An approach to resources management using the Umgeni Water System as an example

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INTRODUCTION

The efficient management of water systems requires consideration of different aspects of planning and operational strategy. These are continuously evolving. Originally the objective was to supply sufficient good quality water to meet all demands at all times. Where the supplier is a private company there is usually a requirement for a profit to be made, which can cause conflict with the objective of providing affordable clean water for all. Debts have been incurred by many water suppliers in providing facilities such as abstraction, storage and treatment works. These debts need to be serviced. Legislation has also imposed both mandatory water quality standards and access to all. Often a basic supply may be allocated at minimal or no cost to the user. These obligations vary according to the location of the sources, the demands and not least the culture. Is the region developing economically or is its industry in decline? As a result different management strategies are required to meet the local objectives especially in the developing world.

The initial phase starts with managing the resource. This may be relatively straightforward. There are a number of different mathematical models that may be used to forecast the hydrological inputs with varying degrees of accuracy. It is possible to develop scenarios to show the effects of global climate change on the hydrological pattern. Environmental requirements may be more accurately assessed and allowances made for them. However, this may appear to reduce the overall availability of water to meet the demand for a clean supply.

THE TEST LOCATION

The concepts were developed using the Umgeni catchment as a useful model. There are three major reservoirs on the river system. There is an interbasin transfer and water is reprocessed and subsequently re-used. Water is also exported to the neighbouring water scarce regions. Two of the three reservoirs, Midmar (259 MCM) and Albert Falls (286 MCM) are greater in size than the mean annual runoff. In this region the mean annual runoff is exceeded only about one third of the time. Both these reservoirs rely to some extent on transfers from adjacent river systems that rise in the mountainous area (catchments at 3000 m) while in geological time the mountainous area of the Umgeni appears to have been captured by two adjacent river systems so that the effects of both rainfall and the possible influence of snow are reduced. The lowest of the three reservoirs, Inanda Dam (225 MCM), is a relatively deep reservoir with a dam wall 52 m high. In addition there is a river intake at the Nagle Dam (25 MCM) downstream of Albert Falls. The system supplies the two conurbations of Durban and Pietermaritzburg. The sewage works of the latter discharges into the Umzimduzi, a large tributary which joins the Umgeni just downstream of Nagle dam and upstream of Inanda Dam. The region has experienced extremes of drought and flood in the last twenty years. It has a rapidly increasing population but industry is evolving more slowly. There is a major bulk water supplier (Umgeni Water) and Municipal reticulation. Water is metered and charged for on a form of rising block tariff. Industry in parts of Durban uses sewage effluent that is treated to better than potable standard.

DATA REQUIREMENTS

Originally, for traditional simulation-based studies, many years of river flow data were required. These datasets would need to include typical low flow events, as well as more normal weather patterns. However, even these would only allow a strategy to be developed to meet past events. It is now practicable to generate sufficient data sets to give a typical range of values so that different eventualities may be catered for. Even so complete knowledge is not possible. Using local data it has been possible to generate sufficient sets of river flow to test the operating strategy. At least ten sets of 100 years of generated data were used to provide a statistically acceptable minimum set of meaningful results.

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THE CONCEPT

While water demand varies almost continuously there are diurnal, weekly and monthly patterns. The short-term changes are usually smoothed by storage in suitably sized treated water reservoirs. However, longer-term changes require careful management. Smoothing in the longer term may be aided by some form of raw water storage. It is the management of the storage that is of concern here. Storage may vary from river bank balancing storage to a large reservoir or even an aquifer. The prime objectives will be to ensure that as much water is supplied at the least cost while maximising the storage to meet anticipated future demands.

There are different methods of deriving the control strategy. The original alternative approach (Tollow, 1989a) used an appropriate historic drought to derive the 'control bands'. This was subsequently combined with a set of median flow data to allow for more flexibility. The concept of the 'control band' rather than a specific 'control rule' was to ensure flexibility, especially as both the demand and the inflow would vary from the historic values used to determine the selected control rule. While the author originally derived the concept for comparatively large water supply pumped storage reservoirs in East Anglia, the subsequent development was on large gravity filled reservoirs on the Umgeni River system in Durban, South Africa. The approach was verified and refined using generated data and linear programming.

Nevertheless, the Umgeni system reservoir sizes are relatively small when compared to flood flows. No attempt was made to develop an algorithm for their use as flood regulating reservoirs. In fact, Inanda, the lowest of the Durban Reservoirs, filled from empty in 17 hours during a major storm, when the river flow was estimated at about 7000 $m^3 sec^{-1}$ (Tollow, 1990). Low flows vary across South Africa and dry and wet cycles vary. The author found that these may be from three to five in Natal and longer elsewhere. Pseudo cycles of seven and nine years were identified. (Tollow,1987, 1989b). Recent works have highlighted the variability of low flow events in South Africa (Rouault and Richard, 2003).

