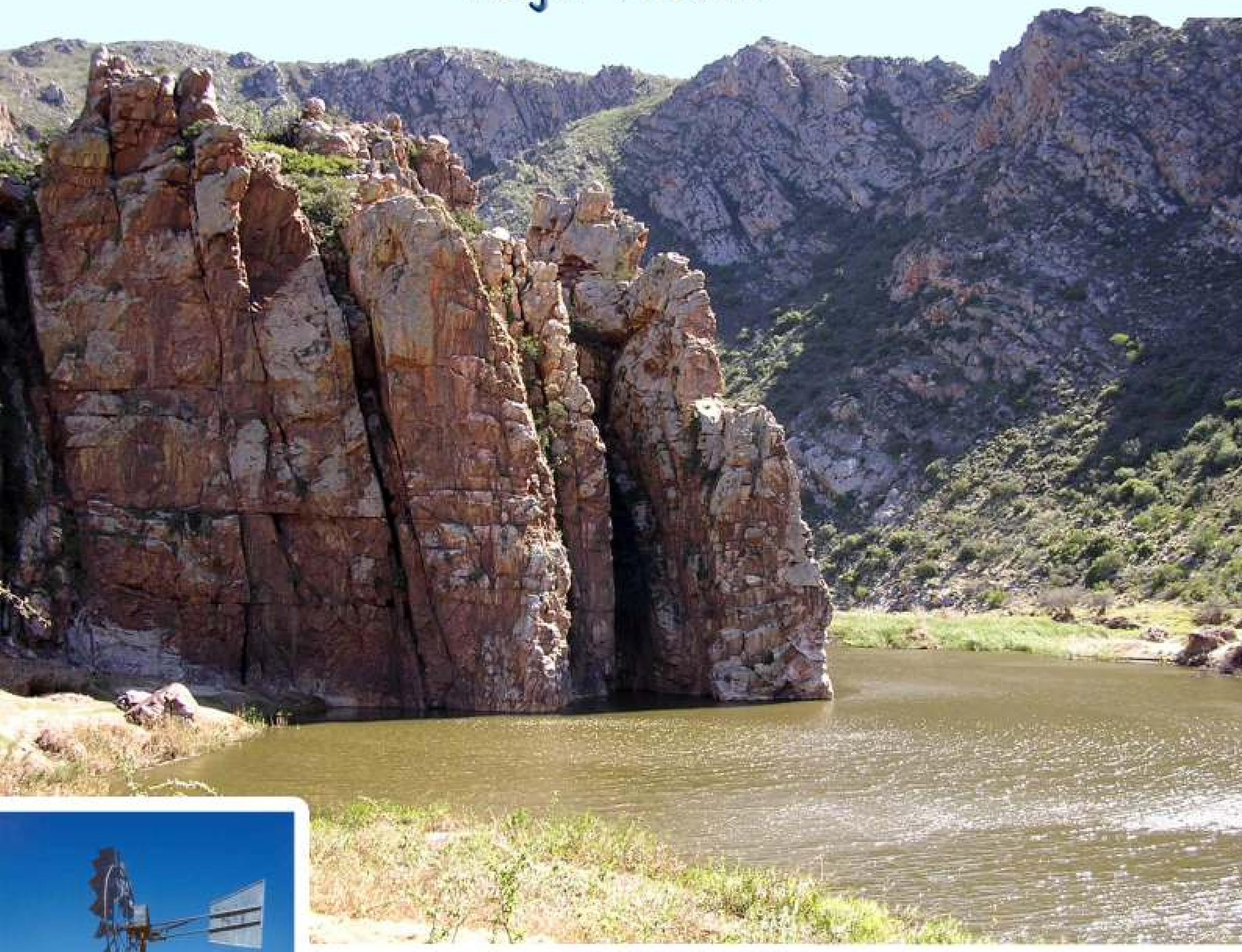
Surface Water: Groundwater Interaction in a South African Context

- A Geohydrological Perspective -

Roger Parsons



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Surface Water – Groundwater Interaction in a Southern African Context

Prepared for the
Water Research Commission

by

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Discharge of interflow from a subsurface pipe structure in the Piekenierskloof Formation, Table Mountain Group a week after significant rainfalls.

EXECUTIVE SUMMARY

In response to a greater awareness of the role of groundwater in sustaining the environment and recognition of a unitary and interdependent hydrological system, surface - groundwater interaction has emerged as an issue requiring greater attention. In response to this, the Water Research Commission commissioned this handbook to provide water resource managers and environmentalists with information regarding surface – groundwater interaction and facilitate a better understanding thereof. Three issues have been identified as contributing to the current poor understanding of surface - groundwater interaction:

- Not all subsurface water is groundwater – only that water in the saturated zone is defined as groundwater.
- Not all baseflow is derived from groundwater – baseflow also includes the contribution of interflow discharged into streams and rivers from the unsaturated zone.
- Inconsistent and misuse of terminology amongst the hydrological fraternity, and elsewhere.

The correct and consistent use of hydrological terms is considered key for developing a better understanding of surface – groundwater interaction. It is proposed *stormflow* and *baseflow* be used as non-process related terms to signify high amplitude, low frequency flow in a river during and immediately after a precipitation event and low amplitude, high frequency flow in a river during dry or fair weather periods. Baseflow is not a measure of the volume of groundwater discharged into a river or wetland, but it is recognised that groundwater does make a contribution to this component of river flow.

Water held or percolating through the unsaturated zone is often forgotten about, or simply ignored. However, it plays a key role in the hydrological system and helps to sustain aquatic ecosystems and terrestrial fauna and flora. Groundwater not only plays a significant role in sustaining baseflow of perennial rivers, but sustains wetlands across the country under a range of climatic, topographical and geological conditions.

Tools to identify and quantify the groundwater contribution to river flow and wetlands are lacking. Maps should be produced to indicate where groundwater makes a contribution to baseflow, while adaptation of the Pitman model and traditional baseflow separation techniques require investigation as useful quantification tools.

Unless research to improve our understanding of surface - groundwater interaction is undertaken, current misunderstandings will prevail - with serious implications. The Water Situation Assessment Model, for example, assumed a direct relationship between groundwater abstraction and its impact on surface water. Given that groundwater only significantly contributes to perennial rivers that drain about a third of the country, the assumption of the model is clearly invalid. Research results - together with documented case studies – should be widely published to facilitate an improved understanding of surface - groundwater interaction amongst water resource managers and practitioners alike.

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ABBREVIATIONS AND NOTATIONS USED

ARD	acid rock drainage
BFI	baseflow index
DWAF	Department of Water Affairs and Forestry
KL/ha/month	kilolitres per hectre per month
L/s	litres per second
MAP	mean annual precipitation
MCM/a	million cubic metres per annum (also written as x 10^6 m^3/a)
mamsl	metres above mean sea level
m/a	metres per annum
m/d	metres per day
mg/L	milligrams per litre
mm/a	millimetres per annum
mS/m	millisiemens per metre

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1. INTRODUCTION

More than ever before, understanding the interaction between surface and groundwater is required to facilitate appropriate decision-making and resource management. Historically, surface and groundwater were isolated in policy and regulation, partly as a result of the private status of groundwater under the old Water Act (Act 56 of 1956). This resulted in surface and groundwater practitioners working in isolation and seldom appreciating the interconnectivity between the two. Similarly, surface and groundwater resources were managed separately. Promulgation of the National Water Act (Act 36 of 1998) and other environmental legislation now require water resources be managed in a holistic and integrated fashion.

Levels of resource management or public environmental concern are frequently not matched by equivalent levels of understanding. To provide water managers and environmentalists with information regarding surface - groundwater interaction and to facilitate a better understanding thereof, the Water Research Commission commissioned the preparation of this handbook to address, *inter alia*:

- general principles of groundwater movement, storage and chemistry
- general principles of surface - groundwater interaction
- interaction in various geohydrological settings
- effect of abstracting groundwater on surface water flows
- methods and approaches to quantify surface - groundwater interaction
- appropriate and consistent terminology
- future research needs

While not intended as a detailed scientific document addressing the topic, an extensive reference list is provided to facilitate further inquiry. Further, readers are referred to the work of Winter *et al*. (1999) and Gardner (1999), both of which considered the issue of surface - groundwater interaction in a non-technical way. Good basic geohydrological textbooks such as those by Davis and DeWeist (1966), Ward (1975) and Driscoll (1995) may also be of interest and value.

Background information pertaining to the hydrological cycle and groundwater use in South Africa is presented in Chapters 2 and 3 of this report. The principles governing the occurrence and behaviour of groundwater is presented (Chapter 4) before describing the manifestation of groundwater at surface (Chapter 5). The interaction of groundwater with rivers, lakes, wetlands, estuaries and the sea is addressed in Chapter 6 while the ecological importance of this interaction is considered in Chapter 7. Approaches used to quantify surface - groundwater interaction are described in Chapter 8, activities impacting interaction and implications of not understanding the interaction are addressed in Chapters 9 and 10. The document is concluded with consideration of future research needs and recommendations on how to improve the current understanding of surface groundwater interaction.

An extensive glossary is provided at the back of this document, as is a list of references to be consulted for further information. Use is made throughout the document of text boxes presented related interesting information, highlight key considerations and provide a summary of information presented in the relevant chapter.

2. THE HYDROLOGICAL CYCLE

All water is part of the hydrological cycle, which is well documented in most general hydrological texts (Figure 2.1). However, linkages between the various interdependent components are now only starting to be understood as scientists are forced to take a more integrated perspective. Because of this, the term *hydrological system* might be more appropriate than *hydrological cycle* as most components operate in parallel rather than in a cyclic series.

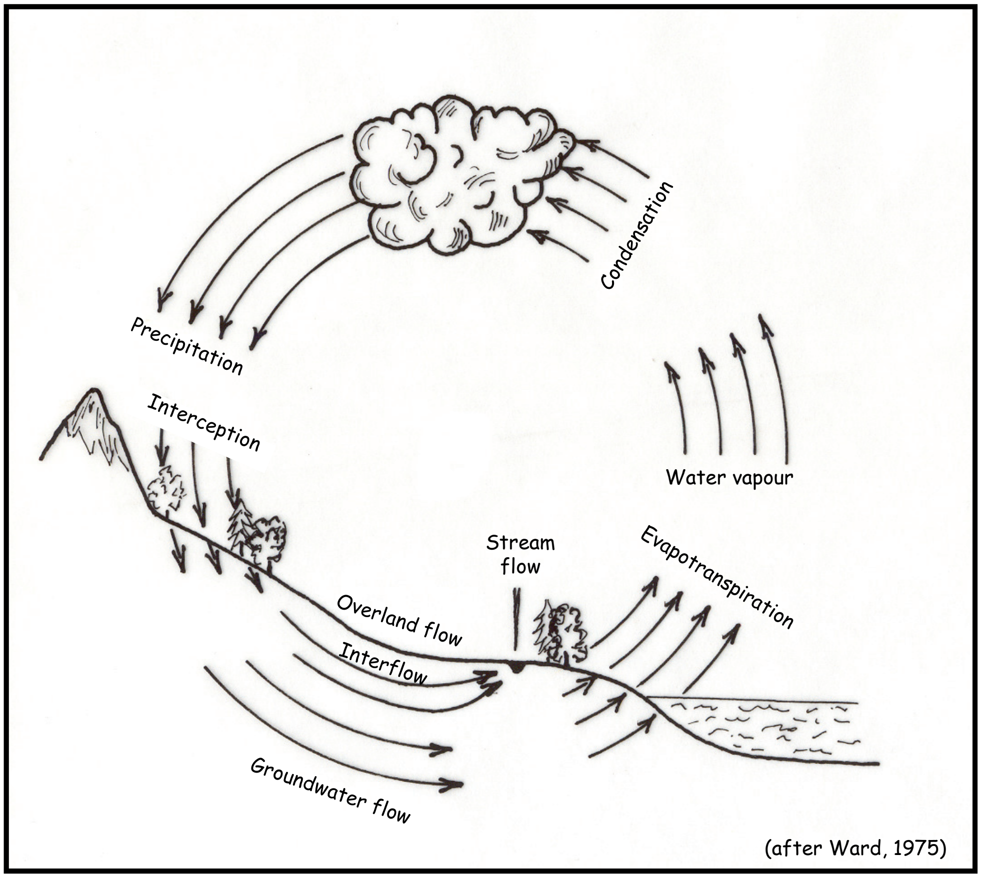

Figure 2.1: Simplified diagram of the hydrological cycle

The hydrological cycle illustrates the continuous movement of water above, on, and below the surface of the earth (Winter *et al.*, 1999). Classical depictions of the hydrological cycle generally illustrate water held in the atmosphere by clouds, precipitation (mainly through rainfall), lakes and river flow, with often only a vague and inaccurate acknowledgement of groundwater. Because it is not visible, groundwater generally attracts less attention than its visible counterparts. However, the volume of water stored beneath the surface is estimated to be more than 100 times greater than that stored in lakes and rivers (Figure 2.2).

Early Understanding of the Hydrological Cycle

In Ecclesiastes 1:7 the Bible presents the idea that water is cycled out of the sea and back into rivers. During the Middle Ages it was thought rivers were fed by seawater draining into holes in the sea floor, ascending through the earth and discharging high up in the mountains as springs. These springs then formed the headwaters of rivers, which dutifully carried the water back to the sea. A number of mechanisms were proposed to explain how water was lifted from the sea and discharged at the top of mountains, including "by virtue of the Heavens", suction and a great fire in the centre of the earth which vaporised the water. The latter idea was particularly good as it accounted for seawater becoming fresh as it was discharged. These ideas were formalised by Kirchner, a Jesuit priest, in the 17th century. However, with time and observation, a better understanding of the cycle evolved which did not require mysterious subsurface fires to lift water to the top of mountains.

At about the same time Kirchner was developing his theories, Pierre Perrault, a young French lawyer, calculated enough rainfall fell in the Seine River basin to account for all river flow. Based on this, he concluded seawater was not required to provide sufficient river flow and water cycled through the atmosphere provided the source of water. Antonio Vallisnieri, president of the University of Padua, who considered the origin of rivers using observations made in the Alps, supported Perrault's calculations. Vallisnieri did not observe water gushing out the top of mountains, but observed many alpine streams disappearing into the ground which fed a vast system of subterranean conduits. He concluded rainfall and snowmelt in the mountains resulted in the formation of rivers and the flow thereof. His findings put to rest the idea of the hole-in-the-sea floor theory and led to our current understanding of the hydrological system.

(Chapelle, 1997)

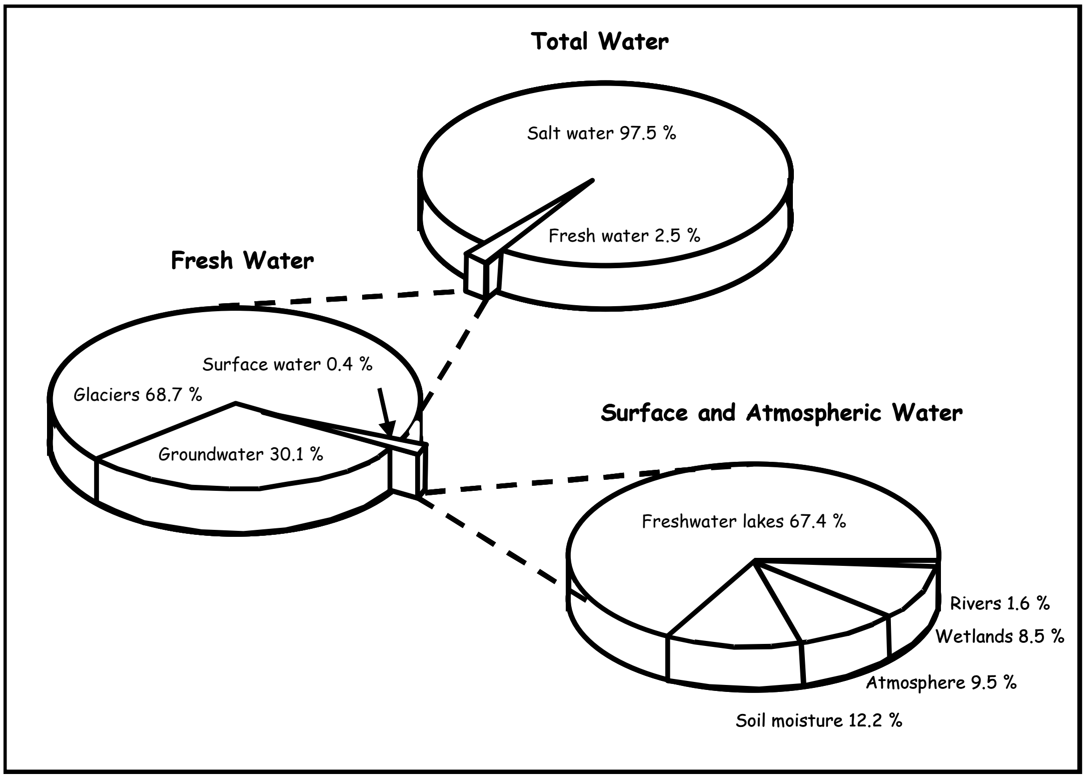

Figure 2.2: Distribution of the Earth's water bodies.

Key issues in providing a better understanding of the hydrological system are *interaction* between surface and groundwater and the *exchange* of water between the two components. Further, the hydrological cycle fails to illustrate variability in both time and space. For example, rain falls nearly everywhere, but its distribution and amount is highly variable. As a result, some rainfall never reaches the ocean as surface run-off, but either infiltrates the ground or is lost back into the atmosphere by evapotranspiration. In trying to understand surface – groundwater interaction, one needs to visualise interactions between the various components at different spatial and temporal scales.

Fresh Water Distribution

Almost one fifth of the world's fresh surface water resources are stored in the five Great Lakes in the United States of America (Lake Superior, Lake Michigan, Lake Huron, Lake Erie, Lake Ontario).

(National Geographic, 2002)

The Planet's Water Balance

Because we can see the sea, lakes and rivers, it is generally thought that this is where most of the planet's water is stored. Oceans cover 71 % of the earth's surface while most of the world's water is too saline to drink. Of the fresh water, almost 70 % is frozen and glaciers, permanent snow cover, ice and permafrost. About 30 % is stored underground and only 0.25 % is found in lakes and rivers

Saline Water ~ 97.5 %	*Fresh Water ~ 2.5 %*
Sea water ~ 99.0 %	Ice and snow ~ 70 %
Saline groundwater and lakes ~ 1.0 %	Ground water ~ 30 %
	Lakes and rivers ~ 0.25 %
	Soil, wetlands and biota ~ 0.1 %
	Atmospheric water vapor ~ 0.04 %
	Rivers only ~ 0.007 %

(National Geographic, 2002)

For such a simple chemical compound comprising two atoms of hydrogen and a single atom of oxygen, water is a complex, powerful and treasured substance. It occurs as water vapour, liquid water and ice and constantly changes form. We can also classify water in terms of where it is found:

- Meteoric water – water in circulation in the atmosphere
- Surface water – water found in rivers, lakes, wetlands and the ocean
- Subsurface water – all water found below the surface of the earth, including soil water, capillary water and groundwater
- Groundwater – all water in the zone of saturation i.e. below the water table

A major source of interdisciplinary confusion arises from not appreciating the difference between groundwater and subsurface water (Figure 2.3). While the term *subsurface water* is a recognised geohydrological term (Davis and DeWiest, 1966; Driscoll, 1995), it is seldom used. Many non-groundwater specialists (and some groundwater specialists for that matter) confuse groundwater and subsurface water. By definition, groundwater is that water found in the zone of saturation and does not include water stored in soil horizons or the vadose zone. The upper limit of groundwater is the water table or piezometric surface.

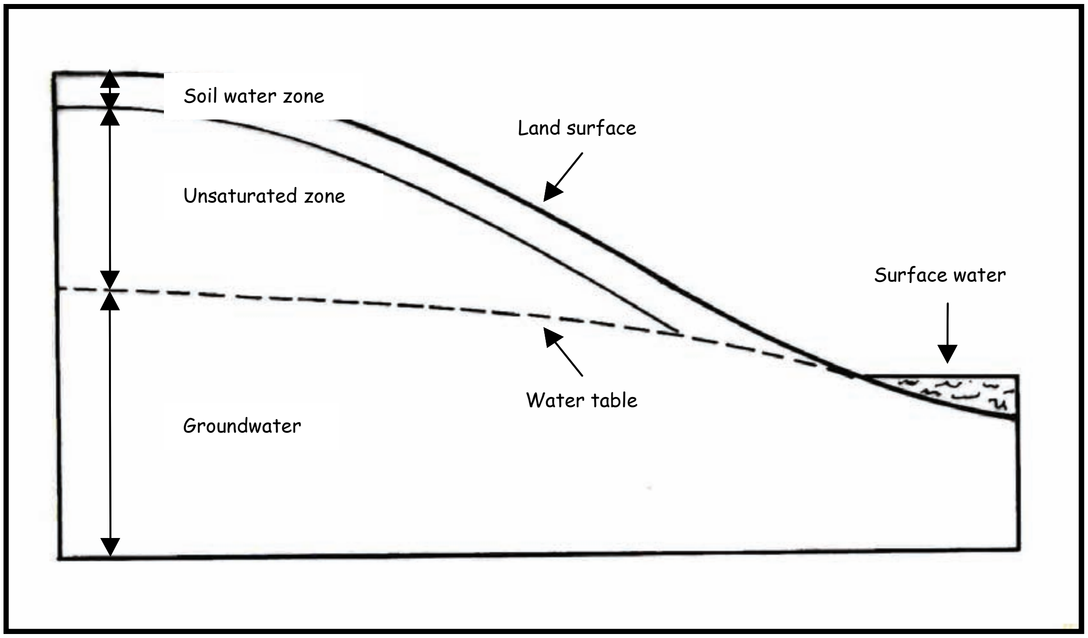

Figure 2.3: Distinction between groundwater and other subsurface waters.

The National Water Act (Act 36 of 1998) recognises a unitary, interdependent hydrological cycle and that all components form a single resource - water. While the unique characteristics of surface and groundwater need to be recognised and understood, so too must their interaction and ability to enhance or detract from each other.

Incorrect Use of Terminology

An issue to emerge from closer working relationships between scientists from various hydrological and related disciplines is the incorrect use of terminology. Baseflow, groundwater and perched aquifers are good examples of terminology frequently used incorrectly. Accepted terminology and definitions must be used at all times to prevent confusion. Senior scientists must take an active role in promoting proper use of terminology.

3. GROUNDWATER USE IN SOUTH AFRICA

Historic estimates of groundwater use in South Africa suggest about 15 % of the total volume of water used in the country is groundwater. In addition to large rural populations in KwaZulu Natal and the Eastern Cape being dependent on groundwater, more than 300 towns use groundwater, either as a sole source of water or conjunctively with surface supplies. This is particularly true of towns in the drier western two thirds of the country where surface water resources are scarce and unreliable due to the aridity of the area. Groundwater is also widely used in smaller coastal resorts that experience seasonal influxes of visitors and an associated increase in water demand.

