Sustainable groundwater use, the capture principle, and adaptive management

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Abstract

The purpose of this paper is to review the case for using 'capture' rather than recharge as the conceptual basis for sustainable groundwater use in South Africa. Capture refers to the sum of the increase in recharge and decrease in discharge brought about by pumping. Definitions of sustainability are reviewed, and the capture process is outlined. Implications for using the capture principle in the implementation of the NWA are discussed, and adaptive management is proposed as an appropriate management approach. Implications for groundwater monitoring are also discussed. Case studies are described that support the need for adaptive management and the application of the capture principle.

Keywords: groundwater, capture, sustainability, safe yield, recharge, adaptive management, monitoring

Introduction

Key thrusts in South Africa's National Water Act of 1998 are sustainability and equity, encapsulated in the slogan 'some for all for ever.' Numerous tools are provided by the Act to facilitate sustainability and equity, although defining sustainability is not one of them. Ensuring sustainability in the groundwater field poses a number of challenges. Not the least of these challenges is how to interpret the concept of sustainability – an issue that appears to be poorly understood as far as groundwater is concerned.

Equating groundwater sustainability to average annual virgin recharge appears to be endemic. The central argument of this paper is that it is conceptually incorrect to define sustainability (or safe yield) by average annual (natural) recharge. It is further argued that it is also conceptually incorrect to assume that recharge minus the Reserve (aquatic ecosystem requirements and basic human needs) gives an amount of groundwater that can be sustainably allocated. These arguments are not new. Theis (1940) has already explained how sustainable groundwater use is dependent on increased recharge, and/or reduced discharge, rather than natural recharge. This increased recharge and/or reduced discharge has been termed capture (Lohman, 1972). What is new is the managerial **application** of the capture concept in South Africa. An internet search failed to reveal any South African pages containing the capture principle in a groundwater context, while many hundred pages were found that contained both groundwater and recharge, or groundwater and water balance.

Case studies are given to illustrate why natural recharge is an inappropriate basis for determining sustainable groundwater use, and why the capture principle should be used instead. The case studies also explore the need for an adaptive management approach, and are used to suggest appropriate monitoring strategies.

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Sustainability – Historical background

The classic definition of sustainable development in general, given by the Brundtland Commission (World Commission on Environment and Development, 1987), is *'development that meets the needs of the present without compromising the ability of future generations to meet their own needs.'*

Similar concerns for the present and the future in the water resources management field are given by Loucks (2000) who states that: '*Water resource systems that are managed to satisfy the changing demands put on them, now and on into the future, without system degradation, can be called 'sustainable.''* The demands placed on the resource include the objectives of society, as well as ecological, environmental, and hydrological integrity (Loucks and Gladwell, 1999).

These definitions of environmental sustainability only really began to emerge in the past few decades. However, sustainability's forerunner – safe yield – has been used in groundwater for nearly a century. In the 'journey from safe yield to sustainability' Alley and Leake (2004) trace the first definition of safe yield back to Lee (1915) who defines safe yield as the quantity of water that be pumped 'regularly and permanently without dangerous depletion of the storage reserve.'

In the ensuing decades issues outside the purely hydrological definition of Lee were added, leading to Todd (1959) defining the safe yield of a groundwater basin as 'the amount of water that can be withdrawn from it annually without producing an undesired effect.' According to Todd (1959) four factors are usually considered when determining safe yield:

1. **Water Supply:** This can either be the recharge to the basin, or the rate of movement of groundwater through the basin, whichever is the lesser.
2. **Economics:** Excessive pumping may lower water levels to such an extent that the use of groundwater is no longer economic. In such cases the safe yield hinges on specifying maximum borehole yields or minimum water levels.

3. **Water Quality:** The intended use of the water defines the minimum acceptable groundwater quality, which in turn places limits on pumpage that could draw in water of a poorer quality.
4. **Water Rights:** Legal restrictions may place a limit on safe yield.

The concept of safe yield has been severely criticised, chiefly because of its misinterpretation by people unfamiliar with groundwater that it implies a fixed, underground water supply (Todd, 1959). Sophocleous (1997) criticised ongoing use of safe yield concept in water-management policies, pointing out that safe yield is not a sustainable yield because discharges to streams, springs and seeps are ignored, and because it ignores the sustainability of the system – maximising safe yield by drying up streams, for example, ignores the fact that streams are more than just containers of usable water. Other concerns with safe yield are its vagueness, and it dependence on the particular location of wells (Alley and Leake, 2004).

Lohman (1972) addresses some of these concerns when he defines safe yield as 'The amount of ground water one can withdraw without getting into trouble,' with 'trouble' meaning 'anything under the sun.' Lohman admits that his definition might be regarded as facetious by some, but argues that it makes more sense than many definitions. To avoid 'getting into trouble' Lohman advocates **not putting a number on safe yield before or in the early stages of development**. Even Lohman's definition of safe yield falls short of the current usage of sustainability, however, because whatever rate of groundwater abstraction is chosen, including zero, it will almost always cause 'trouble' with someone, somewhere, across the broad spectrum of users, conservationists, and other concerned parties.

Freeze and Cherry (1979) also tackle the shortcomings of safe yield by arguing there is no single, fixed, safe yield, but rather an optimal or compromise yield. They suggest that, from an optimisation viewpoint, 'groundwater has value only by virtue of its use, and the *optimal yield* must be determined by the selection of the optimal groundwater management scheme from a set of possible alternatives. The optimal scheme is the one that best meets a set of economic and/or social objectives associated with the uses to which the water is to be put.' This approach of selecting the optimal yield could be of great value in current, more environmentally-aware, stakeholder driven, management approaches, provided use is not limited to consumptive use, but also includes non-consumptive use. Whether this yield should be regarded as an **optimal** yield, though, is open to debate. A **compromise** yield seems a much more accurate definition.

