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# WADE

## Floodwater Recharge of Alluvial Aquifers in Dryland Environments

STREP

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## Project Conclusions

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## CONCLUSIONS INCLUDING SOCIO-ECONOMIC RELEVANCE, STRATEGIC ASPECTS AND POLICY IMPLICATIONS

### The WADE approach

A principal source of water in arid environments around the world is related to floods in ephemeral rivers. In drylands, significant floods are caused by intense rainstorms of short duration that may last from minutes to days depending on drainage basin size. Though floodwater itself is not considered a sustainable water resource, floodwater infiltrating alluvial aquifers has always formed the basis of traditional water supplies in arid areas. In spite of this intensive reliance on alluvial aquifers, at present there is no reliable methodology to analyse a) the processes that control flood recharge and b) the quantity of recharge over climatic cycles. Both are necessary to the sustainable management of this water resource. The key objective of WADE project was to develop and apply an innovative method of investigating the occurrence of floodwater resources, in time and space, to quantify the sustainable water yield of selected ephemeral streams and to formulate integrated water management strategies for their use. This research addresses critical aspects of water resource management in arid and hyperarid areas, as well as semi-arid regions which are likely to become highly limited water resource environments as foreseen within the Global Change context.

Multidisciplinary projects such as WADE are required in order to understand the water resource (quantity, quality and mechanisms for recharge), the water management and supply, and site-specific socio-economic problems and limitations (including the cultural, historical and political context).

### The main conclusions of WADE:

### In relation to long-term flood reconstruction (palaeoflood hydrology)

The case study basins were explored for location of flood related sedimentation, providing in all cases positive results with excellent accumulation of slackwater sedimentation. Palaeoflood reconstructions were carried out in the Kuiseb (>5 sites), Buffels (4 sites), Avara (2 sites) and Andarax (2 sites) rivers. The reconstruction of flood events (frequency and magnitude) was obtained from detail stratigraphical and geomorphological analysis, topographic survey and hydraulic modelling. The main results of this research can be summarised as follows:

- Geological, botanical and historical flood evidence allowed a record of extreme events to be compiled over centuries to millennia. This past flood record was crucial to understanding flood patterns in arid areas where flood frequency is one per year, and large floods occur on average once every three decades.

- Instrumental records are a basic source of information in analysing floodwater recharge into the alluvial aquifers. However, stream flow records in ephemeral rivers all over the world are scarce, incomplete and often inaccurate.

- The estimated discharges from palaeofloods and historical floods exceed those recorded by instrumental flood series, illustrating that an improved knowledge of extreme events can be gained from geological and documentary evidence. In Namibia, the WADE project has shown that at least 10 events during the last 1300 years produced discharges twice greater than the biggest gauged flood events of this century. In South Africa, the palaeoflood record shows that over the last 400 years the largest paleoflood discharges (510 $m^3s^{-1}$) were almost five times the largest reconstructed (from rainfall-runoff models) discharge over the rainfall record (106 $m^3s^{-1}$).

• New methods on palaeoflood analysis have been developed including: (1) a systematic procedure of collecting, storing and analysis of slackwater flood deposits, (2) advances in chronological constrains using multiple dating methods such as optical stimulated luminescence (OSL), and radiocarbon dating (AMS). In particular, OSL has been revealed as an excellent method for dating fluvial deposits on hyperarid environments, even on recent (<1000 years) sediments.

• The combination of palaeoflood data and hydrological analysis either with rainfall-runoff models (as in the study cases of the Buffels and Andarax rivers), or with hydrograph routing (as in the case of the Kuiseb river) have resulted in a very powerful tool for understanding the role of floods on groundwater recharge, as well as to quantify the associated long-term groundwater recharge.

