HYDROLOGICAL INFORMATION REQUIREMENTS AND METHODS TO SUPPORT THE DETERMINATION OF ENVIRONMENTAL WATER REQUIREMENTS IN EPHEMERAL RIVER SYSTEMS

Report to the Water Research Commission

by

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ACKNOWLEDGMENTS

This project was designed to support larger projects (K5/1587 and K5/1414) being undertaken for the WRC by the University of the Free State entitled 'Environmental Requirements in Non-Perennial Systems'. The objective of the larger project was to develop methods for determining the environmental water requirements of non-perennial systems and includes project members with specializations in several relevant areas. The author of this report has interacted with various members of the main project and they have all made contributions to the contents of the hydrology report. The author would specifically like to acknowledge the contributions made by Dr Jackie King, Prof. Maitland Seaman and Prof. Gerrit van Tonder. The contribution of Prof. van Tonder has been substantial and has ensured that the results of the hydrology report are consistent with the conclusions reached during the hydro-geology investigations. The importance of this issue cannot be stressed too much and is referred to further in the conclusions section of the report.

As this project was a consultancy there was no Reference Group or Steering Committee appointed to oversee progress. However, the author would like to acknowledge the contributions of Dr Steve Mitchell, the WRC research manager in charge of the project.

EXECUTIVE SUMMARY

This report represents the final report on the Water Research Commission funded consultancy project K8/679:

'Ephemeral Rivers Hydrology'

The report is divided into 7 main sections (plus references) which largely reflect the main deliverables that were proposed for the project. The first section concentrates on the definition of ephemeral, or non-perennial systems, as well as identifying some of the characteristics that differentiate non-perennial systems of different types.

Section 2 examines the hydrological (quantity and quality) characteristics of non-perennial river systems and attempts to identify those which are likely to be ecologically significant. The main characteristics are high degrees of variability in time and space, coupled with extended periods of zero flow during which the storage and quality dynamics of static pools (if present) may play a significant ecological role. The frequency and extent of longitudinal connection of flow is thought to be of major significance and will affect other hydrological processes (pool storage and quality) as well as ecological processes. The characteristics of individual ephemeral systems will depend to a large extent on the nature of the interactions between surface and ground water processes. Ephemeral rivers developed on extensive alluvial aquifers are expected to have very different characteristics to those that are developed on or above hard rock aquifers. The depth of the regional ground water table will be very significant in the latter case. The development of in-channel weirs and dams, together with ground water abstractions through riparian boreholes, are expected to be the most likely anthropogenic impacts on water quantity, which could also impact on water quality. However, land use practices may also affect the sediment dynamics of the channel environments and therefore the geomorphology.

Part of section 2 refers to the specific processes in the Seekoei River system and notes that the observed streamflow response at the outlet of the catchment is dominated by the lower part of the catchment where a dolerite ridge and steep topography promote the occurrence of interflow springs above the regional water table. There is general agreement on the mechanisms leading to the development of these springs between the surface and ground water hydrology specialists.

Section 3 discusses the available continuous models that could potentially be used to simulate the relevant hydrological variables, such as flow and pool dynamics. The section discusses the concepts of flow processes within the Seekoei River and the implications for quantifying the parameters of available models. The applications of the Pitman monthly model (with recent modifications to the surface-ground water interaction routines), as well the daily VTI model are presented. While there exist a number of uncertainties related to the lack of information to validate certain aspects of the model results, the section concludes that the models can be applied successfully in the Seekoei River catchment for some of the purposes of EWR determination.

One of the issues not adequately covered by the continuous modelling approaches is the hydrology of flood events and their propagation through the channel systems of ephemeral rivers. Section 4 therefore investigates the use of relatively simple flood routing models. Simple models are referred to as the effort required to collect enough channel cross-section data for more complex models is considered to be beyond the resources of most EWR determinations.

During the course of the project a simple water quality model, focusing on TDS, was developed. This model (section 5) has been linked to the detailed runoff and storage component outputs from both of the continuous simulations models (Pitman and VTI). The results, measured against observed TDS values at the catchment outlet, are encouraging. The additional model parameters required are the TDS signals of the different runoff components (surface water, interflow springs and ground water). These have been quantified from the limited number of field observations that are available.

Section 6 discusses the use of the models in the analysis of future development scenarios. The conclusions about the usefulness of the models rather depend upon how well the hydrological impacts of the scenarios can be conceptualized. This emphasizes the need for a sound conceptual understanding of the hydrology of ephemeral systems, from both surface and ground water points of view.

The final section addresses a series of questions that were posed during the introductory section and attempts to use the example of the Seekoei River to provide answers. The overall conclusion is that existing hydrological analysis and modelling tools are appropriate for ephemeral systems, but that they may have to be applied in somewhat unconventional ways.

1. INTRODUCTION

This consultancy project was designed to provide hydrological data analysis support for a larger WRC project (K5/1587) undertaken by the University of the Free State entitled 'Environmental Water Requirements in Non-Perennial Systems'. The main project was a continuation of an earlier project (K5/1414) of the same name, which focused on (*inter alia*) the existing literature, the information requirements for non-perennial systems and an assessment of existing methods which have largely been developed for perennial systems. The current project is focused on the further development of environmental water requirement (EWR) methods using the example of the Seekoei River, a tributary of the Orange River located close to the south eastern border of the Northern Province.

The project was divided up into four main research components, the results of each one being summarised in separate deliverables, which are available from the author in electronic format (e-mail address denis@iwr.ru.ac.za) upon request, or from the WRC.

The first component ('Hydrological issues of ecological importance' – Deliverable 1) was to identify the hydrological issues that are of considered of ecological importance within EWR determinations for non-perennial river systems. The purpose of this component was to focus on the important hydrological issues, but also to initially address some issues associated with providing the required information. Some of these have already been discussed in previous work (Hughes, 2005), including the final report on the first phase of the University of the Free State project (Rossouw et al., 2005). Hughes (2005) noted that there is quite an extensive body of literature on arid zone EWR issues from Australia, which is recognized as having quite similar hydrological characteristics as South Africa.

The second component ('Initial model set-ups and calibration' – Deliverable 2) was to establish appropriate hydrological models, calibrate or calculate their parameters and critically assess the initial results. Three modelling approaches are referred to in the report; continuous monthly or daily simulations of flow and pool dynamics using rainfall-runoff models, simple water quality mass balance modelling of the pools using the detailed outputs of the rainfall-runoff models and some parameters to identify water quality signals of different runoff components and high flows and their routing through the channel system.

The third component ('Results assessment and further model refinements' – Deliverable 3) represents a continuation of the previous component using any additional information that was generated by the main project team through field work.

The fourth component ('Use of models in scenario analysis' – Deliverable 4) represents an example of the use of some of the models to estimate the impacts of development scenarios that were considered appropriate for the Seekoei River catchment by the main project team. The second and third components also refer to some aspects of scenario analysis, but are focused mostly on the present day situation rather than any realistic future scenarios.

This report is designed to answer several important questions about the role of hydrology, hydrological data and hydrological specialists in EWR determinations associated with non-perennial systems. These are listed below, in no specific order of importance:

- Are existing data sufficient to identify the characteristics of a specific non-perennial system?
- Are existing hydrological models in general use within South Africa appropriate for providing the required information for non-perennial system EWRs?
- If not, can relatively straightforward modifications be made that will ensure that they are appropriate?
- Are the available data sufficient to apply these models in practice for a range of different non-perennial systems?
- What are the uncertainties associated with the application of the models and are these likely to be too high for the outputs to be used in conjunction with other physical driver information (water quality, geomorphology) or ecological response information?
- Do hydrological modellers require any specific skills or training to be able to apply models successfully in non-perennial systems?
- Are there specific issues associated with non-perennial hydrological studies that practitioners need to be aware of?
- Is it realistic to expect that surface and ground water hydrological analyses can be properly integrated in non-perennial EWR studies?

All of these questions are associated with the hydrological component of EWR studies, which has been the focus of this project. However, it is important to recognize that these need to be seen in the light of the methods that will be developed and will necessarily include the other specializations (water quality, geomorphology, fish, invertebrates and riparian vegetation) involved in a typical EWR assessment. It is also important to recognize that all the outputs need to be applicable in terms of the ecological Reserve legislation that exists for South Africa.

1.1 Definition of and distinction between non-perennial systems

There are many different types of non-perennial river systems, from seasonal regimes which would be expected to experience more-or-less continuous flow during a well defined wet season to truly ephemeral regimes with highly variable frequencies of connected channel flow. The focus of this report is on ephemeral, rather than seasonal rivers, which may be considered to be transitional flow regimes.

Ephemeral rivers are generally considered to be characterised by the erratic occurrence of fully connected channel flow and the lack of baseflow. However, under certain weather conditions (such as extended wet periods) many ephemeral rivers are known to experience prolonged low flows, derived from various sources. During periods of no connected channel flow, the characteristics of in-channel pool storage could be used to distinguish between different ephemeral systems. Some ephemeral systems have more-or-less permanent pools maintained by either sub-surface inflow from the surrounding ground water, sub-surface water movement within the channel itself, channel flows that are sufficiently frequent to maintain storage despite evaporation losses or other hydrological process mechanisms. As pools represent potential refugia for biota during no-flow periods, these are expected to be ecologically important. However, understanding their quantity and quality dynamics will also require that the mechanisms of replenishment be understood as well. This is a critical issue as far as hydrological modelling of ephemeral rivers is concerned.

It is also important to recognise that river systems may not be ephemeral throughout the basin. Even if they are, the type and characteristics may vary within a single river basin depending upon the topographic, geological, vegetation and climate variations that occur within the system. It is therefore very important to consider the basin as a whole and identify the variations that are likely to occur before setting up a hydrological model. While this is an advisable approach in all systems, including perennial rivers, it may be more critical in ephemeral river basins.

2. HYDROLOGICAL CHARACTERISTICS OF EPHEMERAL RIVERS

Rossouw et al. (2005) identified three categories of non-perennial rivers based on the percentage of time that flow occurs and made some distinction between those rivers where seasonally occurring flow is reasonably reliable. Hughes (2005), however, emphasizes that perennial, seasonal and ephemeral river regimes are merely points on a continuum and it is not always straightforward to assign rivers to simple categories and the basis of their flow regime characteristics. A more useful approach is represented by Figure 1 in the Rossouw et al. (2005, page 6) report that illustrates the continuum concept based on:

- The degree of abiotic control on ecological communities.
- The connectivity of surface aquatic habitats.
- The degree of flow predictability
- The degree of flow variability.
- The degree of natural disturbance in the regime.

2.1 Natural characteristics

Ephemeral systems are characterized by high degrees of variability and natural disturbance and low degrees of surface connectivity and flow predictability. This is largely caused by the typically high levels of temporal and spatial variability in rainfall, the main hydrological forcing variable, coupled with high levels of evaporative demand.

From a temporal variability point of view, intermittent rainfall and high evaporation rates suggest that soil profiles are rarely saturated for extended periods of time and consequently that subsurface moisture movement (lateral and vertical) occurs predominantly in macropores during rainfall events. The result of this is that sustained baseflow in river channels does not occur except after infrequent prolonged rainfall events. Sparse vegetation and high intensity rainfall also promote soil surface sealing in some semi-arid and arid areas which leads to a reduction in infiltration rates and less opportunity for sub-surface moisture storage.

Spatial variations in rainfall, as well as surface conditions (soil and vegetation) lead to high spatial variability in the incidence of runoff generation. This means that even at relatively small scales there are large spatial discontinuities in runoff. In-channel processes, related to transmission losses to pool storage and the material in the channel bed and banks, further contribute to runoff discontinuities at almost all spatial scales.

The following points summarise some of the hydrological processes that have been observed during detailed studies of semi-arid catchments in the Eastern Cape during various research projects undertaken over the last 3 decades (Moolman, 1985; Hughes and Moolman, 1987; Hughes and Sami, 1992; Hughes, Sami and Murdoch, 1993):

- Very rare occurrence of lateral soil water movement on hill slopes due to infrequent levels of soil saturation.
- Surface runoff on upper slopes (thin soils, sparse vegetation) observed during storm rainfall events, but re-infiltration further down slope (deeper soils, better vegetation cover).
- Substantial transmission losses into coarse alluvium deposits, notable at points where the longitudinal channel slope decreases.

- Substantial transmission losses into fractured rock tributary channel beds, especially where structural controls limit downstream flow and cause shallow ponding.
- Sustained pool storage in some channels during extended periods of no channel flow leading to the conclusion that the storage is sustained by effluent groundwater.
- Extended periods of baseflow after long duration rainfall events, despite the fact that soils are dry and the water table is well below the channel bed. This suggests deep (within the fractured unsaturated zone) interflow processes, a conclusion supported by the fact that this seems to occur predominantly in areas of relatively steep topography (i.e. promoting a significant lateral component of interflow).
- Relatively complex spatial and temporal variations in natural water quality that are partially due to past sequences of wet and dry periods and the concentration of salts within near-channel environments.

While there are expected to be certain characteristics common to most semi-arid catchments in similar regions of South Africa, all will have specific characteristics that depend on the climate, geology, topography, soils and vegetation, combined with highly interdependent impacts. One of the most important components of any hydrological study of semi-arid regions is therefore the development of a conceptual idea of the main processes that occur within the specific catchment. This may not always be a straightforward process, given the frequent lack of available information.

2.2 Anthropogenic modifications

Hughes (2005) emphasized the need to account for modifications to natural regimes in semi-arid catchments and identified some of the issues that might be of relevance to ecological impacts. These may include:

- Interbasin transfers and reservoir releases for downstream users converting ephemeral rivers into perennial rivers.
- Farm dams storing tributary flow contributions and exacerbating the natural spatial and temporal discontinuity of channel flow.
- Weirs on main channels creating additional in-channel storage and increasing the amount of upstream runoff needed to generate continuity of flow within the channel system.
- Groundwater abstractions from near channel environments reducing the inflow to channel pools, or promoting channel transmission losses through induced recharge.

2.3 Alluvial river systems

The majority of sections 2.1 and 2.2 refer to situations where the whole catchment is part of a semi-arid system. However, there are other situations where the headwaters of a relatively large river basin are perennial, or at least seasonally flowing, while downstream the main river passes through a semi-arid region with ephemeral inflows. Many of these rivers have substantial alluvial aquifers (Boroto and Görgens, 2003), which play a major role in determining downstream patterns of flow, especially at the start of the wet season. The dynamics of water exchange between the alluvial material and the channel will be the dominant local process and may partly determine the duration of surface flow over the wet season.

2.4 Ecologically important processes

Previous work has already identified many of the ecologically important processes, (see Rossouw et al., 2005 and the references included therein) some of which have already been alluded to in the previous section.

2.4.1 Pool storage dynamics

There seems to be little doubt that one of the most critical hydrological issues that have the potential to impact on ecological functioning in ephemeral river systems is the dynamics of pool storage. Increments to pool storage may occur from effluent groundwater (channel bed below the water table), intermittent interflow in unsaturated zone fractures or intermittent channel flow. In any one system one or more of these processes may be represented in different reaches of the total channel system. It would appear that it is also possible for adjacent pools in the same reach to be supplied by different processes. This is especially the case in areas that are dominated by interflow processes in fractured unsaturated zones and where the density of fractures can be highly variable and dependent upon local geological structure.

