Unconventional Water Supply Options in South Africa
A Review of Possible Solutions

Vladimir Smakhtin, Member IWRA, Peter Ashton, Allan Batchelor, Reinhard Meyer, and Eric Murray, Division of Water, Environment and Forestry Technology (CSIR: Environmentek), Pretoria, South Africa, Bohuslav Barta, Fellow IWRA,University of Witwatersrand, Sandton, South Africa, Norbert Bauer, Institute for Environmental Affairs, Munich, Germany, Dhesigen Naidoo, Department of Water and Forestry Affairs, Pretoria, South Africa, Jana Olivier, University of South Africa, Pretoria, South Africa, and Deon Terblanche, South African Weather Bureau (METSYS), Bethlehem, South Africa

Abstract: South Africa faces escalating freshwater problems and will experience prolonged water deficits within the next 25 to30 years if current patterns of water use continue unchanged. The level of conventional water resources utilization in the country is very high and new approaches are necessary to stretch the limited water supplies available to meet projected demands for water. Significant research into new technologies and sources of supply has been carried out in South Africa and abroad during the past few decades. This has resulted in the development and evaluation of a number of innovative concepts and methodologies, as well as novel adaptations to existing approaches. These concepts and methodologies include: integration of surface water transfers into a national water grid, transfers of untapped surface water resources from countries located to the north of South Africa, exploitation of deep groundwater and the use of aquifers for storage of surplus water, atmospheric water (fog and cloud) harvesting, iceberg water utilization, desalination and direct use of sea water. Some of these options are still theoretical and unproven, while others have reached different stages of practical testing and implementation. Information on these alternatives for water supply is widely scattered over many different sources. This paper reviews the available information and examines some of these unconventional sources and options for future water supply in terms of their technical aspects, potential applications, likely impacts, approximate costs, and regional relevance in terms of alleviating predicted water shortages.

Keywords: Water scarcity, surface water resources, deep storage, international water sharing, virtual water, deep groundwater, artificial recharge, rainfall enhancement, fog water, desalination, iceberg water harvesting, wastewater reuse, water demand management.

Introduction

South Africa is classified as an arid country with a mean annual precipitation (MAP) of 497 mm, which is far less then the world average of 860 mm. The rainfall is unevenly distributed both seasonally and spatially and the mean annual potential evaporation across the country exceeds MAP by a factor of at least three. These climatic features result in surface water resources that are in relatively short supply, and unevenly distributed spatially. The total mean annual runoff (MAR) of the country is estimated at approximately 50,000 Mm^3/year (Pitman, 1995; Basson *et al*., 1997), of which about 60 percent originates from less than 20 percent of the area (Midgley *et al*., 1994). Low rainfall, combined with high rates of evaporation, contributes to low rates of groundwater recharge. Some estimates suggest that, on average, only about three percent of the MAP in South Africa infiltrates deep enough to recharge the groundwater (Orpen, 1992), which predominantly occurs in fractured hard rock secondary aquifers (Vegter, 1995). The estimates of groundwater resources in the country vary from 16,000 to 37,000 Mm^3 (Commission of Enquiry, 1970) and include a high degree of uncertainty. The maximum volume of groundwater that can be abstracted on a sustainable basis from South African aquifers has been estimated to be between 5,000 Mm^3/year (Vegter, 1984a) to 5,400 Mm^3/year (DWAF, 1986).

In the last few years, the availability of fresh water in South Africa has fluctuated between 1,000 and 1,700 m^3 per person per annum (Basson et al., 1997). According to Falkenmark's thresholds of water stress and water scarcity (Falkenmark, 1991; Falkenmark and Widstrand, 1992), the country may be classified as water stressed. The problem of adequate water supply is exacerbated during droughts. For example, during the drought of the early 1990s, it was estimated that 12 million South Africans existed on less than 15 litres of water per person per day (Olivier and van Heerden, 1999).

The ecological flow requirements for aquatic ecosystems (the “ecological Reserve”) are currently being established at the national scale for all types of water bodies (rivers, estuaries, wetlands, groundwater) as part of the implementation of the new National Water Act (Act No. 36 of 1998; Republic of South Africa, 1998). This inevitably places additional limits on the availability of water for many users and may potentially reduce the current levels of water availability by 15 to 20 percent. Estimates of anticipated future water use in the country suggest that demands for water will increase by between 28 percent (agricultural sector) and 219 percent (domestic use) (Basson *et al*., 1997). Such predictions imply that the effective limit of the country’s exploitable water resources will be reached within the next 20 to 30 years, and that fresh water availability is likely to continue to decline and remain below the threshold of 1000 m^3 per person per annum (Falkenmark, 1986). This implies that South Africa will experience chronic water scarcity. It will therefore no longer be possible to reconcile water demand and supply without the development of further high-cost supply options.

At present, South Africa is close to the halfway mark in terms of the exploitation of its conventional water resources (largely surface water). Many regions of the country already experience severe water shortages and the demand for water has far exceeded the local supply in the key inland economic centers. In past decades, water resources development focused predominantly on structural solutions such as the construction of water storage reservoirs and water transfer schemes (DWAF, 1986; Basson *et al*., 1997). At present, the combined capacity of large and small water supply reservoirs in South Africa amounts to some 37,000 Mm^3; this is equivalent to almost 74 percent of the total country’s MAR and represents a very high level of “resource capture” (Ashton and Haasbroek, 2000). Most water-deficient inland areas of South Africa currently receive major proportions of their water via large and expensive inter-basin transfers and a high degree of reliance on physical (structural) solutions continues to dominate water resources planning approaches in South Africa (as well as in the rest of the world). Despite the fact that such solutions face increasing opposition on environmental and social grounds (WCD, 2000) and are also becoming progressively more expensive, their potential has not yet been exhausted. Indeed, new possibilities to extend the application and efficiency of conventional water supply systems have been the subject of several recent studies. At the same time, a number of alternative ideas and options for water supply are also being explored or implemented in South Africa and other arid regions of the world.

It is possible to distinguish between the two major groups of such ideas or approaches. The first group focuses primarily on improved utilization of conventional water resources by means of new technologies and management approaches. These ideas focus on innovative water resource planning, suggest greater cooperation between countries of the Southern African Development Community (SADC) and explore new engineering solutions. The second group focuses on the utilization of unconventional water sources that have not yet been utilized or have only been exploited marginally at the present time. These options include: desalination of seawater and full reclamation and reuse of industrial effluents, water transport in different forms over long distances (e.g., using marine vessels, floating bags or towing icebergs), rainfall enhancement through cloud seeding, as well as innovative ways of water collection and storage (for example, water harvesting, and the artificial recharge of aquifers).

Alternatively, it is also possible to distinguish between methods that intend to bring more water into a water supply system, augment the existing water yield of river catchments or increase the efficiency of water use. However, any classification system is usually somewhat arbitrary and every idea or technology application can usually be viewed from many different angles.

This paper reviews recent trends in, and new approaches to, water resources development in South Africa, and seeks to analyze the feasibility of several unconventional water supply options in terms of their technical aspects, potential applications and impacts, costs and regional relevance. This “changing water paradigm” (Gleick, 2000) is examined primarily in the specific context of South Africa, although relevant studies that examine similar problems in other SADC countries or at a regional level are also taken into account. The paper also seeks to draw the attention of the international water resources audience to the range of water problems faced by the region and to examine the validity and practicality of recent concepts that have been suggested as well as their potential to relieve the water resource problems faced by the region.

Innovative Surface Water Resources Planning and Engineering

Water Sources: “Attractive” vs. “Convenient”

It is estimated that of the total exploitable surface water resources of South Africa (that part of the MAR which can be utilized) amount to some 33,600 Mm^3 per year, of which about 60 percent has already been allocated for use (Basson *et al*., 1997). Unfortunately, the geographic distribution of water resources in the country follows a very different pattern to that of the demand for water. Surface water resources development in South Africa in the past was largely “demand-driven,” in that the most convenient water sources (often located closest to the major demand centers) were developed first and often without regard to overall water resource planning for the country as a whole. Pitman (1995) has demonstrated that this approach has resulted in a steady decline in the efficiency of reservoir storage utilization in South Africa and over-exploitation of some major river systems, while many other large rivers remained largely untapped. In order to arrest this unfavorable trend in water resource utilization, Pitman suggested an alternative, “supply-driven” approach, which implies that emphasis should be shifted to the exploitation of the most “attractive” water resources, i.e., those that have the most favorable storage/yield characteristics, but may not necessarily be located closest to the demand centers.

An analysis of the resources of the 37 largest river systems in South Africa has illustrated that the most suitable candidates for supply-driven development are those with large unregulated MAR values, rather then those river systems with a large total exploitable MAR. These rivers, with a total unregulated MAR of 23,500 Mm^3 could provide a cumulative yield of about 14,000 Mm^3 per year (provided that a storage capacity in each catchment is equivalent to 1 MAR). This would allow the present water supply to be doubled and would also satisfy the country’s projected water demands for the next 25 to 30 years.

Supply-driven water resource development effectively places the emphasis on further expansion of inter-basin water transfers. Pitman (1995) suggests that the most efficient way of utilizing South African surface water resources would be to link all the rivers in the country by means of a “water grid” in a fashion similar to the national electricity grid. Such a water grid would allow water to be transferred in any direction to cater for the spatial variability in droughts, floods, and water demands.

In contrast to this opinion, the numerous inter-basin transfer schemes that already exist in South Africa have generated considerable environmental concern; further developments of this nature would accentuate these fears. However, it can be argued that implementation of the water grid concept would allow ecological demands to be catered to in a more systematic way. Nevertheless, reconciliation of the principles embodied in the ecological Reserve with the water grid concept would also represent a major challenge to water resource managers should this concept ever become accepted.

The concepts of demand- and supply-driven water resources developments may be useful in evaluating the efficiency of current and planned water supply schemes. In this context, the most significant new development in the region, the Lesotho Highlands Water Project (LHWP), intends to deliver additional water to the Vaal water supply system in South Africa and represents a continuation of the historical demand-driven trend. New dams are being constructed upstream of existing major reservoirs on the Orange River and, despite the large projected increase in storage capacity in the upper Orange Basin (due to the LHWP), the overall increase in yield of the entire Orange system (of which the Vaal River forms a part (**Figure1**) is relatively small. (All geographical names referred to in this paper may be found in **Figures 1 or 2**).

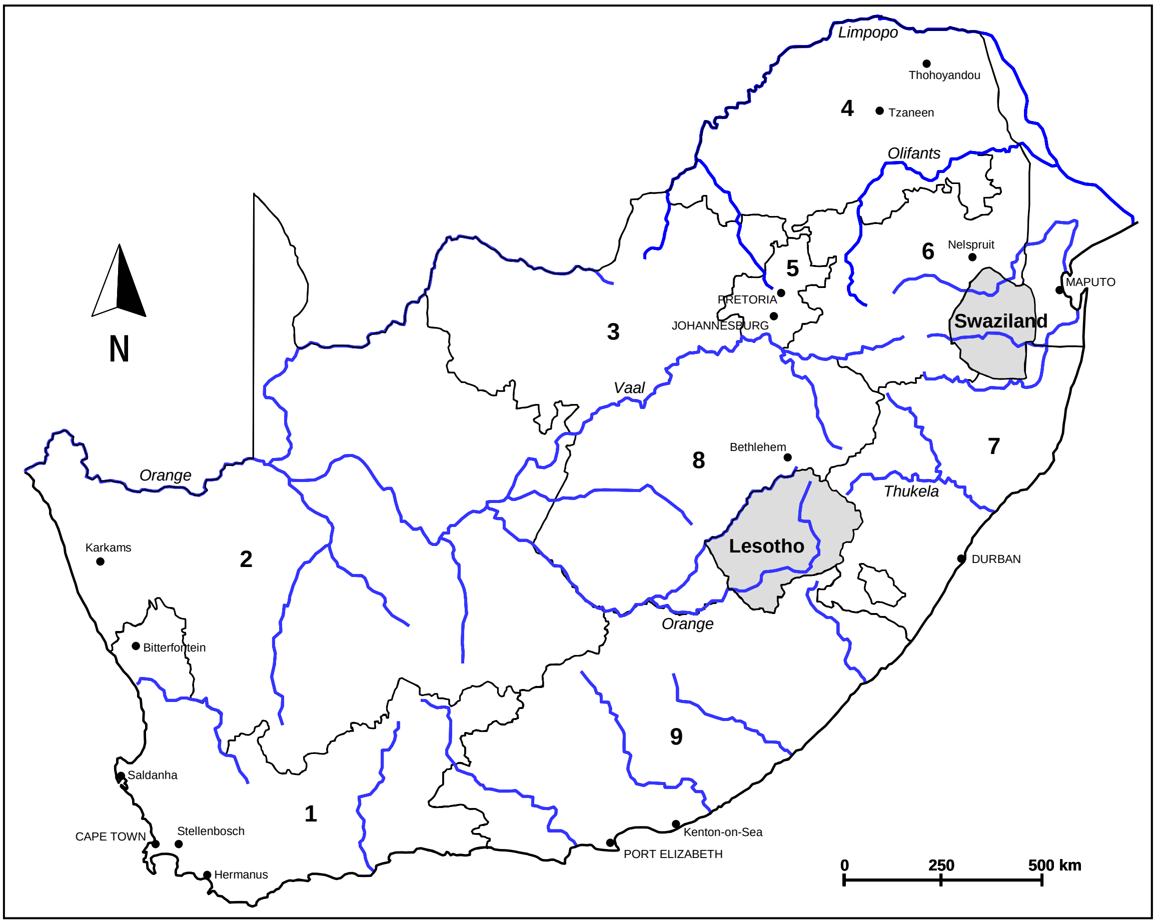


Figure 1. A map of South Africa showing provincial boundaries, rivers and towns referred to in the paper. (1. Western Cape Province, 2. Northern Cape, 3. North-West, 4. Limpopo, 5. Gauteng, 6. Mpumalanga, 7. KwaZulu-Natal, 8. Free State, 9. Eastern Cape).