• New mathematical procedures for Flood Frequency Analysis (FFA) and high return period quantiles using upper bounded probability distribution functions have been explored based on a combination of palaeoflood, documentary, instrumental and modelled data, together with upper flood limits based on maximum (non-exceeded) palaeoflood evidence. The reliability of the high return period quantiles were computed using Monte Carlo simulations. In the Buffels River, flood frequency analysis using modelled discharges (1965-2006) and palaeoflood records was carried out, providing a return period of 500 yr for the largest palaeofloods at the upper basin, and 300 yr for the one at the lower basin. In the Kuiseb River, the largest palaeoflood evidence (1,300 $m^3s^{-1}$) has an associated return period of 100 years.

• Palaeoflood and historical flood evidence also allows investigation into the effects of climatic variability on flood events. In the Buffles River flood series derived from palaeoflood and historical data, periods of increases in flood magnitude and/or frequency were observed over the last 1000 years (1400-1500 AD and 1700-1900 AD). In the lower basin floods were also dated to BC 1100-950 and 650-750 AD. This indicates that climatic variability clearly effects flood magnitude and frequency. The last century has witnessed reduced flood magnitude/frequency. These past flood-climate relationships can be used for a better understanding of the potential effects of the present Greenhouse Global Warming.

**In relation to Surface hydrology**

Surface hydrology modelling was carried out in the WADE project case study basins. This modelling complemented the palaeoflood hydrology results. It was used in conjunction with groundwater modelling, which was coupled within new modules to allow good performance of the surface-groundwater interaction. Different surface hydrological modelling approaches were used depending on the catchment size climatic variables and rainfall patterns in the case study catchments. In the Buffels basin where floods are mainly generated by homogeneous winter fronts, a rainfall-runoff model was implemented (TETIS model). In the Kuiseb River, the availability of stream gauge station records allowed a hydrological analysis based on hydrograph routing along the stream channel. The flow observations at upstream and downstream stations in the Kuiseb River presents a unique data set to study the processes of flood routing and alluvial aquifer recharge in arid to hyperarid rivers. A detailed quality control of the data was a crucial step in the analysis.

The main conclusions of this analysis are summarised as follows:

- In the Kuiseb River, a kinematic wave model calibrated with recorded data (stream discharge and water table change) estimated the infiltration rate into the alluvial channel bed at 8.5 mm/h. Most of the recharge volume to the alluvial aquifer is from medium and large magnitude floods. In rivers with different conditions of higher infiltration opportunity (e.g., higher channel bed infiltration rates, longer or wider channels) a larger proportion of floods infiltrate on the way downstream. Consequently, in such conditions, recharge to the alluvial aquifer downstream is contributed mainly by large magnitude floods.

- A hydrological model has been implemented for the Buffels and Andarax river basins, allowing the estimation of discharge data in a basin which lacks flow records. This model provides daily discharge data series at any stream location, which can be used for future analysis to improve the knowledge of the patterns of flood events, in combination with palaeoflood data (e.g. flood frequency analysis) or with groundwater modelling (e.g. estimation of recharge associated to historical flood events)

- In the Buffels River, flood volume-duration frequency curves have been developed, providing a useful tool to characterise the flood events, allowing the estimation of the recharge through a coupled surface-groundwater model. An average groundwater recharge of 870,000 $m^3$/a was estimated over the period 1966 to 1990. To yield a maximum amount of water from floods, the water table in the aquifer should remain low. Since this also increases the risk of total depletion during prolonged periods without flow, the optimal depth to water table will be around 5 to 6 m below ground on average. Based on the model runs it was recommended that the pumping rate has to be restricted to less than 800,000 $m^3$/a if water levels drop to less than 6 m. As long as the water table remains higher, the pumping rate may exceed this limit.

- From this aquifer recharge estimation, a frequency analysis has been performed and two scenarios of recharge have been estimated for different time horizons: (1) scenario with actual consumption (groundwater level at 3m depth); and (2) scenario with high consumption (groundwater level at 9m depth). In scenario 2, in spite of a high consumption, the recharge is higher than in scenario 1, this is because the high consumption causes deeper water level in the aquifer, and favours higher recharge. This is true only if the frequency of occurrence of the flood events that produces the recharge remains constant in time, which is unlikely within the global warming conditions.

