Ref No: P WMA19/000/00/0409

Department of Water Affairs and Forestry

Directorate: National Water Resource Planning

The Assessment of Water Availability in the Berg Catchment (WMA 19) by means of Water Resource Related Models

Report No. 8 : System Analysis Status Report

FINAL

February 2010

Submitted by:
Ninham Shand (Pty) Ltd
in Association with
Umvoto Africa (Pty) Ltd

NINHAM SHAND CONSULTING SERVICES

UMVOTO

DEPARTMENT OF
WATER AFFAIRS AND FORESTRY

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THE ASSESSMENT OF WATER AVAILABILITY IN THE BERG CATCHMENT (WMA 19) BY MEANS OF WATER RESOURCE RELATED MODELS

REPORT No. 8: SYSTEM ANALYSIS STATUS REPORT

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REPORT No. 8: SYSTEM ANALYSIS STATUS REPORT

APPROVAL

DWAF REF NO.	:	P WMA19/000/00/0408
CONSULTANTS	:	Ninham Shand in association with Umvoto Africa
AUTHORS	:	Anton Sparks and Louise Hayes
REPORT STATUS	:	Final
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STUDY TEAM : Approved for Ninham Shand / Umvoto

....
G ENGLISH / K RIEMANN

....
A H M GöRGENS / R HAY

DEPARTMENT OF WATER AFFAIRS AND FORESTRY
Directorate National Water Resource Planning
Approved for Department of Water Affairs and Forestry

....
I THOMPSON
CE : NWRP (South)

....
J A VAN ROOYEN
Director : NWRP

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Prepared by Ninham Shand (Pty) Ltd in association with Umvoto Africa on behalf of the Directorate : National Water Resource Planning. DWAF Ref No. P WMA19/000/00/0409.

REPORT No	REPORT TITLE	VOLUME No.	VOLUME TITLE
1	Final Summary Report		
2	Rainfall Data Preparation and MAP Surface		
3	The Assessment of Flow Gauging Stations		
4	Land Use and Water Requirements	Vol 1	Data in Support of Catchment Modelling
		Vol 2	Invasive Alien Plant Mapping
		Vol 3	Water Use and Water Requirements
5	Update of Catchment Hydrology	Vol 1	Berg River
		Vol 2	Upper Breede River
		Vol 3	Peripheral Rivers
6	Water Quality	Vol 1	A Literature Review of Water Quality Related Studies in the Berg WMA, 1994 - 2006
		Vol 2	Updating of the ACRU Salinity Model for the Berg River
		Vol 3	Update Monthly FLOSAL Model to WQT
7	(Report No Not Used)		
8	System Analysis Status Report		
9	Groundwater Model	Vol 1	Overview of Methodology and Results
		Vol 2	Data Availability and Evaluation
		Vol 3	Regional Conceptual Model
		Vol 4	Regional Water Balance Model
		Vol 5	Cape Flats Aquifer Model
		Vol 6	Langebaan Road and Elandsfontein Aquifer System Model
		Vol 7	TMG Aquifer, Piketberg Model
		Vol 8	TMG Aquifer, Witzenberg – Nuy Model
		Vol 9	Breede River Alluvium Aquifer Model
10	Berg and Mhlathuze Assessment Studies (Refer to Report No.1)		
11	Applicability of the Sami Groundwater Model to the Berg WAAS Area		

THE ASSESSMENT OF WATER AVAILABILITY IN THE BERG CATCHMENT (WMA 19) BY MEANS OF WATER RESOURCE RELATED MODELS

REPORT No. 8: SYSTEM ANALYSIS STATUS REPORT

EXECUTIVE SUMMARY

The purpose of the Berg WAAS System Analysis Status Report is to present the verification of the hydrology and the updated system model for the Western Cape Water Supply System which will be taken forward to the Western Cape Feasibility Study of Potential Surface Water Development Options for options and scheme analysis in the Western Cape. The incorporation of the updated Berg WAAS hydrology into the system model for the Western Cape system configuration represented the last opportunity to check and, if necessary modify, the streamflows prior to their being used to model the yields of the Western Cape Water Supply System. During the determination of the hydrology a number of factors were identified that required further investigation. Additionally, the results were compared with those from the original Western Cape System Analysis to identify and explain anomalies.

As a result of the above investigation the following modifications were made to the hydrology:

- Farm dam volumes were re-evaluated
- The crop types were refined, for instance by differentiating between table and wine grapes
- The irrigation water demands were calculated using the ““Original WRSM Method” as the WQT method, which was used originally, did not work in high-rainfall winter rainfall areas.
- The streamflows at the following sites were corrected / adjusted:
    - Theewaterskloof (H6R001)
    - Hermon (G1H036)
    - Drieheuwels (G1H013)
    - Campanula (G4H030)
- The rainfall stations used for a number of catchments were changed to improve the calibrations obtained at the following flow gauges:
    - Driefontein (G1H004)
    - Wemmershoek (G1R002)
    - Hermon (G1H036)
    - Drieheuwels (G1H013)
    - Campanula (G4H030)

The hydrological analysis identified some key streamflow gauges and flow meters that should be checked as soon as possible, namely:

- The transfers from Theewaterskloof Dam into the tunnel and the transfers to Kleinplaas Dam
- Gauge G1H036
- Gauge G1H013

Note – The other problematic gauge, G4H030, was checked and corrected during the analysis period.

One of the goals of the Berg WAA study was to model the groundwater / surface water interaction, specifically the conjunctive use of the Table Mountain Group aquifer and the Breede River Alluvium. Details describing the incorporation of these features into the WRYM have also been included.

The Western Cape System model configuration was updated to incorporate the refinements of the current study including groundwater / surface water interaction, additional farm dams and modifications to the system operating rules. The updated hydrology for the Berg, Riviersonderend and Palmiet catchments was imported to the modified system configuration and run in the Water Resources Information Management System version of the yield model. The table below presents a summary of the historical firm yield obtained for individual system components as well as for the integrated system, and also the change in natural incremental MAR for the components of the hydrology that were revised as part of the yield modelling analysis.

<table>
<tr><th>Component</th><th>Historical Firm Yield (HFY) (mcm/a)</th><th>WAAS Post-review HFY (mcm/a)</th><th>% Change</th></tr>
<tr><td>Theewaterskloof / Kleinplaas</td><td>197</td><td>219</td><td>11%</td></tr>
<tr><td>Voëlvlei</td><td>94</td><td>88</td><td>-6%</td></tr>
<tr><td>Wemmershoek</td><td>47</td><td>49</td><td>4%</td></tr>
<tr><td>Steenbras</td><td>37</td><td>36</td><td>-3%</td></tr>
<tr><td>Palmiet</td><td>20</td><td>19</td><td>-5%</td></tr>
<tr><td>Berg River Dam</td><td>77</td><td>67</td><td>-13%</td></tr>
<tr><td>Berg River Supplement</td><td>22</td><td>20</td><td>0%</td></tr>
<tr><td>Wemmershoek Exchange</td><td rowspan="4">32</td><td rowspan="4">32</td><td rowspan="5">0%</td></tr>
<tr><td>Summer streamflows at Siphon</td></tr>
<tr><td>Kleinplaas compensation</td></tr>
<tr><td>Riviersonderend Compensation</td></tr>
<tr><td>Winter abstraction from the Berg River</td><td>5</td><td>5</td></tr>
<tr><td>Total of sub-systems</td><td>529</td><td>535</td><td>1%</td></tr>
<tr><td>Additional yield from integrating sub-systems</td><td>20</td><td>15</td><td>-25%</td></tr>
<tr><td>Total System Yield</td><td>549</td><td>550</td><td>-0%</td></tr>
<tr><th></th><th colspan="3">MAR (mcm/a)</th></tr>
<tr><td>Driefontein G1H004 (incremental)</td><td>105</td><td>112</td><td>7%</td></tr>
<tr><td>Hermon G1H036 (incremental)</td><td>136</td><td>126</td><td>-8%</td></tr>
<tr><td>Drieheuwels G1H013 (incremental)</td><td>127</td><td>100</td><td>-21%</td></tr>
<tr><td>Campanula (cumulative)</td><td>73.6</td><td>81</td><td>10%</td></tr>
</table>

A number of refinements will be included in the WRYM during the Western Cape Feasibility Study of Potential Surface Water Development Options, including:

- The updated environmental streamflow requirements
- The updated diversion at the Supplement Site, incorporating the latest reserve environmental water requirements
- A diversion taking into account the actual spillage occurring at the Kleinplaas Dam
- Evapotranspiration Losses in the Lower Berg River
- Incorporating the proposed augmentation options, including the Voëlvlei Augmentation, Wit River Diversion, Mitchell's Pass Diversion, Campanula Dam and the raising of the Steenbras Dam.
- The evaporation from Theewaterskloof and Voëlvlei Dams will be set equal to the average evaporation over a three year drought period.

The integration of groundwater into the WRYM and the conjunctive use of groundwater and surface water showed that the additional yield from optimising the conjunctive use can be significantly higher than the actual groundwater abstraction. This requires further investigation, especially with respect to the TMG Aquifer development (Report 9, Volume 1; DWAF, 2009).

THE ASSESSMENT OF WATER AVAILABILITY IN THE BERG CATCHMENT (WMA 19) BY MEANS OF WATER RESOURCE RELATED MODELS

REPORT No. 8: SYSTEM ANALYSIS STATUS REPORT

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ABBREVIATIONS

ARC	Agricultural Research Commission
DFPT	Deciduous Fruit Producers Trust
DT	Discharge Table
DWAF	Department of Water Affairs and Forestry
GIS	Geographical Information System
HFY	Historical Firm Yield
MAR	Mean Annual Runoff
MAP	Mean Annual Precipitation
mcm	Million cubic metres
mcm/a	Million cubic metres per annum
SAWI	South African Wine Industry
SW-GW	Surface Water - Groundwater
TMG	Table Mountain Group
WAAS	Water Availability Assessment Study
WCSA	Western Cape System Analysis
WMA	Water Management Area
WRPM	Water Resources Planning Model
WRSM	Water Resources System Management
WRYM	Water Resource Yield Model

1 INTRODUCTION / ISSUES ARISING

The incorporation of the updated WAAS hydrology into the system model for the Western Cape System Configuration represented the last opportunity to check and, if necessary modify, the streamflows prior to their being used to model the yields of the Western Cape Water Supply System. During the determination of the hydrology a number of factors were identified that could require further investigation. Additionally, the results were compared with those from the original Western Cape System Analysis to identify and explain anomalies

As a result of the above investigation the following modifications were made to the hydrology:

- Farm dam volumes were re-evaluated
- The crop areas were refined, for instance by differentiating between table and wine grapes
- The irrigation water demands were calculated using the ""Original WRSM Method" as the WQT method, which was used originally, did not work in high-rainfall winter rainfall areas.
- The streamflows at the following sites were corrected / adjusted:
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- The rainfall stations used for a number of catchments were changed to improve the calibration, including:
    - Driefontein (G1H004)
    - Wemmershoek (G1R002)
    - Hermon (G1H036)
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The hydrological analysis identified some key streamflow gauges / meters that should be checked as soon as possible, namely:

- The transfers from Theewaterskloof Dam into the tunnel and the transfers to Kleinplaas Dam
- Gauge G1H036
- Gauge G1H013

Note – The other problematic gauge, G4H030, was checked and corrected during the analysis period.

One of the goals of the Berg WAA study was to model the groundwater / surface water interaction, specifically the conjunctive use of the Table Mountain Group aquifer and the Breede River Alluvium. Details describing the incorporation of these features into the WRYM have also been included.

2 REVISION OF FARM DAM VOLUMES

The volumes of farm dams were estimated during the pre-review hydrology for the updated farm dam areas obtained from GIS, and using the A and B coefficients from the WCSA hydrology (DWAF, 1993). During the catchment verification process, these volumes were found to be over-estimated in many catchments, and they were subsequently revised using the previous WCSA methodology for individual farm dams, as well as the DWAF dam safety register for verification.

The initial calculation applied the WCSA A and B coefficients to the lumped farm dam areas. The revised calculation applied the WCSA methodology (DWAF, 1994c) to individual farm dam areas. The WCSA coverage was matched to the updated dam coverage using GIS tools, and the corresponding volumes for 100% capacity were applied to the overlapping dams. The remaining farm dams were then assumed to represent all the new dams in the catchment since the WCSA, and some of these were matched with dams listed in the DWAF dam safety register.

The remaining dam volumes were calculated individually using the area-capacity relationship from the WCSA farm dams for individual farm dams in each catchment. The individual farm dam areas and volumes were then summed for each catchment and the final areas and final revised volumes are shown in Table 2.1 and Table 2.2 respectively. It should be noted that some of the registered dams were assigned to dams in the existing WCSA coverage dams and these were excluded from the calculation of the volumes for the new farm dams.

Table 2.1: Final farm dam areas in the study area per catchment

Catchment	**WCSA total area (km^2)**	**WAAS total area (km^2)**	**New dams area (km^2)**
Berg	12.61	26.82	14.21
Diep (1)	-	10.71	10.71
Eerste	3.76	6.16	2.40
Lourens	0.78	0.94	0.16
Palmiet	5.51	5.50	0.00
Riviersonderend	3.35	3.00	0.00
Upper Breede (1)	-	21.08	21.08
TOTAL	**26.00**	**74.20**	**48.55**

(1) These catchments did not form part of the WCSA

Table 2.2: Final farm dam volumes in the study catchment

Catchment	**WCSA Capacity (mcm)**	**DWAF dams registered volume for dams after 1990 (mcm)**	**Calculated volumes (mcm)**	**Total Capacity (mcm)**
Berg	51.83	7.56	30.06	89.42
Diep (1)	0.00	3.09	33.26	35.67
Eerste	15.85	0.54	8.18	25.37
Lourens	4.80	0.58	1.30	6.56
Palmiet	19.39	2.89	0.07	22.12
Riviersonderend	9.48	1.52	0.15	10.84
Upper Breede (1)	65.47	2.53	6.94	72.58
TOTAL	**166.82**	**18.71**	**79.96**	**262.56**

Detailed information on the farm dam volumes in each calibration subcatchment is summarised in Table 2.3.

Table 2.3: Final farm dam volumes in the Berg WAAS area per calibration subcatchment

Gauge	Area from GIS (km^2)	WCSA volume (mcm)	DWAF volume (mcm)	Calculated volume (mcm)	Total WAAS volume (mcm)
G1H003	0.34	0.33	0.13	0.52	0.97
G1H004	0.00	0.00	0.00	0.00	0.00
G1H008	4.92	9.78	1.22	3.81	14.81
G1H013	5.29	6.01	3.33	6.75	16.09
G1H019	0.08	0.22	0.03	0.03	0.28
G1H020	3.89	13.78	1.17	4.73	19.68
G1H021	0.05	0.09	0.16	0.00	0.23
G1H029	0.00	0.00	0.00	0.00	0.00
G1H035	2.36	1.11	0.13	4.33	5.57
G1H036	7.36	15.22	0.62	6.53	22.37
G1H037	0.84	1.53	0.00	0.83	2.36
G1H040	0.60	0.42	0.06	1.29	1.77
G1H041	1.26	2.88	0.71	0.43	4.02
G1H043	0.37	0.46	0.00	0.81	1.27
G2H012	2.09	-	1.58	0.83	2.41
G2H013	5.35	-	0.74	24.81	25.55
G2H014	0.53	-	0.00	0.28	0.28
G2H042	2.84	-	0.08	7.35	7.43
G2H005	0.00	0.00	0.00	0.00	0.00
G2H015	3.91	7.89	0.58	4.73	13.19
G2H016	1.08	4.80	0.46	1.30	6.56
G2H020	2.34	7.96	0.77	3.45	12.18
G4H005	1.32	3.85	0.00	0.07	3.92
G4H007	0.00	0.00	0.00	0.00	0.00
G4H030	3.70	15.54	2.89	0.00	18.20
G4R002	0.00	0.00	0.00	0.00	0.00
H1H003	13.21	23.74	0.17	6.94	30.85
H1H012	0.98	15.39	0.00	0.00	15.39
H1H013	1.19	4.39	0.00	0.00	4.39
H1H018	0.00	0.00	0.00	0.00	0.00
H1H033	0.01	0.00	0.00	0.00	0.00
H4H006	5.57	21.95	2.36	0.00	21.95
H6R001	2.56	7.97	1.23	0.00	8.89
H6R002	0.38	1.51	0.29	0.15	1.95
Total	**74.42**	**166.82**	**18.71**	**79.96**	**262.56**

Figure 2:1 shows the distribution of farm dams across the catchment, with the WCSA dams shown in red, the new dams on the DWAF dam safety register shown in green and the new dams for which volumes were calculated in blue.

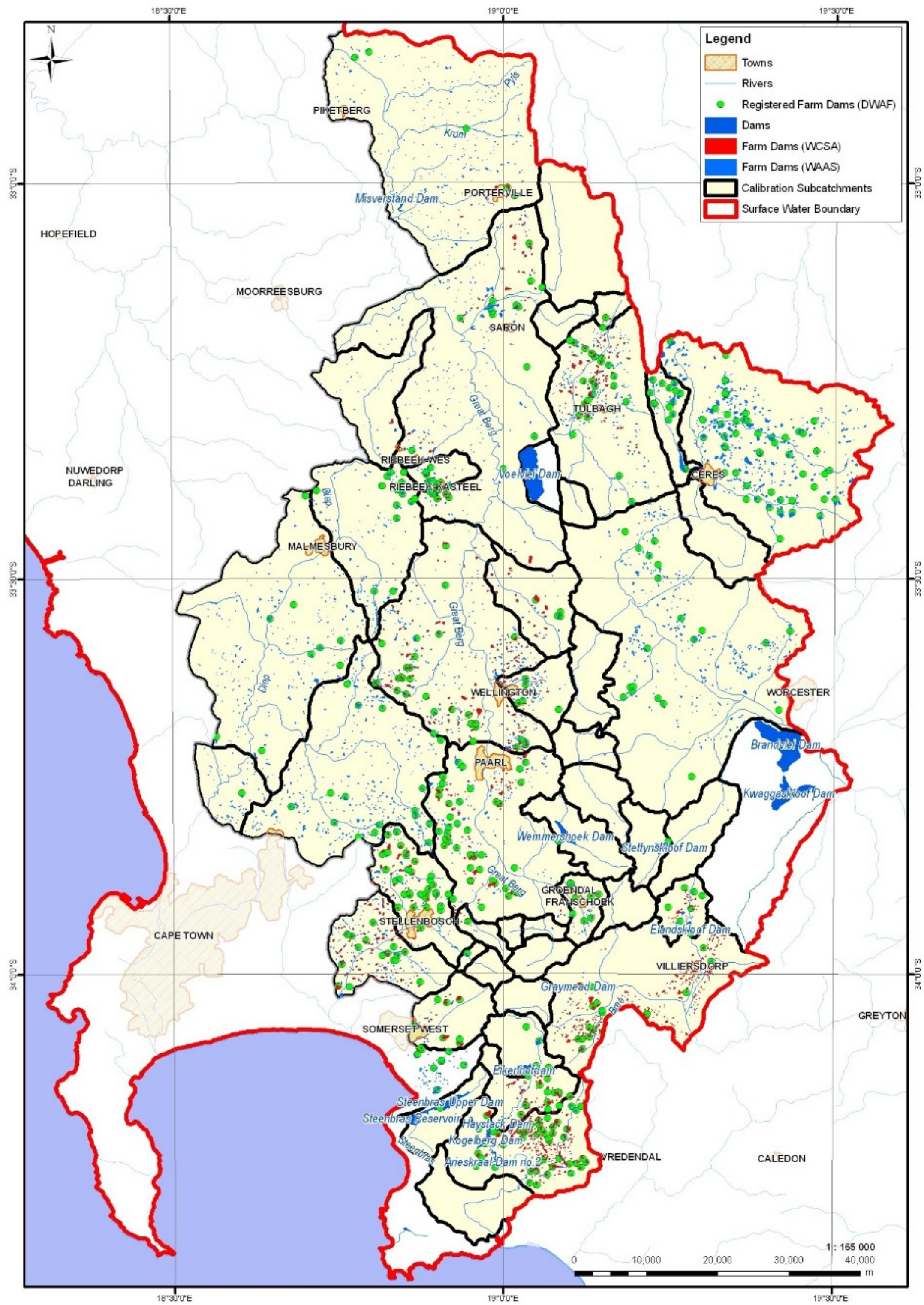


Figure 2:1: Farm dams in the Berg WAAS area

3 IRRIGATION DEMANDS AND RETURN FLOWS

During the initial phase of identifying different crop types from the irrigated land coverage from GIS, five different crop types were distinguished by eye from the 1:10 000 aerial photographs, namely lucerne, pasture, vegetable, orchard and vineyard. The crop factors for each of these crop types were obtained from the WCSA (DWAF, 1993). Following the completion of the calibration using WRSM2000, and the generation of current day water use and requirements for the WRYM, a verification exercise was carried out and the irrigation demands (crop water requirements) were found to be lower than expected. In consultation with the ARC and DWAF (P.Keuck and B van Zyl, personal communication), the crop water requirements were updated according to their latest figures. In addition, a distinction was also made within the vineyards for wine and table grapes because of the different water requirements of the two (P. Myburgh, personal communication). This distinction was made primarily by using available industry statistics from the South African Wine Industry (SAWIS, 2008) and the Deciduous Fruit Producers Trust (DFPT, 2008).

The total area of wine grapes was provided by SAWIS according to growing region and four of the regions fall within the Berg WAAS area, namely Malmesbury, Stellenbosch, Paarl and Worcester. The WAAS catchments were matched to the SAWIS regions and the areas of wine grapes allocated according to their geographical distribution. The total area of wine grapes in the Berg WAAS area according to SAWIS statistics is estimated to be 634 km^2, approximately 70 km^2 of is assumed to be table grapes. The total area of vineyards from the WAAS GIS coverage is estimated to be 878 km^2, therefore the difference of 255 km^2 is assumed to be a combination of table and dry grapes and possibly some orchards that were incorrectly identified as vineyards previously. This total was then checked against the areas for orchards and table grapes provided by the DFPT which are also allocated according to geographical areas. These areas were matched to the Berg WAAS catchments and used for verification. The total area given for the corresponding DFPT areas in the Berg WAAS area for orchards is 334 km^2 and 44 km^2 for table grapes, a combined total of 378 km^2. The corresponding area for orchards and unidentified vineyards (table grapes) from the WAAS GIS coverage is 523 km^2. Therefore, for each catchment, the DFPT proportion of orchards and table grapes to their combined total was applied to the WAAS GIS areas of orchards and unidentified vineyards. The final revised crop distributions in the Berg WAAS area are shown by catchment in Table **3.1** and by calibration subcatchment in Table **3.2**.

Table 3.1: Final crop type distribution in the Berg WAAS area per catchment (km^2)

Catchment	Total Area	Lucerne	Pasture	Vegetable	Orchard	Wine Grape	Table Grape
Berg	482	5	5	12	151	210	99
Diep	157	2	0	8	4	129	14
Eerste/Lourens	173	2	8	0	9	153	1
Palmiet	115	1	1	0	89	25	0
Riviersonderend	65	0	0	0	47	18	0
Upper Breede	212	1	13	1	109	89	0
Grand Total	**1204**	**10**	**26**	**22**	**409**	**624**	**114**

Table 3.2: Final crop type distribution per calibration subcatchment (km²)

Catchment	Calibration Gauge	Total	Lucerne	Pasture	Vegetable	Orchard	Wine Grape	Table Grape
Berg	G1H003	14.74	0.14	0.15	0.35	4.62	6.43	3.03
Berg	G1H004	0.16	0.00	0.00	0.00	0.05	0.07	0.03
Berg	G1H008	45.58	0.43	0.47	1.10	14.30	19.90	9.38
Berg	G1H013	63.65	0.60	0.66	1.53	19.97	27.79	13.10
Berg	G1H019	3.26	0.03	0.03	0.08	1.02	1.42	0.67
Berg	G1H020	121.59	1.15	1.26	2.93	38.15	53.09	25.02
Berg	G1H021	8.95	0.08	0.09	0.22	2.81	3.91	1.84
Berg	G1H028	0.31	0.00	0.00	0.01	0.10	0.14	0.06
Berg	G1H029	0.45	0.00	0.00	0.01	0.14	0.20	0.09
Berg	G1H035	14.42	0.14	0.15	0.35	4.52	6.29	2.97
Berg	G1H036	151.05	1.43	1.56	3.64	47.39	65.95	31.08
Berg	G1H037	25.61	0.24	0.26	0.62	8.04	11.18	5.27
Berg	G1H040	9.45	0.09	0.10	0.23	2.97	4.13	1.95
Berg	G1H041	20.63	0.19	0.21	0.50	6.47	9.01	4.25
Berg	G1H043	1.86	0.02	0.02	0.04	0.58	0.81	0.38
Diep	G2H012	25.51	0.29	0.00	1.36	0.66	20.89	2.32
Diep	G2H013	96.59	1.11	0.00	5.13	2.48	79.07	8.79
Diep	G2H014	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Diep	G2H042	34.89	0.40	0.00	1.85	0.90	28.56	3.17
Eerste/Lourens	G2H015	101.49	1.31	4.72	0.17	5.31	89.66	0.32
Eerste/Lourens	G2H016	10.49	0.13	0.49	0.02	0.55	9.27	0.03
Eerste/Lourens	G2H020	61.42	0.79	2.85	0.10	3.21	54.26	0.20
Palmiet	G4H005	36.04	0.17	0.16	0.07	27.89	7.75	0.01
Palmiet	G4H007	0.52	0.00	0.00	0.00	0.41	0.11	0.00
Palmiet	G4H030	75.55	0.35	0.34	0.14	58.46	16.25	0.01
Palmiet	G4R002	2.67	0.01	0.01	0.00	2.06	0.57	0.00
Upper Breede	H1H003	63.55	0.17	3.75	0.33	32.62	26.66	0.02
Upper Breede	H1H012	0.20	0.00	0.01	0.00	0.10	0.08	0.00
Upper Breede	H1H013	10.08	0.03	0.59	0.05	5.18	4.23	0.00
Upper Breede	H1H018	0.09	0.00	0.01	0.00	0.05	0.04	0.00
Upper Breede	H1H033	0.05	0.00	0.00	0.00	0.03	0.02	0.00
Upper Breede	H4H006	138.05	0.38	8.14	0.71	70.87	57.92	0.04
Riviersonderend	H6R001	59.31	0.17	0.00	0.00	42.92	16.22	0.00
Riviersonderend	H6R002	5.95	0.02	0.00	0.00	4.30	1.63	0.00
Total		**1204.16**	**9.90**	**26.04**	**21.54**	**409.13**	**623.51**	**114.04**

Another problem identified during the calibration was that the water demands calculated using WQT in the "WRSM2000" package differed from those obtained from other methods such as the "Original WRSM Method". The problem manifested itself in high rainfall winter rainfall catchments where the crop water demand was in summer. Because of the low crop water demand in winter, the rainfall tended to accumulate and spill from the soil in winter. As a result the runoff from some lands actually increased when additional crops were introduced into a catchment and modelled using WQT. For the purposes of calibrating the crop water demand it was necessary to revert to the "Original WRSM Method" in the "WRSM2000" package and to factor the demand sequence by a return flow factor to account for return flows. The problem with WQT was one of the factors leading to the review of the calibration in the Berg River (see Section 5) and also meant that the Upper Breede River Catchments will be recalibrated as part of the Feasibility Study (see Section 4).

4 UPPER BREEDE RIVER HYDROLOGY AND SYSTEM ANALYSIS

At gauge H1H003 (Breede River at Ceres Toek) the irrigated area from groundwater and surface water is 53.9 km^2. The original WQT irrigation routine underestimated the irrigation demand as being 34.8 million m^3/a, which means that if the registered groundwater use (21.85 million m^3/a) is deducted, then the residual water demand of surface schemes is only 12.7 million m^3/a, about half that of the registered surface water use by schemes in the area (22.6 million m^3/a). This problem of underestimating demands has cascaded through the system and means that the hydrology of the Upper Breede River must be revisited.

5 THEEWATERSKLOOF, BERG RIVER AND PALMIET / STEENBRAS CALIBRATION REVIEW

An ongoing review of the hydrology and sub-catchment calibration was undertaken while verifying and updating the system model for the WAA study. Using the previous hydrology and estimates of historical firm yield (WCSA (DWAF, 1994b) and Skuifraam Study (DWAF, 1999)) for major dams in the system as a means for comparison, discrepancies with the updated hydrology within the yield model were highlighted. In the following sections, the key areas where differences occurred are investigated.

In the discussion below, reference is made to the pre-review and post-review hydrology and calibrations. The pre-review hydrology is the outcome of the calibrations completed for the study area which underwent numerous checks, one of which was importing the hydrology into the WRYM and comparing the yields to those obtained in the WCSA. The pre-review hydrology is reported in Report No. 5 Volumes 1, 2 and 3 (DWAF, 2008). The following sections describe the factors that impacted on natural flows and yield including the revision and update of the hydrology which is referred to herein as the post-review hydrology.

The incremental natural streamflows from each sub-catchment resulting from the revision of the hydrology were converted to unit runoff depth by dividing the runoff (million m^3/a) by the surface area (km^2). This was plotted against the mean annual precipitation (MAP), expressed in mm, in the expectation that wetter catchments would display a higher unit runoff. In general, the results shown in Figure 5:1 confirms this trend. The exceptions appear to be streamflow gauges G4R001 and G1H021 where the runoff is more than expected for a given MAP, which may be because the MAP was underestimated.

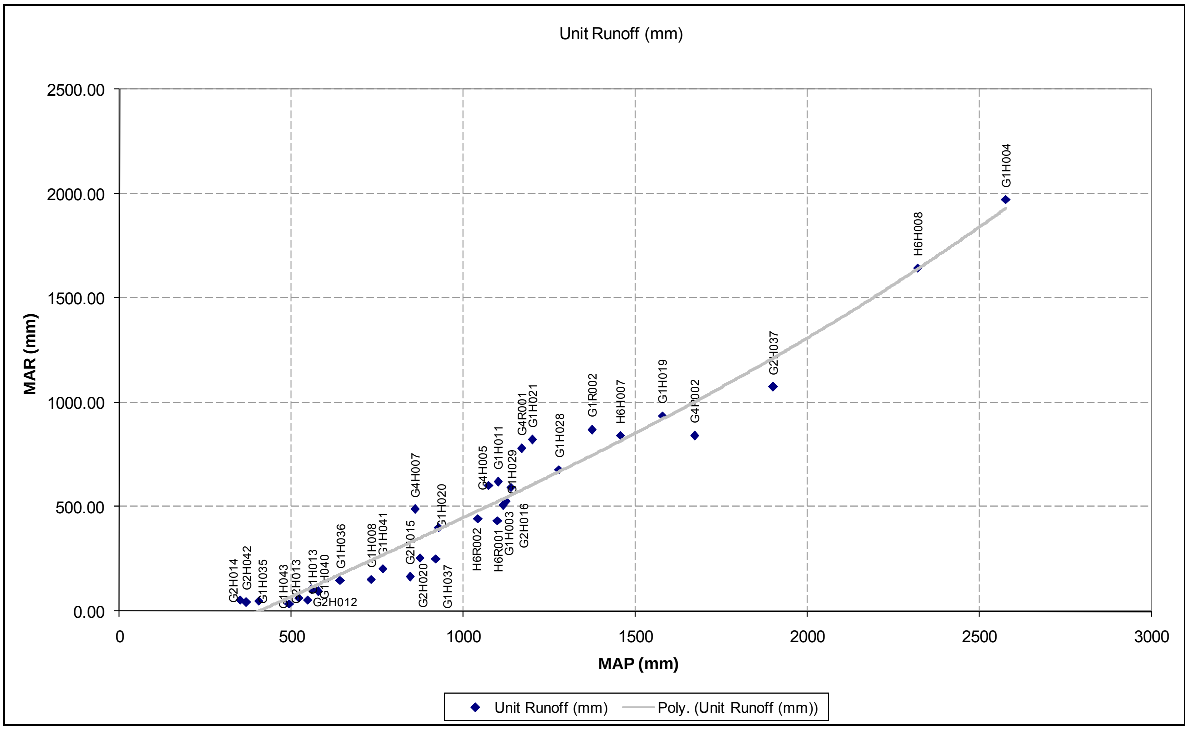


Figure 5:1. Unit Runoff vs. MAP for the gauges in the Theewaterskloof, Berg River and Palmiet / Steenbras Catchments

Table 5.1 compares the features of the updated hydrology with the legacy hydrology from the Theewaterskloof, Berg River and Palmiet, Steenbras areas. A detailed comparison of the system flows based on the legacy and the revised flows is included in Appendix A.

Table 5.1: Comparison of the updated hydrology with the legacy hydrology from earlier studies

<table>
<tr><th>Component</th><th>Historical Firm Yield (HFY) (mcm/a)</th><th>WAAS Post-review (HFY) (mcm/a)</th><th>% Change</th></tr>
<tr><td>Theewaterskloof / Kleinplaas</td><td>197</td><td>219</td><td>+11%</td></tr>
<tr><td>Voëlvlei</td><td>94</td><td>88</td><td>-6%</td></tr>
<tr><td>Wemmershoek</td><td>47</td><td>49</td><td>+4%</td></tr>
<tr><td>Steenbras</td><td>37</td><td>36</td><td>-3%</td></tr>
<tr><td>Palmiet</td><td>20</td><td>19</td><td>-5%</td></tr>
<tr><td>Berg River Dam</td><td>77</td><td>67</td><td>-13%</td></tr>
<tr><td>Berg River Supplement</td><td>22</td><td>20</td><td>0%</td></tr>
<tr><td>Wemmershoek Exchange</td><td rowspan="4">32</td><td rowspan="4">32</td><td rowspan="5">0%</td></tr>
<tr><td>Summer streamflows at Siphon</td></tr>
<tr><td>Kleinplaas compensation</td></tr>
<tr><td>Riviersonderend Compensation</td></tr>
<tr><td>Winter abstraction from the Berg River</td><td>5</td><td>5</td></tr>
<tr><td>Total of sub-systems</td><td>529</td><td>535</td><td>+1%</td></tr>
<tr><td>Additional yield from integrating sub-systems</td><td>20</td><td>15</td><td>-25%</td></tr>
<tr><td>Total System Yield</td><td>549</td><td>550</td><td>-0%</td></tr>
</table>

Component	Historical Firm Yield (HFY) (mcm/a)	WAAS Post-review (HFY) (mcm/a)	% Change
	MAR (mcm/a)		
Driefontein G1H004 (incremental)	105	112	+7%
Hermon G1H036 (incremental)	136	126	-8%
Drieheuwels G1H013 (incremental)	127	100	-21%
Campanula (cumulative)	73.6	81	+10%

5.1 Theewaterskloof Dam (H6R001)

The pre-review calibration parameters for the Theewaterskloof Dam incremental catchment resulted in natural simulated incremental annual flows of 231 million m³/a compared to 155 million m³/a in the WCSA. This was nearly a 50% increase in simulated natural flows to the dam. Table 5.2 shows the relevant Pitman parameters obtained in the WCSA compared to those obtained in the pre-review calibration in the current study for the Riviersonderend catchments. The parameters in the contributing catchments upstream of the Theewaterskloof catchment (H6H007, H6H008 and H6R002) compare well, whereas the parameters for the incremental Theewaterskloof catchment (H6R001) are quite different. The WCSA parameters suppress the streamflow while the WAAS parameters enhance the streamflow, resulting in much higher incremental natural runoff in the current study.