The concept of the 'control band' may be compared in some ways to the fuzzy logic approach to water pricing (Hall, 1991). It may be used where there are either ranges of optimal solutions or there is no one acceptable optimal solution. Both these ranges of scenarios may occur in resource management problems. In itself the control band at first sight allows for sub-optimal operations. However, the flexibility that the band allows may in fact help to achieve a desired optimal solution. The key lies in the band width. This is set up to suit the resource and the circumstances. A wide band width allows for a large range of solutions. Conversely a small band width may in the extreme result in only one solution. When the actual operation moves out of any particular band then a series of constraints may be activated depending on:

i) whether the point lies above or below the band;
ii) the characteristics of the various resources forming the system;
iii) forecasts of demands and future availability;
iv) the overall trends of the past and current operations;
v) the desired risk of failure, either to achieve complete optimality or impose restrictions and be unable to meet demand.

One approach in designing the relevant sets of control bands is to use simulated sets of data (Tollow, 1989a). These may be made up as five year sets of median, high and low flows so that the appropriate control bands may be developed. Then the bands are tested on 100 year sets of data, either generated (Tollow, 1989b) or original. Multiple sets of generated dat often help identify weaknesses in the original strategy (Tollow, 1991a) which then allows consideration of modifying the control band and operating policy or modifying the infrastructure to make it more efficient. Control bands are usually considered as an operational tool but they may also become a management planning tool too. The system needed individual control bands for each resource as well as a 'combined' value because of different constraints on each resource.

MODERN APPROACHES

An adaptive programming approach was developed. In addition, quadratic programming with constraints was tested but no significant improvements were noted. Non-linear programming was tested but no advantage was found (Tollow, 1992) . However, a hypothesis using non-linear mixed integer programming has been developed for the Durban reticulation system (Biscos *et al*., 2003). The results show that the adaptive learning process with suitable algorithms and constraints will yield promising solutions. An adaptive approach has been used to develop the South African Water Policy. The policy development was compared to a mountaineering expedition (MacKay *et al*., 2003).

THE CONSTRAINTS AND OTHER BOUNDARIES

The constraints used in the optimisation included the limits imposed by a reservoir becoming full and spilling downstream. There were also target points that required to be reached at the end of each season. These were manipulated to include the requirement of sufficient stored water to last for a set number of seasons given a pre-determined inflow. Initially a set outflow would be provided. Only after using a test set of 100 years of data would further adjustments be made.

Operating constraints such as the ability to transfer water regionally needed to be included. In the case of the Umgeni, it is possible to supply the whole of the region from Midmar but, in practice, to do so would result in the reservoir being emptied since the regional demand could no longer be met from the one source. Nor is it possible for the lower reservoirs to supply water to the upper areas which are fed from Midmar. However, at considerable cost in terms of both electrical energy used for pumping and chemicals used to treat a poorer quality water, it is possible to supply most of the area supplied ideally from Albert Falls, the middle reservoir, from Inanda, the bottom reservoir.

Other constraints and objectives may be set up as required. For example, one might be that it would be desirable to have the reservoirs 90% full on 1 May every year. This would also imply that the reservoirs should be at least half full on 1 October. Also, using the previously generated five-year batches of test data, control bands may also be derived using an adaptive iterative approach until an acceptable compromise solution is reached. The solution may then be tested using further 'operating constraints' to assess the performance of the system (Tollow, 1991a). However, there will be some cases where the reservoir level goes below the control band. In this case further measures will be required. These would need to be developed as a set of operating strategies. Again these may be tested (Tollow, 1993). One method would be to encourage the reduction in consumption, either in the short or long term depending on the local conditions.

REDUCING CONSUMPTION

There are two different approaches to the reduction in the requirement to supply water: the first is short-term, the second long-term. As an example taken from domestic use, consider the short-term measure of putting a brick in the WC cistern to reduce capacity and the long-term one of designing and fitting a more efficient smaller cistern complete with a dual flush action. Both actions reduce the requirement for water but the latter, although more expensive, may be considered more efficient in the long term. Both have implications when considering water re-use. It has been interesting to note that as a result of short-term action because of the 'drought' in the early 1980s, the total consumption in Durban was suppressed for a number of years afterwards (Tollow, 1993). Perhaps it took some years for householders to take the bricks out again?

SHORT-TERM REDUCTIONS IN CONSUMPTION

Short-term reductions in water consumption may be intended to last from a few days to a few months. The action may be triggered by a temporary disruption in supply or as a result of reservoir levels being below the relevant control band. The reduction may be as simple as a ban on the use of hosepipes, as has recently occurred locally in parts of the Umgeni Catchment. The severity of the required reduction dictates the methods employed, from a temporary increase in charges, when all supplies are metered, to the installation and forced use of standpipes, when no alternative action is possible. Water meters make it easier to select the appropriate action since there are increased numbers of options available, to deal with both short- and with long-term reductions. In one case in 1987, a major flood (approximately 1 in 200 year return period) on the Umgeni destroyed part of the water transmission system. This resulted in a severe reduction in the supply of clean treated water and most of Durban was virtually without water for ten days. The only solution was to supply water by tanker. This was in fact more severe than the measures imposed some three years earlier when there was a major drought and customers were restricted to 400 litres per household per day (Tollow, 1995a).