The early San hunter-gathers who roamed southern Africa relied on rivers and springs for fresh, potable water. The Khoi probably dug the first water wells in the area, as a number of water wells reportedly thousands of years old are located in close proximity to cave paintings (Woodford and Chevallier, 2002). Following the pastoral revolution some 2 000 years ago, water and grazing became key drivers in migration patterns, with springs playing an important role in areas without rivers and in areas with ephemeral and seasonal rivers. A number of skirmishes and battles during the Great Trek are documented where the Voortrekkers and local inhabitants clashed over access to fresh water supplies. The Battle of Vanwyksvlei, for example, started when aggrieved local inhabitants attacked Voortrekkers after the Voortrekkers' livestock trampled precious springs used by the locals.

Groundwater played a pivotal role in the establishment of many towns and cities in South Africa. For example, groundwater discharged from dolomitic aquifers at the Fountains of Pretoria provided water to early settlers, and still plays a conjunctive role in the supply of potable water to the city. Springs north of Graaff-Reinet provided the early Voortrekkers with a source of water and resulted in the establishment of the town. Similarly, discharge of groundwater from the Springs resulted in the establishment of Uitenhage and this water is also still used today as a source for municipal supply. The role of water - and specifically groundwater - is reflected in the naming of many towns through the country e.g. De Aar (the vein), Bloemfontein (flower fountain), Bitterfontein (bitter fountain) and Putsonderwater (pit without water).

In 1999 it was estimated about 15 million South Africans were dependent on groundwater in one form or another (Parsons *et al*., 2001). Given the reported progress between 1999 and 2003 in addressing basic water needs, this estimate could be increased to about 19 million as most of the 9 million South Africans supplied with basic water supplies by the government since 1994 have been supplied from groundwater resources. Similarly, groundwater resources provide a measure of protection against the outbreaks of cholera experienced in the Eastern Province and KwaZulu-Natal.

The agricultural sector is highly dependent on groundwater as a source of water. Examination of early cadastral farm names reflects the role of springs in supplying water for agriculture, with names such as Springfontein (spring fountain), Brakfontein (salty fountain), Tweefontein (two fountains) and Wolwefontein (wolf fountain) being common. In addition to the volume of groundwater estimated to be used for irrigation, the number of windpumps seen in the drier parts of South Africa bears testimony to the dependence of the agricultural sector on groundwater.

Accepting quantification of groundwater use in South Africa is probably no better than an educated guess, estimates by Seward and Baron (2001) suggest about 2 100 MCM/a of water used in South Africa is obtained from the subsurface. Of this, about 69 % is used for irrigation, 15 % for rural water supply, 6 % by municipalities, 5 % for livestock watering and 5 % by the mining sector. Given that the groundwater harvest potential (maximum volume of groundwater that may be abstracted per square kilometer per annum without depleting the aquifers) of South Africa was estimated by DWAF to be in the order of 19 250 MCM/a (Baron *et al.*, 1998), significant potential for an expansion of groundwater use in this country exists. This is in stark contrast to Basson *et al.* (1997) who intimated little further expansion of groundwater use seems possible.

Groundwater Use

Given that the estimated volume of water used in South Africa in 2000 was in the order of 13 280 MCM/a and about 2 100 MCM/a was obtained from boreholes and springs, groundwater accounts for about 16 % of the total volume of water consumed in South Africa.

(Seward and Baron, 2001)
(DWAF, 2002)

A Need for Improved Understanding of Groundwater

Groundwater has played - and continues to play - a critical role in the development of South Africa. Because of the relatively small volume of water derived from groundwater resources, it pales into insignificance when compared to large dam schemes and inter-basin transfer schemes. However, the value of groundwater should not be measured by its contribution to the total volume of water used, but rather by it's availability in the western two thirds of the country where surface water is absent and / or unreliable, by its availability to rural populations whose water needs have - until recently - been ignored, it's ability to bridge dry periods and it's relatively low cost of development.

Very few senior water resource managers in DWAF, water boards and other water-related institutions have any geohydrological knowledge and expertise. As a result, they continue to focus on resources and solutions in which they are knowledgeable and decisions about groundwater remain uninformed. It is crucial all water resource managers be educated about the value and role of groundwater. It is hoped that this will trigger a wider appreciation of groundwater and thereby promote closer attention to the resource. Through wider education, better research, greater use and monitoring and assessment, a better understanding of groundwater will develop.

A first step in this process could be the quantification of groundwater use in South Africa. Such a study should determine the locality and use of groundwater in the country, document resources allocated to the exploration and management of groundwater resources and record problems experienced in the use thereof.

(Parsons *et al*., 2001)

4. A QUICK INTRODUCTION TO GROUNDWATER

One of the difficulties of groundwater is that it cannot be seen. This results in it being difficult to visualise or conceptualise, in turn causing the resource to be poorly understood and often ignored. Groundwater obeys the laws of physics and moves in a predictable manner. Like surface water, groundwater moves by gravity from higher lying areas to lower lying areas. However, groundwater is also driven by hydraulic pressure differences resulting from heterogeneities in the subsurface.

In trying to visualise groundwater movement, it is helpful to recognise groundwater moves far slower than surface water. While flow in rivers is typically measured in metres per second, the rate of groundwater movement is usually expressed in metres per annum. A rate of between 10 and 20 m/a are considered to be relative slow, while rates in excess of 100 m/a are considered relatively fast. As a result of these slow rates of movement, aquifers generally respond far more slowly to change. For example, the effects of drought may only be felt a few years after the event while contamination is often only detected years after contamination occurred.

However, it is important to recognise that it is not the movement of groundwater that controls the discharge of groundwater into surface water bodies, but rather hydraulic pressure. This aspect is addressed further when describing translatory flow (page 4-11) and quantifying surface – groundwater interaction (Chapter 8).

Groundwater and the Vadose Zone

Water beneath the land occurs in two principal zones, namely the saturated zone and the unsaturated or vadoze zone (Figure 2.3). In the case of the unsaturated zone, interstices or pore spaces contain both water and air. Though the amount of water held in this zone may be appreciable, it is held in place by capillary forces and is not removed during pumping. However, most of this water is available to plants.

The unsaturated zone, which includes unsaturated soil horizons, has a unique position in that it integrates many of the components of the hydrological cycle. For example, it forms an interface between land and the atmosphere, the land surface and underlying aquifers and controls infiltration and surface runoff processes.

Fractures and other macropores within the unsaturated zone could be saturated, but pore spaces in the matrix rock adjacent to the fracture will contain both water and air. While it is recognised very localised areas may be saturated, the distinction between the unsaturated and saturated zone is not made on a micro-scale.

It is also of relevance that downward gravitational forces largely drive water movement in the unsaturated zone. Lateral flow may be induced by localised differences in the hydraulic properties of the aquifer material. Downward movement of water is stopped when the matric forces of individual soil or rock particles exceed that of gravity.

A capillary zone is found between the unsaturated zone and the saturated zone. In this zone, the capillary forces of the individual soil or rock particles attract water molecules. Finer materials such as clays exert a stronger capillary action than coarser materials. The degree of saturation decreases from the water table upwards while the thickness of the capillary zone ranges from a few millimeters to tens or hundreds of millimeters.

The water table (or piezometric surface) marks the beginning of the saturated zone where pore spaces are completely filled (saturated) with water. Here, the pore water pressure is equal to atmospheric pressure. As a general rule, the water table mimics topography. The difference between a water table and piezometric surface is described in the section on unconfined and confined aquifers (page 4.3).

Water beneath the water table is considered by geohydrologists to be groundwater and that above the water table to be soil water or water of the vadose zone. Often non-groundwater specialists consider all water beneath the surface of the earth to be groundwater. **This is a major source of confusion when working with a range of professional disciplines and lay people.**

Aquifers

The term aquifer comes from Latin (*aqua* = water and *fer* = bearing). Geologic formations that contain groundwater in sufficient quantities to be used for domestic, agricultural, commercial, industrial or mining purposes are referred to as aquifers. The thickness and aerial extent of aquifers vary greatly.

Groundwater is encountered almost everywhere. In instances where very little water is stored or transmitted, the word aquifer is inappropriate. Terms such as aquitard (a geologic formation that retards the movement of groundwater, but may store groundwater) or aquiclude (a geologic formation that neither transmits or stores groundwater) may be more appropriate.

Primary and Secondary Aquifers

Groundwater is stored and transmitted in voids between individual soil, sediment or rock particles (Figure 4.1). These spaces are referred to as pore spaces or interstices. It stands to reason that more water can move through large pore spaces than through smaller pore spaces. One would hence expect more water to flow through coarse sand than clay.

One would also expect very little water to flow through solid rock, where interstices have been filled by cement during the rock forming process. However, should the rock be altered by weathering, folding, faulting or uplifting, groundwater can move in the voids created by the alteration (Figure 4.1). Such voids are referred to as secondary openings and give rise to the concept of primary and secondary aquifers. In the case of primary aquifers, groundwater moves through the original pore spaces of the geological material while in the case of secondary aquifers, movement occurs through pore spaces and fractures created during the physical alteration of the aquifer medium.

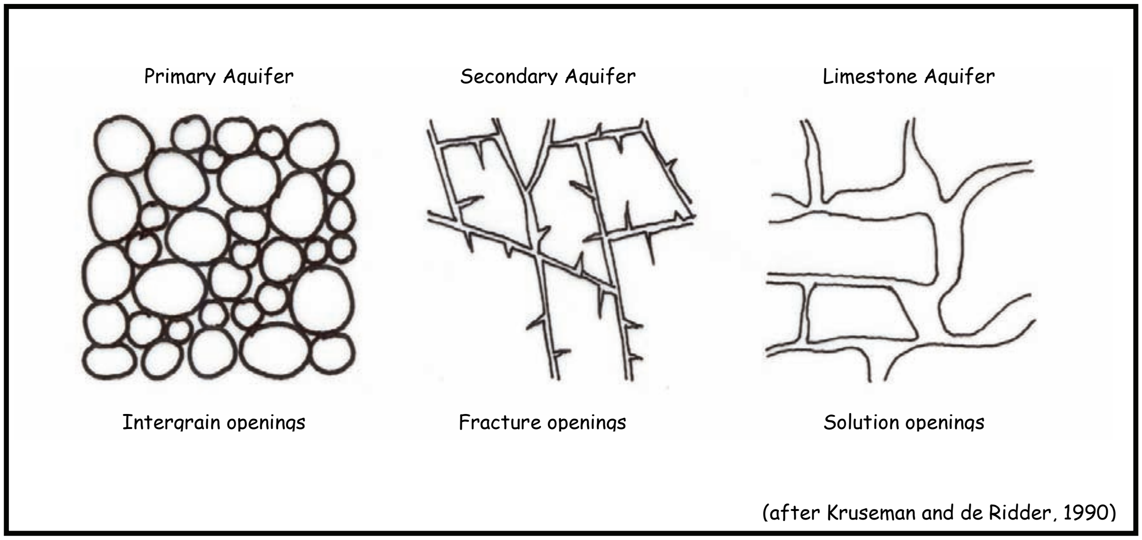

Figure 4.1: Types of interstitial openings.

A striking feature of secondary aquifers is the variability of aquifer parameters over short distances. Water moves through cracks, fractures and fissures, but is mostly stored in the host rock. Both the hydraulic conductivity and storativity of fractured rock aquifers can vary by several orders of magnitude over very short distances.

Almost 98 % of aquifers in South Africa are classified as secondary aquifers, with only a few coastal primary aquifers and those associated with alluvial deposits of major rivers being of significance. Examples of significant primary aquifers are found at Atlantis and on the Cape Flats of Cape Town, along the Zululand coast north of Durban and in major river channels such as the Mokolo and Crocodile Rivers in the Northern Province. Examples of major fractured aquifers include those of the Table Mountain Group, the Karoo Supergroup and dolomitic rocks of the Transvaal Supergroup.

Unconfined and Confined Aquifers

Unconfined aquifers occur in permeable geological formations where the water table can move freely up or down, without restriction (Figure 4.2). At the water table, water pressure is equal to atmospheric pressure. These aquifers are mostly recharged by the downward migration of water from precipitation and / or surface water bodies.

Aquifers overlain by material with a hydraulic conductivity significantly lower than that of the aquifer are called confined aquifers. The overlying confining layer prevents upward movement of the water table, resulting in an increase of hydrostatic pressure in the aquifer. An imaginary line connecting points of equal pressure is referred to as the piezometric surface, and is the equivalent of a water table found in unconfined aquifers. These aquifers are usually recharged by the lateral or upward migration of water and seldom recharged by direct downward percolation of subsurface water. Artesian aquifers are good examples of confined aquifers with the Great Artesian Basin in Australia being a well-documented system.

The Uitenhage Artesian Basin is the only significant artesian system in South Africa, but localised confined conditions result in artesian boreholes being found throughout the country.

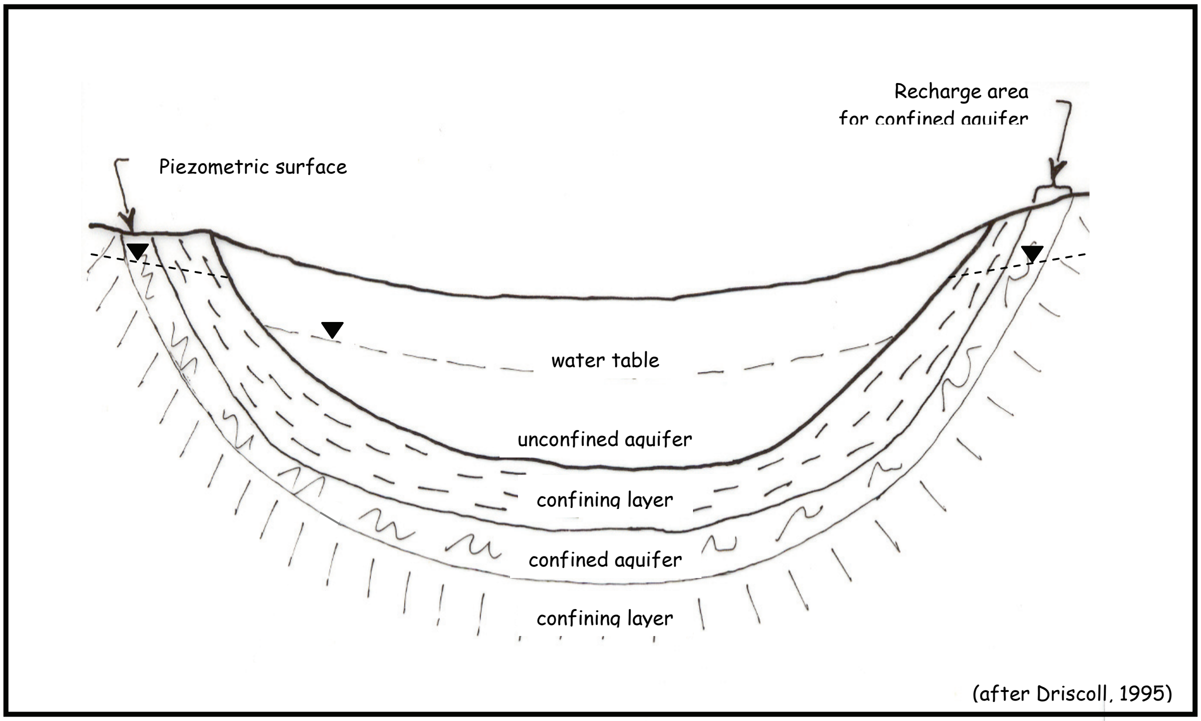

Figure 4.2: Schematic representation of confined and unconfined aquifers.

Uitenhage Artesian Basin

The Uitenhage Artesian Basin comprises weathered mudstones and siltstones of Cretaceous age overlying hard, fractured quartzites of the Table Mountain Group. The mudstones and siltstones act as a regional confining layer (aquiclude), resulting in widespread artesian conditions. Uncontrolled drilling and over-exploitation of the aquifer in the early 1900s resulted in a steady decline in groundwater pressures and an associated drop in groundwater levels, forcing the government to declare a groundwater control area in 1957. The basin covers an area of about 3 700 km^2, and stretches from the Groot Winterhoek Mountains north-west of Uitenhage to Algoa Bay in the east. Groundwater from the aquifer has been used to supply Uitenhage with water and support the local citrus industry. The Uitenhage Springs initially flowed at about 80 L/s, before over-exploitation resulted in the yield dropping to about 45 L/s. The yield of the springs increased to about 65 L/s as a result of the government intervention, but heavy drought-induced groundwater abstraction in the 1980s again resulted in the yield of the springs declining to 55 L/s.

(Maclear, 2001)

To complicate matters, geohydrologists also talk about semi-confined or semi-unconfined aquifers. This is particularly true in South Africa where the secondary nature of aquifers results in relatively large differences in hydraulic conductivity over short distances. Confined and unconfined aquifers are opposite end members of a continuum from aquifers under pressure to those where the water table is in equilibrium with atmospheric pressures (Brown *et al*., 2003). Semi-confined and semi-unconfined aquifers are found between the two end members. While not preventing the upward movement of water, differences in hydraulic conductivity retard the movement of water, thereby resulting in both lateral and vertical localised pressure differences. Most aquifers in South Africa are semi-confined or semi-unconfined.

Perched Aquifers

Non-groundwater specialists often erroneously use the term *perched aquifer* to describe near-surface or shallow aquifers. However, the term specifically relates to a saturated groundwater body that overlies an unsaturated zone (Figure 4.3). Often these are localised bodies where an underlying layer has a significantly lower hydraulic conductivity than the saturated water body, thereby preventing or retarding the downward percolation of water. Springs or seeps often form where localised perched conditions induce a lateral migration of water, which then discharge at surface.

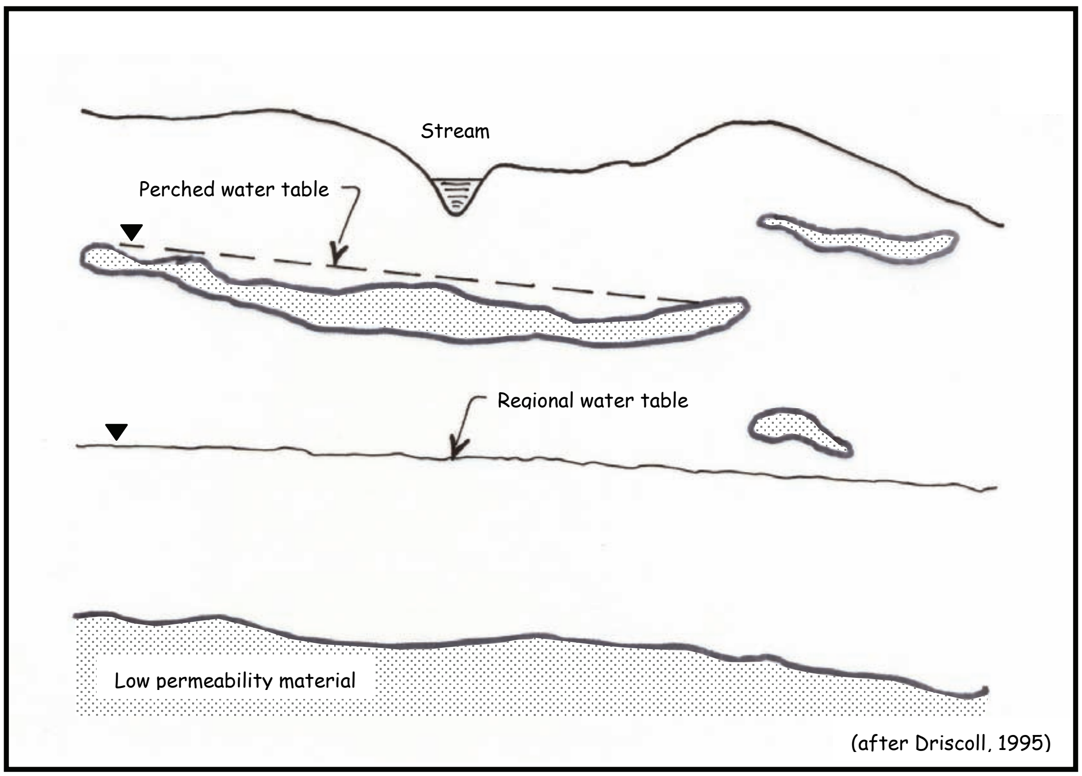

Figure 4.3: Illustration of a perched water table.

South African Groundwater Regions

Vegter (1995, 2001) prepared maps depicting groundwater regions in South Africa. Much of the subdivision was based on lithostratigraphy, but also included consideration of surface relief, topography, mean annual rainfall and vegetation. Lithostratigraphy includes consideration of lithology (the physical character of the rock) and stratigraphy (the study of stratified rocks, and particular their sequence in time). Vegter (1996) defined 65 groundwater regions, but these have been simplified into 11 groundwater provinces (Figure 4.4). The purpose of defining regions is to demarcate aquifers of similar character, behavior and potential.

Aquifer Management Classification System

Sole Source Aquifer System: An aquifer which is used to supply 50 % or more of domestic water for a given area, and for which there are no reasonably available alternative sources should the aquifer be impacted upon or depleted. Aquifer yields and natural water quality are immaterial.

Major Aquifer System: Highly permeable formations, usually with a known or probable presence of significant fracturing. They may be highly productive and able to support large abstractions for public supply and other purposes. Water quality is generally very good (less than 150 mS/m).

Minor Aquifer System: These can be fractured or potentially fractured rocks which do not have a high primary permeability, or other formations of variable permeability. Aquifer extent may be limited and water quality variable. Although these aquifers seldom produce large quantities of water, they are important both for local supplies and in supplying base flow for rivers.

Non-Aquifer System (also called a Poor Aquifer System): These are formations with negligible permeability that are generally regarded as not containing groundwater in exploitable quantities. Water quality may also be such that it renders the aquifer as unusable. However, groundwater flow through such rocks, although imperceptible, does take place, and needs to be considered when assessing the risk associated with persistent pollutants.

Special Aquifer System: An aquifer designated as such by the Minister of Water Affairs, after due process.

(Parsons, 1995)

Recharge and Discharge

While some groundwater may have been trapped in the subsurface during the rock forming process (connate water) or formed during the rock forming process (juvenile water), most groundwater is meteoric in origin and aquifers are replenished by rain. Recharge results from the percolation and infiltration of precipitation (including snowmelt and surface run-off) into the subsurface and the accretion of water to the upper surface of the saturated zone. Aquifers may be recharged from water infiltrating vertically into the aquifer, by groundwater flowing laterally into an aquifer system or by water seeping upwards from underlying sources.

Rates of recharge vary significantly, depending on antecedent moisture conditions, rainfall volumes and patterns, temperature, geology, topography and other factors. Recharge of the Table Mountain Group is expected to range between 7 and 23 % MAP while that to Karoo aquifers is in the order of 2 to 3 % MAP. Recharge to sandy alluvial aquifers may be in the order of 20 to 30 % MAP while recharge of dolomitic aquifers is estimated at 8 to 14 % MAP.

