A water balance approach to the sustainable management of groundwater in South Africa

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Abstract

The water balance approach, based on the principles of conservation of mass, is applied to the issue of sustainable groundwater management in South Africa, incorporating the ethos of the National Water Act of 1998, prioritising basic human needs and the needs of aquatic ecosystems over inessential uses. The principle of water balance is described and the benefits (such as prevention of resource misallocation), of applying such an approach to groundwater management, are outlined, with additional practical considerations briefly reviewed. It is hoped that the approach will be tested and refined through application to groundwater case studies.

Introduction

Until recently, groundwater in South Africa has been managed as a separate entity to surface water. Additionally, the status of groundwater as private has led to unsustainable management and subsequent resource degradation, necessitating a new approach.

The new National Water Act (*Government Gazette*, 1998) attempts to redress the problem of past groundwater mismanagement by presenting a number of important policy principles for the guidance of groundwater protection strategies. These include:

- Protection of all significant water resources
- Resource sustainability
- Integrated water resource management (as an ideal).

When applied to groundwater usage, 'sustainability' implies use that does not cause long-term deterioration of the overall resource, in terms of any measurable criteria (e.g. quality and quantity). Although it is uncertain whether this goal can ever be practically achieved, it is recognised that such principles, together with a pro-active and adaptable approach to protection, are of paramount importance to successful groundwater management over the long term.

The Act calls for the following resource directed measures (RDMs) for the protection of all significant water resources, including groundwater:

- Resource classification
- Setting of the reserve
- Setting of the resource quality objectives (RQOs).

The concept of the "Reserve" translates as the quantity and quality of water required to satisfy basic human needs for people who are now or who will, in the reasonably near future, be in some way reliant upon the resource (the 'basic human needs' Reserve), in addition to the quantity and quality of water required to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource (the 'ecological' Reserve) (*Government Gazette*, 1998). The reserve is to be calculated for each designated water management area (WMA) of South Africa and water for such high-priority uses will be set aside before allocation to relatively inessential uses is considered. As all water is now recognised as belonging to a larger hydrologic cycle, in a state of continual flux (whereas previously surface and groundwater were treated separately), the determined reserve for each WMA is likely to comprise a surface and groundwater component.

Due to the complexity and spatial heterogeneity of the South African geohydrological system, accurate calculation of the quantity and quality of groundwater sustainably available for use over a large area tends to pose problems. In addition, groundwater may flow between the designated WMAs, emerging to feed surface water or aquatic ecosystems of a different WMA to that from which it originally entered the groundwater system. Planning of the groundwater resource should account for such mechanisms if optimal allocation is the desired goal. Therefore, planning of this component of the overall water resource should occur at a scale at which all water entering and leaving the groundwater system can be accounted for.

The water balance approach is based upon the principle of the conservation of mass and attempts to ensure that chances of mis-accounting and subsequent mis-allocation of the water resource are minimised. The approach has been successfully applied to the estimation of recharge, utilising the CRD (cumulative rainfall departure) and SVF (saturated volume fluctuation) methods (Bredenkamp et al., 1995). This paper explores the possibilities of applying the water balance methodology to groundwater management in South Africa and presents an alternative approach to that put forward in Version 1.0 of the *DWAF 1999 RDM for Protection of Water Resources - Groundwater Component* manual (DWAF, 1999).

It may also be worth noting that a user-friendly Excel-based groundwater balancing tool has been produced, with an accompanying users guide (Wright and Xu, 1999). The model allows simple groundwater modelling at the unit scale, with low resolution, and rough estimation of the impact, of allocating quantities (based purely on volumetric criteria at this stage) of groundwater, upon the surface environment, with reference to requirements of overlying aquatic ecosystems.