LONG-TERM REDUCTIONS IN CONSUMPTION

Longer-term reductions can take many forms. One is the introduction of 'rising block tariffs' (Tollow, 1994). Another is the planning and implementation of policies of encouraging industry to practice 'waste minimisation' (Tollow, 2000). Waste minimisation tackles not only the problem of reducing the requirement for water but also of reducing the discharge of polluted effluent. In addition, these actions often stimulate byproduct recovery. This may show greater cost savings to industry than the savings made by the reduction in consumption of fresh water. With modern chemicals it is often more cost-efficient to recover them and re-use them rather than discharge them to the river or sea. Actions by industry may also be determined by the charges incurred in discharging, diluting or treating the effluent.

Waste minimisation may take many different forms. One uses linear programming to demonstrate the advantages of various options. However, there has been some resistance (Tollow, 2000). Other means of demonstrating the effectiveness of waste minimisation have been shown using 'Pinch analysis' (Buckley *et al.,* 2000). Other forms of analysis have also been applied to specific industrial applications (Friedrich and Buckley, 2000). In addition, support systems have been set up. These include waste minimisation clubs (Wynne *et al.,* 2001). Despite original industry scepticism due to the 'commercial in confidence' problem (Tollow, 2000), these appear to be working in certain industries. Considerable savings, due in part to byproduct recovery and also in part to the reduction in use of chemicals, have taken place (Buckley *et al.,* 2000). Indirectly, the desired result of reducing the requirement for potable water has been achieved. The Waste Minimisation Clubs in Durban have breakfast meetings which also allows for a degree of networking and comparison which is possibly why the local Durban Group seems to be working. In addition the meetings have allowed networking between parties to be built up and an easy informal indirect communication system appears to have been created.

Another alternative to individual re-use has also been developed. This is the conversion of treated sewage effluent from an industrial area to potable quality water for re- use in industry. The effluent would otherwise have been discharged to the sea. The reclaimed potable quality water is then sold to nearby paper, petro-chemical and other industries with a high water demand. The result of this action has been to postpone the development of alternative resources which otherwise have been needed. Considerable savings are anticipated, however, the initial effect has been an increase in the cost of potable water to the domestic consumer and to other industries, since less 'fresh' water is needed. This is a problem that only occurs where water is metered and charges levied on actual consumption. In other cases the resulting costs are offset against an income derived from a tax of some description.

SUSTAINABILITY, RELIABILITY, RESILIENCY AND VULNERABILITY

It is desirable to measure the effectiveness of proposed policies to be able to demonstrate their effectiveness. One approach has been the development of credibility factors and a credibility index which was tested on possible scenarios for the operation of the main Umgeni reservoirs and the original 'Mooi–Midmar' transfer system (Tollow, 1991b). The objective was to quantify in numerical terms, the reliability, risk, resiliency and vulnerability of the system using a single index, the credibility of actions taken. This simulation was successfully applied to the experimental results found for the Umgeni catchment. However, scope for further development remains. Other means of describing the resilience, reliability and vulnerability for the same catchment have been formulated (Kjeldson and Rosbjerg, 2001). These included samples of some of the system users, including irrigators, as well as environmental demands. In addition both 'demand management' and 'resource provision' were included. The method described the sustainability of the resources (Kjeldson and Rosbjerg, 2002). A global value for the system as a whole was estimated using a sustainability index and sustainability criteria. The need for further development was highlighted.

MANAGING CONSUMPTION

In practice, managing consumption is the management of the perceived requirement for water by all users, including the environment. An example has been developed, which used the Umgeni system. This demonstrated the desirable constraints to consumption. Highlighted was the need for a different approach for both system planning and for operations (Tollow, 1995b). Although the cost of developing resources is increasing worldwide, in one instance selected sustainability criteria, as applied to the Umgeni River system, indicated that it would be better to develop new resources rather than practice a revised management policy using existing resources. However, this phenomenon was explained as being due to the choice of 'selected users' as well as other shortcomings. An alternative approach was needed to see if this conclusion could be verified (Kjeldson and Rosbjerg, 2001). However, from research on the same catchment, using different criteria and data, a significantly different outcome, more in line with global trends, appeared to be more likely (Tollow, 1995b).

CONCLUSIONS

The flexibility permitted by control bands could allow a system to be operated automatically, provided sufficient rules were embedded in the operating procedure. However, even if used as a guide when it is developed in conjunction with other management tools, it would aid the efficient use of water resources when operated under extreme conditions. Additional requirements may be needed in conjunction with the control band which may be basically considered a means of successful operation of the water resource. Other bands may be developed. An example would be a band where once demand exceeds a certain level constraints are imposed. In the short term this may take the form of a forced reduction in pressure. In others this took the form of inserting Orifice plate washers in the supply line to physically limit supply to that property (Tollow, 1994).

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