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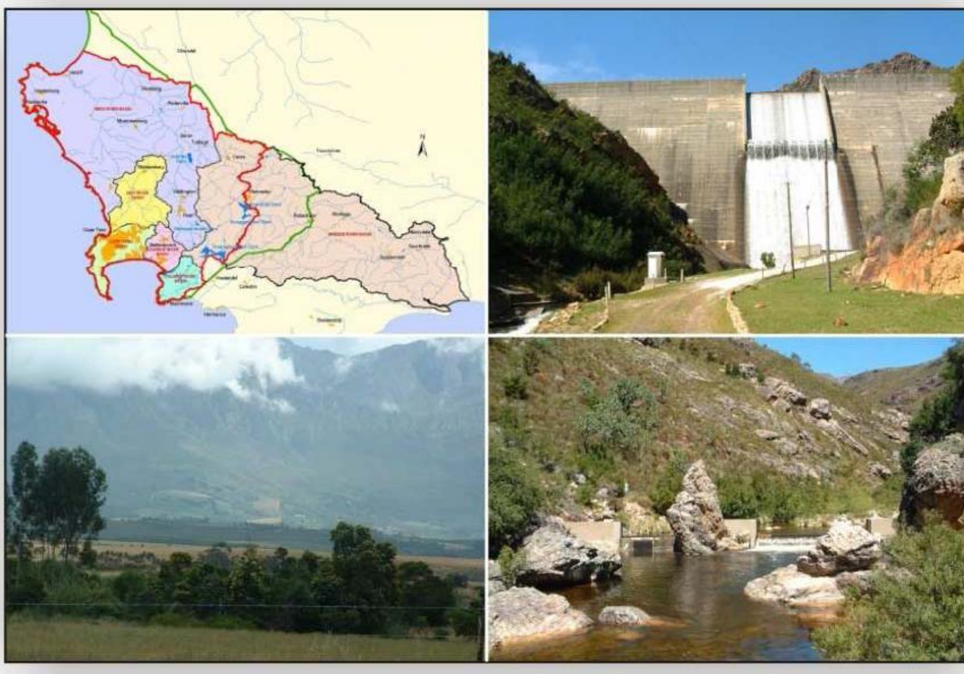
Department of Water Affairs and Forestry

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. 11 : Applicability of the Sami Groundwater Model to the Berg WAAS Area



FINAL **March 2008**

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. 11

APPLICABILITY OF THE SAMI GROUNDWATER MODEL TO THE BERG WAAS AREA

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APPROVAL

DWAF REPORT NO.	:	P WMA 19/000/00/0407
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Prepared by Ninham Shand (Pty) Ltd in association with Umvoto Africa (Pty) Ltd on behalf of the Directorate : National Water Resource Planning. DWAF Report No. P WMA 19/000/00/0407.

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. 11

Applicability of the SAMI Groundwater Model to the \ Berg WAAS Area

EXECUTIVE SUMMARY

At the groundwater technical committee meeting of 30 May 2007 it was requested of the Berg Water Availability Assessment Study (WAAS) project team to evaluate the applicability of the GRAII / Sami Groundwater model to the Berg WAAS area. The purpose of the Sami model, which has been incorporated into the later versions of the WRSM2000 (Pitman) model, is to model surface water-groundwater interaction in monthly time steps at a quaternary or sub-quaternary catchment scale. The WRSM2000 model can be run with this model enabled or disabled.

The primary purpose of this report is to describe the applicability of the Sami model in the Berg WAAS study domain by evaluating where, how and why, or why not, physical reality can be simplified to model definition or concept in the different quaternary catchments. Based on a practical evaluation and a conceptual analysis of whether and how different aquifers exchange water with the tributaries and main stem of the river in each catchment in the study domain, it was concluded that the Sami model is not appropriate to use in 84% of the quaternary catchments in the Berg WAAS area. In all of these catchments the groundwater flow regime is truly 3D and cannot in any meaningful way be simplified to 1D, as is the case in the Sami model. In the remainder of the quaternary catchments, the Sami model can possibly be applied, although it is also not recommended.

On the basis of the above assessment, two catchments representing each of the above categories were selected in which to test the Sami model by running the WRSM2000 model with the Sami model enabled and disabled and by using both the default as well as derived input parameters for the Sami model. The results of this assessment showed that, in both catchments, the default Sami parameters generally result in a slight decrease in simulated runoff - even when no groundwater abstractions are modelled, while the improved Sami parameters result in a fairly significant increase in simulated runoff. The results also showed that the introduction of groundwater abstractions, with the improved Sami parameters, reduces the long-term mean annual runoff (MAR) by about 25% of the actual annual volume that is abstracted. Furthermore, the investigation confirmed that re-calibration of the Pitman model, once the Sami model (with groundwater abstraction) is enabled, may be achieved by means of adjustments to ST, FT, ZMIN and ZMAX. However, a more drastic re-calibration is required for those catchments that are classified as "inappropriate" as opposed to catchments in which the Sami model was deemed to be "possibly appropriate". This was necessitated by a significant increase in simulated flow during the wet season in the "inappropriate" catchment.

In light of the findings of this evaluation, three possible approaches to facilitate the modelling of surface water-groundwater interaction in both the catchment and system models were considered, *viz.*:

- Conventional Pitman modelling (Sami groundwater model disabled)

- Pitman modelling with Sami model enabled
- Pitman model with external source representing groundwater contribution to discharge and "dummy" groundwater reservoir representing aquifer storage in the system model.

The first approach takes into consideration the serious concerns which have been raised with regard to the applicability of the Sami model and therefore proposes the use of conventional Pitman modelling, i.e. with the Sami model not enabled, as an option for the Berg WAAS. Such an approach assumes that the Pitman model implicitly accommodates the groundwater contribution to baseflow and that this is reflected in the calibrated Pitman parameters. The shortcoming of this approach however, relates to the most appropriate way in which to accommodate groundwater abstraction in the WRYM system model, taking into account that the naturalised flows, which will be produced by the calibrated Pitman model and which will be used as input to the system model, already reflect the impact of any groundwater abstractions as well as the groundwater contribution to baseflow.

The second approach is based on the fact that, in spite of the findings of this report that the Sami model assumptions and implications for the hydrological process are not appropriate for the majority of the subcatchments in the study area, DWAF did put the Sami model forward for undertaking groundwater resource assessments in the WAA studies. It could therefore be considered appropriate for application in the Berg WAAS, as long as its limitations and the level of confidence in the results are clearly stated. Furthermore, as the Sami algorithms have been integrated into the system model, the effect of groundwater abstractions on baseflow and system yield can be assessed. However, it is the opinion of the study team that this approach will result in low levels of confidence in the modelling results due to the Sami model being considered "inappropriate" for 84% of the Berg WAAS quaternary catchments.

The third option aims to avoid the issues surrounding the application of the Sami model and promotes a simple, transparent conceptual model for accommodating surface water-groundwater interaction in both the catchment modelling and system modelling phases of the Berg WAAS. During the catchment modelling phase, it is envisaged that estimates of groundwater contribution to baseflow, as available on a quaternary catchment basis from the GRDM data (DWAF, 2006b), will be introduced into the Pitman network configuration as an external water source. This, in conjunction with the existing technique whereby the areas that are irrigated from groundwater sources are excluded from the total irrigated area, will ensure that the calibrated Pitman parameters reflect the net cumulative impact of groundwater use and groundwater baseflow on simulated river flow. During the system modelling phase, the effect of groundwater use on baseflow (and system yield) will be simulated by introducing a "dummy" groundwater reservoir to represent the aquifer from which groundwater is abstracted. Estimates of aquifer capacity (size of the reservoir), recharge (inflow into the reservoir) and groundwater baseflow (outflow from the reservoir), will be based on best available knowledge. It is important to note that the GRDM estimates of groundwater contribution will be refined in those areas where the detailed numerical groundwater modelling which is currently underway, leads to an improved understanding of the surface water-groundwater interaction. During this refinement, which will take place before system modelling commences, the necessity for the reconfiguration of the catchment at a finer spatial resolution in order to accommodate aquifer specific groundwater discharge will also be considered.

Although the conceptual approach does not attempt to simulate all the groundwater processes that are treated as standard in conventional groundwater models, it is considered to be the most appropriate methodology within the context of the Berg WAAS and it is recommended that this approach be implemented.

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

Report No. 11
Applicability of the SAMI Groundwater Model to the Berg WAAS Area

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APPENDIX C: PARAMETERS OF THE SAMI MODEL

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ABBREVIATIONS

ASR	Aquifer storage and recovery
BRHS	Breede River Hydrological Study
CAGE	Citrusdal Artesian Groundwater Exploration
CMA	Catchment Management Agency
CRD	Cumulative Rainfall Departure
CSIR	Council for Scientific and Industrial Research
CVA	Change Vector Analysis
DEM	Digital Elevation Model
DWAF	Department of Water Affairs and Forestry
EFR	Ecological Flow Requirements
E-W	east west
EWR	Ecological water requirement
FE	Finite Element
GIS	Geographical Information System
GRA	Groundwater Resources Assessment
ISP	Internal Strategic Perspective
IWRM	Integrated Water Resources Management
km	kilometre
LRA	Langebaan Road Aquifer
m	metre
N-S	north-south
NEMA	National Environmental Management Act
NEMP	National Eutrophication Monitoring Programme
NGDB	National Groundwater Database
NMMP	National Microbiological Monitoring Programme
NWRS	National Water Resources Strategy
NWA	National Water Act
op.cit.	work previously cited
PAJA	Promotion of Administrative Justice Act
RDM	Resource Directed Measures
SFRA	streamflow reduction activities
STCC	short term characteristic curve
SVF	Saturated Volume Fluctuations
TDS	Total dissolved solids
TMG	Table Mountain Group
TMGA	Table Mountain Group Aquifer
WAA	Water Availability Assessment
WAAS	Water Availability Assessment Study
WARMS	Water-use Authorisation and Management System
WCSA	Western Cape System Analysis
WCWSS	Western Cape Water Supply System
WECSA	Western Cape Situation Assessment
WMA	Water Management Area
WRYM	Water Resources Yield Model

BACKGROUND AND INTRODUCTION

1. INTRODUCTION

1.1 THE WAAS PROJECT

1.1.1 Project Background

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.

Two major water resource management and planning undertakings have been initiated by the Department of Water Affairs and Forestry (DWAF) in the environment of the WCWSS:

a) 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 streamflow salinity increases, might place parts of the WCWSS in a water-stress condition during the foreseeable future.
b) 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 recommends 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 timeously so as 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 objectives of the Study are to (DWAF, 2005a):

- 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.
- Incorporate changes in concepts, models and approaches, as derived from pilot studies initiated by DWAF elsewhere, if these become available in time.
- Support the Reconciliation Study with model-based assessment of water resource augmentation options.

Ninham Shand (Pty) Ltd is the lead consultant and is responsible for the surface water components of the Study, as well as study management, while Umvoto Africa (Pty) Ltd is responsible for the groundwater components. Both consulting firms contribute either conceptually or directly to certain shared tasks.

1.1.2 Study area delineation

The study area shown in **Figure 1-1** comprises the following drainage systems and bulk water infrastructure:

- The total Berg River catchment from its source in the Groot Drakenstein Mountains to its estuary at Laaiplek on the Atlantic West Coast
- The Cape Town Basin, which includes all of the localised catchments which drain the Cape Town Metropolitan Area
- The Eerste, Lourens and Sir Lowry's Pass Rivers – all of which drain into False Bay.
- The Diep River, which flows westerly from its source in the Riebeeck Kasteel mountains to its mouth in the northern suburbs of Cape Town.
- The complete Palmiet and Steenbras catchments in the south of the Study Area, which flow in a south-westerly direction to the south of False Bay.
- The Breede River, which flows easterly to the Indian Ocean and of which the Upper and Middle Breede and the Upper Riviersonderend catchments are focus areas for this Study.

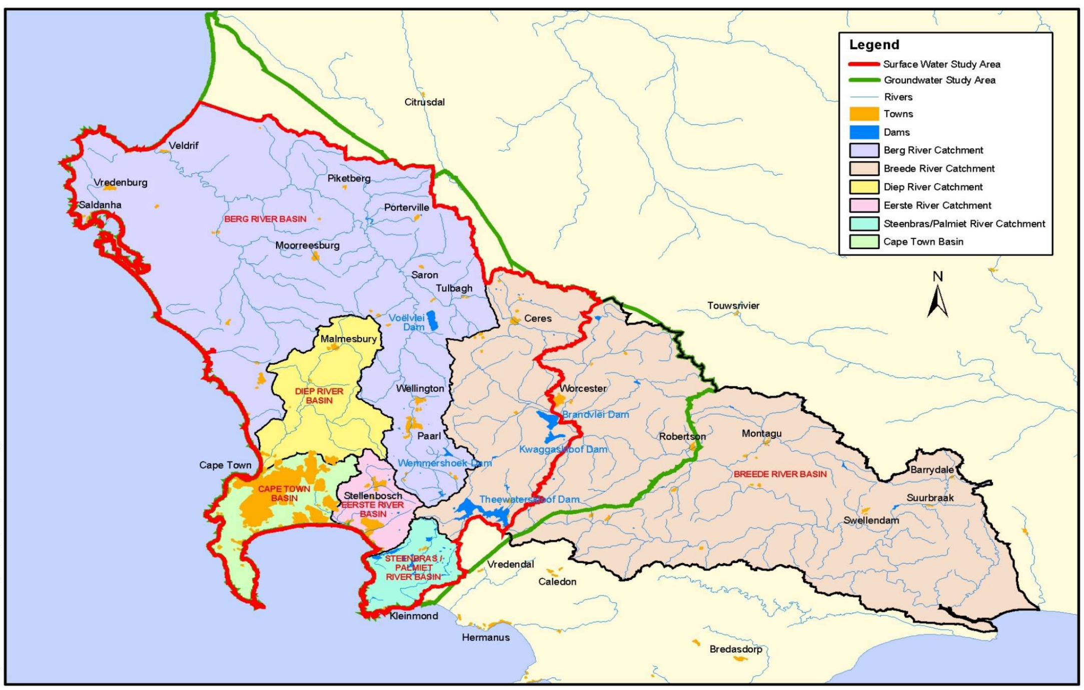

Figure 1-1 Study area locality

The Western Cape Water Supply System (WCWSS) is an integrated system of reservoirs, linked via a complex network of tunnels, pump stations and pipelines that stores and reticulates the runoff from rivers for use in the greater Cape Town Metropolitan Area. Surface water inter-basin transfers take place between the Berg, Riviersonderend and Eerste catchments, while water from the existing Steenbras Scheme is supplied from the Lower Steenbras water treatment works into the Cape Town Water Undertaking network. The Palmiet Scheme is a dual hydro-electric pumped-storage and water transfer scheme (to the Steenbras pumped-storage scheme), of which the water transfer component has not yet been fully implemented.

The study domain for the groundwater component extends beyond the boundary of the Berg WMA and includes the upper part of the Breede WMA as well as southern portions of the Olifants/Doorn WMA. This extended area between Tulbagh-Ceres, Kleinmond and Robertson approximately coincides with the “syntaxis” zone of N-S and E-W cross- or interference folding in the Cape Fold Belt. The high mountain exposures of the Table Mountain Group (TMG) in the anticlinal folds and the confined TMG fractured-rock aquifers in the synclinal folds are the main structural elements forming natural boundaries of groundwater flow and would therefore underlie sound groundwater models in the Berg WMA.

1.1.3 Project Components

The Study comprises two phases: Phase 1 (Inception) and Phase 2 (Model configurations for assessment of current water availability and selected augmentation options). Phase 2 comprises several distinct components that can be grouped into:

- Surface water hydrology
- Groundwater hydrology
- Surface water quality
- Water resources analysis
- Reconciliation options analysis
- Study management and review

1.2 REPORT ON APPLICABILITY OF GRAII/SAMI MODEL

At the groundwater technical committee meeting (30 May 2007) it was requested of the project team to evaluate the applicability, in this study area, of the GRAII / Sami Groundwater Model now available for use in the Pitman model. The purpose of the Sami model is to model surface and groundwater interaction in monthly time steps during the calibration of rainfall/runoff using the Pitman Model at a quaternary or sub-quaternary catchment scale. The Pitman model can be run with this model switched on or switched off.

Prior to the inclusion of this model in the Pitman model, groundwater abstraction was not modelled explicitly and the impact of groundwater use on river flow was partially accommodated by excluding areas that are irrigated with groundwater from the total irrigated area in a runoff model. Furthermore, it was assumed that once the Pitman calibration parameters have been adjusted to provide a good fit between observed and simulated streamflow, these parameters implicitly allow for the contribution of groundwater discharge to baseflow as well as the net cumulative impact of groundwater use on groundwater baseflow.

The Sami model is a one dimensional deterministic model with particular assumptions. The applicability thereof is therefore primarily a function of where, in this study domain, the model assumptions are appropriate. In any modelling exercise it is necessary to make assumptions in order to simplify the real world enough to be able to efficiently reproduce the outcomes of the key natural processes at the correct spatial and temporal scale. In groundwater flow or mass balance modelling it is important to decide the physical scale of the processes one wishes to model, the minimum level of geological complexity needed to reproduce these processes and whether it is possible to obtain physical data that can support model design, calibration and verification.

At the simplest level the model assumptions can assist one to decide whether a model is applicable or not in any one setting. Thereafter, if it is decided to use a model, it is necessary to evaluate how the model assumptions have been implemented mathematically. On this basis it is possible to decide whether a model is appropriate to use in solving a particular problem or not.

1.2.1 Purpose of this Report

The primary purpose of this report is to describe the applicability of the Sami model in the Berg WAAS study domain by evaluating where, how and why, or why not, physical reality can be simplified to model definition or concept in the different quaternary catchments.

It is assumed that the critical review of the original Sami model by Dr Ingrid Dennis of the IGS, UOVS (See Appendix A) is adequate evaluation of the mathematical robustness of the model. A comparison of the mathematical approach taken in this model with that used in other models is contained in Appendix B but no detailed critique is presented.

This report presents the results of a practical evaluation based on a conceptual analysis of whether and how different aquifers exchange water with the tributaries and main stem of the river in each catchment in the study domain. This conceptualisation starts with the known 3D geology and available hydrogeological data as well as best local knowledge of the flow in the rivers at different times of the year or in response to different rainfall events and the available hydrological data and modelling results.

On the basis of this assessment two catchments were chosen in which to test the Sami model by running the Pitman model with the Sami sub-model switched on and switched off and using both the default as well as derived input parameters for the Sami model.

Comment is made on the input parameters and the impact of spatially averaging these for more than one aquifer and also on the sensitivity of the Pitman model to the use of the Sami model with default or estimated parameters. This is considered an important aspect of applicability especially in catchments with known seasonal variation in groundwater discharge either through spring flow or groundwater contribution to base flow.

1.2.2 Structure of this Report

The report is structured into sections with several sub-sections each.

Section 1 describes the background to the project, summarises the terms of reference and outlines the purpose of this specific report.

Section 2 describes the Sami model approach and the hydrologic processes and possible settings for which the Sami model would be relevant

Section 3 describes the hydrological processes and settings within the Berg WAAS study domain and reasons why the Sami model would or would not be recommended for use.

Section 4 documents the results of testing the Sami model in selected catchments

Section 5 summarises the conclusion and recommendations arising from this study with respect to improving the manner in which the interaction of surface water and groundwater is quantified for resource evaluation and planning purposes.

Section 6 contains references.