It is important to note that the countrywide water grid concept appears to be extremely expensive. Additional storage associated with new dams on rivers that are already heavily exploited is cheaper than water transmission costs over long distances (via pipeline or canal) from "attractive" sources. However, excessive storage capacity usually also translates into excessive evaporation losses. At present, some 2,200 Mm^3 is lost each year via evaporation from storage reservoirs. This equates to about 7.5 percent of total storage capacity in the country (in 1990 figures) and is approximately equal to the volume of water stored in the Vaal Dam, one of the largest dams in South Africa.

Deep Storage Reservoirs

The issue of evaporation losses from storage reservoirs calls for innovative engineering approaches and deserves special mention. Because evaporation losses are proportional to the surface area of a reservoir, it is theoretically possible to minimize these losses by reducing the surface area and, at the same time, increasing the depth of a reservoir. Clearly, this is not feasible in the case of existing reservoirs, but it could be an important consideration in the choice of sites for construction of new water storage reservoirs.

Many South African reservoirs have a capacity that is equal to, or greater than, the MAR at the dam site. According to some sources (Lund, 1997), the safe yield of such dams may be in the range of 50 percent of the MAR. This means that about half of the MAR either evaporates or is lost downstream during floods. For example, spillage from the Vaal Dam during 1995 to 1996 was sufficient to refill the dam at least three times. Such floods may be stored in a deep storage reservoir. Another potential benefit of such a scheme could be a reduction in evaporation losses. Lund (1997) claims that such a strategy, if successful, could increase reservoir yield to a level of approximately 90 percent of the MAR. However, to achieve this, the storage capacity (of new deep storage dams) would have to be increased to a level of approximately 400 percent of the MAR. This would clearly require massive capital investment, careful identification of suitable sites at which favorable depth-area relationships of a reservoir may hold, and careful assessment of eco-geomorphological impacts of diversion of large floods into deep storage reservoirs.

Another possible option for consideration would be to trap portions of floodwaters and store this water underground in abandoned mines. Clearly, this could pose several potential problems and risks for other working mines that may be located in the vicinity and these risks would need to be carefully evaluated. Similarly, it would also be important to assess the extent to which the “additional” water might dissipate into the surrounding geological formations and not be recoverable. In addition, it is possible that any water stored in an abandoned mine could become contaminated with a wide variety of undesirable constituents. Mine water pumped from many of the deeper gold mines in South Africa is contaminated by acid rock drainage and trace metals, and often contains evidence of radioactivity. It would be inadvisable to store water underground if its quality were subsequently to render the water unfit for use. The ideas of storing surplus (e.g., flood) water in underground “reservoirs” is closely linked to the artificial recharge technology, which is described in a section below.

Two major limitations associated with the idea of constructing (new) deep storage reservoirs in South Africa are the absence of suitable sites for construction and the anticipated costs of such construction. However, if this approach is considered in the broader geographical context of southern Africa, rather then at the scale of South Africa alone, the possibilities for achieving the potential goals may increase. Suitable sites could be chosen on the basis of their basin topography as well as their elevation and annual range of temperatures. Reservoirs constructed at suitable sites in higher elevations would experience lower ambient temperatures and have smaller surface areas; they would therefore experience smaller water losses via evaporation. Water could be transferred via gravity-fed pipelines from these reservoirs to the sites where it is required. The higher elevation of such sites would also enable hydropower to be generated and this could help to offset pumping costs.

The issue of increased efficiency of utilization of the remaining surface water resources in South Africa should be viewed from every possible angle. The concept of supply-driven water resource development based on “attractive” water sources suggested by Pitman (1995) could help to identify the most suitable “candidate” sources or sites for future water supply schemes, while the deep storage concept may offer an engineering solution for efficient use of so-called “surplus water” and help to reduce evaporation losses. Both concepts should, therefore, not be ignored in planning future water supply projects and need to receive more attention in southern Africa in the future.

International Water Sharing

One of the more complex ways to further extend the limited South African water resources is to embark on development of international river catchments elsewhere in southern Africa. This concept can be equated with a conventional bulk water supply scheme, but embodies a source that is located more remotely than those exploited in present circumstances. Therefore, the major differences associated with this option would relate to the long-distance transfer of water via canals or pipeline systems. Such long-distance water transfers are unconventional at least in a sense that no such projects are implemented in southern Africa to date.

The overall quantitative utilization of exploitable surface water resources within the shared river basins in Southern Africa (excluding the Congo River system) is estimated at one quarter of the SADC region’s potential (SARDC, 1996). The resources of some international river basins such as the Congo, Cunene, Okavango, Rovuma, Save, and Zambezi (**Figure 2**) are relatively under-utilized. Some of these catchments (e.g., Cunene, Congo) are also characterized by limited industrial and agricultural development partially caused by political instability in the respective countries forming their headwaters. Generally, the levels of MAR utilization in SADC countries to the north of South Africa are considered to be low, ranging from one to 11 percent of each country’s MAR, with exceptions of Malawi and Zimbabwe (over 20 percent), (calculated from Barta [2000]). Therefore, any option to draw on the water resources of the major river systems located to the north of South Africa represents a very attractive alternative and should receive more attention in the future. Clearly, such an option would require a great deal of negotiation with the basin states responsible.

South Africa, with its population of approximately 43 million people and its extensive industrial and agricultural activities, presently uses almost 50 percent of all water used in the continental SADC region (Barta, 2000). However, most of South Africa’s current water use consists of its own water resources, as well as a portion of the water from rivers shared with Botswana, Lesotho, Mozambique, Namibia, and Zimbabwe (Basson *et al*., 1997). If sufficient water is to be set aside for basic human needs and aquatic ecosystems in these “shared” rivers to meet the requirements of the National Water Act, the availability of water for other uses could be reduced by between 15 and 30 percent. This would suggest that the opportunities for additional abstraction from these rivers are limited and that the current levels of utilization represent a state that is close to the limits of the potential of these river systems.

For logistical and economic reasons, the Zambezi River is viewed as the most likely source of future water abstractions to relieve growing water stresses in Botswana, Namibia, Zimbabwe, and Mozambique. However, South Africa does not form part of the Zambezi basin and thus cannot claim a riparian or other right to a share of the water from the Zambezi River (Pallett, 1997). Therefore, if South Africa wishes to obtain water from the Zambezi River, this would have to be negotiated, and then the water purchased, from the eight riparian countries forming the Zambezi basin. If a water supply scheme from the Zambezi were to be constructed to supply water to South Africa, it should ideally be designed with a view to supplying water to Gaborone in Botswana, and perhaps also to Bulawayo in Zimbabwe. Additional negotiations would then have to take place with Botswana and Zimbabwe to allow the required pipelines and diversion weirs to be constructed. Clearly, it is essential that the development of regional water resources be carried out in close collaboration with all countries in the region so that each may derive direct benefits (Ashton, 2000).

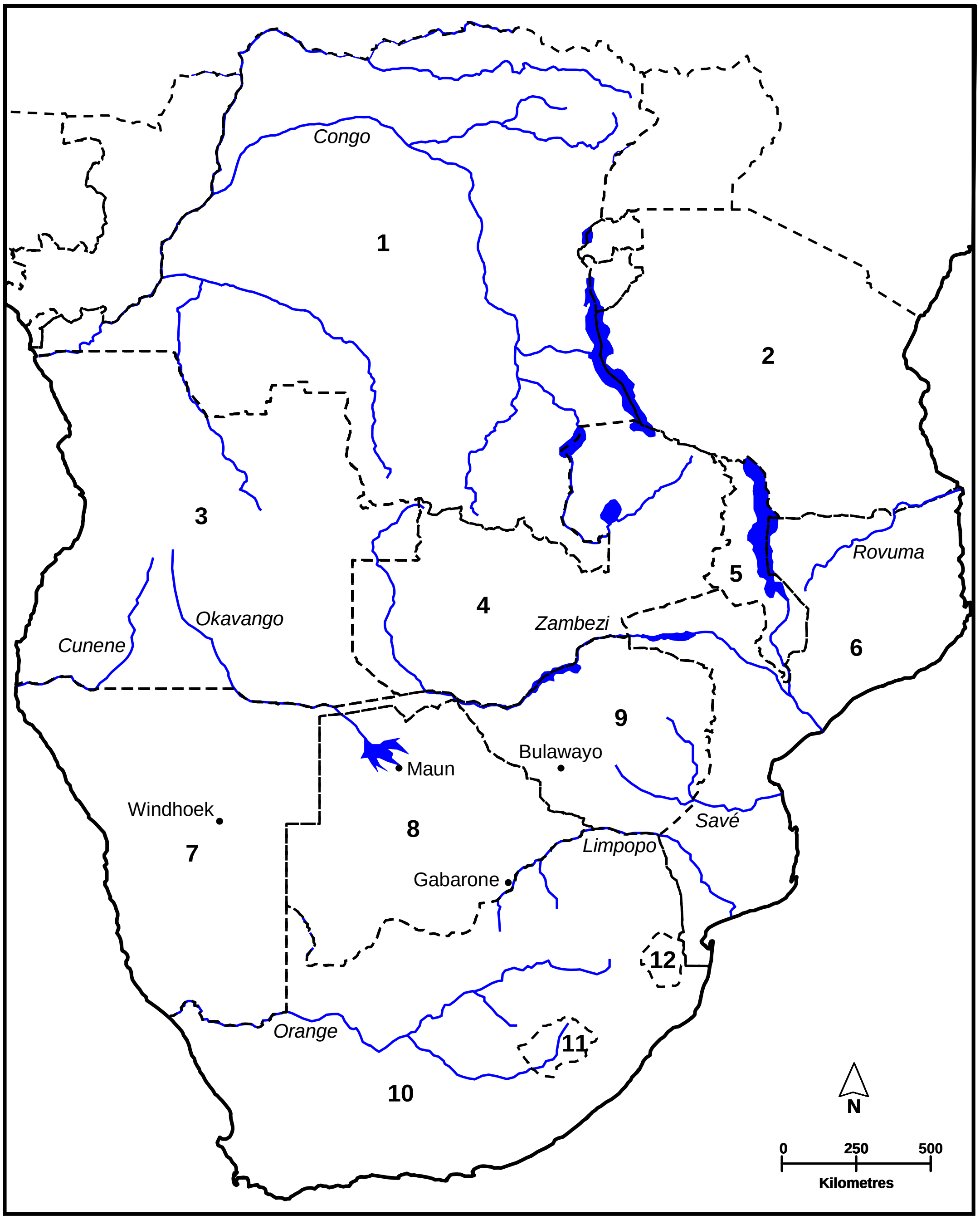


Figure 2. A map of Southern Africa showing the countries' boundaries, major rivers and towns outside South Africa referred to in the paper (1. Democratic Republic of Congo, 2. Tanzania, 3. Angola, 4. Zambia, 5. Malawi, 6. Mozambique, 7. Namibia, 8. Botswana, 9. Zimbabwe, 10. South Africa, 11. Lesotho, 12. Swaziland).

