INTEGRATED WATER CYCLE MANAGEMENT: ANALYSIS OF RESOURCE SECURITY

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Abstract

This paper summarises a systems analysis of the impact of Integrated Water Cycle Management approaches on the security of regional water supplies. The synergistic impacts of supply and demand management approaches on the security of regional water supply systems can be accurately evaluated using a combination of non-parametric regional demand methods: the PURRS lot scale water balance simulator and the WATHNET network linear headworks model. The systems methodologies described in this paper have widespread application.

A case study analyses regional water security in the Greater Sydney region to demonstrate the capability of the methodologies. The use of different pump marks for extractions from the Shoalhaven River, various frequencies of water restrictions, rainwater tanks and demand management measures has been investigated. An increase in acceptable frequency of water restriction to 5% and a pump mark of 70% will defer the requirement to augment the water supply headworks system by 26 years. The use of demand management measures alone will not defer augmentation whilst installation of 5 kL rainwater tanks for hot water, toilet, laundry and outdoor uses can defer augmentation beyond 2090. A Pareto diagram is employed to examine conflicting environmental and economic objectives.

Introduction

About 4 million people currently occupy the Greater Sydney region that extends from the Hawkesbury River in the north to Gerroa in the south and from Mt. Victoria in the west to the east coast. Sydney Water Corporation (SWC) is responsible for the provision of reliable water supply to people living in the Sydney region and for managing water demand. The Sydney Catchment Authority (SCA) supply bulk water from the water supply catchments (see Figure 1) to SWC.

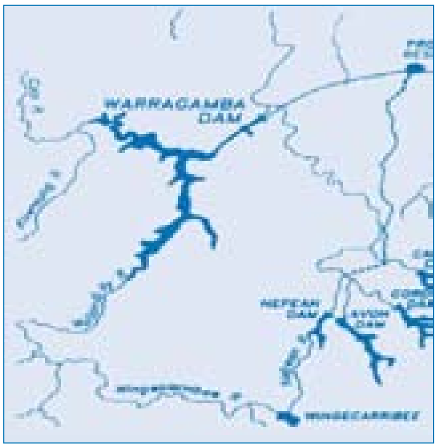

Figure 1. Sydney headworks system.

Since the 1960s Sydney's water consumption increased dramatically due to growth in population, prosperity and subsequent urban development. The increased consumption was driven by use of water consuming domestic appliances and a water inefficient heavy industry. Water demand decreased following the 1978 - 1983 drought and during economic recession that led to restructure of heavy industry. During the late 1980s and early 1990s public education programs and pricing policies also assisted in management of water demand. Deen [2000] reported that the introduction of user pays pricing for water, accompanying media campaigns and water restrictions during the 1992-1998 drought reduced water demand by 10% - 15% during the mid 1990s. Sydney's water demand has increased by over 11.5% since 1995.

It is an operating license requirement that SWC reduce per capita water demand by 35% over 1991 water demand in order to avoid construction of the Welcome Reef Dam on the Shoalhaven River. Note that the triggers to augment a regional water supply system are an unacceptable change of water restrictions and risk of failing to supply water. A Least Cost Planning (LCP) model was developed to rank various demand management strategies on a unique cost effectiveness basis. Using the Least Cost Planning Model as a guide SWC began to implement a demand management strategy using a limited range of demand side options in 1999. Nonetheless water demand increased by 5.4% since 1999 in response to population growth.

Reviews of the Demand Management Strategy found that a wider range of demand and supply management options was required to avoid augmentation of the water supply headworks system. Selection of demand and supply management methods should also consider the long term system impacts on the environment, the water supply headworks system and the community.

Rainwater collected from roofs and stored in tanks to supplement mains water supplies for domestic consumption has been shown to significantly reduce household mains water use. Importantly Coombes *et al.* [2000] and Spinks *et al.* [2003] found that the quality of water supply from rainwater tanks was acceptable for hot water, toilet and outdoor uses. Coombes *et al.* [2002] found that the use of rainwater tanks will defer the requirement to augment the Lower Hunter and Central Coast water supply headworks systems by 28-100 years. Many authors including White *et al.* [1998] claim that the use of dual flush toilets, and AAA rated shower roses and washing machines will significantly reduce domestic mains water demand.