DESCRIPTION OF THE SAMI MODEL

2. METHODOLOGY

This report does not address the mathematics of the Sami model. The algorithms used in the model were reviewed by Dr Ingrid Dennis of the UOVS in 2006 and the summary of the review is contained in Appendix A-5 of this report. A summary of the different mathematical approaches between the Sami model and a physically based model, and between the Sami/Pitman and numerical model or Mike SHE approach, to quantifying surface groundwater interaction is tabled in Appendix B. Other relevant background documentation to the Sami model and the integration thereof into the Pitman model is contained in Appendix A as background material for ease of reference and sake of completeness. A robust and practical approach to testing model applicability was taken.

2.1 RATIONALE

The Sami model was developed as part of the Groundwater Resource Assessment Project, Phase II (GRAII), to estimate the surface water–groundwater interaction and impacts of groundwater abstraction on stream flow at a national scale. The methodologies for these initiatives are explicitly described in the report output of the GRAII project (DWAF, 2005b).

The DWAF sub-directorate Integrated Hydrological Planning (IHP) reviewed the Sami model with the objective of conducting feasibility studies on the potential use of the:

- GRAII groundwater and surface water interactions code and
- GRAII code as an alternative approach used in the Pitman Model (1973).

Concerns about the applicability of this model to the physical circumstances in the Western Cape and in particular in the Berg WAAS study domain were raised during the Inception phase of this study (Umvoto Africa, 2005). It is widely recognised that there are inherent shortfalls in the Sami model and that it is also a beginning in the process to solving the challenge. This study is designed to objectively specify the nature of these pitfalls, evaluate in what hydrogeological settings the approach could possibly be useful, and to make recommendations as to the way forward.

2.2 STRUCTURE OF METHODOLOGY

The methodology was developed for the GRAII project in a MS-Excel environment that determines the impacts of abstraction on baseflow (DWAF, 2005b). The methodology has been extended since GRAII to use a time series of the Pitman S variable (subsurface storage) as input data, from which a time series of recharge is generated. The model is then calibrated against the stream flow hydrograph. This direct link to the Pitman Model and the use of hydrographs for calibration facilitated the integration of the Sami model into the WRSM and WRYM. The methodology is based on

1. Utilising the catchment soil moisture time series (Pitman S) generated by the WRSM 2000 to calculate a time series of recharge
2. Incrementing a percolating storage by recharge, with any recharge in excess of percolating storage capacity being moved to aquifer storage (see item 4)
3. Calculating interflow from the percolating storage utilising the Pitman methodology
4. Incrementing groundwater storage from the percolating storage up to a maximum recharge rate, with any recharge in excess of the maximum recharge rate contributing to interflow
5. Depleting groundwater storage by evapotranspiration and groundwater outflow to other catchments as a function of groundwater storage until static water level conditions are reached
6. Calculating groundwater baseflow or transmission losses in a non-linear manner as a function of groundwater storage and runoff volume
7. Depleting groundwater storage and groundwater baseflow due to abstraction as a function of aquifer diffusivity, time since pumping started, borehole distance from the river, and recharge.

The flow diagram of the methodology is shown in **Figure 2-1** and the structure of the methodology is shown in **Figure 2-2.** **Figure 2-1** summarises the various increments and decrements done in the model to reach a flux that is discharged from or into the aquifer from the river and which is thereafter used in the Pitman model i.e. either increases or decreases the flow in the river in any one month. The model variables are illustrated in **Figure 2-2** below taken from the model documentation.

The model is not calibrated against any transient groundwater level data and results are therefore dependent on initial start conditions as well as realistic input parameters and the calculated recharge rate, which is itself derived and not calibrated against field data or alternative methods. Interflow and groundwater baseflow are calculated in the Sami model and used to simulate groundwater contribution to baseflow and input to the Pitman model instead of adjusting groundwater contribution to baseflow as a simple uptake, as is the uptake of water by alien vegetation.

The input parameters to the Sami model and the Pitman model are summarized in Appendix C. Default input values are given for all the variables needed in the Sami model but some variables can be specified if this data or information is available in any particular catchment. Whether physically relevant data can be inferred or measured in any catchment depends very much on whether the model assumptions apply in the catchment or not.

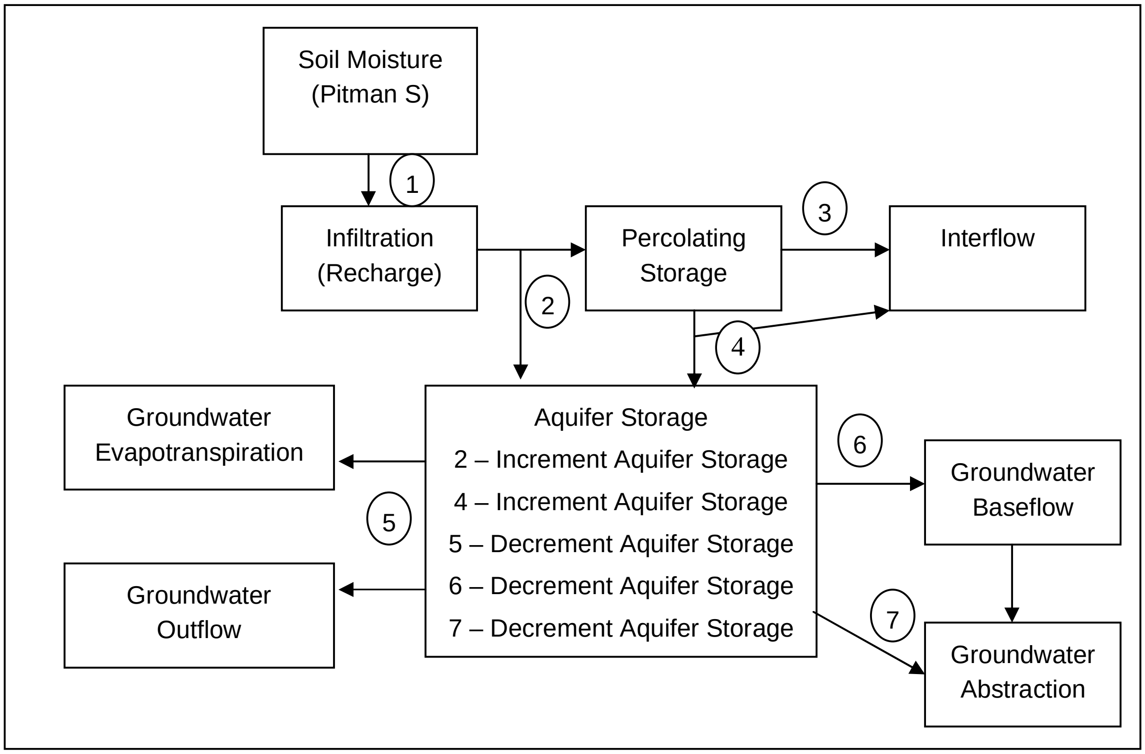

Figure 2-1 Process flow diagram

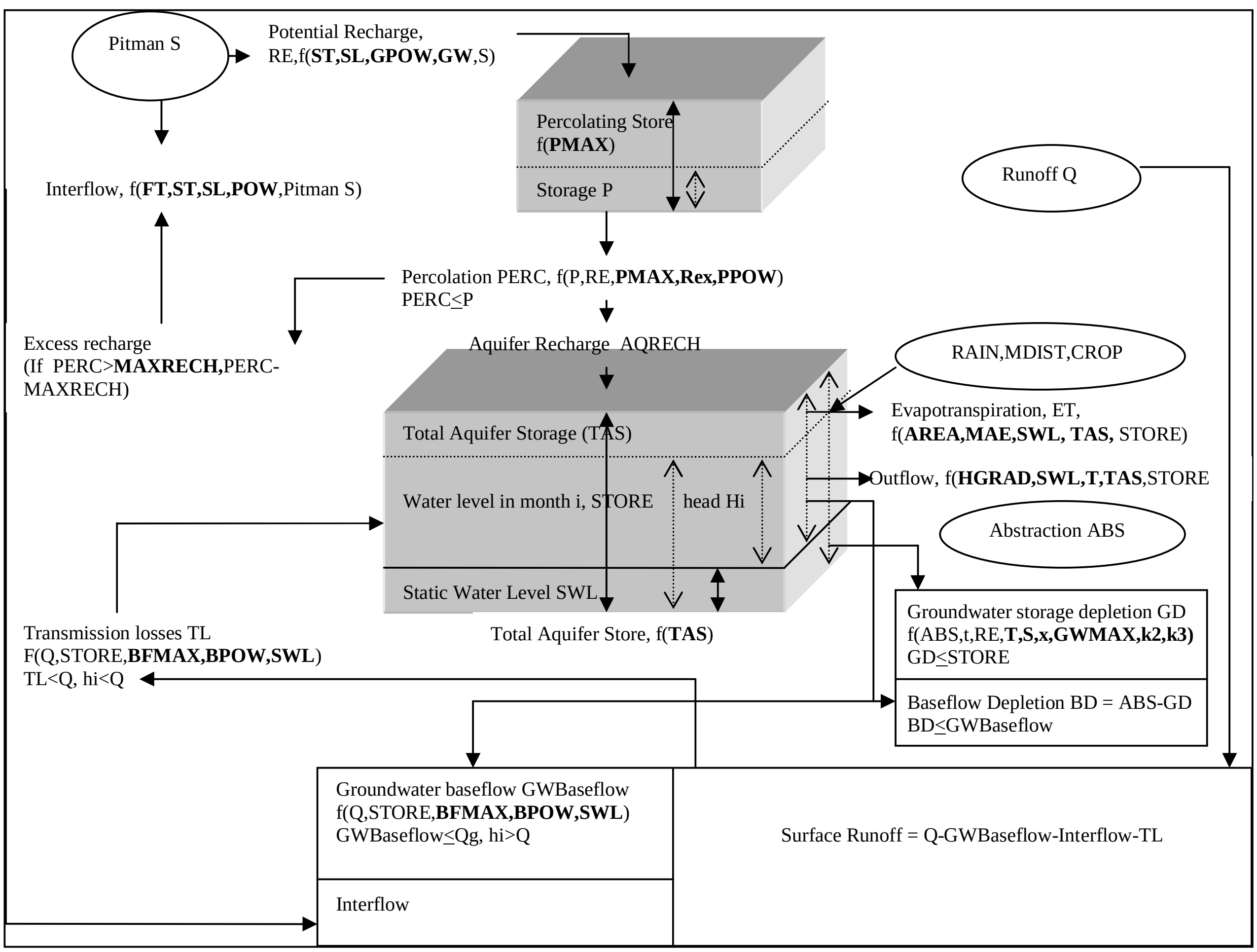

Figure 2-2 Structure of the Sami model interaction methodology (Parameters are indicated in bold) (after DWAF, 2006a)

2.3 SAMI MODEL ASSUMPTIONS AND APPLICABILITY CRITERIA

The Technical Documentation for Surface-Groundwater Interaction for use in System Models (DWAF, 2006a) states the underlying assumption and limitations of the model as follows:

> The proposed model for surface-groundwater interaction depends on several assumptions and encounters a number of limitations listed below:
>
> - Baseflow depletion due to groundwater abstraction as well as groundwater outflow from the catchment is calculated using a Darcian approach, i.e. assuming a porous media (primary aquifer). It has to be corroborated whether this approach is valid for a fractured/secondary or karstified aquifer system. Depending on the degree of fracturing and fracture interconnectivity a secondary or karstic aquifer can be represented as an equivalent porous media on a quaternary catchment scale.
> - The baseflow depletion calculation assumes that all abstraction takes place from the regional aquifer, not from perched aquifers.
> - Since the baseflow depletion calculation uses the weighted mean distance of abstraction points from the main channel, it is not applicable to assess the impact of a single groundwater abstraction point on baseflow. However, the cumulative effects of groundwater abstraction in the catchment can be addressed.
> - The hydrogeological parameters of the model are determined with water balance approaches and averaged over a quaternary catchment scale. Though they might resemble hydrogeological parameters determined on a local scale during hydrogeological field investigations, they usually differ from these physically based local parameters and should not be used as such.

In addition to the assumptions listed above, the model has inherent assumptions and limitations that arise from:

1. the reduction of the different processes to one dimension
2. the assumption that there is one aquifer throughout a quaternary which is recharged within the same quaternary as it discharges
3. the requirement that the aquifer is an unconfined aquifer in direct hydraulic contact with the main stem of the river, or alternatively that it is a reasonable model simplification to use one “symbolic” aquifer of this nature to represent all aquifers underlying or in hydraulic contact with a river
4. the difference in time lag between the response times of different aquifers is less than one year
5. an aquifer underlying a quaternary in which it is recharged, also discharges into the same quaternary whether it be via rejected recharge (interflow) or groundwater contribution to baseflow
6. the hydraulic gradient in the aquifer is the same in all directions, whether it be towards the river or along the length of the river.

These assumptions are summarized as six simple physical characteristics (see **Table 2-1**) to be used as an applicability check list in deciding whether or not the actual physical reality in each quaternary could be reasonably simplified to meet the above model assumptions without introducing significant and possibly unknown errors.

Table 2-1 Applicability Criteria for Sami Model

Criteria	Description
1	Single homogenous aquifer in catchment, with uniform gradient and isotropic parameter distribution
2	Shallow aquifer, water table near surface, that is connected to surface water body along the whole length of the river reach
3	Unconfined aquifer
4	Well established initial water level for starting month of simulation period
5	No significant, perennial tributary; assuming that groundwater flow is perpendicular towards the main stem
6	No endoreic drainage areas within catchment.

With reference to the simplification of physical reality and the consideration of the modeling of a fractured rock aquifer as an Equivalent Porous Media (EPM), this limitation of the model is less of an issue, in deciding applicability, than the actual manner of physical connection of any aquifer, primary of fractured, to the river network. Therefore the structural, stratigraphic and temporal relationships between different aquifers and the river network are considered once catchments have been excluded based on the simple 2D characteristics detailed above.

The possibility for horizontal outflow is described, but appears to be contradictory to the required 1D hydraulic gradient towards the riverbed. The Technical Documentation (DWAF, 2006a) does not elaborate on the calculation for the outflow.

Since all parameters are average or mean values for the entire catchment, it is required to have a homogeneous system in terms of topography, geology, aquifer properties and hydraulic gradient. It further requires a symmetric surface water drainage system towards the main stem that does not contain significant tributaries.

ASSESSMENT OF SAMI MODEL APPLICABILITY

3. APPLICABILITY IN THE BERG WAAS STUDY DOMAIN

3.1 MODEL ASSUMPTIONS AND IMPLICATIONS FOR HYDROLOGIC PROCESS

The comparison of the model assumptions, the applicability criteria selected and the implications for hydraulic processes are summarized in **Table 3-1** below.

Table 3-1 Relationship between Model Assumptions, Applicability Criteria and Hydrologic Implications

Model Assumptions	Applicability criteria	Process/Hydraulic Implications
One Dimensional (1D) Flow	Single homogenous aquifer in catchment, with uniform gradient and isotropic parameter distribution	All aquifers can effectively be modelled as one unconfined, single layer aquifer of constant thickness The aquifer has a constant and equal hydraulic gradient on both sides of the river Vertical flow is the primary direction of exchange between the river and aquifer No horizontal groundwater inflow Lateral recharge to downstream will happen at the same water table gradient as exists towards the river
All abstraction is from one regional aquifer	Shallow aquifer, water table near surface, that is connected to surface water body along the whole length of the river reach	Recharge and discharge for the aquifer occur in the same catchment No perennial springs sustain low flow in river bed There is no significant time lag between recharge and discharge Abstraction from every borehole will impact on groundwater contribution to baseflow
All abstraction in the catchment does impact on baseflow and is a linear function of distance from the river	Unconfined aquifer (see also above)	Significant implications for evaluating impacts of abstraction from confined aquifers where the behaviour of the drawdown cone is dependent on the length of time pumped rather than the volume and or the distance from a river.
Spatial and temporal averaging of aquifer parameters and hydraulic processes over a quaternary scale	Well established initial water level for starting month of simulation period	Transient model results strongly dependent on start time conditions; lack of data and or model simplification of lumping all aquifers into one single unconfined aquifer further compounds unreliability of any evaluation of impacts of abstraction, regulatory decisions, and resource availability on an aquifer scale.
	No significant, perennial tributary; assuming that groundwater flow is perpendicular towards the main stem	Spring flow is not accounted for

Model Assumptions	Applicability criteria	Process/Hydraulic Implications
Water that cannot be stored in the aquifer or soil is transferred out of the system as interflow, baseflow or loss to next quaternary	No endorheic drainage areas within catchment	Model results depend on an accurate spatially averaged estimation of recharge based on prior Pitman model results and assuming that all recharge to the underlying aquifer is derived from rainfall in that catchment (see above) Model results are not calibrated against any groundwater level time series (*how it is transferred to next quaternary is unclear*)

3.2 COMPARISON BETWEEN REAL WORLD AND MODEL WORLD

Using available data and local knowledge, each quaternary was checked against these obvious physical characteristics without consideration of the 3D geology or quaternary scale patterns of surface and groundwater interaction. Although criterion 6 is contained implicitly in criterion 2 it is used separately as the endorheic terminations of surface drainage networks impact quite specifically on recharge characteristics of underlying aquifers.

If at least 3 of the 6 applicability criteria were met, if further simplification of physical reality (if needed) could be introduced to comply with the model assumptions, and if it was reasonable to estimate the Sami input parameters, the Sami model was judged to be potentially applicable or "possible" (POS) in that quaternary, otherwise not (NOT).

The results of applying the check list above in the Berg WAAS study area are documented in Appendix D and illustrated in **Figure 3-1** below. In summary, the Sami model is considered as not being appropriate to use in 84% of the catchments. In all of these catchments, coloured red in **Figure 3-1**, the groundwater flow regime is truly three-dimensional (3D) and cannot in any meaningful way be simplified to 1D. This is considered a fatal flaw.

Although the aquifers in the remaining catchments are, at face value, unconfined regolith or primary aquifers, where the flow is two-dimensional (2D) and can possibly be simplified to 1D, we would not recommend the use of the model. These catchments have been listed as 'Possible' and are coloured yellow. The reasons for this recommendation are listed below and relate to the temporal and spatial patterns of surface and groundwater interaction/processes at a quaternary scale or the apparent dependence of the model results on certain factors.

- starting conditions, which are unknown,
- lateral recharge is a significant factor and therefore the recharge rate as derived from the Pitman S parameter, *viz*., lag time before the rivers begin to flow, is not appropriate
- the groundwater flow direction is not perpendicular but parallel to the river
- the rivers are recharged by spring flow
- groundwater is primarily accessed in dykes or faults which also control the drainage patterns of the rivers and
- groundwater is primarily related to palaeochannels disconnected from modern rivers and therefore borehole distance from the river is not a relevant factor in modeling the impact of abstraction.