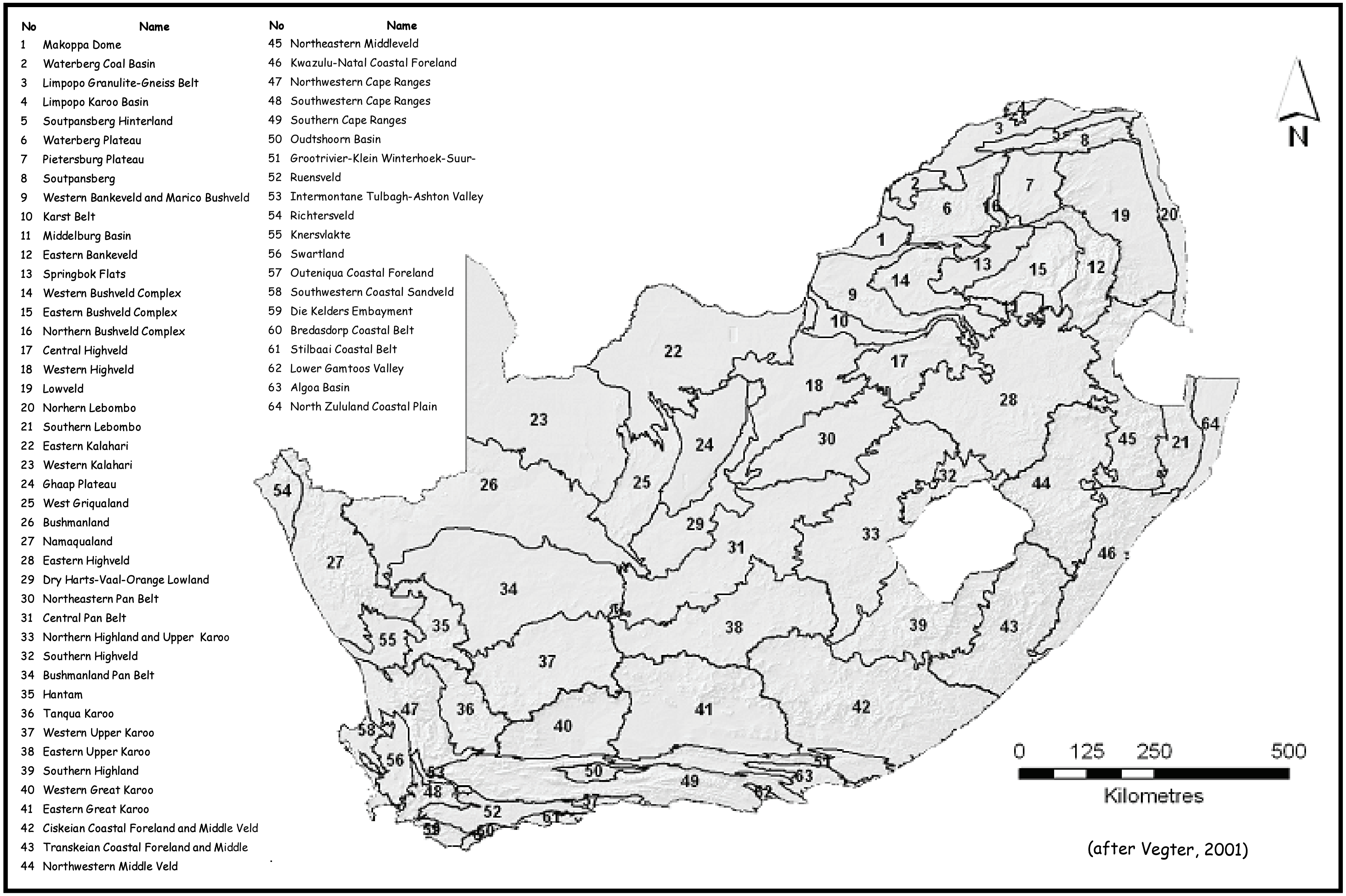

Figure 4.4: Groundwater regions of South Africa.

Recharge Estimation

Recharge is a very complex process that varies significantly in both space and time. The amount of precipitation reaching the groundwater body depends on a host of factors, including the rate and volume of rainfall, soil type and antecedent moisture conditions, geology, topography and others. For comparative and estimation purposes, recharge is often expressed as a percentage of mean annual precipitation (% MAP). However, it must be recognised that this is a gross oversimplification of a complex process.

It is often thought water moving downwards in the unsaturated zone does so in a uniform manner and only after the soil moisture deficit has been satisfied. However, the concept of preferential flow is now well recognized. In fractured aquifers, downward moving water does so in cracks and fissures, thereby bypassing much of the rock mass. Similarly, water moving downwards in unconsolidated sediments does so in fingers and seldom has a uniform advancing front. A lateral component to flow occurs at a localised scale as a result of significant changes in hydraulic properties of the aquifer media. It hence needs to be remembered that water movement in the unsaturated zone is - at a macroscale - generally downwards and driven by gravitational forces. However, on a micro-scale, water movement can be complex, influenced by local heterogeneities and can include both vertical and lateral flow components.

Groundwater discharge occurs when the water table intersects the earth's surface and is much of the focus of this document. Most groundwater discharge is to rivers (Stone and Lindley Stone, 1994), but groundwater is also discharged to wetlands, lakes, estuaries and the sea. While discharge can manifest itself as springs or seeps, not all springs or seeps are fed by groundwater. Many are fed by interflow or subsurface water found above the water table.

Recharge is a key parameter in understanding and quantifying groundwater resources, as it provides an indication of the volume of groundwater that can sustainably be abstracted from an aquifer without inducing groundwater mining, i.e. a continual decline in groundwater levels as a result of over-abstraction. Unfortunately, recharge is difficult to quantify as it varies in both time and space and can change in response to groundwater abstraction (induced recharge). A number of techniques exist for quantifying recharge, including simple mass balance calculations, numeric modeling and isotopic methods. All are reliant on measured rainfall data, monitored groundwater level and abstraction data and water chemistry data.

Direction of Groundwater Flow

Groundwater moves from areas of higher hydraulic pressure to areas of lower pressure in the direction of the hydraulic gradient, i.e. from areas of recharge to areas of discharge. The hydraulic gradient is the driving force behind groundwater movement and is defined as the change of head per unit distance. By measuring the depth to groundwater in a borehole and calculating the position of the water table above a datum (such as mean sea level), the direction of groundwater flow can be determined. At least three boreholes are required to calculate the direction of groundwater flow.

If sufficient static (or rest) groundwater level data are available, a flownet can be constructed and groundwater flow directions over a wide area can be determined (Figure 4.5). A flownet is essentially a contour map of the water table, with the direction of groundwater flow being perpendicular to the contour lines.

Flownets can be used to determine whether groundwater discharges into a river or whether a river discharges into the underlying aquifer system. To do this one must have sufficient groundwater level data measured at about the same time, as the direction of flow between a river and the underlying groundwater system changes both spatially and temporarily.

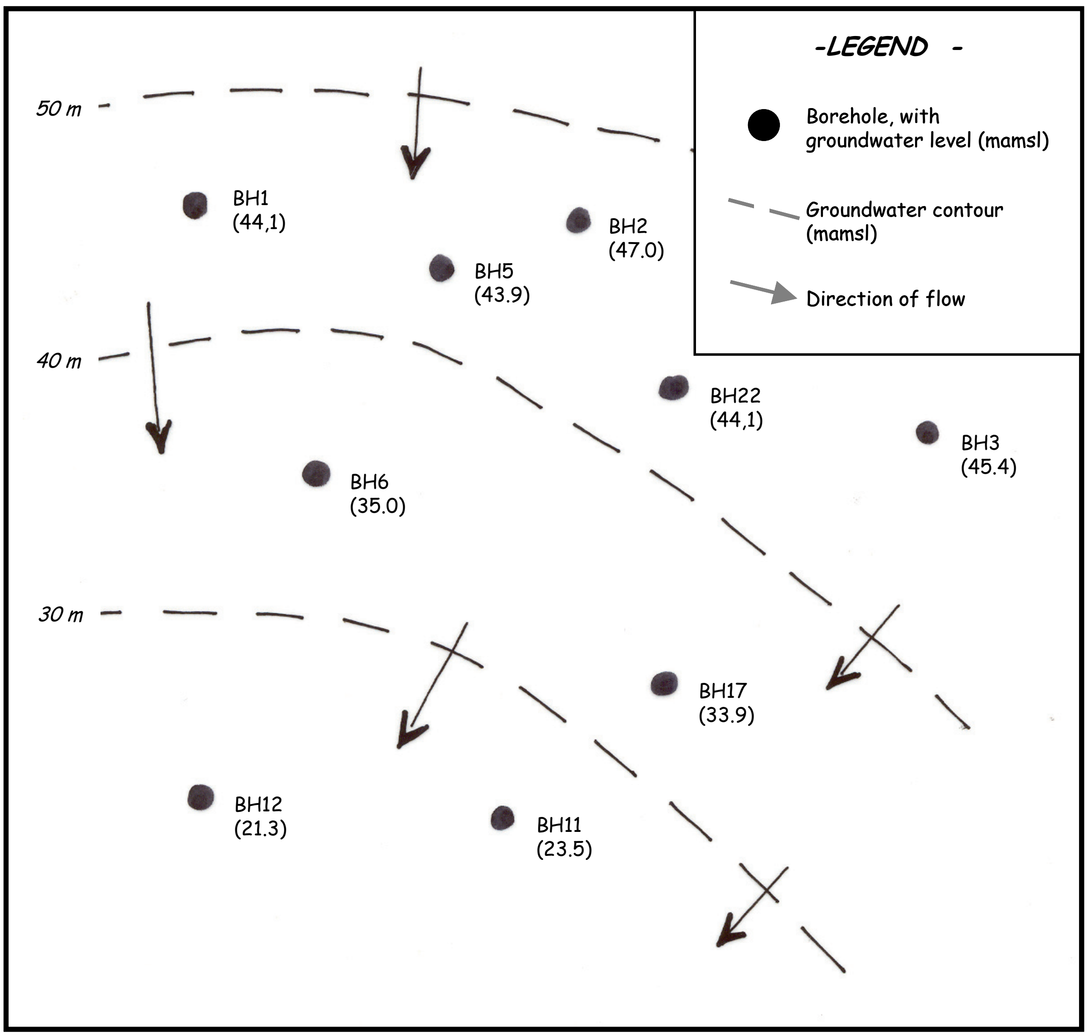

Figure 4.5: Flownet, showing groundwater elevations and direction of flow.

Rate of Groundwater Movement

In 1856, a well-known French engineer by the name of Henri Darcy laid the foundation for groundwater theory while working on the public water supply for Dijon. Darcy discovered that the rate of groundwater movement was a function of hydraulic gradient and the ability of the aquifer material to allow water to flow through it.

$$Q = K\,A\,\frac{(h_1 - h_2)}{L}$$

where	Q	=	discharge (L^3 / T)
	K	=	constant (L / T)
	A	=	area (L^2)
	h	=	height difference between two points (L)
	L	=	length difference between two points (L)

The constant K is referred to as the hydraulic conductivity of the geologic material and describes the rate at which water is able to move through the saturated soil or aquifer media. It is a function of the size, shape and connectedness of the interstices. Typical ranges of hydraulic conductivity for different aquifer materials are shown in Figure 4.6. Because of the secondary nature of aquifers in South Africa, hydraulic properties vary significantly over short distances. Further, if the secondary openings have a dominant orientation (as is usually the case when the openings are the result of folding and faulting), then the properties may vary in a specific direction.

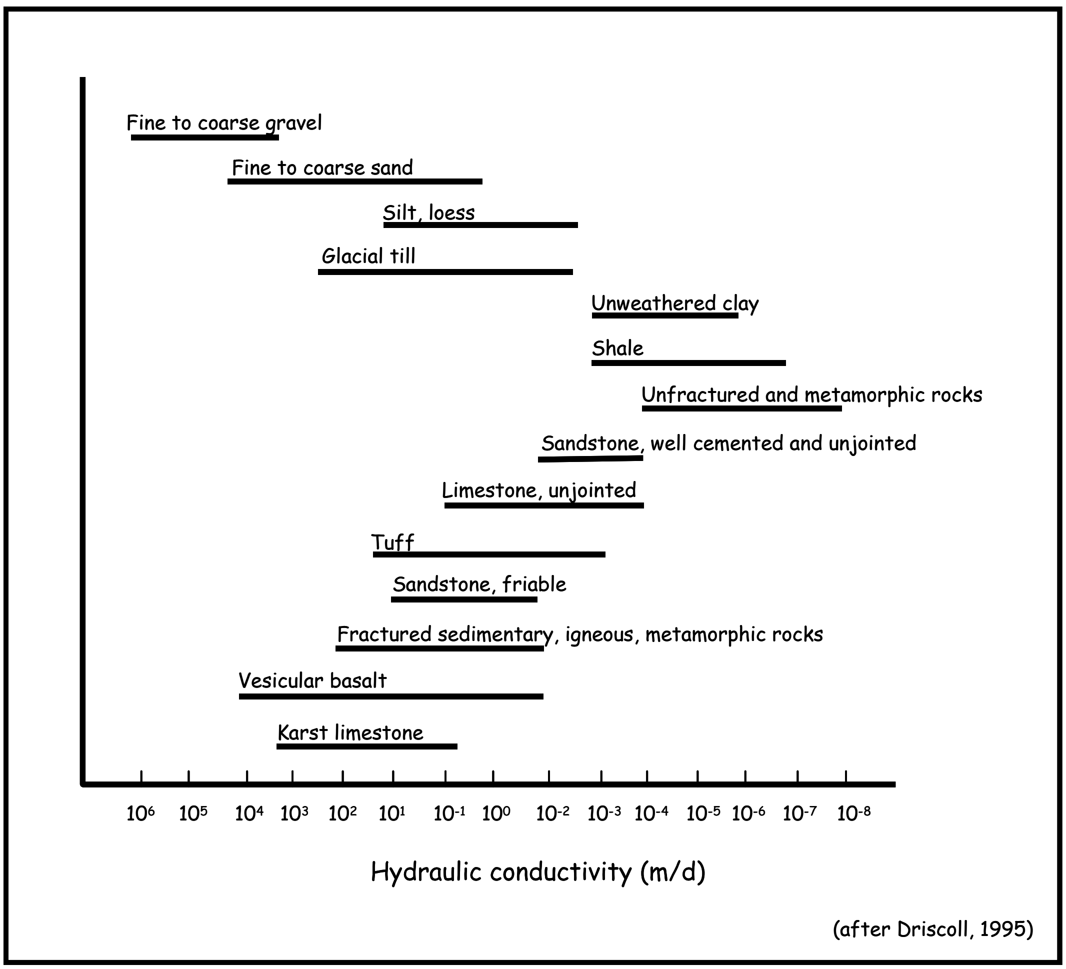

Figure 4.6: Typical values of hydraulic conductivity for different aquifer media.

Hydraulic Conductivity and Permeability

The terms *hydraulic conductivity* and *permeability* are often erroneously used interchangeably. While similar, hydraulic conductivity relates specifically to the movement of water in the subsurface while permeability includes a fluid density function.

Porosity and the Transmission of Water

The term *porosity* is often used incorrectly to indicate the ease with which water can move through a material. Porosity is a ratio of the volume of pore space in relation to the total volume of a rock. Clays have a relatively high porosity, but because most of the interstitial pore spaces are not connected, the pore spaces are small and water is held in place by strong molecular forces, the rate of water movement through clays is very slow. To transmit large quantities of water, the material needs to be both porous and permeable.

Groundwater generally moves very slowly, with the rate of movement being measured in metres per annum. A rate of between 10 and 20 m/a are considered to be relative slow, while rates in excess of 100 m/a are considered relatively fast.

As a result of the slow rate of groundwater movement, the age of groundwater ranges between years and tens of thousands of years. Decay of various isotopes provides a useful tool for aging water, with chloroflurocarbons (CFCs) and tritium (^{3}H) being useful for younger groundwaters and deuterium (2H) and carbon (^{14}C) being used to date older groundwaters. Groundwater in a permeable, regularly recharged system such as the primary Atlantis Aquifer would be relatively young, say less than 10 years old. In the dynamic fractured aquifer system in the Agter-Witzenberg valley, groundwater was aged to be in the order of 20 years old. In the Dewetsdorp area, groundwater in the upper parts of the Karoo aquifer was found to be younger (20 years old) than that in the deeper parts of the aquifer (50 years old). However, groundwater in slow moving aquifer systems with low permeabilities could be in excess of 10 000 years old. For example, groundwater in some Kalahari aquifers has been estimated to be older than 40 000 years, while groundwater sampled from the Stampriet and Uitenhage artesian aquifers was estimated to be older than 30 000 years.

Translatory Flow

While groundwater moves slowly, aquifers often respond almost immediately to recharge i.e. within hours to days. Through a process of displacement, new water added to the subsurface “pushes” the old water molecule in front of it forward. The old water molecule then pushes the even older water molecule in front of it forward, creating a piston effect. This process of displacing individual water molecules allows the impact of the additional water to be felt elsewhere in the system without the new water having to travel to the point of impact. This is known as *translatory flow* and is an often forgotten mechanism of groundwater movement.

Underground Rivers and Lakes

Non-groundwater specialists often talk about underground rivers and lakes. However these are misnomers generally used in ignorance or used to support the lore of water divining. It is only in the case of karstic or limestone environments where one encounters cavities large enough to allow direct comparison with rivers. In all other aquifer types, groundwater moves between pores and cracks and fractures measuring in width from a few centimeters down to fractions of a millimeter.

Storage of Groundwater

Groundwater is stored in pore spaces between individual soil particles or interstices between cracks and fissures (Figure 4.1). The coefficient of storage (or storativity) is defined as the volume of water an aquifer releases per unit plan area of aquifer per unit change of head. Laboratory tests or aquifer tests are used to determine the storativity of an area. In primary aquifers, storativity generally ranges between 0.1 and 0.2, while in fractured and weathered rocks, storativity is usually less than 0.01.

State of Dynamic Equilibrium

Though usually slow to respond to change (except recharge), groundwater systems remain in a state of dynamic equilibrium. Under natural conditions, the position of the water table reflects an equilibrium between aquifer recharge and discharge. However, if recharge should reduce in response to lower rainfall, the water table will start to fall and, in turn, result in a reduction in aquifer discharge. The water table will settle at a new level, reflecting the new equilibrium between recharge and discharge. Similarly, abstraction of groundwater will increase the volume of water discharged from an aquifer, thereby inducing a shift in the water table until a new dynamic equilibrium is reached. The continual changing of the position of the water table – whether by a few millimeters or a couple of meters – clearly impacts the amount of groundwater discharged to surface water bodies.

Groundwater Quality

Two fundamental controls on water chemistry are the type of geological material present and the time that the water is in contact with these materials (Winter *et al.*, 1999). Because of the longer period of rock - water interaction, groundwater is generally more mineralized than surface water. However, both surface and groundwater qualities reflect the controls of the underlying bedrock. For example, waters in the Western Cape underlain by chemically-inert quartzitic sandstones of the Table Mountain Group display a low salinity, acidic and sodium chloride character. Waters in the Eastern Cape underlain by argillaceous rocks of the Karoo Supergroup tend towards higher salinities and pH and a more alkaline character.

Interaction between surface and groundwater bodies provides a mechanism for chemical exchange between various waters. In turn, this affects the supply of oxygen, nutrients and other chemical constituents to ecosystems dependent on these waters.

Monitoring and analysis of both surface and groundwater quality could provide a useful tool for identifying and quantifying surface - groundwater interaction. For example, during periods of stormflow when rainfall makes the biggest contribution to flow in the river, the quality of water in the river will tend towards that of rainwater quality. However, as water levels in the river recede and the relative contribution of groundwater increases, the quality of water in the river will tend towards that of groundwater.

Threats to Groundwater

Since groundwater cannot be seen, it is often assumed that everything underground is in order. Unfortunately, this sometimes is not the case. Probably the three main threats to groundwater are a lack of recharge, over-abstraction and contamination. While there is little we can do to control rainfall, we can increase recharge using a variety of artificial recharge techniques (Murray, 2002). This can be used to counteract the impacts of over-abstraction and urbanisation, where increasing the area of hard, impermeable surfaces reduces the amount of precipitation entering the subsurface. Artificial recharge can also be used to increase the potential yield of an aquifer.

Over-abstraction of groundwater can result in depletion of the groundwater Reserve. Amongst others, it can also result in saline intrusion, land subsidence, sinkhole formation and a reduction in the groundwater contribution to river flow. Appropriate monitoring of abstraction (rates and volumes) and groundwater levels facilitates aquifer management. This, in turn, ensures that groundwater resources can be used in a sustainable manner. The impacts of over-abstraction are described further in Chapter 9.

Because groundwater cannot be seen, the effects of aquifer contamination are often only realised long after the event. Once an aquifer is contaminated, it is both expensive and technically difficult to remedy. From a surface - groundwater interaction perspective, contamination of aquifers and the subsurface discharge into surface water bodies is an obvious problem. Some examples of this are given in Chapter 9.

In Summary

- Groundwater is disadvantaged as it cannot be seen. It is poorly understood by the lay person, who generally accept mystical ideas about its location and movement. However, groundwater obeys the laws of physics and moves in a predictable manner.
- Not all subsurface water can be defined as groundwater. Only that portion in the saturated zone below the water table is classified as groundwater.
- Aquifers in South Africa are generally heterogeneous and isotropic, with hydraulic properties varying significantly over short distances.
- Over-abstraction and contamination are arguably the two greatest threats to the sustainable use of groundwater in South Africa. Appropriate monitoring and management is required to ensure these resources continue to play a meaningful role in the development of the country.

5. MANIFESTATION OF GROUNDWATER DISCHARGING AT SURFACE

Groundwater discharging at surface generally occurs at seeps, springs, wetlands and in and around the riparian zones of streams and rivers. Where spring flow is substantial or ongoing, it forms the start of rivers and streams and can contribute significantly to baseflow. Elsewhere, the relative position of the water table in relation to the base of a river or stream bed dictates whether the underlying groundwater system is in hydraulic connection with the river or stream. Where there is connection, then an assessment of baseflow could be used to quantify the groundwater contribution to flow.

Unfortunately, a degree of confusion exists regarding what baseflow is and where it comes from. This chapter describes general concepts relating to the discharge of subsurface water in general, and groundwater in particular, into surface water bodies and provides some clarity on what baseflow is. The quantification of baseflow is addressed in Chapter 8.

Springs

Springs are unique in that they are essentially an expression of subsurface water discharging at surface. They form an important part of the ecological landscape because of the dependencies that form around them. Because of their visibility and role played in supplying water to early settlements, rural populations, fauna and agriculture, the value of springs is generally better appreciated than that of groundwater.

Early settlers and travelers in the Cape used to travel from the Castle in Cape Town over the rugged Hottentots Holland Mountains to Caledon to relax and recuperate at the Caledon springs (Heap, 1993). Many hot springs are scattered around the country, including those at Aliwal North, Brandvlei, Goudini and Warmbaths. Some have been developed into popular resorts, largely because of their perceived healing powers.

However, not all springs are fed by groundwater. Some springs are fed by water in the vadose zone and interflow. These springs - termed *perched springs* by Cleaver *et al*. (2003) - are unlikely to be impacted by groundwater abstraction. Typically, they are seasonal in character, occur above the regional water table and can sometimes be distinguished from groundwater by their chemical or isotopic composition. Springs found in mountain headwater areas are characteristically of this type. Because they tend to dry up during prolonged dry periods, they generally only contribute to baseflow in the dry months immediately after the rainy season.