Table 5.2: Pitman parameters for Theewaterskloof catchments: WCSA vs. WAAS

	WCSA					WAAS					
	MAP	ST	FT	ZMAX	TL		MAP	ST	FT	ZMAX	TL
H6H007	1455	350	100	550	0		1238	400	99	500	0
H6H008	2320	200	90	330	0		2133	400	30	200	0.25
H6R002	1165	470	10	700	0		1042	375	50	500	0
H6R001	1144	290	35	550	0	Pre-review	1099	100	75	165	0.25
						Post-review	**1099**	**200**	**65**	**335**	**0**

POW = 2, (SL, ZMIN, GL, R) = 0 THROUGHOUT

The MAP for the Theewaterskloof incremental catchment in both studies is similar, however there remains some uncertainty in the MAP due to the paucity of reliable rainfall gauges in the high-lying areas of the catchment. The simulated natural inflows from the incremental Theewaterskloof system were found to be considerably higher than in the WCSA, shown in Table 5.3.

Table 5.3. Simulated natural inflows in Theewaterskloof catchments (WCSA and WAAS)

Flow Gauge	Description	WCSA Incremental MAR (1926-1988) (mcm/a)	WAAS Incremental MAR (1927-2004) (mcm/a)
H6H007	Riviersonderend	39.1	38.6
H6H008	Du Toit's	66.1	63.2
H6R002	Elandskloof	26.7	22.1
H6R001	Theewaterskloof	154.8	230.6
TOTAL	**Cumulative**	**286.7**	**307.9**

5.1.1 Calibration

The WCSA calibration of the inflows to Theewaterskloof Dam was based on a composite observed flow record comprised of three flow gauges. There was some uncertainty regarding the reliability of this composite record which indicated that the observed high flows may have been underestimated, and several detailed checks were carried out on the data as described in the WCSA study (DWAF, 1994a). These checks were as follows:

- Inspection of stage records for missing or exceeded data revealed gaps in stage data record for H6H003 which had not been flagged. Gaps during winter months were marked for patching and a total of 15 months were patched.
- Assessment of the stationarity of the composite record and comparison with the Du Toit's and Riviersonderend gauges indicated an underestimation of flows during the earlier period of the Theewaterskloof record.

The WCSA stated:

"Despite uncertainties with the observed record provided by H6H003 (between October 1967 and May 1974) this part of the record was retained to err on the conservative side in terms of the yield-storage characteristics."

5.1.2 Revised Calibration Using Composite Observed Record

The pre-review calibration of the Theewaterskloof catchment was based on the observed inflows to the dam for the period 1987 to 2004. In order to verify the pre-review calibration in light of the discrepancies with the observed inflows, it was checked against a composite record which was made up of the WCSA observed flows from 1967 to 1988, and the inflows from the dam balance from 1989 to 2004. This provided a 38-year record on which to calibrate. The calibration was then revised based on this longer period of record. The monthly simulated versus observed flows are shown graphically in Figure 5:2.

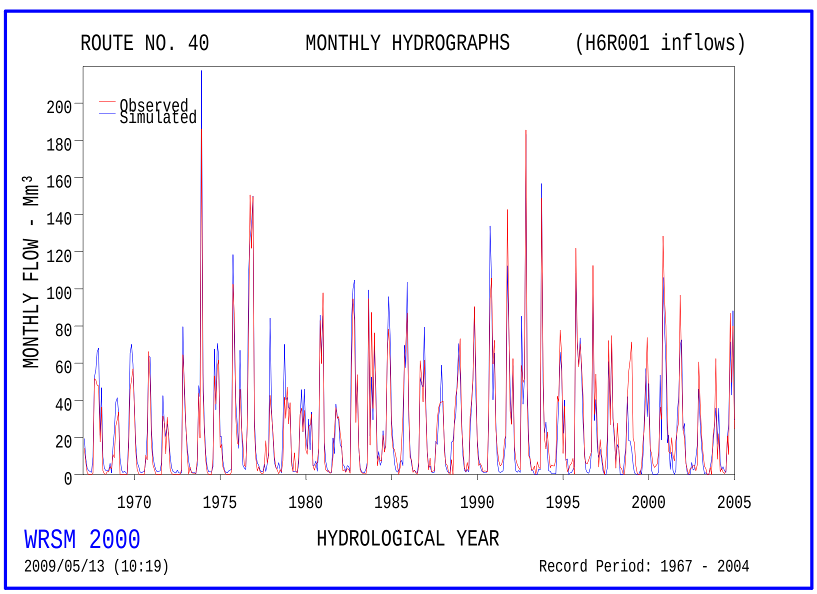


Figure 5:2. Plot of monthly simulated and observed cumulative inflows to Theewaterskloof Dam

5.1.3 Flow Validation

The inflows to Theewaterskloof Dam were determined by DWAF using a "reverse mass balance" calculation, which means that for any time period of interest,

Inflow = Spills +
Δ Storage +
Abstraction +
(Evaporation – rainfall) on the dam surface.

In Theewaterskloof, the abstraction comprises 45% of the calculated inflow and any error in the measurement of these abstractions will affect the accuracy of the inflow calculation. Several analyses were carried out on components of the dam inflows to check whether the Theewaterskloof inflows derived by DWAF between 1992 and 2004 were over-estimated, and also to determine whether there may be some inconsistencies in the observed flows or in the calculation of the inflows to the dam. They are described briefly below:

A. The inflows into Theewaterskloof were derived from adding back the transfers into the Theewaterskloof Tunnel, measured by gauge G1H053 which account for about 45% of the total inflow. These inflows were compared to the outflow from the tunnel which is measured at flow gauges G1H044, G2H031, G2H032 and G2H033. The tunnel inflow (G1H053) is termed "irrigation releases" in the mass balance but actually also includes significant urban releases. The analysis concluded that the irrigation inflows were approximately 10% higher than the outflows. This error implies that the inflows into Theewaterskloof could have been over-estimated and could have been caused by the reversal flows in the tunnel at G1H053. For this reason, the flows at flow meters G2H031 to G2h033 were checked against G1H053.

B. The inflows to Kleinplaas dam, which are primarily releases from the tunnel, were checked with the supply from Kleinplaas to the City of Cape Town. The flows from the tunnel were found to be approximately 8% higher than the records from the City of Cape Town. If the flows at G2H031, G2H032 and G2H033 are greater than recorded, then the "error" reported in (A) would reduce significantly.

C. Analysis was carried out to check the spill from Theewaterskloof Dam with the flow gauge downstream of the dam (H6H012). This comparison was shown to be acceptable.

5.1.4 Conclusion

The outflows from Theewaterskloof Dam to the tunnel could be accurate but the record used to check the record was very short. The outflows from the tunnel which are estimated to be about 8% less than the inflows will be used as a conservative measure until the flow meters have been calibrated and cross-checked with the meters at G2H031 and G1H044. The meter in the tunnel could also be affected by the turbulent two-way nature of the tunnel flows. Based on this indication, the present day cumulative inflows to Theewaterskloof dam from 1992 to 2004 could be reduced from 292 million m^3/a to 280 million m^3/a.

If the reduced flows from 1992 to 2004 were used for the calibration, then a simulated MAR of 280 million m^3/a would have been targeted. The post-review calibration was however based on the longer record from 1967 to 2004 which included the drier early period. This calibration results in a simulated MAR for the shorter record that is only 10 million m^3/a less than 280 million m³/a. Table 5.4 presents a summary of the annual inflows to Theewaterskloof from the analysis.

The hydrology used for yield analysis was derived by naturalising the observed streamflow sequence. The observed streamflow coincides with the critical period for the system (November 1968 to April 1974) so the yield of the system calculated in this manner is similar to that obtained for the WCSA. However, should the observed streamflow record under-estimate the streamflow, as seems likely, then this assumption is conservative. Table 5.4 shows that the average annual natural simulated inflow during this period could be 45 million m³/a higher than the naturalised observed streamflow sequence. Adopting streamflow based on the simulated sequence could increase the historical firm yield by a similar quantity although the stochastic yields might not increase by as much. The 1 in 50 year stochastic yield of the system obtained during the WCSA of 219 million m³/a is already 26 million m³/a more than the WCSA historical firm yield of 193 million m³/a.

Table 5.4. Summary of Theewaterskloof inflows

	MAR (mcm/a)
DWAF inflow from reverse balance (1992-2004)	292
DWAF inflow with 8% reduction in tunnel flows	281
Simulated flow (1992-2004)	270
Observed flow (1967-2004)	289
Simulated flow (1967-2004)	290
Critical period (Nov 1968 - April 1974): Incremental Natural Simulated	125
Critical period (Nov 1968 - April 1974): Incremental Natural Observed	80

5.2 Voëlvlei Dam (G1R001)

The historical firm yield (HFY) at Voëlvlei Dam in the WCSA was 94 million m³/a, and the HFY obtained for the pre-review hydrology in the WAAS was 81 million m³/a. Further investigation indicated that the natural observed flows for the 24 Rivers flow gauge (G1H028) in 1971 were suspect due to missing data and patching problems. This year was therefore discarded from the natural observed flow sequence and substituted with the natural simulated flows. The HFY was updated to 88 million m³/a which is still less than the yield obtained in the WCSA by 6% (6 million m³/a).

This difference can likely be attributed to the increase in irrigation in the Klein Berg catchment. The WCSA demands were 9.8 million m³/a and 9.5 million m³/a were supplied. In the WAA study, the irrigation demands have increased to 24 million m³/a (based on the original WRSM2000 method for calculating irrigation demand) and 12 million m³/a is supplied on average assuming the capacity of the farm dams is 15 million m³/a. It is possible that:

- A larger proportion of the irrigation demand is supplied from groundwater, or
- A larger proportion of the vineyards are sub-optimally irrigated.

The irrigation area appears to have increased from 19 km^2 in 1990, to 45 km^2 in 2004, whereas the farm dam volumes have increased from 10 to 15 million m³/a. It seems likely that the crop water application rates would have to have decreased to allow for this expansion in irrigated area.

5.3 Wemmershoek Dam (G1R002)

The HFY at Wemmershoek Dam in the Skuifraam Study (Ninham Shand, 1997) was 47 million m³/a , and the HFY for the pre-review hydrology was 54 million m³/a , however the critical period for the yields in the two studies did not coincide. In the Skuifraam study, the critical period was from 1932 to 1937, and in the WAAS it was from 2002 to 2005. Despite minor improvements to the hydrology calibration, the critical period for the Skuifraam study was still early in the record and for the WAAS, late in the record.

This prompted further investigation into the rainfall stations that were selected for the catchment calibration. Table 5.5 shows a summary of the representative rainfall stations in the Wemmershoek catchment. The WCSA combination was used in the pre-review WAAS calibration, however in the Skuifraam study a different combination of rainfall stations was used. All of these stations were reviewed and a new, more representative combination of stations was selected. Specifically, the inclusion of the rainfall station at Paarl – despite its distance from the Wemmershoek catchment, provided a much better representation of rainfall and hence runoff simulation in this catchment. This new combination of rainfall stations was then used to generate a new catchment rainfall file, and the pre-review WAAS calibration was revised. An improved calibration was achieved, especially for the annual low flows. Figure 5:3 and Figure 5:4 show the simulated versus observed annual plots for the Wemmershoek calibration using the WCSA combination of rainfall stations (also used in the pre-review WAAS calibration), and the improved calibration obtained by revising the rainfall station combination for the WAAS configuration respectively.

Table 5.5: Summary of Rainfall stations used in Wemmershoek calibration

Rainfall station number	Rainfall station Name	MAP (mm)	Record Length	WCSA	Skuifraam	WAAS
0021778W	Jonkershoek	1076	1927-2004	✓		
0021823W	Paarl	895	1927-2004			✓
0022113W	La Motte	835	1927-2003	✓	✓	✓
0022116W	Driefontein	1842	1927-1960	✓		
0022140W / 9112301	Wemmershoek Dam	984	1957-2004	✓	✓	✓
0022148W	Robertsvlei	1995	1961-2004		✓	✓

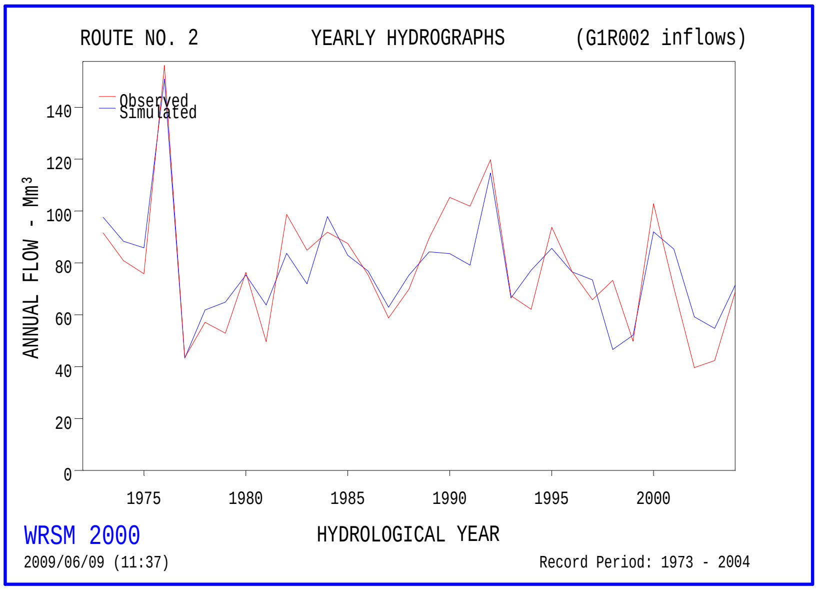


Figure 5:3: Annual hydrograph using WCSA rainfall stations

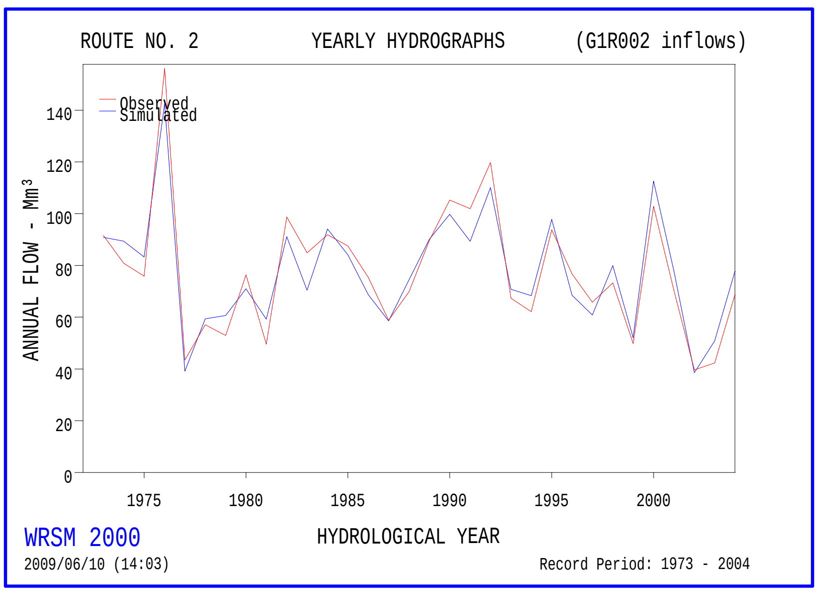


Figure 5:4: Annual hydrograph including Paarl rainfall station (final WAAS calibration)

5.4 Berg River at Driefontein (G1H004)

The HFY at the Berg River Dam was for a different critical period than in the previous work. This can most likely be attributed to the lack of representative rainfall stations during the early period of simulation. There was only one rainfall station that covered the early period of the simulation, namely the La Motte station (022113W) which appears to be underestimating the rainfall during this early period. Table 5.6 presents a summary of representative rainfall stations for the Driefontein catchment and Figure 5:5 shows the location of these rainfall stations. Figure 5:6 shows the annual rainfall as a percentage of MAP for selected stations in the catchment. During this early period, the La Motte station has a lower MAP than the other stations. In both the previous studies, this was the only station used to represent catchment rainfall during this early period. In order to obtain a better representation of the catchment rainfall, the Paarl rainfall station (021823W) was once again included in order to balance out the rainfall estimations for the dry early period. In order to validate its inclusion and suitability for use in the upper reaches of the Berg, the flows were simulated using just this station and just the La Motte stations shown in Figure 5:7 and Figure 5:8 respectively. Figure 5:9 shows the post-review calibration using the Paarl, La Motte and Robertsvlei rainfall station combination.

Table 5.6: Summary of Rainfall stations used in G1H004 calibration

Rainfall station number	Rainfall station Name	MAP (mm)	Record Length	WCSA	Skuifraam	WAAS
0021809W	Jonkershoek (2D)	1463	1935-2004	✓	✓	
0021823W	Paarl	895	1927-2004			✓
0021838W / 90200004	Jonkershoek (4M)	2116	1935-1990	✓	✓	
0022113W	La Motte	835	1927-2003	✓	✓	✓
0022148W	Robertsvlei	1995	1961-2004			✓

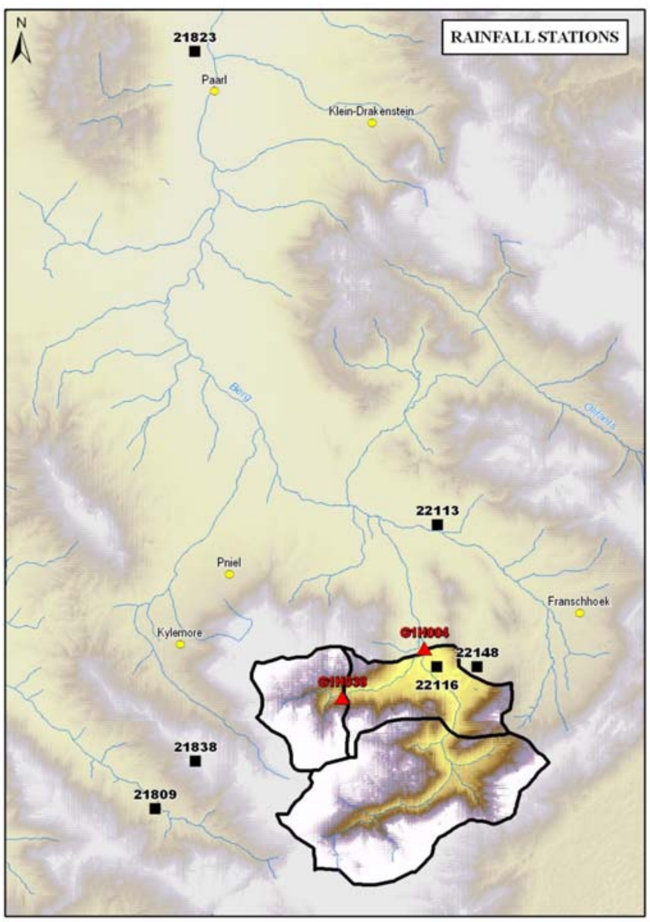
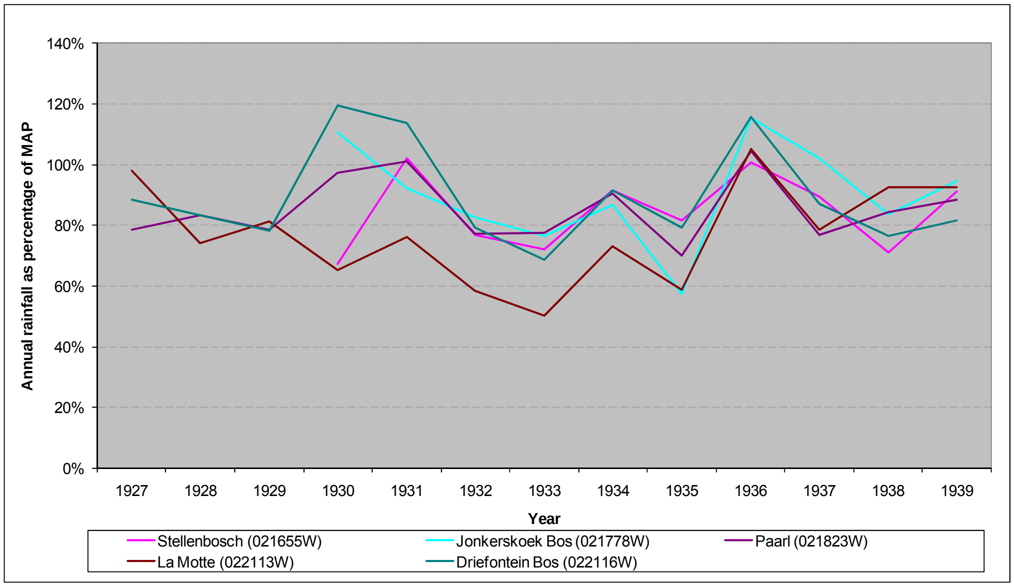


Figure 5:5. Location of rainfall stations in the G1H004 catchment



\HYDRO\400820 WC Modelling\WRYM\Verification\G1h004\%rainfall during critical period.xls "Sheet: Plot (Pat)"

Figure 5:6. Annual rainfall totals as a percentage of the MAP for stations in G1H004 catchment

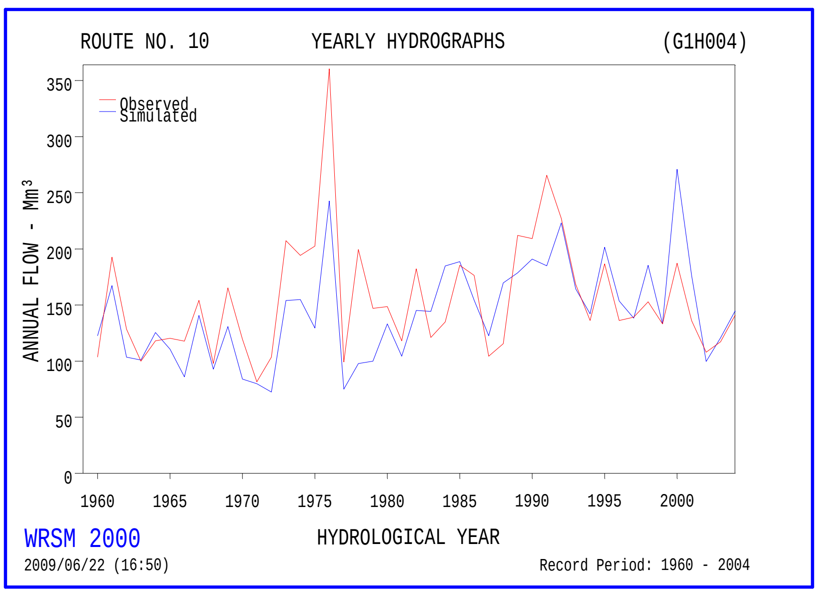


Figure 5:7: Calibration flows with Paarl rainfall station 021823W

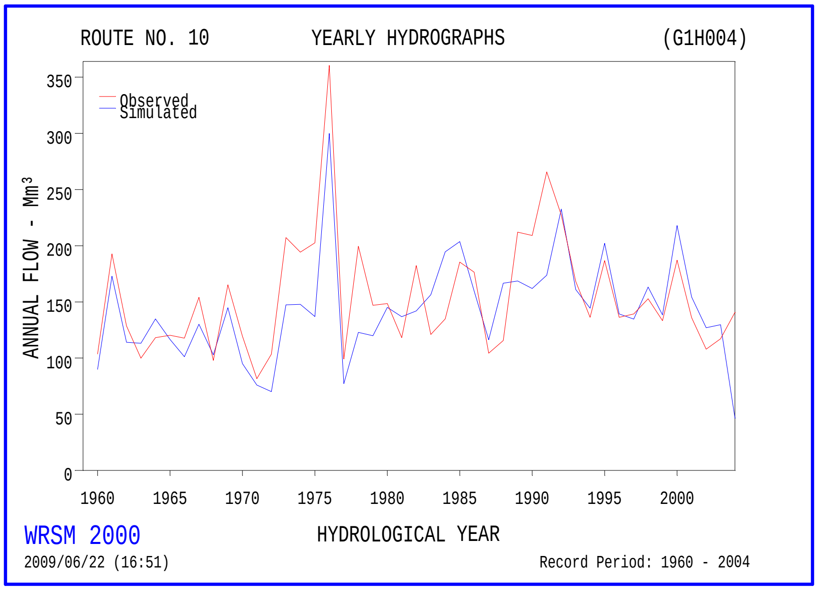


Figure 5:8: Calibration flows with La Motte rainfall station 022113W

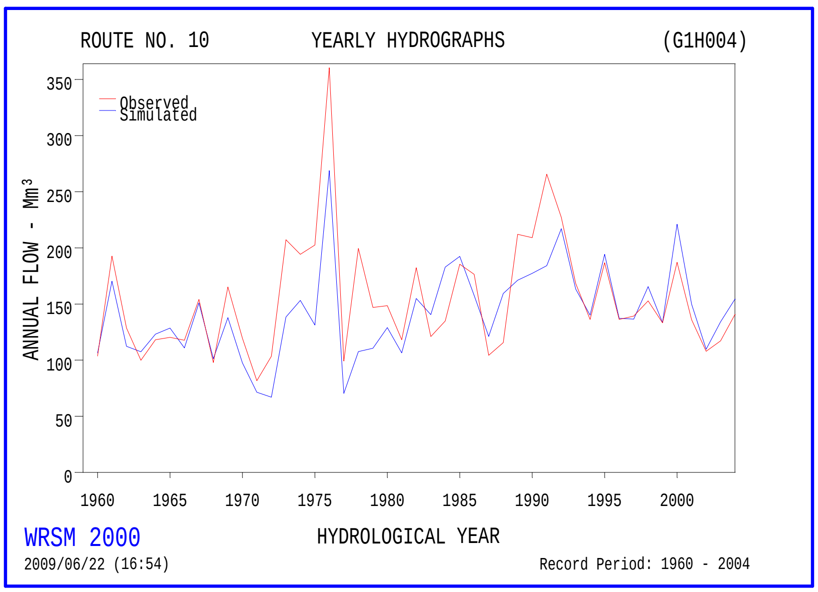


Figure 5:9: Calibration flows with final rainfall stations (Paarl, La Motte and Robertsvlei)

5.5 Berg River at Hermon (G1H036)

The pre-review calibration of gauge G1H036 estimated the natural runoff from the incremental catchment that was about 30% less than that determined in the earlier WCSA study. As discussed below, this could be due to errors in the high-flow readings from gauge G1H036. After adjustment of the streamflows from gauge G1H036 the incremental inflow was 17% less than that determined during the WCSA study.

The review of gauge G1H036 in WAAS Report No. 3 (DWAF, 2007c) mentions that:

- High flows can erode and bypass the right side of the gauge G1H036 (see Figure 5:10)

- Data was missing for the period from Jul 1995 to May 1997 (This data appears to have been subsequently located)
- The gauge may be submerged and overestimate flows when the water level is only 0.75 – 0.8 m (corresponding to flows of about 17 m^3/s)
- Stepped low flow crump weirs were introduced to measure low flows in 1985 and the rating table was changed.


Figure 5:10 : Streamflow gauge G1H036 (copied from DWAF April 2007)

The review of gauge G1H020 in WAAS Report No. 3 (DWAF, 2007c) mentions that:

- Hydrodynamic modelling has been undertaken by Stellenbosch University. This found that the observed flows seem to be too high during flood periods. This could be due to the damming effect caused by the bridge piers situated just downstream of the weir (See Figure 5:11).
- The discharge table was changed in 1995, from DT7 to DT8 when the central pier dividing the weir into two separate sharp crested weirs was removed.


Figure 5:11 : Streamflow gauge G1H020 (copied from DWAF April 2007)

The construction of the Berg River Dam started after June 2004 and could also have affected the relative magnitude of the flows at gauges.

When investigating the anomaly it was noticed that average flood events at G1H036 prior to about 1998 were about 30% ***more*** than at gauge G1H020, while after 1998 the flood events were slightly ***less*** than the flows at G1H020. In some flood events (Aug 2004, Jul 2005 and May 2007) this shortfall was caused by the improper measurement as only one or two readings were taken per day during the floods although more frequent measurements were taken on other days. The cause of this anomaly should be investigated.

However, the lack of readings does not explain the general reduction in high flows that is illustrated in Figure 5:12 and Table 5.7 since about 1997. This reduction in measured streamflows is after the period when data was originally reported missing and could also be related to further erosion of the bank to the right of the gauge. There is a slight chance that the gauge G1H020 could be over-recording since the change in DT in 1995, but this is not evident in the calibration at that gauge.

Table 5.8 illustrates that prior to about 1997 the medium flows (5-50m^3/s) and high flows (>50m^3/s) at gauge G1H036 were about 132% and 137% more than the flows at G1H020. However, after 1997 the medium and high flows were only about 122% and 115% of the corresponding flows at G1H020. The reduction in the high flows (22%) is more significant than that in medium flows (10%).

In order to patch G1H036, a relationship was developed between the streamflows at G1H020 and the streamflows arriving 1 day later downstream at G1H036. The relationship was based on the recorded flows for the earlier period, from 1978 to 1997. For streamflows exceeding 150 m^3/s at G1H020 it was assumed that the streamflows at G1H036 would be about 16% greater in the second quarter and 20% greater in the third quarter. This relationship between the streamflows for quarter 2 and quarter 3 are shown in Figure 5:13 and Figure 5:14.

This relationship was initially used to only ***patch*** the missing and exceeded values in gauge G1H036 by factoring the previous day's flow at G1H020. However, the streamflows at G1H036 still appeared too low so the relationship was then used to also ***adjust*** all streamflows at G1H036 after 1997 that exceeded 50m^3/s. As can be seen in the last two columns of Table 5.9 applying this relationship increased the streamflows between October 1996 and September 2007 from 117% to 128% of the streamflows at G1H020. The factor of 128% is close to the 131% determined for the earlier period from 1 October 1978 to 30 September 1996. The daily streamflows were aggregated into monthly streamflows and presented in Table 5.10. This table compares the "***Patched and Adjusted***" streamflows (left hand side) with the "***Patched***" streamflows (right hand side) and presents the difference in annual flows in the column on the right hand side.

The hydraulics of gauge G1H036, especially the impact of erosion on the banks around the gauge, should be checked to confirm that increasing the high flows, as described above, is not overoptimistic

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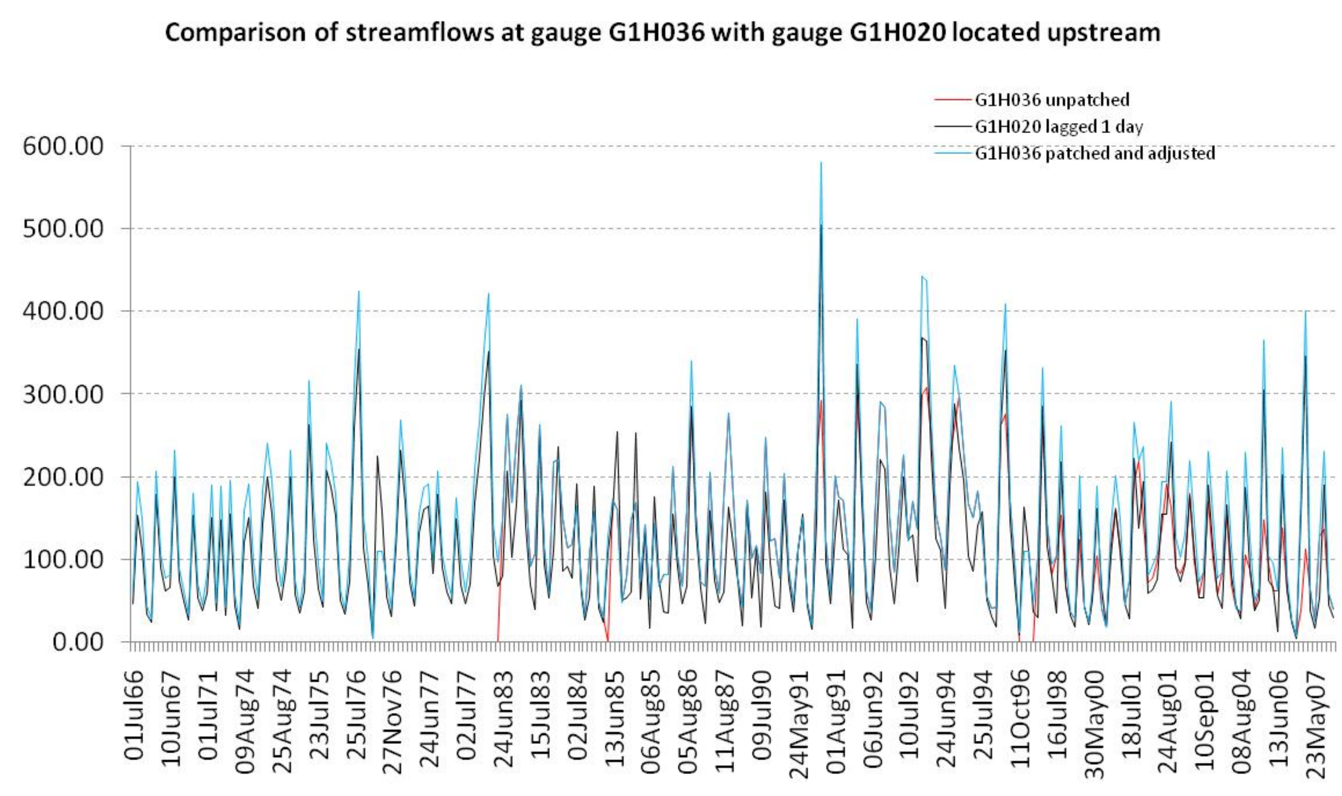


"\\hydro\400820\WRSM2000_Berg\HermonFlw\Daily Patching Modelv14(daily patch for divs).xlsx" sheet "CheckPlot2"

Figure 5:12 : Comparison of winter streamflows at gauge G1H036 with gauge G1H020 located upstream

Table 5.7: Comparison of flood events at G1H020 and G1H036 since 1983. (Flood events included peak daily flows exceeding 100m^3/s plus one antecedent day and two following days)

Values	Year and Month of flood																						
	198306	198307	198405	198407	198506	198507	198508	198607	198608	198708	199004	199005	199007	199008	199105	199106	199108	199206	199207	199307	199406	199407	199606
Average of Unpatched Flow	204	136	176	91	115	133	87	117	116	178	43	131	145	105	83	91	154	95	170	140	159	104	103
Average of Ref Gauge Flow (lagged / advanced)	152	110	132	83	129	125	77	83	82	104	20	111	85	82	82	72	130	56	142	104	107	95	79
Ratio flow @ G1H036 to G1H020	135%	124%	133%	109%	89%	107%	113%	142%	142%	171%	212%	117%	170%	128%	102%	126%	118%	168%	120%	135%	148%	109%	130%
	132%																						

Values	Year and Month of flood																		Grand Total
	199706	199807	199907	200005	200006	200107	200108	200109	200207	200208	200408	200507	200606	200705	200707	200708	200808	200809	Grand Total
Average of Unpatched Flow	149	91	55	81	30	123	128	106	103	42	68	92	72	50	108	41	142	123	115
Average of Ref Gauge Flow (lagged / advanced)	128	89	61	107	42	113	132	106	96	46	85	124	76	113	96	31	112	130	102
Ratio flow @ G1H036 to G1H020	116%	102%	90%	75%	72%	108%	97%	100%	106%	91%	79%	74%	95%	44%	112%	133%	127%	94%	113%
			>30			9	6		>30		2	2	>30	2	>30	>30	>30	>30	
	96%																		

"\hydro\400820\WRSM2000_Berg\HermonFlw\Daily Patching Modelv14(daily patch for divs).xlsx" sheet "CheckPlot2"

Table 5.8 : Ratio of streamflows at G1H036 relative to those at G1H020 for the second half of winter for flow rates above and below 50m^3/s

Period		Jul-Sep					
		5-50			50+		
		avg m3/s		% Gain	avg m3/s		% Gain
		G1H036 (Patched)	G1H020	G1H036 wrt G1H020	G1H036 (Patched)	G1H020	G1H036 wrt G1H020
Oct-78	Sep-96	19.7	14.9	132%	98.8	72.3	137%
Oct-96	Sep-07	17.2	14.1	122%	90.5	78.4	115%
Oct-78	Sep-07	18.7	14.5	129%	96.3	74.1	130%