- Alluvial recharge depends on other factors such as flood duration and water table elevation, as well as being limited by the aquifer size. As a result, in small alluvial aquifer such as in the Buffels River, flood magnitude may play a minor role in relation to infiltration amount, which doesn't increase with low frequency floods (100, 500 yr) in the same proportion to those with low flow volumes.

**In relation to infiltration and recharge of the stream channel alluvial aquifers**

Flood water infiltration from ephemeral rivers and groundwater recharge of the shallow alluvial aquifers was investigated in four different rivers in Namibia, South Africa, Spain and Israel. The selected rivers are located in arid environment and represent different morphological, hydrological and geological conditions. Ten vadose zone monitoring stations were established: (a) two on the Kuiseb River near Gobabeb research centre (main channel and side bank), (b) two on the Buffels River (Roifontein and Bufferlsrivier), (c) two on the Rio Andarax (main channel and irrigated field on the flooding terraces), and (d) four in Wadi Arava (two in stream channels and two in the bottom of infiltration reservoirs). Detailed descriptions of the monitoring setups and results from monitored events are provided by Shani (2007), Tatarski (2008), Talby (2008), Dahan et al. (2007), Dahan et al. (2008). All monitoring stations recorded flood events and collected data on the infiltration process and groundwater recharge.

Several main hydrological conclusions may be drawn out from the data.

- The vadose zone monitoring system recorded vital information on the dynamics of flood water infiltration and ground water recharge in each and every flood event.

- Flood events in the stream channels resulted in deep infiltration and ground water recharge of the alluvial aquifers. Yet a minimal flood head threshold of 15 to 20 cm is required to initiate an infiltration event that will cross the vadose zone and produce a significant recharge event. This conclusion in based on observations from most monitoring stations except Roifontein where the alluvial material is made of very course well sorted gravel.

- Each significant flood recharges the alluvial aquifer, increasing its storage and significantly improving its water quality.

- Flood water infiltration and ground water recharge is primarily dependent on the flood duration, width of the active flowing channel and alluvial composition (grain size distribution).

- The natural layered structure of alluvial deposits in stream channels affects the dynamics of the infiltration process. It is the alternation of microscale layers between fine and coarse that activates capillary barriers and air entrapment processes which limits the infiltration capacity. During the downward percolation, the vadose zone remained unsaturated (<20% water content) even though the rivers were flowing bank to bank for many hour/days. Saturation of the sediments took place from the bottom of the unsaturated profile upwards and was governed by the rising water table.

- Measured infiltration fluxes range from several millimetres to several cm per hour, depending sediments properties. Flood stage seems to have only a minor and insignificant influence on the recharging fluxes.

- Infiltration from flooding terraces during high flood peaks is limited and probably does not contribute significant amounts to the total ground water recharge. It is the flood water infiltration from the active channel that controls the main recharge process.

- The hydrological relationship between the alluvial aquifer and the surrounding base-rock or regional aquifer affects the quality the aquifer. In this respect two main aquifer types can be classified: (a) alluvial aquifers deposited on low permeability base rock such as the Kuiseb River and the Buffels River, and (b) alluvial aquifers deposited in a high transmissivity formations such as the Rio Andarax and Wadi Arava. In the second type the hydrological boundaries between the surrounding aquifer and the alluvial aquifer may physically not exist and the alluvial aquifer may well be connected to the regional aquifer. Thus the recharging flood water is augments the regional aquifer from lateral recharge. In the first type however, the aquifer is primarily recharged by flood events and thus both the water quantity and quality is dependent on flood frequency.

- The structure of the alluvial aquifers which are situated in low permeability base rock, such as the Kuiseb River or the Buffels River, are structured as a linear set of interconnected basins. Thus their recharging capacity is limited by the water table. Accordingly recharge is active as long as the water level does not reach the surface.

- When the water table rises to the land surface, recharge rates are reduced and the river flows from groundwater seepage as base flow and not as a drainage to surface water runoff. Accordingly in this stage the aquifer is loosing water to the stream by seepage and not gaining by stream water infiltration.

