Chapter 11

Summary and Conclusions

> "Can we move nations and people in the direction of sustainability? Such a move would be a modification of society comparable in scale to only two other changes: the Agricultural Revolution of the late Neolithic and the Industrial Revolution of the past two centuries. Those revolutions were gradual, spontaneous, and largely unconscious. This one will have to be a fully conscious operation, guided by the best foresight that science can provide.. If we actually do it, the undertaking will be absolutely unique in humanities' stay on the Earth." (William D. Ruckelshaus, 1989)

11.0 A Brief Outline of the Thesis

This thesis has examined the impact of rainwater tanks used to supply domestic hot water, toilet and outdoor uses on the urban water cycle. Chapter 1 introduced rainwater tanks and the urban water cycle. In Chapters 2 and 3 experimental studies of the Figtree Place and Maryville developments were presented to assess the performance of rainwater tanks in field conditions. The water quality and health aspects of using rainwater stored in tanks were examined in Chapter 4 and institutional resistance to the use of rainwater tanks was discussed in Chapter 5. In Chapter 6 models were developed to simulate outdoor water use, the behaviour of a first flush device and the overall domestic allotment water balance that includes rainwater tanks. The impact of rainwater tanks installed on domestic allotments on the performance of subdivisions was assessed in Chapter 7. A regional demand model was developed in Chapter 8 to determine the impact of rainwater tanks on regional mains water demand. Chapter 9 used the results from the regional demand model to assess the impact of rainwater tanks on the water supply headworks systems in the Lower Hunter and Central Coast regions. In Chapter 10 an investment model was developed to determine the benefits that accrue to community from the installation of rainwater tanks.

11.1 Moving the Constrained Pareto Frontier

In this thesis it has been shown that the introduction of rainwater tanks for domestic hot water, toilet and outdoor uses can be a superior economic solution to traditional provision water supply and stormwater management options for the Lower Hunter and Central

Coast regions. However traditional water supply planning concentrates on regulation of rivers and aquifers [Loucks et al., 1981, pp.15; Hunter District Water Board, 1982; and IEAust, 1999], and does not consider rainwater tanks as a viable water source. Similarly traditional stormwater management planning concentrates on the provision of pipe drainage systems [IEAust, 1987] and does not consider rainwater tanks as a viable method of managing stormwater.

The water supply and stormwater management industry appears to only consider a limited set of solutions for water supply and stormwater management. Indeed stormwater and water supply solutions are typically considered separately. It was shown that the use of rainwater tanks provided greater economic benefits to the community than the traditional water supply and stormwater management options. Yet in Chapter 5 it was argued that the current stormwater management and water supply paradigms exclude the use of rainwater tanks as a solution. Traditional solutions for water supply and stormwater management are selected from an artificially limited set of separate technical solutions that form a constrained solution space. An example of the constrained solution space is provided below.

To keep our example manageable we start with the premise that the community requires the provision of urban water cycle services to a certain standard. For example, the urban community may require that water supply services are secure during all but the severest drought and provide potable water at an acceptable pressure. The community may require that stormwater be managed so that frequent nuisance flooding is avoided and damage in major flood events is mitigated. There are many ways that water cycle services can be provided at the required level of service. To rationally choose between competing options, the community may decide that these services be provided in a way that trades-off two objectives, minimise community lifecycle costs and maximise the sustainability of the ecosystems that underpin the water cycle services.

The light grey region in Figure 11.1 represents the performance outcomes of all technically feasible solutions that provide water cycle services to a certain standard. The Pareto frontier describes the solutions that the community should carefully examine in order to arrive at a preferred solution. Solutions that do not lie on the Pareto Frontier are unambiguously inferior. For example, solution A has lower lifecycle costs and better sustainability than solution B. No rational person would prefer B to A unless there are other objectives not articulated in the analysis. On the other hand, one cannot argue that solution A is better than solution C. Although A has lower lifecycle costs than C it has worse environmental performance. The community must examine the trade-off between A and C and in doing so implicitly value sustainability in monetary terms.