"\hydro\400820\WRSM2000_Berg\HermonFlw\Daily Patching Modelv14(daily patch for divs).xlsx" sheet "Flow Ratios"

Table 5.9 : Ratio of streamflows at G1H036 relative to those at G1H020 for different periods and flow magnitudes

Period		Apr-Jun													
		5-50							50+						
		avg m3/s				% Gain			avg m3/s				% Gain		
		G1H036			G1H020	G1H036 wrt G1H020			G1H036			G1H020	G1H036 wrt G1H020		
		Unpatched	Patched	Patched and adjusted		Unpatched	Patched	Patched and adjusted	Unpatched	Patched	Patched and adjusted		Unpatched	Patched	Patched and adjusted
Oct-78	Sep-96	15.2	15	15	12.4	123%	123%	123%	121.6	127	127	99.7	122%	128%	128%
Oct-96	Sep-07	14.8	15	15	12.4	119%	123%	123%	86.9	93	115	90.1	96%	104%	127%
Oct-78	Sep-07	15.09	15	15	12.5	121%	122%	122%	112.1	118	124	97.1	115%	121%	127%

Period		Jul-Sep													
		5-50							50+						
		avg m3/s				% Gain			avg m3/s				% Gain		
		G1H036			G1H020	G1H036 wrt G1H020			G1H036			G1H020	G1H036 wrt G1H020		
		Unpatched	Patched	Patched and adjusted		Unpatched	Patched	Patched and adjusted	Unpatched	Patched	Patched and adjusted		Unpatched	Patched	Patched and adjusted
Oct-78	Sep-96	19.7	20	20	14.9	132%	132%	132%	97.6	99	99	72.3	135%	137%	137%
Oct-96	Sep-07	17.2	17	17	14.1	122%	122%	122%	87.2	91	111	78.4	111%	115%	142%
Oct-78	Sep-07	18.7	19	19	14.5	129%	129%	129%	94.4	96	103	74.1	127%	130%	138%

Period		Apr-Sep							Apr-Sep						
		5+							0+						
		avg m3/s				% Gain			avg m3/s				% Gain		
		G1H036			G1H020	G1H036 wrt G1H020			G1H036			G1H020	G1H036 wrt G1H020		
		Unpatched	Patched	Patched and adjusted		Unpatched	Patched	Patched and adjusted	Unpatched	Patched	Patched and adjusted		Unpatched	Patched	Patched and adjusted
Oct-78	Sep-96	33.46	34	34	25.8	130%	131%	131%	25.7	26	26	19.8	130%	131%	131%
Oct-96	Sep-07	25.17	26	28	22	114%	117%	129%	17.7	18	20	15.5	114%	117%	128%
Oct-78	Sep-07	30.36	31	32	24.3	125%	127%	131%	22.5	23	24	18.1	124%	126%	130%

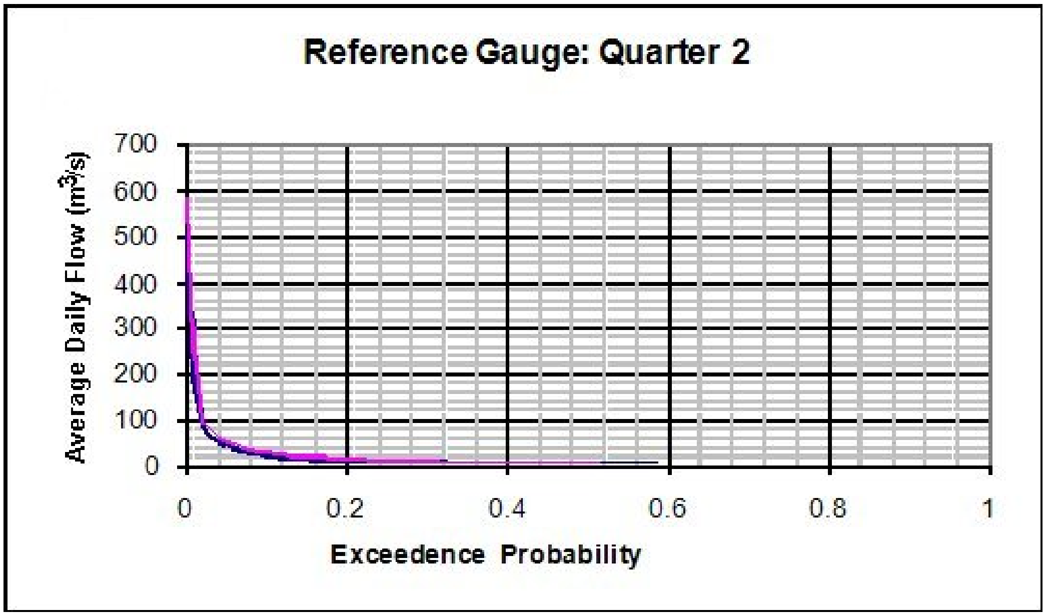
"\hydro\400820\WRSM2000_Berg\HermonFlw\Daily Patching Modelv14(daily patch for divs).xlsx" sheet "Flow Ratios"

Table 5.10 : Streamflows at G1H036 after “patching” the missing and exceeded values (B see RHS) and after “adjusting” the streamflows exceeding 50m^3/s after 1997 (A see LHS). The annual difference is summarize in the RHS column (A-B)

Year	“Patched and Adjusted” streamflows : Patching all G1H036 after 1997 with flow > 50m3/s assuming 116%Xg1h020 in Apr-Jun and 120%Xg1h020 in Jul-Sep (A)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1966				14.904	10.372	21.012	131.262	80.583	46.867	10.845	0.439	0.462
1967	0.647	0.164	0.217	10.740	28.465	117.546	33.977	45.077	32.393	30.148	7.778	1.384
1968	1.198	0.309	0.094	5.608	73.550	82.254	103.309	86.586	26.925	50.709	5.205	0.991
1969	3.414	0.568	0.188	6.753	4.281	21.770	40.662	57.284	59.069	33.627	2.907	0.313
1970	0.318	0.311	0.150	0.002	39.565	72.203	94.968	85.558	59.644	22.736	3.732	4.743
1971	0.487	0.524	0.366	2.262	11.890	9.847	99.625	73.369	28.800	6.866	0.514	0.687
1972	0.356	0.365	0.184	0.020	33.449	29.315	13.591	40.520	34.892	5.787	0.431	0.647
1973	0.188	0.041	0.862	0.000	2.041	4.306	79.843	52.705	29.516	13.340	0.705	8.539
1974	0.480	0.420	0.187	0.006	9.010	85.587	35.464	232.631	83.520	36.368	14.134	1.783
1975	0.748	0.682	0.407	16.549	98.481	67.872	149.341	100.511	20.006	18.986	4.228	0.979
1976	0.566	0.166	0.264	0.284	3.066	159.099	149.066	71.973	28.284	14.453	40.926	33.619
1977	17.124	2.575	1.603	28.708	89.229	247.628	201.893	207.524	51.116	20.907	1.486	5.347
1978	1.038	0.609	6.517	18.873	35.231	17.600	12.041	54.954	48.765	30.514	11.197	1.603
1979	2.040	0.898	1.603	3.739	28.653	76.493	38.681	53.296	23.420	64.583	11.607	2.444
1980	2.721	1.175	0.013	12.223	38.782	53.013	33.388	35.618	19.860	6.784	19.608	20.447
1981	18.389	6.844	3.886	2.429	5.034	16.756	100.717	125.984	107.559	19.523	5.670	14.137
1982	13.265	3.891	7.046	12.088	28.420	47.264	46.524	53.681	19.035	24.424	5.509	6.257
1983	3.644	3.105	3.886	2.189	62.247	160.577	151.412	58.904	68.569	19.571	2.767	2.436
1984	1.890	0.677	2.493	2.022	107.064	18.201	100.945	52.495	85.087	53.622	3.458	13.582
1985	4.702	4.558	23.439	14.564	21.574	84.864	93.535	79.052	17.675	6.417	2.608	3.439
1986	2.185	3.024	2.771	13.059	25.723	73.842	143.314	164.909	77.908	13.760	4.303	2.441
1987	5.122	1.395	1.527	3.099	58.274	78.118	95.977	126.072	83.342	26.643	5.687	7.345
1988	1.591	1.013	1.535	11.820	32.884	40.874	76.159	48.182	72.569	20.033	5.122	2.168
1989	1.234	1.596	11.149	13.777	29.319	41.527	98.012	97.618	109.174	30.154	13.956	2.522
1990	1.723	5.472	1.273	39.851	83.293	86.787	194.417	121.010	28.497	8.064	3.579	4.743
1991	1.502	1.584	1.741	2.629	39.053	120.200	155.849	110.720	129.394	43.156	11.723	2.405
1992	1.977	3.799	2.497	24.231	27.751	205.413	168.312	54.808	56.035	74.381	18.455	4.143
1993	2.945	3.548	2.743	44.457	67.154	90.053	287.546	111.869	25.215	8.400	4.198	4.407
1994	3.530	2.048	3.700	7.117	8.441	173.667	93.353	35.491	26.754	13.502	5.716	2.653
1995	2.263	3.561	4.735	1.439	10.904	31.157	101.828	95.975	19.910	48.788	8.391	10.984
1996	6.397	4.590	2.484	5.019	3.742	136.962	87.104	90.650	134.875	70.395	38.873	18.573
1997	3.639	3.055	1.859	3.671	11.158	114.186	55.891	79.902	43.112	6.397	13.175	2.507
1998	2.371	1.765	1.813	4.904	70.102	45.825	101.031	34.746	21.532	8.833	17.635	4.339
1999	2.199	3.091	2.599	7.958	17.824	46.662	91.982	105.124	92.585	20.024	6.264	3.566
2000	4.853	4.461	5.555	2.625	26.599	31.357	46.052	33.811	51.573	10.872	2.971	1.807
2001	3.187	1.851	1.901	4.124	22.930	38.090	216.976	187.061	156.306	33.390	17.780	3.582
2002	11.757	2.700	2.597	6.277	27.523	50.212	112.014	79.074	35.356	25.469	8.660	6.695
2003	4.910	3.505	5.831	4.949	5.005	5.664	9.301	52.177	38.677	20.666	4.183	4.896
2004	2.647	2.478	3.015	6.770	1.374	24.100	21.402	89.854	13.040	16.620	2.227	1.634
2005	3.213	3.580	1.655	6.086	19.690	95.151	76.759	101.074	32.113	14.843	7.073	2.705
2006	3.451	3.453	4.889	4.391	65.728	60.044	59.148	85.658	18.733	9.773	11.286	4.227
2007	2.838	3.290	2.429	7.693	74.334	102.020	96.449	97.881	42.283	11.665	11.847	5.103
2008	4.902	5.848	3.411	2.687	13.178							

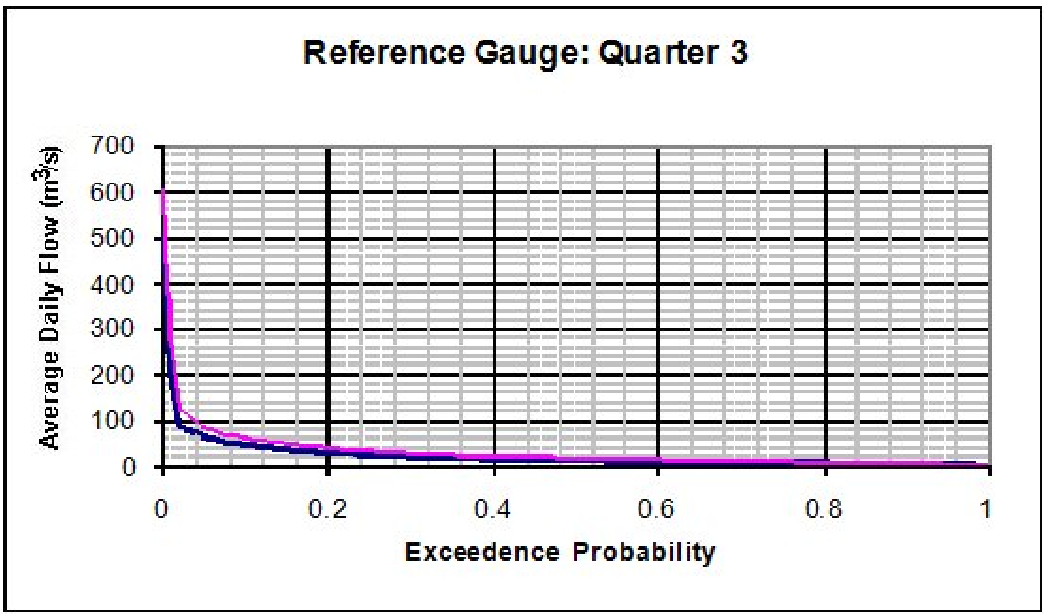
Year	“Patched” streamflows : Only patching exceeded and missing flows, including all G1H036 after 1997 with flow > 310m3/s assuming 116%Xg1h020 in Apr-Jun and 120%Xg1h020 in Jul-Sep (B)												(A-B)	Comment
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Difference	
1966				15.003	10.356	20.932	130.774	79.640	46.171	10.845	0.439	0.462	2	Extrapolated from G1H020 as this is before gauge G1H036
1967	0.647	0.164	0.217	10.756	28.191	117.265	33.757	45.319	32.370	30.148	7.778	1.384	1	
1968	1.198	0.309	0.094	5.592	72.843	81.547	101.987	86.871	26.949	50.709	5.205	0.991	2	
1969	3.414	0.568	0.188	6.742	4.282	21.929	40.209	57.701	59.248	33.627	2.907	0.313	0	
1970	0.318	0.311	0.150	0.002	39.196	72.238	94.790	85.181	59.666	22.736	3.732	4.743	1	
1971	0.487	0.524	0.366	2.252	11.919	9.841	98.333	73.711	28.852	6.866	0.514	0.687	1	
1972	0.356	0.365	0.184	0.020	33.249	29.387	13.545	40.016	35.061	5.787	0.431	0.647	1	
1973	0.188	0.041	0.862	0.000	2.034	4.302	79.366	52.929	29.567	13.340	0.705	8.539	0	
1974	0.480	0.420	0.187	0.006	9.042	84.307	35.668	227.118	83.819	36.368	14.134	1.783	6	
1975	0.748	0.682	0.407	16.426	97.716	67.682	146.899	100.404	20.021	18.986	4.228	0.979	4	
1976	0.566	0.166	0.264	0.284	3.070	158.094	148.048	71.974	28.306	14.453	40.926	33.619	2	
1977	17.124	2.575	1.603	28.463	87.896	244.909	197.818	206.220	51.321	20.907	1.486	5.347	9	
1978	1.038	0.609	6.517	18.873	35.231	17.600	12.041	54.448	47.846	30.514	11.197	1.603	1	
1979	2.040	0.898	1.603	3.747	28.488	75.870	38.796	52.867	23.653	64.583	11.607	2.444	1	
1980	2.721	1.175	0.013	12.223	38.782	53.013	33.388	35.618	19.860	6.784	19.608	20.447	0	
1981	18.389	6.844	3.886	2.429	5.034	16.756	100.717	125.984	107.559	19.523	5.670	14.137	0	
1982	13.265	3.891	7.046	12.088	28.420	47.264	46.524	53.681	19.035	24.424	5.509	6.257	0	
1983	3.644	3.105	3.886	2.189	62.247	160.577	151.412	58.904	68.569	19.571	2.767	2.436	0	
1984	1.890	0.677	2.493	2.022	107.064	18.201	100.945	52.495	85.087	53.622	3.458	13.582	0	
1985	4.702	4.558	23.439	14.647	21.520	84.560	93.535	79.052	17.675	6.417	2.608	3.439	0	
1986	2.185	3.024	2.771	13.059	25.723	73.842	143.314	164.909	77.908	13.760	4.303	2.441	0	
1987	5.122	1.395	1.527	3.099	58.274	78.118	95.977	126.072	83.342	26.643	5.687	7.345	0	
1988	1.591	1.013	1.535	11.820	32.884	40.874	76.159	48.182	72.569	20.033	5.122	2.168	0	
1989	1.234	1.596	11.149	13.777	29.319	41.527	98.012	97.618	109.174	30.154	13.956	2.522	0	
1990	1.723	5.472	1.273	39.851	83.293	86.787	194.417	121.010	28.497	8.064	3.579	4.743	0	
1991	1.502	1.584	1.741	2.629	39.053	120.200	155.849	110.720	129.748	43.156	11.723	2.405	0	
1992	1.977	3.799	2.497	24.231	27.751	205.350	168.312	54.808	56.035	74.381	18.455	4.143	0	
1993	2.945	3.548	2.743	44.457	67.154	90.053	287.546	111.869	25.215	8.400	4.198	4.407	0	
1994	3.530	2.048	3.700	7.117	8.441	173.667	93.353	35.491	26.754	13.502	5.716	2.653	0	
1995	2.263	3.561	4.735	1.439	10.904	31.157	101.379	95.888	19.927	48.788	8.391	10.984	1	
1996	6.397	4.590	2.484	5.019	3.742	136.962	87.182	90.459	134.875	70.395	38.873	18.573	0	
1997	3.639	3.055	1.859	3.671	11.159	102.641	53.900	78.184	39.880	6.397	13.175	2.507	18	G1H036 high flows underestimated wrt G1H020
1998	2.371	1.765	1.813	4.904	68.092	45.825	87.257	34.746	21.532	8.833	17.635	4.339	16	
1999	2.199	3.091	2.599	7.958	17.824	42.908	77.931	97.442	89.291	20.024	6.264	3.566	29	
2000	4.853	4.461	5.555	2.625	18.381	31.357	41.849	33.811	49.815	10.872	2.971	1.807	14	
2001	3.187	1.851	1.901	4.124	22.930	33.216	182.641	143.672	131.528	33.390	17.780	3.582	107	
2002	11.757	2.700	2.597	6.277	27.523	48.992	97.439	74.323	35.356	25.469	8.660	6.695	21	
2003	4.910	3.505	5.831	4.949	5.005	5.664	9.279	51.880	38.677	20.666	4.183	4.896	0	
2004	2.647	2.478	3.015	6.770	1.374	20.041	21.402	86.214	13.040	16.620	2.227	1.634	8	
2005	3.213	3.580	1.655	6.086	19.690	81.097	75.607	86.713	32.113	14.843	7.073	2.705	30	
2006	3.451	3.453	4.889	4.391	56.866	50.004	55.399	77.921	18.733	9.773	11.286	4.227	30	
2007	2.838	3.290	2.429	7.693	74.211	90.002	85.031	96.448	42.283	11.665	11.847	5.103	25	
2008	4.902	5.848	3.411	2.687	13.178								0	

"\hydro\400820\WRSM2000_Berg\HermonFlw\Daily Patching Modelv14(daily patch for divs).xlsx" sheet “Streamflow comparison”



"\hydro\400820\WRSM2000_Berg\HermonFlw\Daily Patching Modelv14(daily patch for divs).xlsx" sheet “Ref vs UnPat Curves”

Figure 5:13 : Flow exceedence curves for April to June for G1H020 (blue) and G1H036 (pink) adopted for patching and adjusting G1H036.



"\hydro\400820\WRSM2000_Berg\HermonFlw\Daily Patching Modelv14(daily patch for divs).xlsx" sheet “Ref vs UnPat Curves”

Figure 5:14 : Flow exceedence curves for July to September for G1H020 (blue) and G1H036 (pink) adopted for patching and adjusting G1H036.

5.6 Berg River at Drieheuwels (G1H013)

The pre-review naturalised flows in this catchment were found to be much lower than those in the WCSA by 42% (DWAF, 2008a). As discussed below, this could be due to changes in the observed flow record as a result of changes to the discharge table since the WCSA.

In the Assessment of Flow Gauging Stations Report (DWAF, 2007c) it states that:

> *"Many current gaugings have been taken at this station, of which the most recent work was undertaken in 2002. The DT limit has been extended to 5.86 m (equivalent to 978 m^3/s). As a result, this station is now capable of recording major flood events. DT 9 extends to the new upper limit and is applicable from 1965".*

However, the observed streamflows at flow gauge G1H013 on the Berg River at Drieheuwels are consistently lower than those used for the WCSA calibration. Comparing the cumulative observed flows during August from 1983 to 1989 at G1H013 in the WCSA and the WAAS, shown in Table 5.11, it was noted that the WAAS patched observed flow record is consistently lower than the WCSA – except in 1988.

Table 5.11 : Comparison of patched observed flows during August 1983 to 1989

	WCSA: Patched Observed DT7 (mcm/month)	WAAS: Patched observed DT9 (mcm/month)	% Difference
August 1983	79.44	72.65	-9%
August 1984	80.33	70.86	-12%
August 1985	225.92	184.27	-18%
August 1986	305.20	244.85	-20%
August 1987	205.69	173.35	-16%
August 1987	78.78	69.47	-12%
August 1988	78.78	161.78	105%
August 1989	196.21	177.01	-10%

The conclusions and recommendations of the WCSA state:

> *"Both recorder pipe and h_a gauge plate should be moved further upstream, because in their present position medium to high flows will be underestimated. Moving the pipe would require correlation with station G1H031A01 to be recalculated for high flows."*

The observed streamflows used in the WCSA were derived from DT 7 which has been superseded by DT 9. The plot in Figure 5:15 shows the difference between the stage level and the observed flows for DT 7 and DT 9. The observed MAR for the overlapping period for DT 7 and DT 9 (1982-1989) is 747 million m^3/a and 640 million m^3/a respectively, a difference of 107 million m^3/a .

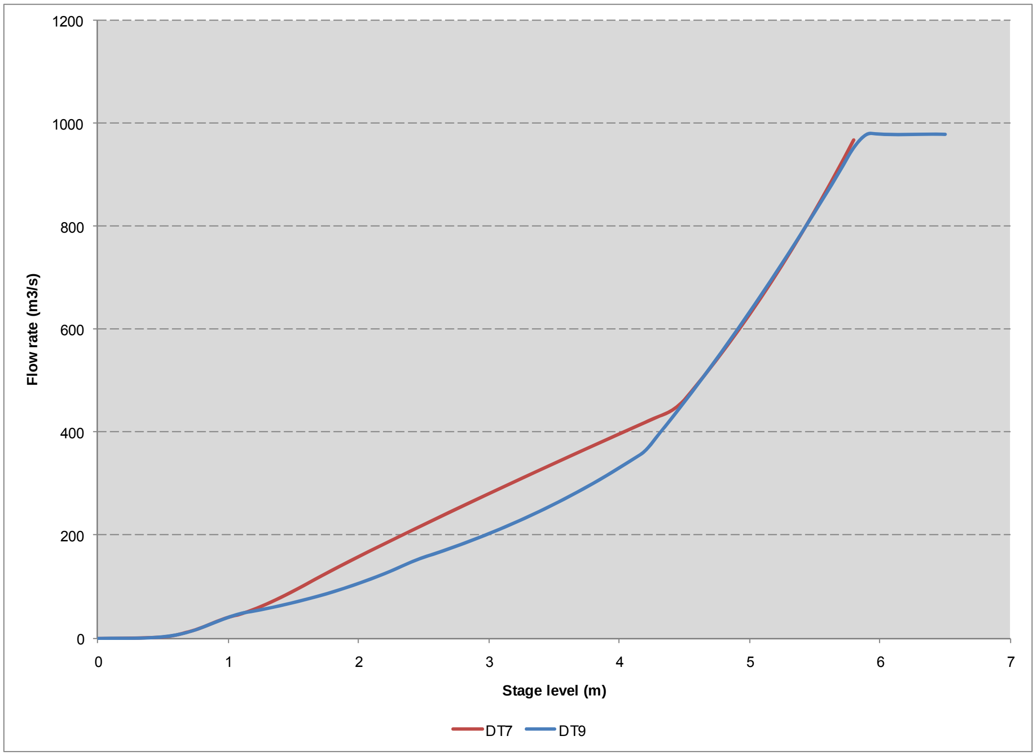


Figure 5:15 : Comparison of discharge tables at G1H013

In order to verify the simulated flows that were generated at the flow gauge, the calibrated Pitman parameters from upstream catchment G1H036 were transferred to the G1H013 incremental catchment while retaining the rainfall and evaporation data representative of the G1H013 catchment. The resultant simulated flows were compared to both observed incremental flows for DT 7 and DT 9 on an annual basis, and are shown in Figure 5:16. At the monthly time step, the low flows are simulated well however there is considerable uncertainty with the high flows due to the large difference between the observed flows for each discharge table.

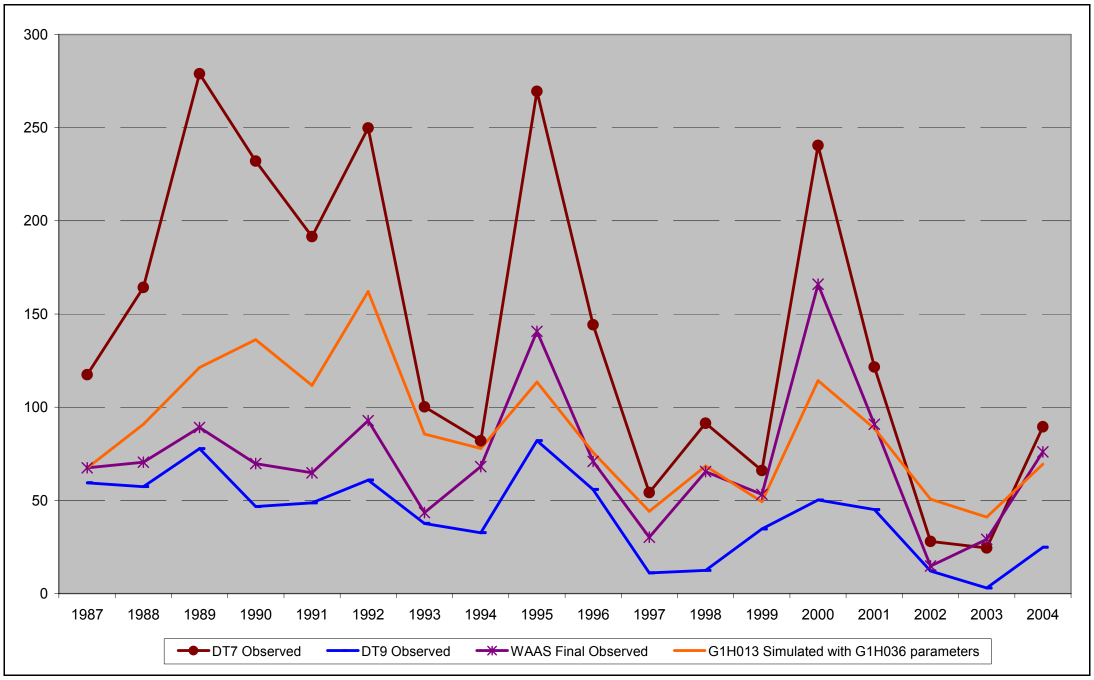


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Figure 5:16 : Annual Incremental flows at G1H013: Simulated versus observed streamflows

An incremental calibration was undertaken in this catchment in both the previous and the current studies. However, the post-review calibration for this catchment was abandoned because of this uncertainty and the simulated streamflows were generated using Pitman parameters transferred from upstream catchment G1H036. It is important that the streamflow gaugings at this gauge be reviewed and augmented by further work to improve the accuracy of the observed flows.

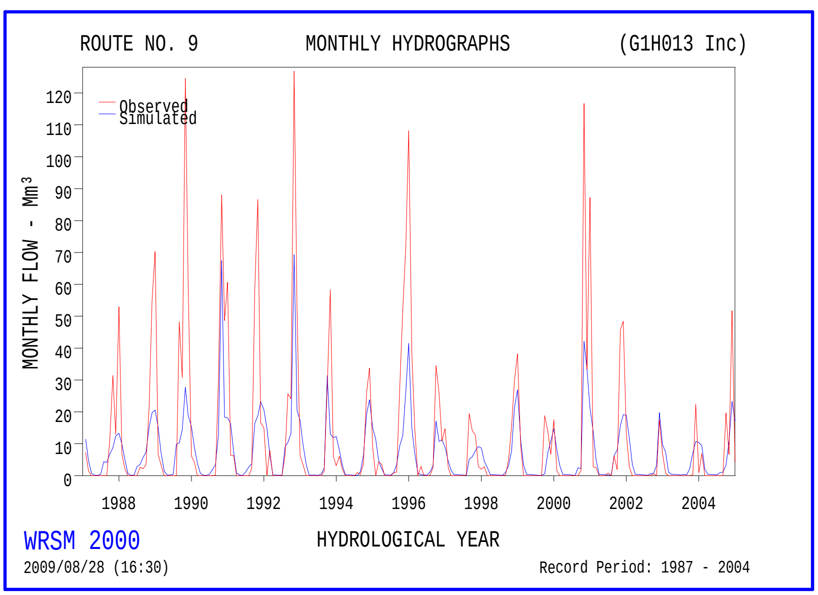


Figure 5:17 : Monthly Incremental flows at G1H013: Simulated with G1h036 parameters versus observed DT7

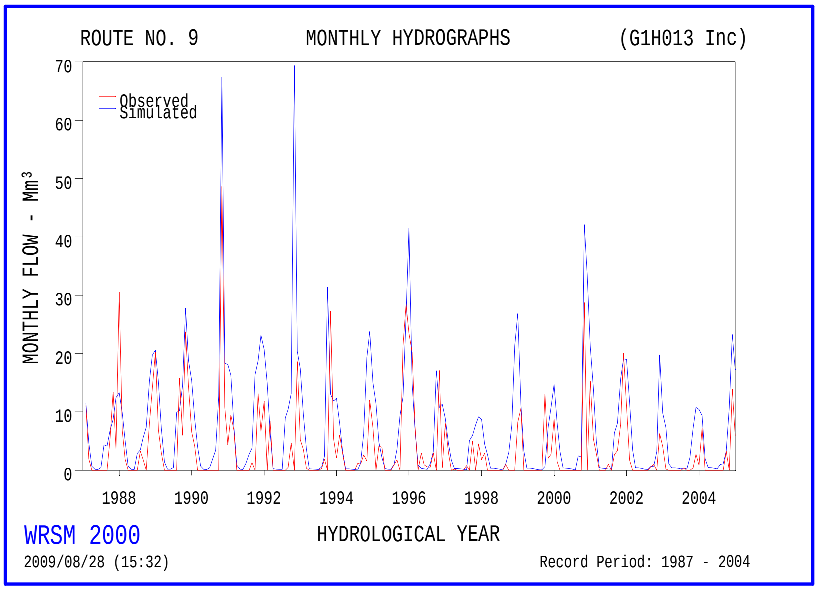


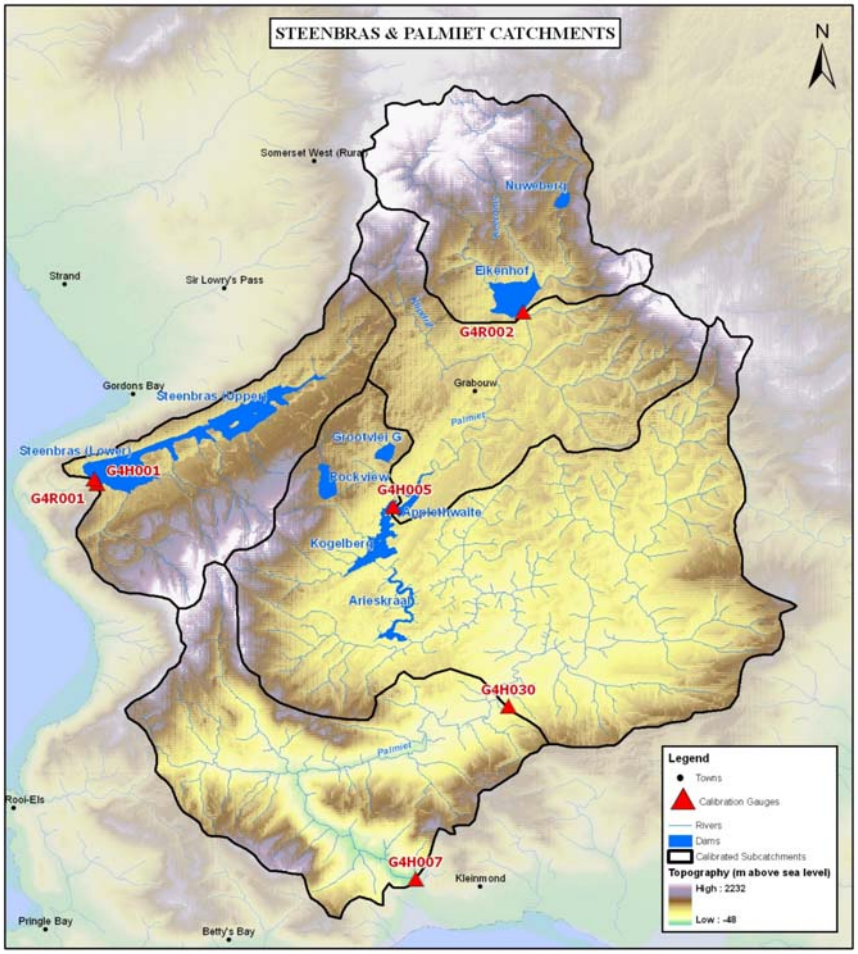
Figure 5:18 : Monthly Incremental flows at G1H013: Simulated with G1H036 parameters versus observed DT9

5.7 Palmiet River at Campanula (G4H030)

Following the pre-review catchment calibration, there were concerns with the accuracy of the observed flows at G4H030. A reasonable calibration at this point was not achieved and as a result, the simulated flows in the Palmiet catchment below Kogelberg were calibrated on the downstream flow gauge at Hangklip (G4H007). This was of particular concern because G4H030 is a relatively new streamflow gauge and is considered to be accurate.

There are three gauges downstream of the Kogelberg Dam in the Palmiet River, shown in Figure 5:19:

- G4H029, located just downstream of the Kogelberg Dam,
- G4H030, located at Campanula,
- G4H007, located at Hangklip near the mouth of the Palmiet River.



s:/projects/H400820/mxd/calib_steenbras.mxd

Figure 5:19 : Palmiet catchment flow gauge locations

At the start of winter some of the releases from Kogelberg will be used to fill Arieskraal (about 3 million m³/a). Also some of the streamflow generated in the Krom catchment between G4H029 and G4H030 will be intercepted by the farm dams in the area (about 18 million m³/a). However, once the farm dams are full, then the streamflows at G4H030 should be at least halfway between those measured at G4H029 upstream and G4H007 downstream. This assumption is based on the expected magnitude of flow following examination of the MAP and the incremental subcatchment area between G4H029 and G4H030, and between G4H030 and G4H007.

It appears as though the observed streamflows at G4H030, in particular the high flows, may be underestimated. Figure 5:20 and Figure 5:21 illustrate the problem during 2001 and 2006 respectively.