Losses from pool storage may occur as direct evaporation from the pool surface, seepage into the banks of the pool to replenish soil moisture lost through riparian vegetation evapotranspiration or through leakage through the pool bed as recharge to groundwater.

The combination of these various processes will determine the amount of water stored in pools, their depth and areal extent, as well as their water quality dynamics (temperature, solute content and turbidity). All of these are assumed to have ecological significance. These processes will also determine the frequency with which pools are connected within a specific river reach by flowing water and therefore the opportunity for organisms to recolonise parts of the channel system.

In large ephemeral river systems developed on highly transmissive alluvial material (an example would be the Limpopo River) and where upstream flows are generated in wetter regions, one of the major issues will be the timing of connected channel flow at the start of the wet season. This will clearly depend upon the level of storage in the alluvial aquifer and therefore how much of the upstream flow can be absorbed before channel flow downstream is initiated. This represents a similar problem to understanding the dynamics of pool storage in smaller ephemeral systems. However, the approach to modelling may be different.

2.4.2 Flow event routing dynamics

In the context of semi-arid catchments, flow events are considered to occur when the main channel system is connected and includes a wide range of event magnitudes from small events through to large floods. As already noted, the frequency of the small events is expected to have ecological significance through the role that they play in establishing connectivity between otherwise isolated pools and replenishing pool storage. The larger events will have further significance from a geomorphological point of view and their impacts on channel size and shape, as well as sediment dynamics.

The extent to which runoff generated on the catchment surface will survive as channel flow will depend upon the magnitude of the generated runoff, its spatial extent, as well as the antecedent storage conditions within the channel network. The rate at which the generated flow will move through the channel network and the degree of attenuation will similarly depend on the antecedent storage conditions, but also on the hydraulic geometry of the channel and the in-channel vegetation conditions.

2.5 Processes specific to the Seekoei River

Without specific site investigations over an extended period of time it will always be difficult to infer hydrological processes within a specific catchment. However, knowledge of the climate, topography, geology, soils, vegetation and drainage pattern can provide a great deal of information about possible active processes.

The area experiences summer rainfall with a mean annual total of some 300 to 340 mm with a monthly coefficient of variation of about 1.1, suggesting quite high variations. Mean annual potential evaporation is greater than 1900 mm. The topography is quite flat having a mean catchment slope of 1 to 4%. The video of the river indicates that the near channel environments are typically very low gradient and steeper valley side slopes are mostly experienced a long way from the river close to the catchment boundary. However, there is one exception to this general rule and that occurs in the lower part of the catchment (within quaternary catchment D32J – Figure 1). Figure 2 shows two Google Earth images of the catchment, the left hand side being the area within D32J, while the right hand side illustrates the characteristics of the area further upstream which is more representative of the catchment as a whole. The left hand image of Figure 2 clearly shows steeper topography where the river passes through a 'gorge' related to the occurrence of a dolerite ridge. This area is expected to have very different hydrological response characteristics to the rest of the catchment.

The geology consists of interbedded sandstones, shales and mudstones of the Beaufort Group with relatively frequent dolerite intrusions, some of which can be highly weathered. It appears that shallow colluvial (weathered material) aquifers can be found below the river channel in some areas, while in others the channel is clearly developed on solid rock. Soils are mostly stony and thin, although they can be deep close to the river channels. Vegetation cover is very sparse except in some channel margins where presumably there is improved access to sub-surface water. Drainage densities are low, largely due to the low gradients and this implies that surface runoff processes will be dominated by surface sheet and shallow gulley flow during heavy rainfall.

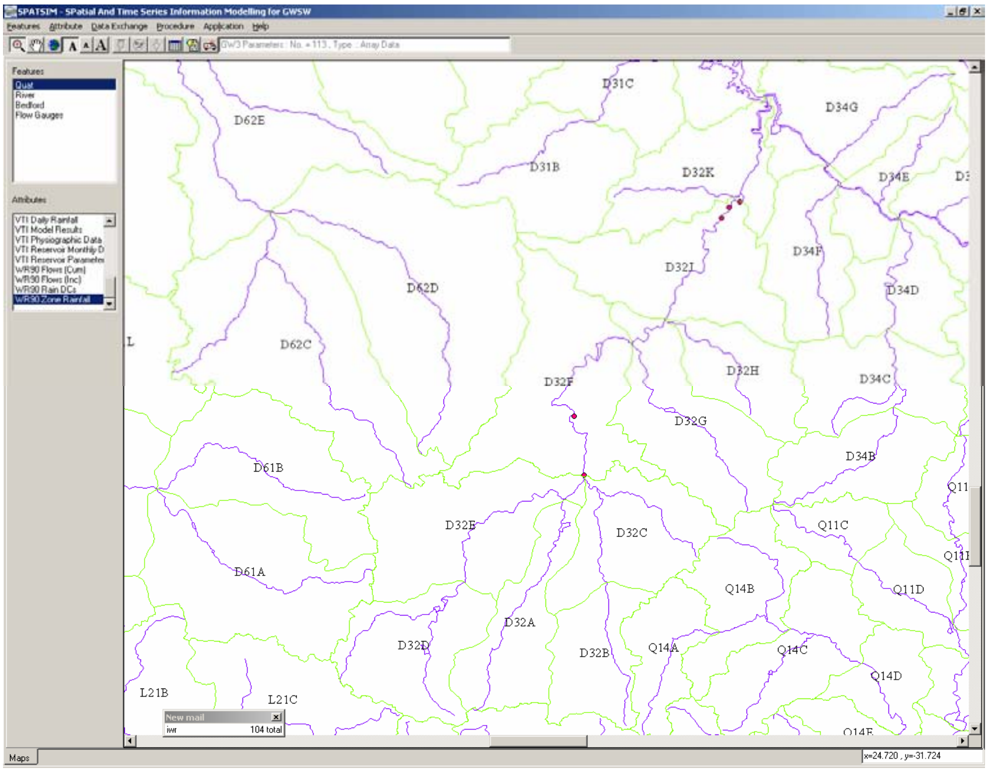

Figure 1 Location and layout of the 10 quaternary catchments (D32A to D32K) of the Seekoei River.

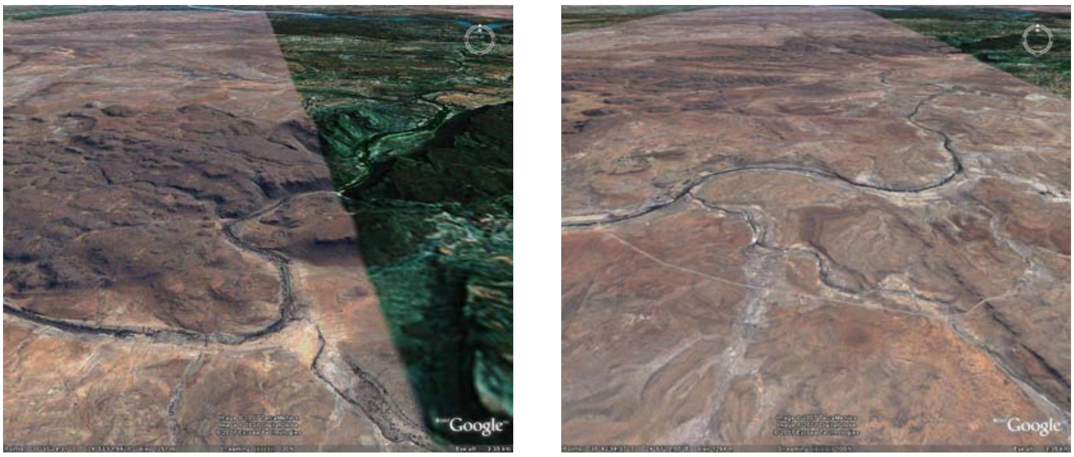

Figure 2 Google Earth images (altitude of 3.4 km) of the Seekoei River at the start of the gorge (left) and further upstream in the flatter part of the catchment (right).

The only gauging station (D3H015) within the catchment is at the outlet of quaternary catchment D32J and below the gorge area. The gauged records suggest that flow is quite frequent, even under present day conditions which are affected by a large number of in-channel weirs and dams. The records also indicate that extended periods of baseflow occur after wet periods. However, field visits indicated that these flow characteristics do not extend very far upstream of the gauging station and that while there is flow in the channels of the lower part of the catchment, the upstream channels do not experience flow. This observation is consistent with the low topographic gradients in the upper parts of the catchment.

A close inspection of the 1:50 000 topographic maps suggests that the high topography area occupies some 20-30% of the total area (1112.5 km^2) of D32J and is drained by 12 major tributary streams. The maximum topography within 10 km either side of the channel is up to 200 m within the gorge, while it is typically less than 20 m in other parts of the catchment. Several of the tributaries that were visited during field trips were flowing and it is apparent that the source of this flow is spring flow that originates a relatively short distance from their confluence with the main channel. In some cases this spring flow appeared to come from a very concentrated source, while in other cases it originated in a more distributed manner. While geological contact zones could be identified at the spring sources they were not very clear. The current DWAF flow records at D3H015 suggest that a flow event with a peak of about 2 $m^3 s^{-1}$ occurred at the end of August 2006 such that the flow experienced during the field visit would have been the recession after that event.

Figure 3 illustrates the conceptual concepts of subsurface flow contributions to the channel within the gorge area developed by the geohydrological investigation team of the University of the Free State from the initial site visits and test boreholes. The movement of water to the channel is considered to occur within the perched water table associated with weathered dolerite, as well as within the hardrock aquifer. The colluvium beneath the channel bed is also considered to play a role in the sub-surface movement of water in the direction of the channel. Contributions to the channel are expected to be highly localized (in springs) due to structural differences and the occurrence of more transmissive fracture zones and weathered material. These contributions are expected to contribute to pool storage, support riparian vegetation and be lost to evaporation. The exact water balance in any specific part of the channel system will largely depend on the balance between the seepage contributions and the evaporative losses.

The low surface and groundwater gradients in the majority of the catchment suggest that sub-surface contributions to channel flow or pool storage will be relatively small in all the other quaternary catchments. However, observations from boreholes close to the river channel suggest that the regional groundwater level is very close to the bed of the river and that exchanges do take place between the groundwater and pools. The low gradients suggest that these exchanges will be very slow.

With respect to anthropogenic affects, there are many farm dams and main channel weirs within these catchments. The river channel video suggests that some of the main channel weirs are little more than low walls at the end of natural pools (which are unlikely to increase the channel pool storage by a large amount), although there are also several quite substantial earth dams that will increase in-channel storage and affect downstream runoff during small to moderate sized runoff events. It is very difficult to speculate on the impacts of the many farm dams that are remote from the channel system in an area with such low gradient topography.

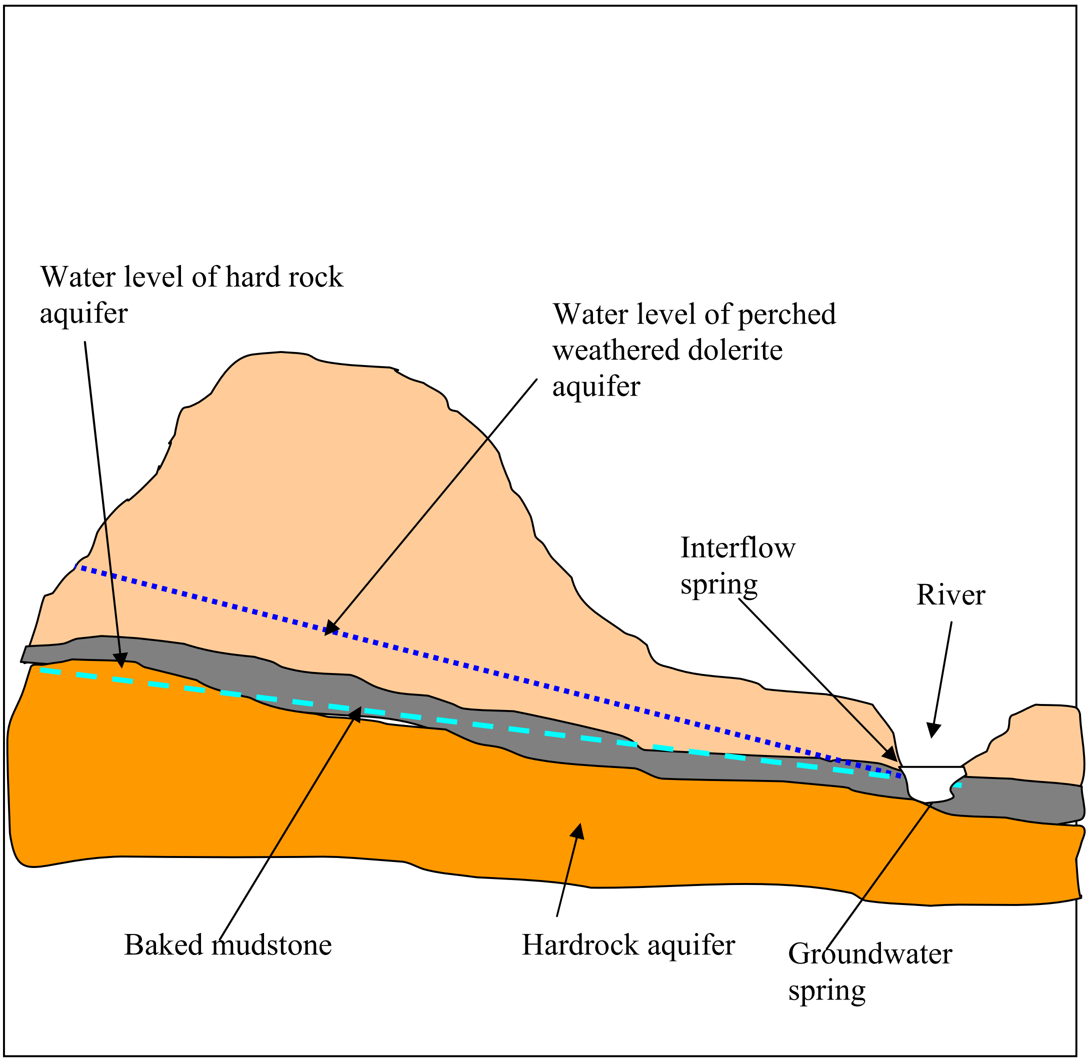

Figure 3 Conceptual model for interflow and groundwater springs (from the initial geohydrology report of the University of the Free State project team).

One issue that is worth noting is that if the conceptual model represented by Figure 3 is realistic then channel losses to groundwater are likely to be a negligible component of the overall water balance. This is because the model assumes that the water table is close to the channel bed. There may be parts of the channel system that are losing water during surface runoff events, while other parts of the channel system are gaining water through groundwater discharge. However, on balance the losses are expected to be small.