Two opposing chains of thought can be seen to pervade the attempts to define safe yield and sustainability. On the one hand is the body of opinion that recognises a purely hydrological definition is of little relevance to the real world where subjective, value-laden principles determine sustainability. On the other hand is the body of opinion that is frustrated with all the ambiguities of sustainability, and wants to return to a definition that can be determined solely by science.

With both safe-yield and sustainability being such vague, ambiguous, value-laden concepts, and because both are concerned about avoiding detrimental, long-term effects, it might be inferred that the terms **safe yield** and **sustainability** are interchangeable. However, **safe yield** is generally limited to the factors of supply, economics, water quality, and legal rights, as defined by Todd (1959), while **sustainability** is generally taken as a much broader concept, revolving around the complex interdependence of the resource, the environment, and society (Alley and Leake, 2004). Concerns about the long-term effects of groundwater abstraction on lakes, springs, rivers, wetlands, and estuaries would be seen as sustainability rather than safe yield issues (Alley and Leake, 2004).

Why recharge does not determine sustainability

In this paper recharge is defined in the broad sense, following the approach of Beekman and Xu (2003), as an addition of water to a groundwater system. Thus this definition (Beekman and Xu, 2003) includes water reaching the aquifer system via:

- Downward flow through the unsaturated zone
- Lateral and/or vertical flow from other aquifer systems
- Induced flow from nearby surface bodies as a result of groundwater abstraction
- Borehole injection or man-made infiltration points.

Discharge is then simply the reverse of recharge, i.e. water leaving an aquifer system, via natural or artificial means. Groundwater abstraction would be one form of discharge.

Todd's (1959) definition of safe yield clearly indicates that recharge does not equate to recharge, since the amount of water flowing through a basin, economics, water quality issues, and legal rights could all result in a safe/sustainable yield that is less than the recharge.

Seymour and Seward (1996) in their 'Harvest Potential' map of South Africa describe three broad scenarios for the interrelationship between recharge, aquifer storage, and 'sustainable use':

- Size of the aquifer considerably exceeds average annual recharge – average annual recharge can be 'safely' abstracted
- Size of the aquifer is insufficient to bridge abstraction during droughts – sustainability is therefore limited by **storage,** not recharge
- Size of the aquifer cannot absorb all the recharge in the wet season to bridge abstraction during the dry season – **storage**, not recharge, is the limiting factor to sustainability.

The term 'Harvest Potential' coined by Seymour (Seymour and Seward, 1996) is basically the same as Lee's (1915) definition of safe yield, i.e. it is a purely hydrological concept, does not take socio-economic or environmental issues into account, and thus gives a maximum rather than a sustainable yield. However, even at this level of simplification, the consequence is that in roughly three quarters of South Africa, sustainability is determined by the second and third factors listed above, i.e. **storage**, rather than recharge.

Another example of sustainability being less than average annual recharge is given by Freeze and Cherry (1979). Gradual increases in abstraction in a hypothetical groundwater basin were studied using the aid of a complete saturated-unsaturated zone model. The exercise showed that if pumping rates are allowed to increase indefinitely an **unstable** state will eventually be reached. At this point of instability rainfall no longer provides the same percentage of recharge because evapotranspiration from the unsaturated zone now takes more of the infiltrated precipitation before it has chance to percolate down to the aquifer. To prevent the chances of a basin from becoming unstable, production must be limited to significantly less than the average annual recharge.

The above examples have shown that even when using groundwater-basin scale and other 'broad-brush' approaches,

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there are serious problems with simply assuming that sustainability equals recharge. In many cases sustainability will be considerably less than average annual recharge, and so the generalisation that sustainability equals recharge is incorrect.

However, when the detailed geohydrological conditions of aquifers and aquifer systems within a given basin are studied, even more serious shortcomings with the 'sustainability-equals-recharge' concept emerge because 'capture' has to be taken into account.

Capture

Under pre-development conditions, a groundwater system is in long-term equilibrium, and recharge equals discharge (Alley et al., 1999), as shown schematically in Fig. 1.

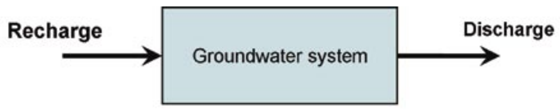

Figure 1
Pre-development water budget (after Alley et al., 1999)

Discharge could be to streams, lakes, wetlands, saltwater bodies, springs, or via evapotranspiration, while recharge could be from precipitation percolating through the unsaturated to the water table, or from losing streams, lakes and wetlands (Alley et al., 1999).

When groundwater is withdrawn by pumping (Fig. 2), this abstraction must be supplied by (Theis, 1940):

- More water entering the system (increased recharge)
- Less water leaving the system (reduced recharge)
- Removal of water in storage
- Some combination of the above 3 factors.

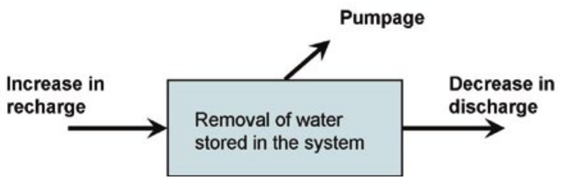

Figure 2
Water budget showing changes brought about by abstraction (after Alley et al., 1999)

The sum of the increase in recharge and decrease in discharge is referred to as **capture** (Lohman et al., 1972).