The darker grey region in Figure 11.1 represents a constrained technically feasible solution space which is a subset of the technically feasible solution space. The constrained space may arise because of institutional constraints that limit or prohibit implementation of alternative feasible solutions (such as rainwater tanks) or may arise because it is believed that the alternative solutions are not feasible.

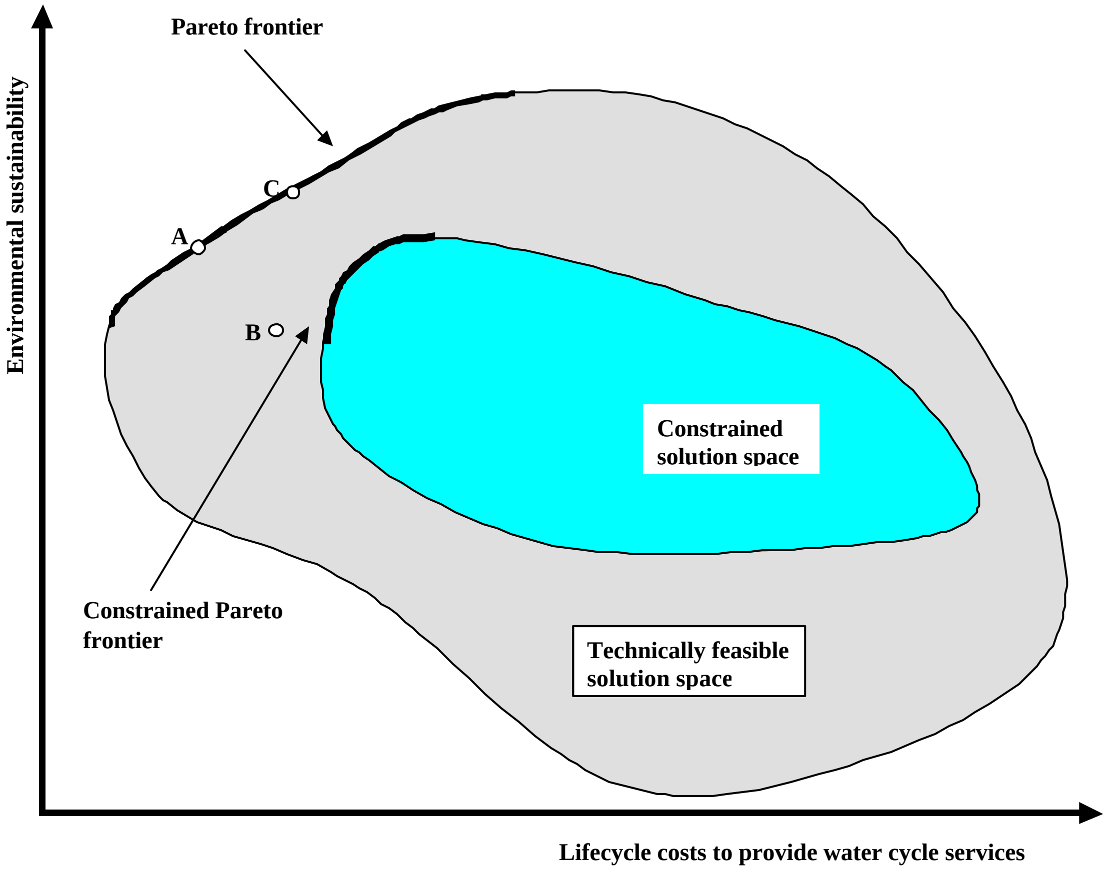

Figure 11.1. Conceptualisation of the constrained Pareto Frontier.

The price paid for artificially constraining the solution space can be considerable. In Figure 11.1 the constrained Pareto Frontier is unambiguously inferior to some solutions on the unconstrained Pareto Frontier. For example, solution C produces lower lifecycle costs and a more sustainable outcome than any solution in the constrained space. Removing the "artificial" constraints on solutions will produce a more beneficial outcome for the community.