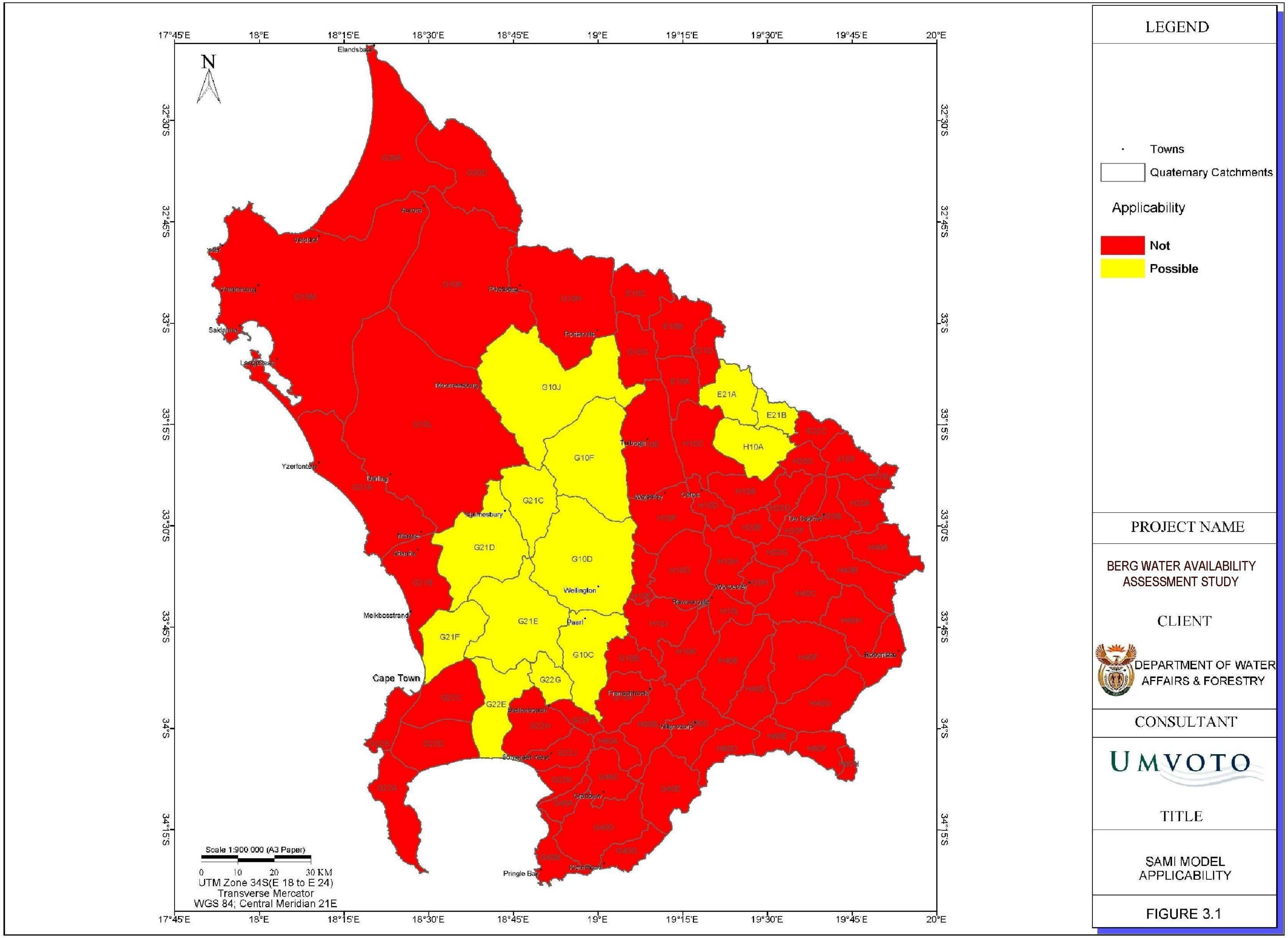

Figure 3-1 **Applicability of Sami model in Berg WAAS area**

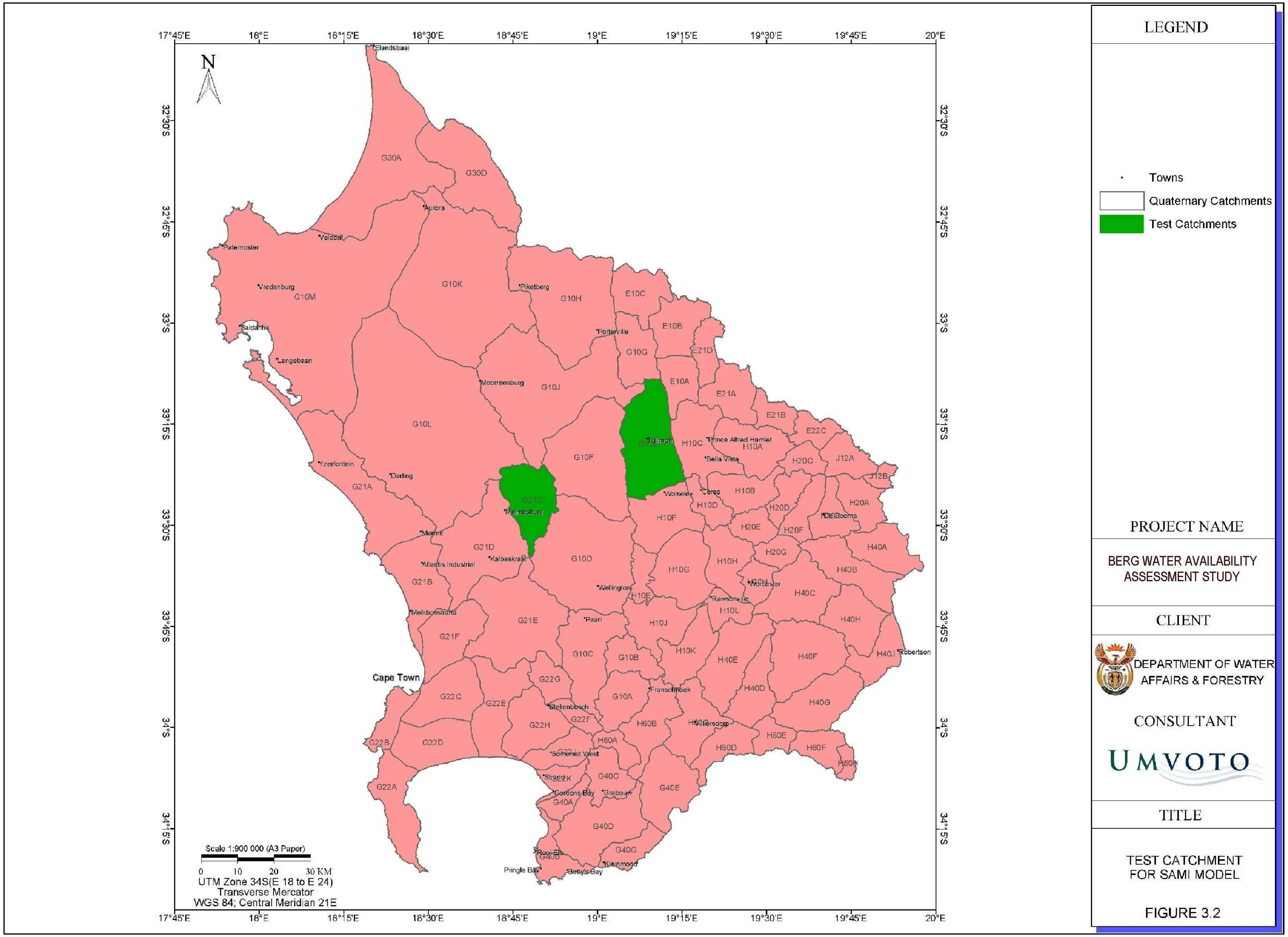

Figure 3-2 **Quaternary catchments where Sami model will be tested**

SAMI MODEL APPLICATION

4. APPLICATION OF SAMI MODEL IN KLEIN BERG AND DIEP RIVER CATCHMENTS

4.1 INITIAL INPUT PARAMETERS

On the basis of the results shown in **Figure 3.1**, the Sami model was applied, within the WRSM2000 environment, in the Klein Berg quaternary catchment (G10E) and in one of the quaternaries in the Diep River catchment (G21C) (see), the former being a catchment in which it is not considered applicable and the latter being one in which it could possibly be applied.

There are default values for each variable in the Sami model per quaternary catchment. However, some of these default values are not considered realistic and have been updated for the Diep and the Klein Berg quaternary catchments (see **Table 4-1**). The parameters have been estimated based on the known stratigraphy, pump test data that was available in these or comparable catchments or aquifers, water level data available from a recent Hydrocensus and which could be inferred to be relatively unimpacted by abstraction and assumed therefore to be ambient and acceptable starting conditions.

Table 4-1 Estimated Input parameters for Selected Quaternaries in the Diep and the Klein Berg Catchments

Parameter	G10E	G21C	G21D	G21E	G21F
Aquifer thickness [m]	100 - 200	100	100	100	35
Storativity (S)	0.05 - 0.1	0.005 - 0.05	0.005 - 0.05	0.005 - 0.05	0.1 - 0.3
Static water level (SWL)	Use default values, double check with NGDB				
MAXRECH [mm/month]	20.5	18	14.5	20.5	10.5
Max groundwater discharge (BFMAX) [mm/month]	3.4	2.0	1.9	2.1	2.0
BPOW	Use default values				
Hydraulic gradient (HGRAD)	0.04	0.01	0.004	0.004 - 0.009	0.0009
MAE	Use updated estimates				
GW evap. Area (AREA)	Use Riparian Zone Area				
Transmissivity [m^2/day]	10 - 1000	10 - 100	10 - 100	10 - 100	350
Distance-river (X) [m]	500	500	500	1000	800
K2	Calibrated				
K3	Calibrated				
Abstraction	No time series available				

4.2 RESULTS OF TESTING IN WRSM2000

Table 4-2 and **Table 4-3** display the results of the Sami model test applications in the Klein Berg and Diep catchments respectively. In essence, the tables show the effect of enabling the Sami groundwater model on simulated runoff (Mm^3) as represented by key statistical indices. The main column headings in the tables represent the following:

- Observed: The observed, patched runoff at the calibration gauge
- Pitman (without Sami): The conventional application of the Pitman model with the Sami model switched off. Areas that are irrigated with groundwater are excluded from the total irrigated area. Statistical indices represent the runoff as simulated with the calibrated Pitman model.
- Pitman (Sami defaults): Application of the Pitman model with the Sami groundwater model enabled. Use of default Sami parameters and Pitman parameters as calibrated without the Sami model.
- Pitman (improved Sami parameters): Application of the Pitman model with the Sami groundwater model enabled. Use of improved Sami parameters (see Table 4-1) and Pitman parameters as calibrated without the Sami model.

The results show that, in both catchments, the default Sami parameters generally result in a slight decrease in simulated runoff - even when no groundwater abstractions are modelled, while the improved Sami parameters result in a fairly significant increase in simulated runoff. The results also show that the introduction of groundwater abstractions, with the improved Sami parameters, reduces the long-term mean annual runoff (MAR) by about 25% of the actual annual volume that is abstracted.

There is no significant difference between the findings for the Klein Berg (considered inappropriate for Sami modelling) and the Diep (considered possibly appropriate for Sami modelling), except that the seasonal index seems to be more sensitive to the activation of the Sami model in the Klein Berg catchment than in the Diep catchment. A detailed review of the simulation results revealed that the activation of the Sami groundwater model in the Klein Berg catchment had very little effect on dry season flows, but caused a significant increase in simulated flows during the wet season, which explains the increase in the seasonal index.

Table 4-2: Results of Klein Berg Analysis (G10E)

Index	Observed	Pitman (without Sami)	Pitman (Sami defaults)		Pitman (improved Sami parameters)	
			No groundwater abstraction	Groundwater abstraction activated(1)	No groundwater abstraction	Groundwater abstraction activated(1)
MAR	71.64	71.57	70.23	68.26	79.97	79.16
Standard Deviation	37.07	35.33	39.61	38.92	39.45	38.93
Seasonal Index	41.46	33.04	40.68	40.68	37.36	37.37

(1): Annual groundwater abstraction estimated at 3.20 Mm^3/a

Table 4-3: Results of Diep Analysis (G21C)

Index	Observed	Pitman (without Sami)	Pitman (Sami defaults)		Pitman (improved Sami parameters)	
			No groundwater abstraction	Groundwater abstraction activated(1)	No groundwater abstraction	Groundwater abstraction activated(1)
MAR	11.84	11.97	11.46	10.81	13.72	12.81
Standard Deviation	12.67	12.08	11.53	11.06	11.70	11.45
Seasonal Index	57.76	51.29	51.39	52.39	48.90	50.00

(1): Annual groundwater abstraction estimated at 3.42 Mm^3/a

Whereas **Table 4-2** and **Table 4-3** explored the effect of the Sami model on simulated runoff, the following tables display the effect of the Sami model on the original set of Pitman parameters i.e. the degree of re-calibration that is required once the Sami model (with groundwater abstraction) is enabled. **Table 4-4** and **Table 4-5** show that the re-calibration of the Pitman model may be achieved by adjustments to ST, FT, ZMIN and ZMAX. From the tables it also appears as if the activation of the Sami model in the Klein Berg catchment necessitates more drastic changes to the original set of Pitman parameters than is the case in the Diep catchment, which might be confirmation of the fact that the former catchment is considered to be inappropriate for application of the Sami model.

Table 4-4: Effect of Sami model on Pitman parameters (Klein Berg catchment)

	POW	SL	ST	FT	GW	ZMIN	ZMAX	PI	TL	GL	R
Pitman	2	0	315	10	5	80	750	1.5	0	2.5	0
Sami (default)	2	0	**310**	10	-	**25**	**650**	1.5	0	-	0
Sami (Improved)	2	0	**350**	**5**	-	80	**850**	1.5	0	-	0

Table 4-5: Effect of Sami model on Pitman parameters (Diep River catchment)

	POW	SL	ST	FT	GW	ZMIN	ZMAX	PI	TL	GL	R
Pitman	2	0	305	10	0	75	400	1.5	0.25	0	0
Sami (default)	2	0	**285**	10	-	75	400	1.5	0.25	-	0
Sami (Improved)	2	0	**310**	**8**	-	75	400	1.5	0.25	-	0

The results of the Sami model application in the Klein Berg and Diep catchments have shown that, except for the apparent sensitivity of the Seasonal Index and Pitman parameters in the case of the Klein Berg catchment, there are no distinct differences in the response of these catchments to the activation of the Sami groundwater model. On the basis of the findings of Chapter 3 that the Sami model assumptions and implications for the hydrological process are completely inappropriate for application in the Klein Berg catchment whereas it might be considered possibly appropriate in the Diep River catchment, a more prominent difference in the responses of these catchments in terms of runoff and re-calibration was expected once surface water-groundwater interaction as modelled by the Sami model was enabled. The more or less similar responses of these catchments therefore suggest that the Sami model is probably also not appropriate for application in the Diep catchment.

CONCLUSIONS AND RECOMMENDATIONS

5. CONCLUSIONS AND RECOMMENDATIONS

In light of the findings of this evaluation and the Berg WAAS programme, which requires that a decision with regard to the way forward in terms of the modelling of surface water-groundwater interaction is taken as a matter of priority, three possible approaches to facilitate the modelling of surface water-groundwater interaction in both the catchment and system models are proposed viz.:

- Conventional Pitman modelling (Sami groundwater model disabled)
- Pitman modelling with Sami model enabled
- Pitman model with external source representing groundwater contribution to discharge and "dummy" groundwater reservoir representing aquifer storage

The first approach takes into consideration the serious concerns which have been raised with regard to the applicability of the Sami model and therefore proposes the use of conventional Pitman modelling, i.e. with the Sami model not enabled, as an option for the Berg WAAS. Such an approach assumes that the Pitman model implicitly accommodates the groundwater contribution to baseflow and that this is reflected in the calibrated Pitman parameters. The catchment modelling will be relatively simple and there will be no need for recalibration once the Sami model has been enabled. The shortcoming of this approach however, relates to the most appropriate way in which to accommodate groundwater abstraction in the WRYM system model, taking into account that the naturalised flows, which will be produced by the calibrated Pitman model and which will be used as input to the system model, already reflect the impact of any groundwater abstractions as well as the groundwater contribution to baseflow.

The second approach is based on the fact that, in spite of the findings of this report that the Sami model assumptions and implications for the hydrological process are not appropriate for the majority of the subcatchments in the study area, DWAF did put the Sami model forward for undertaking groundwater resource assessments in the WAA studies. It could therefore be considered appropriate for application in the Berg WAAS, as long as its limitations and the level of confidence in the results are clearly stated. The Sami model does add enhanced groundwater simulation capabilities to the Pitman model and provides a generic algorithm that can be applied on a quaternary catchment scale to simulate groundwater-surface water interactions. Furthermore, as the Sami algorithms have been integrated into the system model, the effect of groundwater abstractions on baseflow and system yield can be assessed. It has also been demonstrated that the default Sami parameters may be replaced with improved estimates thereof by groundwater specialists with an intimate knowledge of the groundwater dynamics in the study area in order to improve confidence in the modelling results.

The third option aims to avoid the issues surrounding the application of the Sami model and promotes a simple, transparent conceptual model for accommodating surface water-groundwater interaction in both the catchment modelling and system modelling phases of the Berg WAAS. During the catchment modelling phase, it is envisaged that estimates of groundwater contribution to baseflow, as available on a quaternary catchment basis from the GRDM data (DWAF, 2006b), will be introduced into the Pitman network configuration as an external water source. This, in conjunction with the existing technique whereby the areas that are irrigated from groundwater sources are excluded from the total irrigated area, will ensure that the calibrated Pitman parameters reflect the net cumulative impact of groundwater use and groundwater baseflow on simulated river flow. During the system modelling phase, the effect of groundwater use on baseflow (and system yield) will be simulated by introducing a "dummy" groundwater reservoir to represent the aquifer from which groundwater is abstracted. Estimates of aquifer capacity (size of the reservoir), recharge (inflow into the reservoir) and groundwater baseflow (outflow from the reservoir), will be based on best available knowledge.

Table 5-1 and **Table 5-2** display the effect of introducing the GRDM estimates of groundwater discharge as an external source of water into the WRSM2000 network configurations for the Klein Berg and Diep catchments respectively. The tables show that the degree of re-calibration that is required is not significant, with the adjustments to the original parameters mainly necessitated by the need to improve the fit between simulated and observed flows during the dry season, which is when the effect of groundwater contribution to discharge is most evident.

Table 5-1: The effect of modelling groundwater discharge as an external source on Pitman parameters (Klein Berg)

	POW	SL	ST	FT	GW	ZMIN	ZMAX	PI	TL	GL	R
Pitman	2	0	315	10	5	80	750	1.5	0	2.5	0
Pitman (recalibrated)	2	0	**330**	**5**	**0**	80	750	1.5	0	**0**	0

Table 5-2: The effect of modelling groundwater discharge as an external source on Pitman parameters (Diep)

	POW	SL	ST	FT	GW	ZMIN	ZMAX	PI	TL	GL	R
Pitman (original)	2	0	305	10	0	75	400	1.5	0.25	0	0
Pitman (recalibrated)	2	0	**290**	10	0	75	**410**	1.5	0.25	0	0

It is the opinion of the study team that the conventional Pitman approach should not be used in the Berg WAAS due to its limitations with regard to accommodating groundwater use in the system model. Similarly, although the Sami model approach is the preferred methodology for WAA studies, in the case of the Berg WAAS this approach will result in low levels of confidence in the modelling results due to the Sami model being considered "inappropriate" for 84% of the Berg WAAS quaternary catchments. It is consequently proposed that the conceptual groundwater model be used for modelling surface-water groundwater interaction in Berg WAAS. Although the proposed conceptual model is a very simple model, which does not attempt to simulate all the groundwater processes that are treated as standard in conventional groundwater models, it is considered to be the most appropriate methodology within the context of the Berg WAAS. It is also proposed that the original GRDM estimates of groundwater contribution to baseflow are refined in those areas where the detailed numerical groundwater modelling which is currently underway, leads to an improved understanding of the surface water-groundwater interaction. During this refinement, which should take place before system modelling commences, the necessity for the reconfiguration of the catchment at a finer spatial resolution in order to accommodate aquifer specific groundwater discharge will also be considered.