This study examines the economic, environmental and water supply systems impact of the use of demand management measures and rainwater tanks in the regional water supply system; namely the Greater Sydney region. The non-parametric regional demand model developed by Coombes *et al.* [2002] and the network linear program for headworks simulation WATHNET by Kuczera [1992] was used to analyse water demand, streamflows and headworks security. The Pareto analysis presented by Kuczera and Coombes [2001] is used to compare the environmental and economic performance of different scenarios. A more complete description of this study is provided by Coombes *et al.* [2003].

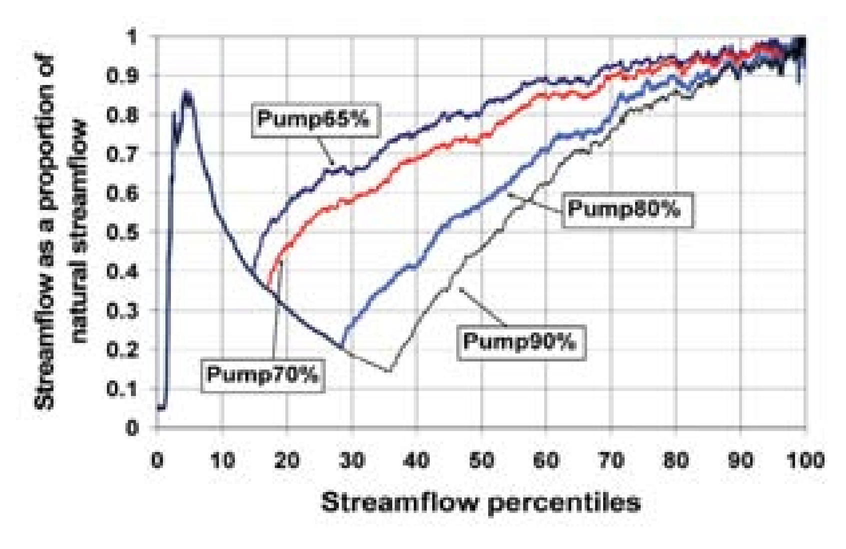

Figure 2. Impact of pump marks on the Shoalhaven River in the year 2020.

The Headworks System

Water is currently supplied to the Sydney region from the Warragamba, Upper Nepean, Shoalhaven and Woronora river catchments that have a combined area of 16,850 km^2 (Figure 1). Streamflow from the Warragamba catchment is captured in Warragamba Reservoir that has a storage capacity of 1890 gigalitres (GL). Water from the Cataract, Cordeaux, Avon and Nepean Dams located in the Upper Nepean catchment is conveyed via a system of pipes, natural river channels, weirs, tunnels and aqueducts to Prospect Reservoir whilst also supplying various communities along the routes. The South Coast region is supplied with water from the Avon and Cordeaux Dams and Nepean Dam via the Nepean-Avon tunnel.

Streamflow from the Shoalhaven catchment is captured in Lake Yarrunga and Tallowa dam where water is raised 612 metres to Wingecarribee Reservoir via Fitzroy Falls Reservoir when the water storage volume in Warragamba Dam is less than 65%. Water from the Wingecarribee Reservoir is distributed to Nepean dam and Lake Burragorang via the Wingecarribee and Wollondilly Rivers. The townships of Mittagong and Bowral are also supplied with water from the Wingecarribee Reservoir.

Simulation of Headworks System Performance

Performance of the water supply headworks system and impact of urban water demand on streamflow in the water supply catchment was simulated using the WATHNET network linear program for headworks simulation by Kuczera [1992].

The streamflow records and climate data (rain depth, rain days and daily maximum temperature) from the period 1909 to 2000 were used in this study. To preserve the climatic correlation between the urban and water supply catchments 2000 replicates of streamflow and climatic variables in both catchments were simultaneously generated for the period 2001 to 2090.

