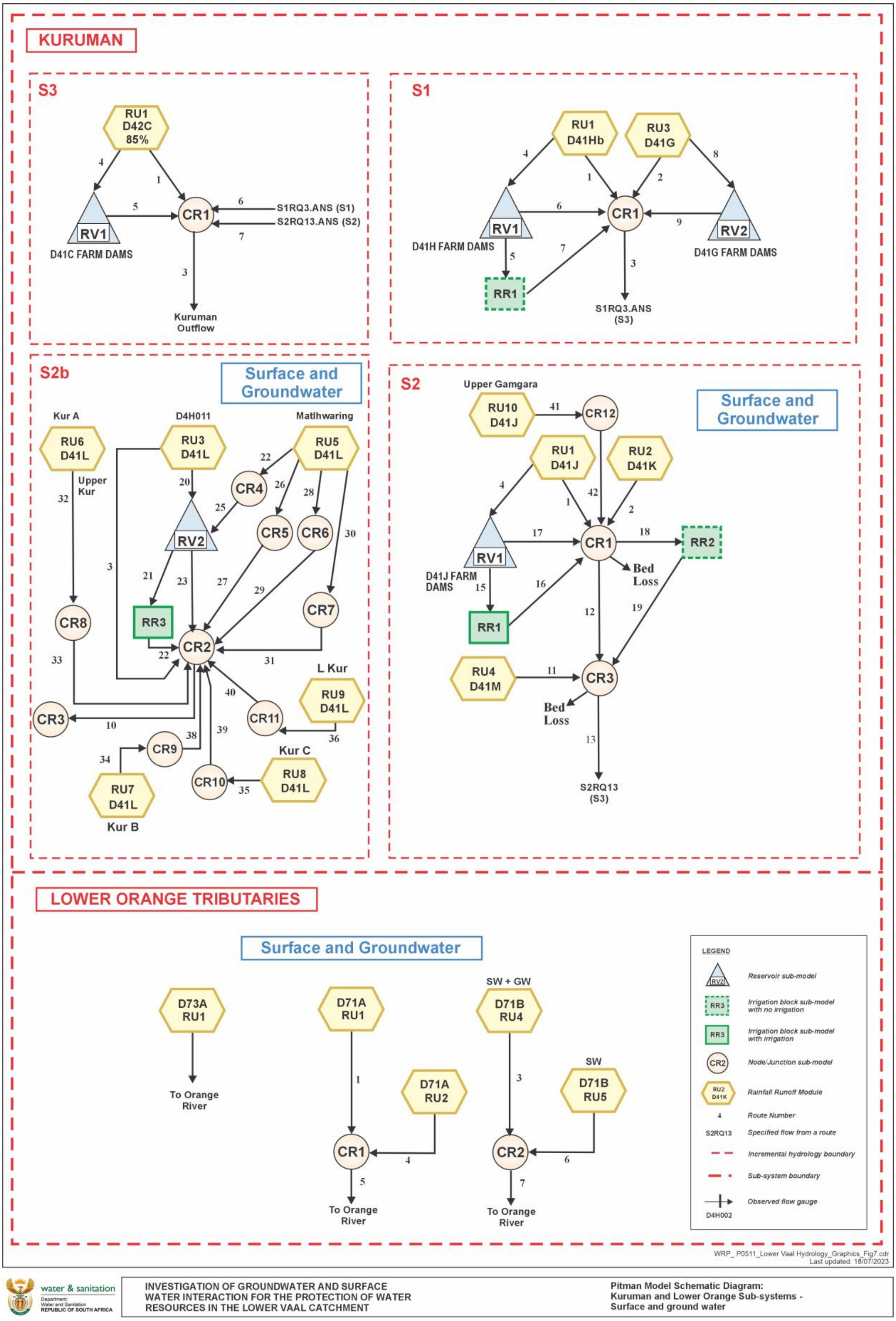
5 CONCLUSIONS

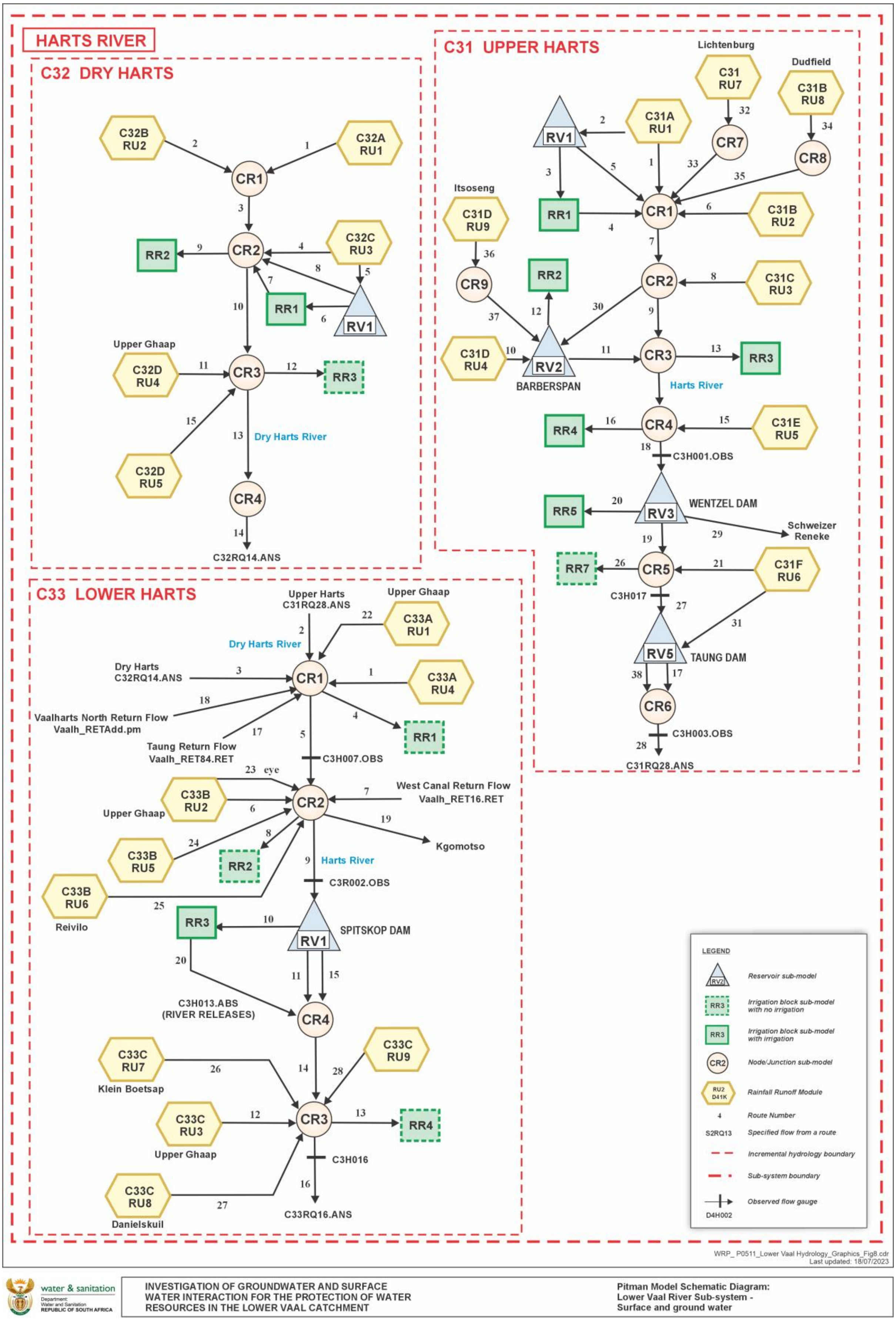
The entire catchment generates 805.09 Mm^3/a of recharge, of which 109.06 Mm^3/a emerges as baseflow. 105.39 Mm^3/a of the baseflow is from dolomites. Channel losses are 223.57 Mm^3/a, of which 96.4 Mm^3/a are in the Vaal and consist of runoff generated upstream and released from the Bloemhof dam. The remaining 127.17 Mm^3/a are channel losses of the baseflow generated largely from dolomites, and of surface runoff from non-dolomitic areas lost as channel losses downstream, largely in the Kuruman, Molopo and Harts rivers. The nett runoff generated in the Lower Vaal after accounting for channel losses is 87.76 Mm^3/a. The Gross runoff from the Lower Vaal when upstream inflows and channel losses are included is 2058.21 Mm^3/a.