Table 1 presents a summary of the estimated natural pool characteristics in the different quaternary sub-catchments, as well as the extent to which the storage has been increased with the development of weirs and dams. The approach adopted for the natural pools assumed that 40% of the total channel length would be 'pooled' at the point when channel flow starts and that the maximum effective surface area (allowing for the effects of seepage into the non-pool areas of the channel) would occupy some 60% of the total channel. The channels were assumed to be 20 m wide on average and between 1 and 2.5 m deep, depending on the upstream catchment area (and therefore the channel size). It was further assumed that the surface area for evaporation loss purposes would remain quite large even as the pool dried out (allowing for evaporation from a larger area than simply the visibly wetted area).

Table 1 Reservoir (natural and present day) parameters for the 10 sub-catchments

Catchment	Channel length (km)	Max. pool volume (m^3 *10^6)		Abstractions (P.Day - m^3 *10^6)
		Natural	Present Day	
D32A	53	0.76	5.5+0.76 = 6.26	1.65
D32B	33	0.30	0.5+0.3 = 0.80	0.15
D32C	22	0.32	0.4+0.32 = 0.72	0.12
D32D	31	0.28	18.0+0.28 = 18.28	5.40
D32E	45	0.65	0.6+0.65 = 1.25	0.18
D32F	49	0.98	5.5+0.98 = 6.48	1.65
D32G	52	0.75	2.5+0.75 = 3.25	0.75
D32H	31	0.28	0.1+0.28 = 0.38	0.03
D32J	34	0.75	0.4+0.75 = 1.15	0.12
D32K	22	0.66	0.5+0.66 = 1.16	0.15

Note: The natural volume estimates are based on the discussion in Deliverable 2 of this project, while the additional volumes for the present day scenario are based on information contained within WR90. The abstraction estimates are very approximate and largely based on the volume of storage.

2.6 Water quality and flow relationships

It is possible that the relationships between water quality and flow could provide some further insight into the runoff processes that are dominating within the Seekoei River catchment. There are water quality and flow data at D3H015 (outlet of D32J) for the period of about 1980 to the present day, while Table 2 provides a summary of water quality data collected by the main project team. While there are a number of apparent gaps in the water quality data, some interesting observations can be made using the TDS data:

- The initial groundwater investigation report suggests that the groundwater spring flow that sustains pools during periods of zero flow has a TDS of approximately 400 mg l^{-1}.
- The observed runoff at D3H015 has TDS values ranging from less than 100 to over 1500 mg l^{-1}.
- The highest TDS values occur after prolonged periods of baseflow or at the start of flow events that have very low flows.

- Several assumptions can be made about flow processes based on the previous bullet point.
  - If the start of an event has very low flows, most of the runoff at D3H015 will be displaced pool water that has very high TDS values due to the concentrating effects of evaporation.
  - If the start of an event has quite high flows the TDS will be more a reflection of surface runoff water quality, which appears to have low (±100 mg l^{-1}) TDS values.
  - The quite rapid increases in TDS during the baseflow recession period suggest an additional mechanism apart from the spring flow and surface runoff already identified. This may be related to the storage of salts within the pools and adjacent soils which is incremented during pool drying and gradually released after pools have been re-filled.
- Relatively simple mass balance modelling of the system using assumed pool storage volumes, evaporation rates and TDS values for different water sources could provide a possible method for simulating the general trends of pool water quality under different flow conditions.

Table 2 Summary of observed TDS (mg l^{-1}) data

Site	Boreholes	Pools			
	July 2006	March 2006	May 2006	June 2006	August 2006
1	1064	968	1490	2582	2224
2	644	205	251	277	347
3	653	451	391	635	767
4	626	369	365	614	719
Spring 1	483	455			
Spring 2	459	458			

3. CONTINUOUS SIMULATION MODELS OF POOL DYNAMICS AND STREAMFLOW

3.1 Modelling issues

Many hydrological investigations are faced with a common problem of a lack of observed information and rely heavily on simulations using hydrological models. In perennial systems, modelling is frequently more straightforward as the natural processes that contribute to sustained baseflow 'damp' or smooth both spatial and temporal variability in the forcing rainfall. Not only is this smoothing process generally absent in semi-arid catchments, but the forcing rainfall is often more spatially and temporally variable, as well as being poorly defined by the available data in most circumstances.

The spatial variability of real hydrological responses should never be ignored in any system, including perennial catchments. However, given the discontinuous nature of surface flow in semi-arid systems, it is possible that defining the spatial heterogeneity may be more important from an ecological response point of view. Unfortunately, most of the models that are traditionally applied in South Africa operate at spatial scales that are unlikely to provide the required information, or do not include representations of the relevant processes. Calibration and verification/validation exercises necessarily focus on the information available at the outlet of moderately large catchments (> about 100 km^2). While the flow at such points may be frequently zero, there may be in-channel processes occurring upstream that are of critical ecological importance. Even more unfortunately, even if the modelling tools were available, it is unlikely that the data required to establish truly representative parameter values would be available.

Perhaps the critical issue is that while upstream developments may have a relatively small impact on runoff at the quaternary catchment scale, they may have a much larger impact on ecologically important sub-quaternary scale processes. The basis of this argument is that a large proportion of the runoff generated in many semi-arid catchments occurs during relatively few events, which are unlikely to be impacted by farm dams, pool abstractions and groundwater pumping. However, these same activities could have substantial impacts on pool storage, the frequency of pool water replenishment and the frequency with which pools are connected by surface channel flow. If the natural sub-quaternary processes cannot be simulated by a hydrological model, it is clear that neither can the impacts of upstream development activities.

While the dynamics of flow events may not be captured by the temporal scales used in many continuous hydrological models, it has to be recognized that the data available to establish models at finer spatial and temporal scales are generally not available. There are therefore two possible approaches (not necessarily mutually exclusive):

- Use some of the existing, standard modelling approaches and attempt to infer some of the finer scale processes from the information generated by the model. This may involve a more detailed analysis of the internal state (process) variables of the model, rather than simply the volume of runoff at the catchment outlet, than is normally undertaken.
- Use more detailed modelling approaches and extrapolate from limited observed data to provide the necessary inputs.

Both of these approaches will be subject to uncertainty which will always remain largely unknown without an extensive programme of additional data collection.

3.2 Available continuous models

There are two frequently used continuous hydrological models in South Africa; various versions of the Pitman monthly model (Pitman 1973; Hughes, 2004) and the daily ACRU model (Schulze, 1994). A further possibility is the daily VTI model developed and used by the IWR (Hughes and Sami, 1994).

While the daily ACRU model has many potential advantages in terms of spatial and temporal scale of modelling and the allowance for the variation of soil parameters at sub-modelling unit scales, there appear to very few reported examples of its use in semi-arid catchments and the approach to surface-groundwater interactions are not considered appropriate for the problems that need to be addressed for Reserve determinations in ephemeral rivers.

Hughes (2004) reported on the addition of more explicit surface-groundwater interaction components into the original Pitman model and these have been subsequently extended (Hughes and Parsons, 2005). The original model has been used extensively in semi-arid catchments and there are existing guidelines for quantifying parameter values. However, the spatial and temporal scales of application are serious constraints. While the new model components address some of the ephemeral river process issues already referred to (unsaturated zone interflow, groundwater discharge to channels, riparian zone evaporation loss, channel transmission losses, etc.), it does so at scales that are not very appropriate for this specific application. Whether or not the internal state variables of the model can be used to infer the dynamics of pool storage and degree of surface water connectivity remains to be assessed. Other on-going studies identified that attention to the simplified channel transmission loss routine (particularly at low flows) was required. This has now been attended to, but the revised approach (which generates higher losses at low flows) requires further testing.

The daily VTI model includes functions that can be used to distribute daily rainfall totals into shorter intervals based on a ‘knowledge’ of the seasonal rainfall intensity and duration characteristics. It was developed to account for semi-arid catchment hydrology processes and has relatively explicit groundwater and unsaturated zone flow components. It is, however, a model that is difficult to apply and requires quite a lot of user experience to obtain satisfactory calibrations. As with other daily models it is also quite dependent upon the quality of the available daily rainfall data. The VTI model has similar surface-groundwater interaction components as the revised Pitman model and can allow for small increments to channel flow to be ‘lost’ in evaporation from pool storage. This implies that while ‘baseflow’ can be generated by the model, it does not generate sub-catchment outflow, but is lost to evaporation.

Both the revised Pitman and VTI models have the potential to be able to simulate the type of processes that appear to be dominating the hydrology of the Seekoei River at the scale of quaternary catchments. They also both have functions and parameters that allow the effects of small farm dams (the dominant development effect in the Seekoei) to be simulated. The question (and challenge) is whether the internal model state variables can be used to infer time series variations of pool storage state and connectivity and whether or not these will be sensitive to changes in the model parameters that are used to simulate the effects of development (specifically the existence of farm dams and abstractions from these).

3.3 Conceptualization of flow processes

A prerequisite for any modelling exercise should be the conceptualization of the system being modelled to ensure (as far as possible) that the model results are consistent with the assumed physical hydrological processes active within the catchment. This section is therefore designed to suggest a conceptual picture of the hydrological processes that occur within the Seekoei catchment during a major rainfall event, as well as through the recession period and into a period of dry weather. The assumption is that the rainfall event occurs after a prolonged dry period.

During the rainfall event it is assumed that surface runoff will be generated predominantly from the near-channel margins, where a ‘channel’ includes the main river channel as well as many tributary channels. The assumption that the runoff will be generated mostly from the near channel margins is based on the generally very low topography of the catchment surface and that infiltration excess surface water will largely exist as ponds over much of the catchment. The exception will be where there the topography is locally steeper (such as in the lower parts of D32J, as well as in the headwaters of the total catchment). Some of this runoff is likely to be lost to transmission losses where there are colluvial and alluvial deposits (with high infiltration rates) under and adjacent to the channel. These losses are expected to occur during the early part of the event. A part of the initial runoff will also be use to fill up both natural pools and man-made storage (weirs and dams).

The rainfall event will also generate input to the unsaturated zone, particularly in those areas where the surface soil conditions are thin and stoney (such as the dolerite ridges). This input contributes to both ground water recharge as well as additions to either perched water tables and/or water stored in the unsaturated zone fractures. The latter are assumed to be the source of the relatively rapidly responding spring water that is evident in certain parts of the catchment (mainly those with steep topography). The ground water recharge process will be much slower and any changes in ground water levels are expected to be small and substantially delayed relative to both the surface runoff response and the spring flow.

The addition of water to the unsaturated zone and the consequent increase in spring flow is assumed to account for the relatively long recessions experienced at the D3H015 gauging station. This is also related to the fact that the source of the spring water appears to be dominantly in the lower part of the catchment. These long recessions and the maintenance of a ‘baseflow’ component is not thought to be representative of the catchment as a whole, but is assumed to occur only in the lower parts of the catchment. It is possible that small spring flow contributions exist in the middle and upper parts of the catchment, but these may be too small to overcome evaporation from the channel pools and are not expected to result in prolonged low flows after major rainfall events. It is suspected (but not confirmed) that this process may be the cause of the low salinity at site 2, despite the fact that the TDS values in this pool are below the TDS of the spring water in the lower parts of the catchment (Table 2).

As the catchment dries out it is assumed that the combined discharge from the springs in the lower part of the catchment will decrease (either due to lower discharge from individual springs, or because fewer springs remain actively discharging), such that the inflows to the channel are lower than the evaporative losses. The result will be a cessation of flow at the gauging station. The dynamics of the pool storage will then depend upon the balance between spring discharge and pool evaporation, which will clearly depend upon the season and the evaporative demand. In the upper parts of the catchment, where there is little evidence of spring flow, it is possible that small contributions to pools are made through connections with the ground water, but these are expected to be relatively small due to the low hydraulic gradients. Most of the pools in the upper part of the catchment are therefore expected to dry out relatively rapidly depending on the evaporative demand. While there is certainly evidence from the October 2005 video (after approximately 1 year of no flow at the gauging station) that there are fewer pools in the upstream areas, there are also some pools that have been maintained over a long dry period. The implication is that these are being partially sustained by some source of sub-surface inflow. Without additional monitoring sites it is difficult to speculate about the source of that water.

3.4 Implications for parameter quantification using the Pitman model

The revised Pitman model generates contributions to the channel in three possible ways:

- The first is through the surface runoff function controlled by the parameters ZMIN and ZMAX and the total monthly rainfall depth. It is assumed that this process is active during high rainfall months and generates the vast majority of the runoff in large events.
- The second is through the so-called 'soil moisture' function and is controlled by the level of the main moisture store (S mm), the parameter representing the maximum value of the store (ST mm), the parameter representing the runoff from 'soil moisture' when S=ST (FT mm month^{-1}) and the power of the runoff-storage relationship (POW). Recent revisions to the conceptual interpretation of this function suggest that this runoff component represents runoff from the complete unsaturated zone. In the case of the Seekoei, this will be dominated by the spring flow referred to in the previous section, rather than from the soil profile. This function is only expected to be applicable (i.e. FT > 0) in the quaternary catchment D32J. The topography in the other sub-catchments is too flat to expect anything other than very minor contributions from this process.
- The third process is through ground water contributions to the channel (via recharge controlled by parameters GW and GPOW). This was the process that was used in the first version of the setup for the Seekoei catchment (see Deliverable 2) to generate all of the 'baseflow' contributions. It is now thought that these will be relatively minor in all catchments due to the very low hydraulic gradients in the vicinity of the channel. However, this process may still be significant in maintaining some pools in the upper parts of the catchment.

The main objectives of the setup of the model were to simulate the main 'baseflow' contribution within D32J using the 'interflow' function (parameters ST, FT, POW). However, a problem arises immediately. The 'interflow' function depends upon the storage level S which is decreased through evaporation. In the Seekoei situation the majority of the storage and the runoff is considered to derive from relatively deep (compared to the surface soil horizons) unsaturated interflow, which would not be affected by evaporation to the same degree. In fact the majority of the evaporative influence would be at the points where the interflow re-emerges. The use of the normal evaporative demand simulated in the model will therefore reduce the storage levels too rapidly. To account for this the annual evaporative demand can be reduced (from 1900 mm to about 800 mm), but this change has to compensated for in other parts of the model. For example, the annual evaporative demand also controls evaporation from the pools and if the annual value is reduced, the surface area (for any stored volume) must be increased. Similarly, the effect on evaporation of ground water discharge to the channel (from the riparian strip) can be compensated for by increasing the riparian strip factor parameter.

The overall result of using this approach to quantifying model parameter values should be the following:

- Inflow to the pools within all sub-catchments except D32J will be small, except during infrequent surface runoff events and therefore they will experience fewer periods of overflow and generally lower levels of storage. The impacts on the downstream simulations for the present day will be minor, as a great deal of the upstream runoff is not expected to pass the large weir within D32F.
- The majority of the recession flow (after large rainfall events) will be generated in sub-catchment D32J. The calibration of the relevant parameters (ST, FT and POW) will have to reflect the low-flow characteristics of the gauged record in terms of the amount of recession flow and length of time. It is possible that the interflow function will not be able to achieve the objective of generating substantial 'baseflow' immediately after events, as well as a continuous, but small spring flow contribution to the pools even during periods when the main channel is not flowing. The reason for this lies in the shape of the relationship in the model.
- To compensate for the previous limitation, the parameters controlling the ground water contribution to the channel may have to be quantified to generate the background spring flow response. While this will make no difference to the runoff simulations, it will affect the pool storage dynamics and any attempts to simulate the water quality dynamics.