Groundwater-fed springs are more permanent in character than perched springs and have chemical and isotopic compositions similar to that of the underlying groundwater body. These springs are at a similar elevation as the regional water table or piezometric surface and contribute to the groundwater component of baseflow. Generally, these springs are found in low-lying areas.

Healing Power of Springs

Human imagination, backed by a lack of understanding about the resource, has fuelled much of the mystique about groundwater. Good examples include the idea that a forked stick can be used to find groundwater and throwing coins into a well will bring good luck. However, many of the myths about groundwater can be rationally explained. For example, it is widely believed springs have mystical healing powers, an understanding manifested by people flocking to springs to heal all sorts of ailments. At one stage the healing powers of springs and wells were actually codified into accepted medical practice.

In 1750 the Shenandoah Valley of Virginia became renowned for its variety of springs, with depth of origin and mineral content controlling water temperature and colour. In the nineteenth century, the springs gained a reputation for being able to heal a variety of ailments, with different springs reputed to heal different ailments. This led to developers building resorts around the springs and the beginning of a booming industry. Visitors would travel from spring to spring in search of magical cures. It became common practice to refer to those sad individuals who had nearly run out of springs to try as being "down to their last resort".

While the uninformed considered the healing powers of springs magical, rational explanations exist for the effects they had. In addition to the faith of the patient in the treatment being given (placebo effect), heat is used to treat muscle injuries and arthritis. Simply by lying in warm water discharged by hot springs brings relief and helps ease many aches and pains. Similarly, sulphur, iron, salt and iodine found in mineralised spring waters helped cure ailments such as stomach problems, indigestion, liver complaints, sores and the like. Many of these elements are commonly used in medicines we use today.

(Chapelle, 1997)

Spring Classification

Type 1 – shallow seasonal springs and seeps emanating from perched water tables; represents localised discharge of interflow, not connected to the groundwater flow system and will not be impacted by groundwater abstraction.

Type 2 – lithologically controlled springs, often discharges at lithological contacts; flow is more permanent and plays an important role in sustaining baseflows; susceptible to the impacts of localised groundwater abstraction.

Type 3 – fault controlled springs that are permanent in character; may discharge either hot or cold water; only potentially impacted by large scale regional abstraction.

(Kotze, 2001)

Kammanassie Springs

Using a spring classification developed by Kotze (2001), Cleaver *et al*. (2003) estimated 51 % of springs in the Kammanassie area were Type 1 springs not dependant on groundwater as a source of water. These springs were all above the water table and isotopic composition of the spring water showed them to be different to groundwater. These perched springs are not vulnerable to potential impacts by groundwater abstraction. 30 % of the springs were classified as Type 2 fed by groundwater and were considered potentially vulnerable to the effects of groundwater abstraction. 19 % of the springs could not be classified as an element of doubt exists with respect to their dependence on groundwater

(Cleaver *et al*., 2003)

Using the spring classification system proposed by Kotze (2001), springs in low-lying areas have a higher probability of being groundwater fed springs (Type 2) than those on the slopes of mountains (Figure 5.1). Those in topographically elevated areas are probably perched springs (Type 1 springs above the water table), but cognisance must be taken of structurally and piezometrically controlled springs (Type 3) such as hot springs and artesian springs.

Karstic landforms are those produced primarily by the dissolution of mainly limestone and dolomite. While not abundant in South Africa, they provide unique hydrological features. Dissolution of rock by chemical weathering results in large underground cavities being formed. These can be quite extensive and are capable of transporting large volumes of groundwater. Collapse of these subsurface features results in a landscape characterised by closed surface depressions and, in cases, sinkholes visible at surface. Intermittent or disrupted streams are characteristic of these landforms. When a river encounters a dissolution cavity, surface flow may disappear and continue underground until some geological structure forces the “underground river” to emerge as high yielding springs or “eyes”. Good examples of this are found at Kuruman, Sterkfontein and the Fountains in Pretoria. Kok (1992) reported the yield of these three springs to be 260 L/s, 75 L/s and 310 L/s respectively.

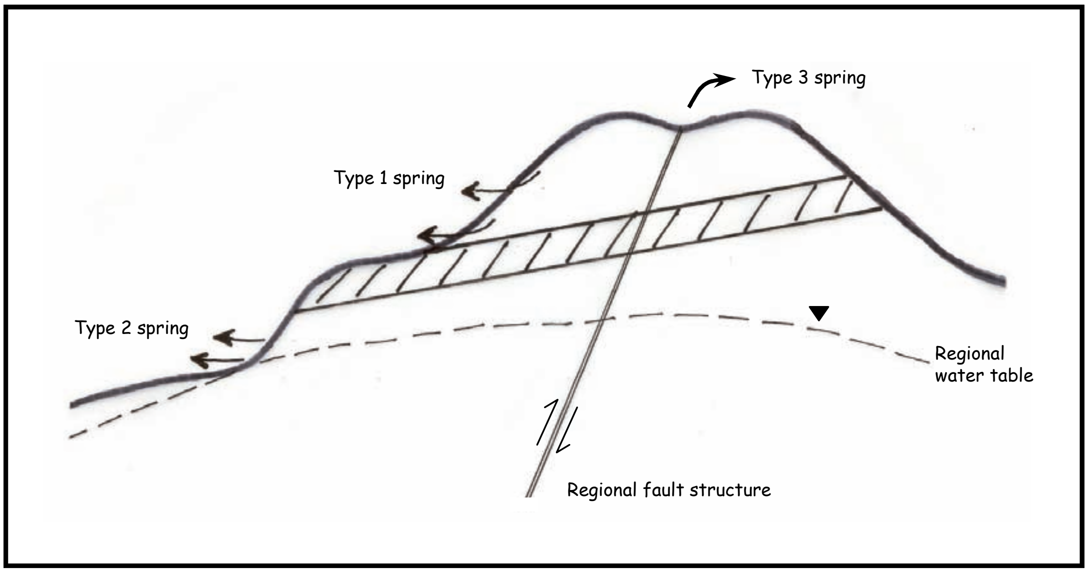

Figure 5.1: Spring classification system.

Groundwater Discharge to Surface Water

It is widely understood groundwater can discharge into bodies of surface water (rivers, streams, lakes, wetlands, etc.) and can sustain flow during dry periods. However, not all surface waters are fed by groundwater. Exchange of water between surface and groundwater bodies is controlled by the relative position of the water level in the river to that of the water table. If the water level in the surface water body is higher than that of the groundwater body, water will flow from the surface water body into the groundwater body. Similarly, if the water table or piezometric surface is higher than the water level in the surface water body, the underlying groundwater system is in hydraulic connection with the surface water and groundwater will discharge into the surface water.

The terms *influent stream* and *effluent stream* are used to describe this interaction, but can be both confusing and overly simplistic. Further, because of the range of climatic conditions experienced in Southern Africa, the classification requires expansion to account for arid and semi-arid conditions encountered in the region.

Note:

The term *effluent stream* should not be confused with *effluent*, which is liquid waste or sewage discharged into a river or the sea.

Influent streams are also referred to as *losing streams* while effluent streams can be considered *gaining streams*. (Figure 5.2) In the case of influent or losing streams, water flows from the stream into the groundwater body, while the reverse is true for effluent streams. It stands to reason groundwater flow would be away from influent streams and toward effluent streams. If sufficient groundwater level data are available, groundwater flownets can be used to assess the relationship between surface and groundwater bodies.

In many instances in the drier parts of South Africa, no or very little interaction takes place between surface and groundwater bodies. These rivers are referred to as *detached streams* (Vegter and Pitman, 1996), *remote streams* (Lerner, 1996) or *disconnected streams* (Winter *et al*., 1999) and are a special case of influent rivers (Figure 5.2). After very heavy rains, flow may occur in the river. During this time (usually only hours or days after the storm) water in the river will seep into the subsurface, resulting in the river attaining an influent character for a short period of time. However, as soon as flow ceases, the river reverts to its more dominant detached character and the riverbed is separated from the underlying groundwater body by a vadose zone. The Kuiseb River in Namibia is a good example of such a river.

In certain instances where the water table rises up to the base of the stream, the character of a river can range from a detached stream to an effluent stream. As the water table recedes, the stream could attain an influent character before reverting back to a detached stream. Many rivers in the Karoo display this sort of *intermittent* or *interacting* character.

Seasonality of River Flow

Flow in rivers (and other surface water bodies) is not constant all year round. In addition to responding to short duration rain events, flow also responds to seasonal variations in the long-term relationship between stormflow and baseflow determining the main flow characteristics of a river. This gives rise to perennial rivers, seasonal rivers and ephemeral rivers (Figure 5.3). While this classification may be useful, the three river types represent a continuum of flow conditions.

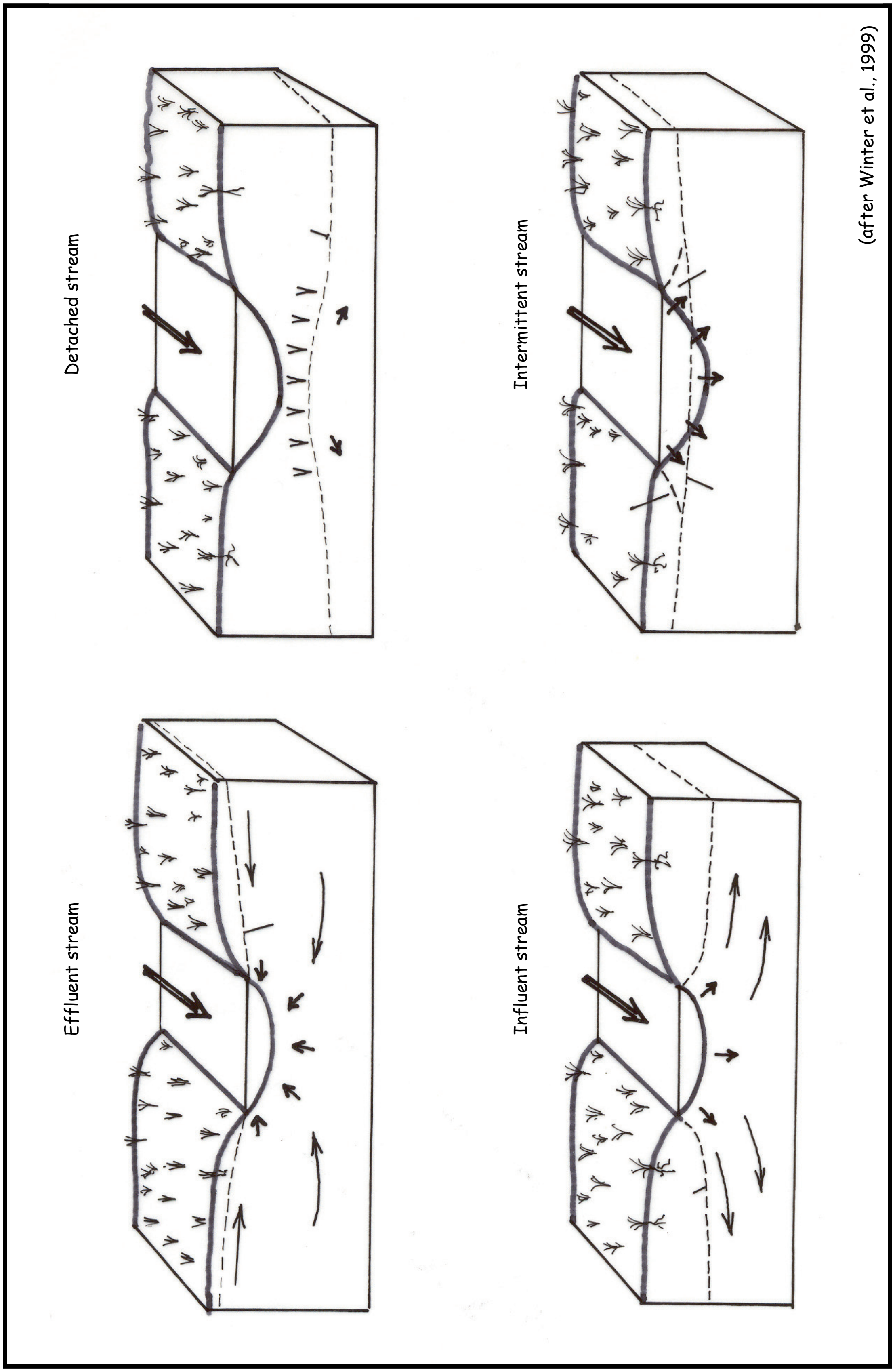

Figure5.2: Types of rivers, based on the connectivity with underlying groundwater bodies.

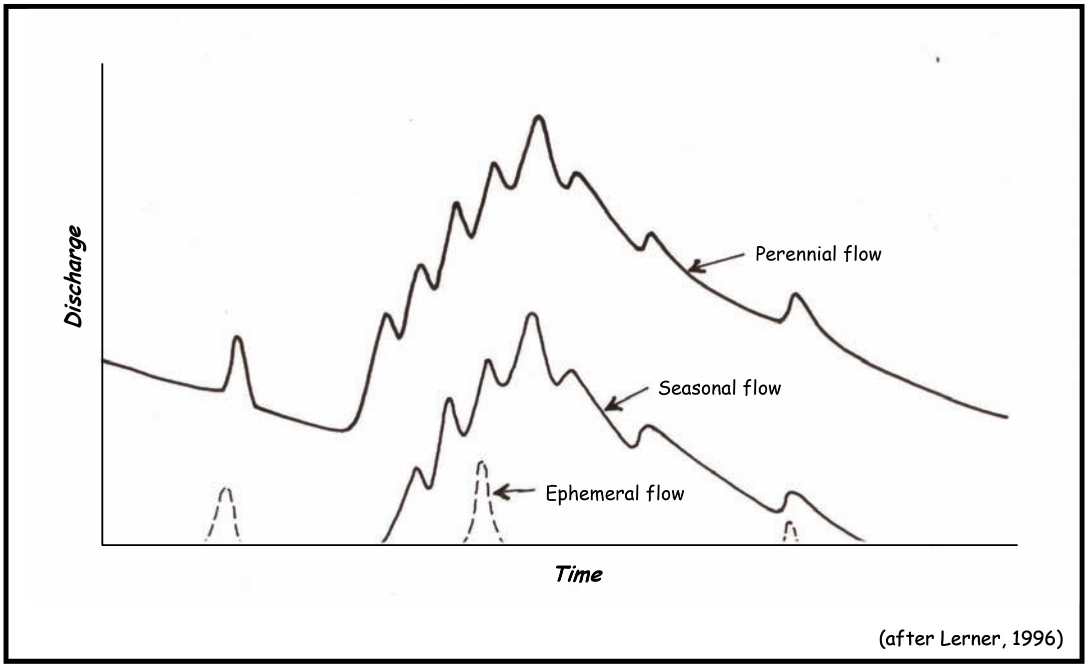

Figure 5.3: Types of rivers, based on seasonality of flow.

Types of Rivers

Perennial rivers: These rivers are generally found in the wetter parts of the country where flow occurs more than 80 % of the time (generally these rivers flow continually). Examples of perennial rivers include the Thukela River in KwaZulu-Natal, the Crocodile, Komati and Sabie Rivers in Mpumalanga and the Berg River in the Western Cape. In general these rivers have a high baseflow index (BFI) and groundwater plays an important role in sustaining flow during dry periods.

Seasonal rivers: Seasonal rainfall patterns drive these rivers where flow occurs between 20 and 80 % of the time. In general these rivers do not originate in areas of high rainfall while contributions from tributaries and groundwater are variable. Examples of seasonal rivers include the Limpopo River, the Letaba River, the Fish River in the Eastern Cape, the Shingwetsi River in Mpumalanga and the Molagwena River.

Ephemeral rivers: Most rivers in the drier parts of the country such as the Karoo and Kalahari are ephemeral in nature. These rivers are generally event driven and flow occurs less than 20 % of the time. Typically, flow is a result of heavy or persistent rains and flow usually ceases within days of the rainfall event. The BFI of these rivers is expected to be low. Groundwater would contribute little in terms of flow, but may be crucial in sustaining pools and refugia. Examples include the Doring River in the Western Cape, the Kuiseb River in Namibia and the Matlabas River in the Northern Province.

Baseflow

It is well understood groundwater contributes to river flow, particularly in wetter areas that experience high rainfall. However, the concept of baseflow does not enjoy a common understanding between surface water hydrologists and geohydrologists.

- Surface water hydrologists usually define baseflow as those low flow events during dry periods of little or no precipitation (or snowmelt), i.e. low amplitude high frequency flow events. They distinguish between stormflow and baseflow using well established, but arbitrary baseflow separation techniques, with no distinction being made between the origins of the water and the mechanisms and processes by which it arrived in the river.

- Geohydrologists generally understand baseflow has its origin from groundwater discharged into streams and propose estimates of baseflow provide an indication of minimum levels of recharge. Vegter and Pitman (1996), for example, used this approach.

Implementation of the National Water Act (Act 36 of 1998) and other environmental legislation has required the two disciplines work together in an integrated manner. The difference in their understanding of baseflow has emerged as a result.

Baseflow separation techniques are used to analyse hydrographs and estimate the relative proportion of stormflow and "fair weather" or baseflow (Figure 5.4). These techniques are described by Hughes and Munster (2000), Smakhtin (2001), Xu *et al*. (2002) and Hughes *et al*. (2003). Using graphical separation techniques, baseflow rating curves or recession-curve displacement methods, hydrologists attempt to calculate a baseflow index (BFI), which is the proportion of baseflow to total flow or runoff. It must be noted this is not an estimate of groundwater discharge to rivers, but rather a measure of slowly responding flows (Lerner, 1996). Traditionally, baseflow separation techniques have not attempted to differentiate the origins of baseflow nor the process by which it reaches a river. Efforts by Moore (1992), Xu *et al*. (2002) and Hannula *et al*. (2003) to quantify the groundwater component of baseflow are exceptions to this.

Because of the wide belief that groundwater sustains low flows during dry periods and periods of low rainfall, the geohydrological community has accepted baseflow represents the groundwater contribution to river flow. However, when comparing estimates of recharge to baseflow, it has emerged that baseflow is commonly significantly greater than estimates of recharge. This is particularly true in the wetter eastern parts of South Africa. Hughes (2003), for example, observed estimates of baseflow are up to 10 times greater than expected recharge. Further, the order of magnitude increase in groundwater discharge to streams predicted by most baseflow separation techniques does not match observed changes in groundwater levels. Accepting groundwater discharge to rivers is governed by Darcy's Law and transmissivity and aquifer width remain (relatively) constant, the only mechanism for increasing groundwater discharge to rivers during storm events is to significantly increase the hydraulic gradient. While groundwater levels may increase in response to recharge from rainfall (and seepage from the river), increases of a magnitude sufficient to explain the increase in groundwater discharge predicted by baseflow separation techniques are not observed in monitored groundwater level data. Quantification of the groundwater contribution to baseflow is discussed in more detail in Chapter 8.

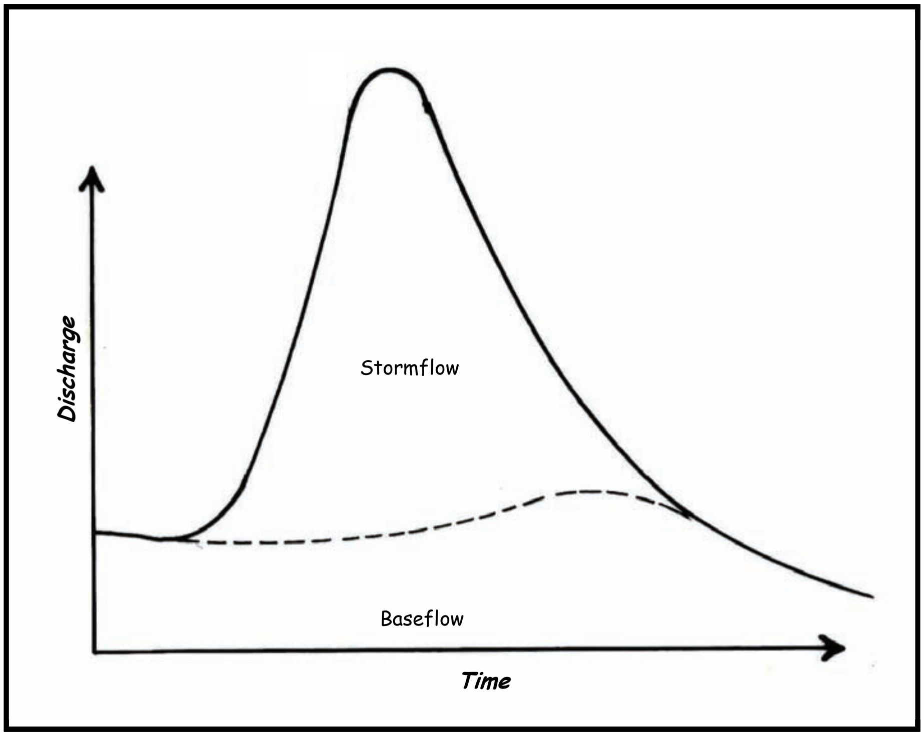

Figure 5.4: Separation of hydrographs into stormflow and baseflow components.

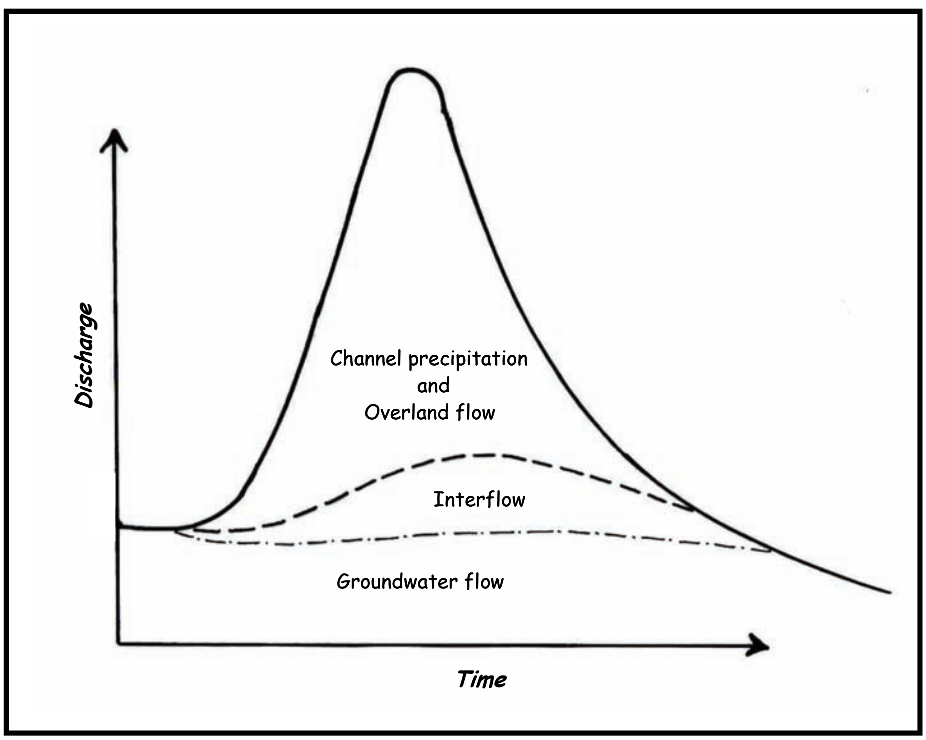

Figure 5.5: Separation of hydrographs into different mechanisms by which water reaches a river and contributes to flow.