A similar situation applies to any attempt to exploit the under-utilized water resources of the Democratic Republic of Congo (DRC). However, the political instability that currently prevails in the DRC makes it extremely difficult to initiate proper feasibility studies for developing these water resources. The Congo River contains the largest volume of water in Africa (830,000 Mm^3/year) and offers a tantalizing opportunity to provide sustainable supplies of water to augment the scarce and over-utilized water resources of the southern African countries. Biggs (2000) has recently postulated some of the possible options for transferring water from the Congo River or its major tributaries into different receiving rivers in the Zambezi, Okavango, and Cunene basins. While some options are likely to be significantly cheaper than others, a water transfer project of the scale envisaged would require extensive feasibility studies to determine the likely social, environmental, and economic impacts associated with each of the options considered. One of the major concerns relates to the possibility that a variety of water-borne diseases, as well as other possibly unwelcome organisms, may be transferred with the water and lead to unacceptable consequences in the receiving rivers.

Despite the rather obvious economic implications and their associated environmental disadvantages, the Congo River development options offer many possible benefits if Congo water could be transferred to the Zambezi, Okavango, or Cunene rivers. If more water (due to such transfers) is available in the Zambezi River, for example, a portion of this water could be transferred, via northeastern Botswana, to the water-short Gauteng Province of South Africa. This would help to reduce the demand for water from the Limpopo River and thereby also reduce adverse effects on Mozambique (Biggs, 2000). In addition, such a water transfer to South Africa could also reduce the growing demands for water from the Orange-Vaal system in South Africa and thereby allow Namibia to exploit a larger share of the lower Orange River.

Another option associated with flows in the Congo River is one that considers the use of water as it flows out of the mouth of the Congo River. These flows that enter the Atlantic Ocean are effectively lost for beneficial (land-based) human use (from an engineering point of view). This has prompted investigators to evaluate options to collect this water in refurbished super-tankers and then transport it to the coastal ports of Namibia. The preliminary evaluation of this option has concluded that it is feasible (DWA-KFW, 1996) but has also revealed that the unit cost of Congo water would be approximately 50 percent higher than that associated with other options (e.g., seawater desalination at the Namibian coast).

Similar conclusions have emerged from investigations into the transportation of Congo water to Cape Town that were undertaken by DWAF (1994) and, more recently, by Delft University of Technology (DUT, 2000). The earlier study investigated the transport of water from the mouth of the Congo River by tankers only and concluded that a fleet of nine tankers (each carrying about 0.28 Mm^3 of water) would be required to make a significant impact on the City's water supply. The cost of "tanker water" was estimated at ZAR 8/m^3, which amounted to approximately US$2/$m^3$ at 1994 exchange rates.

The latter study (DUT, 2000) investigated three alternatives for water transport from the mouth of the Congo River (tanker, water bag, and pipeline transport) using several evaluation criteria (cost, environmental impacts, flexibility, etc). The study was based on the assumption that additional 250 Mm^3/year of water would need to be supplied to the Cape Town Metropolitan area by the year 2030. Water transport by tankers was found to be the quickest and cheapest option (at US$2.45/$m^3$) but a fleet of 40 to 50 tankers would be needed to supply the total additional volume required. The water bag option was marginally higher in cost (US$2.70/$m^3$), but would require a fleet of some 250 tugs, and was therefore unlikely to be feasible. The pipeline option was the most expensive (US$5.30/$m^3$), but was considered to have the least environmental impact (only during the construction phase). The first two options were also likely to be associated with pollution by fuel spills, as well as disturbance of Congo delta flora and fauna. The reliability of the pipeline and tanker options for water supply was considered to be high, although extreme weather conditions could cause delays to tanker shipping schedules and congestion at Cape Town harbor. The reliability of a water bag option was found to be uncertain particularly during bad weather conditions. In cost terms, however, all three options were much more expensive then desalination of seawater, which could be obtained at a price of about US$1/$m^3$.

While the wide variety of ideas to utilize water from the Congo River slowly gain credibility, they still remain an interesting engineering and political challenge. Further development of these ideas and evaluation of their technical, economic, and environmental feasibility would be required before choices can be made. The most attractive options would appear to be some form of a multi-purpose project, where water supply options are combined with hydropower generation. If this type of scheme were ever to be implemented, it could effectively change the entire economic status of the SADC region and would represent the largest and most ambitious water resources development scheme in Africa in the 21st century.

The Issue of "Virtual Water"

The reliance on structural water resources development projects in SADC region may not necessarily be the only approach to alleviate water scarcity. Some of the alternative thinking focuses on the concept of "virtual water" that was originally suggested by Allan (1996). Virtual water represents the volume of water that is necessary to produce a unit of product (agricultural, industrial or other) or a service. According to Allan (1996), it takes roughly 1,000 tonnes of water to grow 1 tonne of grain and similar values of water consumption, or water equivalents, can be computed for every other product. Turton (1997) also refers to the virtual water that is present in hydroelectric power and suggests that this can be compared to the water usage by conventional (thermal) power stations and used as a basis for assessing the "water costs" of the energy consumed by society.

Allan (1996) has also suggested that water shortages within a particular country may be averted or postponed if the country is able to purchase water-intensive agricultural products, such as grain, from major grain-producing states such as Canada or the USA and thereby re-direct the water-short economy away from a policy of "food security," towards a policy of "economic security." However, it is important to remember that in order to do this, the country concerned must have the economic ability to purchase the "product" required. If water is re-directed away from a specific crop or product and that crop or product is imported instead, then the financial return on the "re-directed" water must be at least equal to the cost of importing the crop or product.

One important implication of the virtual water concept to the SADC region is that the water policies and strategies of individual sovereign states would need to be harmonized in order to achieve the maximum possible benefit within the context of a regional economy. Turton (1997) and Barta (1999) have suggested that full application of the concept of virtual water could help to solve the looming water scarcity problems of the SADC region. However, as indicated above, this would only be possible if it was adopted as part of a cohesive regional development strategy. It would not be sufficient if only one or two countries adopted this approach. At this time, no detailed study has been conducted on the implications of this approach to the different countries in the SADC region. Given the varying levels of political stability and the relatively strong tendency to maintain territorial sovereignty and resource (water, energy, food) security that characterize several SADC countries, this concept could only be introduced and managed effectively if all SADC countries develop and maintain a strong regional inter-dependence and identity.

In summary, virtual water can simply be considered as another form of international water sharing, where an important part of the value of the goods that are exchanged lies in their "water equivalence," or the quantity of water used in their production. If this approach is adopted, it will encourage new and innovative forms of water accounting where society can more fully understand the implications of their patterns of consumption in water terms. In turn, this will raise public awareness of, and support for, the need for national water demand management strategies and water conservation efforts.

New Developments in Groundwater Supply

Deep Groundwater as an Additional Water Resource Similar to surface water, groundwater supplies in South Africa are relatively limited and below world averages. In 90 percent of the surface area of South Africa, groundwater occurs in fractured hard-rock secondary aquifers (Vegter, 1995). Primary aquifers occur mostly in the unconsolidated sediments of Quaternary and Tertiary age located along the coastal areas, shallow alluvial deposits, gravels in riverbeds, and the inland Kalahari beds. The maximum thickness of these partially saturated formations is of the order of 150 meters. Therefore, over most of South Africa, groundwater exploitation is confined mainly to fractured hard rock systems and from relatively shallow depths.

Different assessments of the groundwater resources of South Africa (based on the condition that the maximum volume of water that can be abstracted from aquifers on a continuous basis is limited to their recharge) have concluded that the groundwater resources of the country are between 16,000 and 37,000 Mm^3 (Commission of Inquiry, 1970). Vegter (1984a) estimated that the maximum sustainable volume of groundwater that could be abstracted from South African aquifers is approximately 5,000 Mm3/year, while the groundwater contribution to total water use in South Africa was some 1,800 Mm3/year. This apparently low contribution is, however, a somewhat skewed representation if one considers that well over 250 smaller towns and villages, and most of the country's farms, are almost totally dependent on groundwater supplies (DWAF, 1986). At present, many South African aquifers are already subjected to high abstraction rates and some are overexploited. All groundwater estimates, however, apparently contain a great degree of uncertainty and will continue to remain a subject for heated debate in South Africa.

The estimates of available groundwater do not normally include the groundwater that is contained in deep geological formations. Some recent studies illustrate that the bulk of the readily accessible and exploitable groundwater in different parts of the country occurs at depths between 15 and 85 meters (Vegter, 1995; 1999). These results, however, do not mean that no water will be found at greater depths. The occurrence of a large number of thermal springs (Kent, 1949; Vegter, 1995) provides a clear indication of deep circulation, and hence the presence of groundwater at great depths. Many cases of groundwater occurrence have been reported by drilling contractors at depths of more than 200 meters, and during the land oil exploration program of the 1960s and 1970s, groundwater (although often brackish) was frequently found at even greater depths (Rowsell and de Swart, 1976).

Further support for the presence of deep groundwater in South Africa is provided by the enormous problems experienced by many deep (>1,000 meters) gold, platinum, and other mines with excess water when mining processes intersect with fault planes, fissures, joints, and different geological formations. The more than 1,000 m thick dolomitic sequence in the Gauteng Province constitutes one of the most important groundwater reserves in South Africa and overlays the economically important gold bearing Witwatersrand deposits. These dolomite formations are divided into compartments by a number of almost impervious dykes (Wolmarans and Guise-Brown, 1978) and have a large water holding capacity that poses great risks for the deep gold mines. Under natural conditions, a total of about 0.15 Mm^3/day of deep groundwater has been recorded as emerging from natural springs in five dolomitic compartments associated with four adjacent gold mines. To reduce the risk to mining operations, several of these compartments had to be systematically dewatered and a total of 2 Mm^3 of deep groundwater was pumped from the four gold mines over a period of approximately three months. The present rate of pumping is about 40 Mm^3/year. These statistics illustrate the potential of deep groundwater stored in the dolomite formations of Gauteng Province.

Enslin and Kriel (1967) first proposed the idea of utilizing the large capacity of the dolomitic groundwater compartments in conjunction with dams in the Vaal River and operating the latter on a basis of variable draft to increase the efficiency of water use. The 1983 drought caused severe water shortages in the Vaal River catchment and inspired the national Department of Water Affairs to initiate a major investigation aimed at the utilization of deep dolomitic groundwater as an emergency water supply. These investigations revealed the volume of groundwater held in dolomitic rocks to be in the order of 12,000 Mm^3 of which 1,000 Mm^3 could be safely abstracted if the recharge occurred at an average rate of about 270 Mm^3/year (Vegter, 1984b). This recharge, regarded as the assured yield, was equivalent to almost 30 percent of the total volume of water supplied each year by the Rand Water Board (which supplies water to most of the Gauteng Province). However, the exploitation of these groundwater resources at such high rates would require the establishment of an extensive infrastructure of about 170 boreholes operating at some 50 liters/second.

Despite the presence of significant quantities of deep groundwater that can be considered as an important additional water resource, mining poses a serious threat to the quality of the groundwater once mining operations are stopped and groundwater levels are allowed to return to pre-mining conditions. The presence of sulphide-bearing minerals and radioactive isotopes of uranium and thorium associated with the gold-bearing Witwatersrand rocks results in the generation of acidic mine water and contamination by radioactivity.

Extensive deep groundwater reserves have been reported in the secondary aquifer associated with Table Mountain Group (TMG) rocks in the southern and western parts of the Western Cape Province. Rosewarne (1998) quoted groundwater storage estimates of 50,000 Mm^3 for this aquifer with annual recharge figures as high as 2,000 Mm^3. This volume is four times larger than the total annual water use in Cape Town at present. However, a more detailed study of a section of this aquifer system reported a much lower annual recharge figure of 260 Mm^3 (Hay, 1998). The debate around the exploitation potential of the deep flowing aquifer system of the Table Mountain Group quartzite around Cape Town continues unabated. Umvoto Africa (2000) presents evidence that the >1,000 m thick TMG can extend for up to 3,000 m below seal level in the area, north of Cape Town. Weaver and Talma (2000) suggest that the total volume of water in storage, within a radius of 200 km from Cape Town, could be as much as 66,000 Mm^3 with an annual recharge of about 2,600 Mm^3/year. According to these recharge estimates, the total deepwater storage in this formation alone may therefore exceed the entire surface water resources of South Africa and the estimated recharge volume is about five times higher than the present total annual water consumption of Cape Town. If true, this hypothesis has enormous implications for water supply to Cape Town and for the whole of the country. However, the considerable scepticism that surrounds these estimates cannot be ignored and more research is needed to prove the realism of such studies.