The total runoff from the Lower Vaal has been reduced by 474.54 Mm^3/a due to surface and groundwater use. Baseflow has been reduced by 12 Mm^3/a due to a groundwater abstraction of 340.8 Mm^3/a. Much of the large-scale abstraction occurs in catchments with little or no baseflow, hence it does not impact on baseflow and reduces evapotranspiration from groundwater. The remainder of the flow reduction occurs due to surface water abstraction. Channel losses reduce by 49.0 Mm^3/a due to baseflow reduction which reduces discharge from dolomitic eyes.

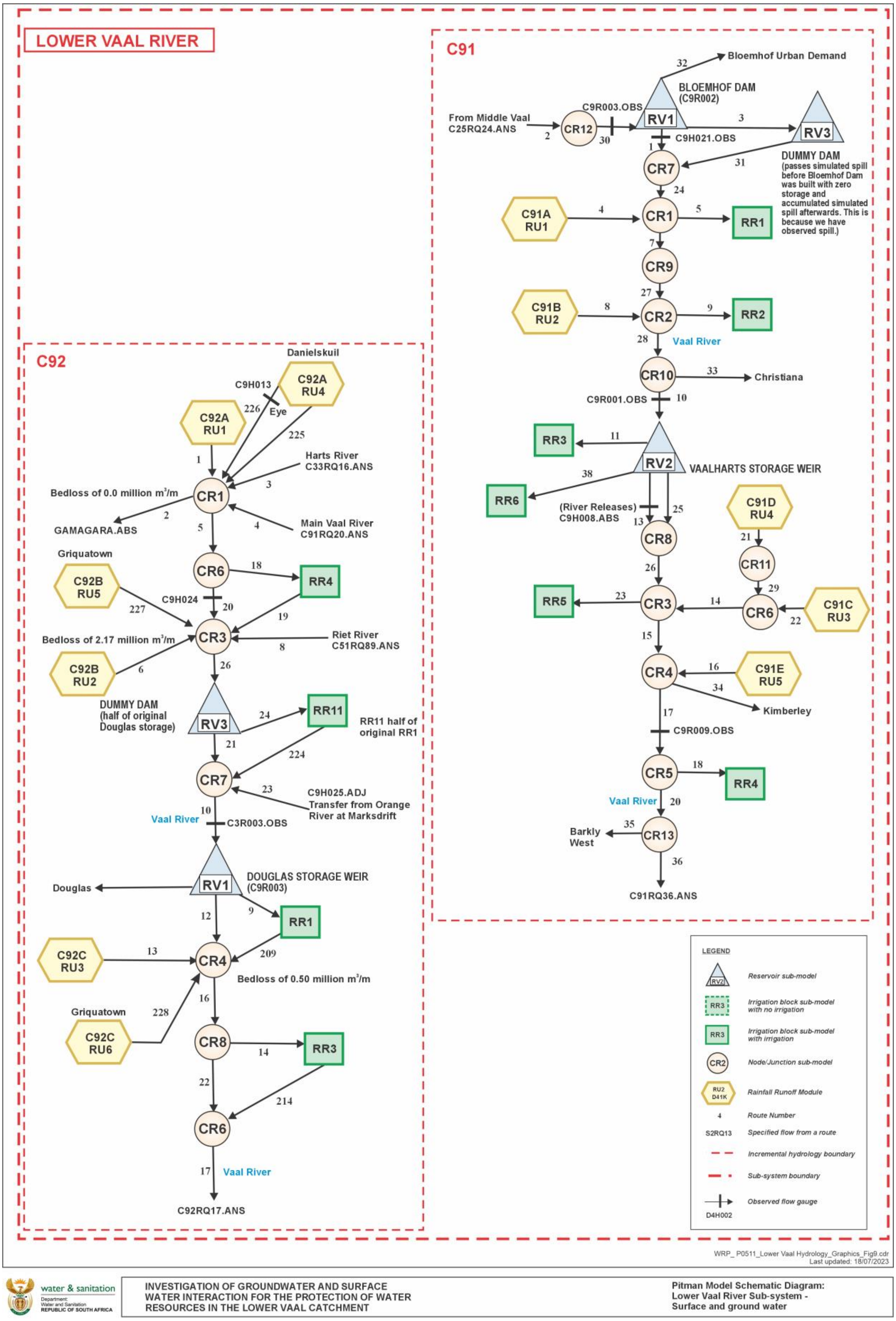
The largest impact of groundwater abstraction occurs in the dolomites D41L around Kuruman and in D41J, in the Lichtenburg dolomites of C31A, and in the Ghaap Plateau dolomites of C32D.