Runoff Generation

Four components are recognised in the runoff generation process, namely channel precipitation, quickflow (which includes overland flow), interflow and groundwater flow (Figure 5.6). In turn, overland flow during storms is generated by two basic processes, with one being caused by saturation from above and the other by saturation from below. Overland flow, as described by the Horton runoff model, occurs when the intensity or rate of rainfall is greater than the rate of infiltration, resulting in excess rain that cannot infiltrate flowing over the land surface towards a river or stream. Saturated overland flow occurs when available storage in the soil is saturated, preventing the infiltration of rainfall into the subsurface. This water then flows over the land surface in response to gravity. While these two concepts may appear simplistic, spatial and temporal variations in rainfall, soil characteristics and antecedent moisture conditions and slope result in complex rainfall response patterns.

Interflow includes the rapid flow of water along essentially unsaturated flow paths, water that infiltrates the subsurface and moves both vertically and laterally before discharging into other water bodies. Significant differences in vertical and horizontal hydraulic properties and macropore flow such as that in fractures and subsurface pipes induce a lateral flow component, which in turn results in water entering and leaving the subsurface as it moves downwards towards saturated water bodies.

While groundwater generally moves very slowly, water recharging the saturated zone can result in relatively quick responses through translatory flow (see page 4-11).

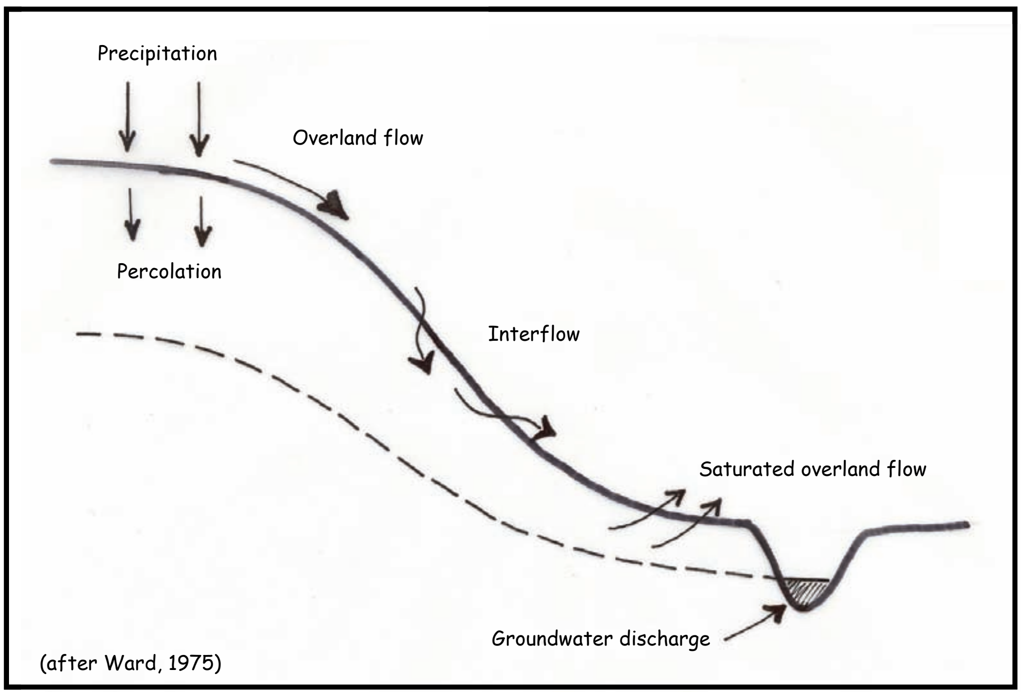

Figure 5.6: Runoff generation mechanisms.

Given the need to understand the role of groundwater in sustaining aquatic ecosystems, geohydrologists see baseflow separation as a useful tool for quantifying groundwater discharge to streams *in instances where there is hydraulic connection between the groundwater system and rivers*. Instead of separating hydrographs into stormflow and baseflow (Figure 5.4), they want to consider the mechanism and processes by which water reaches the stream, i.e. quickflow, interflow or groundwater discharge (Figure 5.5). Using hydrogeomorphic type settings, Xu *et al*. (2002) developed an empirical baseflow separation technique to quantify the groundwater contribution to river flow. However, they note the technique should be used with caution, as it requires further development and testing.

Baseflow Index as an indicator of Groundwater Contribution to River Flow

While it will be incorrect to use a simple BFI to quantify groundwater discharge to rivers, a high BFI may indicate a perennial river sustained by groundwater discharge into a river. Conversely, a low BFI suggests an event-driven ephemeral river where groundwater probably plays a small or insignificant role in sustaining flow.

Groundwater – River Interaction

Conventional thinking on stream flow generation suggests stormflow observed in rivers is the result of direct surface run-off from a particular rainfall event, as suggested by the classical Horton run-off model. Research by Midgley and Scott (1994) showed almost all stormflow in the Jonkershoek Valley was "old" water, i.e. water that was older than the observed rainfall event. Using stable isotopes in water, they estimated less than 10 % of storm event stream flow was due to recent rains and more than 90 % of storm flow resulted from water discharged from soils or groundwater. Their findings were supported by research by Richey *et al*. (1998) in New Zealand, North America and Europe. This indicates mechanisms for rain water getting into streams during storm events is not simple and that the concept of overland flow may be too simplistic and interflow and groundwater discharge play an important role in the generation of stormflow.

(Midgley and Scott, 1994)
(Richey *et al.*, 1998)

Proposed Terminology

Inconsistent use and misuse of terminology and over-simplification of hydrological processes have played roles in the current misunderstanding of baseflow. As a result of knowledge gained in implementing the National Water Act (Act 36 of 1998) and attempting to quantify the role of groundwater in sustaining aquatic ecosystems, it would be unwise to accept that all baseflow is derived from groundwater and that baseflow provides a measure of recharge. While these premises may be true for more humid climates, sufficient evidence exists to suggest they do not necessarily hold true for arid and semi-arid environments.

Using terminology presented by Ward (1975) as a guide, it is proposed the terms *stormflow* and *baseflow* be retained in their traditional hydrological sense, i.e. non-process related terms relating to the frequency and amplitude of flow events in a river (Figure 5.7). Traditional approaches to baseflow separation such as those described by Hughes and Munster (2000) and Smakhtin (2001) would be used for this purpose.

It is further proposed the terms *channel precipitation*, *quickflow*, *interflow* and *groundwater contribution to river flow* be used to describe time-dependent processes and mechanisms that result in the water discharging into a river or stream. Quickflow would include essentially surface mechanisms such as direct run-off and overland flow that result in precipitation discharging into rivers during and relatively quickly after a precipitation event (say seconds to hours after the event). Interflow includes those near-surface mechanisms in the unsaturated zone that result in water discharging into rivers days to weeks after a storm event. Because of the range of time that interflow may take to reach a river, rapid interflow and delayed interflow can be distinguished. The groundwater contribution to river flow (or groundwater discharge) is that steady on-going contribution to flow from groundwater.

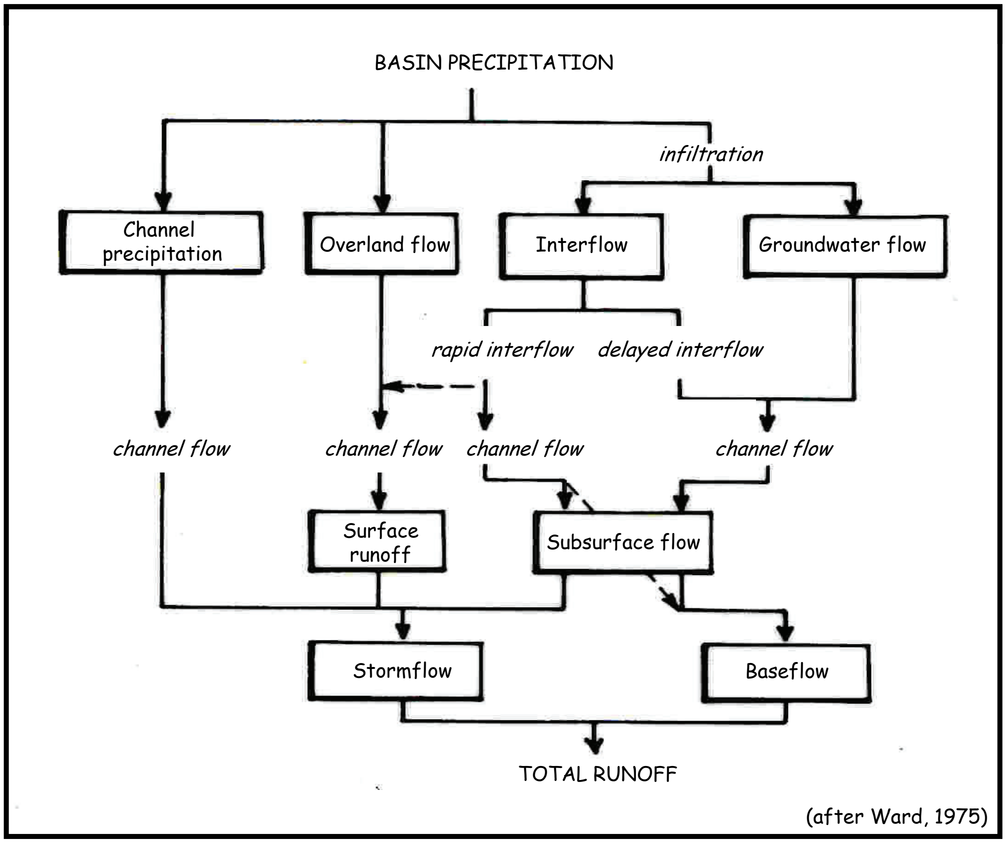

Figure 5.7: Proposed terminology for describing runoff generation

In Summary

- Not all spring flow and baseflow is derived from groundwater. Water stored and transmitted in the unsaturated zone also contributes to stormflow.
- Interflow is transitionary between surface flow and groundwater flow and occurs mostly in the unsaturated zone above the regional water table or piezometric surface.
- Runoff in a river represents a continuum of flow process ranging from direct channel precipitation through to groundwater discharge, with no distinct boundaries.
- Baseflow separation techniques have traditionally attempted to distinguish between flow generated by storms and baseflow during dry periods, irrespective of the source of water.
- Interconnection between surface and groundwater bodies is described as influent, effluent, disconnected and intermittent. Because connectivity varies in both time and space, connectivity of a reach should be assessed rather than for the entire river.
- Many streams and rivers in South Africa are not groundwater-dependent, and it is only the perennial rivers along the eastern escarpment and wetter northeastern parts of the country where groundwater makes a meaningful contribution to baseflow in rivers.
- It is proposed stormflow and baseflow be used as non-process related terms to signify high amplitude, low frequency flow in a river during and immediately after a precipitation event and low amplitude, high frequency flow in a river during dry or fair weather periods.

6. INTERACTION WITH DIFFERENT WATER BODIES

Interaction with Rivers

As discussed in Chapter 4, it is widely understood groundwater can discharge into rivers and can sustain flow during dry periods. It is also understood not all rivers are fed by groundwater. **Exchange of water between surface and groundwater bodies is controlled by the relative position of the water level in the river to that of the water table.**

Groot-Goerap River

Along a section of the Groet-Goerap River, which "flows" into the Salt River some 20 km west of Lutzville, the water table was measured to be 27 mamsl while the riverbed is at an elevation of 80 mamsl. The area experiences an arid climate (rainfall of 150 mm/a) and the river only flows a few times a decade. In this instance, the 53 m between the river and the water table results in the river being classified as a detached river.

It is noteworthy that influent streams are always positioned above the water table or piezometric surface while effluent streams intersect the water table. It is important to note that this situation can change in both space and time. For example, headwaters of rivers usually have an influent character while closer to the river mouth and the flatter floodplain areas, rivers assume a more effluent character. These changes can occur over relatively short distances. Similarly, the water table may rise above the riverbed during periods of rain, but drop below the riverbed during drier periods. Rivers where the relative position of the water table fluctuates above or below the riverbed are said to be *intermittent streams* or *interacting streams*.

Within a particular stream or river, it is not uncommon to have different reaches gaining or losing water. Given that some rivers are hundreds or thousands of kilometers long, and that run-off is governed by rainfall, topography, geology and other factors, it is both dangerous and difficult to generalise about interaction between surface and groundwater bodies interaction on a river or catchment scale. It may be more prudent to describe the influent or effluent status of a reach of a river, rather than for the river itself.

Hex River

In the upper reaches of the Hex River, the river is considered to be effluent in character. Groundwater levels are generally deep, but subsurface water discharges into the river in the form of springs and seeps. At the point where the mountain headwater stream enters the Hex River Valley, the gradient flattens and the river traverses a relatively thick horizon of unconsolidated sediments. Here the river discharges into the subsurface. Further down the river in the vicinity of the Sandhills and Kanetvlei, the topography is significantly flatter and the water table is near the surface. Groundwater discharge from the "Oog van Kanetvlei", the Tweefontein spring and elsewhere into the stream results in a near permanent effluent character. Current estimates suggest the natural groundwater contribution to baseflow was in the order of 12 % MAR.

(Papini *et al*., 2001)

Interaction with Lakes

In general, interaction between groundwater bodies and lakes is similar to that with rivers. Lakes can also be classified as being influent or effluent, but are probably seldom classified as disconnected or interacting. The main difference between the two is that lakes have a much larger surface area and bed area. Further, accumulation of low permeability sediments in the lake floor results in slower rates of water movement through the bottom of the lake.

Born *et al*. (1979) (as quoted by Townley *et al*., 1993) developed a primary lake classification system, recognising recharge lakes, discharge lakes and flow-through lakes. While recharge and discharge lakes may be similar to influent and effluent streams, it was found many lakes receive subsurface inflows along their up gradient perimeter, but discharge into the subsurface along their down gradient perimeter (Figure 6.1). Groenvlei near Sedgefield is considered a classical example of an effluent or discharging lake, while Zeekoevlei in Cape Town is a good example of a flow-through lake.

Water levels in lakes reflect the balance between surface water inflows and outflows, subsurface inflow and outflow and evaporation losses. Generally, evaporation losses from large open bodies of surface water are greater than those from relatively confined river channels. The relationship between lake water levels, inflows (rainfall, surface and groundwater inflows) and outflows (evaporation losses, surface and groundwater outflows) can be measured and modeled to quantify the relationships between the various components of the hydrological system.

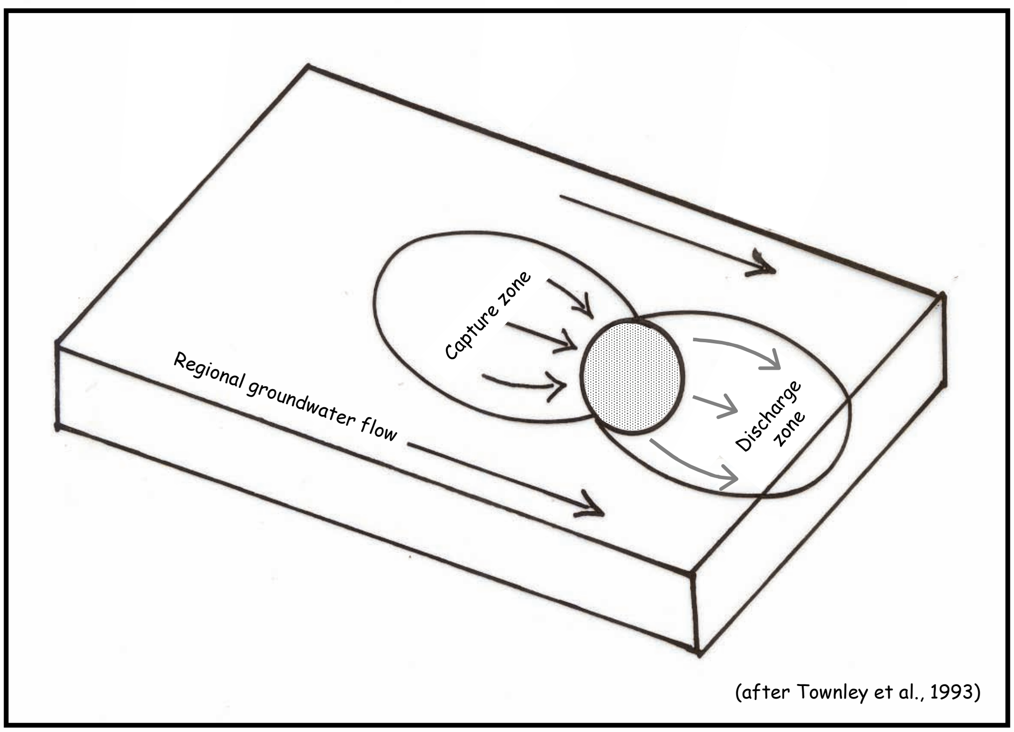

Figure 6.1: Relationship between regional flow and local flow in the vicinity of a flow-through type lake or wetland.

Interaction with Wetlands

In recent years, the ecological value of wetlands has been widely recognised. Amongst others, wetlands help prevent floods, improve water quality, reduce river sediment loads and provide fish and wildlife habitat. It is less well recognised, however, that many wetlands are groundwater driven and without understanding their drivers and functionality, it is difficult to manage and conserve these components of the hydrological system.

Groundwater Discharge into Wetlands and Vleis

Zeekoevlei is a shallow freshwater lake system located on the sandy Cape Flats Aquifer in Cape Town. Though highly modified by man, it was possible to determine that 15 % of all water inflow into Zeekoevlei is contributed via groundwater. More importantly, however, groundwater is the only source of water during the hot dry summer months. Use of a range of data proved invaluable in providing an assessment of the various in and out flows, including daily rainfall and evaporation measurements, daily vlei water level measurements and estimated groundwater fluxes.

(Parsons, 2000)

Interaction between groundwater and wetlands is similar to that of rivers and lakes. It is accepted some wetlands are independent of groundwater systems (i.e. disconnected). However, most wetlands are either fed by groundwater inflows, lose water by seepage into the subsurface, or both. For management and conservation purposes, it may be useful to expand on the classification presented by Dini *et al*. (1998) and DWAF (1999b; Figure 6.2) where the source of water is recognised. This will facilitate imposition of groundwater abstraction limitations in instances where abstraction could significantly impact wetlands.

Wetlands from Springs

For every spring or seep, there is a geological explanation of its occurrence. Many small wetland areas have originated because of the availability of water from springs and seepages. For many other wetlands, at least a portion of their hydrologic budget is derived from springs.

(Stone and Lindley Stone, 1994)

Wetlands are characterised by being permanently, frequently or seasonally wet; are underlain by poorly drained (hydric) soils that are usually saturated and under anaerobic conditions; and favour the growth of hydrophytic (water-loving) plants that can tolerate flooded or saturated anaerobic conditions (Stone and Lindley Stone, 1994).

In some instances, the role of groundwater is not related to the volume of groundwater contributed to the system, but rather the timing of the contribution. During drier months and after river flow ceases, groundwater is the only source of water to sustain these ecosystems.

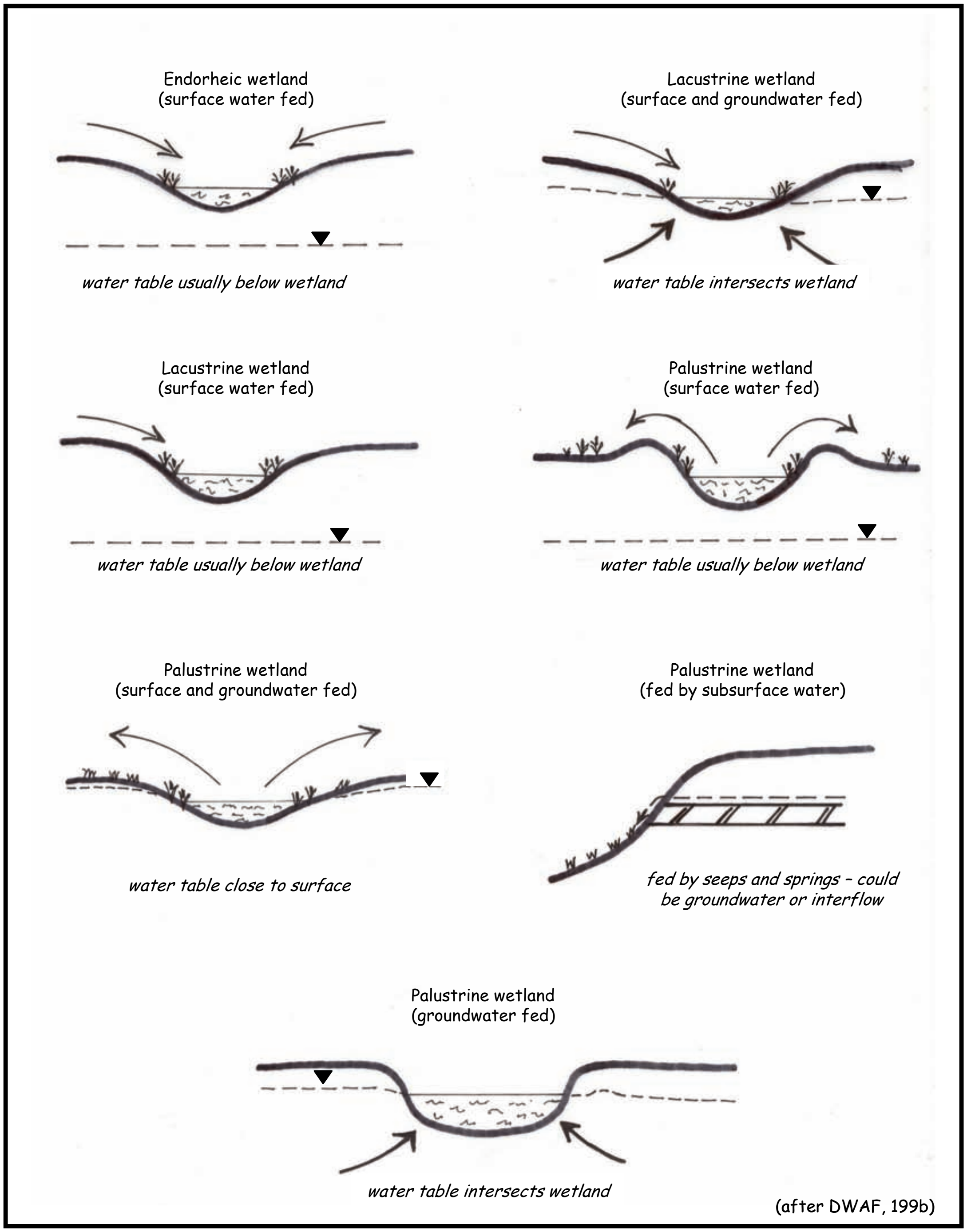

Figure 6.2: Wetland classification based on the contributions from surface and groundwater

South African Wetland Classification

Dini *et al.* (1998) proposed a wetland classification system for South Africa based on the internationally recognised Cowardin classification. The classification recognises six wetland systems, with each system comprising a set of subsystems and classes:

Marine: Marine habitats are exposed to waves and currents of the open ocean and water regimes are determined primarily by the ebb and flow of oceanic tides. Shallow coastal indentations or bays without appreciable freshwater inflow are also considered part of the Marine System as they generally support typical marine biota. Subsystems include the subtidal and intertidal zones.