It is important to highlight the significance of using replicates of streamflow and climatic variables in preference to the use of a single historical sequence of information. The use of a single historical sequence to evaluate the security of a regional water supply can only provide understanding of the water system's response to a single given sequence of climatic events. In contrast, the use of replicates will allow a reliable understanding of system responses to a range of different climate sequences that may occur in the future and allow evaluation of the systems failure probabilities.

Headworks System Reliability

In this study reliability is defined as the probability that water restrictions will not be imposed in a particular year. Restrictions on urban water demand are triggered when storage levels in Warragamba Dam and Avon Dam fall below 60%. The reported effectiveness of water restrictions in the Sydney region during the 1992-1998 drought by Deen [2000] was used to develop restriction criteria and subsequent demand reductions for domestic outdoor demand. Water restrictions were only applied to domestic outdoor demand and non-domestic demand (Tables 1 and 2).

The trigger to augment Sydney's water supply system with the construction of the Welcome Reef Dam was an unacceptable chance of water restrictions and risk of failing to supply water.

Water Demand

The Sydney region was divided into ten water supply zones with different climatic conditions (monthly rain depth, temperature and rain days) that coincided with trunk distribution system monitoring data provided by the SCA. These zones include: Prospect East, Prospect South, Prospect North, Blue Mountains, Orchard Hills, Avon, Nepean, Macarthur, Warragamba and Woronora. The North Richmond zone was not included in the study.

Monthly daily average domestic water demand for different dwelling types within the various demand zones was estimated using climate data from the NSW office of the Bureau of Meteorology, socio-economic data from the Australian Bureau of Statistics and the methods developed by Coombes *et al.* [2002].

Daily water balance results for households was derived using the PURRS (probabilistic urban rainwater and wastewater reuse simulator) allotment water balance model and historical climate data was compiled into resource files. Resource files were also created for households with demand management measures and rainwater tanks.

The method of non-parametric aggregation created by Coombes *et al.* [2002] was used to generate monthly domestic water use for each dwelling type in each climate zone using the historical resource files and the climate replicates generated for the headworks simulation.

Importantly, the use of climate replicates and the non-parametric methods ensures that water demands are temporally and spatially consistent with the rainfall and stream flows in the

Table 1. Water restriction criteria for domestic outdoor demand.

Storage less than (%)	60	55	50	40
Reduction in demand (%)	33	57	75	100

Table 2. Water restriction criteria for non-domestic demand.

Storage less than (%)	50	40	30	20
Reduction in demand (%)	5	10	15	20

water supply catchments. Population data used in this study was provided by the Australian Bureau of Statistics, Planning NSW and SCA.

Pump Marks and Frequency of Water Restrictions

The performance of the water supply headworks system was evaluated using 2000 replicates of streamflow and water demands in the WATHNET program. Variation in the Shoalhaven pump marks and frequency of water restrictions were considered. The pump mark in the base system is considered to be 65% which means when storage levels in Avon and Warragamba Dams fall below 65% pumping from the Shoalhaven River is commenced. Performance of the headworks system subject to variation in pump marks and frequency of restrictions is shown in Table 3.

Table 3 shows that increased pump marks and frequency of water restrictions delays the requirement for augmentation by up to 66 years. At the currently accepted frequency of water restrictions of 3% increasing pump marks can delay augmentation of the water supply headworks system by 24 years. At a pump mark of 65% increasing the frequency of water restrictions can defer the requirement to augment the water supply headworks system by up to 40 years. The impact of variation in pump marks on streamflow in the Shoalhaven River in January 2020 with acceptance of a 3% chance of water restrictions is shown in Figure 2.

Figure 2 shows the cumulative percentiles of streamflows that exceed a given value as a proportion of natural flows. Water extractions from the Shoalhaven River in response to pump marks ranging from 65% to 90% result in very significant reductions in streamflow. Increasing pump marks to 80% and 90% will result in up to 85% depletion of medium range streamflow. Increasing the pump marks will also increase energy consumption, costs and greenhouse gas emissions (Table 4).