The logical consequences of the principle of capture when an aquifer system is subjected to development are:

- Some groundwater must be removed from storage before the system can be brought into equilibrium.
- The time that is required to bring a hydrological system into equilibrium depends on the rate at which discharge can be captured.
- The rate at which discharge can be captured is a function of the characteristics of the aquifer system and the placement of pumping wells – spacing, distance to recharge zones, distance to discharge zones.
- Equilibrium is reached only when pumping is balanced by capture. In many circumstances, the dynamics of the groundwater system are such that long periods of time are necessary before even an approximate equilibrium can be reached (Alley et al., 1999).

Perhaps the most important implication of the capture principle is, however, that **virgin recharge does NOT determine sustainability.** Sustainability is determined by what, if any, induced recharge can be created, and by how much of the existing discharges – natural or otherwise – can be taken up by new abstraction. This is partly a technical problem – positioning boreholes and selecting pumping rates so as to grab as much of the existing losses as possible, and partly a political problem – what reduction in existing discharges is permissible.

Capture – and the implications for sustainability and recharge – can also be described by a simple water balance equation (Lohman, 1972):

$$R + \Delta R = D + \Delta D + Q + S\,\Delta h/\Delta t \qquad (1)$$

where:

- R = virgin recharge
- ΔR = change in recharge caused by pumping
- D = virgin discharge
- ΔD = change in discharge caused by pumping
- Q = rate of abstraction
- $S\,\Delta h/\Delta t$ = rate of change of storage

Devlin and Sophocleous (2005) argue that much of the blame for the misconception that 'sustainability = natural recharge' lies in the lack of appreciation of the 'capture equation', and the use of a water balance equation that is too simple, i.e.:

$$R = D + Q \qquad (2)$$

From an examination of the 'capture equation' (Eq. (1)) it is clear that in the natural state, the long-term conditions would be: $R=D$ and $S\,\Delta h/\Delta t = 0$. Thus if abstraction is introduced, and if equilibrium conditions are eventually obtained, then it follows that:

$$\Delta R = \Delta D + Q, \text{ or:}$$
$$Q = \Delta R - \Delta D$$

Thus these equations confirm that it is the **change** in recharge, if any, brought about **after** pumping has been initiated that contributes to determining sustainable abstraction. The virgin recharge prior to abstraction does **not** determine sustainable abstraction.

The relationship between reduced storage, decreased outflow, and increased inflow, as a result of abstraction is shown graphically in Fig. 3:

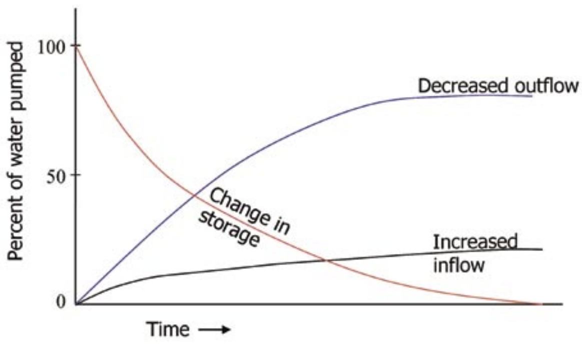

Figure 3
Effects of pumping on inflow, outflow and storage (after Leake, 2001)

Borehole sustainability vs. groundwater basin sustainability

Abstraction from a borehole cannot be 'sustainable' or 'unsustainable' in isolation, but is dependent on other groundwater users, natural discharges, natural and induced recharge, storage and transmissivity, and on what changes to the system are acceptable to the parties concerned. The concept of 'sustainable borehole yield' is therefore untenable.

On the other hand, the concept of 'sustainable basin yield' is equally untenable if it is made without reference to 'production facilities' such as boreholes and springs, since the basin yield can only become a practical reality when accessed via these 'production facilities'. Without practical means of exploitation, a 'sustainable basin yield' might just as well be a purely abstract concept.

Devlin and Sophocleous (2005) use the capture principle to distinguish between borehole and basin sustainability. Boreholes in a basin can be sustainable if their yields do not exceed what can be practically captured. In other words borehole sustainability is dependent on how much throughflow can be intercepted and by how much recharge can be induced by the position, depth, spacing, and yield of boreholes. Thus borehole yield is dependent on what capture of groundwater is **possible**. Basin yield adds to this by including how much capture of groundwater is **permissible.** For example it may be possible to sustain pumping at a given rate, yet the consequences for the environment, or for other water users might not be permissible.

The differences between borehole (or 'production facility') sustainability and groundwater basin sustainability lead to important consequences:

- The 'true' or 'practical' basin yield is actually the sum of all the individual abstraction points where capture is permissible, possible, and sustainable. Doing some form of water balance exercise to arrive at a generalised 'basin yield' without taking production facilities into account is virtually meaningless.
- There is no single, fixed 'safe' or 'sustainable' yield for a groundwater basin, but rather a range of 'permissible' yields dependent on how the groundwater is accessed – i.e. well-field properties – and social, economic, and ecological concerns.

This might seem like an irritating and unsatisfactory muddle of basin, well-field, and societal concerns to those who wish to use science to come up with a single 'sustainable yield' for a groundwater basin or unit or whatever area is being addressed. For example Kalf and Woolley (2005) state that: *'Aspects of groundwater management factors affecting production facility discharge should be regarded as constraints on the way the physical system is used, and not as part of the physical concept.'* But the realities are that a groundwater basin yield cannot be accessed without abstraction points, just as runoff to a surface basin cannot be accessed without dams and other works. The 'safe yield' of a surface catchment is not just a function of dam storage capacity, nor is just a function of runoff. Surface water 'safe yield' depends on a combination of these factors, and many others as well. Groundwater is no different in this respect. Therefore, in reply to Kalf and Woolley (2005) who insist that 'the system' and 'human intervention' must be handled separately, it needs to be pointed out that this cannot be done – once human manipulation takes place **it becomes part of the system** and therefore cannot be treated separately! Without a 'production facility' yield there is no 'sustainable basin yield' – just natural recharge and discharge.