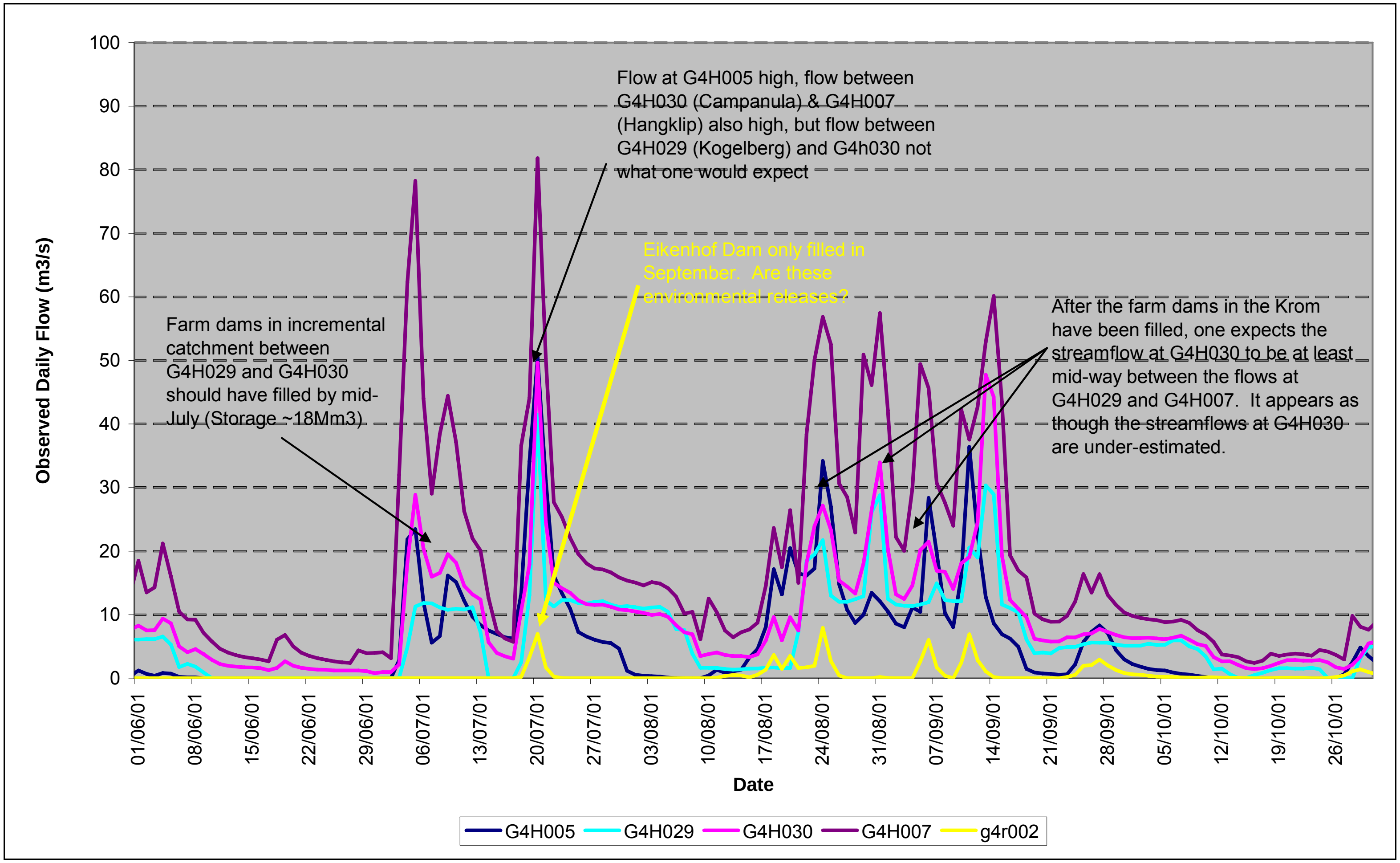


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Figure 5:20: Daily flows in the Palmiet during winter 2001

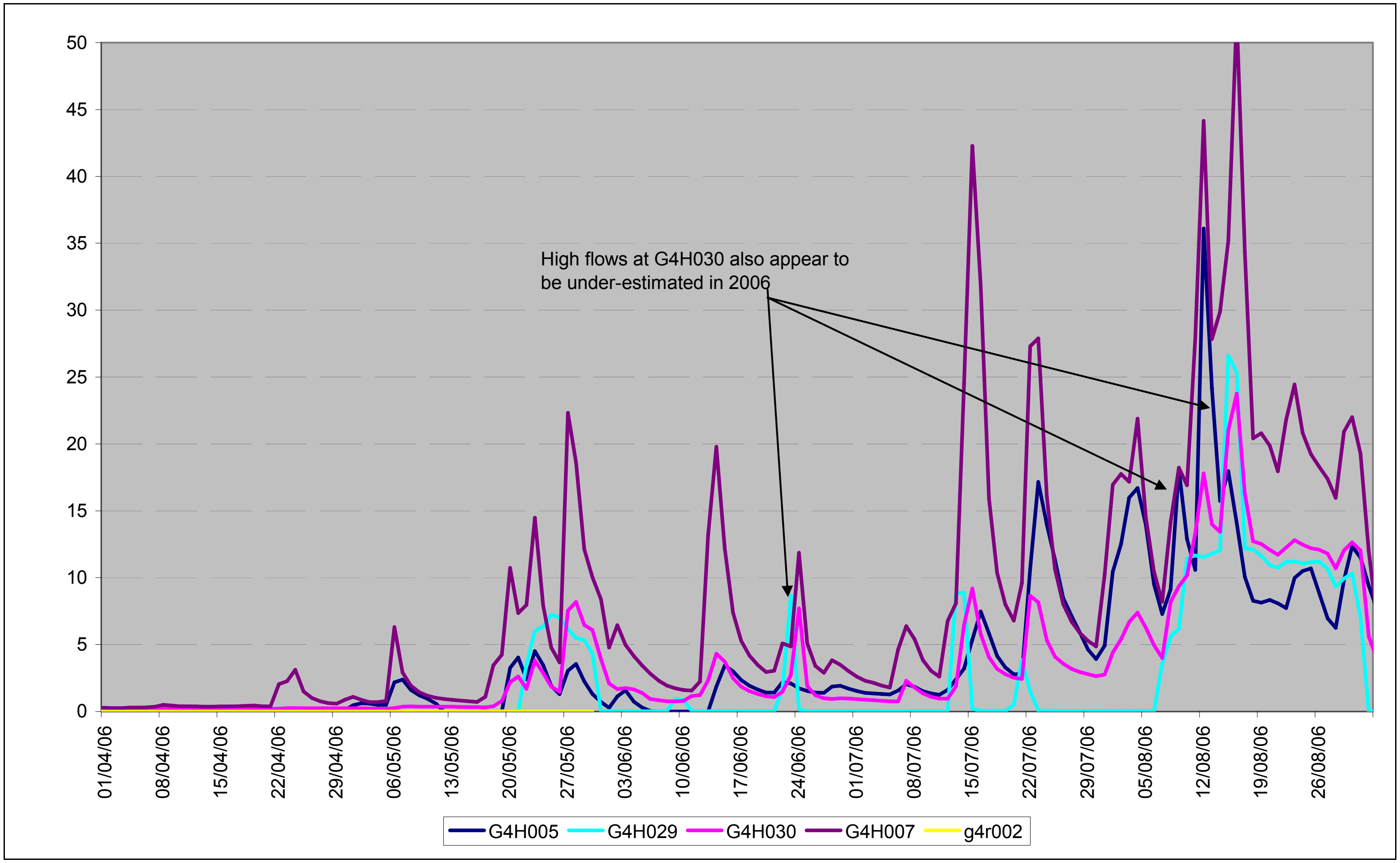

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Figure 5:21: **Daily flows in the Palmiet during winter 2006**

The concerns with the flow gauge at Campanula were reported to DWAF who acknowledged the problem, revised the rating table and recalculated the flows. However, the pre-review incremental simulated flows were calibrated on the observed flows at Hangklip downstream of Campanula. These simulated flows at Campanula were compared to new observed flows at G4H030 and although it was a better comparison, the observed flows were still slightly over-estimated (Figure 5:22. Rainfall stations used to generate the catchment rainfall were investigated and revised which resulted in a better simulation of flows at this point in the catchment (Figure 5:23).

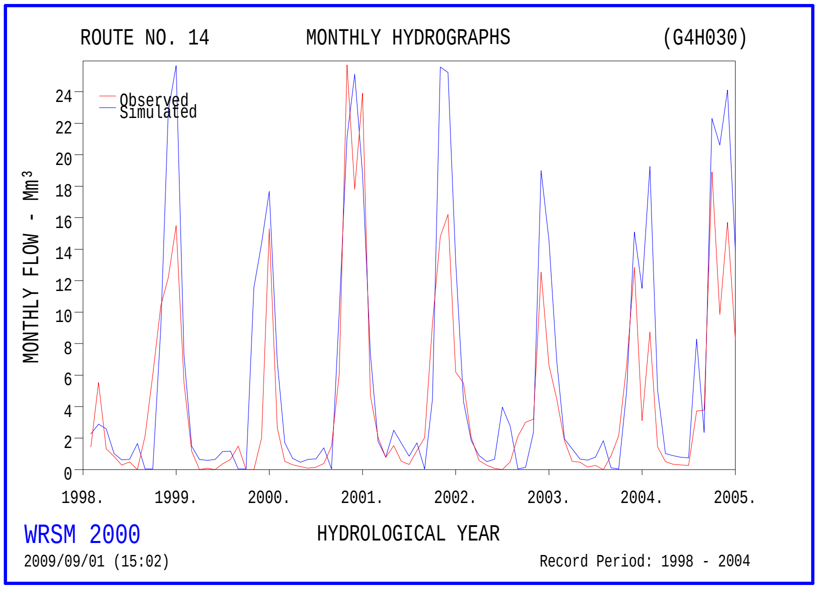

Figure 5:22 : Simulated versus observed flows at updated gauge G4H030

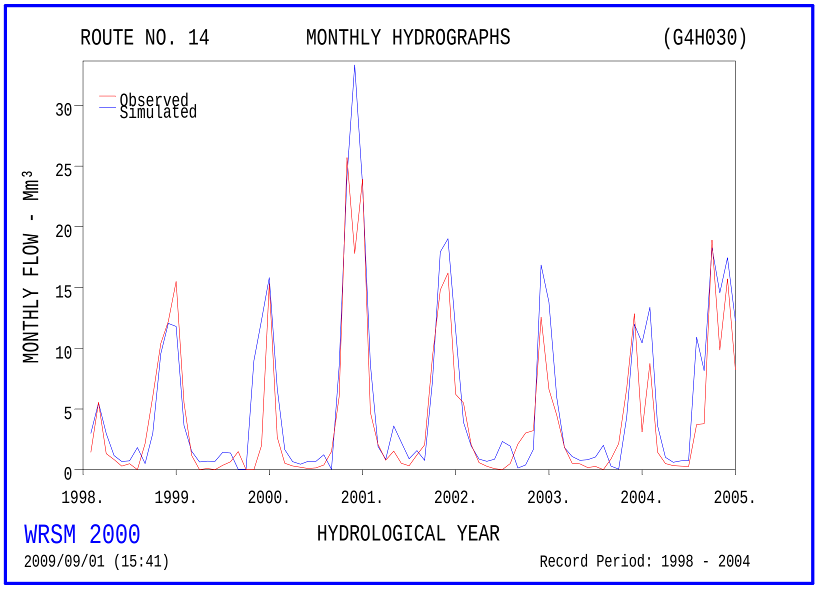

Figure 5:23 : Simulated flows at updated gauge G4H030 with new rainfall station combination

5.7.1 Discussion and Conclusions

The review of hydrology in the Berg WAA Study was an iterative and ongoing process. Notwithstanding achieving fairly good calibrations during the pre-review hydrology task, important discrepancies only became evident during the yield modelling task when detailed comparisons to the previous studies were made. Further investigations have highlighted that the results were strongly influenced by hydrological and land use information that is primary input to the models. Uncertainties in the rainfall network coverages and in streamflow records can affect the accuracy of the hydrological modelling and, in turn, can lead to inaccurate or conservative yield estimates.

It is therefore of great importance that these input data sources are collected and maintained to a high standard. The existing monitoring networks for rainfall and flow gauging need to be maintained and, where possible, extended to include stations in locations that would add particular value to future hydrological assessments. It is not only important to have a structural network in place, but also to have rigorous methods for checking, collection and dissemination of data.

6 GROUNDWATER / SURFACE WATER INTERACTION

6.1 Introduction

In most studies, groundwater is only considered as a stream flow reduction activity, and is modelled within the current framework of the Water Resources Yield Model (WRYM). The approach and methodology implemented in the Berg WAAS differs significantly in that groundwater is considered an integral part of the water resources. The quantification of the groundwater resource is modelled in its own right and then coupled with surface water models to quantify the surface water – groundwater interaction. This allows understanding and quantifying the impact of groundwater abstraction on baseflow, the temporal relationship between groundwater storage and surface water storage, and the impact of reduced streamflows or flood events on groundwater levels. The required model scale and area of interest differs between surface water and groundwater and depends upon the specific model purpose. The integration of the different models requires the definition and delineation of a common domain, called IWRM Domain, which is considered a self-contained unit with defined spatial and temporal distribution of surface water and groundwater. Since the interaction between surface and groundwater is a scale-dependent process, the resource quantification is undertaken at different scales to provide data relevant to the scale of integration. At regional scale a GIS-based water balance model was developed to quantify recharge, storage and discharge per regional aquifer, based on a geologically sound conceptual model. The model results are cross-checked with other models and compared with results from the surface water model. For selected areas of groundwater relevance (e.g. high groundwater abstraction, high potential for surface–groundwater interaction, high groundwater potential for future use) 3-dimensional numerical models were developed at a scale appropriate to the objective of this study. The methodology followed in the Berg WAAS and the lessons learnt from this approach are further discussed in the paper titled “Scale specific methods to quantify SW-GW interaction: lessons from Berg WAAS” which has been included in Appendix B.

6.2 Overview of interactions

The various interactions between groundwater and surface water were identified and assessed by the groundwater / surface water teams to determine the best method of incorporating interactions, where relevant, into the WRYM. Details of groundwater flow and groundwater / surface water interaction are given in the Groundwater Model Report (Report 9 of this series).

Figure 6:1 illustrates the flow of water through an aquifer. A large proportion of the rainfall runs off the ground surface or is ultimately lost through evapo-transpiration. A portion of the remainder infiltrates the soil and percolates downward to the water table or phreatic surface. If the downward flow of the water is blocked by an underlying impermeable layer then a portion of the water can flow into, and recharge the aquifer, and the remaining rejected recharge may emerge at the surface as a spring. The rate at which the aquifer can accept water is dependent on its porosity and the pressure head across the aquifer. In Figure 6:1 the impermeable layer is lower on the left is lower than on the right so water can flow from right to left. Water flowing from right to left will follow the dip of the rock strata and will warm up, depending on how deeply the water penetrates the earth’s crust, and may emerge as a hot spring. A portion of the aquifer is overlain by an impervious layer and that portion is termed a confined, as opposed to an unconfined, aquifer. Breaks in the overlying impervious layer can allow some leakage from the aquifer into the overlying material, but in general the water in the confined aquifer is isolated from the overlying area.

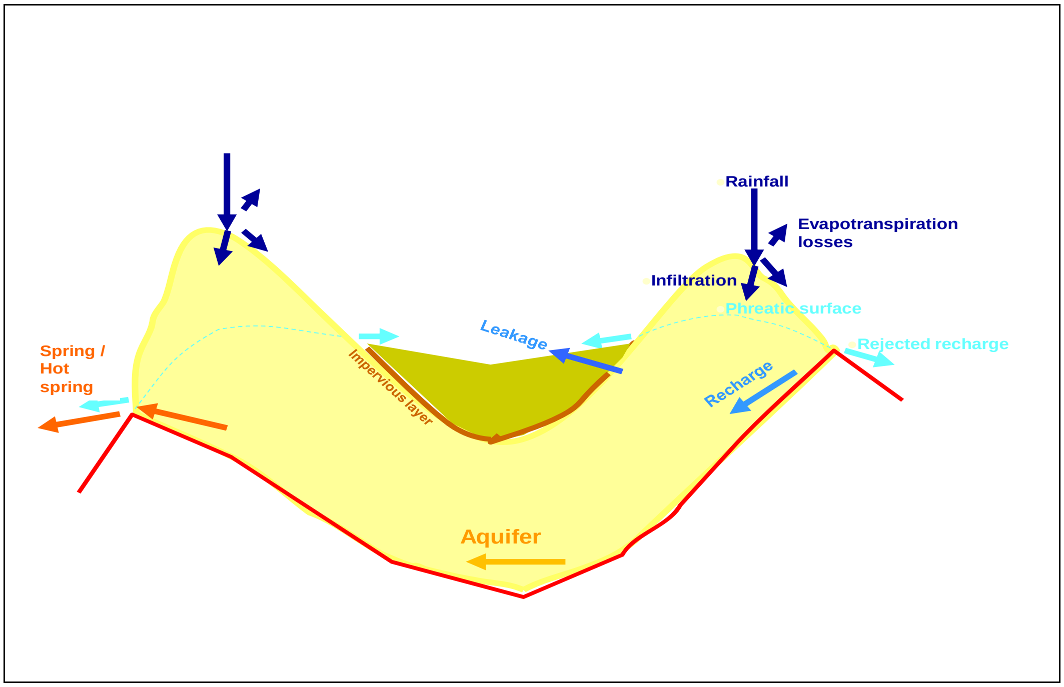

Figure 6:1 : Water flow through an aquifer

If a wellfield penetrates the impervious layer of the confined aquifer and abstracts water then this reduces the water pressure locally within the confined aquifer. This is illustrated in Figure 6:2. Depending on the distance of the wellfield from the edge of the aquifer, this zone of reduced pressure could take decades to reach the perimeter of the confined zone where it might draw down the phreatic surface, where it could cause an increase in the recharge of the groundwater aquifer and a reduction in the rejected recharge. It is important that wellfields be sited as far as possible from sensitive springs to minimize the impact of groundwater abstraction on spring streamflows.

Additional local boreholes could be used to augment the water flows at key springs affected by the reduction in streamflow

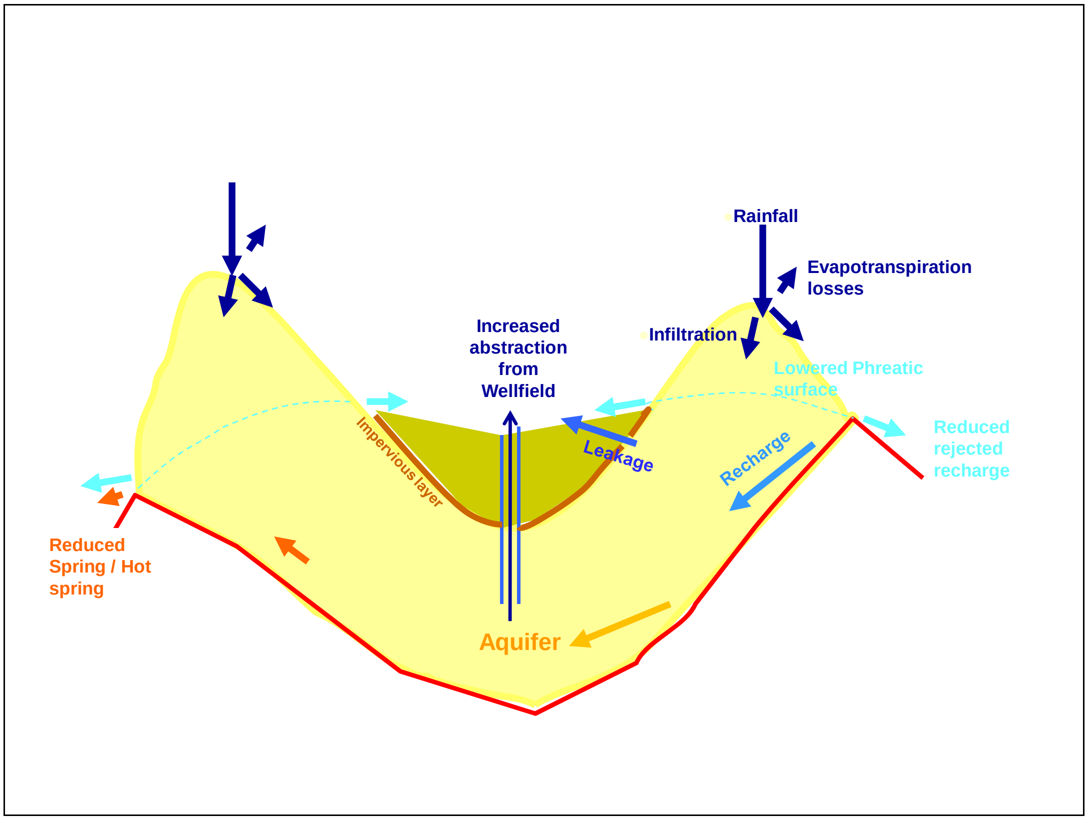

Figure 6:2 : The impact of wellfield abstraction on the available surface water

The different interactions of groundwater with surface water, together with examples drawn from the study area and an indication of how the feature was modeled, have been listed in Table 6.1. Those features modeled within the WRYM model have been highlighted in green. At present the yield model cannot model the extensive lags between the abstraction of water using a wellfield in the confined portion of the aquifer and the impact on springs in the unconfined portion of the aquifer. A spreadsheet was used to estimate the reduction in contribution from groundwater to surface water baseflow, though detailed monitoring and modeling is required for a more defendable estimate.

Table 6.1: Classification of interactions between surface water and ground water

	Feature	Surface water interaction	Example	Modelling
TMG : unconfined	overspill / rejected recharge	seasonal discharge	numerous - eg Mountains around Klein Berg catchment	Included in the hydrology using Pitman groundwater coefficients. Changes in the behavior of the rejected recharge (due to an aquifer being drawn down and capturing more surface water) cannot be modeled in the WRYM.
		constant discharge	large aquifers in the Sand River of the Hex Valley	constant point inflow. The Sand River is not modeled at present as the entire Hex valley is treated as a single inflow sequence into the current WRYM configuration
TMG : confined	leakage through overlying material		Ceres Basin: TMG through Kouebokkeveld	Assumed negligible in this case
	deep (hot) springs	lagged "constant" flows	Brandvlei	Modelled in the WRYM as constant point inflow - ignoring lag
	Reduction in springflow due to drawdown of aquifer	minimized by abstracting away from recharge sites	proposed TMG aquifer abstraction	Modelled externally by Umvoto and re-introduced into the WRYM as discussed in the section describing the modeling of the TMG
	aquifer flow along hydrotects	convey flows with lag	Worcester to Langebaan	Not modeled in the WRYM as these hydrotects do not affect the surface water yield of the Western Cape Water Supply Area. Lags not available in the WRYM at present.
Alluvium	recharge/ discharge	attenuate river flow (Holsloot)	Breede R u/s Brandvlei Dam	Will be included in the WRYM version of the Breede River as a storage reservoir with surface representing recharge area and discharges related to the "level" in the reservoir
		discharge to Breede River	Ceres R Basin, Breede River Valley	

A regional water balance model of the Western Cape was developed as part of the WAA study, which included determining the storage, recharge and discharge to the surface water of the major aquifers of the Western Cape. The results have been summarized in Table 6.2. Figure 6:3 shows the location of the Integrated Water Resource Management (IWRM) Domains referred to in Table 6.2 while Figure 6:4 also shows the storage, recharge and discharge to the surface water of the major aquifers and the routes of the major hydrotects to the sea. A preliminary attempt was made to apportion the contribution of each aquifer to the surface water flows in each catchment using the relative area of the aquifer outcropping in each catchment (See Appendix C).

Table 6.2: Storage, Recharge and discharge to surface water of major aquifers in the Western Cape

Formation	Integrated Water Resource Management (IWRM) domain		Total for all relevant aquifers in (IWRM) domain			Aquifer parameters in Surface Water (SW) model domain		Aquifer specific parameters for IWRM domain					
			Total Of AREA_SqKM	Total Recharge	Discharge_mcm	Outcrop in SW model	Aquifer Recharge	Total outcrop recharge area	aquifer storage volume	Recharge from rainfall	Recharge from other aquifers	Discharge to surface water	Abstraction from GW
			km^2	mcm/a	mcm/a	km^2	mcm/a	Km^2	mcm	mcm/a	mcm/a	mcm/a	mcm/a
COLUMN A	**B**		**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
Peninsula	AWT	Agterwitzenberg	57	7		18	3	99	13163	15		3	
	WBK	Warmbokkeveld	86	13		61	10	81	34109	14		2	
	AWT+WBK		143	20		78	13	180	47272	29		5	
	BRV	Brandvlei	1040	133		559	94	544	31672	110		21	
	RBT	Robertson	3	0		3	0	66	69925	5		0	
	BRV+RBT		1043	133		561	94	610	101597	115		21	
	KGB	Kogelberg	487	53		52	11	122	31749	27		6	
	PUB	Paarl Upper Berg	936	144		275	81	271	2796	82		12	
	THK	Theewaterskloof	513	87		159	42	327	37802	61		8	
Skurweberg	AWT	Agterwitzenberg	57	7		39	4	275	1349	34		8	
	WBK	Warmbokkeveld	86	13		25	4	242	12831	30		6	
	AWT+WBK		143	20		64	8	517	14180	64		14	
	BRV	Brandvlei	1040	133		36	4	87	11788	11		2	
	RBT	Robertson	3	0		0	0	248	17052	8		0	
	BRV+RBT		1043	133		36	4	335	28840	19		2	
	KGB	Kogelberg	487	53		434	42	382	3492	62		16	
	THK	Theewaterskloof	513	87		294	37	313	6677	40		6	
Details of other Aquifers	CFP	Cape Flats – Peninsula,	Modelled outside WRYM - See report dealing with the Cape Flats Aquifer										
		Langebaan Road Aquifer	Modelled outside WRYM - See report dealing with the Langebaan Road Aquifer										
	BRV-RBT	Brandvlei – Breede River Alluvium						489	489	23	8	13	18
Total			**5307**	**731**		**1953**	**331**	**3547**	**274894**	**523**	**8**	**103**	**18**

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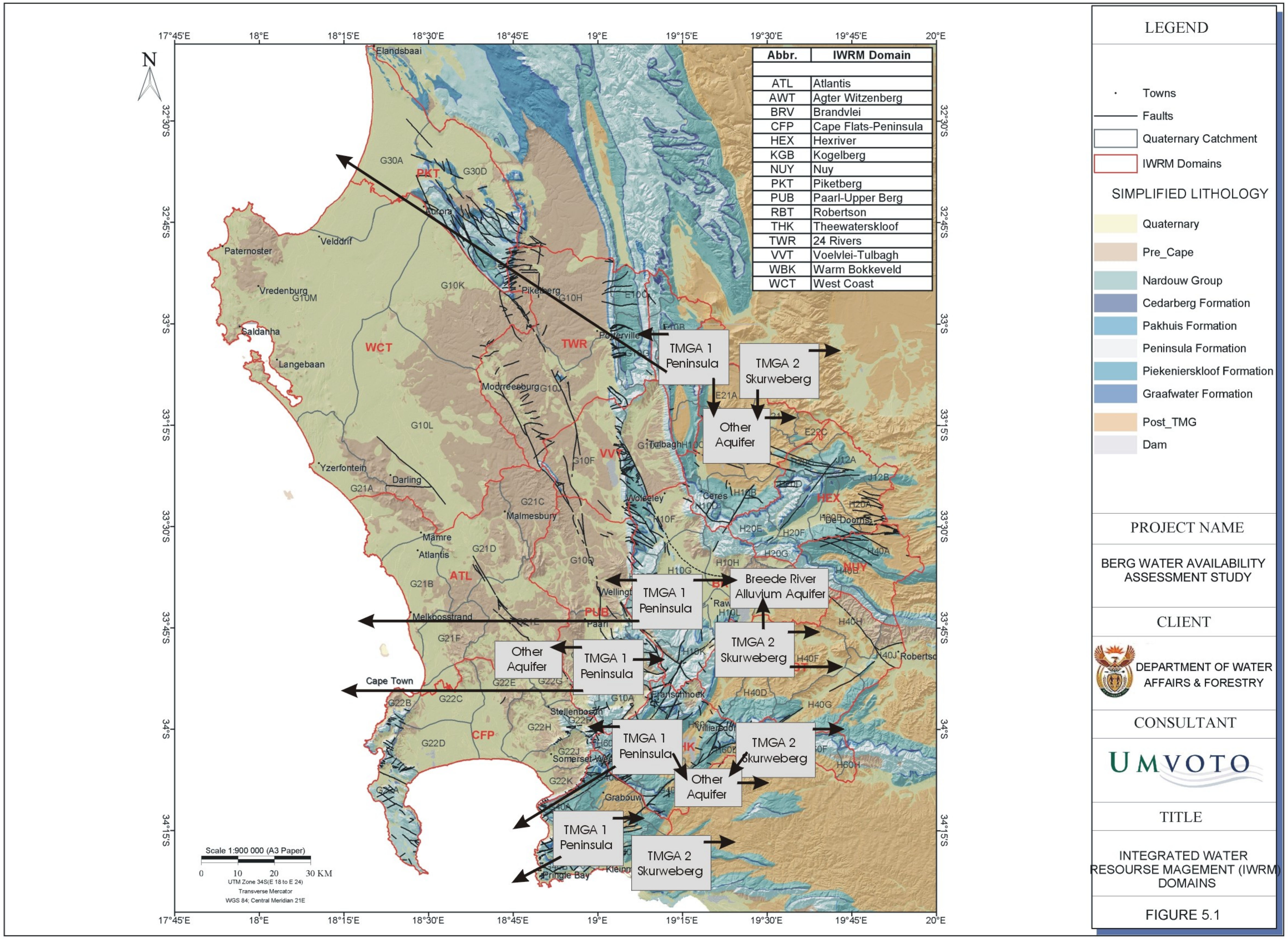

Figure 6:3 : Integrated Water Resource Management (IWRM) Domains

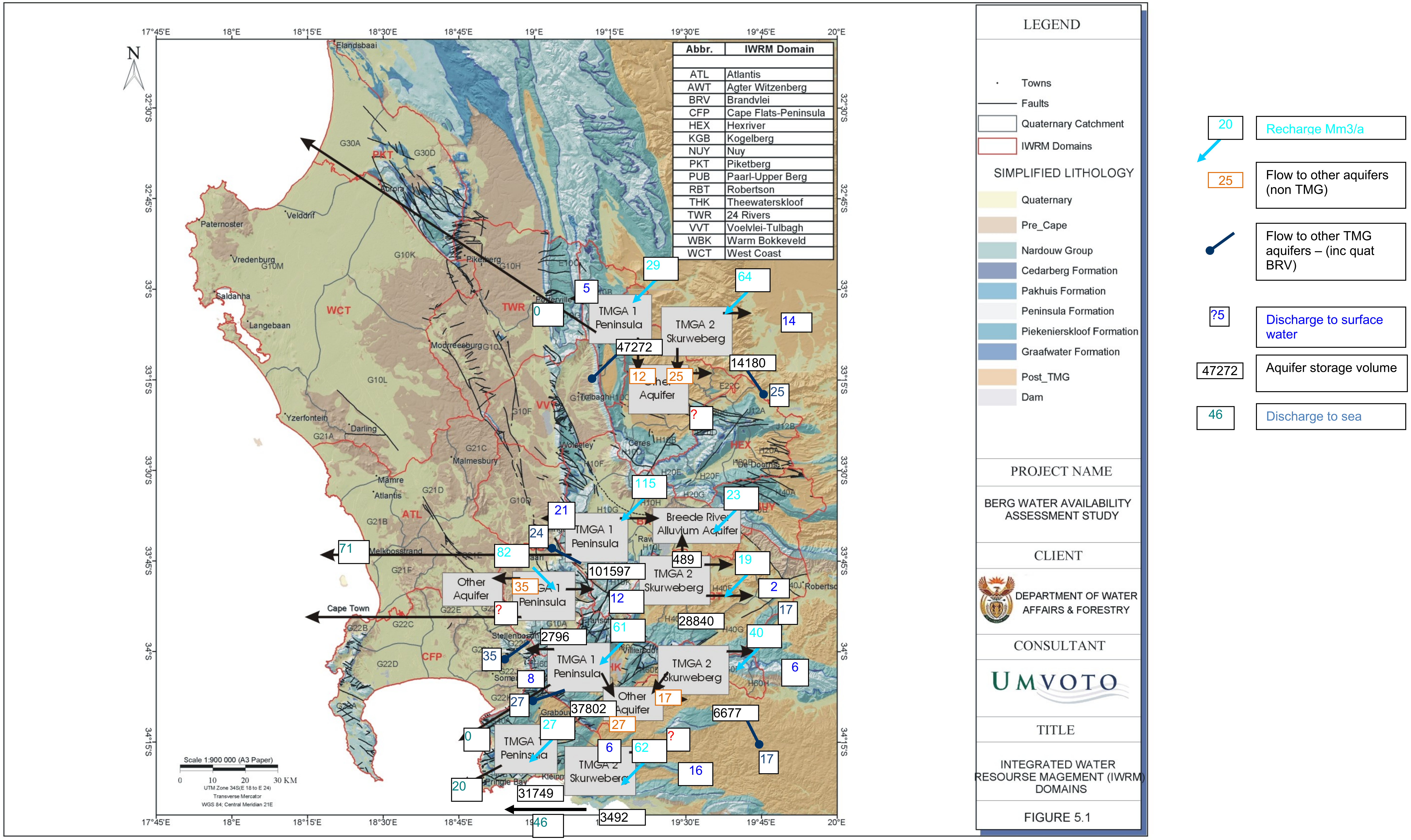

Figure 6:4 : Storage Capacity, Recharge and discharge to surface water and to sea of the major TMG aquifers in the Western Cape Area

6.3 Modelling the interaction between surfacewater and the TMG

6.3.1 Introduction

The data from the regional water balance model indicates that In the Western Cape the ground water resource of the Table Mountain Group (TMG) is a couple of orders of magnitude greater than the surface water resource while the recharge rate of the groundwater is about a third of the inflows to the dams (see Table 6.3). The conjunctive use the two water resources could maximize the benefit of groundwater to the water supply. Initially, mining some of the ground water storage could provide water while other sources are being evaluated and desalination technologies are being refined. Later groundwater could be used to augment the system only during times of drought to reduce the abstraction to the sustainable recharge rate.

Table 6.3: Characteristics of surface water and groundwater

Feature	Surface water	Groundwater
Storage (mcm)	900	82516
Inflows or Recharge (mcm/a)	805	273
Groundwater contribution to surface flows (mcm/a)		< 49

Note that for extended periods of about five years the inflows can reduce to 60% of the average and it is especially during these drought periods that augmentation from the groundwater would be especially beneficial.

6.3.2 Quantifying the benefits of conjunctive use

The benefits of conjunctive use were quantified for the Theewaterskloof compartment of the Peninsula formation of the TMG aquifer. This has the advantage that the groundwater well field accessing this aquifer would be able to use existing storage and conveyance infrastructure. Water could be stored in the Theewaterskloof / Berg River Dams and conveyed to the City using the Theewaterskloof Tunnel. It might be necessary to construct an additional Water Treatment Plant, maybe near Muldersvlei, to process water supplied to the North Western suburbs of Cape Town.

The following approach was adopted:

- The benefits of conjunctive use were first evaluated in the Water Resources Yield Model (WRYM) for various groundwater abstraction capacities and operating rules with different spillage risks.
- Thereafter, a combination of local expert knowledge and a spreadsheet model was used to provide an initial estimate of the impact of the abstraction scenarios on the TMG and on the contribution of groundwater to surface flows.
  The reduced estimate of the contribution of groundwater to surface flows was used to adjust the yields obtained in the WRYM.

6.3.3 Results

The results from the yield analysis have been summarized in Figure 6:5. Various relationships have been identified and illustrated in additional figures. Figure 6:5 illustrates that if the system is operated at a higher spillage risk then the ratio of the yield to the installed capacity of groundwater increases from 60% for spillage risks of about 10% to about 90% for spillage risks of 100%. Due to the summer peak in demand the groundwater abstraction capacity must exceed the average annual water requirement. Were the water requirement constant throughout the year then the ratio of yield to installed capacity would tend to 100% for scenarios with a high spillage risk.

The increase in yield is actually greater than the average volume pumped, especially when using operating rules with a low spillage risk. The difference between the yield and the volume pumped was termed the “conjunctive” component of the yield. The ratio of the conjunctive yield to the total yield varies from 35-40%, if the system is operated at a low spillage risk, down to about 5-10% if the system is operated at a high spillage risk.