The conclusions reached above about the approaches to quantifying the parameters of the Pitman model apply equally to the VTI model. This is a far more complex model and the details of the approaches to quantifying the parameter values are not provided in this report.

3.5 Application of the Pitman model

There are many sources of uncertainty in trying to set up a distributed model when the only observed data are at the catchment outlet and yet it is assumed that there are large spatial variations in the characteristics of the runoff response. It was therefore necessary to make some assumptions based on the previous sections and use these as a basis for model calibration.

- D32J (Figure 1) is the only sub-catchment in which sustained baseflows are assumed to be generated. These are assumed to be generated largely from spring flow (or discharge from perched aquifers) with relatively minor contributions from the regional ground water body.

- In all other sub-catchments the main inputs of water to the channel will be from short-duration surface runoff during high rainfall events. Only very minor contributions from ground water are assumed.

The model was applied to the present day situation initially, as the observed flow data are assumed to represent such conditions. Table 1 provides information on the ‘reservoir’ parameters that were used in the model, where the reservoirs are assumed to represent a combination of natural pool storage, as well as any developments that have occurred within the main channel. These include small weirs that have effectively increased natural pool storage by a relatively small amount, as well as several larger dam walls (within D32 A, D, F and G).

Figure 4 illustrates the flow duration curve characteristics of the observed and simulated present day flows for sub-catchment D32J for the coincident period (July 1980 to October 1990). It is clear that while the high flow volumes do not correspond very well, the low flow characteristics are satisfactory. The third line on the graph shows the simulated upstream inflows, which are negligible for a large proportion of the time.

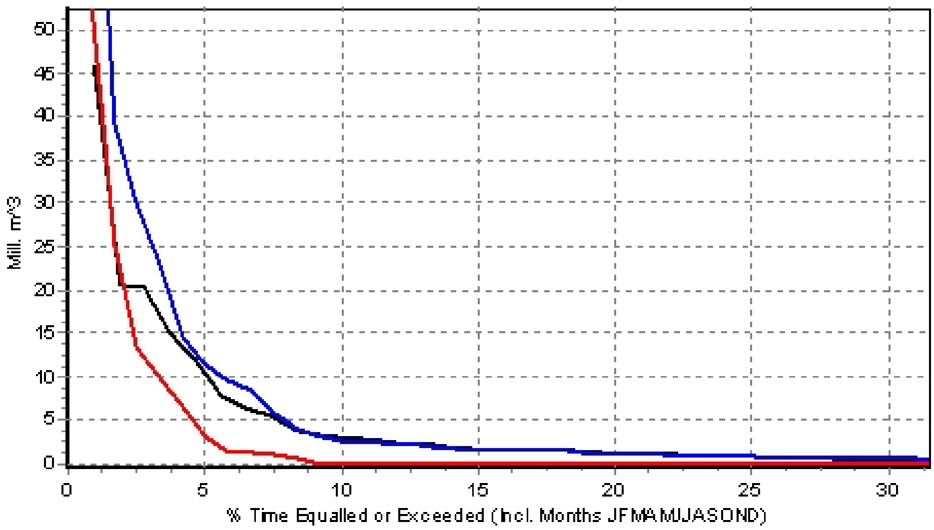

Figure 4 Observed and simulated present day 1-month annual flow duration curves at D32J (Black, middle line at 5% = observed, Blue, top line at 5% = simulated, Red, lower line overall = upstream inflow from other sub-catchments).

Figure 5 illustrates the equivalent flow duration curves for the natural simulations. While the low flows (lower than the flow equalled or exceeded for about 15% of the time) are not affected very much, flows higher than this are substantially greater in the natural simulation compared to the present day situation. Part of this effect is related to the additional storage within D32J itself, while the additional storage in upstream sub-catchments represents the main cause. As very little baseflow is generated by the model in the upstream areas, the natural simulation results are largely caused by small and intermittent surface runoff events that satisfy pool storage deficits and therefore generate overflow to downstream sub-catchments.

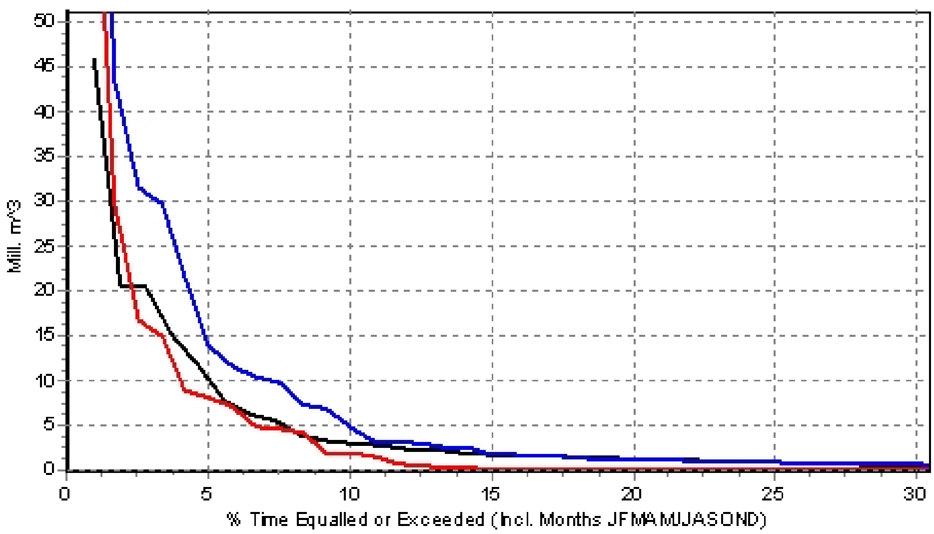

Figure 5 Observed and simulated natural 1-month annual flow duration curves at D32J (Black, middle line at 5% = observed, Blue, top line at 5% = simulated, Red, lower line at 5% = upstream inflow simulated from other sub-catchments).

Figure 6 illustrates the flow duration curve characteristics of the simulated natural downstream flow for 3 upstream sub-catchments (using the total 70 year simulation period). Even as far downstream as sub-catchment D32F, the duration of zero flows has been simulated as approximately 84% (i.e. flow for only 16% of the time). The equivalent value for D32J under both natural and present day conditions is approximately 50% flowing and 50% not flowing, which is reasonably consistent with the observed data. Figure 7 illustrates the impact on downstream flow at the outlet of the quaternary catchment D32E which has substantial upstream storage. Within D32D, which has the highest estimated artificial storage (approximately 18 m^3 *10^6), the model suggests that the frequency of channel flow connectivity has been reduced from some 20 to 25% to less than 2%.

Table 3 illustrates the contributions of the different simulated runoff components for D32A and D32J to the total runoff generated within the sub-catchments. While it is clear that the model is generating more groundwater discharge than might be assumed to occur, it is nevertheless a very small component that has a negligible impact on the downstream hydrology. However, it may have an impact on the water quality simulations as the small simulated groundwater contributions to pool storage are far more frequent than the surface runoff contributions.

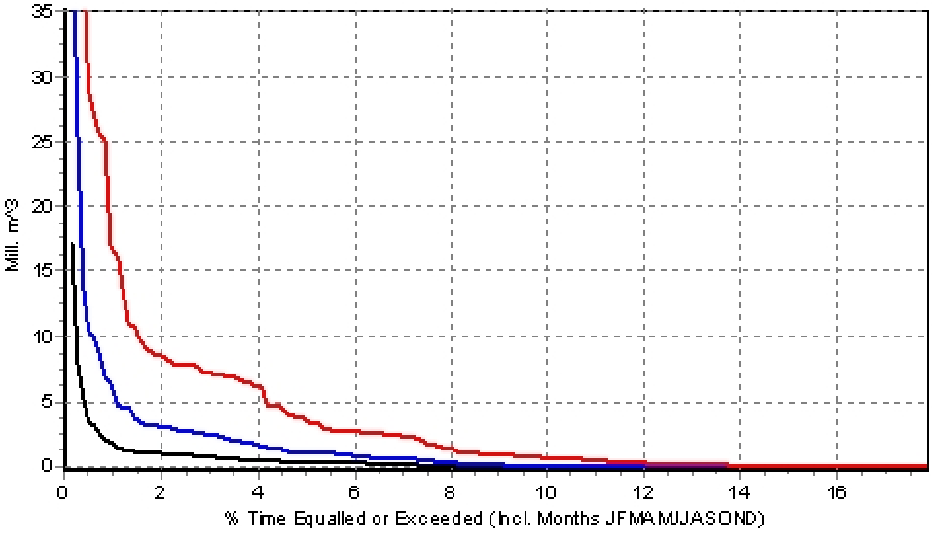

Figure 6 Observed and simulated natural 1-month annual flow duration curves (Black, lower line = D32A, Blue, middle line = D32E, Red, upper line = D32F).

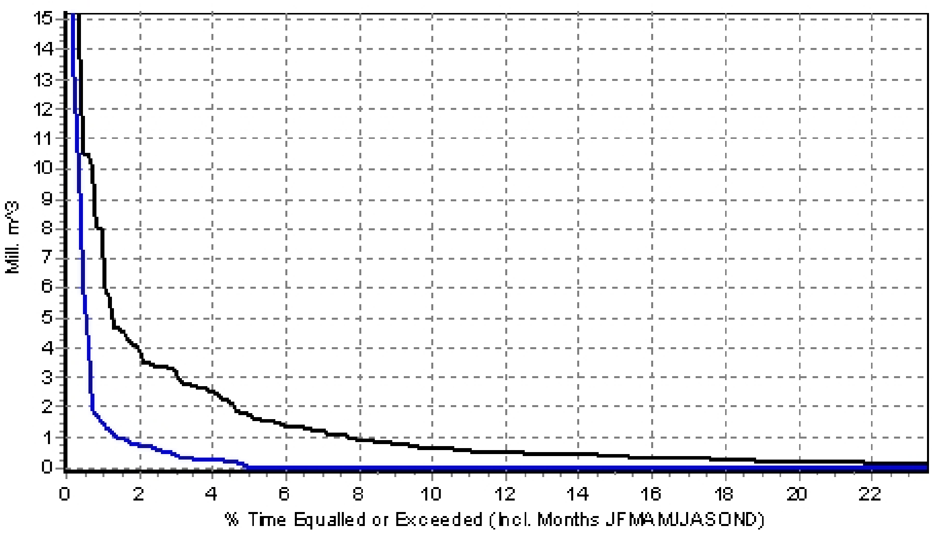

Figure 7 Impacts of in-channel impoundments on the frequency of downstream flow for D32E (Blue, lower line = present day, Black, upper line = Natural)

Table 3 Simulated (Pitman) runoff components (as a % of the total runoff) for D32A and D32J.

Runoff Component	D32A	D32J
Surface Runoff	95.8	79.6
Interflow Runoff	0.0	17.9
Groundwater Discharge	4.2	2.5

In general terms, the revised simulation results are reasonably representative of the conceptual assumptions, while the patterns of simulated monthly runoff volumes for the natural condition at the outlet of D32J are very similar to those provided in the WR90 reports (Midgley et al., 1994). This result has been achieved despite the very significant differences in the model parameters used for this study and those used for the WR90 simulations.

3.5.1 Water balance of the pool storage

The long-term water balance of the simulated pool storage is made up of the following terms:

$$\Delta S = UI - DO + SQ + IQ + GQ - PE - ABS$$

Where
- ΔS is the change in storage between the start and end of the period
- UI is the inflow from upstream
- DO is the outflow to downstream
- SQ, IQ and GQ are the surface, interflow and ground water discharge additions to the pool from the local quaternary catchment
- PE is the evaporation loss from the pool surface
- ABS is the total abstraction volume.

The local runoff additions to storage are expressed as net values, which refer to the additions after any evaporation losses in the channel margins. Table 4 lists the water balance components for the three sub-catchments (D32E, F and J) that contain the identified Reserve sites for both natural and present day conditions. It is clear that the overall impact of the present day level of development (mostly instream dams and weirs) is far greater in the upper parts of the total catchment. The present day downstream outflows expressed as a percentage of the natural downstream outflows are 35%, 56% and 81% for D32E, D32F and D32J respectively. This is largely an inevitable result of the fact that a large part of the downstream flow in D32J is generated within that sub-catchment even under natural conditions (55.6%). The table suggests that a substantial volume of water generated upstream reaches the lower part of the catchment even under present day conditions. However, it should be recognized that this occurs during a relatively short proportion of the total time in the form of periodic short duration flow events.

Table 4 Simulated pool water balance components for three quaternary catchments for natural and present day conditions (all values in $m^3 *10^6$ total flow over the 70 year simulation period).

Component	D32E		D32F		D32J	
	Natural	P.Day	Natural	P.Day	Natural	P.Day
ΔS	-0.195	0.271	-0.415	0.255	0.252	0.382
UI	170.856	35.171	554.988	367.080	933.240	570.192
DO	226.632	79.506	695.352	389.088	1930.320	1558.200
SQ	93.744	93.744	203.868	203.868	855.204	855.204
IQ	0.000	0.000	0.000	0.000	192.276	192.276
GQ	0.292	0.292	2.019	2.019	26.712	26.712
PE	38.455	41.689	65.637	97.944	76.860	77.742
ABS	0.000	8.283	0.000	85.680	0.000	8.060

3.6 Application of the VTI model

There is no doubt that the VTI model is far more difficult to establish and calibrate for a catchment with this type of response. Nevertheless, Figures 8 and 9 illustrate that a reasonable result has been achieved. The patterns of the flow duration curves for the present day situation are similar to the results achieved with the revised Pitman model. Table 5 summarises the simulated runoff components for sub-catchments D32A and D32J. However, these values do not account for the sub-catchment flow routing part of the model which includes a tributary channel storage loss function. This applies to all the low flow components of the runoff and is designed to account for evaporation from small tributary channels during runoff events. In this situation it will mainly affect the more-or-less continuous components such as groundwater discharge and springflow. This means that the proportion of surface runoff contributing to main channel flow will effectively be substantially greater than Table 5 suggests. Figure 10 compares the results of the two models using monthly volumes and includes comparisons of the simulated present day upstream inflows to D32J. It is apparent that the VTI model is simulating a greater amount of, and more frequent, flow from upstream.

Despite the effect described in the previous paragraph, it is thought that further efforts could be made to deal with the possibly excessive groundwater discharge in most of the upstream sub-catchments. However, the balance of runoff components for sub-catchment D32J are considered to be reasonably realistic, with the reservation that some of the low flow inputs from upstream could be over-simulated. The differences between the simulated present day and natural conditions are very similar to those already presented for the Pitman model.

The general conclusion is that the model is representing most of the runoff components in a conceptually realistic manner and that the simulated responses closely match the observed runoff patterns. The main problem with direct comparisons of the daily flows appears to be a relatively consistent delay of approximately 3 days (Figure 9). This may be related to a miss-match between the real patterns of daily rainfall and those recorded at the available gauges.