- Infiltration rates under reservoirs are extremely low compared to infiltration under undisturbed natural channels. Accordingly it may be stated that infiltration under reservoirs is inefficient and actually reduces groundwater recharge potential.

**In relation to groundwater storage and composition of the alluvial aquifers**

The WADE project provided data on the composition of alluvial aquifers, on recharge mechanisms and on ways of using such knowledge for a development of alluvial aquifers or for a better and sustainable management.

In drylands the alluvial aquifers represent areas of runoff concentration. While in many locations direct recharge is very small due to thick unsaturated zones and sparse rainfall, the threshold for recharge is often reached as a result of concentration of runoff in space (through the channel network) and in time (as a result of rainfall spottiness and runoff concentration). However, the same factors that make alluvial aquifers preferred locations for indirect and concentrated recharge, render an analysis of these shallow phreatic aquifers difficult: recharge is rare and not evenly distributed in space and in time. Therefore the estimation of sustainable yields of these aquifers is extremely difficult. WADE as provided an important scientific contribution to this problem. The monitoring of groundwater recharge has established recharge rates for different alluvial channels. These were surprisingly homogeneous. Based on these event-based observations the annual and long-term water balance of selected alluvial aquifers could be established using complementary tools: isotope analysis and age dating, groundwater modelling, coupled modelling.

These studies have shown that alluvial aquifers are also focussed areas of competition about water: major water consumption is related to phreatophytes. These processes result in salinization processes. WADE has contributed to a process-oriented understanding of salinization in alluvial aquifers.

General and regional conclusions could be drawn:

- Recharge is controlled also by aquifer properties not only by flood properties. Coupled models have shed light on these interactions and provided a tool for management of alluvial aquifers.

- Only integrated approaches provide sufficient precision to manage alluvial aquifers: the ecohydrological interaction and the interaction between surface and groundwater is the crucial characteristic of alluvial aquifers in drylands. WADE has developed tools for describing these interactions.

- The interaction between human use and the natural system (alluvial aquifer) modifies the process: groundwater management schemes of alluvial aquifers are non-linear systems. WADE has shown that sustainable yield depends on the natural system ***and*** on the way it is used. Sustainable yield can be increased by a moderate and balanced increase of the use. However, this should be accompagnied by an integrated management and modelling approach including other sectors (nature protection, biodiversity specialists).

- There is a need for simplified yet sufficiently complex tools providing such decision support. WADE has provided an example of such a regionalized management tool: The integrated surface-groundwater model has been used to derive nomograms relating flood magnitude and flood magnitude per year to recharge or flood duration per year to recharge. These nomograms can be used for a fast assessment.

- The study area Buffelsrivier (Spektakel aquifer) may provide **more** water than is presently used on a sustainable basis if managed adequately. Taking into account the importance of groundwater levels before floods and resulting transpiration losses an optimized eco-hydrological balance can be found that maintains vegetation and provides more drinking water.

- Salinization is a process related to surface-groundwater interactions. WADE provides a perspective to manage salinization in some cases. For the upper part of the Buffels River salinization hot spots could be identified and related to a pool – vegetation sequence. Although the process of salinization is natural, its understanding can be used to minimize the effect by a proper choice of abstraction sites.

- The possibility of using the results for decision support systems has been demonstrated for the Kuiseb alluvial aquifer. An integrated flood-groundwater model has been developed and can be used by Namwater, DWA and other stakeholders. The value of such integrated systems for understanding complex systems in drylands is related to the fact that long-term behaviour of aquifers in response to rare floods can be studied and that paleoflood data can be integrated into quantitative schemes for recharge assessment.

**In relation to environmental history and riparian vegetation**

The riparian ecosystems provide goods and services to both commercial and communal farmers living adjacent to the Kuiseb and Buffels Rivers. In arid and semi-arid systems, riparian vegetation represents a key resource in terms of forage production for livestock, and provides building material and fuel wood for local communities that make a significant contribution to the local economy. Flood events provide a pulse of water and nutrients that stimulates plant production and greatly increases the number of livestock the system is able to support.