Estuarine: This system includes both estuaries and lagoons, and is more strongly influenced by its association with land than is the Marine System. In terms of wave action, estuaries are generally considered low energy systems. Salinity and temperature regimes tend to be highly variable, and salinities may periodically be increased above that of the sea by evaporation. Estuarine systems are often highly turbid and contain distinctive fauna. Salt marshes and mud and sand flats bordering estuaries and with an intertidal character are also considered Estuarine. Subsystems include the subtidal and intertidal zones.

Lacustrine: The Lacustrine System includes permanently flooded lakes and dams. Lacustrine waters may be tidal or non-tidal, but ocean-derived salinity is always less than 0,5 g/l. Typically, there are extensive areas of deep water, and there may be considerable wave action. Islands of Palustrine wetlands may lie within the boundaries of the Lacustrine System. Subsystems include limnetic and littoral wetlands.

Riverine: Water is usually, but not always, flowing in the Riverine System. Non-wetland islands or Palustrine islands may occur in the channel, or on adjacent flooded plains, but they are not included in the Riverine System. Oxbow lakes are classified Lacustrine or Palustrine Systems unless connected to a Riverine System by an open channel at both ends, either permanently or intermittently. Floodplain wetlands are included in the Palustrine System. This system is divided into five subsystems: tidal, lower perennial, upper perennial, lower intermittent and upper intermittent. Each is defined in terms of water permanence, gradient, water velocity, substrate and extent of floodplain development. Subsystems have characteristic flora and fauna.

Palustrine: The Palustrine System groups together vegetated wetlands traditionally called marshes, swamps, bogs, fens and vleis, which are found throughout South Africa. Palustrine wetlands may be situated shoreward of river channels, lakes or estuaries; on river floodplains; in isolated catchments; or on slopes. They may also occur as islands in lakes or rivers. The erosive forces of wind and water are of minor importance except during severe floods. Palustrine subsystems include those found in flat areas, sloping areas, in valley bottoms and in floodplains.

Endorheic: These wetlands are commonly referred to as pans in South Africa, and as small closed basins or playas in geomorphological literature. By definition, endorheic wetlands are circular to oval in shape, have a relatively flat basin floor, are less than 3 m deep when fully inundated; and lack any drainage outlet. The majority of these pans occur in areas with a mean annual rainfall of less than 500 mm and an average net evaporation loss greater than 1000 mm per annum. Being located largely in dry regions, pans display characteristic patterns of ephemeral and irregular inundation. Pans in the arid western regions of South Africa may remain dry for years between temporary flooding, while those in the higher rainfall regions display seasonal inundation regimes, and may remain flooded over a number of seasons. Some of the larger pans on the Mpumalanga highveld are permanently inundated, large, deep and have rooted vegetation. As such, these pans would be classified as Lacustrine if their water depth exceeds 3 m. Being endorheic, pans lose water largely by evaporation, which also contributes to the high salinity observed in many of these systems.

Wetlands

Wetlands are transitionary between terrestrial and aquatic systems, where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil

(National Water Act, Act 36 of 1998)

Not all wetlands are located in topographical low points or depressions in the landscape. Some occur on slopes and are fed by springs and seeps. In many instances the springs and seeps are fed by subsurface water, but not groundwater. In these instances, the abstraction of groundwater is unlikely to impact on spring or seep discharge.

Those wetlands connected to underlying groundwater systems could be vulnerable to the effects of groundwater abstraction, but this will probably only be of significance in the case of effluent wetlands (i.e. wetlands fed by groundwater).

Okovango Swamps

The Okavango Swamps are an endorheic system where water discharges from the swamps into the underlying groundwater system.

(Brown *et al*., 2003)

Interaction with Estuaries

Estuarine - groundwater interaction has received little attention in the past. Changing water levels and chemistry as a result of tidal influences suggest a highly dynamic zone at the interface of the two water bodies.

While the Ghyben-Herzber relationship holds true (see page 6-7), the thickness of the interface is probably greater than elsewhere along the coast because of continual tidal-induced changes to the local groundwater gradient.

Interaction with the Sea

Ultimately, groundwater systems discharge into the sea at some point. Generally, little attention is paid to seawater - groundwater interaction as the hydraulic head of groundwater ensures seawater cannot migrate landwards and unimpacted interaction remains uni-directional. However, a delicate balance exists between the sea and groundwater, with over-abstraction resulting in saline intrusion and a deterioration in groundwater quality.

Ghyben-Herzberg relationship

Messrs Ghyben and Herzberg studied the hydrostatic relationship between less dense groundwater and heavier seawater independently. It was found that the interface between the two water bodies occurred at a depth below sea level equivalent to about 40 times the height of the water table above mean sea level (Figure 6.3). During groundwater abstraction, the groundwater level is lowered. This induces a shift in the position of the freshwater – seawater interface. The Ghyben-Herzberg approximation allows for the potential of inducing saline intrusion during abstraction to be assessed.

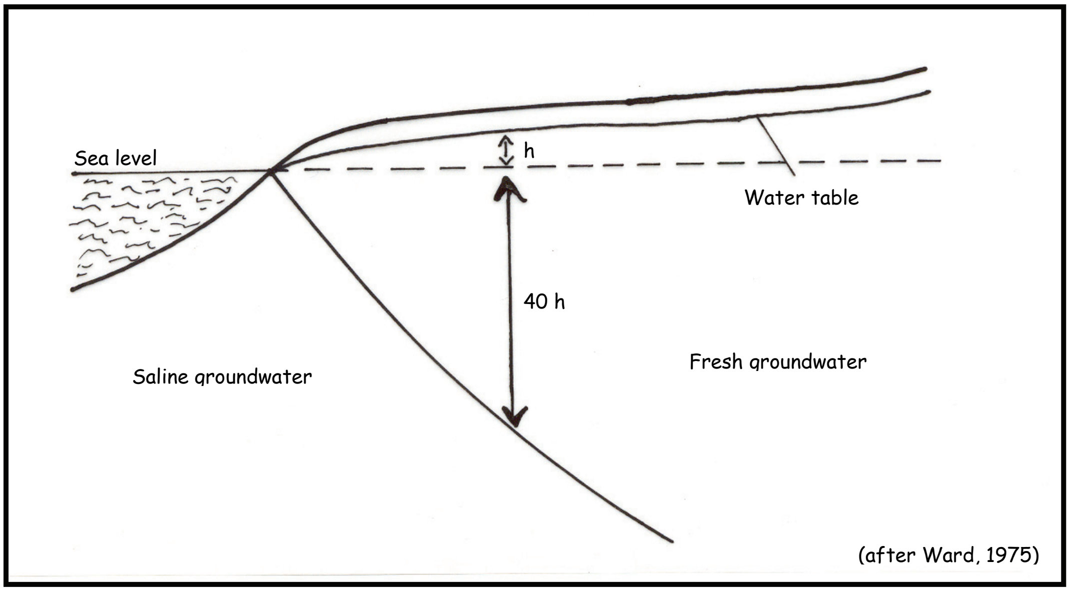

Figure 6.3: Schematic representation of the Ghyben-Herzberg hydrostatic relationship.

Anaulus Blooms

Anaulus blooms at the Alexandria dunefield in the Eastern Cape and at Muizenberg in False Bay are thought to result from groundwater discharge into the sea. Groundwater acts as a source of silica and nutrient-rich freshwater required by the diatom. Concentration of the diatoms result in the surf zone having a dirty brown colour, mistakenly perceived by many in the Muizenburg area to be the result of sewage or effluent discharges.

(Campbell and Bate, 1998)

Need to Recognise Interaction

Groundwater discharges to rivers, wetlands, lakes, estuaries and the sea, and *vice versa*. It is often the only source of water during dry periods and hence plays a crucial role in the environment. While it is important to recognise these links, it is just as important to recognise when groundwater does not play a role in supporting the environment. Attention needs to be paid to improving our understanding and quantification of these links.

7. ECOLOGICAL IMPORTANCE OF SURFACE - GROUNDWATER INTERACTION

Surface - groundwater ecotones form a varied habitat important to both aquatic and wildlife communities (Gardner, 1999). Ecotone is a term used to describe the transition zone between different habitat types. In the context of surface - groundwater interaction, the land - water ecotone encompasses both water flow and living and non-living components of the interaction.

The National Water Act (Act 36 of 1998) recognised the need to set aside water for aquatic ecosystems and basic human rights. It has been interpreted that groundwater generally falls outside the definition of aquatic ecosystems, except where groundwater discharges and sustains surface water bodies. However, groundwater provides a linkage between terrestrial ecosystems and aquatic ecosystems.

Springs are an expression of subsurface water discharging at surface. In addition to providing the groundwater contribution to river flow, they play a critical role in providing fauna and flora with a source of water. Unique ecosystems develop around springs in response to the permanency of available water.

The hyporheic zone is contained within the land - water ecotone and is functionally a composite between surface and groundwater ecosystems. It provides a number of ecologically important services, including: thermal, temporal and chemical buffering; habitat; flow augmentation and refugia. The zone may be significantly different to the overlying surface water body and the underlying aquifer system. Brown *et al.* (2003) noted upwelling (or discharge) of groundwater creates patches of high productivity in the hyporheic zone and aquatic ecosystems, supporting greater animal densities and diversities when compared to non-upwelling situations.

Doring River

Groundwater plays a crucial role in providing refugia during dry periods. In summer, fish survive in groundwater fed pools when surface flows cease in the Doring River. It was recently observed indigenous fish only use pools fed by a fresh groundwater source, while alien fish were found in all pools.

(Brown *et al*., 2003)

Riparian zones, especially in arid and semi-arid areas, are important for maintaining biodiversity, offering refugia and habitat to a variety of organisms not able to survive in adjacent terrestrial and aquatic ecosystems (Brown *et al*., 2003). They create a buffer between terrestrial and aquatic ecosystems, protect rivers from the effects of activities in adjacent terrestrial environments, and stabiles river banks. These zones are typically sustained by a combination of surface and subsurface water, with the contribution of groundwater being critical during dry periods.

Salt marshes in estuarine environments provide a further example of the important role of surface – groundwater interaction. While the marshes are regularly inundated by saline water, the continual discharge of fresh groundwater (often in small quantities) provide refugia habitat for freshwater organisms by maintaining relatively low salinities.

While it is important to recognise the dependence of ecosystems on groundwater, it is equally important to recognise not all aquatic or terrestrial ecosystems are groundwater dependent. Further, demonstration of groundwater use does not necessarily equate to groundwater dependence while groundwater abstraction will not necessarily affect the supply of groundwater to groundwater dependent ecosystems.

It is only in the last few years that the role of groundwater in sustaining the environment has been appreciated. In South Africa, the National Water Act (Act 36 of 1998) makes provision for protecting aquatic ecosystems. This is one component of the Reserve, the other being the provision of water to meet basic human needs. When developing methods to quantify the Reserve, the role of groundwater in sustaining aquatic ecosystems was recognised (DWAF, 1999).

Potential impact of groundwater abstraction on vegetation is a current topic of attention amongst environmentalists. However, not all vegetation (or ecosystems) is groundwater dependent. While hydrophytes, mesophytes and phreatophytes may obtain some or all of their water from groundwater, xerophytes probably obtain most of their water from the unsaturated zone. The role of water stored in soils and the unsaturated zone must not be neglected nor the independence of water in the saturated and unsaturated zones.

The Australians developed a system of classifying groundwater dependent ecosystems (Sinclair Knight Merz, 2001). This was linked to a classification where groundwater dependent ecosystems are ranked in terms of their conservation value, vulnerability to potential threats and the likelihood of these threats being realised.

Groundwater Dependent Ecosystems

Terrestrial vegetation: Vegetation communities and dependent fauna that have seasonal or episodic dependence on groundwater.

River baseflow systems: Aquatic and riparian ecosystems that exist in or adjacent to streams that are fed by groundwater baseflow.

Aquifer and cave ecosystems: Aquatic ecosystems that occupy caves or aquifers.

Wetlands: Aquatic communities and fringing vegetation dependent on groundwater fed lakes and wetlands.

Terrestrial fauna: Native animals that directly use groundwater rather than rely on it for habitat.

Estuaries and near-shore marine ecosystems: Coastal, estuarine and near shore marine plant and animal communities whose ecological function has some dependence on discharge of groundwater.

(Sinclair Knight Merz, 2001)

While it is important to recognise groundwater dependency, it is equally import to recognise the degree and significance of the importance. A fundamental tenet of ecology is that ecosystems generally use a resource in proportion to the availability of the resource (whether it be water, light, nitrogen or some other resource), and the availability of the resource will be a significant determinant of the structure, composition and dynamics of an ecosystem (Tilman, 1988 as quoted by Brown *et al.*, 2003). Where groundwater is accessible, ecosystems will develop some degree of dependence on it, and the degree of dependence is likely to increase with increasing aridity.

Degree of Groundwater Dependency

Entirely dependent: ecosystems would collapse if groundwater fluxes were to diminish or be slightly modified.

Highly dependent: moderate changes to groundwater discharge or water tables would lead to substantial decreases in either the extent or condition of ecosystems.

Proportionally dependent: a unit change in the groundwater system would result in a proportional change in the condition of the ecosystem.

Facultative dependency: changes to a groundwater system would have a minor effect on the condition of the ecosystem.

No dependence: ecosystems are independent of groundwater.

(Brown *et al.*, 2003)

Balance between Utilization and Protection

In response to the National Water Act (Act 36 of 1998), the role of groundwater in sustaining aquatic ecosystems is now starting to be understood. It has also been recognised not all ecosystems are dependent on groundwater. Where a direct link exists between groundwater and aquatic or terrestrial ecosystems, protection mechanisms need to be put in place to ensure groundwater abstraction does not negatively impact those ecosystems dependant on the groundwater. Such mechanisms need to take into account the degree of dependence and the risk of impact. Documented case studies of where groundwater abstraction negatively effected the environment are required to facilitate a better understanding of the cause and effect relationship.

8. QUANTIFYING SURFACE - GROUNDWATER INTERACTION

A range of tools and techniques could potentially be used to quantify surface - groundwater interaction, with sufficient good quality groundwater level and chemistry data possibly being very meaningful. Groundwater contour maps, for example, can be compiled and the relative position of the water table in relation to the riverbed assessed. To do this, one needs a good data set of groundwater levels and a fairly accurate digital terrain model. Losing reaches can be identified by the water table being below the water level in the river and gaining reaches identified where the water table is interpreted to be above the water level in the river.

Darcy's Law

Darcy's Law can be used to estimate surface water losses and gains. The following equation can be used to calculate surface water losses where the water table is below the water level of the stream (Figure 8.1).

$$q = K' L W i$$

where:	q	the rate of flow between the stream and aquifer (L^3/T)
	K'	vertical hydraulic conductivity of the stream bed (L/T)
	L	length of stream reach over which seepage is assessed (L)
	W	average width of the stream over which the reach is assessed
	i	hydraulic gradient between the stream and aquifer

$$i = \frac{h_{aquifer} - h_{stream}}{M}$$

where:	$h_{aquifer}$	elevation of the groundwater beneath the stream (L)
	h_{stream}	elevation of the stream water surface (L)
	M	thickness of the streambed (L)

note: In instances where the stream is disconnected from the underlying groundwater body, the hydraulic gradient is assumed to be 1.

In instances where groundwater discharges into rivers, the following equation is appropriate:

$$q = T \ i \ 2W$$

where:	T	transmissivity (L^2/T)
	i	average groundwater hydraulic gradient
	W	length of river reach (L)

In practice, the influent and effluent status along the length of a river will vary significantly. Also, the status is expected to fluctuate over time. It is understood that as the water table fluctuates relative to the base of the river, so to will the effective average length of the reach. Given that T and i remain (relatively) constant, this changing of the effective river length is thought to be an important mechanism controlling the temporal variability of groundwater discharge to rivers.

Detailed numerical models, supported with sufficient data, will be required for accurate assessments. However, the above equations will provide a coarse estimate of stream gains and losses.

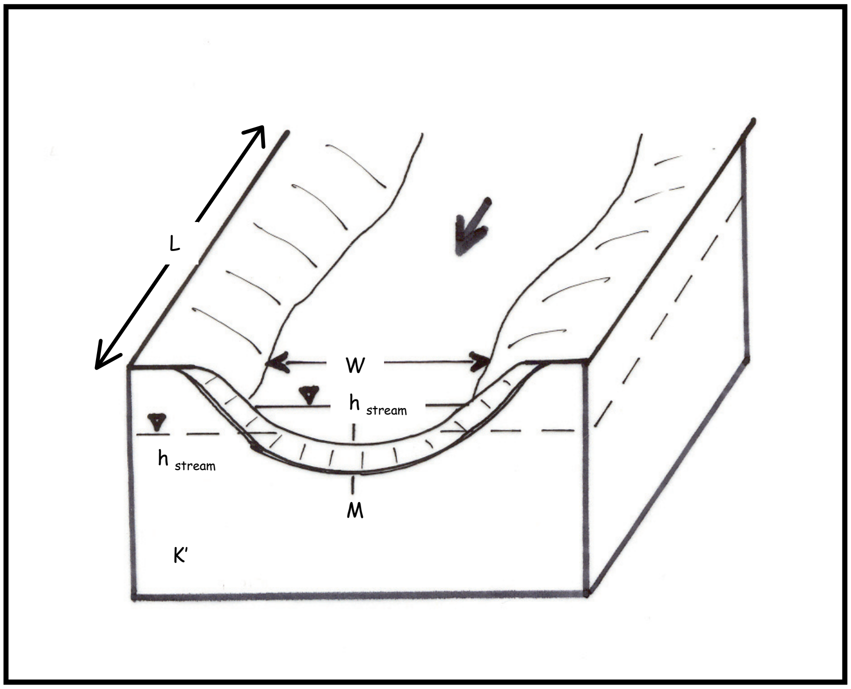

Figure 8.1: Calculating the flow between a stream and aquifer.

Baseflow Separation

Traditional baseflow separation into stormflow and baseflow components has thought to be a measure of groundwater discharge into rivers (Figure 8.2). It is now understood that a component of interflow forms part of both the stormflow and baseflow components (Figure 5.5) and as a result, baseflow comprises contributions from both interflow and groundwater. Hughes (2003) observed that estimates of baseflow are up to 10 times greater than expected recharge.

Examination of baseflow after prolonged periods without rain, however, may give a good indication of the groundwater contribution to flow. While it is argued separation of a hydrograph into stormflow and baseflow components does not provide an indication of the groundwater contribution to flow (as baseflow also includes a proportion of the interflow component), examination of baseflow after extended dry periods may be more meaningful.

This approach was used to some success by Papini *et al*. (2002) and Parsons (2003) in the Hex River and Thukela River catchments. Inclusion of an analysis of surface and groundwater quality data may provide greater confidence when quantifying groundwater discharge into a stream.

Given the need to quantify the groundwater contribution to river flow, baseflow separation techniques described by Hughes and Munster (2000), Smakhtin (2001), Xu *et al*. (2002) and Hughes *et al*. (2003) could be adapted for this purpose. However, cognisance needs to be taken that many surface flow gauging stations are notoriously inaccurate for monitoring low flows. Historically, hydrologists were principally concerned with the magnitude of storm events and high flows, and it is only in recent years that greater interest has developed in the flow and duration of low flow events.

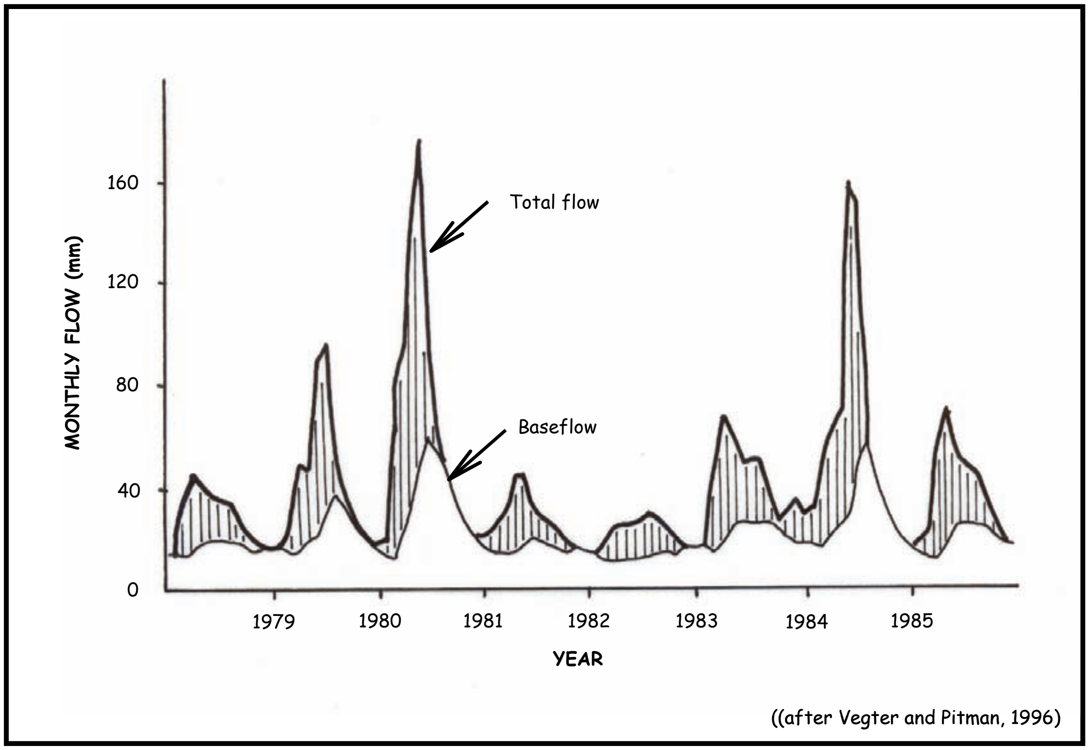

Figure 8.2: Baseflow separation of the Sabie River.

Using Environmental Tracers to Determine Surface - Groundwater Interaction

Groundwater tracers are naturally occurring dissolved chemical constituents, isotopes or physical properties of water used to track the movement of water through watersheds. Useful environmental tracers include common dissolved constituents (such as EC, individual chemical constituents or their relative abundance in relation to each other), stable isotopes ($^{18}0$, ^{2}H), radioactive isotopes (^{3}H, ^{222}Rn), and water temperature. These parameters can be used to identify the source of water, rate of movement or fluxes and the age of water.