Table 4 shows that higher pump marks will increase annual energy costs by $0.7M to $6.9M and greenhouse gas emissions by 39% to 280% in the year 2020. The cost to pump water from the Shoalhaven River to Wingecarribee Reservoir was estimated to range from $62/ML to $84/ML with energy consumption of 1624 kWh/ML. About 0.89 kg of greenhouse gases (CO2) is generated for each kWh of electricity consumption.

Table 3. Variation in pump marks and frequency of water restrictions.

Pump mark	Augmentation year by frequency of restrictions			
	1%	3%	5%	10%
65%	2003	2006	2020	2046
70%	2004	2008	2029	2054
80%	2004	2028	2043	2073
90%	2008	2030	2044	2073

Table 4. Annual energy costs and greenhouse gas emissions from pump marks in 2020.

Pump mark	Cost ($M)	CO_2 (Tonnes)	CO_2 increase (%)
65%	1.8 - 2.4	40,790	-
70%	2.5 - 3.4	56,700	39
80%	5.5 - 7.4	124,000	204
90%	6.8 - 9.3	154,780	280

Adoption of a 70% pump mark and acceptance of a 5% frequency of water restrictions will defer augmentation of the headworks system by 26 years with increases in annual pumping costs of $0.7M to $1M, greenhouse gas emissions increase of 40% and the smallest additional reduction in streamflow in Shoalhaven River.

The Impact of Demand and Supply Management Measures

The impact of various demand and supply management measures on mains water demand in the Sydney region was determined using the regional demand method. A limited selection of approaches was evaluated including 1% and 2% per annum installation of AAA rated shower roses (AAA_1%, AAA_2%), demand management measures including 6/3 litre flush toilets, AAA rated shower roses and washing machines (DM_1%, DM_2%), 5 kL rainwater tanks with mains water trickle top up for domestic toilet and outdoor demand (T_TO_1%, T_TO_2%) and 5 kL rainwater tanks with mains water trickle top up for domestic hot water, toilet, laundry and outdoor demand (T_HTLO_1%, T_HTLO_2%).

Combinations of measures were also considered including 1% per annum installation of demand management measures in combination with 0.25%, 0.5% and 1% per annum uptake of 5 kL rainwater tanks with mains water trickle top up for hot water, toilet, laundry and outdoor uses (T_0.25%DM_1%, T_0.5%DM_1%, T_1%_DM_1%). A pump mark of 65% was used. Regional average annual water demand from some of these scenarios is shown in Figure 3.

Figure 3 shows that a 2% per annum installation of AAA rated shower roses (AAA_2%), demand management measures (DM_2%) and 5 kL rainwater tanks for toilet and outdoor uses (T_TO_2%) will have a moderate impact on regional water demand. The 1% and 2% installation per annum of 5 kL rainwater tanks for hot water, toilet, laundry and outdoor uses (T_HTLO_1%, T_HTLO_2%) produces substantial reductions in regional water demand. Combinations of demand management measures and 5 kL rainwater tanks used to supply domestic hot water, toilet, laundry and outdoor uses, especially the T_1%DM_1% scenario, also produce considerable reductions in regional mains water demand.