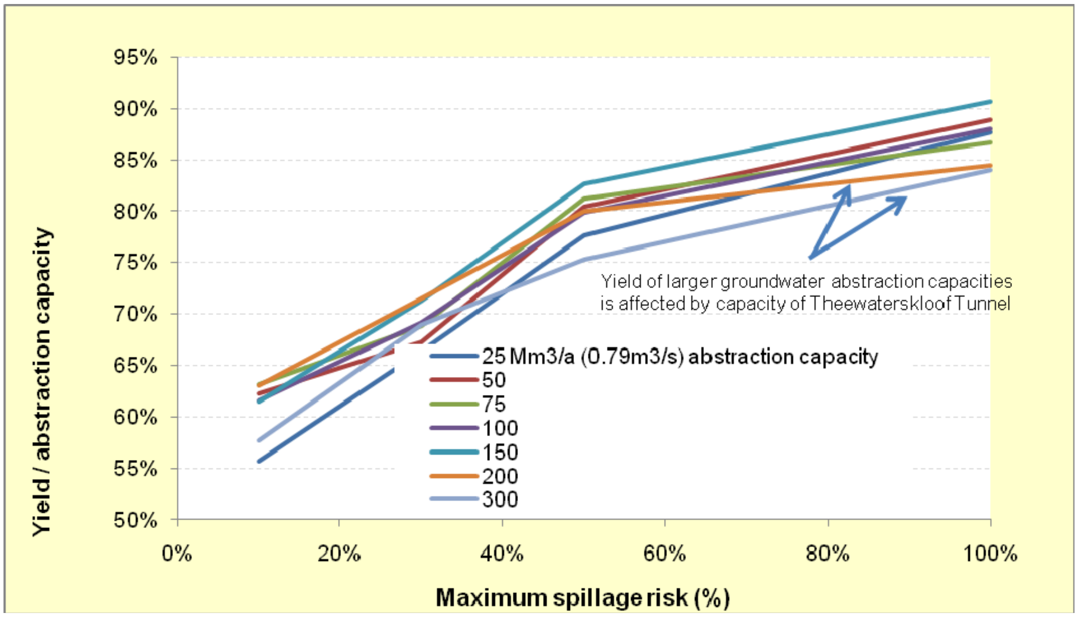

Figure 6:5: Yield / capacity for different groundwater abstraction capacities and for operating rules with different spillage risks

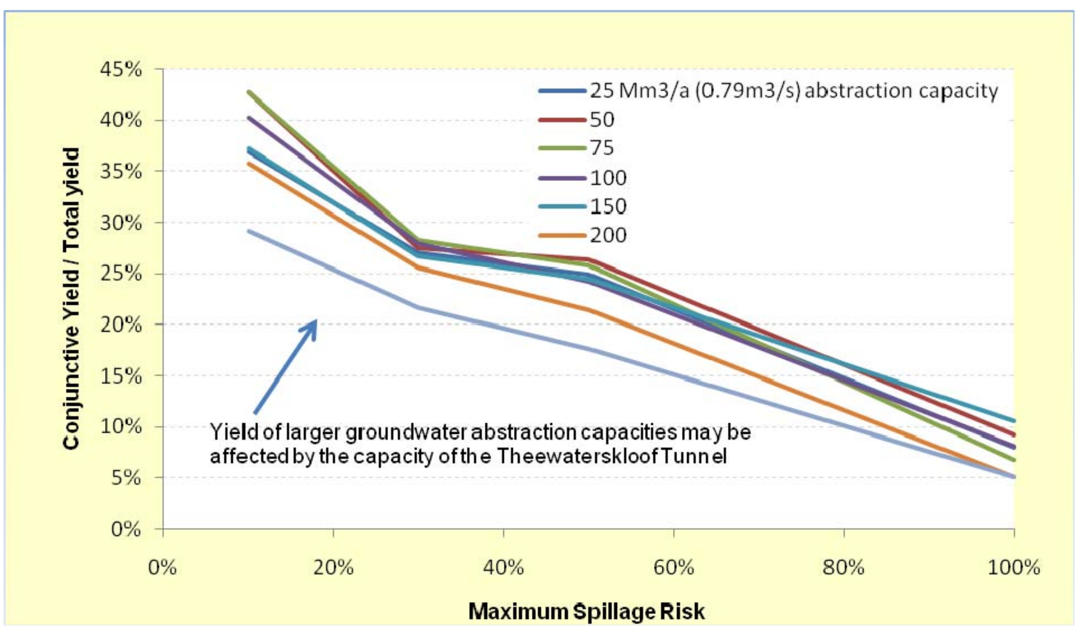

Figure 6:6: Ratio of conjunctive yield to total yield for different groundwater abstraction capacities and for operating rules with different spillage risks

6.3.4 Conclusions

A flexible approach should be adopted in the use of groundwater to augment the Western Cape System. Initially abstractions from the TMG Aquifer could exceed the recharge rate but later the abstractions could be reduced to the recharge rate. The reduction in yield would however be less than the reduction in average long-term abstraction

These results were presented at the 14th SANCIAHS conference and the full paper, which discusses some issues such as the operating rules and the interpretation of the results in more detail is included in Appendix D.

6.4 Breede River Alluvium Aquifer

6.4.1 Key features from the analysis using Modflow

The analysis of the breede river alluvium is described in detail in Volume 9 of the groundwater model reports. It was also described more briefly in a paper submitted to sanciahs titled "assessing aquifer yields through integrated numerical sw-gw modeling – a case study from the berg waas" which has been included as an appendix for reference.

The Breede River Alluvium is mainly recharged by rainfall, though mountain tributaries that pass through the alluvium and leakage from the TMG are an additional source of recharge. The Breede River drains any surplus water. Currently, irrigators abstract about 18 million m^3/a from the alluvium. It is estimated that the recharge from rainfall and the tributaries are about 23 million m^3/a and 8 million m^3/a respectively, leaving about 13 million m^3/a that is returned to the Breede River. Increasing the abstraction from the alluvium will lower the water level in the alluvium, increasing the water intercepted from the tributaries and reducing the water returned to the Breede River.

In addition to the natural recharge, it may be possible to increase the aquifer recharge by infiltrating surplus flood water from the tributaries. The unsaturated volume in the aquifer is estimated between 250 and 1 100 million m^3 for a porosity of 5% and 20%, respectively. About 150 to 300 million m^3 are available for artificial recharge.

The available volume may be increased by drawing down the water level further in summer and identifying larger recharge schemes. The practicality of increasing the storage in the alluvium should be explored in more detail.

Some of the key features of the Breede River Alluvium Model have been summarized in Table 6.4.

Table 6.4 : Key Features of the Breede River Alluvium Aquifer based on Groundwater Model Report Volume 9 covering the Breede River Alluvium Aquifer Model

			Reference from Groundwater Model Report (note 1)
The Volume and surface area of the aquifer are estimated as below:			
23	Average mcm/a rainfall	Recharge from rainfall	Table E.1
47	mm recharge from rainfall		Section 4.4.1
21	multiplier to convert mcm/a to obtain the recharge area	=1/0.047	
489	area recharged	=multiplier x factor = 23 / 0.047	
5%	Porosity	0.05 to 0.35	Section 4.3.3
20	Average aquifer depth		Figure 3-6
489	Volume in aquifer	=Area x average deposit depth x porosity	

The long-term mass balance for the Breede R aquifer for different target demands

Target demand	0	18	
Rainfall percolation	23	23	
Tributaries via alluvial fans	3	8	
Artifical recharge of alluvial fans	0	0	Section 5.6.3 (Natural) and Figure 5-12 (18mcm/a)
Irrigation	0	-18	
Breede River	-26	-13	
Nett gain	0	0	

Rough check to see if a estimated change in level of aquifer for 18mcm/a abstraction compares with observed level changes

4	M	Observed Valley Side level fluctuation	Section 5.5.2
0.4	M	Observed Valley Bottom level fluctuation	Section 5.5.2
0.4 to 0.6	M	Observed River level fluctuations	Figure 5-4 & 5-5
0.94	ht fall for 23mcm outflow	= 23 / (Area x porosity)	
19.99	ht corresponding to 489 mcm (full capacity)		

Rough estimate of the additional storage available for artificial recharge using floods

	depth category	depth	area (%)	volume	
	0	0	5%	0	Estimate based on Figure 6.2 - visual integration of areas corresponding to different depths and a 5% porosity. The figure would be double for a porosity of 10%.
	0-10	2	40%	20	
	10-20	10	30%	73	
	>20	10	25%	61	
154	total mcm			154	

1.25	mcm	Based on 8 cells of 500mx500mx 5m deep with a porosity of 10% and an additional cell which is 10 m deep	Section 6.3 - these values include a conservative factor of safety

Note 1 Department of Water Affairs and Forestry, South Africa. 2008. The Assessment of Water Availability in the Berg Catchment (WMA 19) by means of Water Resource Related Models : Groundwater Model Report Volume 9 - Breede River Allufium Aquifer Model.
Prepared by Umvoto Africa (Pty) LTD in association with Ninham Shand (Pty) Ltd on behalf of the Directorate : National Water Resource Planning. DWAF Report No. P WMA 19/000/00/0408

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6.4.2 Spreadsheet Model of the Breede River Alluvium

A simple spreadsheet model was developed to check whether modeling the Breede River Alluvium as a reservoir in the WRYM would be adequate and to identify any shortcomings. The dimensions of the reservoir were selected so that a given abstraction from the reservoir would result in a realistic reduction in level of the reservoir. This was achieved by eliminating the voids by multiplying the surface area of 489km^2 by the void ratio of 5% to obtain an area of 24.5 km^2 (conceptually achieved by compressing it laterally but not vertically). The rainfall intensity had to be increased to compensate for the reduction in surface area (through dividing the actual percolation by the porosity) to obtain the correct average recharge from rainfall.

The boreholes were assumed to abstract from the reservoir and reduce the volume in storage. The recharge from the tributaries at the alluvial fans was assumed to ***increase*** linearly as the volume in storage dropped. On the other hand, the discharge to the Breede River was assumed to ***decrease*** linearly as the difference in level between the reservoir and the Breede River reduced. One complication is that the level in the Breede River varies with the flows in the river and this was approximated using the seasonal variation in river level.

The parameters of this model were chosen to approximate the annual mass balance obtained for present day conditions. Figure 6:8 shows how imposing a demand of 18 million m^3/a on the system will draw down the aquifer level (red line) and result in an increase in the recharge from the fan (light blue line) and decrease in river discharge (from -18 to -13 million m^3/a).

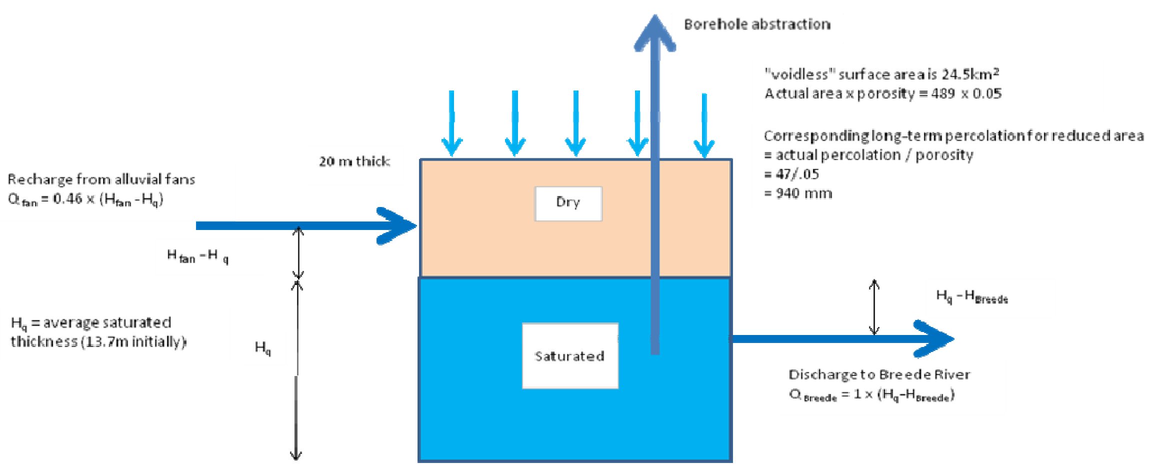

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Figure 6:7 : Key inputs of the spreadsheet model

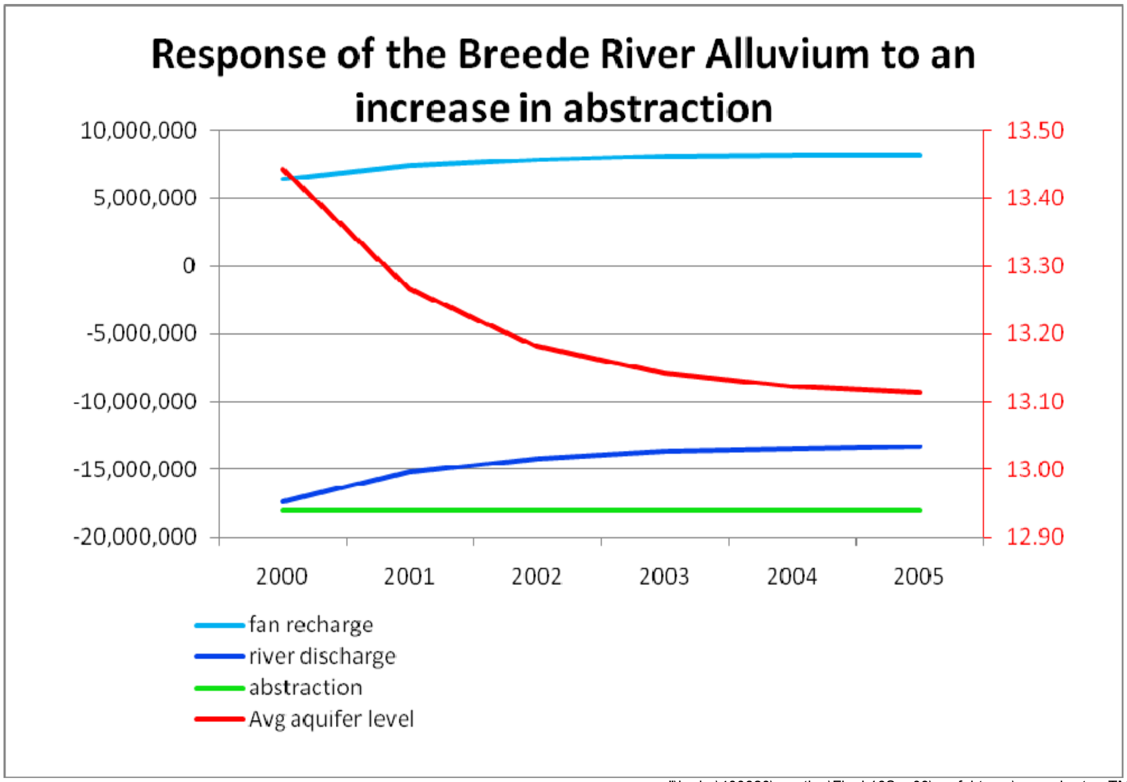

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Figure 6:8 : Response of the Breede River Alluvium to an increase in abstraction from Natural to Present Day Conditions

6.4.3 Proposed Modelling of the Breede River Alluvium in the Water Resources Yield Model (WRYM)

Figure 6:9 indicates how the Breede River Alluvium might be incorporated into the WRYM, including the recharge mechanisms, abstraction and return to the Breede River.

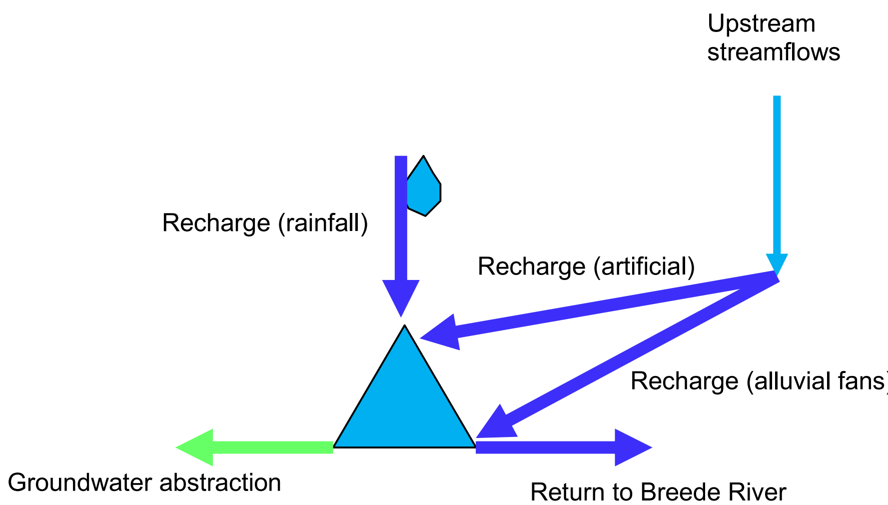

Figure 6:9 : Schematic incorporation of the Breede River Alluvium into the WRYM

7 CONCLUSIONS

The WRYM for the Berg WAAS area provides a useful tool moving forward to the Western Cape Feasibility Study for the assessment of scheme options for future water supply in the Western Cape Water Supply system.

The updated hydrology for the Berg, Theewaterskloof and Palmiet catchments was verified and imported to the WRYM for the Western Cape system. The previous WRYM configuration has been refined and now incorporates some new useful features such as the groundwater / surface water interaction routines, as well as groundwater baseflows which have been included as part of the hydrology for the system. Irrigation return flows have been included and farm dam areas and volumes have been updated.

The historical firm yields obtained for the updated system compare well to those obtained in the WCSA and the WRYM simulations compare well with the hydrology simulations following the extensive verification process.

A number of refinements will still be included in the WRYM during the Feasibility Study, including:

- The updated environmental streamflow requirements,
- The updated diversion at the Supplement Site, incorporating the latest reserve environmental water requirements,
- A diversion taking into account the actual spillage occurring at the Kleinplaas Dam,
- Evapotranspiration losses in the Lower Berg River,
- Incorporating the proposed augmentation options, including the Voëlvlei Augmentation, Wit River Diversion, Mitchell's Pass Diversion, Campanula Dam and the raising of the Steenbras Dam,
- The evaporation from Theewaterskloof and Voëlvlei Dams will be set equal to the average evaporation over a three year drought period.

The integration of groundwater into the WRYM and the conjunctive use of groundwater and surface water showed that the additional yield from optimising the conjunctive use can be significantly higher than the actual groundwater abstraction. This requires further investigation, especially with respect to the TMG Aquifer development (Report 9, Volume 1; DWAF, 2009).

8 REFERENCES

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APPENDIX A

DETAILED COMPARISON OF THE SYSTEM FLOWS BASED ON THE LEGACY SYSTEM AND THE REVIEWED HYDROLOGY

The same WRYM configuration was used for modelling the legacy system and the revised system, with the exception of the catchment upstream of the Theewaterskloof Dam, where it was impracticable because additional farm dams were included during the calibration process.

The legend in the top right of the plot describes the different inflow components, namely incremental inflows, afforestation and diffuse irrigation. The average flows for the period from 1 October 1928 to 30 September 2005 are listed below the “penalty block” associated with each “arc” or arrowed line. The first flow is from the legacy system and is separated from the second number from the reviewed hydrology by an arrow. The units are million m^3/a.

APPENDIX B

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SCALE SPECIFIC METHODS TO QUANTIFY SW-GW INTERACTION: LESSONS FROM BERG WAAS

SCALE SPECIFIC METHODS TO QUANTIFY SW-GW INTERACTION: LESSONS FROM BERG WAAS

E.R. Hay[1] , K. Riemann[1] and I. Thompson[2]

[1] Umvoto Africa,
Muizenberg, Western Cape, South Africa; email: amanzi@umvoto.com

[2] Department for Water Affairs and Forestry, Directorate: National Water Resource Planning
Pretoria, Gauteng, South Africa; email: thompsoni@dwaf,gov.za

Abstract

The Department for Water Affairs and Forestry (DWAF) have embarked on Water Availability Assessment Studies (WAAS) in several Water Management Areas (WMAs) to provide a sound quantitative basis for water allocation and eventually compulsory licensing. Hence, water resource quantification models need to be configured, sequenced or linked in such a way that different scenarios may be assessed for aligning water supply and demand to best meet the Reserve and the Resource Quality Objectives (RQOs) in a given catchment. In most studies, groundwater is only considered as a stream flow reduction activity, and is modelled within the current framework of the Water Resources Yield Model (WRYM). The approach and methodology implemented in the Berg WAAS differs significantly in that groundwater is considered an integral part of the water resources. The quantification of the groundwater resource is modelled in its own right and then coupled with surface water models to quantify the surface water – groundwater interaction. This allows understanding and quantifying the impact of groundwater abstraction on baseflow, the temporal relationship between groundwater storage and surface water storage, and the impact of reduced streamflows or flood events on groundwater levels. The required model scale and area of interest differs between surface water and groundwater and depends upon the specific model purpose. The integration of the different models requires the definition and delineation of a common domain, called IWRM Domain, which is considered a self-contained unit with defined spatial and temporal distribution of surface water and groundwater. Since the interaction between surface and groundwater is a scale-dependent process, the resource quantification is undertaken at different scales to provide data relevant to the scale of integration. At regional scale a GIS-based water balance model was developed to quantify recharge, storage and discharge per regional aquifer, based on a geologically sound conceptual model. The model results are cross-checked with other models and compared with results from the surface water model. For selected areas of groundwater relevance (e.g. high groundwater abstraction, high potential for surface–groundwater interaction, high groundwater potential for future use) 3-dimensional numerical models were developed at a scale appropriate to the objective of this study. This paper presents the methodology followed in the Berg WAAS and the lessons learnt from this approach.

1. INTRODUCTION

The Berg River Catchment forms the heart of the Western Cape Water Supply System (WCWSS), whose supply area constitutes the economic hub of the Western Cape and serves a primary export industry based on agricultural produce. The WCWSS serves the City of Cape Town, both urban water users and irrigators along the Berg, Eerste, Lourens, Steenbras and Palmiet Rivers, domestic and industrial users on the West Coast, as well as irrigators and urban users in the Riviersonderend catchment of the Breede WMA. Currently, the WCWSS relies on surface water through a number of dams in both the Berg and Breede WMA.

The DWAF have initiated two major water resource management and planning undertakings in the environment of the WCWSS:

- Compulsory licensing in terms of the National Water Act (NWA) - Act 36 of 1998 - is due to be piloted in the Berg WMA, in response to concerns that growing water user demands, as well as stream flow salinity increases, might place parts of the WCWSS in a water-stress condition during the foreseeable future.
- A Reconciliation Strategy Study has been completed, which reviewed the future water requirements and the options for meeting these demands. The Study identified the most favourable augmentation options and recommended a programme of feasibility studies and other

investigations to improve the operation and planning of the system, and to ensure that the necessary infrastructure or other interventions are implemented in good time to reconcile the supplies with the future demands.

This Water Availability Assessment Study (WAAS) forms part of five studies commissioned nationally by DWAF to support, *inter alia*, allocable water quantification as a prerequisite for compulsory licensing. The main objectives of the Study are to (DWAF, 2005):

- Reconfigure the existing Water Resources Yield Model (WRYM) configurations at a spatial resolution suitable for allocable water quantification to support compulsory licensing.
- Use reconfigured existing models or newly configured models for allocable water quantification for both surface water and groundwater, where applicable.

Groundwater plays an important role in the Berg and Breede WMA as a significant water resource and for conjunctive use management. Hence, it was considered necessary to assess the groundwater availability, to propose groundwater scheme and conjunctive use options and to assess and quantify the surface water – groundwater interaction and impacts of abstraction on each other. Based on the hydrogeological analysis and the requirements for modelling as well as the over arching strategic management intent established for the Berg Catchment, a variety of models are considered for evaluating the groundwater availability on a basin, catchment and local scale.

2. GENERAL PROCESS

The Internal Strategic Perspective (ISP) Reports of DWAF (2004) highlight the following aspects as integral parts of the broad process of Integrated Water Resource Management (IWRM):

- caring for the environment and where possible, enhancing ecological integrity;
- keeping society at the forefront of all decision-making;
- affording the correct level of attention to addressing water quality issues in relation to both surface and groundwater;
- managing groundwater as an integral part of the total water resource;
- taking cognisance of the recreational and social use of dams and rivers; and
- forging ways to improve co-operative governance with other authorities towards more effective water resource management.

DWAF, as the custodian of the water resources in South Africa, has available several tools under the NWA for ensuring that the goals of IWRM are met within the boundaries of the WMAs. Compulsory licensing is one of these tools and is described by the NWA as a process aimed at stressed catchments, in which every water use must be licensed or registered with the authority, irrespective of other authorisations, such as Schedule 1, General Authorisation or existing lawful use. The aim of compulsory licensing is to distribute the sustainably available supply (i.e. current yield, not potential yield) water within the catchment equitably between all potential users, without compromising the future needs or foreclosing on certain water resource development options.

For surface water allocation this is a simple 2D analysis and allocation of current use. However for groundwater the impact of future users accessing on current users and therefore the sustainable utilisation of water in aquifer storage by both groups can only be assessed if the potential yield rather than the current yield is analysed with appropriate spatial (2D/3D) and time series (4D) detail. It is necessary to appreciate this essential difference in the management or compulsory licensing process as well as in the resource development process.
In order to achieve this, the regulatory authority needs to have knowledge of the following:

- total amount of water available within the catchment;
- temporal and spatial distribution of water availability;
- current and future water demand;
- impact of water abstraction at any point and time on the environment and other users.

The coupling of all processes in the hydrologic cycle (see Figure 1) becomes essential to achieve the understanding and quantification of the water availability and likely impacts of use.

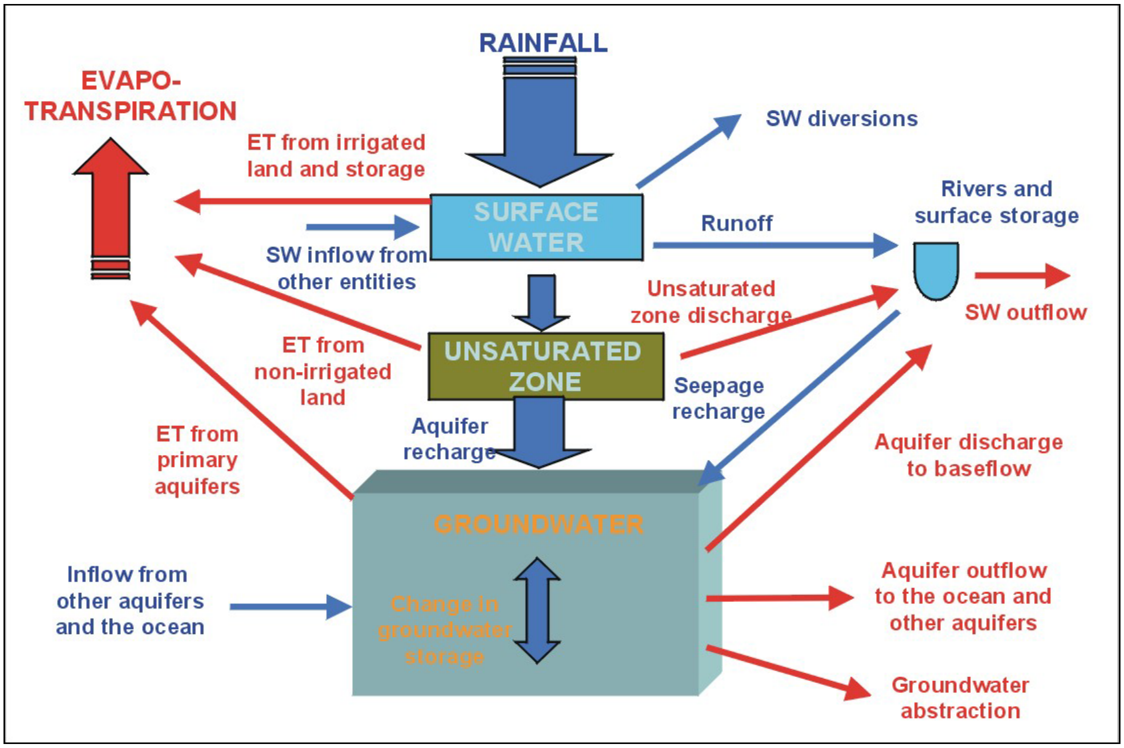

Figure 1 Hydrological processes and interactions, relevant for model approach

Based on the hydrogeological analysis of the study area and the purposes of modelling as outlined above, the following models are considered necessary to address the issues and questions above, relevant to water availability and compulsory licensing. They can be grouped into the following categories:

- Basin scale conceptual groundwater model to identify aquifer-specific flow paths, geometry, recharge/ discharge, surface water / groundwater interaction zones
- Aquifer specific regional water balance model for aquifer-specific estimation of recharge, discharge, storage, groundwater use and potential yield
- Primary (coastal and alluvial) aquifer models to refine the water balance, quantify surface water / groundwater interaction and assess impact of abstraction
- TMG fractured-rock aquifer models to refine the water balance and quantify surface water / groundwater interaction
- Surface water yield model with upgraded groundwater input to assess the surface water / groundwater interaction

The models will be required at different scales and dimensions. To avoid double work and to ensure consistency and common data between these models it is suggested to follow a clear model hierarchy and structure, whereby the regional model feeds relevant data into an intermediate scale model or the local models.

3. RESULTS AND LESSONS LEARNT

The results of the study are summarised below in the sequence of the model approach and according to the relevant scale and dimension.

Data availability and evaluation

In order to determine the groundwater availability in the WCWSS area by means of deterministic and numerical models, a variety of data is required for the different methods and modelling approaches employed. The required data sets refer to the 3D physical, chemical and biological conditions in the study area and the changes thereof over time. However, most often the data are only available in 1D (spatially average per quaternary catchment) or 2D. The main concern with the available hydrological and hydroclimatological data is that they are averaged over quaternary catchments and or time and the detailed spatial component and essentially the seasonal nature of the interaction with the surface water regime is often lost. This inhibits configuring models for conjunctive resource development and surely limits testing conjunctive management scenarios.

However, there is adequate data to initiate modelling, to configure the proposed models, and to run these models to contribute to an improved groundwater resource evaluation, as long as the limitations and resulting uncertainties are acknowledged and sound inferences based on 3D geological insight is optimised to support data extrapolation (DWAF, 2007a). Hence, the data evaluation and the conceptual model are parallel and iterative processes, in that the available data inform the possible conceptual models and the conceptual model allows for further data evaluation.

Conceptual model

An aquifer-specific conceptual model across the study area was developed with the aim to generate a 3D view of the aquifer geometry, hydraulic properties and preferred flow paths, and to identify zones of surface water / groundwater interaction and interaction between aquifers. This requires identification of the groundwater recharge and discharge zones, the preferred flow paths linking these two zones, and the preparation of piezometric maps for each aquifer. The conceptual flow relationship between groundwater and surface-water regimes is based on the 3D characterisation of the aquifers, their likely spatial and temporal relationship with the stream-drainage system, as well as any lateral and vertical recharge between bounding aquifers.

An aquifer-specific approach was adopted to support regulatory decisions (as compulsory licensing) about sustainable aquifer, well field or borehole yield as well as the impacts of abstraction. The major aquifers considered in this study are the Peninsula and Skurweberg aquifers (i.e. fractured aquifers) as well as the coastal and inland alluvium aquifers (i.e. intergranular aquifers). To meet one of the core requirement of the study, viz. to understand and map surface and groundwater interaction and to quantify it so far as possible, to be able to integrate groundwater into the Pitman and the WRYM models, the groundwater study boundaries were defined by areas called Integrated Water Resource Management Domains (IWRM Domains).

An IWRM domain is a defined geographic area within which both the surface water and the groundwater resources, together with water-dependent ecosystems, can be quantitatively assessed, monitored, modeled, and managed in an integrated fashion through the development of conjunctive-use schemes. An IWRM domain aims to integrate the surface-water, groundwater and ecological dimensions of resource management within a unified geographical framework, where these elements share common physiographic and hydrometeorological boundary conditions but may respond on different temporal scales.

The regional conceptual model and selection of 15 IWRM domains (9 classified as fractured, 3 classified as intergranular, and 3 classified as intergranular-fractured; see Figure 2) resulted in reasonable confidence in the boundary conditions selected for the different model domains and an overt understanding of the reasonable simplification to adequately represent the real world in the model configuration (DWAF, 2007b).

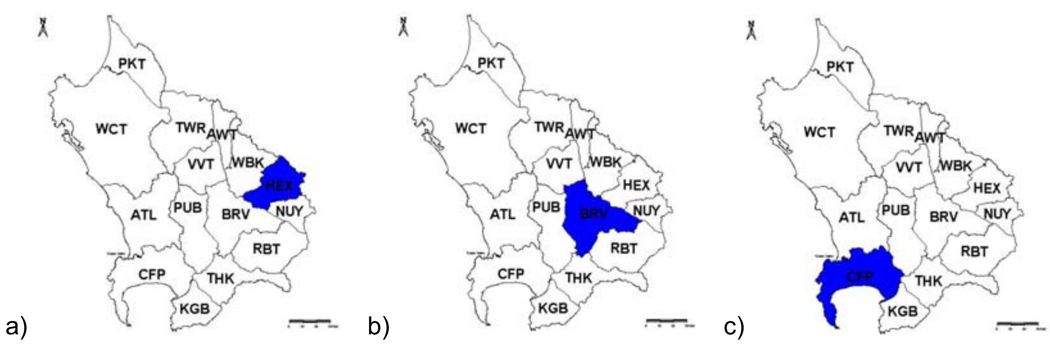

Figure 2 The 15 IRWM domains in the Berg WAAS study area; a) Hex River Mountains – fractured, b) Brandvlei – intergranular fractures, c) the Cape Flats-Peninsula - intergranular

GIS based water balance model [2D]

A robust water balance and yield model was developed to estimate the groundwater potential from different aquifers within the study area as well as to produce reasonable values for input parameters to the groundwater modules of the WRYM and WSAM. The model is based on the following components:

- Aquifer specific recharge, calculated with a variety of GIS-based methods and compared to / verified with results from previous studies;
- Modelled overland flow, based on slope distribution, as input to the recharge model;
- Modelled evapotranspiration, using the Turc (1954) approach, as input to the recharge model;

- Storage capacity in the confined Peninsula Aquifer, based on known and *inferred three dimensional* model of the geological structure and the behaviour of confined aquifers;
- Aquifer specific natural discharge, based on groundwater contribution to baseflow and recharge per quaternary catchment;
- Aquifer specific groundwater use, based on registered use on the WARMS database;
- Storage yield for the confined portion of the Peninsula Aquifer, based on the modelled storativity and reasonable values for specific storage (see section below);
- Groundwater potential, based on recharge, baseflow and groundwater use.

The water balance and yield model suggests a total remaining long-term averaged groundwater potential of 869 million m^3/a using the average of the different recharge estimations. In a very conservative worst case scenario the groundwater potential is 741 million m^3/a, while the best case scenario suggests a total groundwater potential of 1003 million m^3/a. A significant part of the groundwater potential is lost either to the sea or as rejected recharge, if not utilised by man since baseflow and hence, the environmental need, is taken into account (DWAF, 2008a).

GIS based storage yield model [quasi 3D]

The storage capacity, viz. the total available storage of the different aquifers, is calculated with an in-house developed GIS model based on aquifer geometry calculated using first principles of structural geology and estimated values (based on text book and measured data) for effective porosity and storage coefficient.