Evidence drawn from the environmental history of the Buffels River in particular and Namaqualand in general suggests that climate change during the 20th century is related primarily to climate 'amelioration' since the end of the little ice age, manifest in the reduced frequency of large flood events. Coupled with this has been a shift in land-use patterns from highly disturbed landscapes related to mining (charcoal burning), grazing and cultivation during the 19th century to a period of recovery due to the reduced smelting in the early 20th century with agrarian reform and de-agrarianisation since about 1950 having a marked impact on vegetation composition and cover over large areas of Namaqualand. These anthropogenic impacts coupled with climate change have resulted in more stable riparian ecosystems that have enhanced ecosystem services such as water quality improvement, the trapping of sediments, and the modulation of hydrologic processes.

- Riparian ecosystems in semi-arid regions account for as much as 50% of losses from alluvial aquifers due to evapotranspiration. A realistic figure for annual water loss is likely to be 15–20% of the total aquifer volume, 80% of which is due to transpiration, which may lead to a "dry depth" of 2.9 m in the riverbed fifty-one weeks after a flood. However, since the main source of groundwater at the middle-lower Kuiseb alluvial aquifer is floodwater recharge, the water table at Gobabeb (lower Kuiseb River) may recede to a depth of about 7 m below the surface during long dry periods, which may affect trees.

- In the Spektakel aquifer of the lower Buffels River, the transpiration rate was estimated at 19,000 m3 per day, and in the absence of recharge or lateral flow and assuming that the increasing depth of the groundwater did not reduce the evapotranspiration rate, the riparian vegetation would completely drain the aquifer in twenty-five months. The hydrological characteristics of ephemeral river systems on crystalline basements such as that of the Buffels River support vegetation communities that are adaptive, and regulated by the smoothed lag effects from lateral flow.

- Repeat photographs show that riparian vegetation has increased in all reaches of Namaqualand's ephemeral river catchments during the 20th century. This can be attributed in part to a decrease in charcoal burning associated with the mining industry of the 19th century although increases have also occurred in undisturbed 'control' areas indicating that riparian vegetation has increased due to the absence of prolonged drought events or the absence of large scouring flood events or both. This expansion of phreatic vegetation has increased the effectiveness of riparian linear oases in achieving animal and plant migration corridors across environmental gradients.

- During dry periods, hydrologic conductivity at the Buffels alluvial aquifer, characterised by slow release of water at the boundaries of the alluvium, is in balance with the uptake of water by vegetation, resulting in constant water tables in the riverbed to a depth of about 4.5 m below the surface. Groundwater quality can be improved by large-scale abstraction from the Spektakel aquifer, however, it is not certain that this effect can be achieved without negatively impacting the riparian vegetation and hence the goods and services associated with this resource.

- In the Kuiseb, increased mortality of *Acacia erioloba* trees and increased mortality and lower production of *!Nara* melons has been associated with increased abstraction.

**In relation to socio-economic issues and water management**

The WADE project has analysed the socio-economic issues in relation to water demand and water use in the context of policy and institutional frameworks, as well as an analysis for effective implementation of IWRM. The problems encountered in northern and southern countries involved in the WADE project are quite different due to the different economic contexts, as well as to different institutional water management structures. The contrasts and similarities in the way these water resources are managed in different political and institutional contexts provide important lessons for the management of ephemeral rivers in other parts of the arid developed and developing worlds.

In developing countries such as Namibia and South Africa, people have the expectations that they will be supplied with water just as people are in developed countries. Most expect that the supply will be provided with little or no effort from their side. The poorer part of the population in the case study areas expects water to be provided for free partly because it was one of the services dispensed by the previous apartheid and colonial governments. For this reason the Namibian government focuses on payment for supply, not for water *per se*. The less poor portion of the population is willing to pay for their water supply (but not too much) with the expectation that they will have water available at any time in any volume as required. The project has confirmed these preconceptions related to water as an economic good, although at the different case study basins contain cultural and historical particularities.