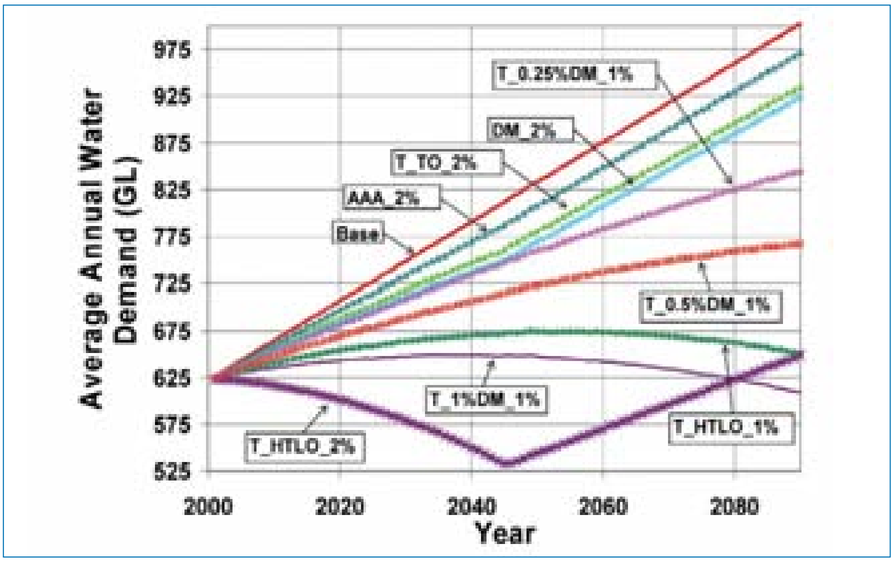

Figure 3. Regional mains water demand in the Sydney region.

Using the WATHNET program the impact of demand and supply management scenarios on the reliability of the water supply headworks system was evaluated. The impact of the different scenarios on augmentation timing is shown in Table 5.

Table 5. Augmentation requirement for the water supply headworks system.

Scenario	Augmentation year by frequency of restrictions			
	1%	3%	5%	10%
Base	2003	2006	2020	2046
AAA_1%	2003	2006	2025	2050
AAA_2%	2003	2006	2025	2050
DM_1%	2003	2006	2025	2050
DM_2%	2003	2006	2029	2061
T_TO_1%	2003	2006	2026	2051
T_TO_2%	2003	2006	2028	2051
T_HTLO_1%	2003	2027	>2090	>2090
T_HTLO_2%	2003	2077	>2090	>2090
T_0.25% DM_1%	2003	2006	2030	2084
T_0.5% DM_1%	2003	2007	2043	>2090
T_1% DM_1%	2003	2090	>2090	>2090

Table 5 shows that under reliability criteria of 3% (similar to current criteria) only the scenarios T_HTLO_1%, T_HTLO_2%, T_0.5%DM_1% and T_1%DM_1% that include 5 kL rainwater tanks used to supply hot water, toilet, laundry and outdoor uses defer augmentation. The T_HTLO_2% and T_1%_DM_1% scenarios result in long term deferral of augmentation by 71 to 84 years. Note that the scenarios with AAA rated shower roses and demand management measures will not defer the requirement to augment the water supply headworks system subject to current reliability criteria. Similar results apply to the scenarios with 5 kL rainwater tanks to supply toilet and outdoor uses.

Interestingly, acceptance of a 5% chance of water restrictions produces the greatest deferral of augmentation timing (5 to 8 years) for scenarios with demand management or rainwater tanks for toilet and outdoor uses. For these scenarios a 10% reliability criteria diminishes the relative impact on augmentation timing. The scenarios with 5 kL rainwater tanks for hot water, toilet, laundry and outdoor supply and/or demand management measures provide greater deferment of augmentation with increases in frequencies of water restrictions from 3% to 5% or 10%. Note that a combination of a 5% reliability criteria and scenarios T_HTLO_1%, T_HTLO_2% and T_1%DM_1% defer the requirement to augment the water supply headworks system beyond the 90 year planning horizon.

Economic Impacts

The investment model developed by Coombes *et al.* [2002] compares economic benefits accruing to the community from a traditional Base scenario to alternative scenarios that include installation of rainwater tanks and demand management measures. The Base scenario considers the status quo: provision of traditional stormwater systems to areas undergoing urbanisation and provision of additional mains water supply by further regulation of river systems.

Costs and benefits for the provision of mains water and the disposal of stormwater considered common to the base and alternative scenarios were not included in the analysis. The costs and benefits that differ from the base scenario are considered in analysis of the alternative scenarios. In the alternative investment scenario a household can purchase water from a water utility, use rainwater tanks for water supply and install demand management measures to reduce water use. The community pays the cost of installing, operating, maintaining and replacing rainwater tank and demand management systems whilst gaining benefits from reductions in mains water use and the requirement for water cycle infrastructure. The reduced requirement for infrastructure results in decreased depreciation and maintenance costs.

Installation of 3A rated shower roses was estimated to reduce water distribution infrastructure installation costs by $21.1 per device at an installation cost of $80 each. 3A rated shower roses have an estimated 10 year life with a replacement cost of $45 per device.