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APPENDIX A

PREVIOUS REVIEWS OF AND WORKSHOP NOTES ON SAMI MODEL

Appendix A-1 DWAF: Water Availability Assessment Studies – Summary of Proposed Methodologies and Algorithms for Water Resource Modelling, Starter Document for Analysis Methodology Workshop 29 October 2004

Department: Water Affairs and Forestry

Directorate: National Water Resource Planning

WATER AVAILABILITY ASSESSMENT STUDIES

Summary of Proposed Methodologies and Algorithms for Water Resource Modelling

(Starter Document for 29 October 2004 Workshop)

WATER AVAILABILITY ASSESSMENT STUDIES

Summary of Proposed Methodologies and Algorithms for Water Resource Modelling

(Starter Document for 29 October 2004 Workshop)

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APPENDICES

Appendix A: Modelling Requirements for Licensing

Appendix B: Groundwater surface water interaction document (separate file)

1. INTRODUCTION

The Directorate National Water Resource Planning is in the process of commissioning five studies on the Mhlathuze, Inkomati, Berg, Crocodile (West) and Olifants river systems with the purpose of quantifying the available water resources in support of the process to license water use.

As part of the preparation and commissioning of these studies, the need has been identified to obtain agreement on the proposed modelling methodologies and algorithms that will be use in the five studies and to coordinate the activities in order to achieve efficient execution of the work. To this end, a workshop has been scheduled for 29 October 2004 to be attended by DWAF officials and representatives from the study teams.

This document, therefore serve as the starter document for the workshop and has the purpose of providing background information on the modelling requirements that were identified as well as describe proposed methodologies for analysis.

The intention is that the participants will use this document to prepare for the workshop by:

- Obtaining an understanding of the modelling requirements that have been identified in a parallel process. (The notes from this process have been included in **Appendix A**).
- Reviewing the proposed methodologies presented in the document and prepare~~s~~ alternative recommendations or amendments that will be discussed at the workshop.
- Suggesting additional aspects that need consideration in the modelling studies.

2. CONTEXT AND LAYOUT OF THIS DOCUMENT

The remaining sections in this document present a brief description of nine modeling aspects that have been identified as requiring clarification with respect to the methodologies and associated algorithms to use in the studies.

These aspects are:

- Streamflow Reduction Processes, including:
    - Afforestation.

  - Alien vegetation.
  - Dry-land-sugarcane.
- Groundwater
- Irrigation requirements and return flows
- Wetlands
- Losses
- Ecological flow requirements
- Higher resolution networks
- Abstraction (diversion) efficiency for unregulated runoff- (daily vs. monthly time scale).
- Risk based assessment methodology.

An important consideration for this methodology selection process is the integration with other parallel studies to ensure consistency across the board.

In this regard, the following parallel processes have been identified as having direct interaction with the analysis methodology selection possess:

- Water Resource 2005 study for the WRC.

  The workshops to decide on the principles of the methodologies to apply in the WRC study have already taken place and some of those aspects have been incorporated into the descriptions in this document. I

- Groundwater/Surface water interactions study for DWAF.

  K Sami, a member of the Mhlathuze WAA Study Team is also involved in this study and he will be responsible for the integration of the processes between the studies. The methodology described in **Section 3.6** of this document is based on the research from this study.

- Research on and the establishment of a protocol regarding streamflow reduction processes. (Process driven by Prof A Görgens).

The SFR processes presented in **Section 3.2** incorporates the broad suggestions from this research.

3. HYDROLOGICAL MODELLING PROCESSES

3.1. GENERAL REQUIREMENTS

The main modeling requirements that have been identified are listed below:

- Consistency between hydrological processes and water resource analysis.
- Consistency in the application of analysis methodologies in the different studies.
- Explicit modeling of processes in order to be in a position to undertake scenarios analysis of management measures. A balance is required between the availability of actual data for verification of the models and the ability to explicitly simulate the processes.
- The legal integrity of the results from the studies should be supported by thorough documentation describing all assumptions and methodologies that were applied in the availability assessments.
- Modelling will, at least initially, be undertaken at a monthly timescale.
- Effective communication to stakeholders would be essential to create confidence in the assessment techniques, assumptions and results of the modelling exercises.

An extended list of all the modeling requirements that were identified is provided in **Appendix A.**

3.2. SFR PROCESSES

General Requirements for SFR Processes:

- Account for impact of distance from water edge.
- More explicit modelling of SFR processes in WRYM.
- Indigenous forests should be simulated explicitly.

Notes / Questions:

- Commercial Afforestation is specified in NWA as a "SFR Activity" requiring authorisation - a license.
- Sugar Cane is not specified in NWA as a "SFR Activity".

3.3. AFFORESTATION

Requirements:

Monthly time-series data for streamflow reduction, representing:

- Actual historical situation, for naturalisation
- Constant development level, for licensing

Concept:

- ACRU-produced median SFR unit values, from GUSH report.
- Gush values based on:
  Based on combinations of:
  - Pine, eucalyptus and wattle
  - Shallow, medium and deep soil depths
  - Total flow and low flow conditions
- Apply confidence bands:
  - For naturalisation, use unadjusted median values
  - For licensing, use upper limit values
- Multiply with area under afforestation
- Based on:
  - Typical average ages, nationally:
    - Pine: 7 years
    - Eucalyptus: 4 years
    - Wattle: 4 years

    – rotation period?
  - Constant soil texture class, nationally: sandy-clay-loam
  - ACRU verified on data from 10 field experiments / catchments and extrapolating to other quaternary catchments

Software:

- To be developed
- Output required as monthly time-series SFR volume data
- Can be incorporated with WRSM2000 configuration as specified abstraction

- Naturalisation process undertaken iteratively

Data elements:

For catchment under consideration:

- Area under afforestation:
    - (1) Historically, in year
    - (2) At selected development level, for licensing
- (3) % of afforested area under pine
- (4) % of afforested area under eucalyptus
- (5) % of afforested area under wattle
- (6) % of afforested area upstream of impoundments
- (7) Monthly time-series of natural runoff
- (8) Soil depth classification
- (9) Median SFR unit values, as % of natural runoff, for combinations of species, soil depths and flow conditions
- (10) Climatic type
- (11) Confidence limits

Data sources:

- (1) Satellite imagery, aerial photographs, 1:50 000 maps, surveys, specialist opinion
- (2) Licences, other?
- (3), (4) and (5) Licences, surveys, specialist opinion
- (6) 1:50 000 maps, GIS
- (7) WRSM2000 / Shell
- (8) "Soils maps"?
- (9) Gush tables, Gush et. al. 2002

- (10) ?
- (11) Gorgens, 2003

Notes / Questions:

- How will afforestation and groundwater module be integrated?
- How will Gush SFRs be incorporated with WRSM2000 - investigate possibility considered at WR2005 workshop to manipulate Pitman model parameters to re-produce Gush results.

will this be "trial & error"?

- Denis Hughes concern about Gush data in certain quaternaries:

?
  - Negative SFRs
  - ~~Impact~~ % impact on low flows smaller that % impact on high flows
- Other concerns:
  - Assumption of "typical" age applied nationally for different species
  - Constant soil texture class applied nationally
- Age of trees:
  - The age of the trees make a large difference to the streamflow reduction – according to WRC research.
  - What is impact of Gush assumption of "typical" age applied nationally for different species
  - Was the age captured in the registration and verification?
  - How will the payment work – different according to age?

3.4. SUGARCANE

Requirements:

Monthly time-series data for streamflow reduction, representing:

- Actual historical situation, for naturalisation
- Constant development level, for licensing

Concept:

- SFR similar to commercial afforestation

— rotation period ?

- Based on SFR of pine with cutting cycle of 15 years (approximately equal to a average age of 7 years)

- Use SFR estimation as for afforestation (**Section 1.1**)

Software:

As for afforestation (**Section 1.1**)

Data elements:

For catchment under consideration:

- Area under dry-land sugarcane:
  - (1) Historically, in year
  - (2) At selected development level, for licensing
- (3) % of dry-land sugarcane upstream of impoundments
- (4) Monthly time-series of natural runoff
- (5) Soil depth classification
- (6) Median SFR unit values, as % of natural runoff, for combinations of species, soil depths and flow conditions
- (7) Climatic type
- (8) Confidence limits

Data sources:

- (1) Satellite imagery, aerial photographs, 1:50 000 maps, surveys, specialist opinion
- (2) Licences, other?
- (3) 1:50 000 maps, GIS
- (4) WRSM2000 \ shell
- (5) "Soils maps"?
- (9) Gush tables, for pine, Gush et. al. 2002 .

- (7) ?
- (9) Gorgens, 2003

3.5. ALIEN VEGETATION

Requirements:

Monthly time-series data for streamflow reduction, representing actual historical situation, for naturalisation, for

- Riparian
- In-catchment

Concept:

- Distinguish between riparian and in-catchment (different water use characteristics)
- Use alien CSIR vegetation runoff reduction curves (2000 ?) Scott ?
- Based on:
    - Biomass classes (tall trees, medium trees, tall shrubs)
    - Average age

Software:

WRSM2000

Data elements:

For <u>riparian</u> and <u>in-catchment</u> alien vegetation, respectively, in the catchment under consideration:

- (1) Equivalent dense area under alien vegetation, historically, in year
- (2) % of alien vegetation classified as "tall trees"
- (3) % of alien vegetation classified as "medium trees"
- (4) % of alien vegetation classified as "tall shrubs"
- (5) % of alien vegetation upstream of impoundments

- (6) Average age of alien vegetation classified as "tall trees"
- (7) Average age of alien vegetation classified as "medium trees"
- (8) Average age of alien vegetation classified as "tall shrubs"
- (9) Monthly time-series of natural runoff

Data sources:

- (1) Surveys, extrapolation, specialist opinion /WfW?
- (2), (3) and (4) Surveys, extrapolation, specialist opinion • CAL spread model for historical time slices
- (5) 1:50 000 maps, GIS
- (6), (7) and (8) Surveys, extrapolation, specialist opinion
- (9) WRSM2000

Notes / Questions:

- What version of CSIR alien vegetation curves have been incorporated with WRSM2000?

3.6. GROUNDWATER

Requirements:

1. Estimate groundwater availability for all situations, including:

- Isolated groundwater resources – no interaction with surface water resources.
- Two directional impacts – abstractions from groundwater are reducing base flows, or high streamaflow volumes generate transmission losses to aquifers.
- Alluvial Aquifers – river flow feeds aquifer and vice verse.
- Dolomitic areas.

2. Correlate availability with surface water resources to be able to account for conjunctive use.

3. Integration with stochastic streamflow generation processes.

Concept:

Surface water and groundwater are often isolated from each other but interact in a variety of ways. The quantification of such interactions is necessary to avoid pitfalls such as double accounting of water resources. For example, hydrologists often consider baseflow as part of stream runoff, hence an allocatable surface resource. Geohydrologists often consider groundwater resources in terms of recharge, a large portion of which generates baseflow. Consequently, the simple addition of surface water runoff volumes and groundwater resources based on recharge (i.e. Harvest Potential) double accounts for baseflow.

A simplistic approach, such as utilised by groundwater models such as MODFLOW, is to assume that flow between the aquifer and river is controlled by Darcy's Law where flow is direction function of streambed conductance and the head difference. This methodology assumes linearity between the head difference and water exchange. This in fact is not the case due to hydraulic resistance, which introduces non-linearity as streamflow increases. The methodology employed by MODFLOW also cannot account for the fact that streamflow varies significantly over time, hence variations in hydraulic head can be significant, resulting in changes between effluent and influent conditions without significant changes in groundwater levels. Linear methods, such as incorporated in MODFLOW , therefore do not provide an avenue in systems where large flow fluctuations occur, such as in South African rivers.

A more realistic approach to simulating interactions could be adopted by using non-linear equations whereby rapid increases in baseflow occur for small head changes when the head difference is small, but baseflow approaches some maximum value as the head difference becomes larger.

Simulation of interactions is also relevant under conditions where groundwater abstraction takes place. The decline of water levels around pumping boreholes near surface water bodies creates gradients that capture some of the ambient groundwater that would have discharged as baseflow. At sufficiently high pumping rates these declines also induce flow out of the surface water body, a process known as induced recharge. Both these processes lead to stream flow depletion.

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

Groundwater managers frequently use recharge or Harvest Potential to determine abstraction potential or safe yield. Such a policy ignores natural discharges and the impact of pumping location on these discharges. Consequently, sustainable yields that consider the importance of natural discharges cannot be attributed solely to recharge, but must consider location and permissible impacts on baseflow and evapotranspiration. Aquifer safe yield therefore varies by location of the proposed abstraction. The idea that recharge represents a term that represents a safe yield is therefore an attractive but simplistic fallacy.

A suitable hydrologic basis for planning to determine the magnitude of possible groundwater abstraction in the vicinity of hydraulically connected water bodies should be aimed at developing relationships between abstraction and baseflow depletion, rather than simply on the projected pattern of drawdown.

(A detail description of the methodology is provided in **Appendix B** – included in e-mail as a separate document.)

Software:

A logical stepped methodology has been developed in a MS-Excel environment that determines the impacts of abstraction on baseflow without the necessity of groundwater or surface water modelling using hydrographs as input data. The methodology was developed as part of the DWAF Groundwater Resources Assessment Phase II project, with an objective of developing an algorithm to quantify surface water-groundwater interaction.

The methodology is based on sequentially:

- Performing a hydrograph separation (Herold Method) to separate baseflow from storm runoff on a monthly time scale using WR90, observed flow data or a stochastic hydrograph.
- Back calculating subsurface storage from baseflow to calculate a time series of recharge using the Pitman algorithm.
- Incrementing groundwater storage from recharge to a maximum level aquifer level, above which recharge cannot be accepted and spills to surface water.
- Depleting groundwater storage by evapotranspiration as a function of rainfall, pan evaporation data, crop factors, groundwater storage level and static water level conditions.
- Depleting aquifer storage according to up and down gradient flows into or out of the aquifer.
- Calculating groundwater baseflow (baseflow from the regional aquifer) or transmission losses in a non-linear manner as a function of groundwater storage and runoff volume.
- Calculating interflow (baseflow from perched aquifers) as the difference between total baseflow and groundwater baseflow.
- Depleting groundwater storage and groundwater baseflow due to borehole abstraction.

The methodology has currently been tested on two catchments for verification purposes. It is envisaged that the software will be developed in a Delphi, C++ or Fortran environment in future. It is also proposed that the algorithms be incorporated as a groundwater module interlinked with the network module of the WRYM.

Data elements:

Hydrograph Separation: The software performs a hydrograph separation of monthly runoff using the method of Herold. Required parameters are:

Decay is a groundwater factor (*0<Decay<1*)

PG, a groundwater growth factor (%).

Parameters for PG and Decay can be visually calibrated. Results can also be calibrated against baseflow figures reproduced in WSAM.

Separations can also be undertaken on observed gauging weir data, or stochastic hydrographs used by the WRYM model.

Estimation of Recharge: Recharge is calculated by first calculating subsurface storage by reverse engineering of the Pitman model. Required parameters are Pitman parameters S_L, S_T, FT and POW. Once soil moisture is calculated, monthly recharge is calculated using the method proposed by Hughes (2004). Parameters required are:

- GW= maximum amount of recharge in mm at maximum soil moisture
- Pitman SL=soil moisture in mm below which there is no runoff
- GPOW=power function of storage-recharge relationship

Parameters for GW and GPOW could either be calibrated to achieve a fit with long term mean annual recharge measurements obtained from other methods, or initially parameters similar to POW and FT could be selected.

Groundwater Storage Increments from Recharge: Direct recharge from soil moisture is incremented to groundwater storage, if the aquifer is not full (aquifer capacity, which is defined by parameters of aquifer thickness and storativity). If the aquifer is full excess recharge above aquifer capacity is dumped to interflow and does not increment groundwater storage. As a result, actual recharge may be somewhat less than potential recharge, and pumping, by depleting the groundwater storage, may increase actual direct recharge up to the potential recharge figure.

Evapotranspiration from riparian Zones of Shallow Groundwater: Monthly rainfall, Mean annual A-Pan evaporation, percent monthly distribution of evaporation and monthly crop factors from WR90 are utilised to calculate monthly demands from groundwater. Evapotranspiration demand is multiplied by an aquifer storage factor to allow evaporation to decrease as groundwater storage is depleted, allowing evapotranspiration at the maximum rate when groundwater storage is at aquifer capacity and declining towards 0 as groundwater storage drops to a level below the stream channel, defined by a parameter of static water level. Required parameters include:

AREA = area where evapotranspiration from groundwater can take place

CAP = aquifer capacity

SWL = static water level

Groundwater Inflow/Outflow: Groundwater flow out of a catchment simulates underflow and regional groundwater flow that does not emerge in surface water courses within the catchment. Groundwater outflow is calculated using the Darcian approach of the product of parameters of transmissivity and maximum hydraulic gradient, which can be defined as the channel gradient. The hydraulic gradient is decremented as the groundwater storage drops to SWL. This format allows groundwater outflow to occur at a decreasing rate as the water level drops, until outflow stops when the static water level is reached.

Groundwater Baseflow and Transmission losses: Groundwater baseflow is calculated as a function of the head difference between groundwater storage and surface water. When groundwater head exceeds surface water head, as occurs during dry months, groundwater baseflow is generated simulating effluent conditions. When surface water head exceeds groundwater head, as occurs during very wet months when groundwater storage is depleted following the dry season, influent conditions arise and transmission losses are simulated. The parameter required is BFMAX, which is the maximum rate of groundwater baseflow.

Groundwater Abstraction: Groundwater abstraction is assumed to deplete groundwater storage and groundwater baseflow in a non-linear fashion depending on the transmissivity and storativity of the aquifer, the distance from the stream channel and the time since pumping started. The required parameters are:

T = Transmissivity

S = Storativity

X = distance from river

k3 and k2 = calibrated curve fitting parameters with k2 =0.01-1 and k3 calibrated so that at early times 100% of abstraction is from groundwater.

The fraction of abstraction that depletes groundwater storage is taken from aquifer storage, while the remainder is taken from calculated groundwater baseflow, thereby depleting baseflow. If calculated baseflow depletion exceeds available groundwater baseflow, the excess is removed from groundwater storage.

Data sources:

Sources of data for parameterisation and inputs include:

- Monthly runoff data from Pitman model simulations, observed data, stochastic hydrographs – similar to WRSM stochastics?
- Pitman model parameters of ST, SL, FT and POW
- Monthly rainfall and evaporation data can be obtained from the SAWS or from WR90
- Groundwater parameters of transmissvity, storativity, and static water level are generally obtained from test pumping, or regionalized based on local expertise of hydrogeologists. Aquifer thickness to determine aquifer capacity is determined from local expertise or can be obtained from the map of groundwater resources of South Africa
- Hydraulic gradients driving groundwater outflow and inflow can be estimated from channel gradients
- Mean annual Recharge data to calibrate recharge estimates can be obtained from the WRC recharge manual, or from the recharge spatial data base being developed as part of GRA II. Groundwater parameters GPOW and GW generally approximate pitman POW and FT. They would require some calibration so that estimated recharge approximates published recharge figures.

3.7. IRRIGATION REQUIREMENTS AND RETURN FLOWS

Requirements:

- Since the water use verification process applies the SAPWAT software to estimate irrigation water requirements, it will be required to make use of a similar procedure in the systems model to ensure consistency. It would however be necessary to incorporate the variability of irrigation water requirements and return flows based on climatic conditions such as evaporation and rainfall.
- It was suggested that a workshop be held to further expand on this requirement and develop an appropriate approach.