For example, with the suggested high annual recharge rate, the question arises as to where is the natural discharge area for the aquifer? Two possible and logical scenarios are: the aquifer constantly discharges through springs and eventually into the river systems of the Western Cape or, secondly, groundwater is released through deep circulation into the near-shore ocean around Cape Town. If discharge occurs into the near-shore ocean zone, the exploitation of TMG aquifer is likely to have important implications for the functioning of coastal ecosystems and their associated fisheries.

Preliminary estimates indicate that the total river baseflow in the Western Cape may be in the range of 1,000 to 1,300 Mm^3/year. Consequently, about half of the reported annual recharge may already be effectively exploited as part of the surface water resources in the Province. It is essential to calculate a realistic groundwater balance for the area based on all available information, identify possible flow mechanisms, groundwater flow paths and decant areas, and determine the likely residence time for groundwater. Other aspects that should be investigated are practical exploitation options, sustainability of the aquifer to large-scale abstraction and the basic concepts of integrating the groundwater and surface water resources. A handbook summarizing the current state of knowledge of the TMG aquifers, identifying deficiencies and research priorities is currently being compiled.

Boreholes with sustainable yields of over 50 liters/second have been recorded in recent years in the fractured quartzite aquifer of the TMG where groundwater was struck at depths in excess of 200 meters. However, detailed investigations and mapping of the structural geological conditions as part of hydrogeological assessment are essential in the selection of deep drilling targets. Individual high-yielding target zones at depths of a few hundred meters are typically less than one meter wide (according to the present knowledge), which constitutes a high risk for the exploration programs. Drilling costs in quartzite are also high and can reach US$50 per meter. An additional factor to consider in deep groundwater exploitation is that deep boreholes should be relatively easily to link to existing bulk water infrastructure so that the infra-structural cost penalty of remote boreholes can be avoided.

Serious concerns have also been expressed about the potential negative impact that deep groundwater abstractions may have on springs and natural vegetation (Le Maitre *et al*., 2000). These concerns highlight the need for extensive investigations of deep aquifer systems in order to understand the occurrence and recharge mechanism properly before any large abstraction schemes are contemplated or implemented.

Artificial Recharge

Shallow or near-surface groundwater resources can be replenished or enhanced by capturing surplus water and artificially recharging this into an aquifer. Theoretically, this process could double the natural recharge in some cases and increase the amount of water available for abstraction. Groundwater can be recharged via surface infiltration or by injecting water directly into the aquifer through recharge boreholes. Higher rates of recharge can be achieved by means of pressurized injection through boreholes than by surface infiltration (Murray and Tredoux, 1998).

Artificial recharge has gained acceptance world-wide as an effective method of conserving water for future use, for improving water quality, for averting saline water intrusion, etc. However, several factors need to be considered before embarking on artificial recharge schemes. These include the chemical character of the recharge water and the natural groundwater, the chemical reactions that may occur between the recharge water and the aquifer host rock, the clogging potential of the borehole infrastructure, water recovery efficiency, as well as social and legal issues. Also, the potential for artificial recharge in South Africa and the rest of southern Africa is determined by two main factors: the availability of raw water for recharge and the ability of the aquifer to physically receive surplus water (Murray and Tredoux, 1998).

Artificial recharge is a relatively new concept for Southern African geohydrology. Only a few full-scale applications have been tested to date, but these have proved the viability of the technique. A form of artificial recharge has been practiced at the town of Atlantis, north of Cape Town, where the alluvial aquifer has for many years been successfully recharged with purified municipal wastewater and storm water runoff (Murray and Tredoux, 1998). Pilot studies on artificial recharge have recently been carried out in Windhoek (Namibia), Maun (Botswana), and Karkams (South Africa). The focus has been primarily on artificially recharging hard rock, fractured aquifers, of which Windhoek and Karkams are good examples.

Windhoek, the capital of Namibia with a population in excess of 200,000, is underlain by a fractured quartzitic aquifer that is highly permeable and has been used as a water source by the municipality since the beginning of the 20th century. The aquifer is, however, vulnerable to over-pumping. Water levels in the aquifer dropped by tens of meters after several years of high abstraction rates and it took about five years for the aquifer to recover to its original levels. The aims of artificially recharging the Windhoek aquifer are to rapidly replenish it after periods of excessive pumping and also to minimize evaporation losses from water storage dams that supply the water for artificial recharge. Four artificial recharge tests have been conducted where treated surface water was injected via deep boreholes into the most permeable parts of the aquifer. The longest test lasted 195 days and the total injected volume of water was 289,000 m^3. The high injection rates (up to 60 liters/second) achieved in these tests are very encouraging and confirm the feasibility of a full-scale artificial recharge scheme.

Karkams is a small village in the arid western part of South Africa where 2,000 people depend entirely on groundwater supplies that are highly vulnerable to overexploitation. The fractured granitic aquifer in this region is of low permeability and porosity, and natural recharge is estimated to be less than 3 mm/year. The artificial recharge scheme aims to rapidly replenish the aquifer by diverting erratic surface runoff into boreholes. The surface water is fed through a slow sand filter prior to entering the boreholes to remove particulate material. Given the low permeability of the aquifer, the highest injection rates that could be achieved were of 2 liters/second. After rainfall events, and with a larger number of injection boreholes, it may be possible to inject up to 500 m^3/day into this highly vulnerable aquifer. If such levels of injection are achieved, this artificial recharge scheme could provide the answer to the persistent water problems faced by this remote rural village (Murray and Tredoux, 1998).

In summary, artificial recharge is considered as an important measure to increase the reliability of water supply at the local level.

Atmospheric Moisture Harvesting

Rainfall Enhancement

All water supply options considered so far have dealt mostly with the water which is already in a river catchment, either in a stream or in a an aquifer. However, there are also several possibilities to utilize atmospheric moisture, or to increase the yields of river catchments through the intensification of hydrometeorological processes. One such option is rainfall enhancement. Rainfall enhancement can be achieved via cloud seeding through stimulating natural precipitation processes by injecting nucleatic agents, either glaciogenic material such as dry ice and silver iodide or hygroscopic material such as sodium chloride, into clouds. However, the results of cloud seeding experiments that have been carried out in many parts of the world during the 1960s to the 1980s remain largely inconclusive. In some tests, cloud seeding appeared to enhance rainfall, but appeared to have no effect in other tests. Due to these contradictions and the uncertainty concerning matters of measurements against the large natural variability in nature, funding for cloud seeding projects has been very variable. However, with the development of new cloud seeding techniques, new instrumentation and statistical techniques to monitor and verify results, and the intention to increase agricultural production while positively affecting, for example, under groundwater reserves, the interest in rainfall enhancement has always remained afloat. According to the World Meteorological Organization, several countries currently carry out more than 100 weather modification projects, particularly in arid and semi-arid regions of the world. Because of predictions that two-thirds of the world population will live under water stress by 2025, there is a renewed interest in rainfall enhancement and a more thorough scrutiny of previous results (Bruintjes, 1999).

South Africa is considered to be an international leader in the field of rainfall enhancement research and cloud seeding experiments have been carried out for over 25 years. The experiments were initially practiced in the summer rainfall region of South Africa, centered on the towns of Bethlehem in the northeastern Free State Province and Nelspruit in Mpumalanga. These two projects combined in 1990 to form the National Precipitation Research Programme (NPRP). Observations of efficient rain-forming processes in clouds developing over a paper mill have indicated that the emissions from this mill, in the form of fine hygroscopic particles, promoted water droplets to grow faster through condensation and to coalesce faster and in greater number (Mather, 1991). This discovery prompted the South African development of a new cloud seeding technique for rainfall enhancement, hygroscopic seeding using pyrotechnic flares, carried on aircraft and electrically ignited at cloud base in the updraft regions of convective clouds (Mather and Terblanche, 1994). The method differs from the original glaciogenic seeding techniques using dry ice and silver iodide as seeding agents to convert super cooled water to ice in the colder parts of clouds. Between 1991 and 1996, a randomized seeding experiment involving 127 individual convective storms were conducted in South Africa and their radar-derived properties were studied (Mather *et al*., 1997). The seeded group of convective storms on average produced about 20 percent more rain than their natural (unseeded) counterparts with high levels of statistical significance ($P < 0.05$). These results were supported by in-cloud observations and numerical modeling studies (Cooper *et al*., 1997).

From 1997, an experiment modeled on that conducted in South Africa, and using the same seeding flares and pilots for seeding, was undertaken in Mexico under the scientific guidance of the United States National Center for Atmospheric Research (NCAR). The results of this experiment replicated those from South Africa, a rare occurrence in the field of weather modification (Bruintjes *et al*., 1999). Although encouraging and intriguing, some of the physical processes responsible for the seeding effect are not fully understood and this is now being addressed through international research cooperation (WMO, 2000).

These previous experiments all involved single storms and the next step was to test the ability of the new cloud seeding technology in the context of augmentation of water resources over an area. This involved the planning and execution of a pilot operational area seeding experiment, which was first carried out in the Northern Province around the town of Tzaneen in 1995 to 1996 (Terblanche *et al*., in press), and which in 1997 evolved into the South African Rainfall Enhancement Programme (SAREP). In this experiment, all suitable clouds that could be reached with the available infrastructure (seeding aircraft, etc.) were seeded. The development of the techniques for evaluating an operational (as opposed to an experimental) cloud seeding project became paramount as were the inclusion of economic studies of the possible hydrological and agricultural benefits. These studies are ongoing and apart from the consistency of results at storm scale, favorable economic projections and more precise indications of the required logistics and infrastructure, a proven, area-wide rainfall enhancement technology is still not available.

In an internal report to the SAREP funding agencies, Görgens and Terblanche (2000) indicated that the cost of increased rainfall through rainfall enhancement is relatively low at around US\$0.01/m^3. However, the quantities of surplus rainfall obtained during this experiment, using the available infrastructure, have also been relatively small. The theoretical studies reported included results from a daily soil-moisture-budget model. This model was applied in high detail, and under simulated operational cloud-seeding conditions, to two representative pilot catchments that together constituted about 14 percent of the target area of 10,000 km^2. Operational conditions were viewed as either "pessimistic" (only 60 percent of all seedable storms utilized) or “optimistic” (95 percent of all seedable storms utilized). A realistic seeding effect, based on previous South African results, was applied in order to obtain areal effects. The results showed potential “average year” benefits to Mean Annual Runoff, Dryland Maize Yield, Dryland Grazing Yield, and Timber Yield per Rotation that, in monetary terms, might far exceed the running costs of a fully operational program.

In general, rainfall enhancement is a capitally and technologically intensive process and, despite recent advances that hold great promise, some facets require further research and development. For example, no investigation has been carried out in South Africa on environmental issues such as possible extra area effects or the potential changes in soil erosion processes, habitat integrity, and bio-diversity that could be caused by increased rainfall.

Fog Water Collection

Fog water collection is another possibility for small-scale water supplies. Despite the fact that fog is usually considered to be a hazard, fog water represents the only source of water for many animals and plants in arid regions and has been passively collected by people living in these areas since ancient times. Fog water collection systems are relatively cheap, easy to install and maintain, environmentally friendly and do not require external energy sources. The research on fog water and fog water harvesting has been extensive and examples of successful fog collection projects in small rural communities (e.g., in Chile) have been reported (Schemenauer and Cereceda, 1994; Cereceda *et al*., 1996). The potential of fog water as a primary source of water supply for rural communities in Namibia has also been investigated (Seely and Henschel, 2000). The frequent occurrence of fog in several regions of southern Africa and the extreme water poverty of large numbers of people prompted the South African Fog Water Collection Project, which lasted from 1993 to 1997 and was carried out by the Universities of Pretoria, the North and Stellenbosh (Olivier, 1997; Olivier and van Heerden, 1999).

Among other features, the project included the identification of areas with high fog water potential, erection of pilot-scale fog collectors to quantify the volume of fog water available, the design of an efficient fog collection system, and assessment of the feasibility of its implementation. The study focused primarily on the West Coast and the mountainous regions of the Northern Province, Mpumalanga, and the Western Cape, where the fog incidence is high and where rural inhabitants regularly experience severe water shortages.