Installation costs for 3A rated washing machines and 6/3 litre toilets were $800 and $85 per device respectively. The washing machines were estimated to have a ten year design life. The demand management scenarios were expected to produce water distribution infrastructure installation savings of $54.40 per dwelling respectively. The installation of rainwater tanks was estimated to cost $2,500 each providing stormwater and water distribution infrastructure savings of $1,300 per dwelling. The tank has a design life of 50 years with a replacement cost of $800 and the pump has a design life of 10 years with a replacement cost of $350. Augmentation of the water supply headworks system by the construction of the Welcome Reef Dam was expected to cost $226M (based on NSW Treasury estimates from 2003, note that the current estimated cost is over $2 billion).

A 5% frequency of water restrictions was accepted for the economic analysis. The present benefits of the demand management scenarios ranged from -$527M to $144.9 and cost of water supply from rainwater tanks varied from -$985M to $774M.

Environmental Impact

The impact of demand and supply management measures on the environmental health of the Sydney region in the year 2020 was considered in terms of streamflow in the Shoalhaven River, stormwater runoff in urban areas, the volume of sewage generated and greenhouse gas emissions. A 5% frequency of water restrictions was accepted for the environmental analysis.

Streamflow in the Shoalhaven River

Increasing water urban demands or the construction of Welcome Reef Dam has the potential to further degrade the Shoalhaven River system. Although the monthly time step used in the streamflow analysis in this study is unsatisfactory from an ecological perspective the changes in streamflow in response to urban water demand will provide an indicator of river health. The greatest reduction in streamflow for January 2020 from each scenario was calculated as a percentage of natural streamflow. These percentages from each scenario were used to develop an environmental flow score that ranged from 75% to 80%.

Frequent Stormwater Discharges

The use of rainwater tanks can result in substantial reductions in stormwater runoff. A stormwater discharge score was developed that determined the percentage reduction in 3 month ARI stormwater discharges in the Sydney region resulting from installation of rainwater tanks. Values for the stormwater discharge score ranged from 14% to 30%.

The Volume of Sewage Discharges

Installation of demand management measures such as 6/3 flush toilets, 3A rated shower roses and washing machines will reduce the magnitude of indoor water use.

The water savings become a reduction in the volume of sewage discharges that will reduce impacts on the environment. The sewage score represents the reduction in sewage discharges in the Sydney region that result from demand management measures. Values for the sewage score range from 1.28% to 6.6%.

Greenhouse Gas Emissions

Changes in energy usage resulting from reduced pumping from the Shoalhaven River, in rainwater tank systems (small pumps that use less energy than delivering water via the mains distribution system) and in the sewage and water reticulated systems and reduced water heating in hot water systems will reduce greenhouse gas emissions. The greenhouse gas score determines the percentage reduction in green house gas emissions in comparison to emission from the Base water supply scenario. Values for the score range from 0.02% to 133% for the T_TO_1% and AAA_2% scenarios respectively. Use of 3A rated shower roses achieved a considerable energy saving. Note that 3A rated shower roses generate additional energy savings derived from heating less water.

The Pareto Frontier

The results from the environmental impact scores were combined with equal weight with the exception of the greenhouse gas score which was given an arbitrary weight of 0.01 in recognition of the relative significance of the other environmental scores to form an environmental criterion. The economic results reported as the present value of alternative solutions were combined with the environmental criteria in the Pareto Diagram shown in Figure 4.

The Pareto Diagram provides a method of comparing conflicting environmental and economic objectives. Inferior solutions are those that have lower economic values and environmental scores than other solutions.

Figure 4 shows that the scenario with 2% per annum installation of rainwater tanks for hot water, toilet, laundry and outdoor uses is a Pareto optimum solution and the disturbing realisation that the currently preferred water industry solutions are far from optimum. Although this study has not analysed enough scenarios to accurately locate the Pareto Optimum a number of observations can be made. It is clear that scenarios with 5 kL rainwater tanks for supply of hot water, toilet, laundry and outdoor uses (T_HTLO_1%; T_HTLO_2%) are close to Pareto Optimum solutions. Similarly scenarios that combine demand management measures and 5 kL rainwater tanks for hot water, toilet, laundry and outdoor uses approach the Pareto Optimum.