In other words, while it may be possible to determine a single figure for average **natural** recharge and discharge, as soon as the system is manipulated, to abstract groundwater for example, a host of factors need to be considered in how the system is manipulated, with the consequence that there is a range of yields describing how much can be got out of the system.

This is not to say science cannot be used in the process – for each option of how to exploit the resource, science can be used to predict, or anticipate the likely outcomes of a given intervention. The mistake is to assume that science only predicts one outcome.

Sustainable groundwater development and the National Water Act

Sustainability is a key principle in South Africa's National Water Act (NWA) of 1998: '*Recognising that the ultimate aim of water resource management is to achieve the sustainable use of water for the benefit of all users*' (Republic of South Africa, 1998). The other key principle is equity: *'Sustainability and equity are identified as central guiding principles in the protection, use, development, conservation, management and control of water resources.'* Although sustainability is not defined, it is used in the contexts of sustainable water use, ecological sustainability, and institutional sustainability, which presumably give some clues as to its intended meaning.

One avenue for addressing sustainability in the NWA is by the setting of resource quality objectives (RQOs) as part of an overall classification process. Once the classification process is complete, the RQOs become binding on water-use authorisations. The RQOs can include, *inter alia*:

- The Reserve
- Instream flow
- Water levels
- Water quality
- Aquatic biota
- Any other characteristic.

The Reserve is defined as the quantity and quality of water required to:

- Satisfy basic human needs
- Protect aquatic ecosystems in order to secure **ecologically sustainable <u>development and use</u>** of the relevant water resource (emphasis added – this factor is often overlooked).

RQOs might imply limitations on the use of groundwater so as to avoid undesirable reductions to base flow, reductions in spring flow, damage to aquatic ecosystems, damage to terrestrial ecosystems, ingress of saline groundwater, ingress of sea water, and so on. It seems clear that avoiding or limiting these negative scenarios will be largely determined by the capture principle – limiting the interception of discharges and of non-groundwater bodies, to what is deemed acceptable. A water balance approach – determining recharge minus abstraction – is of little value in unravelling the dynamics of the situation, and thus will give a misleading impression regarding sustainability.

Water use may be regulated by:

- Licensing
- General authorisations
- Permissible continuation of existing lawful use
- Schedule 1 use – this includes reasonable domestic use, non-commercial small gardens, and stock water (excluding feedlots).

The thinking is that Schedule 1 use would have no or minimal impacts, use controlled by general authorisations would have low risk of impacts, and that a licence is only needed when there is a high risk of impacts. In other words the licensing process is

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only used when there is a risk that sustainability limits might be exceeded.

If the classification process has been completed, then the RQOs are binding on water use authorisations. However, if the classification is not completed, then the only thing that is required before a licence can be issued is preliminary Reserve determination.

For each licence application, the DWAF national office makes an estimate of the recharge, and the Reserve. The ecological component of the groundwater Reserve is normally based on estimates of instream flow requirements (IFR) needed to maintain aquatic ecosystems, using the assumption that maintenance low-flow component of IFR can be met by base flow from groundwater. Thus the amount of groundwater set aside to maintain the ecological Reserve boils down to a certain percentage of base flow. This means that in the parts of the country where there is no base flow, no ecological Reserve based on groundwater can be determined, and the Reserve concept is of little value as a groundwater management tool. It also needs to be pointed out that the Reserve cannot be used to protect terrestrial ecosystems, since it only applies to aquatic ecosystems.

Once the Reserve has been determined, the relevant DWAF regional office then has to decide whether to recommend, or not recommend, the licence application, and what conditions to apply, based on recharge, the Reserve, the quantity required by the licence, existing use, and any other relevant factors. At this stage the normal procedure (Xu et al., 2003) is to 'do a water balance.' The Reserve and the existing lawful use are subtracted from recharge. If anything is left over, and this quantity exceeds the licence application, it is assumed that there is enough water available, and the licence application is normally recommended.

Conceptually, this approach is wrong. The increased abstraction by the licensee has to be met by the capture of **something.** This could be:

- Reduction in groundwater's contribution to base flow
- Drying-up of springs
- Reduced yields from boreholes on adjacent properties
- Terrestrial vegetation dependent on groundwater dying
- Capture of water from surface bodies such as rivers flowing through the area
- Capture of groundwater from adjacent aquifers and aquifer systems.

However, it is exceedingly difficult to predict these effects, and so ongoing monitoring and modelling is advocated (Xu et al., 2003).

Adaptive management

Predicting the dynamic response of an aquifer system to development, and what can be 'captured' will be exceedingly difficult. Aquifer systems are complex, difficult to understand, and the consequences of human intervention are difficult to predict, especially in the case of fractured rock aquifers, which cover 98% of South Africa. It is suggested that the way forward is to accept the complex, difficult-to-predict characteristics of aquifer systems, and build management strategies around those characteristics, rather than deny those characteristics and labour under the misapprehension that just a few more years of research will enable the sustainability of the system to be determined to the nearest decimal place.

Such an approach can be found in adaptive management, which Maimone (2004) considers to be the only viable approach in dealing with the uncertainties in knowledge and the variability of societal attitudes towards groundwater resources. In order to further evaluate the applicability of adaptive management to the sustainable use of groundwater, the key characteristics of adaptive management will be outlined, and then compared with the practicalities of groundwater management.