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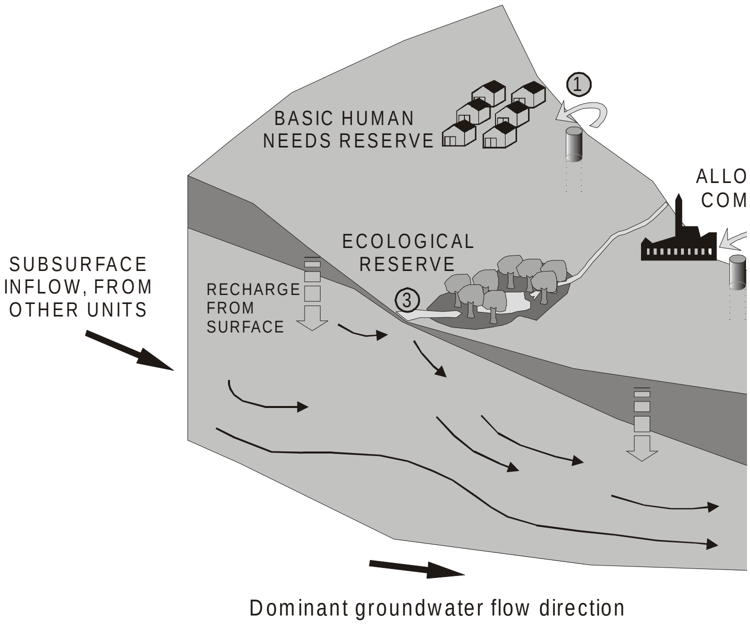

Figure 1
Groundwater recharge and discharge of a distinct geohydrological unit, with reference to different water use groups, as proposed in the Water Act, 1998. Effective groundwater recharge (from infiltration and subsurface flow) will either be allocated locally (shown by points 1, 2 & 3 on figure) or allowed to flow into other areas.

Water balance principle

The water balance principle is based upon the law of conservation of mass. The groundwater entering or leaving a distinct geohydrological unit in an unexploited, steady state, over a period of time, can be described by the following water balance equation:

RECHARGE – DISCHARGE = 0

RECHARGE could take the form of water infiltrating down through the soil zone or lateral subsurface flow from adjacent geohydrological units. Effective recharge describes water actually reaching the groundwater system (having passed through the soil zone, etc.) (Bredenkamp et al., 1995). DISCHARGE includes contribution to surface water courses, subsurface flows into other distinct geohydrological units, evapotranspiration through vegetation and direct evaporation.

When man begins to exploit a groundwater system, ‘natural’ conditions are changed. The impacts are likely to include a reduction in overall discharge from the unit, a decrease in overall storage and a modification of overall recharge. The water balance equation above is therefore modified as follows:

ADJUSTED RECHARGE – REDUCED DISCHARGE – PUMPING + STORAGE = 0

Recharge may have increased and discharges decreased in response to a lowering of the water level. Discharge decreases usually dominate over recharge increases and the yield of a groundwater system is at the expense of the groundwater discharge component. Useful markers, for detection of whether an unsustainable decline of the groundwater resource has occurred over the long term,are deterioration of the local groundwater level/piezometric surface and/or groundwater quality.

The sustainably usable (i.e. not including storage ‘back-up’) groundwater within a distinct geohydrological unit can be considered as belonging to one of two broad groups: that which will be used locally (within the area being assessed); and that which should be allowed to flow from the unit in the subsurface to emerge, available for use, elsewhere (outflow) (Fig. 1).

The mass balance equation illustrates that the smallest of abstractions will have some impact, however minor, on the groundwater system. The setting of a sustainably available quantity of groundwater therefore seems a contentious issue. It could be set at a limit linked to the rate of effective recharge of the area under assessment. The upper limit for abstractions could be set so that it never surpasses the average rate of groundwater replenishment to the unit (with boreholes optimally located). However, natural subsurface outflows, if contributing to important downstream areas, must also be maintained. That is, over a period of time:

Average effective aquifer recharge > Pumping + Necessary outflows

And therefore:

Pumping < Average effective aquifer recharge – Necessary outflows

Groundwater use groups

The quantified groundwater resource of a distinct area is likely to be put to a wide variety of different uses. The Water Act prioritises water-use groups according to importance, as follows (excluding international commitments):

1) Basic human needs
2) Ecological needs
3) Inessential uses - economic development.