The model of the aquifer storage intentionally makes use of low, geologically reasonable values for porosity and aquifer compressibility, so as to provide *minimum estimates of potential yields*. However, as new data accumulate from the TMG aquifers in the study area, these initial porosity and compressibility assumptions will probably be revised. The results indicate a storage capacity within the Peninsula Aquifer alone of 366,705 million m^3, which are 2 to 3 orders of magnitude higher than the capacity of the surface water storage facilities in the study domain. By utilising the storage capacity of the confined portions alone, the Peninsula Aquifer can deliver a yield of between 158 and 633 million m^3/a, depending upon the acceptable average draw down of between 5m and 20m respectively (DWAF, 2008a). Conjunctive management of the confined aquifer and the surface water dams will in general increase the yield of the dams, which are normally managed over 2 hydrologic years.

Aquifer specific groundwater flow model [3D/4D]

Fully 3D numerical modelling of groundwater flow, using Feflow, was focussed on the Cape Flats and Langebaan Road Aquifers. The former emphasis arises from the need to assess the potential contribution of the Cape Flats Aquifer to future water supplies of the City of Cape Town. The latter follows the proposed pilot implementation of Aquifer Storage and Recovery to increase the yield of the Langebaan Road Aquifer and the importance of evaluating the potential impacts on the lower reaches of the Berg River and surface water allocations. In addition, the complex interactions between the TMG aquifers, the Breede River Alluvium and the Breede River and tributaries was modelled in quasi 3D using Modflow .

The results of these different models confirmed the order of magnitude for the estimated groundwater potential, refined the estimates of groundwater fluxes from and to surface water bodies and indicated areas for potential groundwater development with minimal impact on the surface water regime and the environment.

Integration with Pitman and WRYM

The integration of the actual and potential yield from the TMG aquifers into the WRYM poses certain challenges. It was agreed by the consulting team and the study management that the Sami module in the Pitman model was not suitable for use in the TMG dominated terrain (DWAF, 2007c). It also became evident that the groundwater – surface water interaction and the integration of groundwater potential and use into the water resource planning cannot be achieved reliably with the current groundwater modules in the Water Resources Yield Model (WRYM).

It was accepted that these challenges would not be entirely overcome in this study but a combined effort to develop an alternative approach based on first principles was made, comprising:

- Applying the aquifer specific distribution of groundwater contribution to baseflow in the Pitman model as external source
- Applying the aquifer specific recharge, storage and discharge volumes in the WRYM as per scheme and operational concept (i.e. “aquifer reservoir”).

Summary lessons learned

The main lessons from the study are:

- Oversimplification of the real world problem is biggest source of error, i.e. reducing a 4D problem to 1D or 2D can't bring reliable results;
- The model accuracy is a function of the model purpose, the selected scale and the available input data;
- The model detail is a function of the quality of input data, the expert knowledge and insight into the earth science processes controlling the flow of water;
- Data from single monitoring points at the right places are worth more than multiple data points; i.e. the quality of data weighs more than the quantity of data; and
- The aim to be physically and geologically correct needs to be balanced with the need to be numerically reliable and to model at the appropriate scale.

4. RECOMMENDED MODELLING APPROACH

Based on the lessons learnt, the recommended model approach follows discrete steps to allow for increased confidence during the process, while changing the scale of investigation from regional / basin scale to local wellfield and borehole scale. The main elements of this approach are (DWAF, in prep.)

- Good conceptual models tested numerically to design & detail monitoring networks
- Box and or other storage models are cost effective for aquifer specific reconnaissance level
- 3D aquifer specific flow models for preliminary resource evaluation and assessment of impact on surface water regime and existing lawful use
- 4D wellfield models to evaluate wellfield design and management scenarios for all commercial or urban use

This approach follows an iterative process as the models get updated with new and more detailed data and information, while the scale of investigation gets more detailed. Below is a summary of the recommended approach.

Aquifer specific conceptual model [2D-4D]

The three critical steps in building a conceptual model (Anderson and Woesner, 1992) are:

- Defining the hydrostratigraphic units;
- Defining a flow system
- Preparing a water balance.

The first step is always to define the hydrostratigraphic units. This is based on the lithological characteristics of different stratigraphic units, the three dimensional (3D) spatial relationship of the hydrostratigraphic units to each other as well as the process history of their formation to the present day. There is however an iterative nature to the second and third steps because it is not possible to prepare a water balance without defining a flow system and it is not possible to define a flow system without understanding the process relationship between the different hydrostratigraphic units, the hydroclimatology, empirical and measured field evidence of groundwater movement and the surface water flow systems.

The purpose of conceptual model development is to stimulate creative debate within and among surface water, groundwater and environmental professionals, the external review team and the client about model assumptions and boundary conditions, aquifer definitions, hydraulic parameters, possible flow paths, and groundwater-surface water interactions as well as impacts of abstractions. The various components of the models remain open to fundamental re-evaluation after the collation and analysis of further data, and consideration of alternative interpretations. The integration of complex concepts of shallow and deep groundwater flow into the numerical models is indeed the most challenging element of a regional scale model or of modelling individual aquifers in a geologically and topographically complex quaternary or larger scale model domain. The geoscientific method of "multiple working hypotheses" is therefore most appropriate in this case, where "the effort is to think independently, or at least individually, in the endeavor to discover new truth, or to make new combinations of truth, or at least to develop an individualized aggregation of truth" (Chamberlin, 1890).

IWRM domain delineation [2D/3D]

To meet one of the core requirement of the study, viz. to understand and map surface and groundwater interaction and to quantify it so far as possible in order to be able to integrate groundwater into the Pitman and the WRYM models, the groundwater study boundaries were defined by areas called Integrated Water Resource Management Domains (IWRM Domains).

The delineation of IWRM domain boundaries requires an understanding of the overall three-dimensional storage, distribution and transfers of groundwater between aquifers, in addition to knowledge of the spatial patterns of surface-water and groundwater interaction between the drainage network (rivers and streams) and the different (unconfined and confined) aquifer systems. Surface-water catchments and watersheds are therefore important in delineating IWRM domains, together with the 3-D geological understanding required to predict the groundwater flow paths between different aquifers.

The regional conceptual model and appropriate selection of Integrated Water Resource Model domains produce the likely boundary conditions for the different model domains, an overt understanding of what complexities, at what process scale for both surface and groundwater. These can then be simplified to adequately represent the real world in the model configuration because it inherently limits the risk of double accounting ad facilitates conceptual development of conjunctive schemes. Over simplification or failing to represent the relevant scale of process in a model will result in physically incorrect patterns in the model result. Failure to appreciate the scale of the process that a calibration data set represents, will result in incorrect model results or a model that will not calibrate.

Aquifer specific water balance model [2D/3D]

It is possible to abstract and simplify to 2D only if the 3D process and geometry is adequately understood. For this reason the 2D GIS model is summed over an IWRM domain to limit potential double accounting inherent in the simplification of a 4D problem to 2D. Lithological units between which there is known to be lateral or vertical hydraulic connection and seasonal exchange of water are treated as a single aquifer and digitised of the 1:250 000 or 1:50 000 geology map depending upon the level of detail required. This reduces errors since the method only accounts for vertical recharge from rain. The rainfall surface is discretized into annual measure of rain, summed for each rainfall isohyet which overlies these aquifer surfaces. Depending upon the rainfall volume and the aquifer type, a fixed percentage of this volume of water is assumed to recharge the aquifer.

As more detailed ground truth information becomes available, spatial detail about the local variation in recharge depending upon topography, rainfall event type, aquifer characteristics and water table elevation become available spatially weighted detail can be included relatively easily. The standard steady state Mass Balance Equation is applied, using the range of published data for evapotranspiration, surface water runoff and baseflow. The range in the value of these variables illustrates uncertainty in model results because evaluating recharge to any aquifer is about calculating a small number by subtracting various large numbers from a single total viz. Rainfall. Thus ensuring that aquifers are defined by geological characteristics and hydrological and hydrogeological process reduces first order spatial and potential double accounting error ignored in non aquifer specific or 1D approaches which sum/discretize a total groundwater recharge volume per quaternary.

Numerical flow model [3D]

Conceptual and semi-quantitative understanding can be tested against available field measurements and records of exploration results. If the conceptual model proves to be robust, careful selection of measured, derived and extrapolated data sets to configure, calibrate and test the steady state model in a predictive mode will support sensitivity analysis of input parameters to model output and the evaluation of uncertainties in model results. Time steps are generally large.

This approach supports the management of uncertainties in groundwater assessment and it also allows the modeller to prepare a physically real mesh yet limit numerical instabilities. Ongoing upgrade and revision of the model configuration and calibration will provide a sound analytical tool to be used in a Model, Monitor and Manage strategy for groundwater resource evaluation, development and management.

Wellfield design and management model [4D]

The last step in groundwater development and quantifying surface water / groundwater interaction is the development of a local scale, fully 3D transient flow model, which is based on the regional aquifer model to define far field boundary conditions and average hydraulic properties with adequate process insight and data to model at the required fine scale using smaller time steps.

5. CONCLUSIONS

The greatest error in groundwater resource evaluation and prediction of impacts on surface water and the environment is in unwarranted reduction of a 4D problem to 1D or 2D. To quantify a process in 2D it is necessary to have a 3D conceptual model and insight into the long term temporal patterns. To quantify in 3D (numerical models) it is necessary to have a physically real and verifiable insight into the likely variations in volumes, area and, at least the range in, expected seasonal variations and other factors that could influence this. A rule of thumb is that one can predict future behaviour of a system for double the amount of years that one has data provided one clearly understands (even conceptually) the spatial detail and temporal pattern that is mapped by that data.

The recommended approach relies on three critical aspects, viz.

- data collection at appropriate spatial position and frequency intervals relevant to the decisions to be taken;
- team interaction between surface water and groundwater specialists that have the necessary skills and knowledge of the earth and water processes, and good communication between the disciplines; and
- timely implementation of relevant monitoring infrastructure and model upgrade.

The applicability and outcome of these models are summarised in Table 1 with reference to the objectives of this study, i.e. water resource evaluation and compulsory licensing.

Table 1 Applicability and outcome of the various models

	Conceptual Model	Water Balance Model	Numerical flow model	Wellfield model
General (applicable to all themes)				
Design of 2D & numerical models	X			
Design of monitoring networks	X		Refinement	
Evaluation & Assessment of data	X			
Evaluation & Assessment of Model Results	X			
Water Resource Evaluation				
First order ‘planning’ numbers		X		
First order impact assessment,		X		
First Order loss/gain to rivers to update WRYM			X	
Operational yield assessment			X	X
Rapid Reserve determination		X	X	
Compulsory Licensing (requires Water Resource Evaluation)				
Intermediate or comprehensive Reserve determination			X	X
Aquifer yield estimate for license (not of borehole)			X	
Estimate of impact of surface water usage on groundwater in storage			X	
Estimate of impact of groundwater abstraction on surface water flow			X	
Wellfield / Borehole licensing				X
Conjunctive Scheme Development (requires Water Resource Evaluation and Licensing)				
Scheme Concept & Design	X		X	X
Scenario testing for (conjunctive) scheme options			X	
Wellfield management				X

Detailed recommendations pertaining to the evaluationm development and management of the TMG and coastal aquifers in the Berg WAAS study area are given in the study.

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APPENDIX C

FIRST ESTIMATE OF THE CONTRIBUTION OF EACH AQUIFER TO THE BASEFLOW WITHIN SELECTED CATCHMENTS

Table 1 presents estimates of the contribution of the major aquifers listed in column B to each subcatchment's baseflow using the recharge values for each aquifer (from column I), and the proportion of the aquifer outcropping at the surface within each sub catchment. The total contribution to baseflow obtained from summing the contributions inside the individual sub-catchments is 103 million m^3/a.

The approach is slightly different to that used when modeling the hydrology. In the hydrology, the contribution of all aquifers (not just the major aquifers) to surface water is summarized in Appendix D of the Regional Water Balance Model Report prepared for this study (DWAF, 2008a). The contribution was apportioned to each sub catchment or calibration gauge using the area of each subcatchment (not the outcropping area which was not available at the time). The total contribution of groundwater to baseflow determined is 119 million m^3/a, slightly more than the 103 million m^3/a from the major aquifers. Column H of Table 2 compares the relative magnitude of the contribution to baseflow modeled in the hydrology with that reported in Appendix D (DWAF, 2008a). In some catchments such as G10J, G21F, G22H and G22J a portion of the sub-catchment is downstream of the calibration site and the recharge rate used for the calibrations is hence less than that applicable for the entire catchment. The value for subcatchment H60B used in the hydrology differs by about 0.9 million m^3/a from that reported in the Appendix D.

Table 1: Contribution of different aquifers to the surface water of each catchment

Aquifer specific parameters for IWRM domain (Ref 3?) — Discharge from aquifer into catchments, other aquifers and sea — Outside model domain

Formation	IWRM		Recharge	Discharge to surface water	G1H003	G1H004	G1H008	G1H011	G1H013	G1H019	G1H020	G1H021	G1H028	G1H036	G1H037	G1H038	G1H041	G1R002	G2H005	G2H016	G2H015	G2H020	G2H037	G4H005	G4H007	G4H030	G4R001	G4R002	H1H006	H1H007	H1H003	H1H012	H1H013	H1H018	H1H033	H1R002	H4H006	H6H007	H6H008	H6R001	H6R002	Total	Quat BRV	Other TMG	Other Aquifers	Sea
			mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a	mcm/a		mcm/a	mcm/a	mcm/a
column a	b			l	n	o	P	q	r	s	t	U	v	w	x	y	z	aa	ab	ac	ad	ae	af	ag	ah	ai	aj	ak	al	am	an	ao	Ap	aq	ar	as	at	au	av	aw	ax	ay	az	ba	bb	bc
Values from factoring the discharge to surface water using the proportion of an aquifer outcropiing in a given catchment																																														
Peninsula	AWT	Agterwitzenberg	15.2	3	0.0	0.0	0.0	0.0	0.0	0.0			3.3																				0.0									3.3		6	6	
	WBK	Warmbokkeveld	13.5	2	0.0	0.0	0.0	0.0	0.0	0.0																			1.7													1.7		6	6	
	AWT+WBK		**28.7**	**5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**			**3.3**																**1.7**				**0.1**									**5.1**		**11.8**	**11.8**	
	BRV	Brandvlei	110.4	21	0.0	0.0	0.0	0.0	0.0	0.0																				2.8		2.9		0.9	0.4	2.0	11.3					20.6	22			67
	RBT	Robertson	4.97	0	0.0	0.0	0.0	0.0	0.0	0.0																						0.1										0.1	1			4
	BRV+RBT		**115.4**	**21**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**																				**2.8**		**3.0**		**0.9**	**0.4**	**2.0**	**11.3**					**20.7**	**23.7**			**71.0**
	KGB	**Kogelberg**	**26.73**	**6**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**														**0.5**	**2.8**		**0.8**	**2.3**														**6.5**				**20**
	PUB	**Paarl Upper Berg**	**82.35**	**12**	**0.4**	**1.7**	**0.0**	**0.0**	**0.0**	**0.5**	**2.8**				**0.4**	**0.6**	**0.9**	**2.2**																**0.2**	**1.8**							**11.6**		**35**	**35**	
	THK	**Theewaterskloof**	**61.35**	**8**	**0.1**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**														**0.1**		**0.1**		**0.5**										**1.7**	**1.8**	**1.4**	**2.0**	**7.9**		**27**	**27**	
Skurweberg	AWT	Agterwitzenberg	33.95	8			0.0	0.0	0.0																								7.8									7.8		13	13	
	WBK	Warmbokkeveld	29.93	6			0.0	0.0	0.0																				3.0				2.7									5.7		12	12	
	AWT+WBK		**63.88**	**14**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**																			**3.0**				**10.5**									**13.5**		**25.2**	**25.2**	
	BRV	Brandvlei	10.93	2			0.0	0.0	0.0																					0.3							1.8					2.1	9			
	RBT	Robertson	8.49	0			0.0	0.0	0.0																															0.3		0.3	8			
	BRV+RBT		**19.42**	**2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**																				**0.3**							**1.8**			**0.3**		**2.4**	**17.0**			
	KGB	**Kogelberg**	**61.82**	**16**			**0.0**	**0.0**	**0.0**															**2.6**	**2.9**	**7.7**	**2.3**	**0.6**														**16.2**				**46**
	THK	**Theewaterskloof**	**40.3**	**6**			**0.0**	**0.0**	**0.0**															**0.1**				**0.4**										**0.2**	**0.1**	**5.6**		**6.5**		**17**	**17**	
Details of other Aquifers	CFP	Cape Flats – Peninsula	23																																											
	BRV-RBT		522.92	13																																	13.0					**13.0**				
Total				103	0.5	1.8	0.0	0.0	0.0	0.5	2.8	0.0	3.3	0.0	0.5	0.6	0.9	2.2	0.0	0.0	0.0	0.0	0.0	3.4	5.7	7.8	3.1	3.9	4.7	3.1	0.0	3.0	10.6	1.1	2.2	2.1	26.1	2.0	1.9	7.3	2.0	103.3	40.7	116.1	116.1	136.9
Values from WAAS (1) hydrology																																														
					2.0	2.4	4.7	0.4	5.7	0.2	6.1	0.3	2.7	3.7	0.5	0.6	0.9	3.6	0.3	1.1		2.5	1.0	3.6	9.3	4.5	2.9	2.8	2.0	3.2	8.1	3.8	1.2	1.7	2.7	2.2	20.5	1.6	1.4	8.2	0.5	118.9				
Comparison – Hydrology vs Aquifer breakdown (Differences of more than 25% have been highlighted)					27%	78%	0%	6%	0%	245%	46%	2%	121%	1%	94%	99%	104%	61%	0%	2%	#DIV/0!	0%	1%	94%	61%	174%	107%	139%	236%	98%	0%	78%	882%	66%	83%	93%	127%	122%	134%	89%	397%	87%				

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Table 2: Comparison of the contribution of aquifers/groundwater used in the WAAS hydrology with that listed in Appendix D (DWAF, 2008a)

Quaternary	Gauge for calibration	area	catchment	Groundwater baseflow (mcm/a) from the WAAS hydrology		Baseflow from Appendix D	% of baseflow modelled
COLUMN A	B	C	D	E	F	G	H
G10A	G1H003	46	Berg	1.952			
G10A	G1H004	56	Berg	2.359			
G10A	G1H020	56	Berg	2.378			
G10A	G1H038	13	Berg	0.556	7.2	7.2	100%
G10B	G1H020	38	Berg	1.632			
G10B	G1R002	85	Berg	3.626	5.3	5.2	101%
G10C	G1H019	23	Berg	0.158			
G10C	G1H020	305	Berg	2.111	2.3	2.3	100%
G10D	G1H036	498	Berg	3.733			
G10D	G1H037	70	Berg	0.525			
G10D	G1H041	121	Berg	0.904	5.2	5.2	100%
G10E	G1H008	348	Berg	4.738			
G10E	G1H011	26	Berg	0.354			
G10E	G1H021	19	Berg	0.253	5.3	5.4	100%
G10F	G1H013	461	Berg	3.699			
G10F	G1H040	36	Berg	0.289	4.0	4.2	95%
G10G	G1H028	185	Berg	2.731	2.7	2.7	100%
G10H	G1H035	674	Berg	3.526	3.5	3.5	100%
G10J	G1H013	337	Berg	2.007			
G10J	G1H029	36	Berg	0.216			
G10J	G1H043	155	Berg	0.923	3.1	5.2	61%
G10J	d/s G1H013						39%
G21C	G2H012	246	Diep	1.962	2.0	2.0	101%
G21D	G2H042	484	Diep	3.695	3.7	3.7	100%
G21E	G2H013	472	Diep	3.918			
G21E	G2H042	61	Diep	0.504	4.4	4.4	100%
G21F	G2H014	88	Diep	0.712			
G21F	G2H042	42	Diep	0.338	1.1	2.0	54%
G21F	d/s G1H014						46%
G22F	G2H005	8	Eerste	0.341			
G22F	G2H020	33	Eerste	1.352			
G22F	G2H037	24	Eerste	0.977	2.7	2.7	100%
G22G	G2H020	106	Eerste	1.101	1.1	1.1	100%
G22H	G2H015	154	Eerste	1.410			
G22H	G2H020	7	Eerste	0.067	1.5	2.1	71%
G22H	d/s G2H015						29%
G22J	G2H016	92	Lourens	1.143	1.1	1.6	72%
G22J	d/s G2H016						28%
G40A	G4R001	67	Steenbras	2.939	2.9	2.8	104%
G40C	G4H005	84	Palmiet	3.628			
G40C	G4R002	65	Palmiet	2.822	6.5	6.2	105%
G40D	G4H007	210	Palmiet	9.287			
G40D	G4H030	102	Palmiet	4.523	13.8	14.5	96%
H10A	H1H003	230	Upper Breede	0.744	0.7	0.8	99%

H10B	H1H003	158	Upper Breede	3.257	3.3	3.4	97%
H10C	H1H003	200	Upper Breede	4.091			
H10C	H1H013	59	Upper Breede	1.209	5.3	5.3	100%
H10D	H1H006	96	Upper Breede	2.039	2.0	2.1	99%
H10E	H1H007	85	Upper Breede	3.217	3.2	3.1	103%
H10F	H4H006	249	Upper Breede	5.240	5.2	5.2	100%
H10G	H4H006	270	Upper Breede	5.700	5.7	5.8	99%
H10H	H4H006	185	Upper Breede	3.908	3.9	4.0	99%
H10J	H1H018	44	Upper Breede	1.727			
H10J	H1H033	65	Upper Breede	2.538			
H10J	H1H033	0	Upper Breede	0.013			
H10J	H1H033	0	Upper Breede	0.004			
H10J	H1H033	3	Upper Breede	0.108			
H10J	H4H006	103	Upper Breede	4.002	8.4	8.3	101%
H10K	H1H012	96	Upper Breede	3.837			
H10K	H1R002	56	Upper Breede	2.225			
H10K	H4H006	42	Upper Breede	1.671	7.7	7.7	100%
H10L	H4H006	26	Upper Breede	0.000	0.0	0.0	0%
H60A	H6H008	40	Riviersonderend	1.363			
H60A	H6R001	33	Riviersonderend	1.140	2.5	2.5	101%
H60B	H6H007	46	Riviersonderend	1.610			
H60B	H6R001	162	Riviersonderend	5.602	7.2	6.3	114%
H60C	H6R001	161	Riviersonderend	1.469			
H60C	H6R002	50	Riviersonderend	0.454	1.9	1.7	111%

APPENDIX D

COPY OF PAPER PRESENTED AT 14TH SANCIAHS, 2009

ASSESSING AQUIFER YIELDS THROUGH INTEGRATED NUMERICAL SW-GW MODELING – A CASE STUDY FROM THE BERG WAAS

Assessing aquifer yields through integrated numerical SW-GW modeling – A case study from the Berg WAAS.

H. Seyler[1], E.R. Hay[1], K Riemann[1], C.J.H. Hartnady[1], I Thompson[2]

[1]Umvoto Africa (Pty) Ltd, Cape Town
[2]Department for Water Affairs, Directorate: National Water Resource Planning

Abstract

Groundwater and surface water are part of a continuum, and it is often not possible to accurately quantify one without the other. The approach and methodology implemented in the Berg WAAS integrates surface water and groundwater conceptually defining an Integrated Water Resource Model Domains and includes surface water as a component in the numerical groundwater modelling, quantifying the interaction between surface and groundwater (SW-GW) (DWAF 2005). For selected areas of groundwater relevance 3-dimensional numerical groundwater models were developed to:
1. Provide estimates of the water balance
2. Test the sensitivity of the system to certain parameters
3. Test scenarios, such as effect of abstraction on surface water – groundwater interactions

Within the Breede River Alluvial aquifer the surface water and groundwater are hydraulically linked. Perennial rivers fed by springs emanating from the Table Mountain Group aquifers enter the valley and become effluent in alluvial fan areas, recharging the coarse grained alluvium which discharges into the Breede River. This conceptual model was translated to a numerical model (MODFLOW in groundwater vistas) and the various fluxes quantified.

The model results show that recharge from rain is the dominant source of groundwater. Abstracting ~80% of recharge in 1 year causes a reduction in baseflow of 15%, which takes |10 years to return to its natural flux. The aquifer responds fast to changes in river levels; flooded river levels and low flow levels generate variations in baseflow, but the fluxes return to the natural system within 1 year after a flood/ drought event, highlighting the increased storage capacity of the groundwater as compared to the surface water system.

With continued upgrade of the model, it can be used as a basis for fully integrated SW-GW models, and as a basis for smaller scale models required for testing the local effects on of water use on baseflow, for license application, and for implementing water allocations.

Keywords: groundwater modelling, groundwater – surface water interaction

1. Introduction

1.1 The Berg Water Availability Assessment Study (DWA)

In 2005 the Department for Water Affairs (DWA) embarked on Water Availability Assessment Studies (WAAS) to provide large-scale quantification of water availability in 4 Water Management Areas (WMA), and to set up models that will support, *inter alia*, allocable water quantification as a prerequisite for compulsory licensing. The main objectives of the Study are to (DWAF, 2005):

- Reconfigure the existing Water Resources Yield Model (WRYM) configurations at a spatial resolution suitable for allocable water quantification to support compulsory licensing.
- Use reconfigured existing models or newly configured models for allocable water quantification for both surface water and groundwater, where applicable.

Phase 2 of this project entailed model configurations for assessment of current water availability and selected augmentation options.

Groundwater is considered an integral part of the water resources and individual aquifers are modelled before being coupled with surface water models to quantify the surface water – groundwater interaction. This allows understanding and quantifying the impact of groundwater abstraction on baseflow, the temporal relationship between groundwater storage and surface water storage, and the impact of reduced stream flows or flood events on groundwater levels. This integration of the different models requires the definition and delineation of a common domain, called IWRM Domain, which is considered a self-contained unit with defined spatial and temporal distribution of surface water and groundwater (DWAF

2007a). Since the interaction between surface and groundwater is a scale-dependent process, the resource quantification is undertaken at different scales to provide data relevant to the scale of integration and the objective of the model. At regional scale a GIS-based water balance model was developed to quantify recharge, storage and discharge for regional scale aquifers (DWAF 2007b).

3-dimensional numerical groundwater models were developed for aquifers of specific interest (e.g. high groundwater abstraction, high potential for surface water – groundwater interaction, high groundwater potential for future use) (DWAF 2007c, DWAF 2008a, DWAF 2008b). The numerical models 'zoom in' from the regional GIS based water balance model, in order to understand the interaction between surface and groundwater in greater detail. Scenario testing allows the impact of certain activities on these fluxes to be determined. The principal aims of the numerical modelling are to:

1. Provide estimates of the water balance (recharge, stored groundwater volumes, discharge)
2. Test the sensitivity of the models to certain parameters
3. Test scenarios, such as effect of hypothetical abstraction or future reductions in recharge on the water balance.

Each of these 'model questions;' is posed at the regional scale.

1.2 Numerical modelling of surface – groundwater interaction

Groundwater modelling software, such as MOFLOW and FEFLOW, compute exchange with surface water at a specified elevation (river stage) based on the difference in head between that river stage and the groundwater level, as dictated by the Darcy equation. Rivers are represented in the model as a series of point sources or sinks to the aquifer depending on the specified river level (can be a time series) and the groundwater level (modelled). Groundwater software cannot model the actual river flow processes. The software cannot for example translate the computed discharge flux to rivers into a river stage change, as this depends on various factors such as river morphology. For this level of detail fully integrated SW-GW software is required, such as MIKE –SHE:

The software used in the Berg WAAS study is a first step to fully integrated SW-GW modelling, as the fluxes between the two can be determined for various model situations.

Groundwater modelling is a powerful tool to establish the added value of Artificial Storage and recovery schemes, conjunctive management of surface and groundwater resources and improve planning of management of the groundwater and surface water environmental reserve.

1.3 The Breede River Alluvial Aquifer

The upper Breede River valley between Wolseley and Nuy is filled with sand and gravel deposits, which constitute the extensive Breede River Alluvial Aquifer (BAA) (Van Zijl et al, 1981). The agricultural community in the valley utilises groundwater from this aquifer for irrigation as well as for domestic use in some of the towns. The water balance in this area and its split between surface water and groundwater needs to be reconciled. Additionally, the impact of further groundwater development on stream flow, the impact of river diversion on the groundwater level and quality, and the cumulative impact of both activities need to be simulated prior to decisions about upgrading of schemes. This model is seen as a first step towards quantifying the water balance in the valley and understanding the various aquifer interactions which are present.

The main aims are to:

1. Model different scenarios under different hydrological conditions (e.g. flood, drought)
2. Establish at least first order estimates of the rate and volume of exchange between the water in the alluvium and that in the river, and between groundwater in various aquifers
3. Test the possibility for an aquifer storage and recovery scheme to store surplus flood water.

1.4 Breede Valley Drainage

Several tributaries contribute to the flow in the Breede River (**Figure 1**). The most relevant in the Upper and Middle Breede basins and relevant or surface water groundwater interaction are:

Table 1 Drainage in the Breede Valley

River	Catchment	Description
Wabooms River	south-eastern part of H10F	Drains the Waaihoek Mountain; joins Breede River downstream of Wolseley, where the Breede River exits the Elandskloof
Jan Du Toits River	H10H	Drains the southern end of the Hex River Mountains, the Waaihoek Mountain and the Meiring`s Ridge; joins the Breede River just upstream of Rawsonville
Hex River	H20A, H20B, H20G and H20H	Has its source in the Hex River Mountains; flows through the Hex River valley. Downstream of Sandhills, flows south through the Hex River Poort into the Breede River valley has its confluence with the Breede River just north of Greater Brandvlei Dam.
Nuy River	H40B, H40C	Comes from the Koo valley north of the Langeberge; flows southwest towards the Breede River just below Greater Brandvlei Dam
Wit River	H10E and south-western part of H10F	Drains the Limiet Mountains and the south-western slopes of the Slanghoek Mountains; joins the Breede River opposite the Wabooms River
Slanghoek River	western part of H10G	Drains the eastern slopes of the Slanghoek Mountains
Molenaars River	H10J	Originates in the Haweqwas Mountain range; fed by streams on the northern Du Toits Mountains and the south-eastern slopes of the Slanghoek Mountain. Joins the Breede River just north of Rawsonville
Holsloot River	H10K	Draining the southern slopes of the Du Toitskloof Mountain and the northern slopes of the Stetteyns Mountain; joins the Breede River just upstream of the Papenkuils Wetland and Greater Brandvlei Dam

1.5 Geological setting of the Breede Alluvium

The flat-lying, semi- to unconsolidated sediments of fluvial alluvium fill the valley bottoms in the central part of the study area and occur along the watercourses and flood plains of the larger rivers of the Breede River basin. The composition of the alluvium depends on the provenance and varies from quartzose sands to silty soil. Generally the alluvium is unconsolidated but is occasionally semi-consolidated.

Where tributaries to the Breede leave the steep TMG mountain ranges and enter the Breede River Valley, alluvial fans are developed where the slope change is abrupt. An alluvium fan is a body of sediment built up by a mountain stream, at the base of a mountain front, which commonly has a fan shape. The alluvium is thickest in these fans and thinned where it is dominated by finer grained deposits of the Breede River itself. Deposits at the fanhead are mostly quartzitic and coarse grained boulders and cobbles while decreasing in grain size downstream.

The most prominent alluvial fans are at the entry of the Wabooms River, Jan Du Toits River, Hex River, Molenaars River, Holsloot River, similarly, the entry of the Breede River itself, where it crosses the Mitchell's Pass (**Figure 2** and **Figure 3**).

Geophysical results show that the Molenaars and Holsloot alluvial fans comprise thick layers of boulders in the upper parts and thick sand deposits in the lower parts of the alluvial deposits (van Zyl et.al, 1981) (**Figure 4**). The known thickness of the alluvium varies between 10 m and +50 m, with the thickest areas found in the Rawsonville area (Molenaars and Holsloot alluvial fans) and east of Worcester (Hex River alluvial fan). The available National Groundwater Database (NGDB) logs for the BAA record maximum thicknesses of 57 m of boulders drilled in the Hex River Valley, 25 m thickness of boulders in the Rawsonville area, 46 m thickness of boulders in the Jan Du Toit fan and a maximum of 28 m thickness in the central valley of the Upper Breede.

2. Conceptual Model

2.1 Hydrogeological setting of the Breede Alluvium

The TMG and the Breede River Alluvial Aquifer (or simply 'alluvium') represent the significant aquifers in the area, as fractured rock and intergranular aquifer respectively. The model challenge was to accommodate discharge from the TMG into the alluvium through springs and subsurface recharge as well as the seasonally variable flux exchange between the river and the alluvium.

Piezometric data for the TMG Aquifer shows the water flow from the high lying recharge areas towards the confined parts of the aquifer in the centre of the Breede River Valley. The data however show no connection to the surface water of the Breede River and the piezometric map suggests flow to the north towards the Worcester fault and towards spring discharge.

Although the intergranular aquifers cover large areas of the Breede and Hex River valleys they have variable thickness and may be largely unsaturated where they are poorly developed (< 10 m). Areas where there is extensive development of alluvium and where the intergranular aquifers comprise an important resource include those areas where alluvial fans are developed.

Piezometric data for the alluvium shows the general water flow from the edges of the valley towards the Breede River, and along the river eastwards illustrating that the Breede River is the main sink for groundwater discharge from the Alluvium throughout it lengths in this area.

The scale of interest of the model investigation is regional. At this scale the Malmesbury and Cape Granite Suite can be considered aquicludes.

2.2 Surface water – groundwater interaction

There are two relevant processes of surface water – groundwater interaction in the study area; the groundwater contribution to stream flow and *vice versa* in the wider valleys, and the groundwater recharge from stream flow where the mountain streams widen into alluvial fans and enter the bottom valley.

Data on various surface water - groundwater fluxes are available but have been spatially averaged over large areas, and an upgrade of these estimates was necessary.

While it is assumed that the Breede River gains water from the alluvial aquifer over most of its length the surface water and groundwater interaction in the TMG-fed tributaries to the Breede River, which flow over alluvial fans, is more complex. Where the tributaries leave the steep mountain ranges and enter the alluvium fans, the slope change is abrupt and the tributaries are considered to lose water to the fans (i.e. recharge them). Further downstream where the topographic slope lessens the tributaries themselves will drain the aquifer.

2.3 Modelling approach

There is a need to model both TMG and alluvial systems for improved water balance results and in particular surface-groundwater exchange fluxes into and out of the Breede catchment in summer and winter. Because of the large differences in physical and temporal scales between processes in the TMG and processes in the alluvium these models are handled separately. Both models use the Groundwater Vistas software with the quasi-three dimensional Finite Difference (FD) Modflow code.

A model was developed for the Brandvlei hot spring to understand the factors driving flow and discharge in the TMG thus derive input parameters for the BAA model, to estimate the hydraulic properties for the TMG aquifers, and to use temperature measurements as a calibration tool for thermal modelling to determine deep aquifer flow paths and lag times.

The significant TMG model outcome is that the flow/ discharge to SW springs is relatively invariable with rain (Grant, 2007). As a result it is reasonable to assume constant head (which is a constant source) condition(s) along the TMG bounded edge of the model domain.

The flow pattern in the BAA can be divided into three distinct flux elements:

- The lateral inflow from mountain streams and underlying aquifers, situated at the edges of the alluvium, especially at the fans,
- The flow pattern within the alluvial fans from the fan head towards the fan bottom, and
- The discharge into the Breede River.

The conceptual model is summarised as:

- Tributaries to the Breede, or run off directly from the TMG aquifers along the valley walls, enter the valley and are met with a break of slope at the elevation of the alluvial fan head. This change in slope, and the hydraulic conductivity contrast in underlying material from TMG to the coarse gravel deposits at the alluvial fan heads, causes the alluvial fans act as sponges to the perennial surface waters, thus recharging the aquifer (**Figure 5**).