- Tritium (^3H) is a useful indicator of the time water has spent in the subsurface. Nuclear bombs release high concentrations of ^3H into the atmosphere. High concentrations of ^3H resulted from the above ground nuclear-bomb testing in the 1960's. Groundwater recharged at this time can hence be identified by increased ^3H concentrations in groundwater. However, the usefulness of this technique is diminishing as concentrations reduce as a result of radioactive decay.
- Elevated concentrations of ^3H have been detected in leachate generated by landfills, resulting in ^3H becoming a useful tracer for detecting groundwater contamination by waste disposal sites.
- Chloroflurocarbons (CFCs) can be used to date groundwater less than 50 years old.

These approaches have been used to good effect by Richey *et al.* (1998), Saayman *et al*. (2002) and others, but are dependent on the collection and analysis of sufficient samples before, during and after rainfall events.

Undertaking simple EC profile along the length of a river during various stages of river flow could be a potentially powerful tool to identify zones where groundwater discharges into a river. This, together with sampling of surface and groundwater, could facilitate a better understanding of surface - groundwater interaction.

Measurement and Monitoring

Proper measurement and monitoring of hydrological systems is crucial if we are to improve our current understanding of surface - groundwater interaction. While modeling may be a useful tool, failure to calibrate models using measured data merely perpetuates our flawed conceptual thinking. Measurement of low flows in rivers, groundwater levels, water chemistry and rainfall must form the basis of further research into this complex issue.

Need for Quantification Tools

While the National Water Act recognises a unitary and interdependent hydrological cycle, we lack the tools required to quantify and manage the hydrological system as a whole. In addition to developing a better appreciation of this interdependence by water resource managers and practitioners, we need to develop tools to:

- identify where interaction is taking place
- quantify the interaction and assess its significance
- develop management tools so that the interaction is not negatively impacted by groundwater abstraction

9. ACTIVITIES THAT IMPACT SURFACE – GROUNDWATER INTERACTION

Groundwater Abstraction

Groundwater abstraction could potentially impact effluent streams where groundwater is discharged into the river. However, where the water table or piezometric surface is positioned below the base of the river (influent or detached streams), groundwater abstraction is unlikely to have any impact on flow in the river. Similarly, construction of a dam or abstraction of large volumes of surface water directly from a river is unlikely to impact aquifers directly adjacent to effluent streams, but may be of importance in the case of influent streams. Because of this understanding, and given the relatively small area of South Africa drained by perennial rivers, the simplistic assumption that use of groundwater will result in a corresponding reduction in spring flow and surface water resources (as made by Basson *et al*., 1997) is incorrect and invalid.

Abstracting groundwater from a borehole causes the water table to drop, thereby inducing groundwater flow toward the pumped borehole (Figure 9.1). This results in a *cone of depression* forming around the pumped borehole. The depth and extent of the cone of depression is dependent on the rate and duration of abstraction and prevailing geohydrological properties of the aquifer.

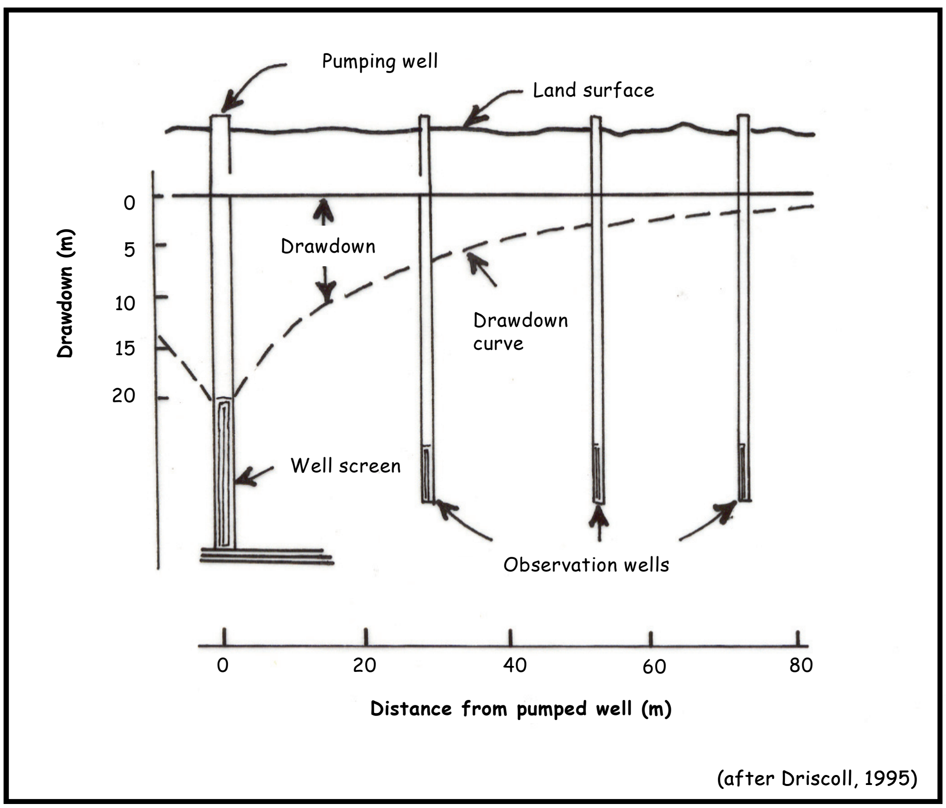

Figure 9.1: Illustration of drawdown resulting from the abstraction of groundwater.

Should the cone of depression around the pumped borehole reach a surface water body (river, lake, wetland or estuary), then localised hydraulic gradients can change and flow induced from the surface water body into the subsurface. The extent of losses from the surface water body will be dependent on localised hydraulic gradients, hydraulic properties of the subsurface and channel bed and the length of intersection of the cone of depression.

The effect of pumping a single borehole will generally remain at a local scale. However, large-scale abstraction from a wellfield or multitude of boreholes could significantly reduce flow in a surface water body on a regional scale. The effect of pumping may only be realised years after pumping started, depending on the rate, volume and duration of groundwater abstracted and the distance between the river and the abstraction points.

Groundwater Disputes

A number of high-profile disputes have arisen in recent years as a result of groundwater abstraction adjacent to surface water bodies, including those of the Mokolo River (below the Hans Strijdom Dam near Ellisras), the Vermaaks River east of Oudtshoorn, the Hex River and Boschkloof near De Doorns and the Kamienassie groundwater abstraction scheme near Oudtshoorn. In most cases, it was claimed abstraction of groundwater was impacting flow in adjacent rivers or springs. While theoretically possible to demonstrate the impacts, provision of sufficient scientific evidence to withstand legal scrutiny is often difficult and usually resulted in protracted (and costly) legal processes.

Measurement of river or spring depletion from groundwater abstraction requires testing in the field. The borehole of interest is turned on for a period of continuous pumping and the effects thereof are determined by measuring the relative change of river or spring flow. While theoretically possible, quantification of impacts in the field is often very difficult, as it requires interference from other nearby boreholes be avoided or minimised and surface water flow measured sufficiently accurately. Mathematical models can be used to quantify or predict the impact of groundwater abstraction on surface water bodies. However, this usually requires a number of simplifying assumptions be made and needs to be based on good data. Models can also be used to calculate set back distances to minimise potential impacts of groundwater abstraction on surface water flow.

Quantification or prediction of impacts resulting from groundwater abstraction is not as straightforward as it may seem. For example, only the permanently abstracted portion of the total volume of groundwater abstracted from an aquifer should be considered (this is now being referred to as *consumptive use*). Some of the groundwater abstracted may return to the subsurface from excess irrigation, seepage ponds, etc. This water will seep through the vadose zone and artificially recharge the aquifer from which it was pumped. However, groundwater used by plants, lost through evaporation or pumped to another location for use elsewhere (consumptive use) will not return to the aquifer from which it was pumped, and is hence of significance. A key issue in trying to assess the impact of groundwater abstraction on surface water is the availability of good quality monitored rainfall, groundwater level, groundwater chemistry and abstraction data.

Vermaaks River

Cleaver *et al*. (2003) concluded groundwater abstraction in the Vermaaks River Valley had reduced groundwater discharging in the Valley, but reported observed impacts were exacerbated by below average rainfall. Spring 009 initially yielded 10 L/s, but flow ceased about 7 years after groundwater abstraction from the wellfield was initiated. In the adjoining Marnewicks River catchment, there was no evidence of direct impact of groundwater abstraction on flow, but the influence of reduced rainfall was observed.

Of the 53 springs investigated, only 1 was found to have been impacted by groundwater abstraction. Flow at 13 other springs ceased, but these were classified as Type 2 springs affected by below average rainfall rather than groundwater abstraction.

(Cleaver *et al*., 2003)

Sea Water Intrusion

One of the clearest illustrations of the links between surface and groundwater bodies is provided by saline intrusion. In almost all cases, groundwater discharges from aquifers into the sea under natural conditions. However, by abstracting too much groundwater or at too high a rate, the hydraulic gradient is reversed and saline seawater then flows into the aquifer. This reversal results in a deterioration of groundwater quality and usually impacts on the suitability of groundwater for a particular use. Examples of where this has occurred include Robben Island (Parsons, 1998), Struisbaai (Weaver, 1997) and Bushmans River Mouth. Saline intrusion is readily prevented by appropriate geohydrological investigation and implementation of effective aquifer management and monitoring.

Robben Island

Early inhabitants of Robben Island relied entirely on springs for a supply of fresh, drinking water. In response to a growing demand for water, the first borehole was drilled on the Island in 1897. Since then, more than 80 boreholes have been drilled. Over-abstraction and poor resource management resulted in a decline in groundwater levels, in turn causing springs to stop flowing and saline intrusion.

(Parsons, 1998)

Storage Dams

Construction of dams can result in a rise of groundwater levels in areas directly adjacent to the dam and, depending on the size of the dam and prevailing geohydrological conditions, can induce extensive water logging. Infiltration of surface water stored in dams into the subsurface results in the artificial recharge of under-lying aquifers. Farmers in drier areas have used this phenomenon to good effect, with windpumps commonly located directly down gradient of small earth dams (Murray, 2002). From a surface water point of view, wetter conditions would prevail than previously the case, resulting in a change in aquatic ecosystems directly down gradient of the dam.

Villiersdorp Dispute

Rosewarne (1991) reported on a case where a farmer in the Villiersdorp area accused his neighbour of impacting his water rights by building a farm dam on a stream in an adjacent catchment. The farmer claimed construction of the dam on the adjacent stream reduced flow in his stream. Using a tracer test, Rosewarne was able to show a geological fracture zone transcended the two catchments and linked the two streams. Building the dam on Stream A reduced recharge to the fault zone. In turn, this resulted in a reduction in discharge from a spring on the same fault zone that fed Stream B.

(Rosewarne, 1991)

Forestry

Forestry is known to impact flow in rivers (Scott and le Maitre, 1997) and is recognised as a streamflow reduction activity. However, less is known about the impact of forestry on groundwater. By assuming baseflow was equivalent to groundwater discharge, Scott and le Maitre (1997) concluded plantations resulted in a decrease in baseflow, and by inference, a markedly reduced groundwater discharge. They suggested the roots of the trees could either abstract water directly from the water table (10 m) or could upset the water balance by taking water from the unsaturated zone. This would result in less water percolating beyond this zone as a greater soil moisture deficit would have to be satisfied before water could gravitate beyond into the saturated zone i.e. reduction in recharge.

Impact of a Wattle Plantation

Kok monitored groundwater levels after the felling of a wattle plantation north of Pietermaritzburg. Groundwater levels rose after clearfelling, but showed reduced recharge peaks as the new plantings of wattles grew. He reported no recharge was evident 5 to 8 years after planting and concluded mature wattles either intercepted or transpired the expected annual recharge of 10 % of the 900 mm MAP.

(Kok, 1976)

Scott and le Maitre (1997) reported a number of instances where clearing of plantations or vegetation resulted in rising water tables. They also provided a number of anecdotal accounts of where groundwater abstraction reportedly negatively impacted vegetation. Unfortunately, these accounts lacked monitored groundwater data to allow proper investigation of the cause of water level changes and impact to vegetation.

Removal of (Alien) Vegetation

Vegetation plays an important role in maintaining the dynamic equilibrium between aquifer recharge, discharge and the position of the water table. Increased evapotranspiration losses from alien vegetation, for example, will result in a fall in water level and a reduced groundwater contribution to river flow. Conversely, removal of alien vegetation would result in a rise in water level as the groundwater system adjusts to a new dynamic equilibrium. The same holds true for the planting and harvesting of forests.

Alien Vegetation Clearing

Response of groundwater levels to clearing alien vegetation was monitored in the Elim area near Bredasdorp. It was found groundwater levels rose almost immediately after clearing by between 17 cm and 25 cm, but then gradually receded to just above pre-clearing levels. However, the adjacent Nuwejaars River changed from a influent stream to an effluent stream. It was estimated evapotranspiration losses from the alien vegetation ranged between 6 300 KL/ha/month in January to 1 400 KL/ha/month in July.

(Toens and Partners, 1998)

Bush clearing in the North West and Northern Province

Studies in the Thababzimbi and Waterberg districts of the North West and Northern Provinces showed bush clearing enhanced recharge to the underlying granitic and crystalline metamorphic aquifers. Even though the piezometric surface was deeper than 40m below surface, the water table rose by 20 m over a 30 year period. It was proposed removal of the bush reduced interception and transpiration of water out of the shallow soil profile.

(Vegter, 1993)

Clearing of Phreatophytes along the Gila River

Detailed monitoring of rainfall, groundwater levels and flow in the Gila River upstream of the San Carlos Reservoir in Arizona over a 10 year period showed the negative impact of phreatophytes on the floodplain on stream flow. Prior to the removal of vegetation, water seeped from the river into the subsurface during most months (i.e. losing stream). On removal of the vegetation, groundwater levels rose and groundwater discharged into the river during March through to June (i.e. gaining stream) and reverted to a losing stream during the remaining months of the year.

(Winter *et al*., 1999)

Mining

A key issue in the development and management of any mine is how to manage groundwater. Groundwater either has to be sealed off or abstracted so mining in the subsurface can take place. Lowering the water table by groundwater abstraction induces flow from adjacent surface water bodies into the subsurface. However, this impact is offset by the discharge of abstracted groundwater into streams, which in turn reduces the natural variability of stream flow and can significantly modify surface water quality (particularly during low flow periods).

Exposure of sulphide minerals – such as those associated with coal and gold mining – results in the oxidation of these minerals to form acidic, sulphate enriched waters. This process – referred to as Acid Rock Drainage (ARD) – has major environmental consequences and is very difficult and expensive to address in any meaningful way.

Agriculture

The agricultural sector is by far the biggest groundwater user in South Africa. In addition to being used for domestic and stock watering purposes, groundwater is widely used for irrigation purposes. Use of groundwater for irrigation may result in a number of impacts (Conrad *et al*., 1999):

- Over-abstraction of groundwater or abstraction to close to surface water bodies may induce flow from the surface water bodies into the subsurface.
- Over-irrigation in areas not suited for irrigation can result in water logging
- Irrigation in areas underlain by saline geologies can result in the increased discharge of saline groundwater into surface water bodies, as experienced in the Fish River and parts of the Breede River.

Use of fertilizers, herbicides and pesticides could also impact both surface and groundwater bodies, sometimes resulting in widespread non-point source contamination. The concentration of large numbers of livestock in feedlots can also lead to contamination of surface and groundwater bodies. Nitrate, for example, is released by the nitrification of fertilizer ammonium and is mobile as a dissolved constituent in shallow groundwater. High concentrations of nitrate discharged into surface water bodies via the subsurface can contribute to the excessive growth of aquatic plants, depletion of stream oxygen, fishkills and general degradation of aquatic habitats (Winter *et al*., 1999).

Salinisation of the Fish River

Irrigation of land underlain by Karoo geology resulted in salinisation of the Fish River. In addition to the concentration of salts by evaporation, mobilization of both natural and accumulated salts in the soils increased the salinity of irrigation water returning to the river. The salinity of groundwater under irrigated lands was in the order of 3 400 mg/L, as opposed to the 2 000 mg/L for aquifers below non-irrigated veld.

(Reynders, 1984)

Salinisation of the Breede River

The Breede River catchment is the fourth largest irrigation area in South Africa, with more than 100 000 ha under irrigation. Irrigation caused a deterioration of river water quality, particularly during low flow periods. Over-irrigation and irrigation in areas underlain by naturally saline shale and conglomerate resulted in saline water discharging into the river via the subsurface.

(Conrad *et al*., 1999)

Urban Environments

Activities in urban environments can have a significant impact on surface – groundwater interaction. Contamination from waste sites, sewage treatment works, septic tanks, underground storage tanks, industrial areas, informal housing and many other potential sources of contamination can impact groundwater quality and ultimately the quality of water in surface water bodies (Figure 9.2). The transport of soluble contaminants in the subsurface is slow, and often only manifests itself long after contamination first occurred.

While it is often argued urbanisation reduces direct recharge to groundwater systems, it is also true urbanisation introduces a new source of recharge (Simmers, 1996). These include leaking water and sewer pipes, leaking underground storage tanks and excessive irrigation of gardens and parks. Given that water losses from reticulated water supplies often exceed 20 % and that these systems are pressurized, recharge from leaking water pipes alone could be substantial. Urban recharge of this nature could lead to an increase in localised discharge into adjacent streams.

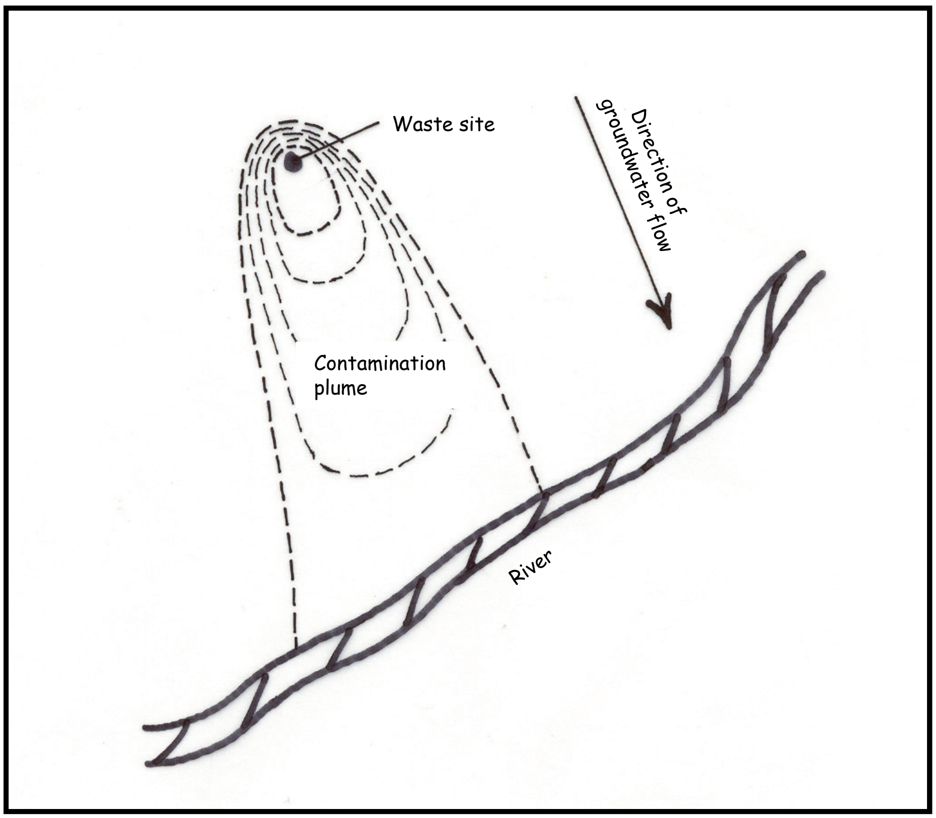

Figure 9.2: Discharge of contaminated groundwater into a river.

When shallow groundwater systems are used both as a source of water and as repositories for human waste, it is almost inevitable groundwater will become contaminated. This was the case in ancient Rome. On detecting foul smelling and tasting groundwater, groundwater was labelled as "unreliable" and the contaminated resource abandoned. Aqueducts were then built to transport pristine water from nearby mountains. Unfortunately, this lesson has had to be learnt time and time again.

Water and Waste

In Charles Town (now Charleston) in South Carolina, early colonists settled in a sandy area underlain by thick clay. Though the site was selected because it was dry and defendable against attack, settlers found they could dig shallow wells in their back gardens and readily obtain good quality water from the underlying aquifer. This situation prevailed for 50 years during which time the town grew steadily. By the middle of the eighteenth century, residents noticed water from their wells was becoming rust-coloured, foul smelling and unfit to drink. This, they thought, was due to an "evil" afflicting their wells.

However, current knowledge allows it to be understood that untreated human sewage seeping from outhouses and privies into groundwater below was impacting the wells from which they drunk. The reason it took more than 50 years for this to occur relates to both the slow rate of groundwater movement and the ability of aquifers to cleanse and renovate themselves. It was only as the town grew that the capacity of the aquifer to protect itself was exceeded, leading to contamination being detected. Realisation of the link between disposal activities and contaminated groundwater took centuries to be made.

(Chapelle, 1997)

Contamination of groundwater by anthropogenic activities can also impact adjacent surface water bodies if groundwater discharges into these bodies. Because of the slow rate of movement and limited groundwater quality monitoring, the impact of groundwater contamination often goes undetected for long periods. When manifesting itself through discharge into surface water bodies, the problem is far greater and more difficult to address.

Contamination of Surface Water Bodies via Subsurface Seepage

Using an integrated team of specialists and considering all possible sources of phosphorus, Harding (2000) was able to show sediments trapped in the vlei account for 25 % of the total annual phosphorus load in Zeekoevlei, 28 % is contributed by contamination in the Big Lotus River catchment and 35 % of the phosphorus load is contributed via subsurface seepage from an adjacent sewage treatment works. While the subsurface seepage was not previously fully recognised nor quantified, failure to address this issue would hamper vlei remedial actions.

(Harding, 2000)

Need for Case Studies

Anthropogenic impacts on groundwater and surface - groundwater interaction are poorly understood. Allegations of impacts are generally not based on measurement. While anecdotal accounts are useful for highlighting potential problems, proper investigation is needed to assess causes and effects. A library of case studies is required to allow for knowledge and expertise around surface – groundwater interaction to develop.

10. IMPLICATIONS OF NOT UNDERSTANDING SURFACE - GROUNDWATER INTERACTION

Historically, the surface and groundwater fraternities have worked apart. Promulgation of the National Water Act (Act No. 36 of 1998) and recognition of a unitary, interdependent hydrological cycle has required a more integrated approach. As a result of closer working relationships, it has emerged our understanding of surface - groundwater interaction is poor and many previous hydrological investigations have not addressed this issue adequately. Failure to improve our understanding of surface - groundwater interaction will perpetuate poor decision making with respect to water resource assessment and management.

Baseflow as an Indicator of Recharge

Assuming baseflow is an indictor of recharge has been shown to be incorrect, as baseflow comprises both interflow and the groundwater contribution to river flow. While the groundwater contribution to river flow may provide an indication of the *minimum* recharge in an area, traditional approaches to baseflow separation cannot be used. Methods to quantify the groundwater contribution to river flow are required for this purpose.