The basic premise of adaptive management is that 'if human understanding of nature is imperfect, then human interactions with nature (e.g. management actions) should be experimental' (Prato, 2003). Some of the key characteristics of adaptive management are (Rogers et al., 2000):

- An approach to deal with uncertainty from an imperfect knowledge base
- Involves a well planned iterative process of selecting and testing hypotheses of responses to management interventions – scenarios and goals are regarded as hypotheses and estimates to be tested and challenged as the knowledge base grows.

Concepts of adaptive management are regarded as a 'work in progress' (National Research Council, 2004), but the following elements have been identified in theories and practice:

- Management objectives are regularly revisited and accordingly revised – while differences between and among stakeholders and scientists are unavoidable, there must be some agreement on some objectives to hold the whole process together.
- Models of the systems being managed – an explicit baseline understanding of and assumptions about the system being managed are a necessary foundation for learning. These models can be conceptual and need not necessarily be mathematical.
- A range of management choices – existing data rarely point to a single best management policy and a broad range of alternatives need to be considered.
- Monitoring and evaluation of outcomes – monitoring is needed to evaluate the outcome of the management option chosen, to better understand the system, and to provide a basis for better decision making.
- Mechanisms for incorporating learning into future decisions – there needs to be a formal way for knowledge gained to be integrated into the decision-making framework, and the political will to act upon that knowledge. Management organisations need to be flexible enough to adjust to the new information.
- A collaborative structure for stakeholder participation and learning – involving give and take, active learning, involving stakeholders in goal-setting, and some level of agreement among participants.

Some of the elements in adaptive management have been in used in groundwater development in South Africa for decades. It is generally accepted by experienced hydrogeologists that it is virtually impossible to predict the development potential of groundwater with any degree of confidence, and that the best way to understand and quantify groundwater is via using it, in other words the '*Learning by Doing*' approach (Walters and Hollings, 1990). While some have seen this as a negative aspect of groundwater, and have been unwilling to develop it because the uncertainties are too high, others have seen this as a positive aspect, since groundwater can be developed in a phased, incremental manner. Hypotheses about a resource are tested using an exploration programme. If the hypotheses are proved reasonable then pumping tests are done. Pilot-scale abstraction might then be implemented. If this is successful, then larger-scale development might be considered, and so on.

In the past, however, there has usually been little or no stakeholder participation in 'adaptive management' of groundwater, and ecological considerations were not normally addressed from the outset. This has now changed, with NWA of 1998 requiring and enabling public participation, and resource quality protection. Ludwig et al. (1993) suggest the following tactics for effective management of natural resources, including an appropriate balance between scientists and stakeholders:

- Include human motivation and responses as part of the system to be studied and managed.
- Act before scientific consensus is achieved. Calls for additional research may delay tactics.
- Rely on scientists to recognise problems but not to remedy them. Scientists and their judgements are subject to political pressure.
- Distrust claims of sustainability. Past resource exploitation has seldom been sustainable, so claims for the future should be viewed with suspicion, especially where sustainability is to be achieved in an unspecified way.
- Hedge - avoid irretrievable commitments, assume that what you're about to do might be a mistake.
- Avoid the delusion that more research will, by itself, solve sustainability issues.
- Favour actions that are informative, probe and experiment.
- Favour actions that are reversible.

The need for adaptive management

The broad principles of adaptive management have been established, and some tactics for its implementation have been listed. It has also been described how some facets of adaptive management have sometimes been used in the management of groundwater in South Africa. Adaptive management is not 'trial and error,' but rather a formal, yet flexible, approach for hypothesis testing, with stakeholder participation, when our knowledge base is imperfect and outcomes uncertain. Stakeholder participation is one of the key requirements of the NWA – a requirement that can be met with adaptive management. Therefore, the key tests for deciding whether adaptive management is needed in the groundwater sector are whether the knowledge base is imperfect, and whether the outcomes are uncertain. To assess these issues, some salient factors in the sustainable management of groundwater are discussed:

Our knowledge of groundwater use is imperfect. For example, in the G30 drainage region, where only groundwater is used for irrigation, and where crop circles irrigated by centre pivots are clearly visible by remote sensing, Conrad and Munch (2006) describe estimates of water use that ranged from 9.5 x 10^6 m^3/yr to 53.9 x 10^6 m^3/yr. Where groundwater and surface water are used conjunctively for irrigation, it will be even harder to come up with an exact figure for groundwater use.

Our knowledge of the regional status of groundwater resources is imperfect. For example, in the Olifants-Doorn Water Management Area (WMA) intensive, although far from optimal, regional monitoring only takes place in the G30 drainage region. In the remaining 11 tertiary drainage regions in this WMA, regional monitoring is either very sparse or non-existent.

Our knowledge of groundwater parameters is highly imperfect, especially our ability to up-scale determinations at a given point to an entire groundwater basin. This is to be expected given the heterogeneous nature of much of South Africa's aquifers. Zhang et al. (2005) assign an average conductivity of 4.5 to 10 m/d for the Sandveld inter-granular aquifers, and describe how calculations of the conductivity of the Table Mountain Group range from 1.99 m/d to 1.99 x 10^{-3} m/d. With such ranges in input parameters being typical, an output parameter predicting the future with any degree of precision is clearly not feasible. At a more qualitative level, Beekman and Xu (2003) note how the temporal variability of rainfall in semi-arid climates as well as the spatial variability in soil characteristics, topography, vegetation and land use, all add to the variability in recharge estimations. Yearly recharge estimates for the Sandveld have ranged from 12% to less than 1% (Conrad et al., 2004). Such variability in parameters and their estimation does not lend itself to predicting future outcomes with certainty.