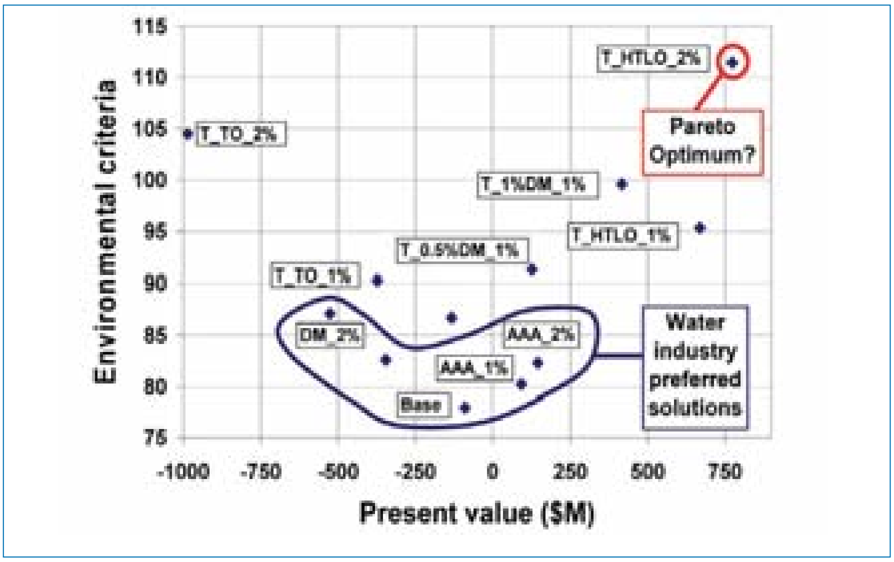

Figure 4. Pareto Diagram of alternative solutions.

Figure 4 also shows that scenarios with 5 kL rainwater tanks for supply of toilet and outdoor uses or AAA rated shower roses or demand management measures alone are inferior solutions and should therefore be discarded.

Conclusions

The most significant contribution of this paper is an explanation of systems methodologies to evaluate the performance of integrated water cycle management scenarios. These methodologies and models have generic application to evaluation of regional water security at any location. Although the systems methodologies have been used in the analysis that evaluated a limited range of water management scenarios, the results are instructive.

Acceptance of a greater frequency of water restrictions will defer the requirement to augment the water supply headworks system by up to 43 years. Increasing the pump mark for water extractions from the Shoalhaven River with current frequency of restrictions will defer augmentation by up to 24 years with substantial impact on the Shoalhaven River. A pump mark of 70% with acceptance of a 5% chance of water restrictions will defer augmentation by 23 years.

Use of demand management measures or 5 kL rainwater tanks for toilet and outdoor uses, and retention of the 3% chance of water restriction rules will not result in deferment of Welcome Reef Dam. However the installation of 5 kL rainwater tanks for hot water, toilet, laundry and outdoor uses with or without demand management measures at rates of 1% and 2% per annum will defer augmentation by 21 to 84 years. If the acceptable chance of water restrictions is increased to 5% these scenarios will defer the requirement to construct Welcome Reef Dam beyond 2090. The present value of scenarios with demand management measures ranged from -$527M to $133.3M and with rainwater tanks varied from -$985M to $774M.

The results of this study indicate that the urban water industry is operating in a constrained solution space resulting in sub-optimal solutions. This observation is particularly relevant given that the water industry claim that rainwater tanks are inferior solutions in comparison to demand management measures. Installation of demand management measures alone will have minimal impact on the requirement to augment Sydney's water supply headworks system. The adoption of a wide range of supply and demand management measures, including recycling of wastewater, will have a significant impact on the security of Sydney's water supply. Importantly, the use of methods outlined in this paper will allow improved understanding of the synergistic and systems benefits of a wide range of water management approaches.

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