One of the major contributions of this thesis is to show that the operation of the traditional water supply and stormwater management paradigms produces a constrained Pareto Frontier resulting in sub-optimal economic and environmental outcomes for the community. It was shown that the use of rainwater tanks provided greater economic benefits to the community and reduced environmental impacts in comparison to the traditional water supply and stormwater management options. Yet the current urban water cycle paradigm has effectively excluded this solution from consideration.

11.2 Conclusions and Contributions to Knowledge

The research undertaken in this thesis analysed the impact of rainwater tanks on the urban water cycle at the allotment, subdivision and regional scales. The conclusions and contributions of this thesis are presented in the context of these three scales.

11.2.1 The Allotment Scale

Analysis of the performance of rainwater tanks at the allotment scale included the Figtree Place and Maryville experimental studies, determination of water quality and public health issues, a discussion of institutional resistance and the development of a comprehensive allotment water balance model.

11.2.1.1 Experimental Results

In Chapter 2 the results of the Figtree Place experiment were presented. It was found that poor design and construction of the project, and institutional resistance hindered the operation of the Figtree Place experiment. Stormwater detention tanks had been installed rather than rainwater tanks. There were many holes and cracks in the walls of the stormwater retention tanks allowing debris, soil and leaves to fall into the tanks from the surrounding garden beds. Ponding in the roof and gutter system also resulted from poor construction practices further compromising water quality. Nonetheless monitoring and analysis of the Figtree Place experiment provided important insight into the performance of source control measures. In particular the performance of rainwater tanks in something akin to a worst case scenario has provided insight into the robustness of the rainwater treatment train.

Although the quality of rainwater collected from roofs at Figtree Place occasionally exceeded the guideline values for ammonia, pH, iron and lead, all samples of rainwater from tanks and hot water systems were found to be compliant with chemical and metals parameters in the Australian Drinking Water Guidelines (except pH). The roof runoff regularly contained high concentrations of bacteria as indicated by Heterotrophic Plate Counts, and the presence of Fecal Coliforms, Total Coliforms and Pseudomonas ssp. However water samples from the rainwater tanks had significantly lower concentrations of bacteria than the roof runoff. The quality of rainwater was found to improve by storage in tanks. Samples of the sludge found at the bottom of the tanks yielded concentrations of chemicals, metals and bacteria that exceeded drinking water guidelines by a considerable margin. The water treatment processes of flocculation, settlement and bio-reaction appear to operate in rainwater tanks to improve water quality.

Storage hot water systems supplied with rainwater contaminated with bacteria was shown to nonetheless deliver water meeting Australian Drinking Water Guidelines provided that they are operated at temperatures in the range 50ºC to 65ºC. Hot water quality was seen to be related to frequency of use, capacity of the hot water service and temperature settings. The processes of pasteurisation (lethal temperature) and tyndallisation (small perturbations of temperatures) appear to destroy bacteria in hot water services. The combination of the rainwater tanks and storage hot water services was found to be an effective water treatment process that produced water quality results compliant with drinking water guidelines.

The overall conclusion is that rainwater collected from roofs in the inner city location of Figtree Place and stored in poor quality tanks was found to have a quality suitable for hot water, toilet and outdoors uses.

Responses to a questionnaire revealed that the Figtree Place residents supported the use of stormwater runoff from paved surfaces and gardens for outdoor purposes, and the use of rainwater for outdoor, toilet, hot water and laundry purposes. The residents of the Figtree Place project also reported that they did not drink from the hot water tap.

The use of rainwater tanks at the Figtree Place experiment reduced mains water use by 11% to 44%. The combination of rainwater tanks, infiltration trenches and an infiltration basin provided a successful stormwater source control strategy. No stormwater discharged from Figtree Place to the street drainage system during a four-year period. The Figtree Place experiment produced small total annual cost savings when compared with traditional stormwater and water supply practices. