Groundwater Discharges to Aquatic Ecosystems associated with the Table Mountain Group Aquifer

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Introduction

Rivers are an indispensable part of all ecosystems by rendering many free services to the terrestrial environment. In spite of acting as corridors for many ecological processes and creating linkages for ecological patterns, all aquatic ecosystems derive most of their characteristics from the catchments that they drain. However, for these functions to be maintained aquatic ecosystems need to be in a healthy and functional state. Considering that most of the physical and biological attributes of river ecosystems are flow dependent, it is inevitable that rivers need to have the variability of a natural flow regime that they evolved with to maintain their ecological integrity. It is therefore imperative that rivers be managed in an integrated manner recognising the full hydrological system. Many authors agree on this approach (King, Brown and Sabet, 2003; Davies and Day, 1998; Davies, O'Keeffe, and Snaddon, 1993).

As a result of a recent focus on large scale groundwater use from the Table Mountain Group (TMG) Aquifer in the Western Cape Province of South Africa, and published information on the intimate link between surface water and groundwater, it became inevitable for ecologists to understand how, and to what extent groundwater from the TMG contribute to surface resources, particularly the different components of the flow regime.

The purpose of this paper is to describe a conceptual model that was developed to link the different groundwater discharges to the different components of the flow regime, and indicating where in the landscape each would dominate. This model enable ecologists to understand the spatial occurrence of the different groundwater discharge types contributing to the flow regime of rivers, and enable the mapping of areas in the Western Cape Province where conflict might exist with surface discharges when using groundwater from the TMG aquifer. With the unique characteristics of the rivers of the Cape Floral Kingdom, one of six plant kingdoms of the world (Low and Rebelo 1996), which is also associated largely with the Cape Fold Belt and the TMG aquifer, it is critical to understand these important linkages.

Components of the flow regime in rivers and streams associated with the TMG in the Cape Fold Belt

With the flow regime of a river being the primary driver of the ecological functioning of aquatic ecosystems we need to understand how the flow regime affect the physical and biological attributes of rivers. Many authors agree that the variable flows in rivers are responsible for creating ecosystem components such as channel type and pattern, water chemistry and temperature, habitat diversity and associated biota, zonation of riparian plants and associated wetlands (King, Tharme and de Villiers, 2000; Gilvear, Heal and Stephen, 2002; King, Brown and Sabet, 2003). Diverse habitats are created through the dynamic geomorphological processes resulting from scouring, deposition and hydraulic sorting of sediments, gravel and cobble under the different flow conditions.

Realising the intimate link between groundwater and surface water it becomes extremely important to relate groundwater discharges to aquatic ecosystem functioning. The starting point therefore is clearly to define the different components of the flow regime from an ecological perspective, and to then conceptualise where and to what extent groundwater from the TMG aquifer contributes to each.

Ecological literature recognise that the flow regime consist of low flows and high flows, and that variable flows should be maintained to protect the ecological integrity any aquatic ecosystem. The low flows are the most critical for any river or stream with its associated aquatic ecosystems. Ironically this is also the time when water use from rivers are the highest. The low flows determine the basic hydrological nature of the river. The variation in magnitudes of low-flow in the dry and wet seasons create more or less wetted habitat and different hydraulic and water-quality conditions, which directly influence the balance of species at any time of the year.

The higher flows, that include intra-annual floods and large floods, are of particular ecological importance in semi-arid areas in the dry season. These flows stimulate spawning in fish, mobilise and sort gravels and cobbles, thereby enhancing physical heterogeneity of the riverbed, flush out poor-quality water and contribute to flow variability. It also essentially re-sets the river ecosystem. Large floods trigger many of the same responses as smaller floods, but additionally provide scouring flows. These scouring flows determine the form of the channel, mobilise coarse sediments, deposit silt, nutrients, eggs and seeds on floodplains, inundate backwaters and secondary channels, re-charge bank storage, inundate floodplains, and scour estuaries thereby maintaining links with the sea.

King et al. (2003) suggested a flow regime for streams and rivers that we feel is directly applicable to rivers associated with the TMG aquifer. Table 1 show how a rivers flow can be divided into its different components.

Table 1. Components of the flow regime (After King et al. 2003).		
Flow regime	Types of flows	Frequency of occurrence
Low flows	Wet-season base flows Dry-season base flows	
High flows	Intra-annual floods: Class I Class II Class III Class IV	 (6 times per year) (3 times per year) (3 times per year) (2 times per year)
	Large Floods: 1 in 2 years 1 in 5 years 1 in 10 years 1 in 20 years 1 in 50 years	

How precipitation becomes runoff

The second aspect that needs to be understood is the routes that precipitation follow to become part of runoff, or to recharge the water table before being discharged to surface resources. It is clear from hydrogeological literature that precipitation that reaches the earths surface will infiltrate into the soil, some water may evaporate, some is taken up by bio-mass, some is lost through evapo-transpiration by plants, some move under gravity and percolate downwards to recharge the groundwater zone, or else flow laterally close to the surface as interflow. This equates to the water balance where the whole water cycle is taken into account.

Hydrogeological perspective on the mechanisms of groundwater and surface water interactions in the TMG

For many decades surface water and groundwater were treated as separate entities on a global scale. However, with the increasing demand for fresh water it became apparent that development of either of these resources affects the quantity and quality of the other. Winter, Harvey, Franke and Alley (1999) and Ward and Robinson (1990) recognise this intimate link. Even floods in river systems can consist of mainly groundwater depending on the geological setting. According to Midgley and Scott (1994) less than 5% of storm flows (floods) comprised of direct runoff in studies in the Jonkershoek valley near Stellenbosch in South Africa. They suggested that the rapid response of these streams to rainfall was mainly due to displaced groundwater in the Table Mountain Sandstone (TMG) and associated well drained soils with high infiltration capacities. Hewlett and Bosch (1985) also found that overland flow play a minor role in the generation of floods in both humid and arid catchments in South Africa. It should be remembered that the percentage overland flow would vary greatly with rainfall intensity, slope, geology, soil types, vegetation type and antecedent conditions in soil moisture.

There is broad recognition al through literature that surface water-groundwater interactions should be quantified in two ways nl. recharge of groundwater by surface water, and discharge of groundwater to surface water (see Figure 1).

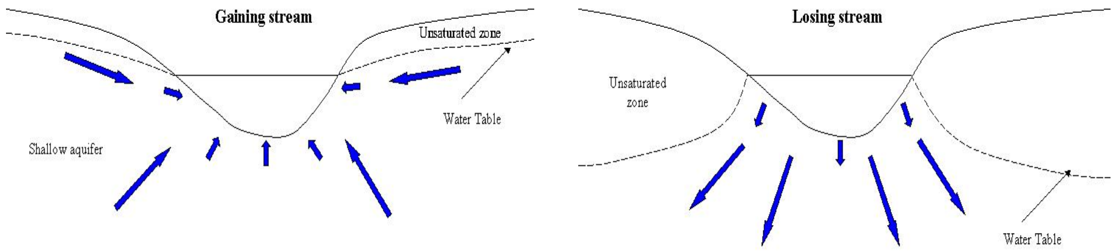

Figure 1. Showing discharge of groundwater to a stream (left), and recharge of groundwater from a stream (right) .

Groundwater discharge to surface resources either through point source discharges (i.e. springs etc.), or diffuse discharges (i.e. through the stream bed or hyporheos). Understanding the discharge and recharge of groundwater through the hyporheos is important to fully understand and characterise groundwater discharge types to surface resources. This movement of water through the hyporheos during groundwater recharge or discharge result in chemical reactions when chemically distinct surface water meets chemically distinct groundwater and will result in a unique biogeochemical environment. Parsons (2004) refer to this interaction of groundwater and surface water in the hyporheos as being an important ecotone, which provides a number of ecologically important services, including thermal-, temporal- and chemical buffering, habitat, flow augmentation, nutrient recycling and refugia. Our own observations during fish surveys clearly indicated that certain fish had a preference for specific spots in pools where groundwater discharges are distinguishable.

The groundwater discharge to and from streams is very dynamic and will be changing with changes in the level of a stream or adjacent water table. It might therefore happen that in a matter of hours, influent seepage in a stream may supersede effluent seepage and *vice versa*, changing from a losing to a gaining stream (Figure 1.). In physio-graphic settings where stream flow is generated in the higher elevation head waters, as happens frequently with rivers associated with the TMG, the changes in stream flow between gaining and losing conditions may be particularly variable. However, there is broad consensus amongst hydrogeologists on the types of groundwater discharges that may contribute to surface resources.

Influence of geomorphology on types of rivers associated with the TMG

To fully understand the link between groundwater and surface water it is essential to know the role that the geomorphology plays in the rivers make-up or characteristics. Pool, riffle, rapid sequences, single or braided river beds, flat fluvial beds, flood plains, bed structure etc. are all determined by the geomorphology. With the variability of the flow regime, river gradient, geology, soils and hydraulic sorting of cobbles any river will have unique but divers habitat types and associated biota. This will also largely determine the type and quantity of groundwater that is discharging to the surface resource. According to Moon and Dardis (1988) it is a known fact that the underlying geological structure determine drainage patterns of rivers most noticeable.

Both denritic and parallel drainage patterns develop on uniform lithology and where there are no *controlling* joints or fractures. Where faults, joints, or other lineaments *control* drainage it will be rectangular, while alternating resistant or less resistant strata will promote the development of trellised drainage. In settings where updoming has occurred annular drainage patterns will be present. In landscapes where tectonic activity is present, radial and centripetal drainage configurations will manifest. In any catchment one or several of these patterns may be present since these patterns are entirely dependant on the underlying structure (Moon and Dardis, 1988). These drainage manifestations will have far reaching effects on the type of groundwater discharges that might characterise certain sections of a river system, particularly those streams and rivers, and other aquatic ecosystems, associated with the TMG.

Taking the above into consideration, the Western Cape Province rivers associated with the TMG will mostly show dendritic (Figure 2-A), parallel (Figure 2-B) and rectangular (Figure 2-C) drainage patterns. The bigger river systems like the Gourits River would show characteristics of all the above drainage patterns.

On a subjective GIS survey it was clear that dendritic and parallel drainage dominates the mountain and foothill reaches of rivers associated with the Cape Folded Mountains and the TMG. Where mountain and foothill river reaches coincided with controlling faults, joints and other lineaments the drainage is rectangular. Even for lowland river reaches near the mountainous areas rectangular drainage dominated due to these lowland reaches coinciding with major faults or lineaments. Lowland river reaches show by and large a dendritic drainage pattern because of the uniform lithology and non *controlling* joints or fractures.

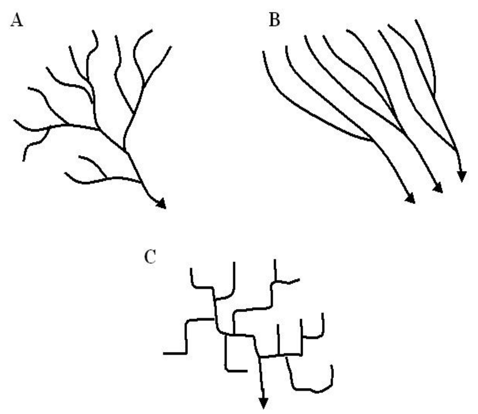

Figure 2. Drainage patterns in different structural settings: (A) dendritic, (B) parallel, (C) rectangular.

Recognised groundwater discharge types to surface resources applicable to rivers associated with the TMG

Hydrogeologists recognise that runoff in rivers associated with the TMG are generated by channel precipitation, overland flow (surface runoff or quickflow), interflow (which may include translatory flow) and groundwater flow. Overland flow may result from either infiltration-excess overland flow, which is generated when rainfall intensities exceed infiltration capacity, or saturation-excess overland flow which occurs when soil becomes saturated from below and rainfall gets rejected.

It is commonly accepted that a rivers hydrograph consists of baseflow and stormflow. Hydrogeologists agree that baseflow consists of mainly groundwater discharges and or interflow. Stormflows consist of direct runoff (Xu, Titus, Holness, Zhang and van Tonder, 2002), translatory flow, interflow and in-channel precipitation. Another important groundwater contribution to the hydrograph is bank storage, which the authors feel does not really fit into any of the above categories, or could be part of more than one of the above types.

The characteristics of the four components of runoff, and the relative proportions of each component present, determine the shape of the hydrograph in any river, including those associated with the TMG. Due to the complex flow composition resulting from local variations in rainfall, infiltration and antecedent conditions, it is impossible to identify each component of runoff in a hydrograph.

Mechanisms of groundwater surface water interactions in mountainous areas associated with the TMG

Xu and Beekman (2003) suggested that interflow in mountainous catchments accounts for part of the base flow in rivers associated with the TMG. The shallower weathered zone of the alluvial and slope deposits in the mountainous TMG areas, in which the interflow occurs, may serve as a reservoir for storing water during the rainy season while at the same time allowing for percolation to the deeper groundwater reservoir, often through a network of fractures. This reservoir would then discharge to the streams base flow and cause continuity of flow. This would also apply to bank storage in certain physio-graphic settings. It is from this zone that interflow will contribute to the base flow component of the hydrograph in the TMG.

Groundwater-surface water interactions for larger rivers that flow into alluvial valleys, are spatially more diverse than it is for smaller streams. Groundwater discharges from regional flow systems may discharge to the river or at various places across the flood plain. In these settings groundwater discharges is affected by the interchange between local and regional flow systems. Many of the larger rivers in the Western Cape would show similar characteristics in the lowland river reaches. However, all the headwater, mountain and foothill reaches of rivers, which are mostly associated with the TMG, will show largely localised flow systems.

In the Western Cape Province of South Africa the Table Mountain Sandstone's (TMG) associated with the Cape Fold Mountains, the focus of the current study, the deeper flow systems are mainly confined to semi-confined with very little discharge direct to rivers beyond the mountain stream and foothill reaches. The lowland reaches could have discharges from the regional flow systems, unless these aquifers are semi-confined to confined. It is expected that most of the direct groundwater discharge from the fractured TMG aquifer is happening in the mountains and foothills before the confining shale layers come into play at the TMG shale geological contacts. Beyond the foothill zones most of the groundwater in the alluvial aquifers get recharged from rivers and rainfall, with limited discharge from deep flow systems.

The semi-confined to confined nature of the TMG aquifer stems from its deep diving sinclinal nature which is sealed of on the sides by the shale layers of the Cederberg Group (See Figure 5). Hence the postulation that the interface between the groundwater and the surface resources are largely located in the geological contact areas of the mountain and foothill zones of the Cape Folded Mountain ranges. Discharges from the deep flow systems generally occur as cold or hot springs eminating in the landscape at fractures or faults, or in the marine environment.

The role of Hydrogeomorphology in the classification of streams in South Africa including those associated with the TMG

Classification of streams may be based on various criteria for different purposes. In the South African context streams are characterise by their geomorphic features for hydrogeological investigations to be in line with ecological reserve determinations as required by the National Water Act. Xu, Mafanya, Van Tonder and Partridge (2001) give a detailed description of this geomorphologic classification for the quantification of groundwater discharge towards streams, which relate well to river reaches associated with the TMG.

Xu *et. al*. (2002) went further and used this classification to describe groundwater interaction with streams (rivers). They described the expected groundwater interactions for each of the classes as described by Xu *et al*. (2001).

Linking the stream types to the different river reaches helps us to understand which types of groundwater discharges one can expect in each river reach.

Conclusions

From the above information it is obvious that there are broad recognition amongst hydrogeologists on the intimate relationship between groundwater and surface water, particularly in river reaches that are associated with the TMG. What is just as clear is that it is extremely difficult to quantify the different types of groundwater discharges or to determine what percentage each discharge type contribute to the flow regime at any given time at any particular place in the landscape.

From the cited literature it is clear that there are consensus on the different mechanisms involved in the different discharge types and where it can be expected to dominate in the landscape. Figure 4 gives a schematic representation of our proposed routes of groundwater discharges (types) contributing to the flow regime of rivers associated with the Table Mountain Group aquifer.

All precipitation within a particular basin or catchment becomes part of channel flow through a) overland flow under specific conditions as described earlier, b) or when it falls directly within the river channel, c) or after infiltration into the soil. The infiltrated water takes one or more of three different routes before it becomes channel flow. The first type of discharge is **interflow** that never became part of the water table. **Rapid interflow** discharges would result from the presence of preferential flow paths or where the soil horizon acts as a flow barrier which hinders direct downward percolation of water. **Delayed interflow** may result from partially saturated flow via a perched water table, or where geometric configurations of fractured networks lead to formulation of interflow.

The second type of discharge resulting from infiltration is **groundwater** “proper” discharges. This water become part of the water table (piezometric surface) and are then discharged to the river or stream. These discharges may happen in different ways. The most common would be spring discharges, and or seeps, both of which are normally associated with geological contact areas or geological faults zones. The geological groups that make contact will have different water permeabilities where the one acts as an aquatard. These aquifer boundary conditions will give rise to a semi-confined to confined aquifer that will discharge water at these geological contacts, or faults, provided that the piezometric surface (water table) is high enough or fully recharged. In this type of setting rejected recharge will be discharged as interflow. Groundwater discharges may also discharge in a diffuse manner through the hyporheos of a stream or river.

Translatory flow will be discharged to streams and rivers in a similar geomorphological setting than interflow. The only difference is that translatory flow is water of a previous recharge event that infiltrated into the soil, never became part of the water table, and are then flushed or pushed out by a next recharge event through infiltration before it could discharge under gravitational forces. The difference between **delayed and rapid translatory flow** is similar to that of interflow and would happen under similar antecedent conditions.

From Figure 4 it is clear that interflow, groundwater and translatory discharges are mainly responsible for base flow in rivers and streams depending on the stratigraphy of the area, the slope, geomorphology and antecedent conditions.

Channel precipitation and **overland flow** discharges will only happen under precipitation events and contribute mainly to storm flows as small, medium and large floods. It will be under these conditions that the river banks will be overflowed and be recharged to form the very important bank storage reservoir. Bank storage essentially reacts as an unconfined or primary aquifer which would slowly release its water to the stream for as long as the streambed is lower than the water table (gaining stream Figures 1). All of the above discharges ultimately equates to the total runoff for the catchment.

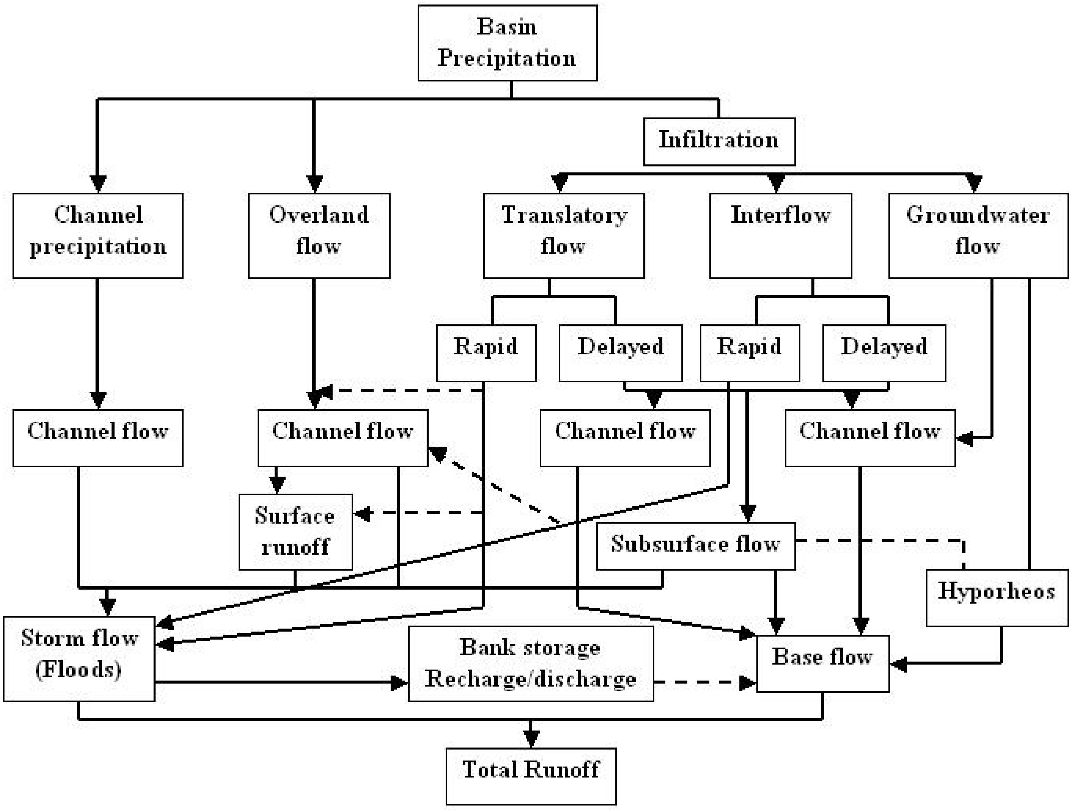

Figure 4. Schematic representation of the *proposed* groundwater contributions to the flow regime in rivers associated with the Table Mountain Group aquifer.

With the particular focus of this study on the groundwater interface of the TMG aquifer with surface water, it is mostly the "groundwater" discharges that would be affected by groundwater use from the TMG. The reason for this is the confined to semi-confined nature of the TMG aquifer that has deep circulation on mainly a regional scale. Local discharge is restricted to springs eminating from the TMG, faults affecting the confining shale layers and or contact zones between different geological units (aquifer boundary conditions) (See Figure 5). Springs may be hot or cold depending on how deep the flow system circulates.

Another possible effect of groundwater use will be the potential drop in the piezometric surface, which will ultimately have an effect on the discharge end of local and regional aquifers with varying time scale coupled to that. The induced recharge may also influence the interflow component, if we accept that a portion of interflow is a function of rejected recharge. Interflow would generally occur where the soil horizon acts as flow barriers, which hinder a direct downward percolation of precipitation, or where partially saturated flow may be formed via a perched water table, or where the unsaturated zone interflow occurs along preferential flow paths, or where favourable geometric configurations of fractured networks may lead to formulation of interflow towards the river. Xu *et al*. (2002) agrees with this postulation.

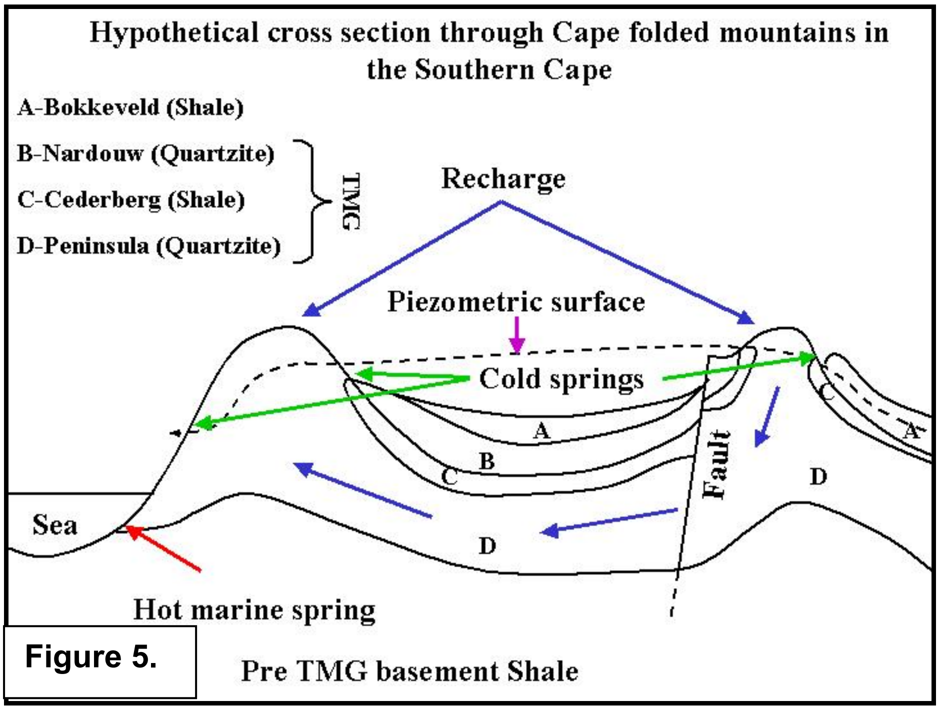

Figure 5.

Considering that a groundwater resource (yield) is recharge and outflow (discharge) dependent, any changes to the resource (yield) through abstraction will affect the recharge or outflow (discharge) of the aquifer. Any aquifer would under natural conditions be in equilibrium and be reflected by a stable water table position. However, when there is a reduction in the recharge in response to reduced rainfall, it will result in a fall of the water table and subsequently a reduced discharge from the aquifer. A new state of equilibrium will develop with a new amount of recharge and discharge. Abstraction of groundwater will have the same effect resulting in a shift in the water table until a new dynamic equilibrium is reached. This dynamic or changing water table level, whether by millimetres or a couple of meters, would clearly impact the amount of groundwater discharged to surface water bodies. Parsons (2004) and. Xu and Beekman (2003) agree and give the following equation for a pumped aquifer:

ADJUSTED RECHARGE – REDUCED OUTFLOW – PUMPING + STORAGE LOSS = 0

This equation acknowledges that recharge may have increased and outflow decreased (surface discharges) in response to lowering the water table. For groundwater development to be environmentally acceptable and sustainable, these loses must be balanced against the beneficial use of the pumped groundwater and whether the impacts on the environment, like base flow reduction, spring flow reduction etc. are within acceptable levels or thresholds. Interflow discharges will also be affected because varying portions of interflow is postulated to be a function of rejected recharge.

Table 2 summarise the cited literature on the different drainage patterns, flow types, groundwater systems, geo-morphological classes and the hydrogeomorphology of rivers associated with the TMG, also indicating the groundwater significance for the ecology.

From Table 2 it is clear that the dominant drainage pattern in the Western Cape Province is dendritic, parallel and rectangular, particularly in the TMG dominated mountain ranges. The dominant groundwater flow types for the four river reaches are also given as described in hydrogeological literature. Interflow dominates the headwater and mountain river reaches, with some translatory flow and base flow (groundwater) discharges from the TMG. Bank storage is unlikely to occur in these reaches. In the foothill reaches, the major groundwater discharge zone, groundwater discharges dominate base flow with some interflow. Storm flows and floods result from interflow, translatory flow, bank storage discharges, channel precipitation and surface runoff. The lowland rivers are getting most of their flow from the upper reaches with some surface runoff, channel precipitation and bank storage discharges. This is the regional recharge zone for the lowland primary aquifers (alluvial storage).

Geomorphologically the headwater and mountain river reaches vary from deeply incised, fracture and lineament controlled, to braided river flows consisting mainly of bed rock and cobble beds. In the foothill areas streams are controlled by bed morphology and alluvial fans. The lowland rivers meander as they hit the flatter fluvial areas where the terrain developed horizontally into a dendritic drainage pattern.

Hydro-geomorphological characteristics for the four river reaches also vary between constantly losing or gaining streams in the headwater and mountain reaches, to intermittent streams, alternating between gaining and losing sequences in the foothill reaches, and gaining streams with or without bank storage in the lowland reaches. In the headwater and mountain reaches the water table will be mostly below the stream stage, but in the foothill reaches it can be alternating from being above and below, and in the lowland reaches the water table will be mostly above the stream stage. However, in the lowland river it is a different aquifer’s water table (primary aquifer) that will be mostly above the stream stage, whereas in the mountain and foothill reaches it is the TMG aquifer water table that applies.

The ecological significance of the groundwater contributions from the TMG is most significant in the foothill reaches which are the primary groundwater discharge area for streams and rivers associated with the TMG. It can also be significant in the mountain reaches where the river or stream is connected to the TMG aquifer, or where there are groundwater discharges contributing to flow. In the lowland river reaches the TMG discharges are unlikely to have a significant direct role to play in its flow regime other than the fact that it is indirectly responsible for the flows in these reaches. If the flow of the upper reaches are significantly affected by groundwater use it will ultimately affect the lowland reaches by reducing the flows and subsequently the recharge of the primary aquifers associated with these rivers. Discharges from the TMG in the lowland reaches will be restricted to faults or fractures where deep flow discharges may be possible either as springs or as recharge to primary aquifers. In the latter case these discharges may support wetlands, estuaries or even marine discharges.

Table 3 is a representation of the proposed conceptual model, which consists of a matrix that gives the groundwater discharge types to each component of the flow regime and for each of the different river reaches for streams and rivers associated with the TMG. The top part (left to right) of Table 3 lists the different river reaches, with the different components of the flow regime listed on the left (top to bottom). The rest of Table 3 was then populated with the conceptualised groundwater discharge types that are contributing to each component of the flow regime in each of the different river reaches. Geo-morphological-, hydro-geomorphological-, and flow regime (hydrology and hydraulics) information was used in the compilation of the matrix (Table 3). The colours from red to light yellow indicate the relative importance of groundwater discharges from the TMG aquifer to each 'river reach type' and each flow regime component. Red represents a very high importance of groundwater discharges to maintain that component of the flow regime for that particular river reach. The lighter the colour gets the less important it becomes. Similarly, the more important the groundwater discharge is for each component of the flow regime in each river reach, the more important it is for the ecological functioning of the aquatic ecosystem. These same colours subsequently indicate the vulnerability of each component of the flow regime in each river reach to groundwater use from the TMG aquifer, and therefore the vulnerability of the ecological integrity of the aquatic ecosystem to the use of groundwater from the TMG.

What is quite clear from this conceptual model is that it is mainly the low flows (dry and wet season base flows) in the mountain and foothill reaches (and indirectly the lowland reaches), that is highly dependent on groundwater discharges from the TMG aquifer (See figures 6 and 7). The important groundwater discharge types in these river reaches for these flow components consists mainly of interflow (normal and rejected TMG aquifer recharge), groundwater discharges from the TMG aquifer (springs, seeps and hyporheic discharges), some delayed translatory flow and limited bank storage may be possible in some geomorphological settings (See Table 2). These discharges are highly dependent on the TMG aquifer equilibrium and will therefore change when the aquifer equilibrium is affected by groundwater use from the aquifer. If we take into consideration that the groundwater flow is localised in the mountain and foothill reaches, the use from this local aquifer is bound to have an effect on the groundwater discharges (see Figure 6B and 7A). Under certain hydrogeological (stratigraphical) conditions the flow may even be regionally affected. This may be the result of one of two effects of the altered aquifer equilibrium: nl. a) a drop in the piezometric surface or pressure gradient in the aquifer that will affect the hydrological conductivity and ultimately affect the discharge end of the aquifer (see Figure 5), or b) the asymmetric draw down cone along preferential flow paths may extend kilometres away from the well field, having the same effect as in (a).

Table 2. Summary of different drainage patterns, flow types, groundwater systems, geo-morphological classes, hydro-geomorphology of rivers as described in cited literature, indicating the groundwater significance for the ecology.

PARAMETER TYPE	*Headwater and Mountain reaches*	*Foothill reaches*	*Lowland reaches*
Drainage patterns	Dendritic, parallel	Dendritic, rectangular	Dendritic
Dominant flow type(s)	Interflow (IF) dominated on local scale. Surface runoff and preferential flow. Some translatory flow. Base flow in TMG (Perennial). No bank storage.	Base flow dominated but with interflow, some bank storage, surface runoff and channel precipitation.	Characterised by bank storage, Base flow increase with bank storage, Surface runoff, regional and local groundwater discharges possible - mainly alluvial storage.
Groundwater system (regional or local)	Local scale – interflow. Regionally - recharge area and may have local and regional groundwater discharge in the TMG.	Regionally a runoff area. Groundwater discharge is local but regionally significant. Discharge and recharge area (through hyporheos at pool-riffle sequences).	Regionally recharging alluvial aquifers. Local bank storage. May get groundwater discharge from regional and local groundwater systems.
Geomorphological classification	Braided, to single channel, deeply incised, fracture and lineaments controlled. High gradient, bedrock cobble bed.	Stream controlled by mainly bed morphology (pool riffle sequences).	Meandering, topographically flat areas, fluvial erosion develop terrain horizontally, alluvial deposits.
Hydro-geomorphological typing	Constantly losing or gaining streams. Regional groundwater level is constantly below the stream stage. Fed by confined aquifer and or local interflow.	Intermittent streams. Gaining and losing stream alternate at pool riffle sequences. Groundwater discharges towards streams during dry period and *vice versa* during wetter cycle. River recharges aquifers during floods (bank storage).	Gaining streams with or without bank storage. Groundwater levels consistently higher that the river stage. Base flow component increase in an S-curve or straight line as a function of the presence or absence of bank storage. Groundwater from TMG unlikely to play role directly.
Significance of groundwater contributions from TMG for ecology (Flow regime)	Significant where base flow from TMG is significant. Interflow may be affected by use from TMG because interflow is also a function of rejected recharge of TMG aquifer.	Highly significant. This is where groundwater discharge from the TMG is most likely and contributing significantly to the flow regime. Flows will be affected by piezometric head drop or development of the draw down cone (cone of depression).	Unlikely to significantly impact direct discharges from TMG aquifer. May affect discreet TMG regional flow discharges in specific settings because aquifer discharge will be impacted by use as given by: ADJUSTED RECHARGE – REDUCED OUTFLOW – PUMPING + STORAGE LOSS = 0

The reason for the lighter coloured dry and wet season low flows in the headwater river reaches is the fact that these streambeds are almost always disconnected from any groundwater table (because of altitude), and it is unlikely to have proper groundwater discharges. Groundwater discharges from perched springs may be possible, in which case it is un-related to TMG discharges. In headwater reaches the important base flow component is completely dominated by normal interflow. Perennial flows in these reaches may result from recharge events that are close enough to one another to maintain the interflow discharges. Figure 6 A gives a representation of the percentage contribution of the different discharges to the flow of the different components of the flow regime in a hypothetical headwater river. From the graph it is clear that Interflow dominates the low flows with overland flow dominating the large flood discharges.

On the other hand the conceptual model indicate that the flows will become less vulnerable to groundwater use under the higher flow regime components nl, intra-annual floods and large floods (Figures 6 and 7). The reason for this being that the contributions from non-groundwater discharges become more intense and seem to screen the low flow discharges that is highly vulnerable to groundwater use. Most of the groundwater type discharges that contribute to this component of the flow regime in all the river reaches are by this time recharged. However, if the groundwater use has significantly dropped the piezometric surface, it may take longer for the floods to develop and it might affect the flood peak. In these instances it may affect the ecological functioning of the aquatic ecosystem in the long run, hence the orange status. In the headwater and mountain reaches (Figure 6A and B) interflow still dominates even under the higher flows. Figure 7A and B shows that interflow also contributes to high flows and that groundwater become less important as the flow-curve increase.

The reason for the orange status of the large flood component of the flow regime in the foothill river reach is the fact that this river reach is the primary groundwater discharge area and the ultimate link between the groundwater and surface water in the TMG.

With regard to the lowland river reaches the most vulnerable part of the flow regime to groundwater use is the dry and wet season base flow, although this will be indirectly related to the TMG aquifer (Figure 7 B). It is for this reason that this reach has orange status, although it is by and large disconnected from the confined to semi-confined TMG aquifer. Base flow is the most critical flow for any aquatic ecosystem.

In conclusion, it can be said that this conceptual model is the first attempt to link groundwater discharges to the flow regime for each recognised river reach. It has also successfully demonstrated the need for an integrated approach to water resource management and is a handy tool in achieving this objective.

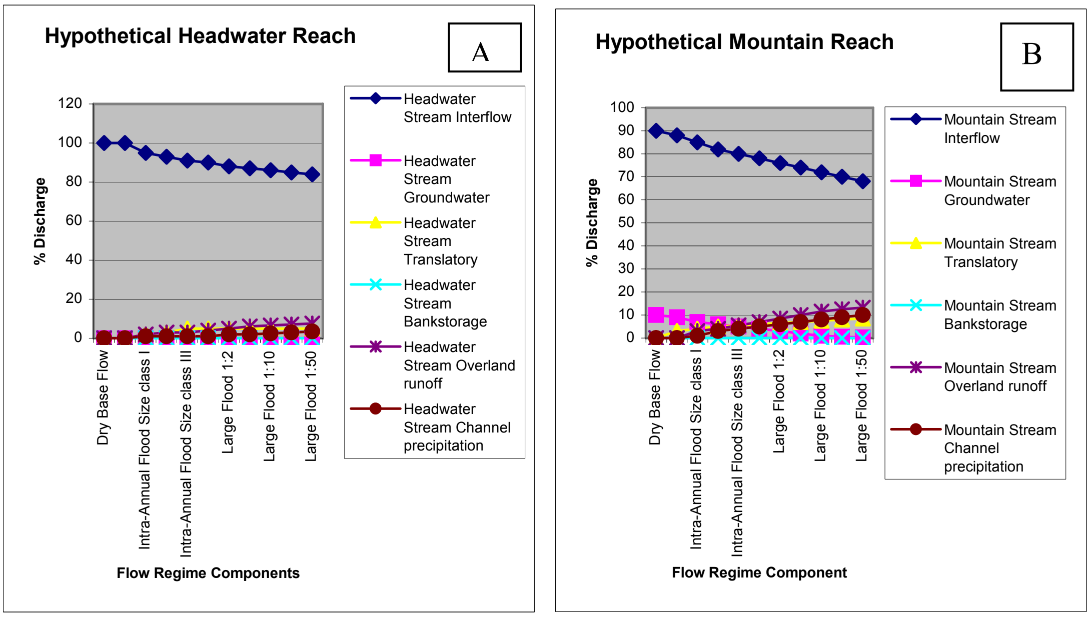

Figure 6 A and B

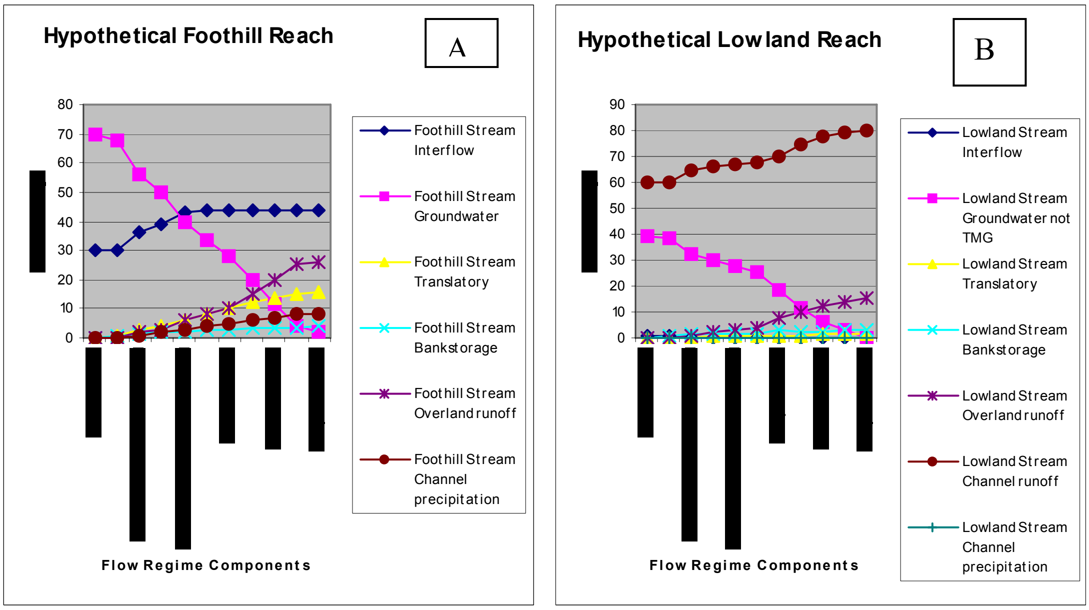

Figure 7 A and B

Table 3. Proposed groundwater discharge types contributing to stream flow for each river reach associated with

FLOW REGIME	FLOW REGIME COMPONENTS	HEADWATER REACH * Water Table below stream		MOUNTAIN REACH * Water Table below stream	FOOTHILL REACH * Water Table interchangeable	LOWLAND REACH * Water Table above stream
		EPHEMERAL	PERENNIAL	(MOSTLY PERENNIAL IN TMG)	(MOSTLY PERENNIAL IN TMG)	(MOSTLY PERENNIAL IN TMG)
LOW FLOW	**Dry season base flow**	- Perched spring discharge - Interflow * (Interflow dominated reach)	- Groundwater (Perched springs) - Interflow * (Interflow dominated)	- Groundwater (TMG springs + seeps) - Interflow dominated in most settings (Interflow might increase as a function of rejected recharge to TMG aquifer in some settings)	- Groundwater from mountain reach (TMG springs) and other discharges (hyporheic) - Primary Groundwater discharge zone from TMG (Confined to semi-confined aquifer) - Interflow - Limited bank storage discharge possible depending on antecedent conditions	- Groundwater from Foothill reach and discreet TMG discharges (Hyporheic etc.) - Bank storage discharge depending on antecedent conditions - Water Table (Alluvial unconfined aquifer not confined to semi-confined TMG aquifer)
	Wet season base flow	- Perched spring discharge - Increased Interflow	- Increased spring flow - Increased Interflow * (Interflow dominated)	- Increased Baseflow (result of increased TMG groundwater discharge) - Increased Interflow (Interflow might increase as a function of rejected recharge to TMG in some settings) - Possibility exists for some delayed translatory flow in some settings	- In creased Base flow (from mountain reach) - Primary Groundwater discharge throughout reach (Hyporheic) - Increased Interflow - Delayed translatory flow - Limited Bank storage discharge (depending on antecedent conditions)	- In creased Base flow (from foothill reach) - Water Table rise - Limited Interflow possible - Limited delayed translatory flow possible - Bank storage discharge (depending on antecedent conditions)
HIGH FLOW	**Intra-annual floods (smaller floods)**	- Base flow - Increased Interflow - Surface runoff	- Base flow (recharge dependent) - Increased Interflow - Surface runoff	- Base flow component -High degree of Interflow (Rejected recharge to TMG aquifer) - Some degree of Translatory flow in some settings - Surface runoff	- Increased Base flow - Increased Groundwater discharge throughout reach (Hyporheic etc.) - Increased Interflow - Translatory flow - Surface runoff - Increased flow from mountain reach - Tributary discharges - Limited Bank storage recharge depending on antecedent conditions	- Increased Base flow - Water Table rise - Limited Interflow possible - Limited Translatory flow possible - Surface runoff - Increased flow from foothill reach - Tributary discharges - Bank storage discharge or recharge depending on antecedent conditions
	Large Floods	- Base flow - High degree of Interflow - Higher Surface runoff	- Base flow (recharge dependent) - High degree of Interflow - Higher Surface runoff	- Elevated Base flow - Very high degree of Interflow (Preferential flow paths) - High degree of Translatory flow possible in some settings - Higher Surface runoff	- Elevated Base flow - Increased Groundwater discharge throughout reach (Hyporheic) - Increased Interflow (Preferential flow paths) - High degree of Translatory flow - High tributary discharges - Bank storage recharge - High Surface runoff	- Elevated Base flow - High Water Table rise - Limited Interflow (Preferential flow paths) - Limited Translatory flow possible - Higher Surface runoff - High tributary discharges - Bank storage recharge - Channel precipitation

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