The study demonstrated that mean daily fog water collection rates vary at different pilot collection sites in the range of 1.3 to 12.2 liters/day per square meter of collecting surface, but could be increased to 20 litres/day/m^2 at some sites by manipulating the height of fog water collectors. It has been demonstrated that the differences in water collecting capacity of the sites may be ascribed to differences in their elevation, and that sites with an elevation of greater than 1,000 meters may represent potential water collection points.

The fog collection structure designed by the University of Pretoria consists of a 72 m2 screen supported by three wooden poles. The cost of the fog collector amounts to US$880 (excluding the costs of labor and water tanks), which converts to around US$12.2/$m^2$. Two such fog water collection systems have been erected in South Africa, one in the Soutpansberg Mountains of Northern Province near Thohoyandou and the other near Bitterfontein on the West Coast. Maximum daily yields in excess of 3,500 liters were obtained at both sites. The average daily yield was approximately 3.2 litre/m^2 of collecting surface. This amounts to 84m^3/ year. The quality of the water is particularly high in the mountainous regions, with that of the coastal sites containing low concentrations of sodium, chloride, and bicarbonate ions. The cost of the fog water itself depends on the period over which the calculation is performed. It is anticipated that a fog collection structure will function for at least 30 years. Assuming the screen has to be replaced three times during this period, the cost of water will amount to US$0.43/$m^3$. Over the period of 50 years it will however fall below US$0.37/$m^3$.

The feasibility of a large-scale fog water collection system depends upon the availability of sufficient amounts of water as fog, the proximity of a water-poor community, and the cost of implementing the system. These analyses should be site-specific. However, the primary output of the Fog Water Collection Project is that relatively large volumes of water can be harvested from fog in regions with favourable meteorological characteristics and that these volumes may be sufficient to supplement more conventional water supplies at remote sites where acute water shortages occur.

Iceberg Water Utilization

A significant increase in non-conventional water availability, particularly for coastal urban centers in southern Africa, could be achieved by towing icebergs close to the continent, or transporting water by tankers. The idea of using iceberg water to augment water supply is not new. The first papers on this subject date as far back as the beginning of 1970s (Weeks and Campbell, 1973). The feasibility of iceberg utilization for fresh water supply specifically in the context of South Africa was investigated by DeMarle (1979, 1980), who suggested the construction of an iceberg processing plant at Saldanha Bay on the West Coast and performed functional analysis of required operations together with the associated costs. The issue of towing Antarctic icebergs was again investigated in the late 1970s and early 1980s by Job (1978) and Mellor (1980). A review of existing perceptions regarding the utilization of iceberg water has also been presented by Husseiny (1978). The detailed analysis of many aspects related to moving bulk quantities of ice water from Alaska to southwestern states of the USA, Mexico, and Pacific Rim countries using marine transport has been done by Davidge (1994).

The range of issues and problems associated with iceberg water harvesting extends from an understanding of the contributory natural driving forces, ocean currents and winds, to melting kinetics, options of iceberg processing, costs, environmental impacts, and legal aspects at national and international levels. Jordaan (2000) recently reviewed the current status of information on iceberg water harvesting possibilities and examined the prospects of this water source for Namibia (the major points made in this source are relevant to South African situation as well). It was indicated that the range of technologies for the full cycle of iceberg harvesting process are not yet properly developed and that a "four-month (iceberg) journey, over five thousand nautical miles having to be traversed, under extreme weather conditions and sea states, with the associated losses due to meltdown, appears a formidable obstacle to be overcome" (Jordean, 2000). Finally the demand for water in Namibia seems to be too small to consider undertaking an iceberg-towing project and the value of the harvested water is too small compared to the costs of obtaining the raw ice from Antarctica. The cost estimates however were not explicitly supplied.

While the Namibian study certainly has very strong arguments, the technological advancements of the last decades may provide new insights into the feasibility of iceberg water harvesting. The Iceberg Water Harvesting Group (IWHG), formed in Munich in 1998, is convinced that the time has come to undertake all possible practical efforts to evaluate and make use of untapped iceberg water potential. One of the major technical challenges in using iceberg water is the problem of how to direct a suitable iceberg to its final destination. The IWHG suggests that icebergs should be steered rather then towed and has developed the theory of kinematics of iceberg drift, based on the earlier work of Epstein (1921) on the drift of continental plates. A full analysis of this theory would require a specialist's insight and is beyond the scope of this paper, but the details are available directly from the IWHG.

The IWHG has developed software that optimizes the routing for individual icebergs and includes rough melting kinetics. The software allows each possible iceberg route to be simulated subject to the following constraints: minimization of energy input for tugs, minimization of travelling time, and maximization of the ice mass at the destination site. Sea currents are also taken into consideration, but in directing icebergs to South Africa, the major currents flow in an easterly direction and can be used as a supporting factor. Nevertheless, the issues of water loss en route due to melting and sublimation will be extremely difficult to overcome.

In practice, the Iceberg Water Project should start with the detection of a suitable iceberg, and satellite image processing can be used to define the shape and size of suitable icebergs. In order to steer an iceberg in a specific direction, the optimum shape would be ship-like. With regard to the size of a suitable iceberg, several requirements must be met: The iceberg must survive the natural melting during its voyage of about six months through progressively warmer waters, while being exposed to extremely strong winds that enhance sublimation from the iceberg surface, and must deliver a volume of water that would satisfy the needs at the destination site for a reasonable period of time. An additional consideration would be the negative impacts of oil pollution in Antarctic seas (related to frequent boat trips) that would have to be avoided. Under these conditions, it is suggested that this period should be in the range of twelve months. The volume of iceberg must be calculated so that it includes all the losses during the transport and utilization phases. Once the losses are estimated and there should be no need to pack the transported icebergs in foil or to protect them otherwise, for example by coating with a reflective layer. However, these calculations are still highly speculative and will require careful investigation. In particular, the estimates of melting rates and sublimation losses will need to be carefully quantified for different iceberg sizes, as well as for different travel trajectories and durations.

An iceberg fulfilling the typical requirements listed above is estimated to measure some 250 to 300 meters in height. Given the fact that slightly less than 14 percent of a floating iceberg is visible above sea level, the submerged part of the iceberg would be over 200 meters deep. This implies that the final (South African) destination of the iceberg must be an offshore location (500 to 1,000 meters from the coast). The near-shore continental shelf of South Africa is unlikely to have in-shore basins that offer sufficient water depths to accommodate icebergs of that size; however, the selection of potential sites, would need to be verified with regard to the location of demand centers.

To direct tabular icebergs, the use of tugboats is considered, but the problem of connecting an iceberg to a tugboat has not yet been resolved. There are also additional difficulties associated with stabilizing an iceberg during its voyage when, presumably, melting and sublimation losses are progressing. According to IWHG, several patents, which deal with problems of fastening and stopping of large floating masses in the ocean, have been recently suggested. The relevance of these inventions to the problem of iceberg transport needs to be evaluated.

While options for conversion of icebergs into water at the final destination are theoretically available, none has been explored in detail to date. Once at the near-shore location, the iceberg becomes continuously exposed to external temperatures of greater than 10 degrees (water) and often greater than 25 degrees (air). The challenge is therefore how the melt water may be preserved and used beneficially and at what cost?

To transfer the iceberg water to the land from its offshore location, either pipelines or tankers may be used (similar technologies are used at oil platforms). Icebergs are perceived as a source of the cleanest water, but the vulnerability of icebergs to oil pollution as well as to pollution from ocean outfall discharges of sewage along the South African coastline should not be ignored. Consequently, some treatment of iceberg water before use may still be required.

The attempts to evaluate the cost of iceberg water are extremely speculative at this stage because the details of technologies associated with iceberg harvesting are not available and the infrastructure at the destination sites is neither well known nor is it yet available. The components of cost calculations will definitely include towing, iceberg detection and route tracking, transportation, operation and maintenance at destination ports, minimization of pollution losses, minimization of sublimation losses, prevention of hazards to shipping using the busy Cape sea route, construction and operation of the shore based “offloading” facility, and construction and operation of a suitable storage facility for the meltwater. Against this background, it is also clear that extremely large investments will have to be made to properly research the development of docking technologies, melting technologies etc. The preliminary calculations made by the IWHG using the expected profit approach, suggest that if iceberg water is sold to potential consumers at a competitive price of US$0.50/$m^3$, and is to satisfy an annual demand of approximately 2,000 Mm^3, a total amount of US$500 M will need to be invested over five years to have the complete iceberg harvesting technology in place. For comparison, the investments required for the design and production of a new car amount to approximately US$500 to US$1,500 M (BMW, 2000) with a cycle of five to seven years.

In theory, icebergs represent a continually renewable supply of high-quality water that is available in large quantities. However, the question as to whether or not iceberg harvesting is likely to have any detrimental effects on the marine or other environments has not been satisfactorily resolved. In particular, it is possible that the cooling effects of melting iceberg material in near-shore coastal waters could cause a dramatic decline in local water temperatures with probable associated adverse effects on sensitive marine organisms in this zone. The scale of any impacts would clearly depend on the extent and duration of the cooling effects, as well as the degree of sensitivity to low temperatures shown by the marine organisms concerned.

It is possible that an iceberg-harvesting project could have extensive synergies in fields of development assistance and international collaboration. In fact, the level of current technological development associated with this alternative is such that no progress is likely to be achieved without international cooperation in this field. Until the first iceberg is brought ashore and is utilized for drinking water supply, and the cost-effectiveness or other advantages of this option are clearly demonstrated, the issue of iceberg water harvesting will remain an ambitious engineering challenge.

Seawater Use

Desalination

Seawater represents another theoretically unlimited water resource, particularly for coastal areas, if it can be desalinated before use. Several technologies are available to desalt water, and the most important of these include distillation and reverse osmosis (RO). Distillation removes fresh water, leaving behind concentrated brine. The process involves boiling the saline sea water at atmospheric or reduced pressure and condensing the vapor as fresh water. Reverse osmosis is a process in which specific membranes are used to separate salts from fresh water. It relies on the tendency for fresh water to diffuse through a semi-permeable membrane into a salt solution under the impact of osmotic pressure, thereby diluting the more saline water. By applying pressure to saline water on one side of a semi-permeable membrane, fresh water can be driven through in the direction opposite to that of the osmotic flow (hence the term “reverse osmosis”). One conspicuous advantages of RO is that it relies on a lower energy consumption compared to most other technologies.

According to some sources (e.g., Mielke, 1999), there are approximately 4,000 desalination plants in 120 countries worldwide at present with a combined capacity of over 5,750 Mm^3/year. About 60 percent of this capacity is concentrated in the Middle East. In southern Africa, the practical implementation of desalination technologies has proceeded slowly. The constraints that preclude installation of large desalination systems include the consideration of costs and the fact that seawater along the southern African coastline contains high concentrations of plankton that rapidly clog the membranes. However, the chemical and petro-chemical industries in South Africa have installed a variety of small desalination plants that are capable of producing between 5 and 45 m^3 of freshwater per day. The capital cost of these plants ranges from US$0.16 to US$1.9 Million, respectively, at current prices (Barta, 1999).

The desalination option may in fact be perceived as a competitor to other unconventional unlimited water supplies such as iceberg water (DeMarle, 1980; Davidge, 1994) because the relevant technologies are much better developed and they are already in use in many areas of the world. It is often indicated, however, that desalination has a number of disadvantages which include, among the others, high energy consumption, a large stream containing waste brine and processed chemicals that is difficult to dispose of, incomplete removal of dissolved salts, occupation of land in coastal zones, etc. Nevertheless, recent advances in desalination technologies have made them practically feasible in the context of water supply for many countries, including South Africa. These technologies are unlikely to produce adverse social reaction, the risk of contamination is lower compared to, for example, treated effluents, and the costs are lower than or similar to other options. In several cases, there may just not be a better option available.

One successful example of the use of desalination technology for municipal water supply exists in the Eastern Cape Province of South Africa, where a recently-constructed desalination plant with a capacity of 400 m^3/day supplies water to the small holiday resort and town of Kenton-on-Sea (Tucker and Kritzinger, 1998). This town experienced a lack of assured water supplies for a long time and various water supply options were considered (utilization of additional groundwater resources, surface water storage, etc). Seawater desalination was eventually selected as being the most feasible, on the grounds of comparatively low capital costs and high assurance of supply.