Local water resource manager(s) are likely to be called upon to devise strategies, based on sound scientific judgment (such as calculated instream flow requirements (IFRs) and basic human needs data), that optimally balance the needs of local populations and aquatic ecosystems whilst minimising damage to the overall resource over the long-term. In order to do this, the role that groundwater plays within each of the use groups must be quantified and the resource apportioned correctly.

Basic human needs reserve

The water necessary to meet basic human needs is currently set at 25 ℓ per person per day (*Government Gazette*, 1998). As basic human needs are the highest priority of any of the water-use groups, it seems sensible to account for this use within the water balance model of a distinct geohydrological unit prior to considering the demands of aquatic ecosystems. Although it would be difficult to police and regulate groundwater used for basic human needs, it may be possible to ensure that the location of borehole abstractions are optimal, with respect to minimising impacts on local ecosystems and outflowing groundwater.

Ecological reserve

Many examples of aquatic ecosystems linked either directly or indirectly to groundwater systems exist (Hatton and Evans, 1998). An example of an indirect linkage is a situation in which groundwater contributes to the baseflow of a river that ultimately supplies a surface-water-fed aquatic ecosystem. Directly, ecosystems could be supported in zones of groundwater recharge and discharge, in addition to areas of throughflow. Of particular importance amongst the various possible interactions between surface and subsurface aquatic ecosystems are **ecotones**, or interfaces between terrestrial and aquatic ecosystems and between surface water and groundwater systems. Ecotones are zones where ecological processes are more intense and resources more diversified. They are also zones which react quickly to human influences and changes in environmental variables. A typical example within South Africa is the groundwater-fed freshwater refugia of Lake St Lucia.

The role of groundwater in the support of aquatic ecosystems must be ascertained. This would involve quantification of the year-round contribution of groundwater, in terms of quantity and quality, under "natural" conditions and of conditions required in the future, for identified ecosystems to obtain their assessed RQOs. A relevant portion of the resource is to be subsequently guaranteed, to ensure a continuation or improvement of the status of the identified aquatic ecosystem. The class of the water-fed area and the importance of groundwater to its survival should determine the frequency at which the groundwater component of this "fixed" Reserve is reviewed.

Outflows and allocation for inessential uses

With the local reserve calculated, groundwater available for allocation to lower priority local uses must be quantified. However, in keeping with the use-group priorities set by the Water Act, *before* this can occur the contributions that local groundwater makes to the Reserve of areas elsewhere, through outflows, must be ascertained. This is to avoid mis-allocation of groundwater on a larger spatial scale, and potential prioritisation of local inessential uses over essential uses elsewhere.

Therefore, a comprehensive determination of the overall groundwater component of the Reserve for any planning area should allow for the setting aside of a portion of the local groundwater resource for the Reserve elsewhere, if it is required. This necessitates a detailed understanding of the geohydrological system (groundwater linkages, pathways, travel times, aquifer characteristics, etc.) and of the linkages between groundwater recharged to the unit and the communities/ecosystems it ultimately supplies. Only when the necessary outflows have been accounted for can the allocation of the remaining sustainably obtainable groundwater, for local inessential uses, occur.

Adapted water-balance model

Taking the groundwater-use groups into account it is possible to revise the basic water balance equation for sustainable groundwater management of a delimited, distinct geohydrological unit, over a period of time, as follows:

Average effective aquifer recharge	≥	Local basic human needs Reserve (groundwater component)	+	Local ecological Reserve (groundwater component)
	+	Groundwater outflow, necessary for the support of basic human needs and aquatic ecosystems elsewhere	+	Groundwater allocated for local inessential uses

However, when all contributions are accounted for, total projected groundwater use may be higher than the estimated effective recharge of the area. Such a situation is likely to cause long-term deterioration of the resource if allowed to persist. Therefore decisions will have to be made regarding reallocation. This could possibly be achieved through:

- Decreasing the reliance on groundwater by increasing surface water use (if available)
- Managing overall water consumption through proven water conservation and demand management measures
- Importing water (surface or ground) from elsewhere
- Lowering inessential allocations
- Utilising groundwater in storage (although could be unsustainable, decreasing security of water supply from local groundwater sources)
- Technical solutions, such as artificial recharge.