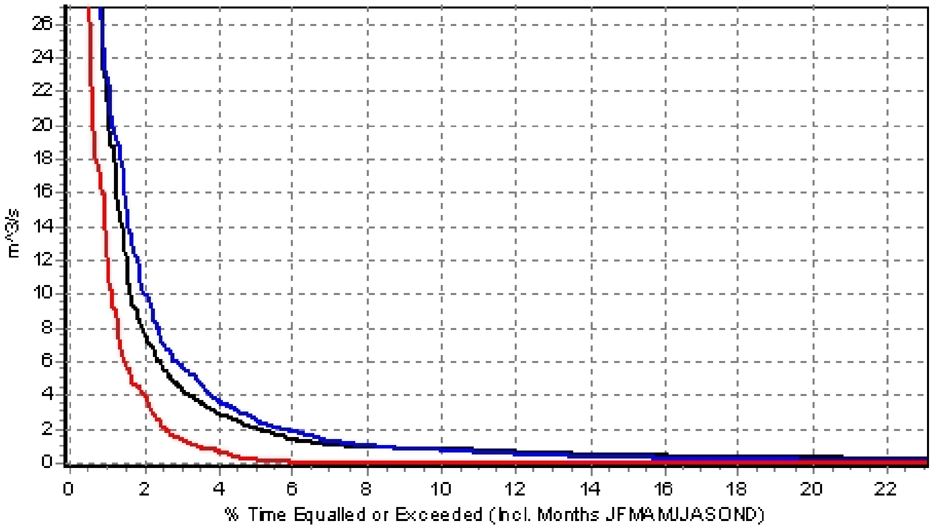

Figure 8 Observed and simulated (VTI model) present day 1-day annual flow duration curves (Black, middle line at 4% = observed, Blue, upper line at 4% = simulated, Red, lower line at 4% = upstream inflow from other sub-catchments).

Table 5 Simulated (VTI model) runoff components (as a % of the total runoff) for D32A and D32J.

Runoff Component	D32A	D32J
Saturated Area Surface Runoff	19.2	18.8
Infiltration Excess Surface Runoff	66.5	28.7
Soil Baseflow	5.2	14.5
Spring flow	0.0	37.2
Groundwater Discharge	9.1	0.8
Total Surface Runoff	85.7	47.5
Total Interflow Runoff	5.2	51.7
Groundwater Discharge	9.1	0.8

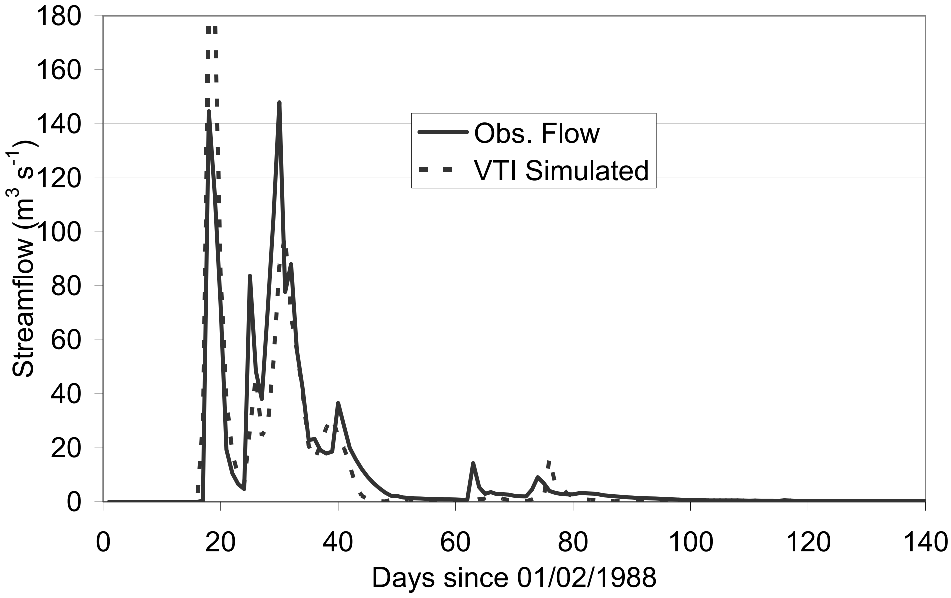

Figure 9 Observed and simulated (VTI model) present day flows D32J.

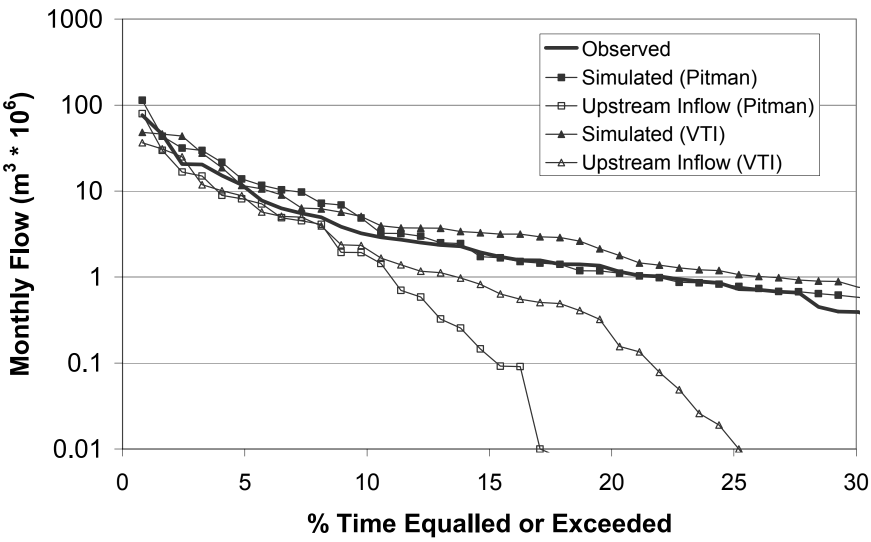

Figure 10 Observed and simulated (VTI model, present day) monthly flow duration curves for D32J over the common period July 1980 to September 1990.

3.7 Observations and uncertainties

There are a number of observations that can be made about the results of applying both of the rainfall-runoff models.

- The WR90 recommended parameters (conventional wisdom) were clearly based on model calibrations against the naturalized observed flow data at gauge D3H015 (outlet of D32J) without any account being taken of variations in runoff generating processes within the sub-catchments D32A to J. This means that while the simulated runoff time series are reasonably consistent with the observed flows, the contributions of all the sub-catchments to the simulated runoff were similar.
- Discussions between the groundwater and surface water hydrologists on the team resulted in broad agreement that the majority of the baseflow response, evident in the observed record, is derived from the relatively steep topography in the middle to lower reaches of D32J. There is also general agreement that this is derived from springs associated with the dolerite ridges within the sub-catchment D32J. Whether this springflow occurs as outflow from a perched aquifer (the hydrogeologists interpretation) or as interflow within the unsaturated zone is largely irrelevant to the way in which the runoff is simulated in the model. A further observation is that groundwater and interflow contributions to streamflow in the headwater sub-catchments, which have very low near-channel topographic gradients, will be quite small.
- The consequence of the conceptual interpretation of the source of runoff, given above, is that a large proportion of the total runoff at the gauging station will be derived from a very small part of the total catchment close to the gauging site. This will therefore be unaffected by the development of weirs and dams in the upper sub-catchments.
- A further consequence is that the most appropriate model parameters to use will be very different for the D32J sub-catchment compared to the others. However, this means that it is very difficult to establish representative parameters for the upstream areas (there are no clear signals to use in the parameter calibration process). The importance of quantifying the model parameters for the upstream areas therefore lies not with respect to the volumes of downstream runoff that they generate, but with the water balance of the pools within these areas.
- The scale of modelling that has been used is much larger (quaternary scale, with 20 to 50 km of main channel length) than the scale of the field investigations (a single pool). This issue should always be taken into consideration when comparing the model results with field observations, both in terms of water quantity (pool storage dynamics), as well as water quality (see later sections of this report). This will always be a problem because, even if a more detailed model is created, there is not enough available information to calibrate the model at the small scale or to assess the results.
- The simulated water quantity dynamics (including flow and pool storage) for the lower part of the catchment appear to be reasonable and are largely based on conceptually acceptable principles. While this is an encouraging result, it tends to overshadow the uncertainties that still exist in the upper catchment areas.
- For the upper areas it may be important to improve the understanding of groundwater – pool water interactions through longer term monitoring.

The overall conclusion from a hydrological modelling point of view is that the development of an improved conceptual understanding of the runoff generation processes has resulted in a more robust and realistic model of the catchment hydrology. This has been achieved with a limited amount of field monitoring, but even so, more monitoring than might be practical in a typical ecological Reserve determination. While the results of monitoring the groundwater and spring flow processes has made an important contribution to the conceptual understanding, experienced judgement based on a very limited number of field visits has probably made a larger contribution. This suggests that in other semi-arid catchments a relatively detailed qualitative conceptualization of the processes of water movement, both above and below ground, could make a substantial contribution to the way in which a model may be set up. The project has emphasized the need for expert judgement from more than a single hydrological discipline and the benefits of sharing the experiences of both surface and groundwater hydrologists in the achievement of a consensus understanding.

The Seekoei River experience suggests that the Pitman model (as well as the more detailed and difficult to use VTI model) can be set up in a manner that is able to replicate quite complex conceptualizations of catchment runoff patterns. However, the success of the approach relies to a large extent on the experience of those proposing the conceptualization, as well as those setting up the model. The project has involved a certain amount of 'thinking out of the box', while not entirely rejecting conventional wisdom. It is essential that hydrologists (both surface and groundwater) are trained to be able to achieve this and not to simply apply models in a 'cookery book' type of way.

The implication is that the hydrological approach adopted for the Seekoei River would be applicable to other ephemeral river ecological Reserve determinations. However, this statement is made in the absence of a definitive statement about the ecological water requirements of such rivers. This means that at this stage it is not entirely clear which hydrological components are important and the success of the modeling exercise is still being measured to a large extent on the assumption that the pool water dynamics are of critical importance in most of the catchment. It is critical that this issue (as well as which aspects of pool water dynamics are considered to be ecologically important) is resolved before any final recommendations can be made about the hydrological modelling approach for Reserve determinations in ephemeral rivers.

4. MODELLING EVENTS AND THEIR PROPAGATION THROUGH THE CHANNEL SYSTEM

Neither of the models referred to in the previous section are likely to be appropriate for simulating the dynamics of single high flow or flood events occurring within the catchment, although the VTI model could achieve this if there was sufficient confidence in the calibrated model parameters and the input rainfall data. It is therefore necessary to consider a parallel modelling approach to provide the information required for the high flow component of an ecological Reserve determination. The relevant issues are:

- The approach should not require information that is impractical to collect within the time frame of a Reserve determination and given the typical resources available.
- The approach should be able to account for both peak attenuation and volume reduction caused by pool storage, in–channel vegetation, channel cross-section variation and development impacts.
- The approach should be able to simulate a range of different events, from small events when connected flow is only just initiated, to large flood events.

There are two main types of models that could be applied to simulating the propagation of events; detailed hydraulic models such as Mike 11 and simple storage routing models using the principles of the Muskingum routing equation (or later modifications). The former have the advantage that they are able to simulate relatively complex hydraulic conditions explicitly, but have the disadvantage of being expensive (in terms of time, data and human resources) to set up. The software itself is also expensive and not all organizations will have access to it. The latter have the potential advantage of being simple, but it is not clear at this stage how successfully they can be applied in practice and they have the disadvantage that no clear guidelines are currently available about how to establish routing parameters from any available data. There is little doubt that if the Muskingum type approach is to be applied, a method will have to be developed that allows for a distributed approach. Both methods would require independent approaches for generating the necessary catchment runoff data that will then be routed through the channel system. This study has only addressed the Nash-Muskingum routing model as the IWR at Rhodes University does not have access to the Mike 11 model or any similar detailed hydraulic routing software.

4.1 Observed flood data

The only observed flood data are for the gauging station at D3H015, which has a rating table limit of 1.5 m, equivalent to a flow of 157 $m^3 s^{-1}$ (Steyn, 2005). It is further noted that this limit has only been exceeded 4 times within the gauging record period of 25 years. This information is of limited use for checking the results of any flood hydrograph generation model. Perhaps the best indication that the observed data can provide is that the 1 in 5 year flood has a peak of greater than 157 $m^3 s^{-1}$ under the present level of development, while a 1 in 2 year event can be assumed to be less than this value.

4.2 Nash-Muskingum routing model

The model that has been applied in this study is based on the design flood determination method of Bauer and Midgley (1974) as well as many of the procedures for determining design rainfalls and losses presented in Midgley (1972). The basis for the model is to determine a design rainfall distribution for each sub-catchment in the system and use the Nash-Muskingum routing equation (with routing coefficients based on guidelines given by Bauer and Midgley, 1974) to determine the sub-catchment flood hydrograph contributions. These contributions are then routed through the channel system of the whole catchment using the Nash-Muskingum routing equation with a routing coefficient appropriate for the channel and incorporating reach storage to delay the hydrograph.

4.3 Initial assessment of the model

The initial results were based on using standard approaches to design flood estimation on each individual sub-catchment and then routing the flows through the channel system. While it is recognized that acceptable values for the channel routing parameter are not known, variations in this parameter are less important than some of the other inputs to the model. The initial results generated flood peaks that are too high to be considered acceptable (160 $m^3 s^{-1}$ for a 1:2 year flood to over 2 500 $m^3 s^{-1}$ for a 1:100 year flood under present day conditions), especially for the shorter return period events. The main problem is considered to be the areal reduction factors (approximately 60%) applied to the input rainfall data based on the areas of the individual sub-catchments. Using this approach the model is essentially assuming that the storm rainfall is occurring simultaneously on all sub-catchments within the total catchment (an area of some 9 150 km^2). It may therefore appear to be more appropriate to apply areal reduction factors associated with the total area (approximately 40%). The result of applying this approach generated results which were generally too low for the short return periods (54 and 140 $m^3 s^{-1}$ for 1:2 and 1:5 year events respectively). It would appear that a compromise solution to the areal reduction factor value is required, or that an alternative approach to combining the flood flows from the various sub-catchments is required. The former is relatively straightforward and has been applied for the purposes of this report, while the latter could be considered as a possible option at a later stage.

4.4 Initial results

The areal reduction factor has been set to generate a result for the present day 1:2 and 1:5 year flood peaks at the outlet of sub-catchment D32J to be consistent with the observed flow data at D3H015, i.e. a peak of less than 157 $m^3 s^{-1}$ for the 1:2 year and greater than this value for the 1:5 year. Table 6 presents the results in terms of peaks and volumes, while Figures 11 and 12 illustrate the results graphically. The present day situation includes channel storage volumes taken from Table 1 (natural pool storage and in-channel weirs and reservoirs), while the natural only includes the natural pool storage. In both cases it has been assumed that the storage is 20% full at the start of the event.

There is clearly a problem with the automated estimates of losses (used to reduce the rainfall) or the design rainfalls for the 1:20 and 1:50 year events and this issue needs to be further examined. The differences between the present day and natural situation appears to be far more dramatic than might be expected. However, considering the large storage volumes (taken from the WR90 publications) that have been used to represent the present day condition the results are understandable. For a 1:2 year event very little outflow is experienced from sub-catchment D32F and the 1:5 year event is severely curtailed at this point. Whether a starting storage of only 20% of total storage is appropriate is open to question.