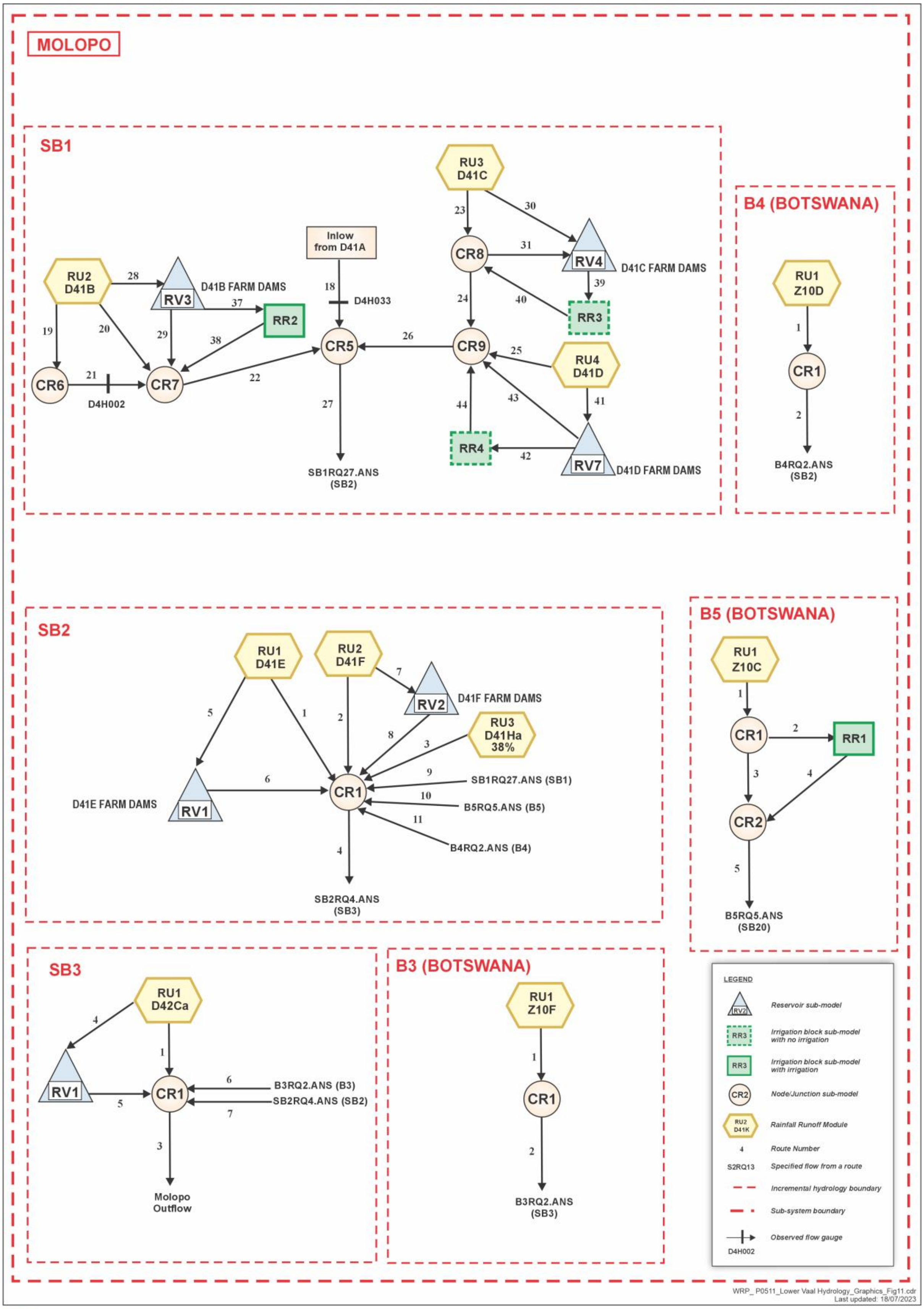
6 APPENDIX 1 WRSM PITMAN NETWORKS


KURUMAN
S3
RU1
D42C
85%
RV1
D41C FARM DAMS
CR1
S1RQ3.ANS (S1)
S2RQ13.ANS (S2)
Kuruman
Outflow
S1
RU1
D41Hb
RU3
D41G
RV1
D41H FARM DAMS
CR1
RV2
D41G FARM DAMS
RR1
S1RQ3.ANS
(S3)
S2b
Surface and
Groundwater
Kur A
D4H011
Matlhwaring
RU6
D41L
Upper
Kur
RU3
D41L
RU5
D41L
CR4
RV2
CR5
CR6
CR7
CR8
RR3
CR2
L Kur
RU9
D41L
CR11
CR3
CR9
Kur C
RU8
D41L
CR10
RU7
D41L
Kur B
S2
Upper Gamgara
RU10
D41J
CR12
Surface and
Groundwater
RU1
D41J
RU2
D41K
RV1
D41J FARM
DAMS
CR1
RR2
Bed
Loss
RR1
RU4
D41M
CR3
Bed
Loss
S2RQ13
(S3)
LOWER ORANGE TRIBUTARIES
Surface and Groundwater
D73A
RU1
To Orange
River
D71A
RU1
D71A
RU2
CR1
To Orange
River
SW + GW
D71B
RU4
SW
D71B
RU5
CR2
To Orange
River
LEGEND
Reservoir sub-model
Irrigation block sub-model
with no irrigation
Irrigation block sub-model
with irrigation
Node/Junction sub-model
Rainfall Runoff Module
Route Number
Specified flow from a route
Incremental hydrology boundary
Sub-system boundary
Observed flow gauge
D4H002
WRP_ P0511_Lower Vaal Hydrology_Graphics_Fig7.cdr
Last updated: 18/07/2023
water & sanitation
Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA
INVESTIGATION OF GROUNDWATER AND SURFACE
WATER INTERACTION FOR THE PROTECTION OF WATER
RESOURCES IN THE LOWER VAAL CATCHMENT
Pitman Model Schematic Diagram:
Kuruman and Lower Orange Sub-systems -
Surface and ground water



HARTS RIVER
C32 DRY HARTS
C32B RU2
C32A RU1
CR1
C32C RU3
RR2
CR2
RR1
RV1
Upper Ghaap
C32D RU4
CR3
RR3
C32D RU5
Dry Harts River
CR4
C32RQ14.ANS