Additional considerations

Isolated use of the water balance approach, in the planning of groundwater management and allocation, is not advised as several issues are overlooked by this broad-brush, largely volumetric assessment. Several of the main potential oversights are reviewed below.

Location of impacts

The purpose of the water balance model is to ensure that groundwater is allocated optimally. However, this process overlooks issues concerning the borehole **location**. It is therefore suggested that, in addition to application of the water balance model, care is taken to ensure boreholes are located optimally with regard to minimising localised impacts of pumping on sensitive aquatic ecosystems. The viability of different pumping scenarios could be assessed through numerical modelling of the geohydrological unit.

A groundwater protection strategy for a unit, once formulated, should include regulations regarding the total quantity that can be pumped for various uses and details of the areas within the unit that are to be protected (e.g. groundwater levels should not be allowed to drop below a certain level, at a certain distance from a sensitive aquatic ecosystem).

Storage

A quantity of utilisable groundwater within a region may be identified as neither entering or leaving a geohydrological unit (i.e. may not be in a state of flux). Such groundwater could be considered as being held in storage. If abstraction is possible, without impacting upon the surface environment, this additional volume of groundwater could be used and, subsequently, included in the water balance equation for an area. However, care must be employed to ensure that this valuable back-up resource is not degraded over the long term.

Water quality issues

The concept of the Reserve encompasses quality as well as quantity issues. Water quality and quantity are inextricably linked factors and it is possible that quality thresholds could be surpassed prior to quantity thresholds. It will therefore often be necessary to adjust the volumetric-focused water balance equations, to account for water quality issues, to ensure that the resource is of an acceptable standard with respect to both criteria.

Recharge characteristics

Effective recharge to an area could be highly variable, temporally and/or spatially, particularly in Southern Africa. Such variations are overlooked when using a single average value for effective recharge of a geohydrological unit. In situations such as this, it is likely that the water balance approach would require adjustment, to account for the long periods of low or no recharge. A possible solution would be separate management strategies for ‘wet’ and ‘dry’ seasons, with reference to local monitored groundwater levels.

Integration with surface water management

The new Water Act requires water managers to consider groundwater as part of the larger hydrologic cycle, in a continual state of flux with surface water. It is therefore essential that any groundwater planning method fits with local surface water strategies, ensuring the two linked resources can be conjunctively used in a pragmatic manner, minimising adverse impacts on the **overall** water resource (i.e. surface and groundwater).

Scale

In order to allocate groundwater resources optimally, groundwater should be balanced at the largest scale (e.g. groundwater flow basin) whilst finer detailed planning, at the scale of the geohydrological unit, takes place. By previously identifying broader-scale groundwater recharge and discharge zones, the possibility of misallocation of the resource at the local level can be reduced. For example, balancing and allocating groundwater within one geohydrological unit whilst failing to consider the ‘bigger picture’ could result in the requirements of another, ‘downstream’ unit being overlooked.

Often, the extent of a quaternary catchment will correspond approximately with the underlying groundwater flow basin. It therefore seems logical to first attempt a groundwater balancing exercise at this scale. If, however, it is not possible to account for all water entering or leaving the unit (with inflowing or outflowing waters remaining unmeasurable, in the subsurface) it may be necessary to include adjacent catchments, broadening the area of the exercise until a large portion of the groundwater can be accounted for. Conversely, obtaining a groundwater balance could involve zooming-in on a portion of a quaternary catchment (e.g. a zone of distinct geological characteristics).

Conclusion

Largely theoretical at this stage, the robustness of applying the water balance approach to sustainable groundwater management needs to be tested through application. Details regarding field assessment of many aspects of groundwater have recently been outlined in the Zero Version document on *Comprehensive Groundwater Determination* (Braune et al., 1999).

Further practical work will almost certainly highlight problems unforeseen in a paper that simplifies many complicated, interwoven issues. However, it is hoped that the problems encountered can be used constructively and fed back into the process, refining the water balance approach as a tool for the future management of South Africa’s precious groundwater resource.

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Disclaimer

This ideas contained within this paper reflect the opinions of the authors alone, and not the Department, or Directorate, as a whole.

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