The Kenton-on-Sea plant uses advanced RO technology described in detail by Tucker and Kritzinger (1998). Seawater inflow for the plant is abstracted from three boreholes next to the Bushmans River. The brine effluent is returned directly to the river mouth and specialist studies have demonstrated that it has a negligible effect on the estuarine environment. The RO water complies with the existing South African drinking water quality standards. The total capital cost of the project was approximately US$340,000 and the unit cost of the water produced fluctuates in the wide range of US$0.5 to 7.0 /$m^3$ (Tucker and Kritzinger, 1998). Other available estimates of the costs of RO water, made in the context of delivering desalinated water to Cape Town, have a range of US$1.10 to 2.04 /$m^3$ (e.g. DWAF, 1992). The study undertaken in Namibia in 1996, which investigated the cost of water from several potential sources, indicated that desalination was the least expensive option available (DWA-KFW, 1996; Harris and Habenicht, 2000).

The Kenton-on-Sea project effectively represents the first successful use of the new desalination technology in South Africa and is also the first that has been used for municipal water supply. However, it also demonstrates that advances in desalination technology may be used successfully and beneficially to resolve water shortages. It is likely that the increasing demand for water and the reallocation of existing water resources according to sectoral and regional priorities will bring similar challenges for other coastal water services authorities to augment water resources by desalination of sea water for industrial and municipal water supply purposes.

Direct Seawater Use

Desalination is not the only way in which seawater could be beneficially utilized. Opportunities also exist (in all coastal towns and cities) for direct use of seawater, for example as a substitute for freshwater for toilet flushing and limited industrial use, where salinity poses no risk to the user. This would permit better utilization of freshwater resources especially where treated/untreated effluents are discharged to sea. Similar schemes have successfully been implemented in Hong Kong, resulting in savings of 18 to 20 percent in freshwater use (Rajyalakshim, 1999). With the development and use of new materials in conveyance systems, the risks of corrosion associated with the direct use of seawater may be considerably reduced. The substitution of seawater for potable water use in selected water use sectors in coastal cities will permit municipalities to extend their potable water systems to serve more people. The real issue is the cost of developing this alternative compared to other supply options (e.g., dams and associated extended conveyance and treatment systems). Sinking a well point on the beach to obtain filtered seawater, chlorinating it to reduce the risk of biofouling, and distributing it in a dual reticulation system could prove to be cost effective. Unfortunately, the possibility of direct use of seawater has received no attention in South Africa to date.

Reuse of Wastewater

Reuse of treated effluent is not necessarily an unconventional or even an independent water supply option and should be viewed rather as a water demand management or water conservation option that can increase the effectiveness of water use within existing water supply or industrial systems. While wastewater reuse continues to attract increasing attention in South Africa and deserves special mention, the volume of wastewater reused at present is low and was estimated to be less than 30 Mm^3 (in 1998). This represents less than three percent of the total volume of wastewater that requires treatment (Gerber, 1997; Grobicki, 2000) and indicates a great potential for growth in re-use of treated effluents. The level of water reuse in South Africa is also low compared to some other regions (e.g., Florida, USA reuses 657 Mm^3/year, Grobicki, 2000). Despite the generally low absolute figures of water reuse in the rest of southern Africa, the relevant reuse volumes may sometimes be significant. For example, over 20 percent of the potable water demand in Windhoek, Namibia, is satisfied from sewage, which is treated to drinking water standards.

In the past, the direct re-use of effluents was not encouraged in South Africa. The treated effluents were to be returned into the catchments from which the water was initially abstracted. This effectively promoted the concept of indirect recycling where the self-purification and dilution capacity of the receiving streams would ensure an adequate and sustained supply of high quality water. The limitations of the ability of self-purification to cope with increasing waste loads, thereby leading to increasing salinisation of natural water bodies, is now well recognized. A number of treatment systems have been developed to treat discharges, primarily from the mining industry, to address the salinity problem. However, none of these result in a net increase in the available water, as these effluents are currently being discharged into the environment. At the same time, they are likely to result in brines, which still have to be managed in an environmentally acceptable manner.

Where water recovery and reuse is practiced in South Africa, it is largely restricted to the irrigation of sports fields and provision of supplementary supplies to power stations for cooling water. The recent construction of a wastewater treatment plant in Durban (KwaZulu-Natal Province) allowed high quality water from treated domestic effluent to be supplied to high-volume water consuming industries. This project is estimated to save over 17 Mm^3/year of potable water and enables the Durban Metropolitan Council to delay further capital investments to augment water supplies by at least five years. In turn, this then allows them to reallocate saved water resources to meet other pressing needs.

One of the major current initiatives related specifically to mine water treatment is known as the Amanzi project. The project deals with the treatment of up to 87.7 Mm^3 of water per annum and represents the combined efforts of several mines in the Gauteng Province. Another initiative deals with polluted mine water in the upper Olifants River catchment in Mpumalanga Province (estimated volume of up to 47.5 Mm^3 per annually) that is currently discharged into public streams. These examples illustrate a trend towards more efficient use of various effluents in the country. However, there is as yet no specific national policy framework for water reuse and it is being implemented only where local opportunities arise.

Managing Water Demand

While a number of alternative unconventional water sources and new technologies are theoretically available, and some of these are under investigation as possible options for water supply in specific cases, it appears that none of them is able (at their present levels of technological development or due to the scale of associated operations and quantities involved) to resolve the short-term problems of escalating water scarcity in South Africa. While many of these alternatives are being developed, progressively more attention is being paid to ensuring the effectiveness and efficiency of water use within existing water supply systems. This emphasizes the importance of Water Demand Management (WDM) as an important option for “extending” the available water resources.

The importance of WDM may be clearly understood in the specific context of some water supply systems that have already reached a level of water scarcity and where the threat of water restrictions may become real in the near future. The Vaal River water supply system provides a good example of this type of situation. By the early 1970s, storage dams in the system were no longer able to deliver sufficient water to the supply centers and several large inter-basin transfer schemes were built. At present, the Vaal system includes six inter-basin transfer schemes that have either been developed over the last fifty years or are currently under development. The optimistic (reduced) future water demand projections for this system (e.g., Smakhtin *et al*., 2000) do not save the situation, because they come in combination with reduced estimates of the system yield. The recent update of the Vaal system yield analysis, based on an extended hydrological record and including the recent prolonged drought period (DWAF, 2000), provided a new estimate of yield that was 23 percent less than the previous best estimate (DWAF, 1996). Because of the drastic yield reduction provided by the new estimate, even the most optimistic projection of likely future water demands still results in a shortage of water in the Vaal System, and which will likely require the imposition of water restrictions, possibly from as early as 2005 to 2007 (Smakhtin *et al*., 2000). The delivery of water via new water transfer schemes under construction or design will only commence in 2010 (from the Thukela River) or 2014 (Lesotho Highlands Water Scheme). Consequently, there is a gap of some five years during which no additional water will be transferred to the Vaal system and the only alternative to water restrictions will be increased effectiveness of water use through the implementation of WDM measures. It must be noted that some most recent studies (DWAF, 2001) suggest a zero growth of water requirements in most of the Vaal River system. This implies that among the others, that water restrictions may not necessarily need to be a future management option, but does not exclude the necessity of WDM measures.

Potentially, the implementation of WDM strategies within the Vaal system could reduce water demand by approximately 15 percent under current water use patterns (DWAF, 1995). This potential “saving” represents the equivalent of about four years’ growth in demand. This may be sufficient to avoid the imposition of water restrictions before the new inter-basin transfer schemes start to deliver water. Water demand management can be achieved over shorter periods if its implementation starts at the right time, despite the fact that large capital investments would be required for certain water saving measures. Higher levels of water savings could be achieved if greater emphasis is placed on water quality management; more specifically, the quality of return flows to the Vaal system will have to be improved. Return flows constitute approximately 20 percent of the total system yield (e.g., Smakhtin *et al.*, 2000) and, at present, these have to be diluted by clean and expensive water to meet the downstream water quality objectives.

While the implementation of WDM measures in the Vaal System is still at the inception stage, the results of some case studies on the effectiveness of WDM from other regions of South Africa are revealing. For example, the introduction of WDM measures in Durban since 1997 has reduced the current water demand growth to zero. It is envisaged that this situation of zero growth in water demand can be maintained for another seven years. In addition, it has also been estimated that an additional reduction of up to 35 percent of the total water consumption is possible (Naidoo and Constantinides, 2000). The small coastal town of Hermanus provides another example of successful implementation of WDM (van der Linde, 1998). In 1996, the Hermanus Town Council implemented a 12-step water demand management strategy that included an intensive communication campaign, a wise water gardening campaign, identification of sources of water losses, an escalating tariff structure and an informative billing system, among the others (van der Linde, 1998; Ashton and Haasbroek, 2000). In combination, these measures reduced the per capita water consumption by 30 percent and increased the Hermanus Municipality’s revenues from water sales. (More recently, however, several households have experienced considerable difficulties as a result of deficiencies in management of the Hermanus WDM scheme and this has detracted from the successes achieved to date).

The examples above do not imply that WDM should be considered as a substitute for future water resources development, whether this is from conventional or unconventional sources, or from the installation of new technologies. However, WDM does represent one of the major national priorities and challenges in water management. Effective WDM does not necessarily rely only on technological innovation. Instead, it is based on good communication, in conjunction with the full acceptance by the general public that the proposed methods are both efficient and effective, while the implementing authority is legitimate (Ashton and Haasbroek, 2000). It is unfortunate that impending water restrictions are the usual drivers around the implementation of WDM measures. A far more convincing factor for investment in WDM is the increased recognition of the value of water in the light of its increased scarcity: A recognition that, in any system, leaks are the priority users and that inefficient water practices cost money, often a tab paid by for by everyone through cross-subsidization in the absence of appropriate WDM tools, like block rate tariff systems.

If implemented correctly, WDM can yield results in the short-term and provide a “breathing space” (in a water-scarce environment) for the development of new unconventional technologies, which are aimed at ensuring a longer-term solution for the problem of water shortages. However, WDM and indeed Water Conservation (WC) should not be viewed as a suite of temporary measures to delay conventional or unconventional supply-side options at best, or ease the discomfort of restrictions at worst. Such point of view would lend impetus to the school of thought that WC and WDM are add-on interventions. A more constructive perspective would be to address the possibility of WDM being a permanent and sustained cornerstone of a holistic water supply solution. Various WDM tools and measures should be used in varying degrees of intensity and investment (and in combination with different supply options) as part of an integrated plan that achieves system efficiency and effectiveness.

Conclusions

Table 1 below summarizes the information on some of the options for water supply in South Africa that have been considered in this paper. In some cases, only qualitative or even speculative information had to be used to characterize the alternative, because no data or limited data were available. The review of these options allows the following conclusions to be made.

The conventional water supply options that rely primarily on surface water utilization, water storage impoundments and inter-basin transfers within the national borders of South Africa have the potential to meet water needs for approximately another 30 years. Importantly, these options are facing increasing opposition from environmental and social sides. They are unlikely to constitute a sustainable, long-term water supply option for the country despite the fact that their effectiveness and, perhaps "environmental sensitivity," may be improved in some cases with innovative engineering approaches.

The country is literally running out of inexpensive water supply options. Inter-basin transfers will become progressively more expensive if water sources located more distantly from demand centers have to be developed. In general, water is becoming more difficult to obtain (whether it comes from conventional or unconventional sources) and consequently more expensive.

The technologies for effective utilization of some unconventional sources of water (fog and rain harvesting, desalination) have been developed, but have either not received wide recognition or have not reached the stage of large-scale implementation. Some of these technologies are capable of augmenting water supplies only at the local scale because of the additional expenses associated with transferring the water to other demand centers.

The technologies for other unconventional water sources, such as iceberg water harvesting, have not been developed to the point where they can be implemented practically. They attract continued attention but are also surrounded by high levels of skepticism due to the many unresolved technological problems, perceived high costs, and the apparent availability of other (cheaper or less technologically intensive) alternatives. A project of the scale required by iceberg harvesting seems to be able to succeed or at least to get off the ground, only if international cooperation (and funding) is assured. Despite this, there are still many practical problems that will be difficult to resolve; a case in point is the absence of suitable docking sites at in-shore areas near to demand centers.