C31 UPPER HARTS
Lichtenburg
Dudfield
C31 RU7
C31B RU8
C31A RU1
CR7
CR8
Itsoseng
C31D RU9
RR1
C31B RU2
CR9
RR2
C31C RU3
C31D RU4
RV2
BARBERSPAN
RR3
Harts River
RR4
C31E RU5
C3H001.OBS
RR5
RV3
WENTZEL DAM
Schweizer Reneke
RR7
CR5
C31F RU6
C3H017
RV5
TAUNG DAM
CR6
C3H003.OBS
C31RQ28.ANS
C33 LOWER HARTS
Upper Harts C31RQ28.ANS
Upper Ghaap
C33A RU1
Dry Harts River
Dry Harts C32RQ14.ANS
C33A RU4
Vaalharts North Return Flow Vaalh_RETAdd.pm
Taung Return Flow Vaalh_RET84.RET
C3H007.OBS
eye
C33B RU2
West Canal Return Flow Vaalh_RET16.RET
Kgomotso
C33B RU5
C33B RU6
Reivilo
C3R002.OBS
SPITSKOP DAM
C3H013.ABS (RIVER RELEASES)
C33C RU9
C33C RU7
Klein Boetsap
C33C RU3
C3H016
C33C RU8
Danielskuil
C33RQ16.ANS
LEGEND
Reservoir sub-model
Irrigation block sub-model with no irrigation
Irrigation block sub-model with irrigation
Node/Junction sub-model
Rainfall Runoff Module
Route Number
S2RQ13 Specified flow from a route
Incremental hydrology boundary
Sub-system boundary
D4H002 Observed flow gauge
WRP_ P0511_Lower Vaal Hydrology_Graphics_Fig8.cdr
Last updated: 18/07/2023
water & sanitation
Department: Water and Sanitation REPUBLIC OF SOUTH AFRICA
INVESTIGATION OF GROUNDWATER AND SURFACE WATER INTERACTION FOR THE PROTECTION OF WATER RESOURCES IN THE LOWER VAAL CATCHMENT
Pitman Model Schematic Diagram: Lower Vaal River Sub-system - Surface and ground water


LOWER VAAL RIVER
C91
C92
Bloemhof Urban Demand
BLOEMHOF DAM
(C9R002)
From Middle Vaal
C25RQ24.ANS
C9R003.OBS
C9H021.OBS
DUMMY DAM