Some of the main conclusions in the studied southern countries are:

- Management of ephemeral river basins according to IWRM presents expected and unexpected challenges. Some of the pre-conditions for successful implementation of IWRM in developing countries as outlined by Schulze (2007) include: local participatory catchment planning methodologies; building on local, indigenous knowledge, experience and practice; planning initiatives that involve local community organisations and that provide capacity building and technical support; and development of a framework of local-level collaboration amongst NGOs, community-based organisations and government departments with relevant government agencies.

- Water service delivery that focuses primarily on physical planning at the broader scale tends to lack the necessary sense of local ‘ownership’ or ‘stakeholder involvement’ and therefore is not sustainable. In a developing country such as Namibia and a newly industrialised country such as South Africa, the ideal of IWRM involving complex infrastructure development and maintenance, high administrative skill levels, long-term planning horizons and wide stakeholder participation, is often unattainable. In practice, a trade-off must be made between levels of institutional complexity and administrative capacity. As a result, in these countries the temporal and spatial scale of planning and implementation is by necessity smaller (at community and municipal levels).

- In the Kuiseb Basin, holistic management is based less on formal management as on dictates of the basin’s geography. In the upper and middle Kuiseb basin, farmers manage resources to meet identified needs with little or no focus on IWRM. In the lower basin, where a large urban population (Walvis Bay with 30,000 residents) is solely reliant on these limited water reserves, the relevant ministry, the bulk water supplier (NamWater) and the municipality manage the alluvial aquifer with only the municipality taking a holistic viewpoint and using demand management and other IWRM approaches.

- Participation is a key to water development and management involving users, planners and policy makers at all levels. To date in Namibia, a management approach based on participation of all local stakeholders has been articulated in policy and is slowly being implemented. The Kuiseb Basin Management Committee is one of the basin management structures in Namibia to encourage wide participation, particularly of users, while involvement of planners and policy makers is evolving. However, new mining concessions in the lower Kuiseb, approved from higher political levels, may break the current balance of sustainable extraction of groundwater resources in the area.

- In the case study site in South Africa, the Buffels River catchment is administratively divided between two local municipal authorities. Secure access to water for basic human needs has largely been achieved in both Municipal areas, including several communal villages reliant on groundwater from the Buffels River. The focus, on the part of municipalities at least, has now shifted to recovering payment for these services. Although the provision of basic and reliable water to all communities has been a significant advance, a broader approach is required that acknowledges the multiple needs as well as the diverse potential of water related development in different parts of the catchment and participation of residents in planning and managing this resource. In the lower catchment, where abundant water is available, the antagonistic relationship between the local municipality and two communal villages is such that the potential for development using the Spektakel aquifer remains untapped. In these circumstances it would be counter-productive to create a catchment-wide management committee or to unnecessarily complicate the administrative structure of water service delivery. On the other hand, a catchment-wide forum under the auspices of the District Municipality might provide a neutral context in which conflicts over rights to control and manage water resources could be resolved.

- The WADE project provides a technical basis from which to plan appropriate IWRM activities. However, this information in and of itself, is not sufficient to promote long-term sustainable management of groundwater resources. These two case study catchments provide examples of the successes and shortcomings of IWRM associated with particular, sometimes contrasting bio-physical, hydrological, socio-economic and political conditions within ephemeral river catchments in southern Africa. To be useful for local communities, municipal and higher-level service providers and administrators as well as for policy makers, appropriate communication of these results is required.

**The main general policy implications derived from the WADE Project:**

- Infiltration reservoirs in arid environments are extremely inefficient, reduce groundwater recharge and cause degradation in groundwater quality.

- The recharging capacity of the alluvial aquifers in the Buffels River and the Kuiseb River at the studied sections is limited by the compartmental structure of the aquifer. These interconnected compartments have a very limited storage and are subjected to over flow or salinization when water table approaches land surface.

- Optional water management of these aquifers requires linear exploitation of the entire aquifer along its length instead of single or point abstraction field.