- It is assumed that these tributaries become influent again close to their confluence with the Breede River where the topographic slope shallows and beyond the extent of the coarse boulder deposits.
- The alluvial groundwater table parallels the topographic gradient and follows the preferred flow paths in the alluvial fans to flow down gradient towards the Breede River.
- At the regional scale the groundwater movement is towards the centre of the valley, discharging at the Breede River, and also along the valley southwards.
- The alluvium discharges to the Breede River along its length and groundwater also flows southwards through the valley, though ultimately discharging to the Breede as the alluvium reduces in volume and therefore capacity to carry the water south of Greater Brandvlei Dam and west of Robertson

2.4 Translation to numerical model: Breede River Alluvial Aquifer Model

The translation of the conceptual model to numerical model is described in Table 2 below.

Table 2: Translation of conceptual model to numerical model

Model Item	Model representation	Assumption
Model Mesh	**3-dimensional finite difference model.** Modelled area 486 km^2 Grid cells 250m by 250m.	Groundwater levels are correct to 1 grid square, i.e. represent an average over $250m^2$
Model Boundary	**No-flow boundary condition** following the 10 m alluvium thickness contour	It is assumed that groundwater flowing in alluvium thinner than 10 m is irrelevant to the regional flow regime, and that any water crossing the boundary is accommodated in the surface flux
TMG-fed tributaries	**Constant head[1] boundary conditions** set at the point at which the TMG-fed springs enter the alluvial fan	This representation assumes: 1. the springs recharge the aquifer at the fan heads 2. discharge from the TMG is a continual source to the alluvium, as suggested in the Brandvlei TMG model
Internal rivers	**River boundary conditions** Tributaries are modelled as rivers from the end of the alluvial fans.	The Breede River is in hydraulic connection with the aquifer along the modeled length and acts as a sink or a source depending on the difference between the use specified river stage and the modelled groundwater Tributaries are recharge sources to the aquifer where they flow over the boulder beds of alluvial fans.
Hydraulic behaviour of the Breede River Alluvium Aquifer	Confined in lower layers (i.e. second and third model layers set as confined, without a confining layer of nominal hydraulic conductivity).	50 years of monitoring data indicates that maximum seasonal variability in the aquifer is up to ~5 m. The alluvium is no thinner than 10 m in the model. To facilitate convergence, using a confined setting the water table is not allowed to drop below half the thickness of the model. Although alluvial aquifers are often considered simply unconfined, Rosewarne (1981) suggested that the Breede River Alluvium was semi-confined to confined.

[1] *"Constant head' is a point at which the groundwater level is user specified (time series or fixed) and therefore can act as a source or a sink to the groundwater depending on the difference between the calculated model head and the specified 'constant head'.*

3 Breede River Alluvium Aquifer Numerical Model

3.1 Model Input data

Table 3 Model Input data

Model Input Parameter	Source	Parameter Type
Topography	20 m and 100 m DEM	Fixed
Bedrock topography	Literature and NGDB	Fixed
Aquifer thickness	Literature and NGDB	Fixed
Layering	Based on geology and numerical requirements	Fixed
Hydraulic conductivity	1st approx from typical literature values	Steady state calibration in BAA model
Storage	1st approx from typical literature values	Transient calibration in BAA model
Porosity	Typical literature values	Assumed from storage parameters
Recharge	BRBS method modified	Fixed for models, varied in scenario testing
Abstraction	WARMS	Fixed for steady state calibration, varied in scenario testing
River stages	Assumption based on topography data	Fixed
Conductance	Assumption based on literature values	Calibration
River Stage variability	DWAF Flow gauging station data	Fixed
Calibration data: Groundwater levels	NGDB	Used to calibrate modelled groundwater levels

The most significant data limitation is that of river stages. Although gauging stations exist along various river reaches, these do not measure river stage to a transferable datum; most give levels in metres above a marker on the v-notch. For integrated groundwater and surface water quantification a common datum, normally metres above mean sea level is required. Therefore all river stages had to be assumed, and an estimated 5m below the smoothed topography of the river course was used.

Monthly river stages for gauging stations in the area were supplied by DWAF for the period 1980 – 2007. Monthly mean measurements over the time series of data recorded, and monthly mean of the daily peaks and minimum flows were supplied. Stations on tributaries to the Breede River close to the position where they cross from TMG into the alluvial fans were selected and analysed for use as model input for variability at the constant heads representing the springs entering the alluvium. Two stations in the central Breede valley were selected for analysis of the variability along the Breede River. An annual mean was calculated from the monthly mean and each month's level was converted to a variation from this annual mean.

3.2 Parameter Calibration

Model runs showed that the equivalent hydraulic conductivity in the valley must be in the range 10-100 m/d. Below 10 m/d the resulting water levels are significantly above topography. Above 100 m/d the valley sides are dry over large distances.

The model was not sensitive to variations in specific yield, as only the upper layer is unconfined. Variations in specific storage affect changes in modelled seasonal variation. Specific yield of 0.1 and specific storage of 5_E^{-4} gives seasonal variability in groundwater levels closest to the average observed 1.5 m.

3.3 Model Result

The major features of the flow regime are replicated in the model. Groundwater flows from the valley sides towards the Breede River, and also through the valley towards the southeast. The observed groundwater gradients are also broadly replicated; the 20m contour lines from observed and modelled groundwater levels match (**Figure 6).**

The model replicates the flow regime at a regional scale and gives expected mass balance numbers. However, with a regional model it is not possible to replicate rapidly changing water level gradients. The steepest parts of the valley remain dry. This is not considered to influence the centre of the model- i.e. flows around the surface water

The model results show that recharge from rain is the dominant source of groundwater. The modelled mass balance is shown in Table 1 below.

Table 4 Modelled groundwater fluxes

Scenario	Influx mcm/a		Discharge to Rivers mcm/a	Balance mcm/a
	Recharge	Tributaries		
Base Case	22.67	2.95	-24.98	0.64

The Wabooms and Jan Du Toits rivers generate the highest recharge to the alluvial aquifer, followed by the Hartbees River. These rivers are on the northern side of the Breede Valley and it is possible that their modelled effect is greater because the valley sides are steeper in the north. It is not possible to determine whether this is a 'real' phenomena or not, without the required river level data. The model suggests that the Breede and Wit rivers are a groundwater sink. This is in agreement with the observed water level map showing that in the northwest of the valley groundwater flows towards the south west.

The seasonality of the mass balance is shown in **Figure 7** below. The 'balance' reflects the storage capacity. In summer months the monthly balance is negative because more water is lost from the system than enters. This situation arises because the vertical recharge is low but discharge to the rivers continues. In winter this is reversed and the water table rises as recharge increases faster that it is discharged to the rivers. This pattern is key to the feasibility of ASR.

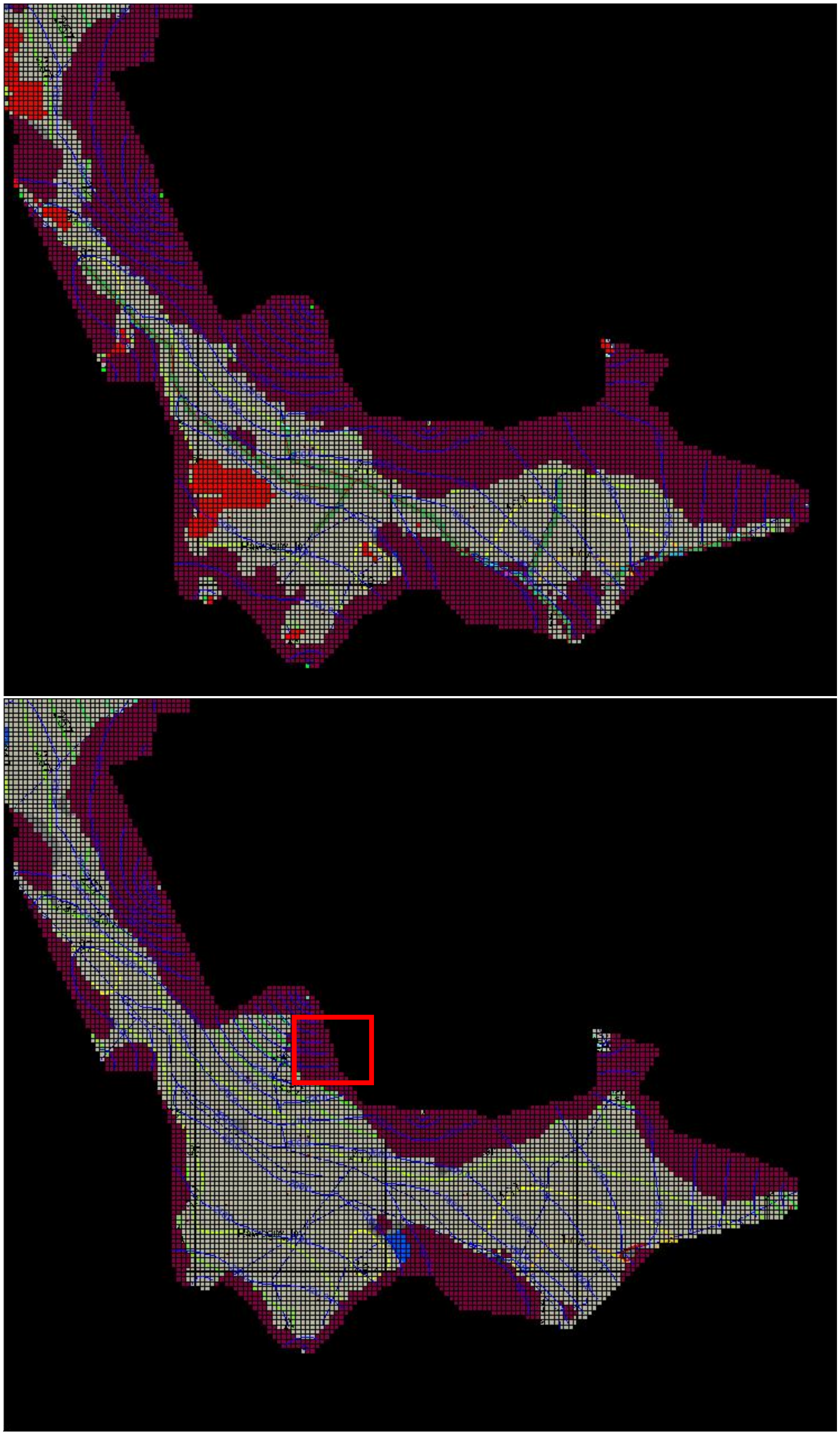

Figure 6 Flow regime in the alluvium aquifer, for the top of the alluvium (top) and base (bottom)
(*Red cells indicate water level greater than ground and purple indicates dry edges of the model. Red box highlights similarity in modelled and observed groundwater gradients)*

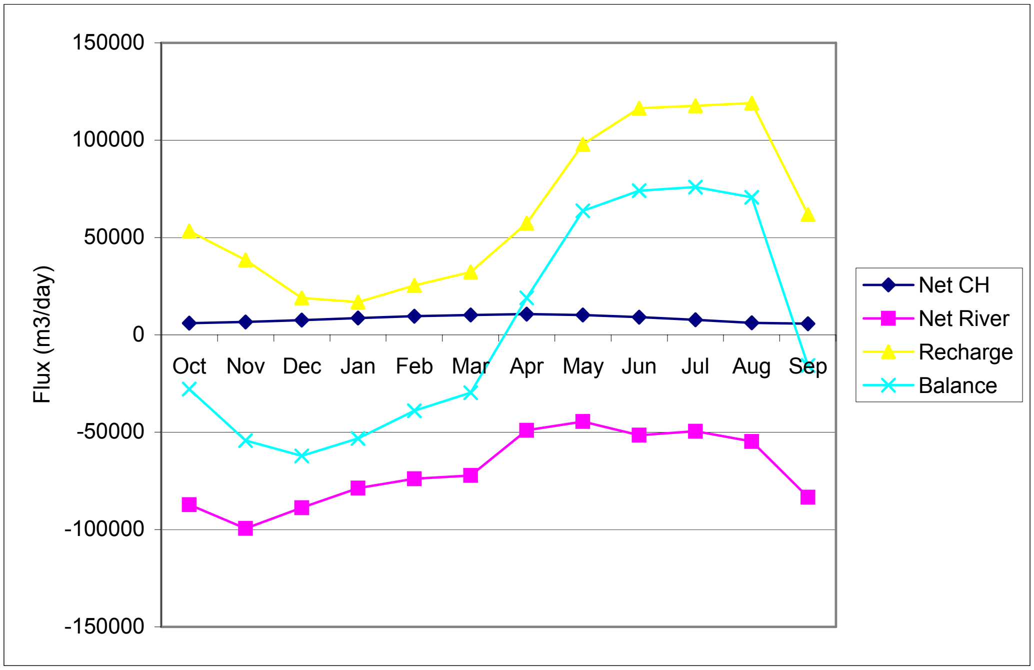

Figure 7 Modelled aquifer fluxes for 1 year

3.4 Scenario testing

3.3.1 Abstraction

Scenario testing on the transient model suggests that the aquifer responds relatively fast to major changes in the influxes or out-fluxes applied to the aquifer.

Inputting an abstraction of 80% recharge to the transient model shows that the system does stabilise to a new steady state with less outflow to the rivers, and reach a stable state where out-flux is equal to influx. As time passes under the new recharge regime, the influx from the constant head sources increases, and the discharge to the rivers decreases (**Figure 8**). The largest changes in flux occurs in the first 5 years and by 10 years the system has almost re stabilised, with the imbalance coming close to zero. The impact on fluxes is shown in **Table 5** below, for year 1.

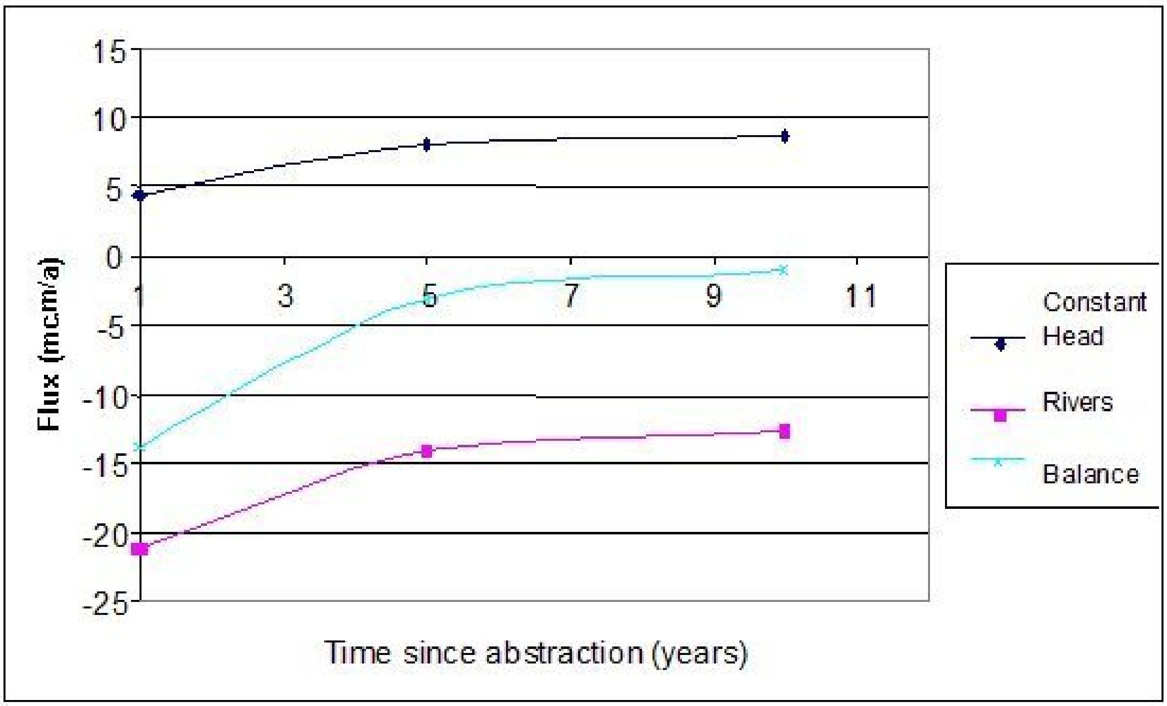

Figure 8 Modelled fluxes over time since abstraction begun showing re stabilisation of surface groundwater fluxes

3.3.2 Low flow & Flood

The modelled system responds within 1 year to maximum and minimum surface water levels taken from flood and low flow records, suggesting a short time lag between groundwater storage and surface water. The relationship does suggest that the alluvium can readily take up excess surface water, and that this time lag could be optimised to store winter flood water for use within the following summer dry period.

Table 5 Mass balance fluxes for various scenarios and their deviation from base case

	Influx mcm/a			
Scenario	Recharge	Tributaries	Discharge to Rivers mcm/a	Balance mcm/a
Base Case	22.67	2.95	-24.98	0.64
Abstraction	2.96	4.47	-21.26	-13.83
Low Flow	22.67	2.92	-25.75	-0.15
Flood	22.67	3.16	-23.86	1.98
Abstraction: Effect		+51%	-15%	Discharge exceeds influx by 4x, 39% of the discharge is from storage i.e. Abstraction is supplied from storage
Low Flow: Effect	-	-1%	+3%	Discharge exceeds influx, 0.6% of total discharge is from storage i.e. Increased baseflow is supplied from storage
Flood: Effect	-	+7%	-4%	Influx exceeds discharge, 7% of total influx enters storage i.e. the increased influx from tributaries enters aquifer storage

3.3.3 ASR

The ASR scenario showed that there is a potential for significant storage within the aquifer, away from the centre of the valley. Local-scale mapping of water levels in metres below ground level is required to quantify such available storage

4. Applicability

The potential use of this model are summarised in Table 6 below (DWA, 2009). With continued upgrade of the model, it can be used as a basis for fully integrated SW-GW models and as a basis for smaller scale models required for testing the local effects of water use, license application, and for implementing water allocations.

Table 6 Applicability and outcome of the various models

	Conceptual Model	Water Balance Model	Numerical flow model	Wellfield model
General (applicable to all themes)				
Design of 2D & numerical models	X			
Design of monitoring networks	X		Refinement	
Evaluation & Assessment of data	X			
Evaluation & Assessment of Model Results	X			
Water Resource Evaluation				
First order 'planning' numbers		X		
First order impact assessment,		X		
First Order loss/gain to rivers to update WRYM			X	
Operational yield assessment			X	X
Rapid Reserve determination		X	X	
Compulsory Licensing (requires Water Resource Evaluation)				
Intermediate or comprehensive Reserve determination			X	X
Aquifer yield estimate for license (not of borehole)			X	
Estimate of impact of surface water usage on groundwater in storage			X	
Estimate of impact of groundwater abstraction on surface water flow			X	
Wellfield / Borehole licensing				X
Conjunctive Scheme Development (requires Water Resource Evaluation and Licensing)				
Scheme Concept & Design	X		X	X
Scenario testing for (conjunctive) scheme options			X	
Wellfield management				X

5. Conclusions and Limitations

Groundwater and surface water are hydraulically linked and therefore water resource quantification is not complete without quantification of both, and of how they interact. Numerical groundwater modelling is a powerful tool for this quantification and through scenario testing can assist management decisions on Artificial Storage and recovery schemes, conjunctive management of surface and groundwater resources, and management of the groundwater and surface water environmental reserve.

The main limitation of the model is the use of estimated surface water data, due to the lack of surveyed gauging measurements (i.e. groundwater and surface water data to a common datum). Recommendations are made for the acquisition of monitoring data (including surface water data, hydrogeological data, and hydroclimatic monitoring) and to address model uncertainty and for further scenario testing. These recommendations are:

1. Design and establish a dedicated groundwater/surface water monitoring network (water levels, abstractions, hydroclimatology and hydrochemistry) in the Upper and Middle Breede to obtain time-series data on fluvial aquifer response to vertical and lateral recharge (short-term priority).
2. Map and understand the time lag between surface water and groundwater in the Breede to identify preferred sites for establishing a pilot ASR scheme as well as to upgrade the hydrological models that are input to the WRYM (medium-term priority).
3. Hydraulic testing of the aquifer at selected sites to determine aquifer properties including storage potential and quantification of preliminary design of an ASR scheme (medium to long-term priority).
4. Undertake model upgrade based on extensive testing and field confirmation of selected assumptions in the formal model test process, such that it can be used predicatively and thereby realise medium to long-term upgrade of the hydrological data and WRYM (short-term priority and ongoing)
5. Evaluate use of heat flow modelling of TMG aquifers (short-term priority).

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Appendix - Figures

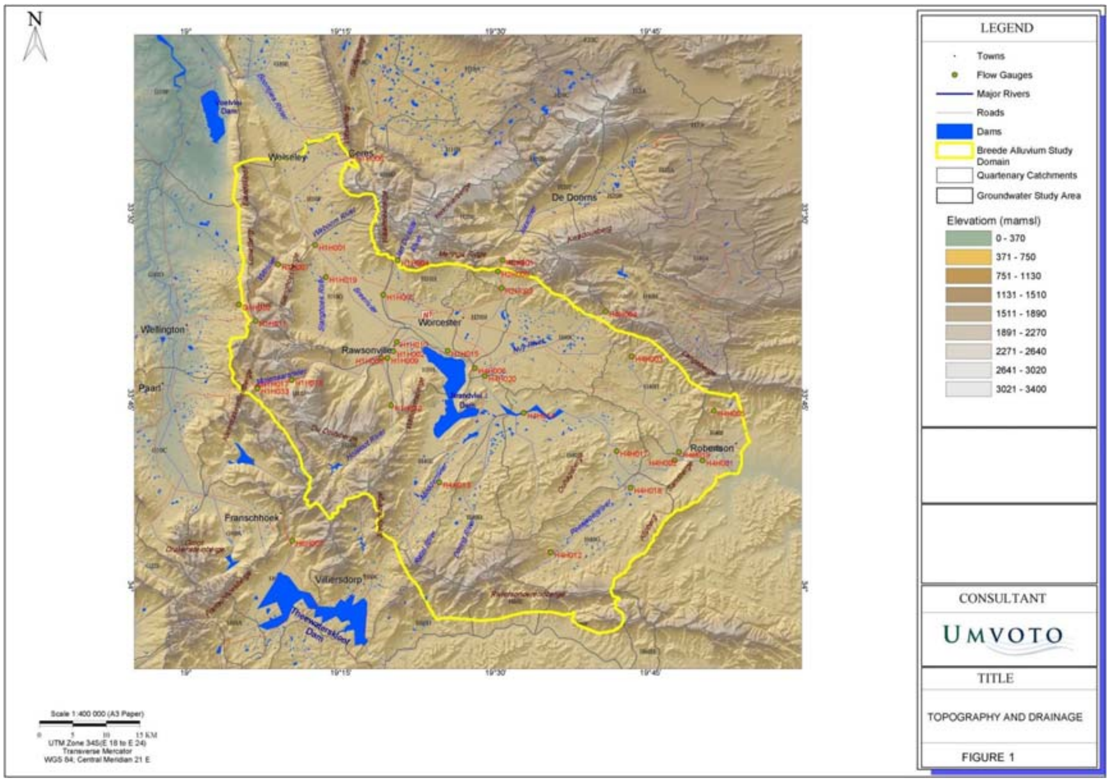

Figure 1 Topography and Drainage

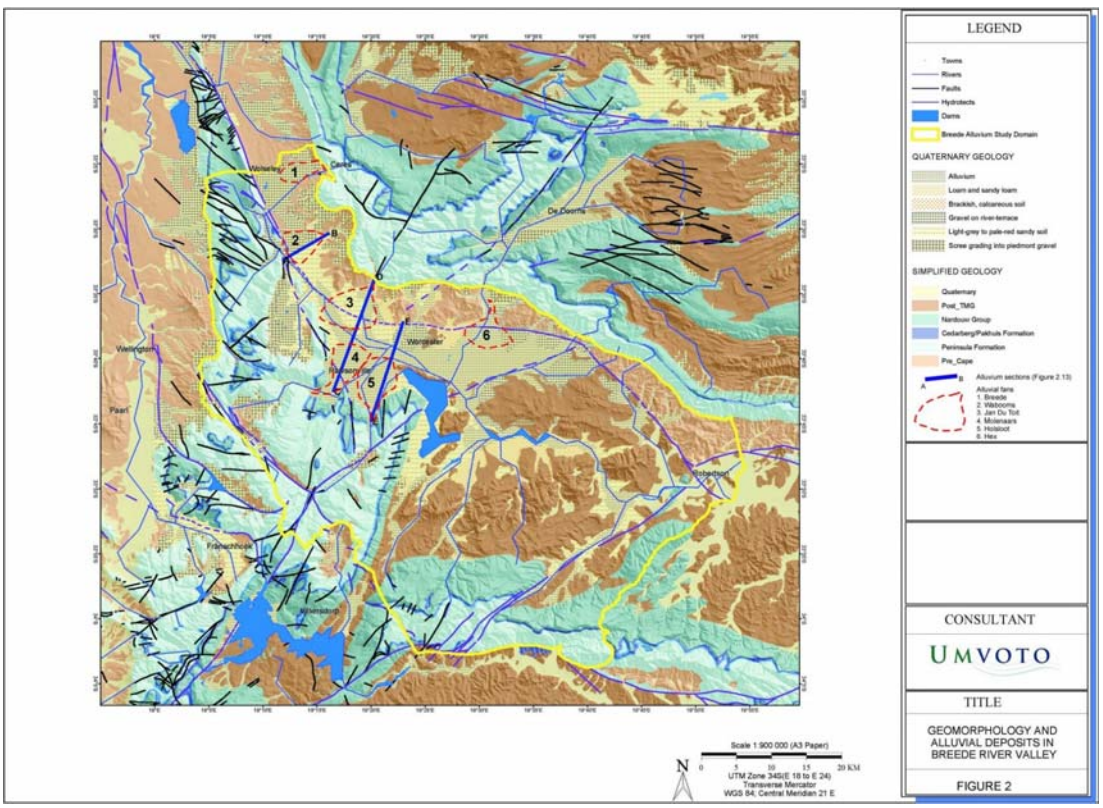

Figure 2 Alluvial geology and extent of alluvial fans in the Breede Valley

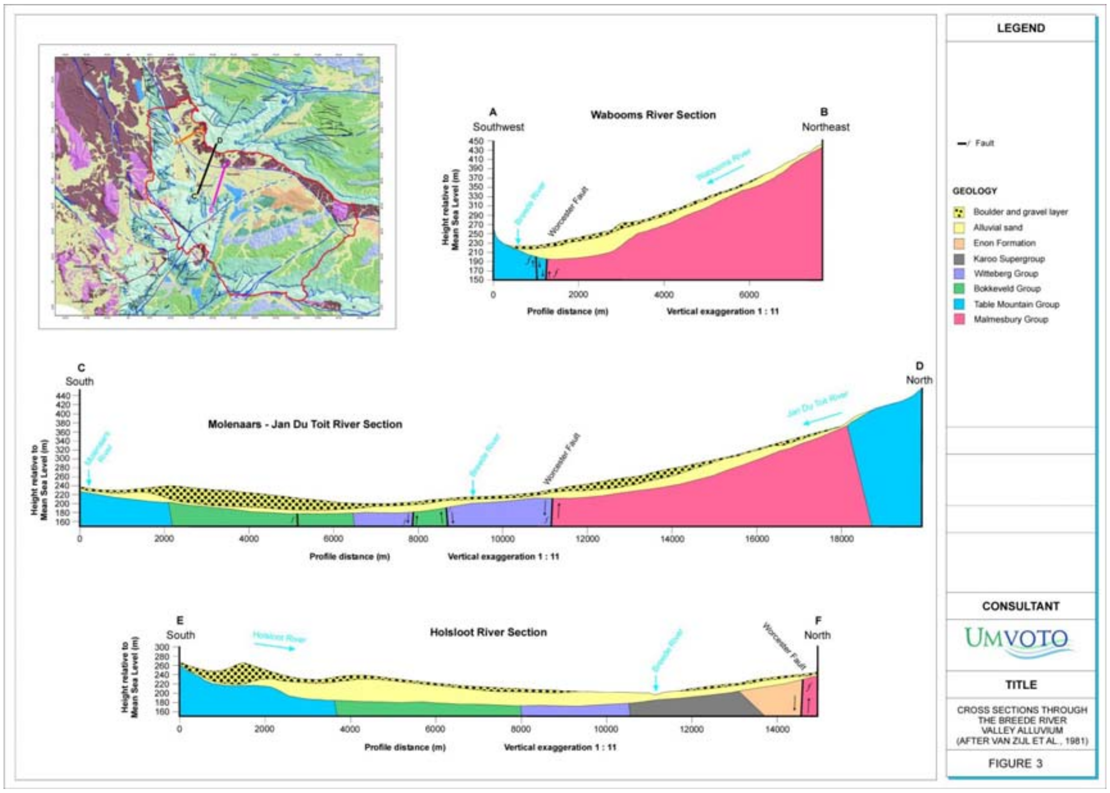

Figure 3 Geological cross sections through the Breede River Valley Alluvium

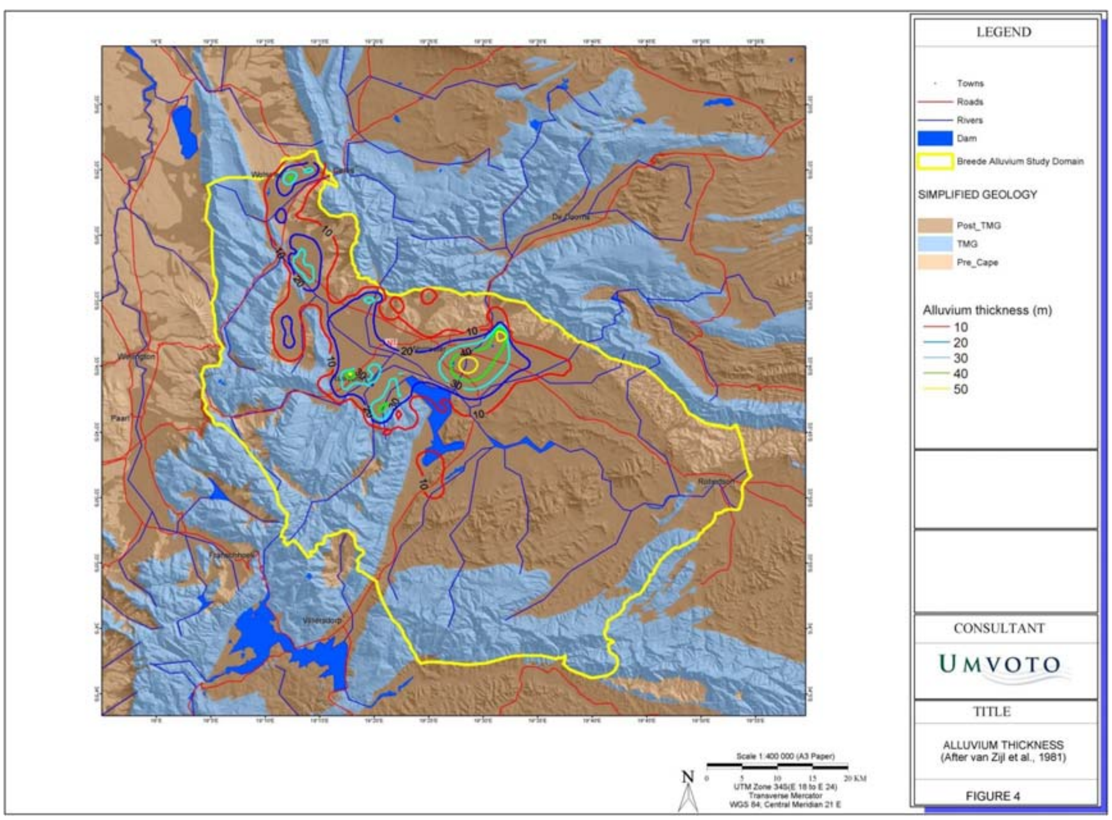

Figure 4 Alluvium thickness (after van Zyl et al., 1981)

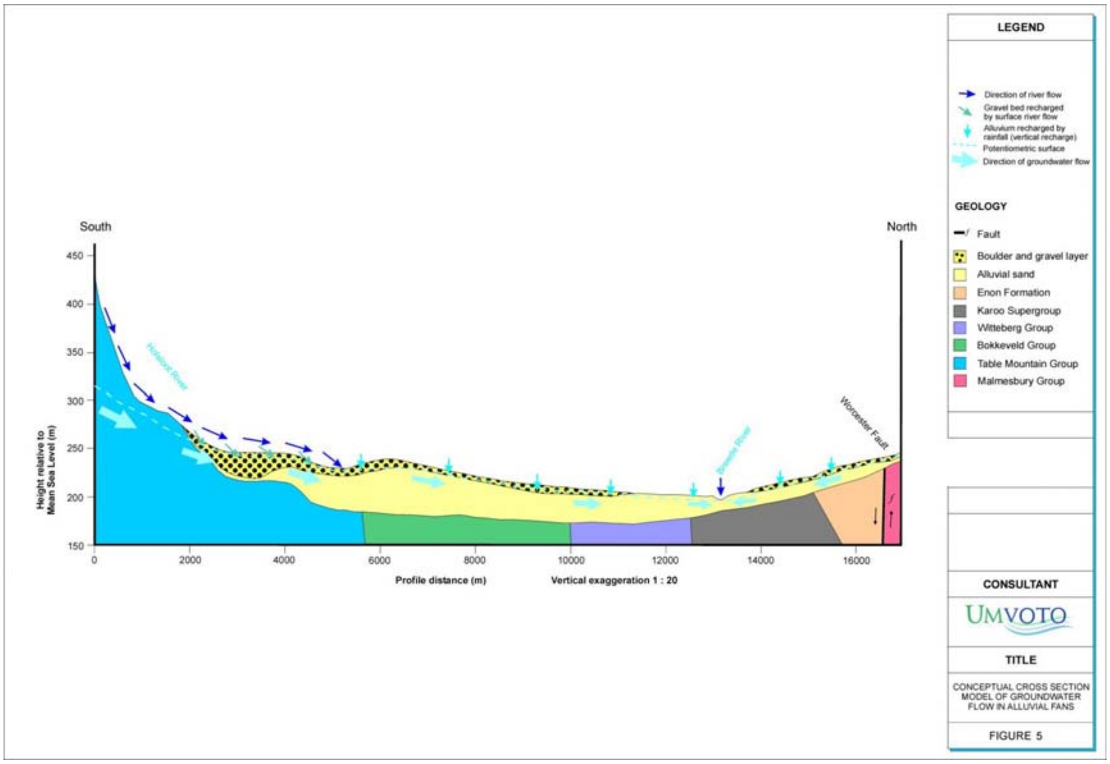

Figure 5 Conceptual cross section of the BAA

APPENDIX E

COPY OF PAPER PRESENTED AT 14TH SANCIAHS, 2009

INTEGRATION OF GROUNDWATER DEVELOPMENT INTO THE WRYM: LESSONS FROM BERG WAAS

Integration of groundwater development into the WRYM: lessons from Berg WAAS

K Riemann[1] & *A Sparks*[2]*; R Hay*[1]*;A Görgens*[2]*, I Thompson*[3]

[1] Umvoto Africa (Pty) Ltd
[2] Aurecon
[3] Department of Water Affairs, Directorate: National Water Resource Planning

Abstract

One of the main objectives of the current Water Availability Assessment Study (WAAS) for the Western Cape was to model allocable water from both surface water and groundwater. Consequently, the surface water component was updated and methods of modelling the groundwater components and the interaction between surface water and groundwater were developed.

The proposed integration of groundwater into the WRYM was tested for abstraction scenarios from the TMG Aquifer, which has a huge storage volume that can be used for climate change adaptation and potential for augmenting the supply to the City of Cape Town. Groundwater was treated as external source of water, adding to the river flow and dam yield.