Management of Water Bodies

Research into management of urban impoundments failed to consider the role of groundwater in sustaining the water bodies (Wiechers *et al.*, 1996). At least three of the ten case studies considered include an important groundwater component. Implementation of management actions that do not consider groundwater aspects are likely to fail, as illustrated at Zeekoevlei. About 35 % of the phosphorus load in Zeekoevlei is contributed via subsurface seepage from an adjacent sewage treatment works (Harding, 2000) and any remedial actions that excluded this source were likely to be ineffective.

Water Situation Assessment Model

The WSAM model assumed a direct link between surface and groundwater, and use of groundwater would simply result in a corresponding reduction in spring flow and surface water (Basson *et al*., 1997). Based on this, it was concluded further exploitation of groundwater would not meaningfully add to the overall water resource capabilities of the country.

Given that much of South Africa is drained by seasonal and ephemeral rivers with little or no link to groundwater, the assumption of a direct linkage between surface and groundwater resources is clearly flawed. As only 2 100 MCM/a of the estimated groundwater harvest potential of 19 250 MCM/a is currently used, significant potential exists for further developing groundwater resources in this country.

Integration

Integration is a catch phrase applied to many hydrological and environmental studies and assessment, but is seldom attained. While attempts may be made to integrate budgets and work programmes, the collection and interpretation of data and understanding of hydrological systems seldom is. Both international and local literature is cluttered with examples where experts have studied systems and proposed integrated management plans, without ever having considered the role of groundwater. In some instances, groundwater will play no or little role in the functioning of a hydrological system. However, in other instances, groundwater will play a key role and failure to take cognizance thereof will result in wasted effort. A challenge created by promulgation of the National Water Act (Act 36 of 1998) is for greater integration of effort between managers and practitioners, and specialists of different disciplines.

Need for Better Understanding and Integration

The above boxes are used to illustrate the implication of not recognising and understanding surface - groundwater interactions. Failure to address surface - groundwater action can only lead to a waste of human and financial resources and poor decision-making. Significant effort is required to improve our understanding of this interaction and ensure a common understanding amongst water resource managers and practitioners. It is proposed universities and other hydrological training organisations be encouraged to use this manual as part of their course notes and water resource projects be required to integrate hydrological, geohydrological, engineering and ecological skills and expertise into the teams undertaking the studies.

11. SOME THOUGHTS ON THE WAY FORWARD

- The hydrological community in South Africa must be encouraged to adopt consistent, but internationally recognised terminology and nomenclature. Preparation of a Southern African dictionary of hydrological terms could facilitate this. To avoid confusion and until such time a consistent terminology is adopted, the hydrological community should define terms used when writing policy, reports and other scientific publications. Further, universities and other hydrological training organisations should be encouraged to use this manual as part of their course notes.

- Use of low flow data to quantify the groundwater contribution to river flow remains a viable tool. However, baseflow separation needs to be process-based, rather than the traditional non-process based. Methodologies used by Moore (1992), Xu *et al*. (2002) and Hannula *et al*. (2003) require further attention.

- Further development and refinement of the adapted Pitman model described by Hughes (2003) is required. The purpose of the adaptation should be to estimate recharge and groundwater discharge time series from available data and integrate them with surface water estimation approaches acceptable to both surface and groundwater practitioners. The model is to be tested in a range of catchments using measured data.

- The model development should be supported with the identification, development and testing of tools to identify the groundwater contribution to river flow in the field. Potential tools include groundwater level contouring, EC profiling and chemical sampling of rivers and groundwater. These tools will facilitate calibration of the adapted Pitman model and the national maps recommended below.

- Consideration should be given to preparing a national scale map on which river reaches dependent on groundwater discharge is specified. River reaches would be classified as influent, effluent, disconnected or intermittent and the classification related back to climatic and topographical characteristics. This map could also be used to guide calibration of the adapted Pitman model. Methods adopted by the LUWRH Working Group (2000) and Xu *et al*. (2002) should be considered when developing the methodologies.

- It is recommended a guideline document be prepared describing procedures to be followed and various methods and techniques that can be used to quantify or predict the impact of groundwater abstraction on adjacent environments.

- It is clear a poor understanding of surface - groundwater interaction played a role in the National Water Balance Model adopting the assumption that use of groundwater reduces available surface water resources. Uninformed assumptions about surface - groundwater interaction adopted in the National Water Balance Model resulted in erroneous conclusions being reached, which in turn are reflected in the National Water Resource Strategy. It is recommended a study be initiated to quantify groundwater use in South Africa.

GLOSSARY OF TERMS

ABIOTIC: not pertaining to living organisms; environmental features such as temperature, rainfall etc.

AEOLIAN: relating to or arising from the action of wind.

ALLUVIAL: sediments deposited by flowing water.

ALLUVIAL AQUIFER: an aquifer formed of unconsolidated material deposited by water, typically occurring adjacent to river channels and in buried or paleochannels.

ALLUVIUM: a general term for unconsolidated deposits of inorganic materials (clay, silt, sand, gravel, boulders) deposited by flowing water.

ANISOTROPIC: having some physical property that varies with direction.

ANTECEDENT: a condition that exists before a particular event e.g. soil moisture conditions before a rainfall event.

AQUATIC: associated with and dependent on water e.g. aquatic vegetation.

AQUATIC ECOSYSTEMS: not defined by National Water Act (Act No. 36 of 1998), but defined elsewhere as the abiotic (physical and chemical) and biotic components, habitats and ecological processes contained within rivers and their riparian zones and reservoirs, lakes, wetlands and their fringing vegetation.

AQUICLUDE: a bed, formation or group of formations essentially impervious to water.

AQUIFER: a geological formation which has structures or textures that hold water or permit appreciable water movement through them [from National Water Act (Act No. 36 of 1998)].

AQUIFER: strata or a group of interconnected strata comprising of saturated earth material capable of conducting groundwater and of yielding usable quantities of groundwater to borehole(s) and / or springs (a supply rate of 0.1 L/s is considered a usable quantity).

AQUIFER SYSTEM: a hetrogeneous body of intercalated permeable and less permeable material that acts as a water yielding hydraulic unit of regional extent.

AQUIFUGE: a seldom-occurring body of rock that contains no interconnected openings and neither absorbs nor transmits water.

AQUITARD: a saturated geological unit with a relatively low permeability that retards and restricts the movement of water, but does not prevent the movement of water; while it may not readily yield water to boreholes and springs, it may act as a storage unit.

ARTESIAN AQUIFER: an adjective referring to groundwater under hydrostatic pressure; see *confined aquifer*.

ARTESIAN BOREHOLE: an adjective commonly used to describe a flowing borehole, where the piezometric level is at an elevation higher than ground level.

BANK STORAGE: water that percolates laterally from a river in flood into the adjacent geological material, some of which may flow back into the river during low-flow conditions.

BASEFLOW: sustained low flow in a river during dry or fair weather conditions, but not necessarily all contributed by groundwater; includes contributions from delayed interflow and groundwater discharge.

BASEFLOW INDEX: the ratio of the annual baseflow in a river to the total annual run-off.

BOREHOLE: includes a well, excavation, or any other artificially constructed or improved groundwater cavity which can be used for the purpose of intercepting, collecting or storing water from an aquifer; observing or collecting data and information on water in an aquifer; or recharging an aquifer [from National Water Act (Act No. 36 of 1998)].

CAPILLARY RISE: the natural occurrence of water in contact with, but rising above, the water table; caused by the tensional forces in the pore spaces of soil, sediment and rock material. In fine grained material capillary rise amounts to 2 – 3 m, but measures only a couple of centimeters in coarser grained material.

CAPILLARY ZONE: the subsurface zone directly above the water table caused by capillary rise; also referred to as the *capillary fringe*.

CATCHMENT: the area from which any rainfall will drain into the watercourse, contributing to the runoff at a particular point in a river system; synonymous with the term *river basin*.

CHANNEL PRECIPITATION: precipitation that falls directly onto a surface water body during a precipitation event and makes an immediate (but usually small) contribution to stream flow; does not flow over or through land to reach the surface water body.

COEFFICIENT OF STORAGE: see *storage coefficient*

CONE OF DEPRESSION: the cone-shaped area around a borehole that results from the lowering of the water table or piezometric surface by abstraction.

CONFINED AQUIFER: an aquifer overlain by a confining layer of significantly lower hydraulic conductivity in which groundwater is under greater pressure than that of the atmosphere; also known as an artesian aquifer.

CONFINING LAYER: a layer of low permeability material overlying an aquifer which restricts the vertical movement of water.

CONJUNCTIVE USE: combined use of surface and groundwater.

CONNATE WATER: water entrapped in the *interstices* of sedimentary rocks at the time of deposition.

CONTAMINATION: the introduction of any substance into the environment by the action of man.

DETACHED STREAM: see *disconnected stream*.

DISCHARGE AREA: an area in which subsurface water, included water in the unsaturated and saturated zones, is discharged at the land surface.

DISCONNECTED STREAM: a stream detached from and not in hydrological contact with the groundwater system below, a special case of an influent stream; also referred to as a detached stream.

DRAWDOWN: the difference between the observed groundwater level during pumping and the non-pumping or rest groundwater level in a borehole.

ECOLOGY: the study of the interrelationships between organisms and their environment.

ECOSYSTEM: an organic community of plants and animals and the physical environment they inhabit.

ECOTONE: a transition zone between different types of ecosystems; a region of overlapping plant associations, as that between two biomes or two adjacent ecosystems.

EFFLUENT STREAM: a stream fed directly by groundwater; the surrounding water table or piezometric surface is above the stream surface; opposite of *influent stream.*

EPHEMERAL RIVERS: these rivers are generally storm-event driven and flow occurs less than 20% of the time; these rivers have a limited (if any) baseflow component with no groundwater discharge.

ENDORHEIC: term used to describe a blind or closed drainage system i.e. without any visible drainage outlet.

ESTUARY: a partially or fully enclosed body of water, which is open to the sea permanently or periodically, and within which the sea water can be diluted, to an extent that is measurable, with fresh water drained from the land [from National Water Act (Act No. 36 of 1998)].

EVAPOTRANSPIRATION: the loss of moisture from the combined effects of direct evaporation from land and sea, and transpiration from vegetation.

FAULT: a zone of displacement in rock formations resulting from forces of tension or compression in the earths crust.

FINGERING: when a high density liquid overlies a less dense liquid, or when a fluid spills onto an unsaturated granular medium, the resultant vertical flow is concentrated into discrete flowpaths (fingers) of very complex geometry. This fingering is, to some extent chaotic, and cannot be exactly reproduced by either digital or analogue simulations.

FISSURES: a general term to include natural fractures, cracks and openings in consolidated rock caused by bedding planes, joints, faults, etc.

FLOWNET: a configuration of flowlines and equipotential contours drawn to illustrate the nature and direction of groundwater flow.

FLUVIAL: relating to or arising from the action of flowing water in a river.

FLUX: rate of groundwater flow per unit width of aquifer.

FORMATION: a general term used to describe a sequence of rock layers.

FRACTURE: cracks, joints or breaks in the rock that can enhance water movement.

FRACTURE FLOW: water movement that occurs predominantly in fractures and fissures.

FRACTURE ZONE: a zone of cracks or fissures within rocks.

FRACTURED AQUIFER: an aquifer that owes its water-bearing properties to fracturing caused by folding and faulting; see *secondary aquifer*.

FRESHWATER: water that contains less than 1 000 mg/L salts.

GAINING STREAM: synonymous with *effluent stream*.

GEOHYDROLOGY: the study of the properties, circulation and distribution of groundwater; in practice used interchangeably with hydrogeology; but in theory *hydrogeology* is the study of geology from the perspective of its role and influence in hydrology while *geohydrology* is the study of hydrology from the perspective of the influence on geology.

GROUNDWATER: water found in the subsurface in the saturated zone below the water table or piezometric surface i.e. the water table marks the upper surface of groundwater systems.

GROUNDWATER BODY: a rock or group of rocks comprising of saturated earth material.

GROUNDWATER CONTRIBUTION TO RIVER FLOW: that groundwater that discharges into effluent streams and sustains baseflow.

GROUNDWATER FLOW: the movement of water through openings and pore spaces in rocks below the water table i.e. in the saturated zone.

GROUNDWATER MINING: a term to describe the unsustainable use and over-abstraction of groundwater; the rate of abstraction is greater than recharge, thereby inducing a continual decline of groundwater levels over the long term.

HARVEST POTENTIAL: a sustainable abstraction volume from an aquifer system, the maximum volume of groundwater that may be abstracted per square kilometer per annum without depleting the aquifers.

HETEROGENEOUS: refers to materials having different properties at different points; diverse in character or content; in reality, all aquifers are heterogeneous, although we assume homogeneity in order to simplify their analysis; opposite of *homogeneous*.

HOMOGENEOUS: a characteristic of the geological unit in which hydraulic conductivity is independent of position or direction; opposite of *hetrogeneous*.

HYDRAULIC CONDUCTIVITY: measure of the ease with which water will pass through earth material; defined as the rate of flow through a cross-section of one square metre under a unit hydraulic gradient at right angles to the direction of flow (in m/d)

HYDRAULIC GRADIENT: the slope of the water table or piezometric surface; is a ratio of the change of hydraulic head divided by the distances between the two points of measurement.

HYDRIC SOILS: soils that are saturated or flooded long enough during the growing season to develop anaerobic conditions in its upper layers.

HYDROGRAPH: a graphical plot of hydrological measurements over a period of time e.g. water level, flow, discharge.

HYDROLOGICAL CYCLE: the continuous circulation of water between oceans, the atmosphere and land; the sun is the energy source that raises water by evapotranspiration from the oceans and land into the atmosphere, while the forces of gravity influence the movement of both surface and subsurface water.

HYDROLOGICAL YEAR: a continuous 12-month period selected to present data relative to hydrological or meteorologically phenomena; usually from 1 October to 30 September.

HYDROGEOLOGY: see *geohydrology*

HYDROLOGY: the study of the properties, circulation and distribution of water.

HYDROPHYTES: plants that take their nutrients directly from water, typically found in water or wet habitats

HYPORHEIC ZONE: the saturated and biologically active zone in the permeable substrate beneath and adjacent to a river bed.

INFILTRATION: the downward movement of water from the atmosphere into the ground; not to be confused with *percolation.*

INTERACTING STREAM: see *intermittent stream.*

INTERGRANULAR FLOW: flow that occurs between individual grains of rock.

ISOTROPIC: the condition of having properties that are uniform in all directions, opposite of *anisotropic.*

INFLUENT STREAM: a losing stream above the water table that discharges into the underlying groundwater system; opposite of *effluent stream*.

INTERACTING STREAM: see *intermittent stream*.

INTERFLOW: the rapid flow of water along essentially unsaturated flow paths, water that infiltrates the subsurface and moves both vertically and laterally before discharging into other water bodies.

INTERMITTENT STREAM: rivers and streams whose interaction with groundwater depends on the fluctuating position of the water table, ranging from effluent streams in the wet season to influent streams in the dry season.

INTERSTICES: openings or void space in a rock capable of holding water.

JUVENILE WATER: groundwater entering the hydrological cycle for the first time; it is doubtful whether any terrestrial water is truly juvenile and is totally insignificant volumetrically.

LACUSTRINE: wetlands such as dams and lakes situated in topographic depressions which have a total area greater than 8 ha.

LITHOLOGY: the physical character and description of rocks.

LITHOSTRATIGRAPHY: delineation and classification of strata in terms of their physical character and sequence in space.

LOSING STREAM: synonymous with *influent stream*.

MESOPHYTES: plants that grow under well-balanced moisture conditions.

METEORIC WATER: water originating from rainfall, usually recent, hence actively involved in meteoric circulation, as opposed to *connate water*.

OVERLAND FLOW: flow of water over the land surface usually originating from precipitation or snowmelt; general term used loosely to include all surface runoff.

PALEOCHANNEL: a buried stream channel.

PALUSTRINE: freshwater wetland environments other than those along rivers and lakes, dominated by trees, shrubs, emergent vegetation, mosses and lichens.

PERCHED AQUIFERS: aquifers that contain perched groundwater i.e. bodies of groundwater separated from an underlying body of groundwater by an unsaturated zone.

PERCHED GROUNDWATER: an independent and unconfined volume of groundwater separated from an underlying main body of groundwater by an unsaturated zone; typically occurs above discontinuous impermeable layers.

PERCHED SPRINGS: springs fed by water in the unsaturated zone and interflow.

PERCOLATION: the process of the downward movement of water in the unsaturated zone under the influence of gravity and hydraulic forces; term used to differentiate from infiltration, which specially refers to the movement of water from the atmosphere into the ground.

PERENNIAL: lasting through a year or several years i.e. a river that flows all year round or a wetland that remains wet all year round.

PERMEABLE: materials that allow liquids (and gases) to flow through it.

PERMEABILITY: the ease with which a fluid can pass through a porous medium and is defined as the volume of fluid discharged from a unit area of an aquifer under unit hydraulic gradient in unit time (expressed as $m^3/m^2/d$ or m/d); it is an intrinsic property of the porous medium and is independent of the properties of the saturating fluid; not to be confused with *hydraulic conductivity* which relates specifically to the movement of water.

PHREATIC ZONE: see *saturated zone*.

PHREATOPHYTES: long rooted plants that habitually obtain water from below the water table or from the capillary fringe directly above the water table.

PIEZOMETRIC LEVEL: the elevation to which groundwater levels rise in boreholes that penetrate confined or semi-confined aquifers.

PIEZOMETRIC SURFACE: an imaginary surface representing the piezometric pressure or hydraulic head throughout all or part of a confined or semi-confined aquifer; analogous to the *water table* of an *unconfined aquifer.*

POROSITY: ratio of the volume of void space to the total volume of the rock or earth material.

POTABLE WATER: water that is safe and palatable for human use.

PREFERENTIAL FLOW: the preferential movement of groundwater through more permeable zones in the subsurface.

PRIMARY AQUIFER: an aquifer in which water moves through the original interstices of the geological formation.

QUICKFLOW: by convention, that portion of stormflow that is not part of baseflow and includes overland flow, occurs in direct response to rainfall.

RECHARGE: the addition of water to the zone of saturation, either by the downward percolation of precipitation or surface water and / or the lateral migration of groundwater from adjacent aquifers.

RECHARGE AREA: an area over which recharge occurs.

REGOLITH: the mantle of fragmented or loose material of residual or transported origin, comprising rock debris, alluvium, aeolian deposits, and *in situ* weathered and decomposed rock and typically overlies bedrock; it includes soil.

REMOTE STREAM: see *disconnected stream*.

REST WATER LEVEL: the groundwater level in a borehole not influenced by abstraction; synonymous with *static water level*, but no groundwater levels are ever truly static as they continually respond to recharge, discharge and abstraction.

RESERVE: the quantity and quality of water required to supply basic needs of people to be supplied with water from that resource, and to protect aquatic ecosystems in order to secure ecologically sustainable development and use of water resources.

RIPARIAN: area of land directly adjacent to a stream or river, influenced by stream-induced or related processes.

RIVER: a physical channel in which runoff will flow; generally larger than a stream, but often used interchangeably.

ROCK: any unconsolidated or unconsolidated earth material, specifically excluding soil.

RUNOFF: all surface and subsurface flow from a catchment, but in practice refers to the flow in a river i.e. excludes groundwater not discharged into a river.

SALINE INTRUSION: replacement of freshwater by saline water in an aquifer, usually as a result of groundwater abstraction.

SATURATED ZONE: the subsurface zone below the water table where interstices are filled with water under pressure greater than that of the atmosphere.

SEASONAL RIVER: these rivers are driven by seasonal rainfall patterns and flow occurs between 20 % and 80 % of the time; these rivers have a limited baseflow component with little or no groundwater discharge.

SECONDARY AQUIFER: an aquifer in which water moves through secondary openings and interstices, which developed after the rocks were formed i.e. weathering, fracturing, faulting.

SEEP: a diffuse wetland area where interflow and groundwater emerges, usually at a slow rate or small volume, to become surface flow.

SEMI-CONFINED AQUIFER: an aquifer that is partly confined by layers of lower permeability material through which recharge and discharge may occur, also referred to as a *leaky aquifer*.

SOIL: the usually thin upper surface layer of the earth's crust comprising living organisms, organic matter, decomposed rock or unconsolidated sediments, water and gases with properties attributable to the interaction of its parent material, time, climate, fauna and flora.

SPRING: a point where groundwater emerges, usually as a result of topographical, lithological or structural controls,

STATIC WATER LEVEL: see *rest water level*

STORAGE COEFFICIENT: the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head

STORMFLOW: increased runoff in a river or stream associated with a particular rainfall event or storm; includes contributions from channel precipitation, quickflow and rapid interflow.

STRATIGRAPHY: the study of stratified rocks (sedimentary and volcanic), particularly their sequence in time, their character and correlation in different localities.

STREAM: a small narrow river; often used interchangeably with *river*.

SUBSURFACE WATER: all water occurring beneath the earths surface, including soil moisture, that in the vadose zone and groundwater.

SUBTERRANEAN WATER: not a widely used geohydrological term, a general term used synonymously with *subsurface water*.

SURFACE WATER: Bodies of water, snow or ice on or above the surface of the earth (such as lakes, streams, ponds, wetlands, etc.).

SURFACE RUNOFF: that part of the total runoff that travels over the ground surface to reach a stream or river channel.

TOTAL RUNOFF: the total volume of water that flows in a stream, including contributions from channel precipitation, quickflow, interflow and the groundwater contribution to river flow.

TRANSMISSIVITY: the rate at which a volume of water is transmitted through a unit width of aquifer under a unit hydraulic head (m^2/d); product of the thickness and average hydraulic conductivity of an aquifer.

UNCONFINED AQUIFER: an aquifer with no confining layer between the water table and the ground surface where the water table is free to fluctuate.

UNCONSOLIDATED SEDIMENTS: consists of fragments of weathered rock material (including clays, silts, sand, gravels and cobbles) that have not been cemented to form solid rock.

UNDERGROUND WATER: not a recognised geohydrological term; used - but not defined - in the National Water Act (Act No. 36 of 1998) and meaning is unclear; thought to be a general term referring to *subsurface water*.

UNSATURATED ZONE: that part of the geological stratum above the water table where interstices and voids contain a combination of air and water; synonymous with *zone of aeration* or *vadose zone*.

VADOSE ZONE: see *unsaturated zone*.

VLEI: a colloquial South African term for wetland.

WATER TABLE: the upper surface of the saturated zone of an unconfined aquifer at which pore pressure is at atmospheric pressure, the depth to which may fluctuate seasonally.

WATER YEAR: see *hydrological year*.

WELL: see *borehole;* in South Africa used to refer to a shallow large diameter hole used for abstracting groundwater; in USA synonymous with *borehole*.

WELL FIELD: a group of boreholes in a particular area usually used for groundwater abstraction purposes.

WELLPOINT: shallow, small diameter hole used to abstract groundwater from primary aquifers.

WETLAND: land which is transitionary between terrestrial and aquatic systems, where the *water table* is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated *soil* [from National Water Act (Act No. 36 of 1998)].

XEROPHYTES: plants that have adapted to dry or arid conditions.

YIELD: the quantity of water removed from a water resource e.g. yield of a borehole.

ZONE OF AERATION: see *unsaturated zone*.

ZONE OF SATURATION: see *saturated zone*.

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