Table 6 Flood peaks and volumes estimated using the distributed Nash-Muskingum model

Return Period	Present Development		Natural	
	Peak ($m^3 s^{-1}$)	Volume ($m^3 * 10^6$)	Peak ($m^3 s^{-1}$)	Volume ($m^3 * 10^6$)
1:2	96	2.9	315	13.6
1:5	265	13.9	620	26.9
1:10	508	24.1	901	39.4
1:20	1275	58.8	1792	78.4
1:50	1222	56.4	1731	76.2
1:100	1676	76.8	2234	98.7

Note: The long-term natural MAR simulated by the revised Pitman model is 31.7 $m^3 * 10^6$

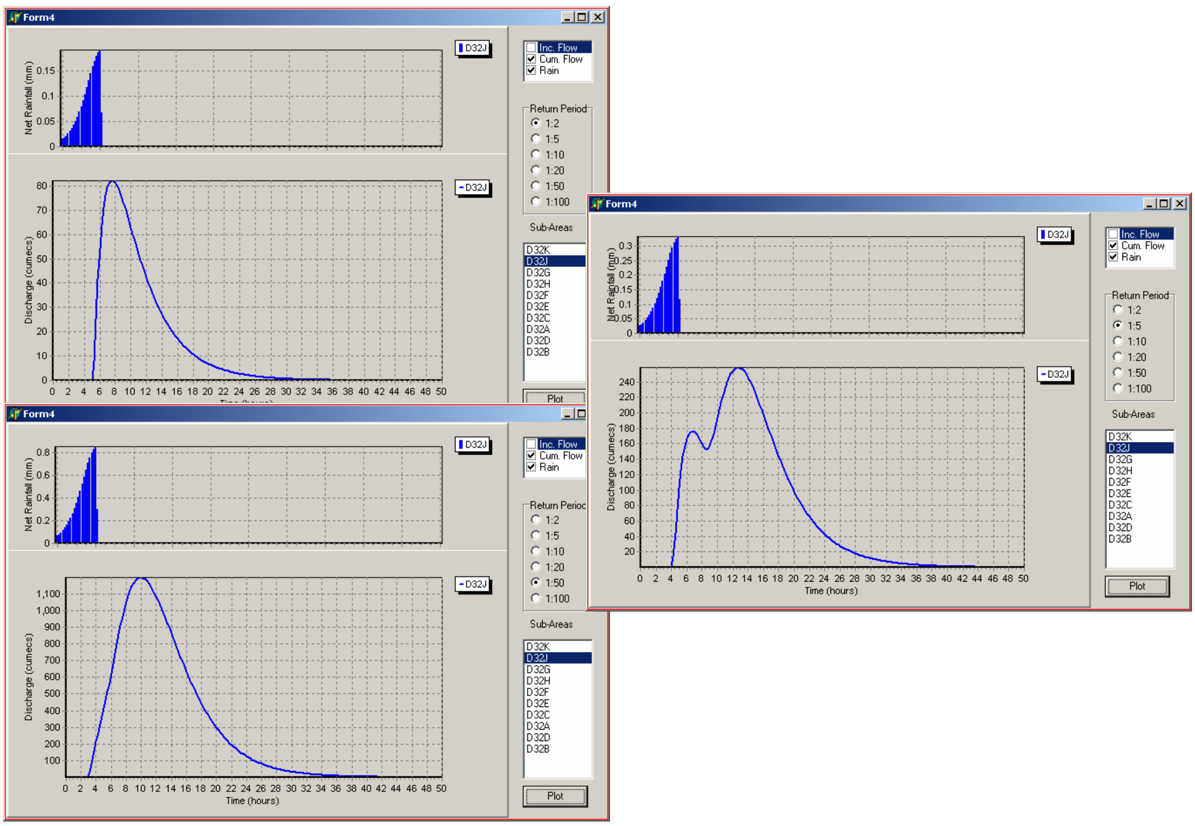

Figure 11 Present day flood hydrograph estimates (1:2, 1:5 and 1:50 year return periods).

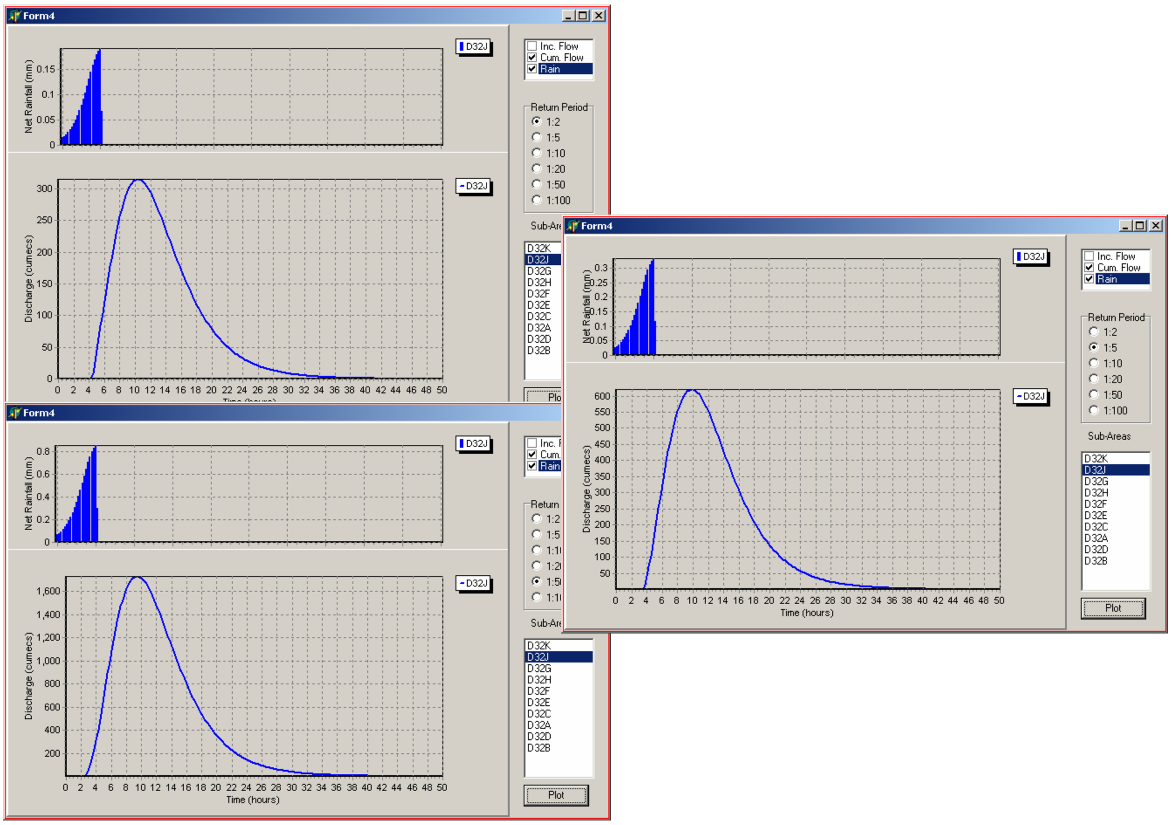

Figure 12 Natural flood hydrograph estimates (1:2, 1:5 and 1:50 year return periods).

The approach adopted for modelling flood events and the impacts of development is very simplistic and has been based on an available model within SPATSIM. Specifically, the channel routing component of the model should treat upstream flows and tributary inflows in a different way, whereas in the current version of the model they are both treated as inflows to the routing equation. There are also many uncertainties associated with the definition of the rainfall inputs and the catchment losses.

5. A SIMPLE WATER QUALITY MODEL

At the start of the project it was assumed that the water quality dynamics of the channel pools would play some role in the ecological functioning of the Seekoei River and similar systems. There are also water quality data available for the gauging weir at D3H015, as well as some observations taken by the main project team during field visits (Table 2). It was therefore considered appropriate to develop a simple water quality model that is based on simulating TDS (total dissolved solids) using the runoff component outputs from the rainfall-runoff models and several parameters to define the water quality signals of these runoff components.

5.1 Basic approach to the water quality simulations

For each sub-catchment the following approach has been used to simulate the water quality dynamics of the total pool storage. The approach is based on a mass balance of the salt load in the pools at the scale of quaternary catchments.

The input load has been estimated as a combination of:

- Load due to groundwater inflows (simulated groundwater discharge * assumed groundwater concentration – a model parameter).
- Load due to spring inflows (simulated spring flow * assumed concentration – a model parameter). It is interesting to note at this point that initial trials of the model indicated that this concentration parameter might need to be substantially higher than observed spring flow concentrations. A possible explanation is that the spring flow concentration observations are all taken at the spring sources which are frequently on tributary channels. By the time this contribution reaches the main channel (which is the focus of attention in the model) the TDS concentration could be a lot higher.
- Load due to surface water inflows (simulated surface water runoff within the sub-catchment * assumed concentration – a model parameter).
- Load due to flow from upstream sub-catchments (simulated upstream inflow * concentration derived from the upstream pool TDS load simulations).

The assumed concentrations of the groundwater and spring flow discharges are based on field observations by the hydrogeologists of the main project team, while the surface water concentration is based on the fact that observed water quality values at D3H015 reach a minimum of approximately 80 mg l^{-1} during high runoff events, implying that surface runoff concentrations are at least as low as this value. Surface runoff concentrations could, of course, be highly variable but unfortunately no additional information is available at this stage of the study.

The output load (during periods when downstream flow occurs) is difficult to estimate but is assumed to be based on the residual pool load (at the end of the last month) plus the input load (as above) divided by all the available water (residual pool storage from the last model period (month or day, depending on the model) plus groundwater and surface water runoff within the sub-catchment plus upstream inflow). One of the complications in a simple model of this type is that the concentration of the pool water cannot be estimated from the current load and the pool water storage volume. The reason for this is that as the pools dry out 'some' of the salt load will necessarily precipitate on the dry part of the pool, while the remainder will contribute to increasing concentrations in the pool water. This process can be summarized as a bank storage process that can store salts during the pool drying process and release then during the pool wetting process.

Figure 13 illustrates the pool drying process when the time step is monthly (using Pitman model outputs). The TDS load associated with the water stored in the 'bank' (which may include part of the bed of the pool as the pool shrinks in area) between the two pool levels is assumed to be immediately added to the 'bank' TDS storage when the pool dries out to the level in month n+1. The amount of water stored in the bank is based on an assumed depth of bank storage and sediment (or soil) porosity. The load added to 'bank' TDS storage is dependent upon the simulated concentration of the pool water.

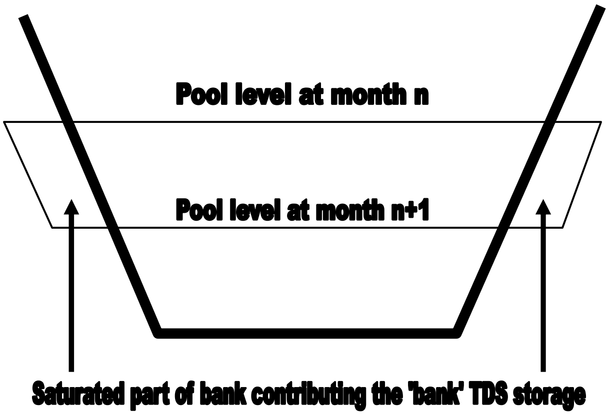

Figure 13 Pool drying process

During the wetting process (Figure 14), it is assumed that the release of salts from the TDS 'bank' storage will be a slower process than the addition of salts during the drying process. A parameter has therefore been included in the model (pool bank storage release rate) to control the rate at which the salts are released back into the pool water. There are checks to ensure that if the concentration of the pool water is greater than the concentration of the release from storage then no salts are added.

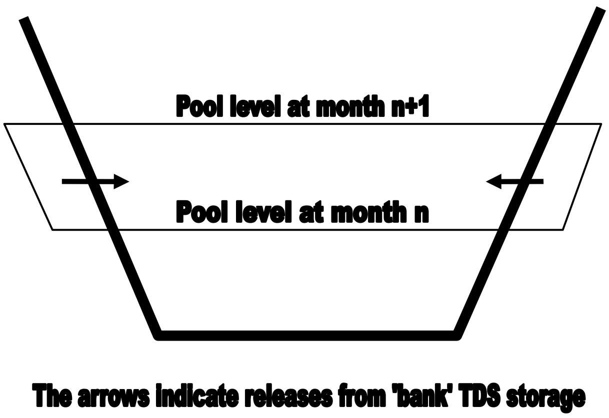

Figure 14 Pool wetting process

While it is accepted that this represents a very simplistic approach to simulating what is probably a highly complex process, the model algorithm does seem to account for some of the water quality dynamics noted in the observed records. For example, the observed TDS increases quite substantially during recessions after major events. While some of this increase can be attributed to concentration effects due to evaporation from pools that are maintaining outflows, this process does not seem to be able to account for the observed increases. A further possibility is that the TDS concentration of the spring flow contributions that are maintaining the baseflow in the river are increasing with time after a major rainfall event. However, observations of the quality of the spring water do not seem to support this possibility. Gradual release of salts from the bed and banks of recently wetted pools therefore offers what appears to be a realistic solution.

5.2 Application of the water quality model

The assumed concentrations of the spring flow and groundwater discharge are based on field observations by the hydrogeologists of the main project team, while the surface water concentration is based on the fact that observed water quality values at D3H015 reach a minimum of approximately 80 mg l^{-1} during high runoff events, implying that surface runoff concentrations are at least as low as this value. Surface runoff concentrations could, of course, be highly variable but unfortunately no additional information is available at this stage of the study. It was found that the best results were obtained with the spring flow and groundwater concentrations set to higher values (800 mg l^{-1}) than the field observations suggest (approximately 600 – 1000 mg l^{-1} for groundwater and 450 – 500 mg l^{-1} for spring flow). The justification for increasing the spring flow concentration lies in the assumption that much of the spring flow emerges in tributary channels and by the time it reaches the main channel its concentration may have increased.

Figure 15 illustrates the simulated pool concentration results (using present day simulated hydrology) for both models compared with the water quality observations at station D3H015. It should first of all be noted that there are no observations (straight lines on the graph) when there is no flow and therefore direct comparisons can only be made during periods of flow at the gauging station. It should also be recognized that if the hydrological models do not simulate the flow very well during specific events, then the water quality will not be expected to be simulated very well either. Figure 16 displays the same results but using water quality duration (frequency of exceedence) curves.

It is encouraging to note that during the three main runoff events (1981, 1988 and 1989) within the period, the patterns of simulated water quality for both models are very good. The two models generate similar results although the monthly simulations tend to generate higher maximum pool concentrations during no flow periods. It should also be noted that the pool concentrations that are simulated are an integration of all pools within the sub-catchment (D32J in this case), while individual pools may differ quite substantially.