The "least limited" naturally available water supplies (icebergs, seawater) have effectively not been tapped in South Africa. Indeed, iceberg water has not been tapped anywhere in the world. These two sources perhaps contain the ultimate solution to the water scarcity problem of many countries. However, given the level of technological advancement in South Africa, these sources are likely to become widely exploitable only in the latter part of the 21st century. They are unlikely to be an option in the short term for South Africa.

Many parts of South Africa already experience water shortages and this situation is likely to deteriorate in the future as the country's population continues to grow; similar prognoses apply for most of the other countries in southern Africa. For these countries, water demand management offers an invaluable opportunity to achieve real water savings and to delay the construction of new water infrastructure. In addition, the benefits of WDM can be experienced in the short-term and, in certain situations, the water supply situation has progressed to the point where there is already no alternative to WDM.

Acknowledgements

The authors would like to thank Mr. Hans Moes (CSIR, Division of Water, Environment and Forestry Technology, Stellenbosch) who suggested the most recent source of information on Congo water transport, and Ms. Linda Godfrey (CSIR, Division of Water, Environment and Forestry Technology, Pretoria) and Mrs Wouna le Roux (CSIR, Beyond Blue Communications) who helped with preparation of maps used in the paper. We also gratefully acknowledge valuable review comments and suggestions made by the three anonymous referees.

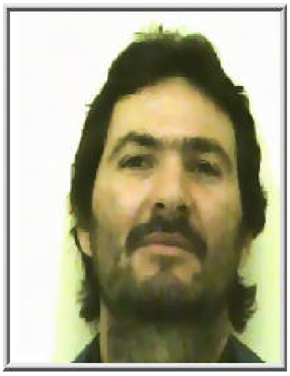
About the Authors

Vladimir Smakhtin was a Hydrology and Water Resources Scientist at the Council for Scientific and Industrial Research, Division of Water, Environment, and Forestry Technology, P. O. Box 395, Pretoria 0001, South Africa, and is currently with the International Water Management Institute in Sri Lanka. Dr. Smakhtin worked extensively in the fields of hydrological catchment modelling, hydrological data provision for water projects with an emphasis on data poor regions, hydrological regionalization, low-flow hydrology, ecological flow requirements of rivers and estuaries. His research interests include water resources assessment, optimization of water allocation in river catchments, environmental flow management, and hydrological time series analysis. Dr. Smakhtin has authored of over 50 research publications, numerous international presentations. Email: V.Smakhtin@cgiar.org.

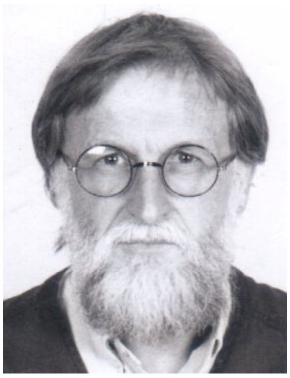
Peter J. Ashton is a Water Quality and Water Resources Specialist at the Council for Scientific and Industrial Research, Division of Water, Environment, and Forestry Technology, P. O. Box 395, Pretoria 0001, South Africa, and an Honorary Professor of Water Resources Management at the University of Pretoria. Dr. Ashton has 30 years experience in water-related research and evaluation studies in southern and central Africa, particularly in relation to water quality management practices and environmental impact assessments. He has a special interest in the role of aquatic ecological issues in decision-making processes for the management of water resources in shared river basins. He publishes extensively on issues related to water quality, international water sharing, and water demand management. Email: pashton@csir.co.za.

Allan Batchelor is an Applied Ecologist at the Council for Scientific and Industrial Research, Division of Water, Environment, and Forestry Technology, Pretoria, South Africa. He specializes in the management of human wastes and the treatment of point and non-point source pollution using biogeochemical processes associated with ponds and wetlands. His current research interests include water reuse and the use of seawater as a partial replacement in freshwater flush systems in coastal environments. Email: abatchel@ csir.co.za.

Reinhard Meyer is a Geology and Geophysics Scientist at the Council for Scientific and Industrial Research, Division of Water, Environment, and Forestry Technology. P. O. Box 395, Pretoria 0001, South Africa. He has extensive experience in the application of geophysics to groundwater exploration in southern Africa, groundwater resource evaluation and contamination, geohydrological aspects of waste disposal site evaluation and environmental impact assessments. Mr. Meyer is currently researching the application of Nuclear Magnetic Resonance soundings to groundwater exploration in fractured hard rocks, environmental impacts of backfilling the worked out underground coal mines and predicting the future quality of groundwater in major coal fields in South Africa. He is a Chairman of Geological Society of South Africa and an author of numerous research publications and specialist reports. Email: rmeyer@csir.co.za.



Eric (Ricky) Murray is a Hydrogeologist at the Council for Scientific and Industrial Research, Division of Water, Environment and Forestry Technology, P. O. Box 320, Stellenbosch 7599, South Africa. He has been working extensively in the field of artificial recharge of groundwater in hard-rock aquifers. Mr. Murray is an author of several specialist reports and has presented his results at a number of international hydrogeological and water resources symposia. Email: rmurray@csir.co.za.



Bohuslav Barta is a Water Resources Engineer and is currently with the School of Civil and Environmental Engineering, University of Witwatersrand in Johannesburg, South Africa. His professional activities are related to research and lecturing in water engineering and water resources management. Mr. Barta has published extensively on water resources engineering issues in southern Africa, including water resources of southern African rivers, the future of water resources in South Africa - desalination. He is a Fellow of IWRA since 2000 and an active member of the water fraternity in South African Development Community (SADC) region. Email: bartab@iafrica.com.

Norbert Bauer is a theoretical physicist and is currently working at the Institute for Environment Affairs, Munich D-82547 Eurasburg, Am Schlossberg 12a, Germany. Dr. Bauer is also a head of the Iceberg Water Harvesting Group, founded in 1998. His interests are investigating the dynamics and kinematics of icebergs in the context of harvesting water as a freshwater resource for arid regions. Email: bauer@pollux.weihenstephan.de.

Dhesigen Naidoo was a Director in the Department of Water Affairs and Forestry of South Africa, where he was responsible for coordination of national programs on water conservation and water demand management. Mr. Naidoo is currently a Chief Director in the Department of Environmental Affairs and Tourism of South Africa Email: dnaidoo@ozone.pwv.gov.za.

Jana Olivier is currently an Associate Professor in the Department of Geography and Environmental Studies of the University of South Africa (UNISA), P. O. Box 392, Pretoria 0003, South Africa. She was a leader of several research projects (University of the North, South Africa), which focuses on fog water collection and fog water supply for rural communities in South Africa. Prof. Olivier is an author of numerous research publications and reports on fog water related issues. Email: jana@ mweb.co.za.

Deon Terblanche is a Meteorologist and a Manager of the Meteorological Technology and System section (METSYS) of the Weather Bureau of South Africa, which deals with the National Weather Radar Network and other meteorological instrument systems in South Africa. Dr. Terblanche was a project leader of the Bethlehem Precipitation Research Project in 1989, and thereafter co-program leader of the National Precipitation Research Program, which focuses on development and testing of the hygroscopic flare cloud seeding technology. Dr. Terblanche is a member of a number of international meteorological committees and an author of multiple scientific articles, which deal with weather radar applications and weather modification. Email: deon@metsysweathersa.co.za.

References

Allan, J.A. 1996. "Water Use and Development in Arid Regions: Environment, Economic Development and Water Resources Politicies and Policy." Water Use and Development 5, No. 2: 107–115.

Ashton, P.J. 2000. "Avoiding Conflicts Over Africa's Water Resources." Proceedings of the GLOBE Symposium on Environmental Security in Africa. Cape Town, 20–21 September.

Ashton, P.J. and B. Haasbroek. 2000. "Water Demand Management and Social Adaptive Capacity: A South African Case Study." J.A. Allan, et al., eds. Water and the Politics of Change. Allocative Water Politics: Society, Politics and International Relations. Elsevier.

Barta, B. 1999. "Development of Water in the Resources Scarce Environment." Proceedings of the Ninth South African National Hydrological Symposium. Cape Town, South Africa.

Barta, B. 2000. "Regional Issues of Shared River Systems in southern Africa." Proceedings of the Fourth Biennial Congress of the African Division of the International Association for Hydraulic Research (IAHR), Windhoek, Namibia.

Basson, M.S., P.H. van Niekerk, and J.A. van Rooyen. 1997. Overview of Water Resources Availability and Utilisation in South Africa. Pretoria, South Africa: Department of Water Affairs and Forestry and BKS (Pty) Ltd. DWAF Report No. P RSA/00/0197.

Biggs, D. 2000. "Transfer of Water from the Congo River to Water Deficient Countries to the South: A Politician's Pipe Dream or an Engineer's Pipeline?" Proceedings of the Fourth Biennial Congress of the African Division of the International Association for Hydraulic Research (IAHR). Windhoek, Namibia.

Bruintjes, R.T. 1999. "A Review of Cloud Seeding Experiments to Enhance Precipitation and Some New Prospects." Bulletin of the American Meteorological Society 80, No. 5: 805–820.

Bruintjes, R.T., D.W. Breed, B.G. Foote, M.J. Dixon, B.G. Brown, V. Salazar, and H.R. Rodrigues. 1999. "Program for the Augmentation of Rainfall in Coahuila (PARC): Overview and Design." Pre-prints of the 7th WMO Scientific Conference on Weather Modification. Chiang Mai, Thailand: 53–56.

BMW. 2000. Bayerische Motorenwerke. Munich, Germany: Press office.

Cereceda, P., A. Cruzat, J. Ossandon, and R. Schemenauer. 1996. Prospection, Evaluation and Construction of Fog Collection Systems: A New Technology of Simple Application and Large Economic and Social Impact. IDRC-GAFCS.

Commission of Enquiry. 1970. Report of the Commission of Enquiry into Water Matters in South Africa. Report RP 34/1979. Pretoria, South Africa: Government Printer.

Cooper, W.A., R.T. Bruintjes, and G.K. Mather. 1997. "Some Calculations Pertaining to Hygroscopic Seeding with Flares." Journal of Applied Meteorology 36: 1449–1469.

Davidge, R. 1994. "Alaska Water Exports." http://www.alaskawaterexports.com.

De Marle, D.J. 1979. "South African Iceberg Utilization. A Proposal for the Freshwater Production at Saldanha Bay." Proceedings of the International Value Engineering Conference. Pretoria, South Africa, October 1979.

De Marle, D.J. 1980. "Design Parameters for a South African Iceberg Power and Water Project." Annals of Glaciology 1: 129–133.

DUT. 2000. Water Supply for Cape Town Area from the Congo River. Delft University of Technology, Faculty of Civil Engineering. Project Group CF578.

DWAF. 1986. Management of the Water Resources of South Africa. Pretoria, South Africa: Department of Water Affairs and Forestry.

DWAF. 1992. Utilization of Less Conventional Water Sources. Western Cape System Analysis. Pretoria, South Africa: Department of Water Affairs and Forestry Report Number P G000/00/3291.

DWAF. 1994. Options for the Supply of Water in the Western Cape. In: Western Cape System Analysis. South Africa: Ninham Shand Inc. DWAF Report N P G000/00/3291.

DWAF. 1995. Water Demand Management in the Vaal River System Study Area. Pretoria, South Africa: Department of Water Affairs and Forestry Report Number PC000/00/15495.

DWAF. 1996. Vaal Augmentation Planning Study, Overview Report. Pretoria, South Africa: Department of Water Affairs and Forestry Report N: PC000/00/15395. DWAF. 2000. Vaal River System Analysis Update: Integrated Vaal River System Analysis. Report Number PC000/00/18496.

Prepared for the Department of Water Affairs and Forestry by BKS Ltd, Steward Scott Inc., and Ninham Shand Ltd in association.

DWAF. 2001. Development of Water Resources Reconciliation Scenarios for the National Water Resources Strategy. Workshop on National Scenarios. February 2001, Pretoria, South Africa.

DWA-KFW. 1996. Water Supply to the Central Namib Area of Namibia – Feasibility Study. Interim Project Report, Volume 1. Contract Report to the Department of Water Affairs, Ministry of Agriculture, Water and Rural Development, Windhoek, Namibia, and Kreditanstalt Für Weideraufbau, Mannheim, Germany, by GKW Consult, Bicon Namibia Inc. and Parkman Namibia (Pty) Ltd.