Our ability to predict the impacts of groundwater abstraction on surface water and ecological systems are highly imperfect. This compounds the uncertainty of future predictions:

- Large uncertainties exist with respect to the nature of groundwater-surface water interactions (Sophocleous, 2002).
- The link between groundwater and ecology is poorly understood, making it very difficult to make even educated guesses as to the likely impacts of groundwater use (Hunt and Wilcox, 2003; Hancock et al., 2005).
- Our knowledge of the environmental impacts of groundwater use is imperfect. Nation-wide ecological monitoring it is at a very embryonic stage.

Our ability to predict future outcomes is highly imperfect. Some form of groundwater model is usually considered to be the best tool to process all the complex factors involved so that future outcomes can be predicted (Anderson and Woessner, 1991). Yet the post audits discussed by Anderson and Woessner (1991) showed that in all of the cases the model did not accurately predict the future. Bredehoeft (2003) has echoed these thoughts, observing that many models have not provided good predictions. The causes for the poor predictions were identified as: the range of parameters was much larger than included in the model; incorrect choice of conceptual model; and because what took place in the real system was not an anticipated scenario. Anderson and Woessner (1991) advocate that a suite of scenarios should be modelled rather than a single scenario, while Bredehoeft (2003) states the rule-of-thumb that models can only predict the future with reasonable confidence for a period equal to the period of history match. The practical implications of these observations are that there are very few areas in South Africa with sufficient data to be able to use groundwater models to make reasonable predictions. Lack of medium- to long-term monitoring data is the rule, not the exception, and so it can be argued that it will be virtually impossible to make any reasonable future predictions regarding the sustainability of groundwater use in most parts of South Africa.

Monitoring data are often not diagnostic. This compounds our difficulties in assessing current processes and making reasonable prediction. *'Water levels alone are ambiguous and cannot be relied upon to determine whether a system is sustainable or not'* (Kalf and Woolley, 2005). For example declining water levels may indicate that a resource is being over-abstracted and will eventually be depleted. Or they may indicate that water is being taken from storage in the short term, as a precursor to equilib-

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rium conditions being established. This issue of non-uniqueness is also encountered in groundwater modelling, where more than one set of modelled parameters can be used to give an equally good match to the observed data (Bredehoeft, 2003). With more than one set of parameters to predict the future, it is clear that more than one outcome can be predicted.

These examples and issues clearly suggest that our groundwater, and groundwater-related, knowledge base is imperfect, and our ability to predict outcomes is highly uncertain. Thus the conditions have been identified where the application of adaptive management would be either beneficial or even necessary.

Case studies

The purpose of the case studies is to give practical examples of the capture principle, and to further investigate the need for the adaptive management of groundwater.

Jan Dissels River

A licence application was received to abstract 150 000 m^3/yr of groundwater for irrigation purposes in the E10H catchment. The location of the borehole from which abstraction requires licensing is shown in Fig. 4.

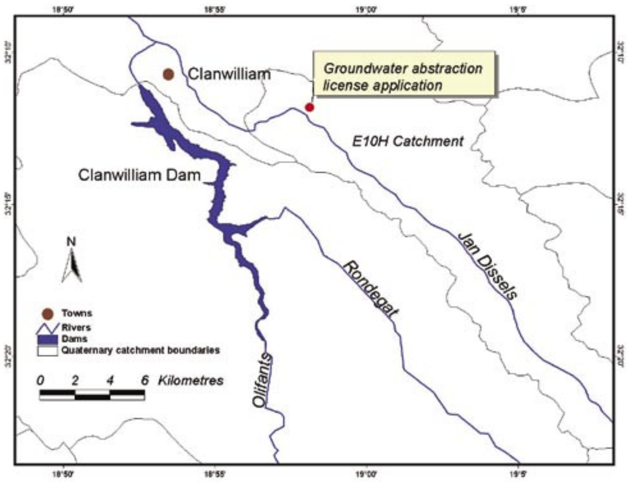

Figure 4
Jan Dissels River licence application

An initial part of the licensing process is to obtain a value for the Reserve from the national RDM (Resource Directed Measures Office). The report from the RDM office indicated that recharge to the E10H catchment is 5.2 x 10^6 m^3/yr, the ecological component of the Reserve is 3.0 x 10^6 m^3/yr, and that the basic human needs component of the Reserve is 0.002 x 10^6 m^3/yr. The report goes on to state that the intended use represents only about 6.8% of the available groundwater after Reserve requirements have been met.

Thus the implication is that the issuing of a licence should not be a problem and that routine monitoring is recommended should the licence be approved.

The 'available groundwater' referred to in the RDM report is based on virgin recharge. No mention is made as to whether the abstraction required by the licensee will be met by increased recharge or reduced abstraction. And – to be fair – such a discussion is probably impossible at the regional scale used by the RDM office.

At the local scale, however, capture becomes more important than recharge, because – in this case – the borehole to be used is located some 40 m from the Jan Dissels River, and the river supplies the town of Clanwilliam with water. The local community is very concerned that groundwater abstraction would reduce river flows. Thus the relatively small ratio of the proposed abstraction to unused virgin recharge is no longer the issue. Instead the issue is whether groundwater abstraction will capture river flow. This could take place as either reduced groundwater seepage to the river, or as river flow replenishing the aquifer.