- Management of the aquifer as a linear resource that is structured as a set of interconnected compartments may increase the total recharge since the main limiting factor is the compartment storage capacity and water table.

- The recharging potential at Rooifontain area is very limited as the aquifer reaches its recharging limit immediately after each flood. Accordingly an addition to the water potential of the area can be gained only if larger sections of the alluvium aquifer are exploited upstream of the village in a set of small lined pumping wells and not through a single well (as at present).

- Total groundwater recharge for the entire study period for the Gobabeb site (lower Kuiseb River) was calculated as ~210,000 $m^3$ per 1 km of stream reach. Recharge estimations for the Buffelsrivier site varied between 200,000 and 2,300,000 $m^3$/km and at the Rooifontein site between 41,000 and 81,000 $m^3$/km. Yet, it should be noted that the study was conducted in a extremely wet season where each of these rivers was flooded several times.

- Conservative calculation of the recharge potential in Wadi Arava reaches ~10,000 $m^3$/km per average flood event, yet this value is limited as the reservoir system limits the flooding capacity of the stream channels and thus reduce the natural infiltration potential.

- The handshake for an efficient interdisciplinary cooperation of water managers and policy makers from Africa and scientists from Europe can be realized through science. WADE has provided empirical data on recharge processes that were not available as such before.

- The IWRM community of Southern Africa is sufficiently trained to work with such data if scientists providing such data are capable of reducing in a way that it can directly be applied in operational integrated water resources management.

- Integrated models are an instrument but not the objective. There is not an efficient tool for translating research into policy making. Therefore, reduction of integrated models to management guidelines and management instruments is necessary. Decision support systems have been used for such purpose; however, they still exhibit a high degree of complexity making their integration into management processes with multiple-stakeholders a demanding task. Often technical support can not be maintained for such systems. WADE has shown that scientific results, (e.g. recharge rates in $m^3/a*km$), general findings, (e.g. in which river reaches higher water levels of alluvial aquifers reduce recharge) are far more effective in making technical cooperation permanent.

- The role of empirical methods and monitoring of subsurface water schemes cannot be overestimated. As groundwater systems, especially alluvial aquifers in drylands are complex systems, we might still not have caught all impacts and interactions.

- Enabling the scientific community and managers to monitor specific key parameters, explaining their relevance for management is an important supporting element of integrated modelling and water resources management – especially in drylands. Monitoring should not be understood only as hourly or daily observation but also as the use of additional integrative methods such as paleo-hydrology and isotope hydrology. WADE has demonstrated these methods (TDR, paleoflood data, isotope methods) and their key role in developing, validating and updating integrative models and management guidelines.

- In both South Africa and Namibia it is the cost of water that is one of the biggest challenges in ensuring that the poor are not marginalised and deprived of one of their basic resources.

- Some of the pre-conditions for successful implementation of IWRM include: local participatory catchment planning methodologies; building on local, indigenous knowledge, experience and practice; planning initiatives that involve local community organisations and that provide capacity building and technical support; and development of a framework of local-level collaboration amongst NGOs, community-based organisations and government departments with relevant government agencies.

- Attention needs to be given to the capacities (financial and technical) of local municipalities.

- A water reserve to meet both people's and environmental demands should be quantitatively estimated and means to implement priority allocations according to this reserve should be exploited. WADE can satisfy an important need to provide groundwater information and to create an improved understanding of groundwater at the local, municipal and ministerial levels.

- Constraints and opportunities of different water technologies, targeting to enhance poor people's access to water inclusive of organisational designs, competitive water markets and stepped pricing systems for poverty reduction need to be studied and tested in varying contexts.

- The capacity and participation of women in water-related matters should be encouraged. This should be done within a framework of integrated water resources management (IWRM) where considerations for poverty alleviation and gender equality are integrated with the ecological, technical and economic dimensions of water management.

- At a community level the integration of water and sanitation management is a key condition to address women's and men's multiple water needs from multiple water sources. All water management structures should include representation of women and men of all social strata.