(passes simulated spill before Bloemhof Dam was built with zero storage and accumulated simulated spill afterwards. This is because we have observed spill.)
Vaal River
Christiana
C9R001.OBS
VAALHARTS STORAGE WEIR
(River Releases)
C9H008.ABS
Kimberley
C9R009.OBS
Barkly West
C91RQ36.ANS
Danielskuil
C9H013
Eye
Harts River
C33RQ16.ANS
Bedloss of 0.0 million m³/m
GAMAGARA.ABS
Main Vaal River
C91RQ20.ANS
Griquatown
C9H024
Bedloss of 2.17 million m³/m
Riet River
C51RQ89.ANS
DUMMY DAM
(half of original Douglas storage)
RR11 half of original RR1
C9H025.ADJ
Transfer from Orange River at Marksdrift
C3R003.OBS
DOUGLAS STORAGE WEIR
(C9R003)
Douglas
Bedloss of 0.50 million m³/m
C92RQ17.ANS
LEGEND
Reservoir sub-model
Irrigation block sub-model with no irrigation
Irrigation block sub-model with irrigation
Node/Junction sub-model
Rainfall Runoff Module
Route Number
Specified flow from a route
Incremental hydrology boundary
Sub-system boundary
Observed flow gauge
WRP_ P0511_Lower Vaal Hydrology_Graphics_Fig9.cdr
Last updated: 18/07/2023
water & sanitation
Department: Water and Sanitation
REPUBLIC OF SOUTH AFRICA
INVESTIGATION OF GROUNDWATER AND SURFACE WATER INTERACTION FOR THE PROTECTION OF WATER RESOURCES IN THE LOWER VAAL CATCHMENT
Pitman Model Schematic Diagram:
Lower Vaal River Sub-system -
Surface and ground water



water & sanitation
Department: Water and Sanitation
REPUBLIC OF SOUTH AFRICA

INVESTIGATION OF GROUNDWATER AND SURFACE WATER INTERACTION FOR THE PROTECTION OF WATER RESOURCES IN THE LOWER VAAL CATCHMENT

Pitman Model Schematic Diagram: Molopo Sub-system - Surface and ground water