Enslin, J.F. and J.P. Kriel. 1967. “The Assessment and Possible Use of the Dolomitic Groundwater Resources of the Far West Rand, Transvaal, Republic of South Africa.” Proceedings of the International Conference on Water for Peace. Washington, USA.

Epstein, P.S. 1921. “Über die Polflucht der Kontinente.” Die Naturwissenschaften 25: 499–502.

Falkenmark, M. 1986. “Freshwater – Time for a Modified Approach.” Ambio 15, No. 4: 192–200.

Falkenmark, M. 1991. “Rapid Population Growth and Water Scarcity: The Predicament of Tomorrow’s Africa.” K. Davis and M. Bernstam, eds. Resources, Environment and Population, Supplement to Population and Development Review 16. New York, New York: The Population Council and Oxford University Press: 81–94.

Falkenmark, M. and C. Widstrand. 1992. Population and Water Resources: A Delicate Balance. Population Bulletin 47, No. 3. Washington, DC, USA: Population Reference Bureau. Gerber, A. 1997. Water Reuse: National Report: South Africa. IWSA World Congress: IRB21- IRB23.

Gleick, P.H. 2000. “The changing water paradigm – a look at the twenty-first century water resources development.” Water International 25, No. 1: 127–138.

Görgens, A. and D.E. Terblanche. 2000. “SAREP: Situation Assessment Summary After the 1999/2000 Season.” Internal report to the Departments of Environment Affairs and Tourism; Water Affairs and Forestry; Agriculture; Arts, Culture, Science and Technology; and the Water Research Commission.

Grobicki, A. 2000. “Making the Most of a Precious Resource.” SA Water Bulletin 26, No. 3: 14–17.

Harris, M. and H. Habenicht. 2000. “Desalination for the Central Namib Area.” Proceedings of the Fourth Biennial Congress of the African Division of the International Association for Hydraulic Research (IAHR). Windhoek, Namibia.

Hay, R. 1998. “Over the Top and Academic – Artesian Groundwater in the Olifants River Catchment.” Unpublished paper presented at a workshop on the Hydrogeology of the Table Mountain Group, Groundwater Division (Western Cape Branch). Geological Society of South Africa, Bellville.

Husseiny, A.A., ed. 1978. “Iceberg Utilization.” Proceedings of the First International Conference on Iceberg Utilization. Ames, Iowa, USA: NY Pergamon Press.

Job, J.G. 1978. “Numerical Modeling of Icebergs for Water Supplies – A Case Study.” Journal of Glaciology 20: 533–539.

Jordaan, J.M. 2000. “Icebergs as a Potential Water Source for Namibia?” Proceedings of the Fourth Biennial Congress of the African Division of the International Association for Hydraulic Research (IAHR). Windhoek, Namibia.

Kent, L.E. 1949. “The Thermal Waters of the Union of South Africa and South West Africa.” Transactions of the Geological Society of South Africa 52: 231–264.

Le Maitre, D.C., D.F. Scott, and C. Colvin. 2000. "Information on Interactions Between Groundwater and Vegetation Relevant to South African Conditions: A Review." Groundwater: Past Achievements and Future Challenges. Proceedings of the XXX IAH Congress on Groundwater (Cape Town, South Africa, November 2000). Rotterdam, The Netherlands: Balkema: 959–962

Lund, B.G.A. 1997. "Water for All?" South African Journal of Science 93: 207–208.

Mather, G.K. 1991. "Coalescence Enhancement in a Large Multicell Storm Caused by the Emissions from a Kraft Papermill." Journal of Applied Meteorology 30: 1134–1146.

Mather, G.K. and D.E. Terblanche. 1994. "Initial Results from Cloud Seeding Experiments Using Hygroscopic Flares." Proceedings 6th WMO Scientific Conference on Weather Modification. Paistum, Italy: 687–690.

Mather, G.K., D.E. Terblanche, F.E. Steffens, and L. Fletcher. 1997. "Results of the South African Cloud Seeding Experiments Using Hygroscopic Flares." Journal of Applied Meteorology 36: 1433–1447.

Mellor, M. 1980. "High-force Towing." Cold Regions Science and Technology 1: 231–235.

Midgley, D.C., W.V. Pitman, and B.J. Middleton. 1994. The Surface Water Resources of South Africa 1990 (WR90). Pretoria, South Africa: Water Research Commission.

Mielke, J.E. 1999. "Desalination R&D: The New Federal Program." http://www.cnie.org/nle/hto-34.html

Murray, R. and G. Tredoux. 1998. Artificial Recharge: A Technology for Sustainable Water Resources Development. WRC Report No. 842/1/98. Pretoria, South Africa: Water Research.

Naidoo, D. and G. Constantinides. 2000. "Integrated Approaches to Efficient Water Use in South Africa." Water Resources Development 16, No. 1: 155–164.

Olivier, J. 1997. "The South African Fog Water Research Project." South African Geographical Journal 79: 161–165.

Olivier, J. and J. van Heerden. 1999. The South African Fog Water Collection Project. WRC Report No. 671/1/99. Pretoria, South Africa: Water Research Commission.

Orpen, W.R.G. 1992. "Artificial Recharge of Groundwater in the RSA." Borehole Water Journal 24: 12–16.

Pallett, J. 1997. Sharing Water in Southern Africa. Windhoek, Namibia: Desert Research Foundation of Namibia.

Pitman, W.V. 1995. "Towards Improved Utilization of South Africa's Water Resources." Proceedings of the Seventh South African National Hydrology Symposium, Grahamstown. Rajyalakshmi, D. 1999. "The Great Water Pursuit." Asian Water 15, No. 1: 11–12.

Republic of South Africa. 1998. The National Water Act (Act No. 36 of 1998). Pretoria, South Africa: Government of the Republic of South Africa.

Rosewarne, P. 1998. "Overview of TMS Hydrogeology from Citrusdal to Port Elizabeth." Unpublished paper presented at a workshop on the Hydrogeology of the Table Mountain Group, Groundwater Division (Western Cape Branch). Geological Society of South Africa, Bellville, 12 February 1998.

Rowsell, D.M. and A.M.J. de Swart. 1976. "Diagenesis in Cape and Karoo Sediments, South Africa and its Bearing on their Hydrocarbon Potential." Transactions of the Geological Society of South Africa: 81–145.

SARDC. 1996. Water in Southern Africa. Harare, Zimbabwe: Southern African Research and Documentation Centre.

Schemenauer, R.S. and P. Cereceda. 1994. "Fog Collection's Role in Water Planning for Developing Countries." Natural Resources Forum 18, No. 2: 91–100.

Seely, M. and J. Henschel. 2000. "Developing Fog Harvesting in Namibia." Proceedings of the Fourth Biennial Congress of the African Division of the International Association for Hydraulic Research (IAHR), Windhoek, Namibia.

Smakhtin, O., D. Naidoo, and M. Singh, 2000. "South African Case Study – Vaal System." Proceedings of the Fourth Biennial Congress of the African Division of the International Association for Hydraulic Research (IAHR), Windhoek, Namibia.

Terblanche, D.E., F.E. Steffens, L. Fletcher, M.P. Mittermaier, and R.C. Parsons. In press. "Towards the Operational Application of Hygroscopic Flares for Rainfall Enhancement in South Africa." Journal of Applied Meteorology.

Tucker, G. and J. Kritzinger. 1998. "Reverse Osmosis Seawater Desalination for the Albany Coast Water Board." Water Sewage and Effluent 18, No. 3: 39–41.

Turton, A.R. 1997. "Southern African Hydropolitics: Development Trajectories of Zambezi Basin States and South Africa." Proceedings of the Second Southern African Water and Wastewater Conference ("Water Africa 97"), September 1997. Harare, Zimbabwe.

Van der Linde, J. 1998. Greater Hermanus Water Conservation Campaign, A Model for Water Demand Management. Promotional publication by the Hermanus Municipality, September 1998.

Vegter, J.R. 1984a. "The Role of Groundwater in South Africa's Water Supply." Proceedings of the International Conference on Groundwater Technology. Johannesburg, November 1984, Volume 1: 3–14.

Vegter, J.R. 1984b. "Dolomitic Water Supplies with Special Reference to the Southern and Western Transvaal." Proceedings of the International Conference on Groundwater Technology. Johannesburg, November 1984, Volume 1: 15–31.

Umvoto Africa. 2000. "Reconnaissance Investigation into the Development and Utilization of the Table Mountain Group Artesian Groundwater using the E10 Catchment as a Pilot Study Area." Unpublished final report submitted to the Department of Water Affairs and Forestry. Pretoria, South Africa, October 2000.

Vegter, J.R. 1995. An Explanation of a Set of National Groundwater Maps. WRC Report No. TT 74/95. Pretoria, South Africa: Water Research Commission.

Vegter, J.R. 1999. Monograph on South Africa's Groundwater Resources. Unpublished Progress Report for Project K5/676. Pretoria, South Africa: Water Research Commission.

WCD (World Commission on Dams). 2000. Dams and Development: A New Framework for Decision-making: The Report of the World Commission on Dams: An Overview. London, United Kingdom: Earthscan Publications.

Weaver, J.M.C. and A.S. Talma. 2000. "Deep Flowing Groundwater in the Table Mountain Group Quartzite." Groundwater: Past Achievements and Future Challenges. Proceedings of the XXX IAH Congress on Groundwater (Cape Town, South Africa, November 2000). Rotterdam, The Netherlands: Balkema: 359–364

Weeks, W.F. and W.J. Campbell. 1973. "Icebergs as a Freshwater Source: An Appraisal." Journal of Glaciology 12, No. 65: 207–233.

WMO. 2000. Report of the WMO International Workshop on Hygroscopic Seeding: Experimental Results, Physical Processes and Research Needs. G. B. Foote and R.T Bruintjes, eds. WMP report No 35. Geneva, Switzerland: WMO.

Wolmarans and Guise-Brown. 1978. "The Water Hazard in Deep Gold Mining of the Far West Witwatersrand – South Africa." Proceedings of the International Conference: SIAMOS-78. Granada, Spain: 329–346.

Table 1. A Summary of Unconventional Sources and Options for Water Supply in South Africa.

Source / Option	***Potential for Supply or Envisaged Effect***	***Level of Technological Development***	***Level of Current Implementation or Use***	***Costs***	***Comments***
Surface Water resources within South Africa	Additional 14,000 Mm^3/yr	Engineering structural solutions: well developed	Approximately 19,000 Mm^3/yr are currently allocated	US$0.04-0.15/$m^3$	Costs for existing water supply systems: converted to US$ using "DWAF (2000) Charges"
Deep Storage	Possible increase in reservoir yield up to 90% of MAR	Similar to structural solutions above	Not implemented	Capital investments increasing linearly with the storage	
Congo Water	10% of the Congo River MAR exceed all surface water resources of South Africa	Existing engineering practices could be used for some transfer options	Not implemented	Tankers: US$2.45/$m^3$ Bags: US2.7/m^3 Pipeline: US$5.3/$m^3$	
Virtual Water	Indirectly involves the water resources of all SADC countries	The concept is not developed	Not implemented	No direct estimates are possible	
Deep Groundwater	A maximum of 1,000-1,300 Mm^3/yr in Western Province only	Deep drilling technology is in place	Not implemented	Not available	Potential for supply is approximated at 50% of the reported recharge figures
Artificial Recharge	Storage of surplus water and increased efficiency of sue	Developed to the level of practical implementation	Pilot experiments	Not available	
Iceberg Water	Unlimited	Requires intensive research and international co-operation	Not implemented	US$500M over 5 years to develop the technology	Very preliminary cost estimates for technology development
Seawater: Desalination	Unlimited	Developed to the level of practical implementation	Limited use (<0.2 Mm^3/yr)	US$0.5-7/$m^3$	
Seawater: Direct Use	Unlimited	Not developed	Not implemented	Not available	
Rainfall Enhancement	Local increase in rainfall amounts	Developed to the level of practical implementation	Pilot experiments	US$0.01-0.02/$m^3$ of enhanced rainfall	
Fog Collection	On average 180-230 litres/day in foggy days	Developed to the level of practical implementation	Pilot experiments	US$0.37-0.43/$m^3$	Localized water supply only
Effluent Reuse	990 Mm^3/yr	Developed to the level of practical implementation	30 Mm^3/yr	Not available	The potential is limited by the total volume of effluents to be treated
WDM	Potential reduction of system water losses up to 30-40%	Multiple measures with varying degree of development	Implemented by several municipalities	Not available	