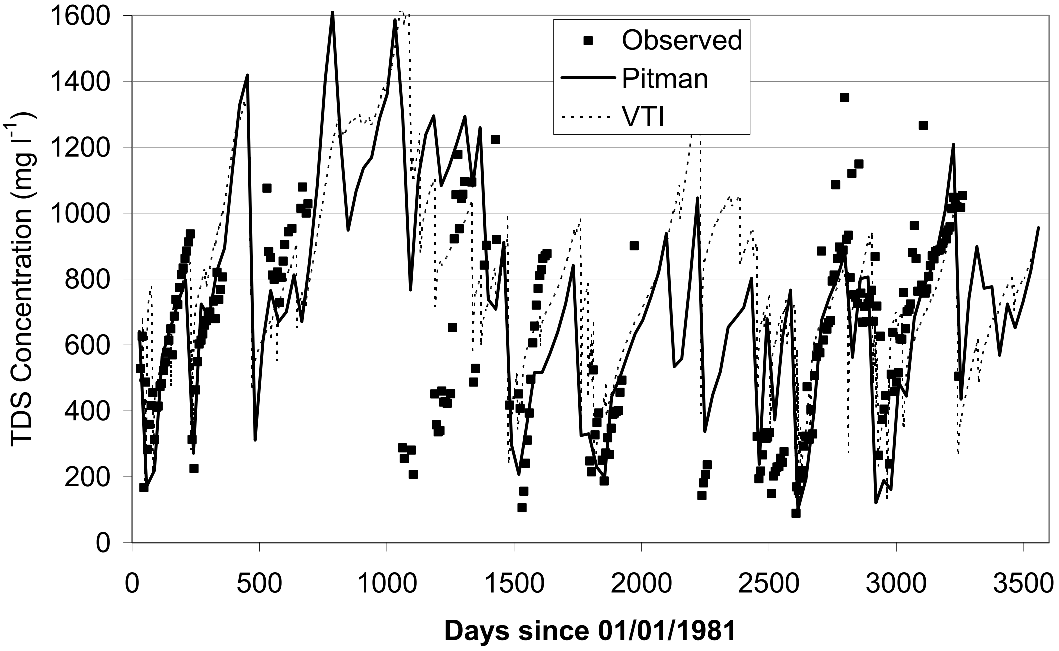

Figure 15 Observed (flow) and simulated (pool water under present day development) TDS concentration for the period January 1981 to September 1990.

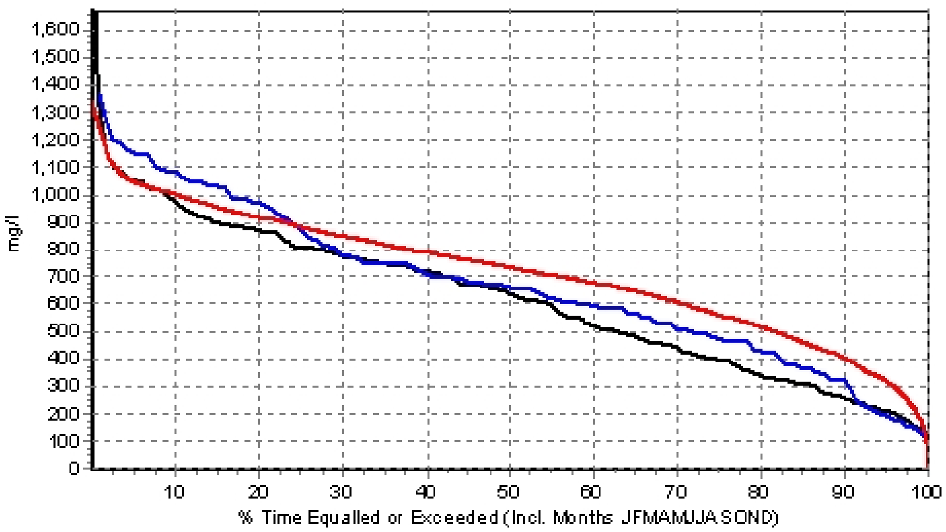

Figure 16 Comparisons of observed water quality and simulated pool concentration duration curves (Black, lower line at 60% = observed, Blue, middle line at 60% = simulated using Pitman model hydrology, Red, upper line at 60% = simulated using VTI model hydrology).

The simulated frequency curves illustrated in Figure 16 are reasonably consistent with the observed data at the flow gauging weir (D3H015), given that the observed only include periods when flow occurs, while the simulated represent the higher concentrations expected during zero flow periods.

It has been noted that the simulation results for the upstream areas are less than satisfactory compared to the few observed pool concentrations collected during the project. However, it should be recognised that the scale of modelling (pools representing complete quaternary catchments) is very different to the scale of the observations (a single pool). It has also been noted that the monthly model generates excessive concentrations during very dry pool conditions, while this is less evident in the daily model. This is largely a consequence of the long time interval used within the monthly model and the fact that the pool volumes can decrease a great deal in a single month. This implies that the exchange of salts between the pools and the 'bank' (Figures 13 and 14) in the model is not happening in a smooth enough manner over a monthly time step. The answer to this problem could be to include some internal iteration steps within the model to smooth the transfer process and prevent the build up of excessive concentrations in the pool.

It should always be remembered that the water quality model is very dependent upon the simulated hydrology and the pool storage parameters. If either of these is in error, the results will be affected accordingly. The model has only been assessed for sub-catchment D32J, which is largely influenced by the unsaturated zone outputs (spring flow) within that sub-catchment. From Figures 15 and 16 it appears that the models (quantity and quality) are generating sensible answers for sub-catchment D32J. There is no guarantee that the model is generating equally sensible answers for the upstream sub-catchments. It is interesting to note the simulated pool water quality characteristics of the natural and present day conditions, notably in the upstream sub-catchments. Under natural conditions there are many periods of quite high concentrations, while some of these are not evident in the present day simulations. This is largely because a substantial part of the salt load is removed through abstractions. The model does not have a component that allows for the abstracted load to be returned to the river through seepage or surface runoff. Either or both of these processes are likely to occur (hence increasing the concentration of the surface runoff or ground water contributions to the pool salt loads), but are difficult to quantify and therefore to incorporate into the model at this stage.

While there are still many areas of uncertainty in the application of the water quality modelling approach, it appears that the simple mass balance model is able to reproduce the processes that are active in the real world and generate results which are sensible. The model requires further testing and refinement in other semi-arid areas before it can be considered for more general use.

6. THE USE OF MODELS IN SCENARIO ANALYSIS

The purpose of the fourth deliverable was to evaluate the use of the models to simulate various development scenarios. One of the major outcomes of the third deliverable was that the lower quaternary catchment (D32J) has a very different hydrological response to the majority of the remaining catchment. This is largely because of the presence of a steeper topography dolerite ridge in D32J, while the majority of the rest of the catchment has very low slopes. The only gauging station that can be used for model calibration purposes is at the outlet of D32J and the implication (referred to previously in this report) is that the ability of the models to simulate the hydrology (and water quality) of the upper catchments cannot be adequately tested against observed information.

There is broad agreement between the surface and ground water hydrologists on the conceptual interpretation of the hydrology that has been used to establish the model calibrations. One of the consequences is that a large proportion of the total runoff at the gauging station will be derived from a very small part of the total catchment close to the gauging site. This will therefore be largely unaffected by the development of weirs and dams in the upper sub-catchments. A further consequence is that the most appropriate model parameters to use will be very different for the D32J sub-catchment compared to the others. However, this means that it is very difficult to establish representative parameters for the upstream areas.

Previous sections of this report have already addressed one scenario of development and that is the present day situation characterised by many in-channel weirs and dams. The effects of these on the pool dynamics and the runoff patterns in the upper parts of the catchment are thought to be substantial.

6.1 Possible future scenarios of development

The present day situation represents the baseline development scenario and the main impact on the natural hydrology is the existence of many in-channel weirs and dams. Table 1 summarised the storage and abstraction volumes that were assumed during the calibration of the models against present day gauged flows. The abstraction volumes given in the table and used in the simulations are approximate as there are no accurate data available.

The additional scenarios that have been identified by the main project team at the University of the Free State are as follows:

- ***Scenario 1***: Intensification of farming activities and a reduction in farm size. The expected consequences are a deterioration in farming practices including over-grazing, loss of bank stability, removal of riparian vegetation, increased sedimentation and erosion resulting from poor land cover.
- ***Scenario 2***: Increased game farming and ecotourism with the possibility of additional ground water abstraction for water supply purposes.
- ***Scenario 3***: Increased flow from the Orange River to local towns and settlements and a consequent increase in return flows to the Seekoei River.

6.2 Baseline development scenario – present day conditions.

This situation was included as part of section 3.5 as the models were calibrated against present day gauged flows. The focus of the analysis was the water balance of the pool storage at the scale of quaternary catchments and the results were summarized in Table 4 for the three sub-catchments that contain the identified Reserve sites (D32E, F and J). The present day downstream outflows expressed as a percentage of the natural downstream outflows are 35%, 56% and 81% for D32E, D32F and D32J respectively. This is largely an inevitable result of the fact that a large part of the downstream flow in D32J is generated within that sub-catchment even under natural conditions (55.6%). While the results suggest that a substantial volume of water generated upstream reaches the lower part of the catchment under present day conditions, it should be recognized that this occurs during infrequent short duration events representing a relatively short proportion of the total time.

The greatest impacts are in D32E and D32F, largely as a result of the increased storage in the upstream quaternary catchments D32D and D32A. Apart from the changes in the water balance components there are also substantial changes in the frequency with which downstream flow occurs. Within D32E the natural frequency of downstream flow was simulated as 10%, while this reduced to some 5% under present-day conditions. The equivalent values for D32F were 16% reducing to 5.5%. The impact in D32J is far less with a frequency of flow of 53% under natural conditions and 51% under present day conditions.

6.3 Scenario 1: Intensification of farming activities

The major catchment changes that are suggested under this scenario relate to land cover and soil erosion. The effects on the overall quantity of runoff are likely to be very small and very difficult to simulate with the hydrological models that have been used. It should be noted that the current land cover is quite sparse and there would appear to be very few opportunities for increasing the intensity of the farming practices in the long-term. While this could conceivably happen in the short-term, it is unlikely to be sustainable and would probably revert to conditions similar to the present day after a relatively short period of time.

If continued over-grazing were to be the pattern of future farming practice there certainly would be additional soil erosion and possibly somewhat higher volumes of surface runoff. However, the low gradients in the majority of the catchment suggests that the source of additional runoff would be limited to areas quite close to main and tributary channels. The overall impact on water quantity would therefore be to increase the amount of surface runoff during infrequent high rainfall events.

While it is straightforward to identify which parameter values to change in the two hydrological models, it is very difficult to estimate the values of such changes. In the Pitman model the appropriate parameters are the catchment absorption parameters ZMIN, ZAVE and ZMAX. The original values of these for the present day situation were 30, 500 and 800 mm month^{-1}. These values represent the minimum, median and maximum value of an asymmetric triangular distribution of catchment absorption rates. Relatively arbitrary changes (to 10, 300 and 700) were made to these values for quaternary catchments D32A to F to represent a decrease in absorption that might result from reduced land cover and greater surface runoff. Figures 17 and 18 illustrate the effects on the simulated outflows for quaternary catchments D32F and D32J.

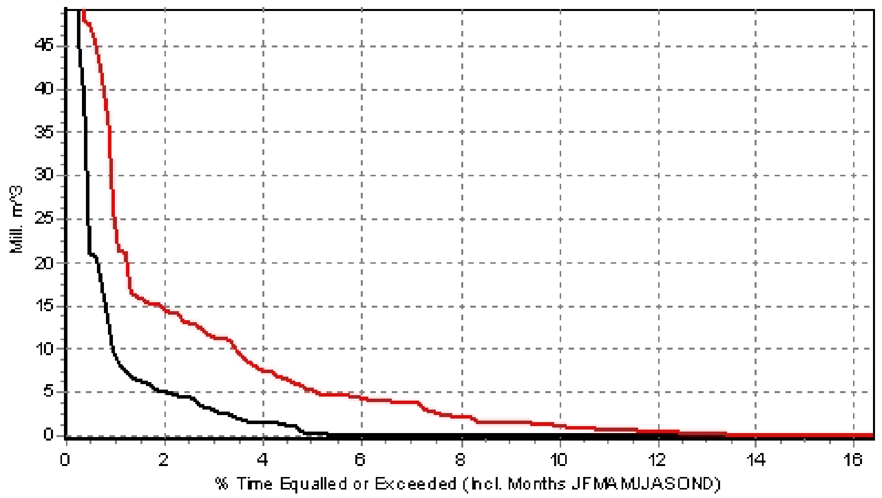

Figure 17 Annual 1-month flow duration curves for D32F representing present day (black or lower line) and scenario 2 (red or upper line) situations.

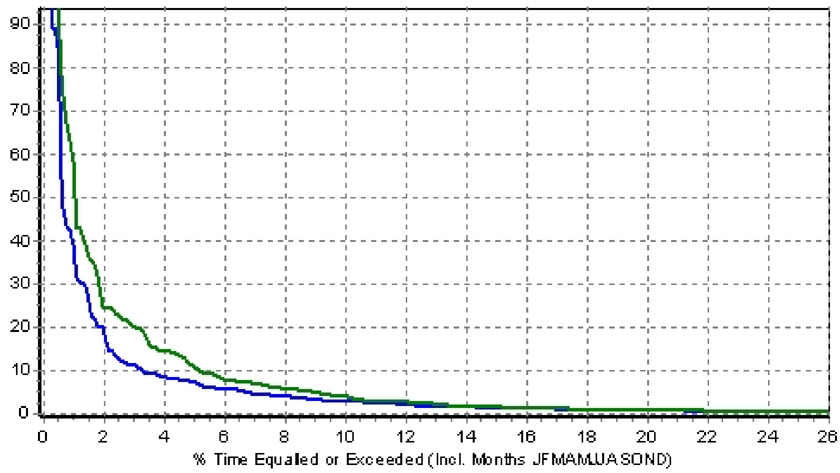

Figure 18 Annual 1-month flow duration curves for D32J representing present day (blue or lower line) and scenario 2 (green or upper line) situations.

The impacts with these parameter changes are quite substantial, the duration of flow in D32F increasing to over 16% and the size of most flow events increasing by a factor of 2 or more. The effects downstream at D23J are less significant due to the smaller relative influence of surface runoff and upstream inflows on this quaternary catchment. The effects on pool storage are also quite substantial, with the frequency of dry pools changing in D32F from some 28% to less than 5% of the time and the volume of pool storage being maintained at higher levels for most of the time.

The simulated effects referred to above and illustrated in Figures 17 and 18 have to be treated with extreme caution as there are no observed data that can be used to compare the model results with. However, it is reasonable to suggest that the impacts that have been simulated are extremes and that the real impacts would be much lower depending on the areal extent of the land use changes. The simulated impacts can therefore be used to illustrate the type of impact but not necessarily the scale of impact.

Increased surface runoff would lead to increased sediment load, while removal of riparian and in-channel vegetation would result in increased channel erosion. The models used in this sub-project are not able to simulate these effects.

6.4 Scenario 2: Increased game farming and ecotourism

The assumption in this scenario is that additional water consumption will be required to account for an increase in tourism and game farming within the catchment. This is expected to be a distributed water requirement that will rely to a large extent upon ground water abstraction from boreholes. In D32J, which has a great deal of potential for tourism, a possible source of additional water could be the springs.