Initial estimates. The increased yield of the existing dams due to groundwater abstraction was determined by Aurecon, assuming potential groundwater abstraction rates for the aquifers in close proximity. Pumping groundwater continuously might maximize the yield but would result in unnecessary spillage during wet periods, if conveyed via the existing dam infrastructure. Different operating rules for maximizing the yield and minimizing the pumping from the groundwater were investigated. Initially, the increased pumping from the groundwater was assumed to not affect the baseflow.

Refined estimates. Umvoto developed a spreadsheet model outside the WRYM which provides annual baseflow sequences for each of the different abstraction scenarios in the WRYM. The spreadsheet model is based on the understanding of the TMG Aquifer behaviour and considers the potential impact of temporal variation in rainfall and abstractions in the TMG Aquifer system having time lags of a number of years on this baseflow. The fluctuation in hydraulic head was calibrated against the available data and detailed groundwater model results.

The reduction in surface water flow from the increased groundwater abstraction was used to refine the initial estimates of the contribution to the yield from groundwater. For the scenario of intermittent groundwater abstraction during dryer periods, the yield increase is about twice the average abstraction from groundwater.

Conclusions. Modelling the TMG Aquifer externally allowed for a more flexible approach to the yield analysis and for more realistic development of operational rules for drought management. The disadvantage of using an external mode is that stochastic analyses are time consuming.

Keywords: *Table Mountain Group, TMG, System Operating Rules, Western Cape Water Supply System*

1. Introduction

In the Western Cape the ground water resource of the Table Mountain Group (TMG) is estimated to be a couple of orders of magnitude greater than the surface water resource while the recharge rate of the groundwater is about a third of the inflows to the dams (see Table 1). The conjunctive use the two water resources could maximize the benefit of groundwater to the water supply. Initially, mining some of the ground water storage could provide water while other sources are being evaluated and desalination technologies are being refined. Later groundwater could be used to augment the system only during times of drought to reduce the abstraction to the sustainable recharge rate.

Table 1: Characteristics of surface water and groundwater

Feature	Surface water	Groundwater
Storage (mcm)	900	82516
Inflows or Recharge (mcm/a)	805	273
Groundwater contribution to surface flows (mcm/a)		< 49

Table 2 shows the detailed breakdown of the surface water supply characteristics in the Western Cape. Note that for extended periods of about five years the inflows can reduce to 60% of the average and it is especially during these drought periods that augmentation from the groundwater would be beneficial.

Table 2: Details of surface water supply characteristics

Surface catchment	Storage	Inflow
Steenbras + Palmiet transfer	65	66
Theewaterskloof	480	290
Berg River Dam + Supplement	130	176
Wemmershoek	59	74
Voelvlei	165	199
Total	899	805

Table 3 shows the detailed breakdown for the ground water supply for the corresponding region. As part of the WAAS study it was estimated that the contribution of the TMG to groundwater was an order of magnitude less than the recharge rate (8 vs 61 million m^3/a)

Table 3: Details of ground water characteristics

Formation	IWRM domain	aquifer storage volume mcm	Recharge from rainfall mcm/a	Discharge to surface water mcm/a
Peninsula	KGB	31749	27	6
	PUB	2796	82	12
	THK	37802	61	8
Skurweberg	KGB	3492	62	16
	THK	6677	40	6
Total		82,516	273	49

2. Quantifying The Benefits Of Conjunctive Use

The benefits of conjunctive use were quantified for the Theewaterskloof compartment of the Peninsula formation of the TMG aquifer. This has the advantage that the groundwater well field accessing this aquifer would be able to use existing storage and conveyance infrastructure. Water could be stored in the Theewaterskloof / Berg River Dams and conveyed to the City using the Theewaterskloof Tunnel. It might be necessary to construct an additional Water Treatment Plant, maybe near Muldersvlei, to process water supplied to the North Western suburbs of Cape Town.

The following approach was adopted:
The benefits of conjunctive use were first evaluated in the Water Resources Yield Model (WRYM) for various groundwater abstraction capacities and operating rules.
Thereafter, a combination of local expert knowledge and a spreadsheet model was used to provide an initial estimate of the impact of the abstraction scenarios on the TMG and on the contribution of groundwater to surface flows.
The reduced estimate of the contribution of groundwater to surface flows was used to adjust the yields obtained in the WRYM.

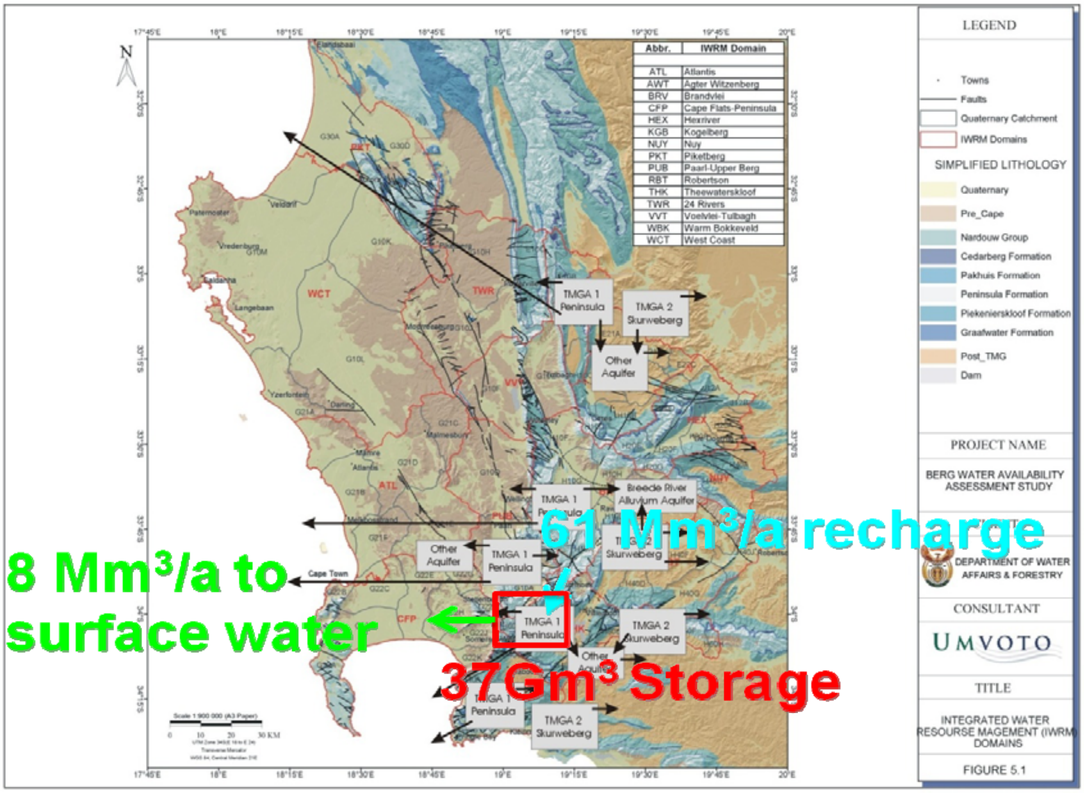

Figure 1: Recharge, Surface Water Recharge and Storage of the Peninsula formation of the Theewaterskloof compartment of the TMG

3. Water Resources Yield Model

The WRYM for the integrated Western Cape Water Supply System was modified to allow groundwater to be pumped into the system at various rates subject to different operating rules.

The capacity of the groundwater supply ranged around the estimated recharge rate of the system of 61 million m³/a, and varied from 25 to 300 million m³/a, or 0.79 m^3/s to 9.5m^3/s.

A range of groundwater pumping rules were generated, either minimizing pumping on the one hand or maximizing yield on the other.

These rules were created by examining the filling of the system during wet winter season. Hypothetically, to prevent groundwater pumped into the system from increasing spillage from the system it would be necessary to determine the maximum increase in storage possible till the end of the rain season for each month. In any month, pumping of groundwater would only be allowed when the *available unused* storage exceeded this possible increase.

In practice, single floods events can fill the system and the system cannot be kept empty waiting for these events. Storage levels corresponding to risks of spillage of 10%, 30%, 50% and 100% were determined and are illustrated in Figure 2. If say the 50% risk of spillage operating rule was adopted then pumping of groundwater would always cease in any month if the system storage rose above the blue line in Figure 2.

It was assumed that water pumped during the peak summer summer period (December to February) would be consumed before the end of winter and the spillage risk rule was not applied during these months.

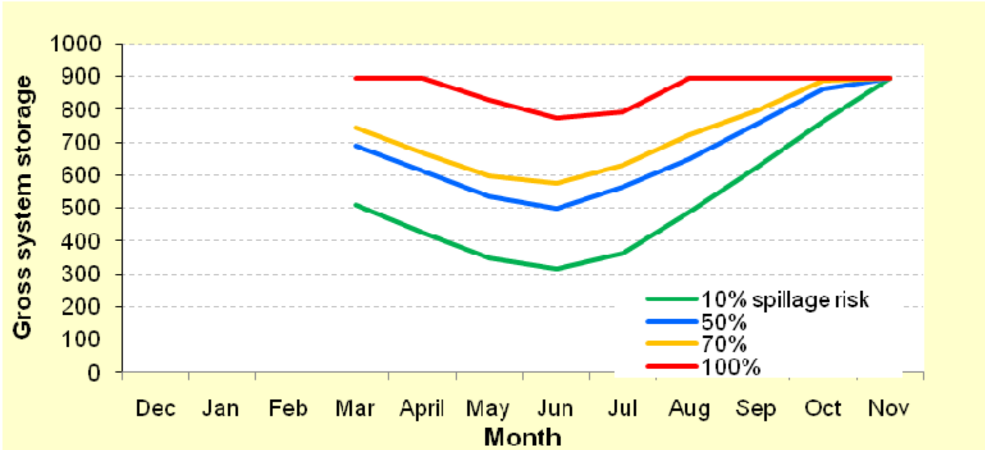

Figure 2: Operating rules halting groundwater abstraction when the risk of it's spillage exceeds a specified target

The initial yields (before considering the reduction in contribution from groundwater to surfaced water) and average volumes of groundwater pumped for the range of groundwater abstraction capacities and spillage risks have been summarized in columns d and e of Figure 4.

4. TMG Spreadsheet

The groundwater pumping sequences determined in the WRYM were imported into a spreadsheet used to model the behavour of the TMG aquifer. The spreadsheet was designed primarily for illustrative purposes as the processes that are modeled are complex and require detailed pumping tests and modeling to comprehensively describe the aquifer. The spreadsheet does however illustrate:
the drawdown of the aquifer as the abstraction rate exceeds the recharge rate,
the lag between groundwater abstraction and the reduced contribution of groundwater to surface water

4.1 Aquifer drawdown

Figure 3 illustrates the drawdown of the surface storage (black), the pumping from the aquifer to augment the surface storage (blue, green and red lines in the top panel) and the corresponding reduction in piezometric head of the aquifer (blue, green and red lines in the bottom panel) . The average pumping rate for each of the scenarios illustrated is close to the estimated recharge rate of the aquifer so the aquifer is does not remain permanently drawn down. In contrast, Figure 4 illustrates the drawdown of the aquifer when the average abstraction rate of 80 million m^3/a exceeds the recharge rate of about 60 million m^3/a

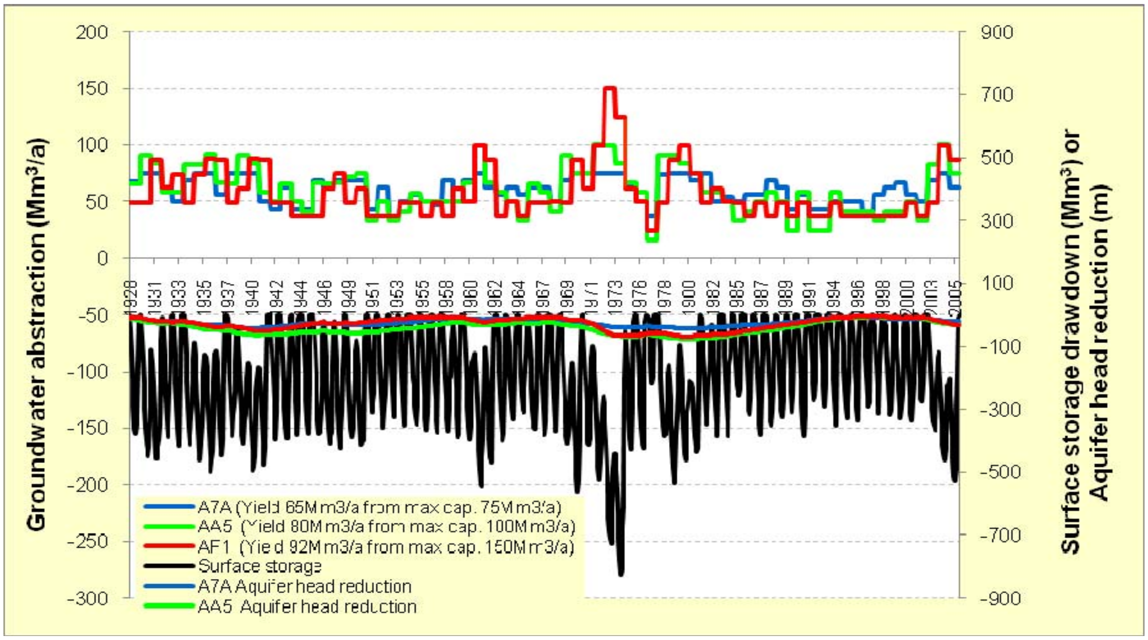

Figure 3: Different yields associated with long term groundwater abstraction of 60 million m³/a

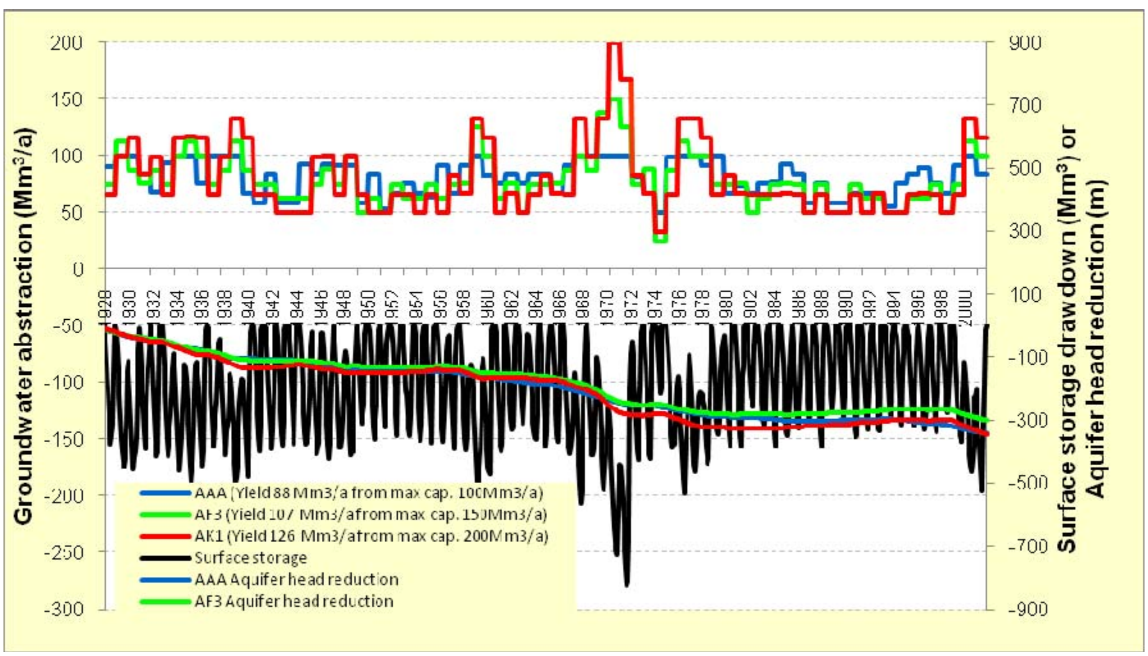

Figure 4: Different yields associated with long term groundwater abstraction of 80 million m³/a

4.2 Lag between groundwater abstraction and the reduction in the contribution of groundwater to surface water flow

The proposed groundwater well fields will be sited in the confined portion of the aquifer where impervious strata limit the effect of groundwater abstractions on overlying areas. Pumping from the well field will reduce the pressure locally within the aquifer and with time the reduced pressure will radiate outward to the edges of the confined aquifer. If the well field is sited 10-15 km from the edge of the confined aquifer this process could take decades. When the reduced pressure zone reaches the unconfined portion of the aquifer, the increased pressure gradient into the aquifer will increase the recharge rate of the aquifer and cause a corresponding decrease in surface streamflows, ie surface streamflows will be "captured". At present, the groundwater contribution to base flow component of surface flow, through springs and seeps is assumed to be 8 million m^3/a. The “capture” of surface streamflows could exceed 8 million m^3/a, though the water would be available for abstraction from groundwater storage.

For illustrative purposes a lag of 5 years was adopted in the spreadsheet, though this could be considerably longer if the well field is located far from the unconfined edges of the aquifer. If the impact of increased groundwater abstraction on the surface water is lagged by 5 years then the contribution from groundwater to surface flow during the drought period may be average or even above average as is illustrated in Figure 4. For the purposes of estimating the impact on the yield the average reduction in baseflow contribution was deducted from the WRYM yields to obtain the yield (see column g inTable 4). The yield estimates do not take account of the “capture” of surface flows that requires detailed modeling and will result in the transfer of yield from surface to groundwater.

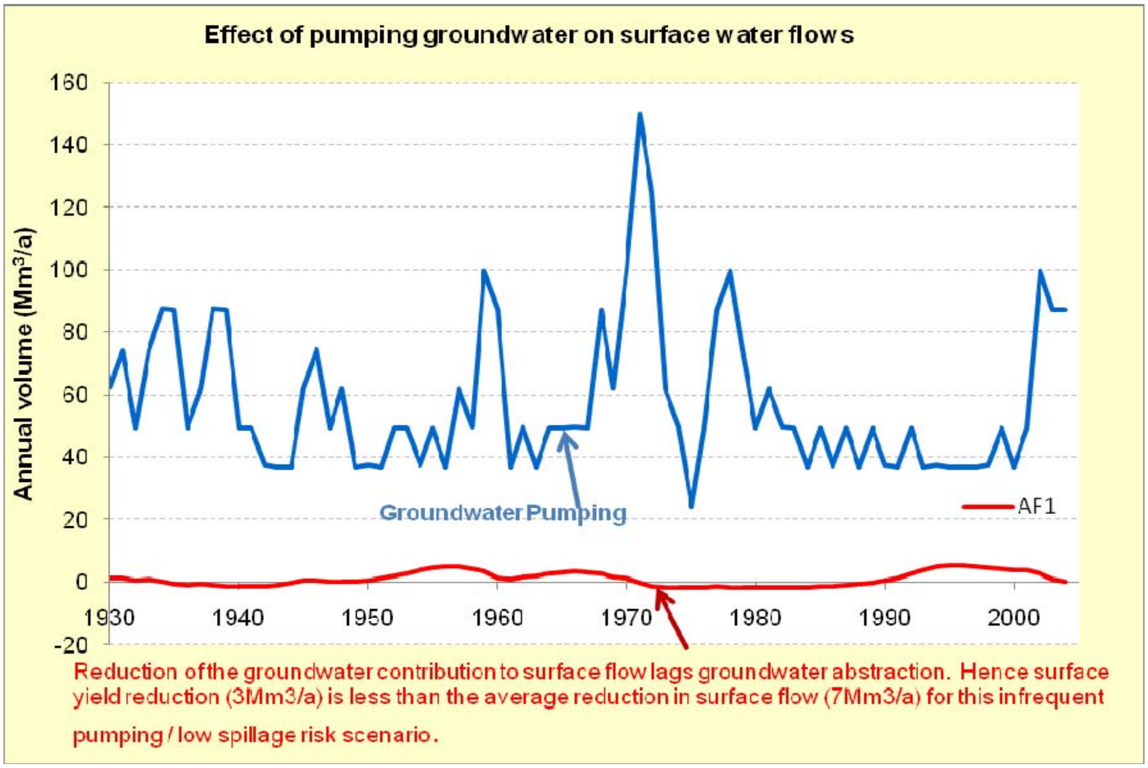

Figure 5 : Effect of groundwater pumping on surface water flows and yields

5. Results

The results from the yield analysis have been summarized in Table 4. Various relationships have been identified and illustrated in additional figures. Figure 6 illustrates that if the system is operated at a higher spillage risk then the ratio of the yield to the installed capacity of groundwater increases from 60% for spillage risks of about 10% to about 90% for spillage risks of 100%. Due to the summer peak in demand the groundwater abstraction capacity must exceed the average annual water requirement. Were the water requirement constant throughout the year then the ratio of yield to installed capacity would tend to 100% for scenarios with a high spillage risk.

The increase in yield is actually greater than the average volume pumped, especially when using operating rules with a low spillage risk. The difference between the yield and the volume pumped was termed the “conjunctive” component of the yield (see column h of Table 4) and the ratio of “conjunctive component” to the yield is illustrated in yield Figure 7. This ratio varies from 35-40%, if the system is operated at a low spillage risk, down to about 5-10% if the system is operated at a high spillage risk.

Table 4: Yield results

Scenario	Ground water capacity (mcm/a)	Max spillage risk	GW pumped	Incremental yield before surface water reduction	Average surface water reduction	Yield	Conjunctive component	Yield / pump capacity	Conjunctive component / Yield
a	b	c	d	e	f	g=e-f	h=g-b	i=g/b	j=h/g
A21	25	10%	9	15	1	14	5	56%	37%
A23	25	30%	12	18	1	17	4	66%	27%
A25	25	50%	15	21	2	19	5	78%	25%
A2A	25	100%	20	24	2	22	2	88%	8%
A51	50	10%	18	33	2	31	13	62%	43%
A53	50	30%	24	36	2	34	9	67%	27%
A55	50	50%	30	43	3	40	11	80%	26%
A5A	50	100%	40	48	4	44	4	89%	9%
A71	75	10%	27	50	3	47	20	63%	43%
A73	75	30%	37	55	3	52	15	69%	28%
A75	75	50%	45	65	4	61	16	81%	26%
A7A	75	100%	61	72	7	65	4	87%	7%
AA1	100	10%	37	65	3	62	25	62%	40%
AA3	100	30%	50	74	5	69	19	69%	28%
AA5	100	50%	61	88	8	80	19	80%	24%
AAA	100	100%	81	96	8	88	7	88%	8%
AF1	150	10%	58	99	7	92[1]	34	61%	37%
AF3	150	30%	78	115	8+[2]	107-	29-	71%	27%
AF5	150	50%	94	132	8+	124-	30-	83%	24%
AFA	150	100%	122	144	8+	136-	14-	91%	11%
AK1	200	10%	81	134	8+	126-	45-	63%	36%
AK3	200	30%	106	151	8+	143-	37-	72%	26%
AK5	200	50%	126	168	8+	160-	34-	80%	21%
AKA	200	100%	160	177	8+	169-	9-	85%	5%
AU1	300	10%	122	181	8+	173-	51-	58%	29%
AU3	300	30%	162	215	8+	207-	45-	69%	22%
AU5	300	50%	186	234	8+	226-	40-	75%	18%
AUA	300	100%	239	260	8+	252-	13-	84%	5%

If groundwater reduction occurs after droughts the yield reduction reduces to 3 million m³/a
Surface water reduction above 8 million m³/a from mining was not determined

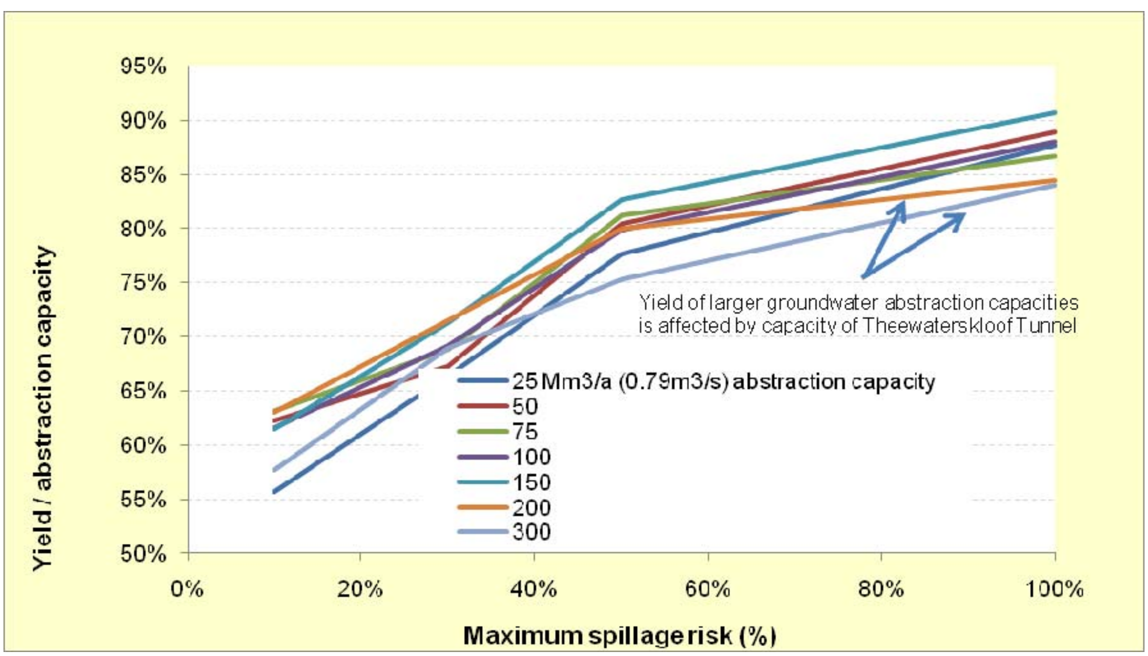

Figure 6: Yield / capacity for different groundwater abstraction capacities and for operating rules with different spillage risks

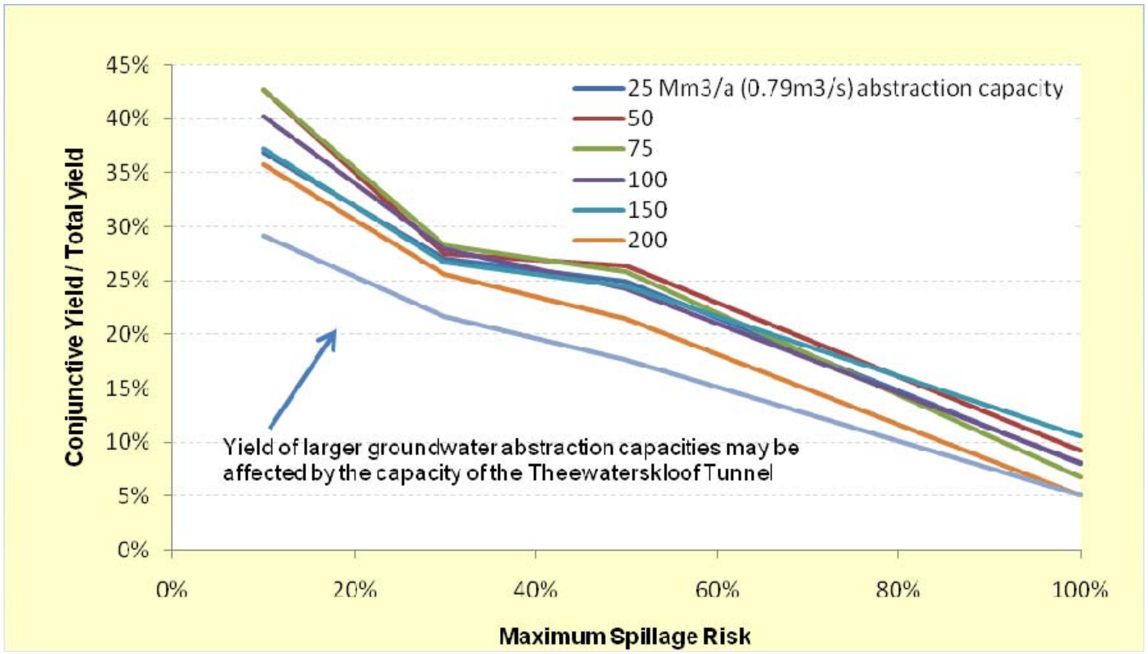

Figure 7: Ratio of conjunctive yield to total yield for different groundwater abstraction capacities and for operating rules with different spillage risks

Figure 8 illustrates how different yields can be obtained for the same long term groundwater abstraction depending on the risk of spillage adopted for the operating rule. A larger abstraction capacity permits an operating rule with a lower risk of spillage to be adopted. The yield may still increase for a given average abstraction rate because the abstractions can be concentrated in the critical drought periods.

This figure also illustrates, for the 100 million m³/a abstraction capacity case, that reducing the average abstraction from say 20 million m³/a above the recharge rate down to the recharge rate will not necessarily cause the yield to reduce by 20 million m^3/a. In this case the yield reduces by about 8 million m^3/a rather than by 20 million m^3/a.

Figure 9 illustrates the same scenario slightly differently. Note, however, that for an abstraction capacity of 150 million m^3/a, the reduction in yield through reducing the average abstraction rate by 20 million m^3/a is about 15 million m^3/a, much larger than the 8 million m3/a reduction obtained for the 100 million m^3/a abstraction capacity case. Note that the lesser reduction corresponds with changing from 100% risk to 50% risk and the larger reduction corresponds to changing from the 50% risk to the 10% risk of spillage.

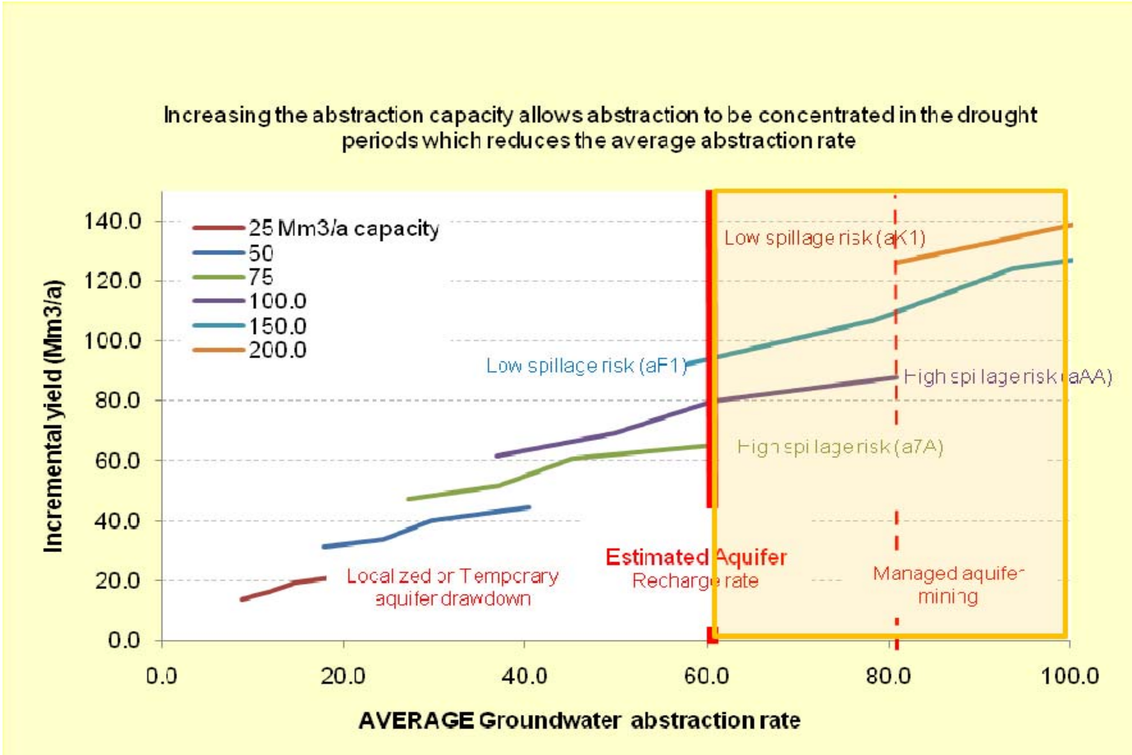

Figure 8: Different yields from the same AVERAGE groundwater abstraction rate

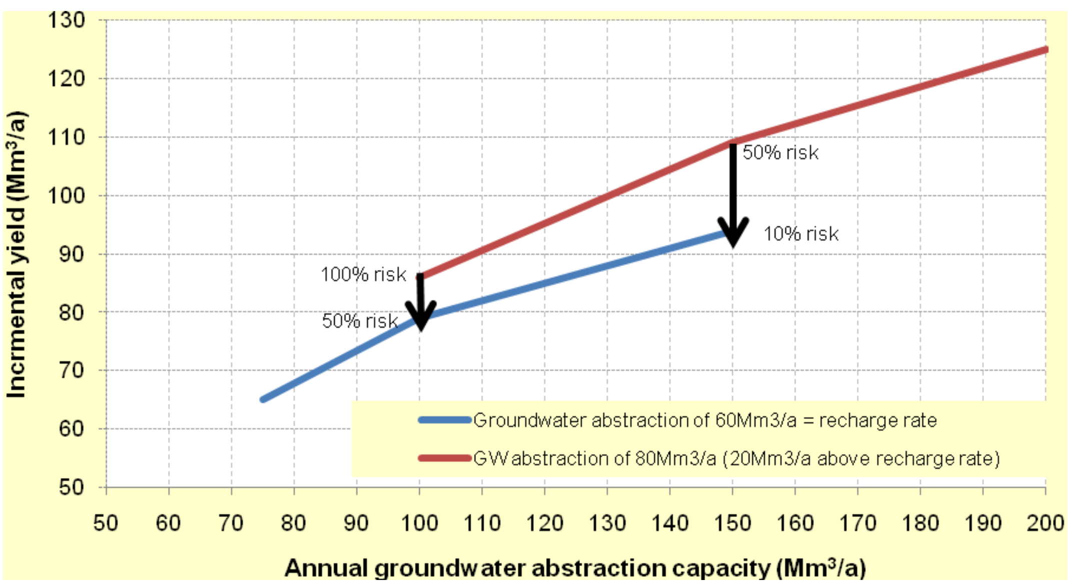

Figure 9: Yields for ground water operated at 20 million m³/a above the recharge rate and at the recharge rate

6. Operating rule and scheme management

When required, the rate of abstraction from ground water can be increased to maximize the yield for a given well field capacity. However, at a later stage, the abstraction from groundwater can be reduced to prevent further drawdown of the aquifer or because of the introduction of a new surface water scheme. The reduction in yield may be significantly less than the reduction in average abstraction rate.

7. Stochastic analysis and planning analyses

Part of the reason for the significant yields obtained from operating the system at a low risk of spillage may be due to the nature of the historical inflows. As can be seen in Figure 3 and Figure 4 the system is drawn down by one significant drought event between November 1968 and April 1974 and supplying groundwater during this event significantly increases the yield. The benefits of the different operating rules should also be checked using stochastic inflow sequences.

It should be adequate to use the same method as described in Table 4 to re-determine the incremental yields in column e at say the 1 in 50 year risk of failure. The same reductions in yield listed in column f could be used to re-determine the incremental benefit in column g.

8. Conclusions

8.1 Modelling

- Modelling the impact on the surface water of the TMG externally allowed for a more flexible analysis to cope with lags in the order of years
- Stochastic analyses will be time consuming using this approach though a reasonable approximation may be obtained using historical reductions in surface water yield

8.2 Conjunctive use

- More detailed testing and modeling is required to test assumptions
- A flexible approach should be adopted in the use of groundwater to augment the Western Cape System
- Initially abstractions from the Theewaterskloof aquifer could exceed the recharge rate
- Later the abstractions could be reduced, but the reduction in yield would be less than the reduction in abstraction

9. References

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