Water level and water elevation data are very scarce in the investigated area, so a water quality investigation was undertaken. Macro-chemistry analyses suggested that the river water and the borehole water were not connected hydraulically. Using the adaptive management approach this was taken as the hypothesis to be investigated, rather than an established fact, and regular water quality monitoring has been recommended as a licensing condition to test this hypothesis. Water use licences are subject to periodic reviews, thus enabling any changes to the licence required by adaptive management to be effected.

In summary, this simple example shows that:

- Sustainable abstraction was determined by whether river water is captured or not, and not by virgin recharge
- The importance of stakeholder concerns in determining a permissible sustainability rate
- The setting of an hypothesis to be investigated by adaptive management
- This approach is possible under the NWA.

Wadrif

The Wadrif aquifer system is located on the Western Cape coast between the towns of Lamberts Bay and Elands Bay (Fig. 5).

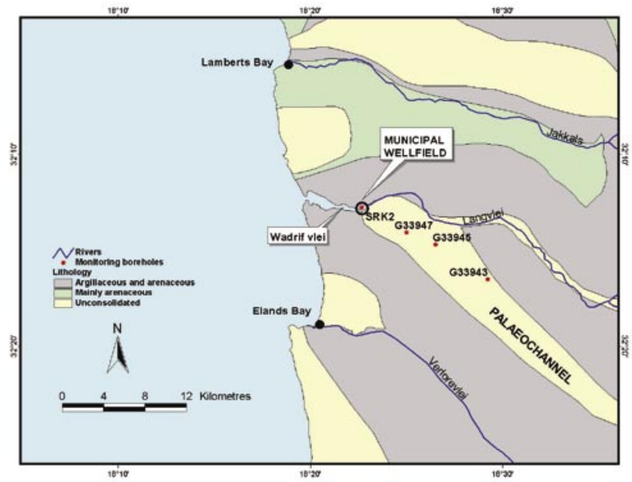

Figure 5
Wadrif wellfield and palaeochannel

The aquifer system consists of a palaeochannel underlain by a fractured aquifer. The aquifer system is separated from the coast by a vlei and a saline pan.

The town of Lamberts Bay has abstracted groundwater from the Wadrif aquifer system since the early 1980s. Current consumption is in the order of 700 000 m^3/yr. The abstraction of groundwater for the irrigation of potatoes has increased significantly over the past 15 years. Groundwater is the only available water source. Irrigation abstraction from the palaeochannel and other aquifer systems in the G30F drainage region was estimated to be 4.9 x 10^6 m^3 in 2004 (Conrad and Munch, 2006).

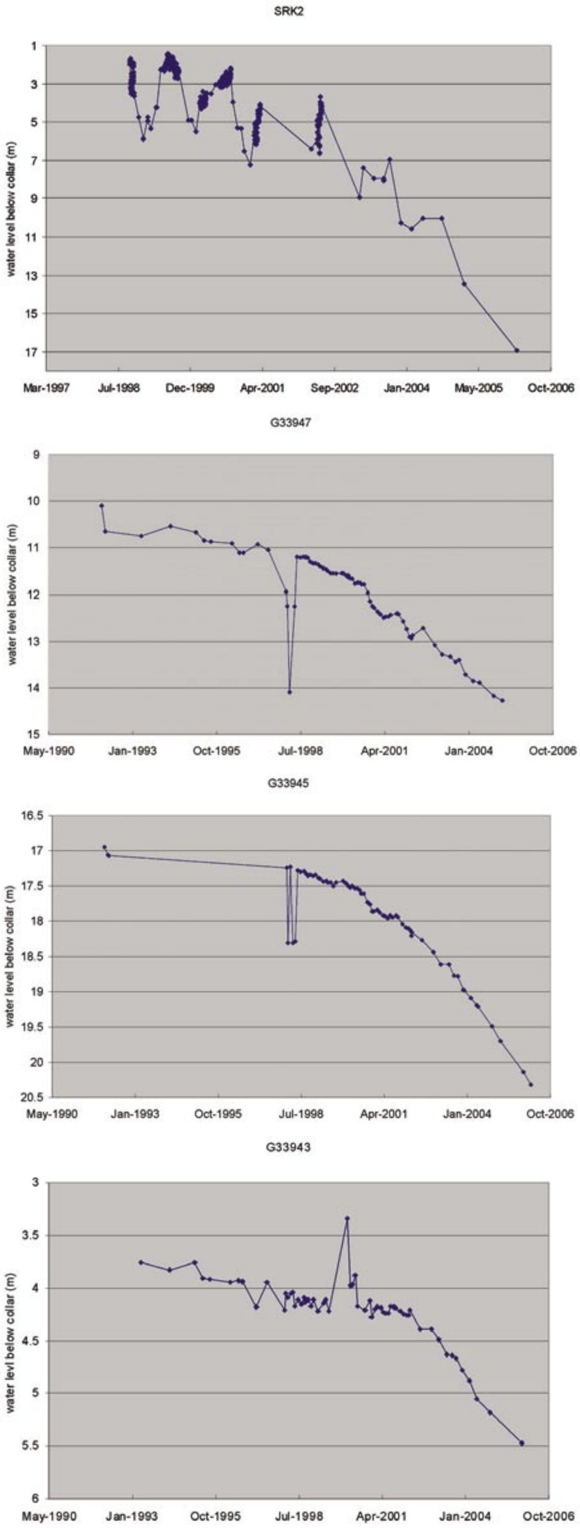

Figure 6
Water-level trends at boreholes SRK2, G33947, G33945 and G33947 – Wadrif palaeochannel

The municipal well-field at Wadrif is clearly under stress with water levels below sea-level. In addition to the threat to the groundwater resource, there are major concerns about the impact of groundwater abstraction on the wetlands at Wadrif. Many concerned environmentalists maintain that groundwater abstraction has essentially destroyed the wetlands, while some potato farmers maintain that a periodic drying-up of the wetlands is a normal, cyclic, occurrence.