- The irrigation water requirement and return flow module should be flexible to be able to assess different scenarios by allowing the selection of different crop types and other variables such as irrigation application methods, leaching requirements and demand management practices. The database currently contained in SAPWAT could be a valuable source of information regarding the water requirement of different crops.
- A simplified return flow module should be incorporated into the model based on existing algorithms and knowledge.

Concept:
Both the SAPWAT and IRRDEM programmes have been applied in the past to estimate the irrigation requirements with there being strong and week points about both models. The resultant outputs from these models can differ substantially so it is important to take cognisance of both models in determining the irrigation water requirements.

Return flows from irrigated lands can make significant contributions to streamflow. To this end, it is proposed that the relationship between infiltration, drainage and irrigation strategy needs to be developed and applied to be able to test scenarios.

An outline of the approach would be as follows :

- The irrigated areas will be classified into homogeneous zones based on soil characteristics, crop type, climate and point of return flow;
- The irrigation water requirements will be estimated as time series of monthly values;
- The return flows from the irrigation lands will be estimated based on the soil moisture balance algorithm; and
- The resultant irrigation requirements and irrigation return flows will be assessed and incorporated into the holistic water resources assessment.

Software:
Preliminary feedback from the recent round of WRSM2005 workshops indicates that the irrigation requirements component may be based on either the SAPWAT approach or the traditional IRRDEM approach. Unfortunately, the SAPWAT approach only provides an

annual irrigation requirement with a monthly distribution based on average climatic conditions. Whereas, the IRRDEM approach provides a time series of irrigation requirements based on the prevailing monthly climatic conditions. SAPWAT is the *de-facto* model used by DWAF for the assessment of water licences. It is proposed that monthly irrigation requirements based on the prevailing meteorological conditions as is output by IRRDEM will be determined. These will be compared to and/or calibrated against the results of SAPWAT, which is an annual crop water requirement model.

Traditionally, irrigation return flows have been estimated as a simple percentage of the requirements, the level of which is based on the knowledge of local experts. It is proposed that a simple soil moisture balance algorithm will be developed, which will be based on a simple hybrid model that will combine a deterministic approach with a parameter calibration approach. This should be undertaken in collaboration with the developers of the WRSM2005 since it is likely that this could be included in that model.

Data elements:

It is proposed that all data elements will be established at the smallest spatial unit, that being the homogeneous irrigation zones mentioned above. The following data elements will be required for each zone :

- Monthly time series of rainfall;
- Average monthly potential evapotranspiration (i.e. crop water use assuming water is not a limiting factor);
- Average soil characteristics (i.e. depth, moisture holding capacity and infiltration rate); and
- Irrigation strategy (i.e. a combination of application rates and frequency).

Data sources:

Rainfall :

- Monthly rainfall data will be acquired from the Weather Bureau, Irrigation Boards as well as local farmers.

Evapotranspiration :

- Pan data (Symons or A-pan) would be acquired from published data and from appropriate Government and Academic agencies;

- Crop factors would be acquired from published data, the Sugar Association of South Africa (SASA) and the Department of Agriculture (DA) and from SAPWAT;

Soils characteristics :

- The land type maps produced by the DA will be the point of departure for acquiring these data, which are GIS based and can be interrogated to ;

- The SASA has mapped significant tracts of the soils in the would be acquired from published Mhlathuze Catchment; ?

- Many commercial farmers have developed farm plans which are predominantly based on soils, therefore recognised agricultural consultants will be approached for anecdotal information in areas that they are

Irrigation strategies : method rate / depth frequency / equipment

- Typical irrigation strategies will be obtained from the Irrigation Boards as well as local farmers.

3.8. WETLANDS

Requirements:

- Explicit modeling of wetlands is required.

Concept:

- At the Water Resource 2005 workshop Bill Pitman presented a proposed wetland module that takes water from the network system, similar to an off channel storage, and having a return flow back to the network at the downstream end. Other enhancements (features) that are currently included in ACRU would also be considered for inclusion in the module.

Software:

- No software available at this stage.

- Requires a stand alone utility if there is a need to simulate wetlands in the current five study areas.

Data elements:

The data elements is currently unknown, however, it would probably contain the following:

- Monthly average evaporation data.
- Factors to simulate evapotranspiration.
- Factors to simulate large surface evaporation.
- Vegetation and open water surface areas, possibly dependant on the storage volume in the wetland.
- Monthly rainfall time series.
- Storage or flow retention characteristics.
- Discharge (head vs. flow) characteristics.

Data sources:

- Meteorological data would be similar to what is used for the Pitman model calibration.
- The extent of the wetland (area) to be obtained from 1:50 000 maps, aerial photos or possibly satellite images and using GIS to "measure".
- The storage, surface area and discharge characteristics would be estimated and probably calibrated.

3.9. LOSSES

Requirements:

- Explicit simulation of river losses is required during the naturalisation process and in the systems modeling.

Concept:

- River Losses
    - Evaporation from the water surface and evapotranspiration from the riparian vegetation can be estimated by considering the length and width of the river section as well as estimating the losses using monthly net evaporation data.

- Variation in the river width at different flow rates may be used to derive a relationship between losses and the flow in the river.
- Percolation to groundwater: The proposed groundwater module has a mechanism of how drawdown of the regional aquifer would lower the water table and induce percolation losses from the river to the aquifer. This options needs to be verified as part of the testing and further development of the model.

- Canal Losses
  - Usually this was simulated a percentage of the flow in the canal.
  - Percolation in unlined canals can be estimated based on the soil characteristics and the extent of the wetted perimeter and length of the canal.
  - The above method could also be extended to simulate return flows that may originate from the percolating channels.

Software:

- The calculations are usually undertaken in spreadsheets and the flow vs. loss characteristics are then included in the WRYM, simulated as the Type 2 Loss channel.
- Currently losses can be simulated as wetlands in WRSM2000 or as a constant bed loss.

Data elements:

- Width of river water surface, average or a relationship with flow if it various significantly with flow.
- Width of riparian vegetation.
- Length of river section.
- Net average monthly evaporation data with conversion factors.

Data sources:

- Aerial photos and possible satellite images and using GIS to quantify the lengths and widths.
- Use catchment evaporation and rainfall from the Pitman model to estimate the net evaporation.

3.10. ECOLOGICAL FLOW REQUIREMENTS

Requirements:

- Provision must be made to simulate all possible EMCs. This will be required when different scenarios are analysed to determine the impact on availability.
- IFRs have to be calculated for all the abstraction points also those located in the tributaries.

Concept:

- The basic concepts are to make use of existing EFR results (from detailed determinations) and extrapolate to other sites using a 'local' calibration of the Desktop Reserve model.
- It may be necessary to fill in gaps where there are perceived differences in the ecological response to flow regime changes. Examples of differences might include different geomorphological zones, differences between main channel rivers and small tributaries.
- The gaps may be filled by a small team of EFR specialists undertaking a limited number of Rapid Reserve determinations and then using these results to refine the 'local' calibration of the Desktop Reserve model.

Software:

- The software for running the undertaking the 'local' calibration and for running the Desktop Reserve model (including all the necessary data interfaces) is available within the SPATSIM package available from the IWR at Rhodes University (software that was developed under WRC funding, but carries an ESRI development application license fee of about R1200).

Data elements:

- The data required are a time series of natural monthly flows, applicable to the sites for which Reserves are required.
- Previous results of Reserve determinations.
- It would normally be necessary to decide on the Present Ecological State (PES), for which some expert opinion might be required (to cover the main ecological elements of the systems – fish, invertebrates, riparian vegetation, water quality, geomorphology and hydrology. Recent methods have been developed to facilitate the PES determination (consult Delana Louw, Neels Kleynhans and/or Christa Thirion).
- Eco-region information (at the highest level available) could be useful to assist with the extrapolation process of previously determined Reserve results.
- If additional rapid Reserve determinations are considered necessary, some limited hydraulics data will be required.

Data sources:

- The flow data would normally be available from other project activities. The default data source would be WR90 (or current updates to WR2005), but care needs to be taken when scaling down to sub-quaternary catchment sizes.
- Previous Reserve determination results should be available from the RDM office of DWAF.
- Data on PES would normally be obtained from relevant specialists and processed through the current methodology (consult Delana Louw, Neels Kleynhans and/or Christa Thirion).
- Hydraulics data (for rapid Reserve determinations), if necessary, would be sourced from a limited programme of fieldwork.

3.11. HIGHER RESOLUTION NETWORKS

Requirements:

- Require increased resolution modelling to simulate interaction among water users in tributary catchments for licensing.

- The following aspects, among other, should be considered in the definition of the increased resolution:
  - The resolution should be dictated by system specific layout, no pre-defined modelling units will be defined.
  - Users receiving water from tributaries and main stem of the river should be analysed separately.
  - Hydrological and climatic conditions.
  - Location of farm dams and water use abstractions.
  - Maintain the ability to generate stochastic hydrology for detail risk assessments.

Concept:

- In the past the focus was on estimating the yield at the large dams in a water resource system, however, what is now required is to estimate water availability at various abstraction points in the system.
- The existing system configurations would therefore need to be extended to realistically simulate the availability within the constraints of the available hydrological information.
- The existing hydrological data need to be disaggregated to be able to estimate availability in tributaries where abstractions occur.
- Basic hydrological principals need to be applied in the disaggregation process.

Software:

- WRYM allows for the configuration of large systems and the dimensions can be increased to suite the needs.

Data elements:

- As defined by the WRYM data files.

Data sources:

- Maps and plans defining the water supply infrastructure.

- Topographical maps to assist in the disaggregation of the hydrological information.

- Rainfall data (MAP) of gauges to estimate the portioning of the natural streamflow.

3.12. ABSTRACTION (DIVERSION) EFFICIENCY FOR UNREGULATED RUNOFF

Requirements:

- Need to account for the utilisation efficiency of unregulated runoff in the monthly time step model.

Concept:

- Use the Loss Type 2 structure in WRYM to simulate utilisation efficiency. This element requires a table of data points that defines the relationship between the monthly flow in the river and what can effectively be utilised.

- The relationship for the Loss Type 2 structure has to be derived using calculations (simulation) on a daily basis and accounting for aspects such as:
    - Size of the abstraction that can take place.
    - Compensation releases that has to be made downstream of the abstraction.
    - Releases for the Reserve, IFR.

Software:

NB: series daily reqs

- A utility, Divflow, has been developed by S Mallory to undertake the calculations in the past.

- Frequent changes in the format of daily flow data and the enhanced functionality of modern spreadsheets made it possible to undertake the simulations in spreadsheets.

- Sub-Directorate: System Analysis is currently considering developing a user friendly utility that can be used to undertake the required simulations.

Data elements:

- Daily flow time series flow data.

- IFR data.
- Abstraction capacities.
- Other compensation releases.

Data sources:

- Flow data from DWAF's database.
- IFR data from D:RDM.

3.13. RISK BASED ASSESSMENT METHODOLOGY

Requirements:

- The differentiation of risk criteria for users abstracting water from the system should be taken into consideration. Water use of the same type would typically have the same risk criteria.
- The definition of a failure and the derived statistics thereof need to be defined and presented as part of the availability assessment.
- Initially, during the process of deriving the allocation schedule, single sequence analysis (historical and other stochastic sequences) will be used for the availability assessments.
- Full stochastic analysis should be undertaken on the final feasible scenarios.

Concept:

- A new feature has been developed for the WRYM which allow for the definition of reliability criteria for abstraction channels and the application of a factor to reduce or increase the abstraction by means of a single variable.
- An algorithm has been developed to analyse the supply results from the simulation and determine if the reliability criteria have been violated.
- Summarised output is produced on the reliability of supply and whether or not the reliability criteria of each abstraction channel has been violated.

- Currently the calculations are made on single sequence (historical) analysis only.

Software:

- Feature is available in WRYM.
- Sub-directorate: Systems Analysis is currently in the process of incorporating the data required from this feature into the WRYM IMS.
- Consideration should be given to extend the algorithm to asses stochastic results.
- Sub-directorate: Systems Analysis is investigating additional methods of accounting for the reliability of supply.

Is this similar to WRPM approach?

Data elements:

- User reliability requirements in the form of a Priority Classification Table.
- Sets of multiplication factors to undertake scenarios analysis of different allocation scenarios.

Data sources:

- Planning studies where the Priority Classification Table has been defined.
- Information from the Verification process. (?)

F16.dat in WRYM.

Appendix A

Modeling Requirements for Licensing

Maintenance and Updating of Hydrological and Systems Software – Phase 3

Modelling and decision support requirements for licensing processes in water resource planning

Table of Requirements, Status and Initial Priorities

Categories and Requirements		Status/ Priority
1.	**MODELLING SYSTEM**	
1.1.	The Water Resource Yield Model (WRYM) with the associated Information Management System that is currently under development will, at least initially, be the main modelling system.	R1
1.2.	Development of the hydrological database for the WRYM should be based on the WRSM2000 (Pitman Model) for the initial reconciliation studies.	R1
1.3.	Implicit to **Items 1.1 and 1.2,** the main modelling time step will be monthly.	R1
1.4.	Apply existing techniques to account for the modelling inaccuracies of the monthly time step, such as: Diversion efficiency modelling method of which the characteristics are determined by means of daily flow data. The daily data should ideally be observed records, however, simulated daily flow data could also be considered.	R1 M&I3
1.5.	Other modelling systems will be considered during the pilot studies through exploratory research investigations including the application of daily time step modelling.	E
1.6.	Consistency is required between the land use methodologies applied during the development of the naturalised hydrology and those used in the water resource analysis.	R1
1.7.	Linkages between the databases which contain the information on water use (WARMS and/or the GIS database system developed as part of the water use verification studies) with the water resource systems model need to be developed. Ultimately a seamless interface will be required, however, in the interim manual processes will have to be applied.	I3
1.8.	A scenario manager is required to make relative or absolute changes to the parameters defining water users in a workshop environment. It is anticipated that the system network layout and operating rules will be configured prior to the workshops therefore eliminating (reducing) the need for scenario changes to the system configuration during workshop events.	I&M1
2.	**SPATIAL RESOLUTION**	
2.1.	Require increased resolution modelling to simulate interaction among water users in tributary catchments for licensing.	R1&M1
2.2.	The following aspects, among other, should be considered in the definition of the increased resolution: • The resolution should be dictated by system specific layout, no pre-defined modelling units will be defined. • Users receiving water from tributaries and main stem of the river should be	R1

	Categories and Requirements	Status/ Priority
	analysed separately. • Hydrological and climatic conditions. • Location of farm dams and water use abstractions. • Maintain the ability to generate stochastic hydrology for detail risk assessments.	
2.3.	Modelling resolution may increase over time and the modelling system should be flexible to accommodate expansion.	R1
2.4.	May need "stand alone" sub-catchment models (even on a daily time scale) to assess detail water resource allocation issues among water users.	I&M3&E
2.5.	Aggregation of detail simulation results for WMA or key catchments, to present high level water balances, may be required.	I1
2.6.	Transfers between large water resource systems should be linked through relevant time series data rather than combining large systems. grouped	R1
2.7.	Individual users might have to be groups to improve ease of modelling and results presentation. This would most likely be pre-processing to data by the IMS to aggregate the data for the WRYM.	I2
3.	**RISK BASED ASSESSMENT METHODOLOGY**	
3.1.	The differentiation of risk criteria for users should be provided. Water use of the same type would typically have the same risk criteria. The risk criteria definitions should account for equity allocations with preferential priorities.	I&M1
3.2.	Curtailment strategy and implementation will form part of systems operation and will only be considered ~~at a~~ later stage in the licensing allocation process.	I&M2
3.3.	The definition of a failure and the derived statistics thereof need to be defined and presented.	I&M1 A1
3.4.	Appropriate analysis methodology (historical or stochastic analyses) has to be applied to balance the time it takes for the analysis against the confidence of the results. In general the historical analysis results would be acceptable in situations where all users have low assurance needs, however, stochastic analysis would be required for high assurance users. The development of guidelines as to what analysis method should be used under what conditions is required. It may be feasible to develop relationships between the historical and stochastic results and use those to interpret results based on the historical analysis in cases where rapid assessments are required.	R3 R3 A1 (I&M3)
3.5.	The modelling of water quality variables to produce probability distributions of concentration and load should be considered.	R4
4.	**SCENARIO ASSUMPTION AND RESULT PRESENTATION**	
4.1.	Require effective & efficient communication to stakeholders in the process of developing and evaluating reconciliation scenarios.	R1
4.2.	The following result presentation features were identified: • Level of assurance attained vs. supply criteria. • Time-series results, duration and frequency of deficits, monthly supply patterns in graphical and tabular form. • Presentation of comparative scenario results to illustrate differences and relative impacts. i.e. wants to see water use/ • Results on all water abstractions including supply to SFRAs, reductions by different users • Display what remains available for allocation after selected water requirements have been satisfied.	I&M1