In the upper catchment areas the mean annual recharge has been simulated as between 1.0 and 1.2 mm y^{-1}. This represents the upper limit to sustainable ground water abstraction without reducing the regional ground water table. In quaternary catchment D32F this recharge depth represents a volume of some $1.5 * 10^6$ m^3. A game farm operating with 50 guests at an average 60% occupancy rate throughout the year is expected to use approximately 3600 m^3 y^{-1}, a mere 0.24% of the recharge rate. There would have to be a large number of game farms within the region before the impact is likely to be felt on the river. If boreholes are situated close to the river the impact will, of course, be locally significant. However, as Tables 3, 4 and 5 suggest the contribution of ground water to the pool and flow dynamics of the river is not expected to be very large and therefore even riparian ground water abstractions are not expected to have major impacts.

Table 4 suggests that the mean annual interflow contribution to D32J is some $2.7 * 10^6$ m^3, which is also at least two orders of magnitude greater than any game farm or ecotourism developments are likely to use. However, the spring contribution that is equalled or exceeded 90% of the time is less than 15 000 m^3 $month^{-1}$. This is only about 4 times the amount that may be required by a single tourism operation. The conclusion is that increased tourism within the region will have a negligible effect most of the time but could have an impact in D32J during drought periods if the springs are developed for water supply purposes. It is possible that improved land management and reduced stock densities may increase the ground cover and have a small impact on surface runoff, but this would be very difficult to quantify and would very much depend on comparing present day with possible future land management practices.

6.5 Scenario 3: Increased flow from Orange River to local towns

There are very few town settlements within the Seekoei catchment, the largest being Hanover (within quaternary catchment D32F). It is very difficult to provide accurate data on likely volumes of increased water supply and therefore return flows. The population census data for the total municipality suggests that the total population is some 35 000, but that includes De Aar and all the farms. A relatively high estimate of water use has been used based on 5 000 households and an average consumption of 15 m^3 per month per household with 70% of the consumed water becoming return flows to the river. This results in a monthly return flow volume of 0.052 * 10^6 m^3. The impact on the frequency of downstream flow is very small, increasing from 5.5% to a little over 6%. The impact downstream at D32J is almost non-existent, while the impact on pool storage in D32F is somewhat greater. Under present day simulated conditions the 'pools' (including in-channel weirs and reservoirs) are more-or-less dry for 28% of the time, while the model suggests that this could reduce to 18% with the added return flows. The greatest impact is likely to be on the nutrient balance of the pools, but this issue has not been addressed as part of the hydrological modelling sub-project.

The conclusion is that an increase in the water supply to existing settlements from the Orange River is unlikely to have any significant effect on the water quantity dynamics of the system, except at a very localized level (i.e. immediately downstream of the effluent return point). The impacts on water quality could be substantial, but again this is likely to be confined to a relatively localized part of the channel system and will depend very much on the type of effluent treatment.

6.6 Water quality implications of scenarios

The water quality model used in this sub-project only dealt with TDS and none of the identified scenarios made significant differences to the simulated water quality dynamics, with the exception of the excessive surface runoff simulated as part of scenario 1. However, it has already been suggested that the simulated increase in surface runoff is not considered realistic. This sub-project has not addressed nutrients or sediment loads and these are the quality variables that are likely to be most affected by some of the scenarios, particularly 1 and 3.

6.7 Conclusions about scenario modelling

As noted previously there are many uncertainties associated with the model results that have been generated by this project. To a large extent these uncertainties are related to the fact that most of the real observations are taken from the gauging station at the outlet of the whole catchment, while there are known to be quite substantial spatial differences in hydrological processes within the catchment. The implication is that while it may be possible to obtain satisfactory simulation results (for both water quantity and TDS) for the outlet of quaternary catchment D32J, there are no guarantees that the way in which the models are representing processes in the other quaternary catchments is adequate.

A further problem is that, although the main project has collected some valuable field information on both quality and quantity, this information is at a much smaller spatial scale than is being used in the models and does not cover a long enough time period to be temporally representative. At the same time it is recognized that spatial variations in pool dynamics are expected to be quite large.

Despite the above uncertainties, the way in which the models are representing processes is considered to be conceptually correct and while some of the absolute values may not be accurate, it is possible to express confidence in the simulations with respect to the relative contributions (to pool storage and stream flow) of different processes. This allows a similar level of confidence to be expressed in the simulations of the effects of different development scenarios. There is little doubt that the greatest influence on the natural hydrology is the construction of in-channel weirs and dams which has already happened. It is possible that this type of development could be expanded, but this seems somewhat unlikely in most parts of the catchment (except D32J) as more artificial storage will simply remove water from the existing structures.

The greatest potential impact on water quantity (pool storage and river flow) is expected to be related to tourism development in the lower part of the catchment if the water supply is based on the springs. While the mean annual volume of spring flow may not be seriously affected, the use of a large proportion of the dry period spring flow could affect the pool dynamics of the lower reaches of the river. If an intensification of farming results in over-grazing and reduced land cover, particularly in the vicinity of the main channel and tributaries, there will almost certainly be increased surface runoff. It is difficult to quantify this effect in a catchment that already has relatively poor surface cover.

In terms of water quality, changes in farming practice that might lead to increased surface and channel erosion will have a large potential impact on the sediment dynamics of the system. Increased return flows from imported water could impact on the nutrient balance of stretches of the river, but the scale at which this is likely to happen suggests that the impacts could be quite localized. Both of these issues are beyond the scope of this sub-project and neither have been addressed in detail within this report.

7. CONCLUSIONS AND RECOMMENDATIONS

The main purpose of the conclusions section of this report is to attempt some answers to the questions that were raised in the introductory chapter based on the experience gained within the Seekoei River catchment. There is inevitably a degree of overlap between both the questions and the answers.

7.1 Are existing data sufficient to identify the characteristics of a specific non-perennial system?

One part of this question should really be 'what are the data required to identify the characteristics?', while the answer is any information that can be used to develop a reasonable conceptual understanding of the hydrological processes dominant within the catchment. Clearly flow data (observed or simulated), together with information about upstream impacts that are reflected in such data, would be important information. Given the lack of observed flow data in many semi-arid areas, the WR90 (soon to be updated to WR2005) database represents an important information resource. However, any regionalized hydrological simulations have to be treated with caution and should be checked against any additional information that is available for the specific site. The Seekoei River example used within this report illustrates that a relatively small amount of field work, together with the interpretation of readily available information (topographic maps, Google Earth, etc.) can be useful to build up a conceptual understanding of the hydrological characteristics of non-perennial systems. However, the correct interpretation of the available information requires knowledge and experience of the hydrology of semi-arid regions.

7.2 Are existing hydrological models in general use within South Africa appropriate for providing the required information for non-perennial system EWRs?

The experience of applying two models in the Seekoei River basin suggests that they can be applied in non-perennial systems and can generate the required information. However, it also has to be recognized that the reliability of the model outputs will depend upon the available information (of all types) that can be used to validate the results. This situation is not different in perennial systems and it is too easy to forget that the simulation results of all hydrological models are subject to varying degrees of uncertainty. The Seekoei River example has suggested that the models can be used to simulate the flow characteristics (and therefore frequency of connectivity), as well as the pool dynamics. The models in this report have been applied at the scale of quaternary catchments and therefore connectivity and pool dynamics have also been simulated at this scale. If more detailed information is required it would be necessary to use smaller spatial units within the modelling system, which is possible given an increase in the effort that would be required to identify appropriate differences in parameter values at finer spatial scales.

The above comments apply to the water quantity dynamics of non-perennial systems. While the linked water quality model used in this study appeared to perform reasonably successfully, it only applies to TDS and has not been tested in other river systems that may have very different quantity-quality relationships.

7.3 If not, can relatively straightforward modifications be made that will ensure that they are appropriate?

The answer to the previous question suggests that existing modelling approaches have been found to work in the Seekoei example. The major consideration within the Seekoei River is whether the spatial scale of the simulated information is appropriate for a Reserve determination. If not it has already been suggested that the spatial scale used within the model could be reduced so that more detailed information is generated. Whether or not the model could be appropriately parameterised at such scales remains to be tested. An alternative is to use a frequency distribution approach to down-scale the model outputs. However, this would require additional information about the variability of 'real' conditions (such as pool storage characteristics) within the spatial units used for modelling. While such information could be collected it would require substantial resources.

There are other non-perennial systems that do not share the characteristics of the Seekoei in terms of the processes of connection between the channel and ground water systems and there remains a degree of uncertainty about the use of the models in these systems. Within many semi-arid areas the regional ground water level will be well below the river channel, implying that channel transmission losses to deeper ground water will play an important role in channel water dynamics (during periods of both connected flow and static pool storage). Channel transmission loss processes are notoriously difficult to model (Hughes and Sami, 1992). While both models used in this study have components to simulate channel transmission losses, the algorithms remain largely un-tested due to the lack of available field data. Another type of non-perennial system where similar modelling problems may be encountered are those where the main channel is developed on alluvial aquifers (the Limpopo, for example) and where exchanges between the channel and the aquifer can be quite complex. It is recommended that the models be further tested in these types of system as only then will it be possible to identify what modifications (to the models or the use of the models) are necessary.

7.4 Are the available data sufficient to apply these models in practice for a range of different non-perennial systems?

This question is related to those raised in sections 7.1 to 7.3. Subject to the issues raised in section 7.3 about different types of non-perennial systems (as well as the next section on uncertainty), the answer to this question is a qualified 'yes'. It should be recognized that there are rarely sufficient rainfall data available to properly describe rainfall inputs to hydrological models in semi-arid areas where spatial variations are expected to be very high. However, at the same time it is not necessary for an EWR determination to simulate the timing and magnitude of every flow event exactly. What is important is the frequency of occurrence of flow events of different magnitudes and the spatial extent of those flow events. While there are certainly semi-arid areas of South Africa where there will not be sufficient rainfall data for this purpose, in most cases the historical rainfall data should be sufficient. However, it should also be noted that the amount of rainfall data being collected has been decreasing in recent years and that there is a real danger that there will be many parts of the country in the future where the availability of rainfall data will become a critical factor in hydrological modelling. While there are plans for alternative measuring systems (using radar, for example), it is important for long-tern hydrological simulations that future data sets are compatible with historical data sets.

The previous paragraph focused on the input rainfall data, while additional information is required to be able to establish appropriate parameter values for the models. Reference has already been made to Google Earth, which can provide very useful information on spatial variations in topography and vegetation cover. While this is not quantitative information it can be useful in developing a conceptual understanding of the active hydrological processes (which will often reflect or be reflected in topography and vegetation). The new Agrohydrology Atlas of South Africa (Schulze, 2007) may prove useful in providing quantitative information on topography, soils and climate variables. However, this is a new source of information and its value has to be assessed when applied in situations other than those that it was originally intended for.

One of the potentially critical items of information is the geometry and potential water storage characteristics of in-channel pools (and the extent to which these have been modified by weir or dam developments). This type of information is generally not available and would have to be collected for a specific EWR study. The main questions are:

- What information can be collected within the time frame of a typical EWR study?
- What information should be collected and at what scale to ensure that the data are representative?
- How should the data be collected? An example might be limited ground surveys combined with aerial surveys of the whole area.

It should always be recognized that the type of information that will be available will not be directly applicable to quantifying the parameters of a model. It will need to be interpreted and this will involve a degree of subjectivity. The critical issue is therefore how best to reduce the subjectivity so that different model users will generate similar results. Should the approach be to develop guidelines for model and information use, or to improve the training and level of expertise of model users.

7.5 What are the uncertainties associated with the application of the models and are these likely to be too high for the outputs to be used in conjunction with other physical driver information (water quality, geomorphology) or ecological response information?

There is uncertainty associated with the complete process of EWR determination regardless of the type of river system being dealt with. This uncertainty is associated with the provision of physical driver information (hydrology, water quality and geomorphology), as well as the interpretation of the ecological responses to these drivers. The real issue is therefore how the uncertainty is propagated through the study and whether uncertainty in one area can be offset by higher confidence in the information used in another part of the study. This is not unique to non-perennial systems and has been a constant cause for concern in the methods used for perennial systems for some years.

In non-perennial systems the natural variability of the drivers suggests that the functioning of the ecology should be quite robust and less sensitive to changes in the drivers than in perennial systems. The implication is that a higher (than in perennial systems) level of uncertainty in the driver information can be tolerated. One of the areas of uncertainty that should always be focused on is the interaction between surface and ground water and ensuring that the physical processes involved in a specific catchment are represented as well as possible in the model being used.

7.6 Do hydrological modellers require any specific skills or training to be able to apply models successfully in non-perennial systems?

The main consideration is that the hydrological modellers have a reasonable understanding of semi-arid hydrology and that there are specific issues that need to be addressed in non-perennial systems. These are covered in the following sub-section.

7.7 Are there specific issues associated with non-perennial hydrological studies that practitioners need to be aware of?

Many hydrological model practitioners in South Africa focus on the accurate simulation of sequences of monthly flows. The main reason for this is that the simulations have been predominantly used for system yield analysis. This approach is not sufficient for non-perennial systems and the type of information required for the ecological assessments will be quite different to that used for water resource yield assessments. However, the Seekoei River experience suggests that it should not be difficult to adapt existing approaches. For example, the way in which pool storage dynamics have been treated in this report are almost identical to the way in which artificial storage dynamics are treated in conventional water resource analyses. It therefore seems to be realistic to suggest that many of the non-perennial issues can be resolved with existing analysis tools as long as those who apply the tools do so in an appropriate manner.

While a strong emphasis has been placed on the importance of surface-ground water interactions in non-perennial systems and of the necessity for cooperation between the two disciplines, this is not very different to what is 'really' required in perennial systems. It is unfortunate that the so-called 'surface water' and 'groundwater' Reserve methodologies have evolved separately in perennial systems. There is an opportunity to ensure that this does not happen in the development of the methods that are recommended for non-perennial systems.

7.8 Is it realistic to expect that surface and ground water hydrological analyses can be properly integrated in non-perennial EWR studies?

This issue is partly related to the differences in the modelling and data analysis tools that have been conventionally used by practitioners in the two disciplines and partly related to differences in the conceptual understanding of surface and sub-surface processes. The experience of the Seekoei River project suggests that it is important to develop a common conceptual understanding, after which the type of analysis tool used becomes less important (as long as the results generated by the tool are compatible with the common conceptual understanding). Put in another way, there is little point in debating which model or tool is appropriate to a specific study if there is a lack of conceptual agreement about the dominant processes. This report would therefore propose that the most effective way to achieve integration of the surface and ground water assessments is to ensure that the specialists involved pool their existing information and conceptual ideas and reach a consensus on the dominant processes at the start of any project. It would then be necessary to embark on any field studies and modelling exercises in the context of this common understanding. If the data or model results suggest modifications to the concepts, then further discussions and interaction would be required. If the surface and ground water specialists cannot agree on the dominant processes and their relative importance, integration will not be possible and the outputs of the hydrological studies will be confusing to the other specialists who have to determine the ecological consequences.

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