Water levels (Fig. 6) at the foot of the palaeochannel showed either a stable trend or a slightly downward trend up until around the year 2000, when water levels began to decline dramatically.

One explanation for the drawdown trends – using the capture principle – is that up until about the year 2000, increased abstraction was met by reduced discharge at the foot of the palaeochannel, and only a minor reduction in storage was needed to accommodate this, hence the relatively minor drawdowns. After the year 2000, abstraction has exceeded these discharges, with the increase in abstraction being met solely by a reduction in storage; hence the dramatic decline in water levels.

Before groundwater use took off, there was a combined spring flow of 30 or so ℓ/s (approximately 1 x 10^6 m^3/yr) from the foot of the palaeochannel, and groundwater levels were very close to the surface. It seems reasonable to infer that discharge was via a combination of spring flows, direct evapotranspiration, and seepages.

If the capture of these discharges by abstraction is accepted as a working hypothesis, it leads to two consequences that need to be addressed using an adaptive management approach:

- Would reducing abstraction to pre-2000 amounts, or less, help restore the wetlands?
- Will the current decline in water levels continue until the resource is depleted, or will a new equilibrium be established when a new source of water is captured? Would this capture be acceptable to stakeholders? (It might well be the capture of water from an adjacent aquifer system, or sea water).

There are no easy answers to these questions. Groundwater flow modelling of the palaeochannel might assist in identifying a suite of possible scenarios. With many future scenarios possible, an adaptive management approach would be highly beneficial. The participation of stakeholders in identifying an option to investigate is crucial. Monitoring will be essential in testing the hypothesis selected. The NWA contains the required tools to enable these questions to be addressed using the adaptive management approach. The most useful tools appear to be the setting of Resource Quality Objectives, and the compulsory licensing process.

Implications for monitoring

If it is accepted that the capture principle and adaptive management are either useful, or necessary, additions to the methodologies used in ensuring the sustainable use of groundwater, then there are practical implications for monitoring. These implications include:

- In addition to monitoring the status of the groundwater resource (e.g. using groundwater levels and groundwater chemistry) the impacts of using that resource must also be monitored (e.g. spring flows, wetland health). Particular emphasis needs to be placed on monitoring potential impacts that are deemed unacceptable.
- A conceptual model, or hypothesis, needs to formulated describing the groundwater system, and the likely impacts of additional abstraction, especially with respect to reduced discharges.
- Monitoring must also be geared to testing the conceptual model.
- Identifying which conceptual model is to be investigated must be done in consultation with all the stakeholders.

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- A constant awareness of the potential ambiguity of monitoring data is needed. The same set of observed data can be consistent with several different conceptual or mathematical models. Groundwater scientists therefore need to beware of making bold, unsubstantiated claims that the monitoring data 'prove' that a particular hypothesis or model is correct.

Concluding remarks

Sustainable groundwater development depends on increased abstraction being compensated by increased recharge and/or reduced discharge ('capture'), and by this capture being acceptable to stakeholders. Virgin recharge is **not** the major factor in determining sustainability, neither is the difference between recharge and abstraction. A borehole with a yield that is a tiny fraction of recharge can still lead to unacceptable and unsustainable conditions if it is located too close to a discharge zone. The critical factor is the positioning of boreholes – with respect to other boreholes, with respect to the discharge zones, and with respect to the recharge zones.

A range of 'sustainable yields' is possible for any given situation, dependent on how intervention takes place, and what is deemed acceptable (or at least permissible). It is therefore open to debate whether 'sustainable yield' is the best term to use, since it appears to suggest that there is a single, fixed yield that can be determined. A more accurate and descriptive term is needed. 'Optimal yield' or 'preferred yield' or 'allowed sustainability' are some preliminary suggestions.

The ongoing debate between those who want sustainability to be a fixed number that science can determine, and those who accept that sustainability is a subjective, value-laden concept appears to be due to a lack of clarity regarding who should be doing what, rather than from a flawed concept of sustainability. The role of scientists should be to identify a range of sustainability options – each with a probable consequence – while it would the managers' and stakeholders' role to ***select a preferred option***. Scientists would then monitor the outcomes of that option and revise the sustainability scenarios as needs be.

With large uncertainties in the knowledge of the systems to be developed, large uncertainties in the likely outcomes of development, and a wide spectrum of societal attitudes towards development, an adaptive management or 'learning by doing' approach is required. Such an approach need not be at odds with the NWA.

Innovative approaches to monitoring are required that help build a clearer model of the system being developed, and test the model selected under an adaptive management approach.

If conceptual models look at recharge and abstraction, but omit discharge then they are only dealing with half the story. Geohydrologists need to develop a clearer 'conceptual management model' of how they propose to exploit a resource. A clear, explicit statement of how it is envisaged that the aquifer system will balance any increase in abstraction must be made. Is it imagined that recharge will increase? Is it imagined that the reduction in discharge will be acceptable and/or have negligible environmental impact? This kind of statement needs to be made, even if it is only a hypothesis to be tested.

This paper has demonstrated that an adaptive management approach is needed in the case studies described, and that such an approach is possible using tools from the NWA. It is suggested that the pragmatic, adaptive management approach, rather than rigid, command-and-control management will be needed to ensure the sustainable development of groundwater in most situations. This suggestion remains, however, a hypothesis to be tested.

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