Categories and Requirements		Status/ Priority
	• Aggregation of results to give a summarised view of the water supply situation in a water resource system. • Demonstrate graphically how the reserve releases work and what the effect of implementing the reserve is on the supply capability of the water resource system. Also present the reserve release requirements in relation to the natural runoff. • Dissemination of results in a workshop environment is required. • When showing the supply results the list of users included as part of an abstraction channel in the model should be shown.	
4.3.	Assumptions that are built into the water resources model need to be clearly presented to stakeholders along with the results. This is to create an understanding of the causes and effects influencing the supply capability of a water resource system. Methods should be devised to illustrate the operating rules applied in the model and show compliance with actual applied operating rules.	I2 (R0.5)
4.4.	Results presentation in the form of time series graphs should be explored with the objective to inform stakeholders and to build confidence in the data and modelling technology by illustrating the behaviour of the water resource system under familiar historical drought and flood events.	I1 (R0.5)
4.5.	Compliance to the Reserve flow requirements must be clearly illustrated in the scenario results.	I1
5.	**MODELLING CAPABILITIES**	
5.1.	**Reserve**	
5.1.1	The current flow duration methodology applied in the WRYM will be used to simulate the flow requirements for the Reserve.	R3
5.1.2	The model should be capable of incorporating sufficient number of In-stream Flow Requirements (IRSs) to be able to implement proportional contribution of catchments can be simulated.	M&I1
5.1.3	The model should be able to simulate Reserve scenarios as defined by the flow requirements for different Ecological Management Classes (EMCs). A database of IFRs should be incorporated into the IMS.	I1
5.1.4	Procedure should be established whereby the latest (most up to date) reserve flow requirements are used in reconciliation assessments. This would most likely require making the databases of the D: RDM (or portions thereof) available on a regular basis.	R4
5.1.5	The model should be capable of simulating releases from farm dams. These releases may be base flow or in accordance with the IFR simulation structure.	R1
5.1.6	Consideration should be given to the model requirements to simulate the operation of the reserve releases. Current research by the WRC in this regard should be taken into consideration.	R4, M2, E
5.2.	**Groundwater**	
5.2.1	Need to account for surface-groundwater interaction in the model.	I&M1
5.2.2	Conjunctive use of surface and groundwater has to be incorporated in the systems modelling. This would imply that the groundwater availability must be reflected as a model network component.	I&M1
5.2.3	Groundwater resources which are independent of the surface water should also be included in the model.	I&M1
5.2.4	It is required to implement a simplified approach of incorporating groundwater	R1

reserve demand at each abstraction node

"Key"

farm dams/ boreholes, etc

Categories and Requirements		Status/ Priority
	modelling into the systems model. The possibility of implementing the concept proposed by Hughes should be explored.	
5.2.5	The suggested method described above require including some elements of the Pitman model into the WRYM.	I&M1
5.2.6	Possible concepts and resources to consider for the formulation of the groundwater component in the model include the following: • The concepts applied in the South African Groundwater Decision Tool software could assist in some of the groundwater modelling requirements. ACGIS is also a database with 1:250000 scale groundwater parameters required to estimate groundwater flows. • Karl Haupt's harvest potential data and methods should also be considered for model development. • In catchments with dolomitic areas the modelling of underground reservoirs to represent the groundwater availability with appropriate discharge (spill) characteristics, to account for the contribution to the surface water resources should, be considered.	R1
5.3.	**Irrigation water requirements and return flows**	
5.3.1	Since the water use verification process applies the SAPWAT software to estimate irrigation water requirements, it will be required to make use of a similar procedure in the systems model to ensure consistency. It would however be necessary to incorporate the variability of irrigation water requirements and return flows based on climatic conditions such as evaporation and rainfall. It was suggested that a workshop be held to further expand on this requirement and develop an appropriate approach.	I,M1, A1
5.3.2	The modelling methodology applied should ensure consistency between the hydrological naturalisation process and the systems modelling.	R1
5.3.3	The irrigation water requirement and return flow module should be flexible to be able to assess different scenarios by allowing the selection of different crop types and other variables such as irrigation application methods, leaching requirements and demand management practices. The database currently contained in SAPWAT could be a valuable source of information regarding the water requirement of different crops.	I1
5.3.4	A simplified return flow module should be incorporated into the model based on existing algorithms and knowledge.	R1
5.4.	**Farm dams**	
5.4.1.	Although increased resolution modelling would be implemented as discussed under **Item 2**, lumping of farm dams may remain a reality due to the vast number of dams in certain catchments.	R3
5.4.2.	The simulation of individual dams should be possible where the need arises.	R3
5.4.3.	The facility to model off-channel storage structures filled by river abstractions (diversions) should be incorporated into the model. In this regard, the model should be able to simulate the utilisation of surplus flow during times of high runoff.	R3
5.4.4.	It will be required to simulate releases from farm dams according to different operating rules.	R3
5.4.5.	The model should be able to simulate the impacts of recreational dams.	R3
5.4.6.	The appropriate starting storages should be used for analysis.	R3

distance from riparian zone

Categories and Requirements		Status/ Priority
5.5.	**Alien plants and other Streamflow Reduction Activities (SFRs)**	
5.5.1.	Alien vegetation located at the water edge or in the river streams is of greater concern that those in the riparian zone and the modelling should allow for a differentiation in the water use depending on the location of the alien plants relative to the river. Knowledge gained from recent and current research should be used to derive the appropriate algorithms.	I&M2
5.5.2.	Consistency is required between the method applied for estimating the impacts of SFRA's when the hydrology is naturalised and the method used in the systems model. The aim should be to model the SFRs more explicitly in the systems model. The latest research information on the water use of SFR's should be considered for inclusion in the systems model.	I&M2
5.5.3.	Some previous work has been done on incorporating indigenous forests into the WR90 hydrological calibrations, and should also be taken into account.	I&M3
5.6.	**Wetlands**	
5.6.1.	Modelling wetlands might also be required, but is initially not a high priority.	I&M3
5.7.	**Losses**	
5.7.1.	A consistent approach is required for account for losses during the naturalisation process and in the systems model. The objective should be to simulate losses explicitly in the systems model.	I&M3
6.	**OTHER GENERAL ISSUES AND REQUIREMENTS**	WQT ?
6.1.	• There is a need to investigate the water quality modelling requirement.	R4
	• It is important to identify the legal requirements for information provided in a Water Allocation Schedule and the concomitant license.	R1
	• Different levels of stakeholders need to be consulted in the public participation process.	R3
	• Information management requirements should have a high priority to avoid duplication in effort.	R1
	• The data collection and verification process should be involved more closely in the modelling requirements definition process.	R1

Status and priority definition, "XY":

Where "**X**" is an alphanumeric character and "**Y**" a number with the following meaning.

"X":

"I" Information Management System development required.

"M" Model functionality development required.

"R" Requirement – no associated development necessary.

"A" Assessment methodology development required. This refers to the development of analysis techniques to deal with specific issues.

"E" Further exploratory investigations into other techniques required.

and, **"Y"**:

"1" Highest priority requirement – immediate implementation.

"2" Priority - implementation before January 2004.

"3" Priority implementation after January 2004, however to be coordinated with the Mhlathuze River Pilot Study requirements.

"4" Medium priority implementation to be considered in subsequent reconciliation studies.

Appendix B

Methodology for

Groundwater-surface Water

Interaction

(Provided in a separate document)

Appendix A-2 DWAF: Water Availability Assessment Studies for Licensing, Notes on Analysis Methodology Workshop 29 October 2004

NOTES ON
WATER AVAILABILITY ASSESSMENT STUDIES FOR LICENSING
ANALYSIS METHODOLOGY WORKSHOP 29 OCTOBER 2004

The following documents are attached:

(I) Agenda
(II) Summary of Proposed Methodologies and Algorithms for Water Resource Modelling
(III) Methodology Groundwater-Surface Water Interactions (which was apparently an early draft and contains a number of errors)
(IV) Groundwater Diagram

1&2 WELCOME AND INTRODUCTION

Johan van Rooyen stated that the purpose of this workshop was to discuss the detailed modelling requirements and methodology for the five studies, and to ensure consistency and coordination between the teams. <u>He offered the teams the opportunity to contact their Chief Engineers in the event that they should wish to reconsider what they had included in their proposals.</u>

3. ACCEPTANCE OF AGENDA

4. REQUIREMENTS FOR MODELLING (Annexure A of II)

(a) <u>Presentation</u>

Pieter van Rooyen spoke on the notes in Annexure A of document II above.

(b) <u>Comment</u>

If new methodologies are to be used as now proposed, it is essential that the methodologies utilized for the calibration of the Pitman Model are consistent with those of the WRYM. These could be stand alone utilities utilized interactively with the Pitman Model, but should preferably be integrated into the Pitman Model as already partially done in Shell. This could result in delays. The proposed modifications to the Pitman Model and WRYM would be reconsidered at the end of the meeting.

5.1 Irrigation Requirements and Return Flows (3.7 of II)

(a) <u>Presentation</u>

Pieter van Rooyen presented a concept model which would consider the supply less Distribution System Losses (consumptive (C) and return flow (R)), irrigation application losses (C&R), soil moisture losses (C&R) and also SAPWAT consumptive usage distributed monthly using IRRDEM. It is envisaged that the Soil Association mapping will provide adequate information on soil depth and drainage characteristics for use in the model.

(b) <u>Comment</u>

(i) The data on return flows is limited to flow and salinity data and therefore it is difficult to check whether the much more detailed modelling is correct and warranted.

(ii) The additional complexity may not improve the result.

(iii) The complexity will have cost implications for the study.

(iv) A small working group will be formed to discuss this.

(v) Pieter van Rooyen will make available the spreadsheet model for the Crocodile Study.

(vi) Validation is necessary for a variety of systems.

5.2 Groundwater (3.6 of II and III)

(a) Presentation

Karim presented the methodology which he had developed and tested on two quaternaries. The model details and its possible integration in WRYM are shown in IV. Use is made of the Pitman regional parameters to develop other parameters. Certain of the parameters are based on geohydrological parameters and in particular groundwater storage (based on permeability and aquifer area and depth) and on the average aquifer level relative to the watercourse (as this decides both base flow and recharge depending on river level). It is envisaged that in the long term this model will be calibrated for all quaternary catchments. The effect of abstractions on base flow depends on how far away boreholes are situated from the river.

(b) Comment

(i) If this model is utilized for the current study, it will be necessary to calibrate the Pitman Model twice, first as it stands to determine the GW and POW parameters from the calibrated Pitman parameters (rather than using the incorrect regional parameters) and then using the other new parameters.

(ii) The main benefit of the proposed methodology seems to be where there is close interaction between the river and adjacent aquifers.

(iii) Lag effects will be taken into account by the storage and the effect of distance from the river (about 1 km being the maximum which needs to be considered).

(iv) Aquifers not linked to the river should be treated differently.

(v) The model seems to provide a more realistic representation of surface/groundwater interaction than the current Pitman Model does, which would be useful for the modelling process.

(vi) The model is similar to the model developed by Dennis Hughes.

(vii) The cost of acquiring the additional data (on aquifers and existing groundwater use) and additional calibration should be considered during the Inception Phase (but preferably communicated to the Chief Engineers before 4 November).

5.3 River and Canal Losses (3.9 of II)

(a) Presentation

Pieter van Rooyen indicated that river and canal losses could be modelled by providing a loss channel with width varying as the flow varies, plus evapotranspiration losses. The loss channel should be calibrated.

(b) Comment

(i) Initial wetting of a dry river bed after a long dry period will result in an initial channel loss.

(ii) A river channel with seekoei gate which does not flow from time to time and from which irrigation abstractions take place can also be modelled as a dummy dam.

(iii) The alien vegetation consumptive use equations could be used for the riparian zone evapotranspiration, but account should also be taken of the evapotranspiration of natural riparian vegetation.

5.4 Streamflow Reduction Processes (3.2 of II)

5.4.1 Afforestation (3.3 of II)

(a) Presentation

Gerald de Jager said that the methodology would be based on André Görgens' presentation at the 2003 SANCIAHS.

(b) Comment

(i) **Johan van Rooyen requested that André Görgens make recommendations on the methodology as soon as possible. When will the model/methodology be available?**

(ii) **André should also consult Mike Warren.**

(iii) Stephen Mallory has concerns about the relative water use of eucalyptus and pine.

(iv) The GUSH curve provides annual usage based on stream flow and these must be disaggregated into monthly usage. Graham Jewitt is utilizing the ACRU Model to do this.

(v) It was mentioned that other land use practices such as contour furrows also reduce runoff. This can be modelled with ACRU, but this level of detail is probably not warranted.

5.4.2 Sugar Cane (3.4 of II)

(a) Presentation

Gerald de Jager said that a procedure had been developed by Erik Schmidt of the Sugar Association. This routine would be incorporated into WR2005. Colin Everson of the CSIR had suggested that sugarcane could be treated similarly to pine trees.

(b) Comment

The view was expressed that although the processes of sugar and trees may provide similar results, they are not necessarily the same.

5.4.3 Alien Vegetation (3.5 of II)

(a) Presentation

Gerald de Jager said that alien vegetation should be considered in two categories: riparian and in catchment. The latest CSIR curves must be incorporated into the model.

(b) Comment

(i) The 2001 CSIR curves are incorporated in Shell, not the latest CSIR update.

(ii) Christo Marais should be consulted as to why alien vegetation is different from afforestation.

(iii) Christo Marais had developed the SPREAD Model to model the spread of alien vegetation taking the effects of fire and growth into account.

(iv) Aquatic weeds occur in some areas, but their impact is not significant.

5.5 Abstraction (diversion) Efficiency Structure (3.12 of II)

(a) Presentation

Pieter van Rooyen said that daily modelling is needed to develop relationships between diverted flow and river flow. The IFR must be taken into account by using the IFR distribution curves.

(c) Comment

(i) Some rivers have highly regulated base flows.

(ii) Flood type diversions may require that modelling be done at hourly or even smaller time intervals.

(iii) Flood type diversions can make provision for the IFR through a return channel.

(iv) Low flow type diversion curves can be developed with daily flow data.

5.6 Risk Based Assessment Methodology (3.13 of II)

(a) Presentation

Pieter van Rooyen described the new FIGDAT routine that has been incorporated into the WRYM. This routine facilitates the development of reliability curves for specified abstraction channels using historical flow sequences or selected stochastic sequences.

(b) Comment

(i) The approach of determining the reliability of a single user does not provide the stakeholders with a good understanding of the risks, particularly where two users with different risk requirements abstract water from the same source.

(ii) Permanent crops (mainly fruit trees) and pasture for dairy requires a higher assurance of supply than cash crops.

(iii) A discussion group should be set up to determine how to deal with the assurance of multiple users.

(iv) Economics and job creation are factors which affect the assurance of supply requirements for different users.

5.7 Ecological Flow Requirements (3.10 of II)

(a) Presentation

Pieter van Rooyen described Dennis Hughes SPATSIM Model that can be used for low confidence reserve determinations and for extending the Reserve into tributaries etc. SPATSIM develops duration curves.

(b) Comment

(i) SPATSIM provides a lookup table that defines the flow duration curve of the Reserve against the naturalised flow duration curve. This is essentially an operating rule.

(ii) The RDM office has agreed to undertake the classification and to do Reserve disagregation for the Study Teams, and also to redertermine the Reserve after the improved modelling has been completed.

(iii) Reserve scenarios must be determined including the status quo scenarios.

(iv) Most farm dams have limited provision for releases and constraint releases may be the most appropriate.

(v) SPATSIM does not take account of the ecological requirements of estuaries, which may or may not be synchronised with the riverine requirements.

(vi) If calibration of the Pitman Model changes the duration curves, then the RDM office should be requested to review and if necessary revise the riverine Reserve requirements.

5.8 Wetlands (3.8 of II)

(a) Presentation

Pieter van Rooyen said that Bill Pitman had suggested the format of the proposed wetlands model.

(b) Comment

The Nyl Study could provide valuable information for the development of the model.

5.9 Higher Resolution Networks (3.11 of II)

(a) Presentation

Pieter van Rooyen suggested that higher resolution subdivision of quaternary catchments may be required for the following situations:

- High rainfall subcatchments
- Groupings of farm dams or a large farm dam
- Groups of similar users

(b) Comment

(i) It was agreed that quaternaries were the starting point for all analyses.

(ii) There may be 50 to 100 users per quaternary in some cases. Subdivisions not smaller than say 5 users may be appropriate.

6. GENERAL

6.1 Water Quality

Water quality modelling was mentioned and the possible use of WQT. Water quality would not be modelled for the Mhlatuse, but it may be important to model this for some catchments like the Berg.

6.2 Integrated Development of Models

(a) Most of the additional modelling requirements would be incorporated into WR2005, but this would not be available for at least a year.

(b) Johan van Rooyen said that he would be assembling a working group to assess which of the additional modelling requirements should be incorporated into the current study. He will also provide a suggested program for making the appointments and addressing the proposals.

(c) Johan van Rooyen again invited the teams to comment to the Chief Engineers.

7. CLOSURE

Pieter van Niekerk thanked everybody for their participation and closed the meeting.

Appendix A-3 DWAF: Water Availability Assessment Studies for Licensing, Minutes of Technical Co-ordination Meeting of 4 March 2005

Department: Water Affairs and Forestry

Directorate: National Water Resource Planning

WATER AVAILABILITY ASSESSMENT STUDIES FOR LICENSING

Technical Co-ordination Meeting

Date :	Friday, 4 March 2005
Time :	11h00
Venue :	WRP Offices: Upper Level Block 5, Green Park Estate, 27 George Storrar Drive, Groenkloof (see attached map for directions).

AGENDA

	ITEM	Presenter
1	**Welcome**	JvR
2	**Purpose of the meeting**	PvR
3	**Acceptance of agenda**	PvR
4	**Feedback on algorithms being implementation**	
4.1	Irrigation block module	AB
4.2	Afforestation	PvR
4.3	Groundwater module	AB
4.4	Dry-land sugarcane (other SFR processes)	PvR
4.5	Invasive alien plants	GdJ
4.6	Wetlands	AB
4.7	Assumption and results presentation requirements	PvR
5	**Consistency among the teams regarding the network resolution (Also considering the Ecological Water Requirements)**	PvR
6	**Application of the groundwater module (appropriate use of the model)**	KS
7	**Reasons (assessment methods) for deciding whether or not the hydrological record should be updated or extended**	PvR
8	**Abstraction type for irrigation (12 monthly values or variable time series)**	SM
9	**Data preparation issues**	AG
10	**Data capture/storage (format and presentation)**	SM
11	**Consistency in GIS information among studies**	JR
12	**WRSM2000 course**	AB
13	**Need for further technical co-ordination meetings**	PvR

(Please note that a light lunch will be served at 13:00)

Department: Water Affairs and Forestry
Directorate: National Water Resource Planning

WATER AVAILABILITY ASSESSMENT STUDIES FOR LICENSING

Technical Co-ordination Meeting

Date :	Friday, 4 March 2005
Time :	11h00
Venue :	WRP Offices: Upper Level Block 5, Green Park Estate, 27 George Storrar Drive, Groenkloof (see attached map for directions).

Meeting Notes

	ITEM	Presenter
1	**Welcome**	JvR
2	**Purpose of the meeting**	PvR
3	**Acceptance of agenda**	PvR
4	**Feedback on algorithms being implementation**	

4.1 Irrigation block module — AB

- 95% incorporated into WRSM2000 – currently being tested.
- A document has been compiled by the implementation team to describe the implementation process as well as list where there are differences with the WQT.
- This document will be incorporated into the report *Hydrological Business and Functionality Improvement Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling*, (MUHSS – Phase 2, Activity 31).

4.2 Afforestation — PvR

- The assessment of the time series data produced for the Gush assessment proved to be problematic and cannot be used as is at this stage.
- Graham Jewitt of the University of Kwazulu-Natal has committed himself to have revised ACRU time-series results by the end of March 2005.
- This data will then again be processes to determine if non-dimensional distribution curves could sufficiently represent the SFR processes.
- A final decision on the method to apply for SFR processes will be taken by middle April 2005. If the proposed methodology is found to be inappropriate, a decision will be taken to revert back to the old CSIR runoff reduction curves.
- Feedback on the process will be given through e-mail.
- The protocol of how to model SFR processes is not yet available. Since Prof A Görgens could not attend the meeting, feedback on the timing of the protocol remains outstanding.

4.3 Groundwater module — AB

- The groundwater module is currently being included in the WRSM2000 and testing of the results against the spreadsheet is being undertaken.

- A minor change was introduced to the groundwater module as presented at the end of October 2004. The change involves replacing the base-flow separation equations with a time-series of monthly soil storage "S" from the Pitman model. The intention is that the "S" time-series will also be used in the WRYM as the means of calculating recharge to the groundwater module stochastically.
- Further testing and documentation of the algorithm will be undertaken as part of a task to be approved by the Directorate: Water Resource Planning System.

4.4 Dry-land sugarcane (other SFR processes) PvR

- Similar feedback as for **Item 4.2**.

4.5 Invasive alien plants GdJ

- Similar feedback as for **Item 4.2**.

4.6 Wetlands AB

- The wetland routine has been developed and refined by Dr Pitman and is being included in the WRSM2000. The process is 95 % complete.
- A description of the routine is available and will be included in the report *Hydrological Business and Functionality Improvement Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling*, (MUHSS – Phase 2, Activity 31).

4.7 Assumption and results presentation requirements PvR

- The detailed descriptions of the business processes (requirements) definitions has commenced and preliminary presentation methods were presented at the meeting.
- These will be refined and documented.
- Further steps will be to develop detailed specifications, implementation and testing.

5 Consistency among the teams regarding the network resolution

(Also considering the Ecological Water Requirements) PvR

- No hard and fast rules could be put forward regarding the level of resolution that should be applied by the five study teams.
- The following broad guidelines were identified:
    - Tributaries that contain abstractions should be simulated as separate catchments in order to reflect the local availability.
    - In all cases the system should have nodes that represent the quaternary catchment outlets.
    - The resolution should allow for assessment of the downstream impacts of one water use on another. The example was given of a mining activity having an impact on the water available of a downstream abstraction.

5a Process for communication with RDM *JAvR*

- The process for communication with the RDM office was spelled out as follows:
    - There is a process currently undertaken by the CSIR to assess the EMCs based on the need for bio-diversity. This will provide guidance on the EMCs that is required in the catchments.

- The Directorate: Resource Directed Measures is currently defining a method of how the IFRs from previous studies at specific sites could be distributed to upstream tributaries. This will be based on the methodology and model developed by Prof D Hughes. The intention is that IFRs will be defined for a range of EMCs in order for the study teams to be in a position to assess scenarios.
- Each team has to define the nodes where IFRs are required and this should be given to Dana Grobelaar, a consultant assisting the D:RDM. Each team should arrange separate discussions with Mr Grobelaar.
- The D:RDM may add to the nodes based on ecological reasons and will therefore comment and give feedback to the study teams on the initial set of nodes.

6 Application of the groundwater module (appropriate use of the model) KS

- Karim Sami demonstrated, through a spreadsheet version of the groundwater module, what the input parameters are and gave an indication of where starting values for the parameters could be obtained.
- It was emphasised that the abstractions from groundwater have to be included in the modelling as reliably as possible. The data being captured by the verification studies should provide such information.

7 Reasons (assessment methods) for deciding whether or not the hydrological record should be updated or extended PvR

The hydrological review process of the Mhlathuze Study indicated that there are several criteria that should be considered when making the decision on whether or not the hydrology should be updated, these are listed below:

- In cases where the extended period of record (new data) contains a dry event (period) that would have a significant impact on the statistics of the natural runoff.
- If entirely new data records at new locations that was not available when the previous hydrology was derived are now available, consideration should be given to update the hydrology.
- The application of improved methods of calibration could also require an update of the hydrology. These aspect include:
  - Patching of previously unused periods of the streamflow data that was used in the calibration.
  - Undertaking calibration on incremental flows for incremental catchments as apposed to only calibrating on the total flows.
  - Explicit modelling of features such as streamflow reductions, irrigation return flows, groundwater module or wetlands that was not done in the previous study and would impact on the calibration rainfall-runoff model.

8 Abstraction type for irrigation (12 monthly values or variable time series) SM

- Stephen Mallory summarised the question by indicating that if it would not be possible to simulate the irrigation water requirement as average monthly values (12 values) as apposed to using a time-series of variable monthly values.
- The response was that the variable time-series reflects the characteristic of the irrigation water use and that it would be important to have that correlation with the temporal availability of the water resource. Furthermore scheduling of irrigation on the basis of rainfall is a valuable demand management measure that should be practiced by irrigators and should be promoted (supported) in the licensing of this sector of water use.

- Pieter van Rooyen also indicated that the irrigation block provide sufficient variation in parameters in order to account for most types of activities, i.e. if the irrigation application is to achieve optimal or sub-optimal crop yields.
- The decision was taken that irrigation will be simulated as a time-series.

9 **Data preparation issues** AG
- This item had no notes to record.

10 **Data capture/storage (format and presentation)** SM
- Proposed methods of data storage with metadata was discussed and it was requested that Bennie Haasbroek give guidance to the study teams in this regard, particularly with respect to providing metadata. It was suggested that a metadata template be prepared for use by the study teams.
- One method of storing the data is to use standard file extension naming conventions. John Hansford indicated the WRSM2000 development team is in the process of defining such file name extensions and it was agreed that these should be used as a point of departure.
- The request was expressed to make available information on the review process as soon as possible. This information is required for the respective Inception Reports.

11 **Consistency in GIS information among studies** JR
- Johan Rossouw provided a list of GIS information their team has requested from DWAF. This list will be distributed to all the teams. It was requested that DWAF compile CDs that contain the data and make copies thereof available to all study teams.

12 **WRSM2000 course** AB
- Allan Bailey confirmed that the date for the course is 14 and 15 March 2005 and indicated that there will be no course fee since DWAF will finance the preparation and presentation costs. He also indicated that each firm could send two representatives.

13 ***WQ consideration to be included into the modelling*** PvR
- The need to incorporate water quality modelling was discussed and the general consensus was that such modelling would only be undertaken at a later stage. It was however recognised that in cases where models are readily available, those could possibly be used. It was proposed that a separate working group be formed (focus on the Olifants River System) to discuss the need and methodology for such modelling as part of the WAA studies.

14 ***Mine Modules to be included into WRSM2000 and WRYM*** PvR
- The need to include the mine modules currently included in the WRPM for the Olifants River System into WRSM200 and possibly WRYM was discussed. It was proposed that a separate working group be formed to discuss the need and methodology of how to deal with the mines.

15 **Need for further technical co-ordination meetings** PvR
- It was decided that further meetings will be arranged as and when the need is identified.

Discussion items that were added at the meeting are indicated in *Italic* text format.

Appendix A-4 AGES: Review of the Surface Water – Groundwater Interaction Model, 24 April 2006

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Department of Water Affairs and Forestry	**For attention:**	**B Havenga**
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Sedibeng Building 185		**Water Resources Planning**
Pretoria		**DWAF**
24 April 2006	**Reference:**	**AS-PP-06-04-24**

REVIEW OF THE SURFACE WATER – GROUNDWATER INTERACTION MODEL

Introduction

Following the project meeting on 24 November 2005, there was a request to review the Surface Water – Groundwater Interaction Model (Sami, 2005) and its applicability for the project.

Objectives

The purpose of the modelling study is to determine the status of the groundwater balance on a quaternary catchment scale level in the study area. The project outcomes must be able to form the basis of future Water Use License Applications required by the National Water Act (Act 36 of 1998). It is important to review and reference the models in terms of basic principles, potential flaws and uncertainties in the output.

Review conclusion

The review process included a visit to Mr Sami and discussions on the technical background of the model, telephonic conversations with Dr Dennis from the Institute for Groundwater Studies and a meeting with Dr K Witthuser from the University of Pretoria. Dr Witthuser did a formal review and applied the model on the Schoonspruit Aquifer.

The model development is an innovative step towards integration of surface water and groundwater assessment methods and should be further developed and investigated.

The general feedback on the applicability of the model was uncertain. Specific aspects of the model are:

1. It could not calculate the lag times in the Schoonspruit dolomite aquifer correctly.
2. The model is based on the base flow components of hydrographs which are influenced by upstream dams. In the semi-arid areas of the country, there are no base flow figures available while groundwater volumes can still be abstracted. It is not clear how the model would calculate flow balances in these cases.
3. It is not validated and its complexity creates room for criticism.
4. The validity of the model assumptions (e.g. Pitman S model) and mathematical formulation in terms of groundwater systems must be reviewed and validated. For example, the use of Pitman parameters which was developed for surface soils are not necessarily valid for the underlying aquifer.
5. The validity of the model further away (+1km) from surface water bodies must be demonstrated.

The (i) development of a model and (ii) its widespread application in industry should be separated by a period of testing and validation in the field.

Recommendations

1. The model should not be used in isolation and must be validated by comparing the results against numerical and other models on a quaternary catchment scale.
2. The overall applicability of the Pitman S model for groundwater must be determined.
3. The use of the model should not be discarded as it could yield flow volumes calculated independently that could be compared with other models for validation.
4. The model should be differentiated in terms of output components that are certain and can be validated (e.g. groundwater balance calculations) and those that are uncertain and not validated (e.g. lag times).
5. The model output must be geared towards accounting of groundwater flow volumes available.

Regards

JJP Vivier (Sent electronically)

Geohydrologist (Pr.Sci.Nat)

Appendix A-5 DWAF: Brief Report on the GRA II Groundwater Surface Water Interaction Algorithm, August 2006

BRIEF REPORT ON THE GRAII GROUNDWATER SURFACE WATER INTERACTION ALGORITHM

1 INTRODUCTION

Integrated Hydrological Planning (IHP) under WRPS conducted feasibility studies on the potential use of the GRA II groundwater/surface interaction algorithm and aimed at advising the CD: IWRP with regards to the potential use of the GRA II algorithm as an option in a rainfall runoff model (Pitman). If the approach is feasible, then generated data series can be used to generate stochastic flows in the Water Resource Yield Model (WRYM) and assess both surface and groundwater availability.

2 METHODOLOGY

The feasibility studies were done as two activities and are available as two separate reports:

- Activity 7: Application of available surface-groundwater interaction methodologies in system models
- Activity 17: Adaptation of GRAII surface-groundwater interaction methodology for use in WRYM and trial case study

3 RESULTS FROM ACTIVITY 7

In this activity GRA II method was reviewed and alternative approaches suggested.

The method is based on pure mathematical parameters. However, in applied earth sciences there must always be some degree of parallel drawn between the mathematical descriptions and the physical world, to ensure that the model simulation is more realistic. In the case of the GRA II method the mathematical conceptualisation describes a physical world where quaternary catchments have similar hydrogeological units with isotropic, homogeneous parameters (primary aquifer) over entire catchments, linear geomorphological gradients, no geological structures etc. In a South African context and using GRA II model, especially in regions with high baseflow, it is difficult to merge these mathematical parameters with the physical world.

The following limitations were also noted:

- Unsaturated parameters are used for saturated conditions and that does not realistically account for saturated conditions in South African aquifers
- The time series of S (subsurface moisture storage) comes from the Pitman model and is equated to the potential recharge and interflow. This assumption could not be validated.
- S input along the river is used as input data and yet it should not be used to calculate the aquifer recharge for the entire quaternary catchment. The rate of recharge infiltration is a function of vertical hydraulic conductivity and geological as well as geomorphological properties of the overlying substrata. Geological and geomorphological complexity, especially in a country like South Africa, makes this assumption unacceptable.
- Recharge time series data is calculated from time series of S. The separation of recharge into (1) water that enters the soil profile (potential recharge), and (2) water that enters the regional aquifer (aquifer recharge), determines the ratio of interflow to groundwater baseflow. The data series does not distinguish between

potential recharge, and recharge to the regional aquifer and no data is available to distinguish between groundwater baseflow and interflow. As a result it is difficult to calculate how much recharge is entering the regional aquifer.

- Furthermore, interflow occurs from both the vadose zone and from excess aquifer recharge. Interflow from the vadose zone is generated and lagged via the Pitman baseflow algorithm. This simulates saturated soils and springs above the regional water table. However, in cases where the regional water table is much lower impacts on interflow from the vadose zone cannot be simulated.
- Aquifer excess interflow, however, can be impacted by abstraction through lower aquifer storage levels. This implies that only aquifer recharge is available for abstraction and this conceptualisation of recharge can over estimate bore abstraction impacts on baseflow.
- The percolating storage zone conceptually represents water that has not reached the regional aquifer, and also serves as a lag function, delaying recharge from immediately having an impact on baseflow. This parameter needs to be calibrated by comparing groundwater baseflow to the observed hydrograph time series data.
- Aquifer capacity (the amount the aquifer can store) is the aquifer thickness (D) multiplied by storativity (S). Aquifer capacity is used and the excess recharge is removed as outflow. The values used S and D used in GRA II are too high and cannot be validated.
- Evapotranspiration from the regional aquifer can occur from zones of shallow groundwater at a rate dependent on the rainfall deficit. Outflows in catchments with no groundwater contribution to baseflow can only be accounted for by means of evapotranspiration and groundwater outflow. Very little data is available to calculate evapotranspiration.
- Groundwater abstraction is taken from aquifer storage and groundwater baseflow based on a distance from stream channel-transmissivity-storativity-time relationship. This results in a time series, which is modified by recharge. Two calibration curve-fitting parameters are inherent in the relationship. These have been generalized from catchments where data is available and avoid calibration. It would be quite challenging to fit these parameters on a quaternary catchment scale and where little data is available.
- The current method assumes that there is no abstraction from springs or perched aquifers and this need to be incorporated.
- There is no time lag for groundwater released from aquifer storage
- All river and boreholes fully penetrate the aquifer. This is not always true.
- The boreholes are pumping at a constant rate and no variations borehole pumping rates are taken into account.

3.1 Alternative methods

The GRA II method needs to be compared and tested with alternative methods. The following alternative methods are proposed:

- Herold's method together with a simple water balance
- The Butler flow depletion model (assumes a finite width of stream of shallow penetration and an aquifer of limited spatial extent).
- Use one of the standard methods to determine recharge such as the cumulative rainfall departure (CRD) method and generate stochastic recharge using a probabilistic approach.

- Use standard numerical models such as Modflow and associated river packages (e.g. branch model) to calculate water balances. It is noted that more data is required for these models but they are at least based on physical parameters.

4 RESULTS FROM ACTIVITY 17 (TRAIL CASE STUDY)

- Model parameters are averaged catchment parameters and usually differ from physical based local parameters
- It is still questionable if the Pitman S has any relation with aquifer conditions, especially in hard rock aquifers
- The GRAII algorithm cannot describe the observed water table (saturated volume fluctuations), therefore while the total water balance is correct, the water is only attenuated in the percolating store and therefore still incorrectly split between the percolating store and the aquifer storage for a given point in time. As a result several data series results from the GRA II model are questionable, and include the groundwater outflow, baseflow or evapotranspiration.
- In semi-arid areas there are no baseflow but groundwater can still be abstracted. In these areas, how will the model calculate available groundwater?
- The aquifer capacity (CAP), which is not defined in Hydrogeology, was removed as a model parameter. It is replaced by a physical more meaningful maximum recharge rate (MAXRECH). Instead of limiting the percolation into the aquifer with the help of an "aquifer capacity" or volume, the current model uses a rate limitation.
- There are still "2 boxes" in the model, representing the percolating zone and the aquifer. A representation of the catchment as a single box proofed at this stage and with the current model as not workable and was discarded
- The interflow is still calculated as the sum of the interflow derived from the soil zone (Q_g in the Pitman S model) or from the percolating zone
- Concerns regarding the term transmission losses proofed groundless. That is a correct technical term to describe flow reductions due to infiltration

5 RECOMMENDATIONS

Like any other groundwater model the GRA II algorithm has certain limitations and these limitations need to be listed. However, from an integrated water resource management perspective, we cannot simply discard the algorithm and we should rather use the opportunity to move closer to integrated water resource management.

We as groundwater specialists need to accept that in South Africa the Rainfall Run-off Pitman Model derive input data for the Water Resource Yield Model (WRYM) and by incorporating it in the Pitman model we are taking a step towards IWRM. Integration of the GRAII algorithm as part of Pitman model has already commenced and will be part of a groundwater dropdown menu in the new Pitman Model GUI. Therefore the final recommendations are as follows:

- WRPS is to review other possible methods and propose and investigate different methods to prove as future input datasets to the WRYM.
- For licensing purposes contribution from groundwater to baseflow results from the new Pitman model and groundwater results from the WRYM need to be checked with other analytical and numerical methods and cannot serve as standalone results.

Thank you

APPENDIX B

COMPARISON OF MATHEMATICAL APPROACH BETWEEN SAMI / PITMAN MODEL AND PHYSICALLY BASED MODELS

Table B-1: Comparison between Mike SHE and Sami/Pitman

MIKE-SHE APPROACH	SAMI- PITMAN APPROACH
1. UNSATURATED ZONE (UZ): SOIL PROPERTY DEFINITIONS	
Soil water content at field capacity or minimum saturation that can be achieved in the laboratory	SL = minimum soil moisture storage below which no run off occurs
Soil water content at saturation/ maximum water content of the soil	ST = total /maximum soil moisture storage and S is the soil moisture storage
2. INTERCEPTION	
The interception is defined as $I_{\max} = C_{\text{int}} * LAI$ Where LAI is the Leaf Area Index, and $C_{\text{int}} =$ is the interception storage capacity of vegetation, it approximately 0.05m	Monthly interception (I) to monthly precipitation is for given interception storage $I = X\left(1 - e^{Y*P}\right)$ Where I = total interception for the month P = total precipitation for he month and **Intercept storage capacities:** $X = 13.PI^{1.14}$ $Y = 0.00099PI^{0.75} - 0.011$
3. INTERFLOW	
1. **The interflow for a linear reservoir** for water level (h) which is above threshold (h_{thresh}) level is defined as: $q_I = \dfrac{(h - h_{thresh})}{k_i}$ If $h > h_{thresh}$ Where q_I is the specific interflow, and k_i is the time constant for the flow	Interflow computed from Sami-Pitman: computed from percolating store and percolation PERC in excess of the maximum recharge rate MAXRECH $q_I = FT\left(\dfrac{S - SL}{ST - SL}\right)^{POW} + \left(PERC - MAXRECH\right)$
The water level (h) expression for interflow: $h_t = h_{t0} e^{-\frac{(k_1+k_2)dt}{k_1 k_2}} + \dfrac{k_i k_p}{k_i + k_p}\left(q_{\inf il} + \dfrac{h_{thresh}}{k_i}\right)\left(1 - e^{\frac{-(k_i+k_p)dt}{k_i k_p}}\right)$ Where h_t is the expression for water level (h) at time (t) when there is both q_I and q_{perc}, S_y is the specific yield, $q_{\inf il}$ is the specific infiltration, usually positive when water is added	

Table B-2 Comparative Analysis between the Sami-Pitman Model and Physically Based Models

	Sami-Pitman	Physically-Based	Comments
Overland flow	UNDEFINED	Saint-Venants two-dimensional Diffusive Wave equation $$\frac{\partial h}{\partial t}+\sqrt{8g}\,\frac{\partial}{\partial x}\left(\sqrt{\frac{S_0 h^3}{F}}\right)-q-r-f=0$$ (h) is the flow depth, (r) is the rainfall rate, (F) is the infiltration loss rate, (q) is the lateral inflow rate, (t) is the time, and (f) is the Darcy-Weisbach friction factor	This is the full dynamic Saint-Venant wave equation used for routing: this equation gives Gives the highest degree of surface prediction under most conditions, e.g., hydrostatic pressure distribution, small channel bottom slope, and a uniform cross-section velocity: Can simulate backwater effects but it Yields complicated flow routing and is computational intensive However, for complete surface water – groundwater interaction hydrologic model, it is expected that Sami_Model to incorporate Overland flow, which is not defined
Interflow	Interflow computed from Sami-Pitman: computed from percolating store and percolation PERC in excess of the maximum recharge rate MAXRECH $$q_I=FT\left(\frac{S-SL}{ST-SL}\right)^{POW}+(PERC-MAXRECH)$$	. **The interflow for a linear reservoir** for water level (h) which is above threshold (h_{thresh}) level is defined as: $$q_I=\frac{(h-h_{thresh})}{k_i} \quad \text{If } h>h_{thresh}$$ Where q_I is the specific interflow, and k_i is the time constant for the flow	Sami-Pitman model: is based on the power law taken from Pitman (1973) and lacks the physics of flow when compared with lumped/physical based models, e.g. linear reservoir which has a hydraulic head in exponential form: It also lacks the time factor.

	Sami-Pitman	Physically-Based	Comments
Evapotranspiration	Covered in Pitman GW EVT in Sami is expressed as: $((MAE * MDIST * CROP) - RAIN)$ $* AREA * (STORE - SWL) / (TAS - SWL)$ where MAE is the mean annual rainfall, MDIST is the monthly distribution fraction of evapotranspiration, CROP monthly A pan crop factor for appropriate Acock vegetation cover, RAIN input data of monthly rainfall, AREA riverine area where evapotranspiration from groundwater can occur, SWL parameter of static water level, and TAS is the total aquifer storage from GRAII total aquifer volume divided by are	The Penman-Monteith form of combination equation $$\lambda ET = \frac{\Delta(R_n - G) + \rho_a C_P \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$ where R_n is the net radiation, G is the soil heat flux, $(e_s - e_a)$ represents the vapour pressure deficit of the air, ρ_a is the mean air density at constant pressure, C_P is the specific hear capacity of air, Δ_a represents the slope of the saturation vapour pressure temperature relationship, γ_a is the psychometric constant, and r_s and r_a are the bulk surface and aerodynamic resistances	The Penman –Monteith method includes all parameters, which govern energy exchange, and corresponding heat flux (evapotranspiration) from uniform expanses of vegetation. The equation can also be used to calculate any crop evapotranspiration because the surface and aerodynamic resistances is crop specific. The surface resistance r_s describes the resistance of vapour flow through stomata openings, total leaf area and soil surface. The aerodynamic r_a describes the resistance from vegetation upwards and involves friction from air flowing over the vegetative surfaces. None of the above physical parameters are defined in Sami_GW evapotranspiration expression

	Sami-Pitman	Physically-Based	Comments
Infiltration	$RE = GW\left(\frac{S-SL}{ST-SL}\right)^{GPOw}$ where RE, is the potential recharge (mm), GW is parameter for maximum recharge at maximum soil moisture (ST), S input data for soil moisture, GPOW parameter for storage recharge relationship	The One Dimensional Richards Equation For the Unsaturated Flow $C_{soil}\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial z}\left(k_v(\psi)\frac{\partial}{\partial z}\psi\right) + \frac{\partial k_v(\psi)}{\partial z} - S(z)$ where ψ is the soil moisture potential or suction pressure, $C_{soil}(\psi)$ is the specific soil water capacity, $k_v(\psi)$ is the unsaturated hydraulic conductivity, $S(z)$ is the sink term	Sami_Pitman model is based on the Pitman (1973) Runoff (RE) versus soil moisture power law curve, which is purely mathematical: This model: lacks mathematical expressions based on the physical properties of the soil, e.g., undefined hydraulic conductivity $k_v(\psi)$ and soil moisture potential ψ of the soil, these are major controlling factors of infiltration No sinks $S(z)$, and specific soil water capacity $C_{soil}(\psi)$ No expression indicating the time dependency of infiltrating water, yet the Sami-Pitman models monthly infiltration
Percolation	Quantification of Percolation storage is not defined. The percolation increments from recharge: $PERC = RE_X * \left(\frac{P}{PMAX}\right)^{PPOW} * \frac{RE_x}{\overline{\overline{RE}}}$ where PERC is the variable percolation from percolating store to aquifer storage, RE_x is the moving average of the recharge RE for x months, P is the percolating storage, PPOW is the relation ship between storage and percolation, PMAX is the maximum percolating storage and RE is mean monthly recharge.	If there is still water in the linear reservoir, the specific percolation output is $q_{perc} = \frac{h}{k_p}$ Where (h) is the depth of the water, and k_p is the time constant for percolation	Sami_Pitman model: lacks an expression based on the physics and mathematics of the soil that quantifies percolation storage

	Sami-Pitman	Physically-Based	Comments
Groundwater Flow	1. Groundwater flow equation: Expression NOT DEFINED 2. Hydraulic gradient as: $HG = HGRAD\left(\frac{STORE - SWL}{TAS - SWL}\right)$ Where HGRAD is parameter of maximum hydraulic gradient	3-D Boussinesq Groundwater Flow equation $\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)-W = S_s\frac{\partial h}{\partial t}$ Where k_{xx}, k_{yy} and k_{zz} are the principal hydraulic conductivity tensor values, h is the hydraulic head, W represents sources or sinks, S_s is the specific storage, and x, y, and z are the axes on the Cartesian coordinate system	Groundwater flow equation of Sami-Pitman model is not consistent with the Physical-based model, and is not explicitly defined, for example: No expression for lateral flow Lack of Quantitative definition of Darcy's, this is crucial for GW flow Undefined hydraulic parameters: e.g. hydraulic conductivity (soil parameters) Sources or sinks are not defined Undefined Storage coefficients No expression indicating the time dependency of the groundwater flow

	Sami-Pitman	Physically-Based	Comments
Base Flow	The groundwater baseflow (GWBaseflow) and transmission losses are computed from: $$q_B = (1-e^{(HEAD*BPOW)})BFMAX$$ Where q_B = GWBaseflow is the amount of baseflow out of the reservoir, BFMAX is the maximum rate of groundwater baseflow, and BPOW relationship between head difference and baseflow The HEAD defined as follows: $$HEAD = STORE - SWL - \frac{RUNOFF}{CATCHMENT}$$ where, RUNOFF = Input stream flow, and CATCHMENT = catchment area	The base flow for a linear reservoir for the water level (h) above the threshold level (h_{thresh}) is defined as: $$q_B = \frac{(h - h_{thresh})}{k_b},$$ Where q_B is the amount of baseflow out of the reservoir, (h) is the depth of water in the baseflow, h_{thresh} is depth of water required before baseflow occurs and k_b is the time constant for base flow The water level (h) expression for baseflow : $$h_t = h_{t0} e^{\frac{-dt}{k_b S_y}} + (q_{IN} - q_{pump})\left(1 - e^{\frac{-dt}{k_b S_y}}\right)$$ where q_{IN} is the amount of inflow to each baseflow, and q_{pump} is the amount water removed via extraction wells. Both q_{IN} and q_{pump} are controlled by split fraction which distribute them between two parallel reservoirs	The Sami_Pitman Base flow expression is unclear in the following respects: Lack of information on the type of reservoir modeled. However However, if the reservoir is linear, the expected expression for the total baseflow would be $$Q = Q_0 e^{-kt} + R(1 - e^{-kt})$$ Where $Q_0 e^{-kt}$ is the baseflow recession term, with Q_0 being the initial baseflow and $R(1-e^{-kt})$ is the rising limb or the gain in baseflow during excess rainfall R For shallow unconfined aquifer, the base flow recession is: $Q = \frac{Q_0}{1 + a_3 t^2}$ which is a special case of power-law for Boussinesq aquifer storage (see Boussinesq, 1904) or see attached table for storage –outflow models Sami_Baseflow expression has not time factor but yet the model computes monthly baseflow The expression for HEAD is physically unclear, since there is no information about its derivation and there is no reference cited

	Sami-Pitman	Physically-Based	Comments
Groundwater Depletions	$t' = \frac{4Tt}{x^2 S}$ Where t' is dimensionless time, t is time since pumping started, T is transmissivity, S is the storativity, and x is the distance from the river. The Groundwater Depletion $Depletion = \frac{100 - GW}{100} * Abstractions * \frac{Recharge_i \, or PERC_i}{MeanMonthly \, recharge}$	$u = \frac{r^2 S}{4Tt}$ u is the dimensionless time Where r is the distance of the piezometer from the drawdown well. All the other parameters are defined in the same way as Sami-Pitman Groundwater depletion is (see Kruseman and Ridder (1991): $Q = \frac{4\pi Ts}{W(u)}$ where Q is the groundwater abstraction, T is the transmissivity of the aquifer, s is the draw down measured in piezometer at a distance r from the well, and $W(u) = \int_u^\infty \frac{e^{-y}}{y} dy = -0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + ...$ is called the Theis well function or dimensionless draw down	The Sami Model dimensionless time is inversed in my view there is no physical rationale why it should be. The dimensionless time (u) in the physical based on Theis method (1953) has significance. There is lack of clarity in how groundwater depletion formula was derived in the Sami model. The author does not reference on this. The Sami model for depletion has no link with physical based methods, e.g. Theis method and the Sami model is unacceptable.

APPENDIX C

PARAMETERS OF SAMI MODEL

				Update		
Item	**Status**	**Not used**	**Default**	**GW**	**SW**	**Calibration**
Catchment Characteristics						
Catchment Area (CATCHMENT)	D		x			
Aquifer thickness	P			x		
Storativity (S)	P			x		
Total Aquifer Storage (TAS)	C			calculated		
Initial groundwater store	I					x
MAP (RAIN)	D				x	
Static water level (SWL)	P		x	x		
Unsat Store (PMAX)	P		x	x		
Initial Store	I					x
MAXRECH	P			x		
Moving average of recharge (Rex)	P			calculated		
Mean annual baseflow	D	x				
Baseflow calculated	C	x				
Pitman Parameters						
FT	P		x		x	
ST	P		x		x	
SL	P		x		x	
POW	P		x		x	
GW	P		x		x	
GPOW	P		x		x	
GL	P		x		x	
Harvest Potential	D	x				
Est. recharge	C	x				
Groundwater – Surface water Interaction						
Max groundwater discharge (BFMAX)	P			x		
BPOW	P			x		
Groundwater Evapotranspiration and Outflow						
Hydraulic gradient (HGRAD)	D		x	x		
MAE	D		x		x	
GW evap. Area (AREA)	D		x	x		
Transmissivity	P		x	x		
Impacts of Abstraction						
GW abstraction	D	x				
Distance-river (X)	D		x	x		
Max % from groundwater (GWMAX)	P		x			
K2	P					x
K3	P					x
Time Series Data						
Discharge	D				x	
Pitman S (S)	D				x	
Rainfall (RAIN)	D				x	
% of MAE (MDIST)	D				x	
Crop factor (CROP)	D				x	
Abstraction	D			x		

APPENDIX D

APPLICABILITY OF THE SAMI MODEL IN QUATERNARY CATCHMENTS IN BERG WAAS STUDY AREA

IWRM	QUAT	Applicability Criteria 1	2	3	4	5	6	Possible / Not	Comments
ATL	G21A (S)	N	N	Y	N	N	Y	**N**	Granite regolith aquifer dominant
ATL	G21B	N	N	Y	N	N	N	**N**	Malmesbury-granite regolith aquifer dominant
ATL	G21C	Y	Y	Y	?	Y	Y	P	As above, only minor TMG on G10F border
ATL	G21D	Y	Y	Y	?	Y	Y	P	Malmesbury-granite regolith aquifer dominant
ATL	G21E	Y	Y	Y	?	Y	Y	P	As above
ATL	G21F	Y	Y	Y	?	Y	Y	P	Malmesbury regolith aquifer dominant, except near coast
ATL	G22C (N)	N	N	Y	N	N	N	**N**	As above
AWT	E10A	N	N	N	N	Y	Y	**N**	Confined, layered, TMG fractured rock aquifers dominate
AWT	E10B	N	N	N	N	Y	Y	**N**	As above
AWT	E10C (E)	N	N	N	N	Y	Y	**N**	As above
AWT	G10G (E)	N	N	N	N	Y	Y	**N**	As above
AWT	H10C (NW)	N	N	N	N	Y	Y	**N**	As above
BRV	H10E	N	N	N	N	Y	Y	**N**	Thick, unconfined TMG fractured-rock aquifer dominant
BRV	H10F	N	N	N	N	Y	Y	**N**	Confined, layered, TMG fractured rock aquifers dominate
BRV	H10G	N	N	N	N	Y	Y	**N**	Thick, unconfined TMG fractured-rock aquifer dominant
BRV	H10H	N	N	N	N	N	Y	**N**	As above
BRV	H10J (NE)	N	N	N	N	N	Y	**N**	As above
BRV	H10K	N	N	N	N	Y	Y	**N**	As above
BRV	H10L	N	N	N	N	N	Y	**N**	Confined, layered, TMG fractured rock aquifers dominate
BRV	H20G (S)	N	N	N	N	Y	Y	**N**	Thick, unconfined TMG fractured-rock aquifer dominant
BRV	H20H	Y	N	Y	N	N	Y	**N**	Alluvial and surrounding regolith aquifer dominate
BRV	H40C (S)	N	N	N	N	N	Y	**N**	Heterogeneous aquifers, TMG on NE border (H40B)
CFP	G22A	N	N	N	N	N	Y	**N**	Thick, unconfined TMG fractured-rock aquifer dominant
CFP	G22B	N	N	N	N	N	Y	**N**	As above
CFP	G22C (S)	N	N	Y	N	N	N	**N**	Malmesbury regolith aquifer dominant, except near coast
CFP	G22D	N	?	Y	N	N	N	**N**	Layered alluvial and aeolian aquifers; endorheic drainages
CFP	G22E	Y	Y	Y	N	Y	N	P	Malmesbury regolith aquifer dominant, except near coast
CFP	G22F	N	N	N	N	N	Y	**N**	Thick, unconfined TMG fractured-rock aquifer dominant
CFP	G22G	Y	Y	Y	N	Y	Y	P	Malmesbury-granite regolith aquifer dominant
CFP	G22H	N	N	Y	N	Y	Y	**N**	Regolith aquifers dominant, but unconfined TMG on borders
CFP	G22J	N	N	Y	N	Y	Y	**N**	As above
CFP	G22K	N	N	N	N	N	Y	**N**	Thick, unconfined TMG fractured-rock aquifer dominant
HEX	E22C (E)	N	N	Y	N	Y	Y	**N**	Post-TMG regolith aquifer(s) dominant

IWRM	QUAT	Applicability Criteria 1	2	3	4	5	6	Possible / Not	Comments
HEX	H20A	N	N	Y	N	Y	Y	N	As above
HEX	H20B	N	N	N	N	Y	Y	N	Confined, layered, TMG fractured rock aquifers dominate
HEX	H20C	N	N	N	N	Y	Y	N	As above
HEX	H20D	N	N	N	N	Y	Y	N	As above
HEX	H20E	N	N	N	N	Y	Y	N	As above
HEX	H20F	N	N	N	N	Y	Y	N	As above
HEX	H20G (N)	N	N	N	N	Y	Y	N	As above
HEX	J12A	N	N	N	N	Y	Y	N	As above
HEX	J12B	N	N	N	N	Y	Y	N	As above
KGB	G40A	N	N	N	N	Y	Y	N	Confined, layered, TMG fractured rock aquifers dominate
KGB	G40B	N	N	N	N	Y	Y	N	As above
KGB	G40C (S)	N	N	N	N	Y	Y	N	As above
KGB	G40D (S)	N	N	N	N	Y	Y	N	As above
KGB	G40E (S)	N	N	N	N	Y	Y	N	As above
KGB	G40G	N	N	N	N	Y	Y	N	As above
NUY	H40A	N	N	Y	N	Y	Y	N	Post-TMG regolith aquifer(s) dominant
NUY	H40B	N	N	N	N	Y	Y	N	Confined, layered, TMG fractured rock aquifers dominate
NUY	H40C (N)	N	N	N	N	N	Y	N	Thick, unconfined TMG fractured-rock aquifer dominant
NUY	H40H (N)	N	N	N	N	N	Y	N	As above
NUY	H40J (N)	N	N	N	?	N	Y	N	As above
PKT	G10K (NE)	N	N	N	N	Y	Y	N	Unconfined and confined TMG fractured-rock aquifer
PKT	G10M (NE)	N	N	N	N	N	N	N	TMG fractured-rock aquifer along fault
PKT	G30A (N)	N	N	N	N	N	N	N	Heterogeneous primary aquifers, with TMG on S border
PKT	G30D	N	N	N	N	Y	Y	N	Heterogenous TMG bedrock aquifers
PUB	G10A (NW)	N	N	N	N	N	Y	N	Thick, unconfined TMG fractured-rock aquifer dominant
PUB	G10B	N	N	N	N	N	Y	N	Unconfined and confined TMG fractured-rock aquifer
PUB	G10C	N	Y	Y	N	Y	Y	P	Regolith aquifers dominant, but unconfined TMG on E border
PUB	G10D	N	Y	Y	N	Y	Y	P	As above
PUB	H10J (SW)	N	N	N	N	N	Y	N	Thick, unconfined TMG fractured-rock aquifer dominant
RBT	H40D	N	N	N	N	Y	Y	N	Confined, layered, TMG fractured rock aquifers in S
RBT	H40E	N	N	N	N	Y	Y	N	Confined, layered, TMG fractured rock aquifers on S and E
RBT	H40F	N	N	N	N	Y	Y	N	Regolith-alluvial aquifers mostly, confined TMG in far S
RBT	H40G	N	N	N	N	Y	Y	N	Heterogeneous regolith-alluvial aquifers, with TMG on S and E
RBT	H40H (S)	N	N	N	N	N	Y	N	Asymmetric GW input from TMG on NE border
RBT	H40J (S)	N	N	N	N	N	Y	N	Asymmetric GW input from TMG on NE and SW border
THK	G10A (SE)	N	N	N	N	N	Y	N	Thick, unconfined TMG fractured-rock aquifer dominant

IWRM	QUAT	Applicability Criteria 1	2	3	4	5	6	Possible / Not	Comments
THK	G40C (N)	N	N	N	N	Y	Y	N	Confined, layered, TMG fractured rock aquifers dominate
THK	G40D (N)	N	N	N	N	Y	Y	N	As above
THK	G40E (N)	N	N	N	N	Y	Y	N	As above
THK	H60A	N	N	N	N	Y	Y	N	As above
THK	H60B	N	N	N	N	Y	Y	N	As above
THK	H60C	N	N	N	N	Y	Y	N	As above
THK	H60D	N	N	N	N	N	Y	N	Asymmetric GW input from TMG on N border
THK	H60E	N	N	N	N	N	Y	N	Asymmetric GW input from TMG on N border
THK	H60F	N	N	N	N	N	Y	N	Asymmetric GW input from TMG on N border
THK	H60H	N	N	N	N	N	Y	N	Asymmetric GW input from TMG on N border
TWR	E10C (W)	N	N	N	N	Y	Y	N	Confined, layered, TMG fractured rock aquifers dominant
TWR	G10G (W)	N	N	N	N	Y	Y	N	As above
TWR	G10H	N	N	Y	N	Y	Y	N	Malmesbury regolith aquifer, except unconfined TMG on E and W border
TWR	G10J	N	N	Y	N	Y	Y	P	Malmesbury regolith aquifer, except unconfined TMG on E salient
VVT	G10E	N	N	N	N	Y	Y	N	Malmesbury regolith aquifer, TMG fractured rock aquifers in SW
VVT	G10F	N	N	Y	N	Y	Y	P	Malmesbury regolith aquifer, except unconfined TMG on E side
WBK	E21A	Y	Y	Y	N	Y	Y	P	Post-TMG regolith aquifer(s) dominant; minor confined TMG in W
WBK	E21B	Y	Y	Y	N	Y	Y	P	Post-TMG regolith aquifer(s) dominant
WBK	E21D	N	N	N	N	N	Y	N	Confined, layered, TMG fractured rock aquifers in W (Hansiesberg)
WBK	E22C (W)	N	N	Y	N	N	Y	N	Post-TMG regolith aquifer(s) dominant
WBK	H10A	Y	Y	Y	N	Y	Y	P	Post-TMG regolith aquifer(s) dominant
WBK	H10B	N	N	N	N	Y	Y	N	Confined, layered, TMG fractured rock aquifers in S
WBK	H10C (SE)	N	N	N	N	Y	Y	N	Confined, layered, TMG fractured rock aquifers in W
WBK	H10D	N	N	N	N	Y	Y	N	Thick, unconfined TMG fractured-rock aquifer dominant
WCT	G10K (SW)	N	N	Y	N	N	N	N	Regolith aquifers dominant; Layered alluvial-aeolian in NW
WCT	G10L	N	N	Y	N	N	N	N	Regolith aquifers dominant; Layered alluvial-aeolian in NW
WCT	G10M (SW)	N	N	Y	N	N	N	N	Heterogenous bedrock and alluvial-aeolian aquifers
WCT	G21A (N)	N	N	Y	N	N	Y	N	Granite regolith aquifer dominant
WCT	G30A (S)	N	N	Y	N	N	N	N	Heterogeneous primary aquifers; ill-defined drainage

1) Quaternary catchments that are shared between IWRM domains are shaded turquoise
2) Catchments in which the Sami Model will be tested are highlighted in yellow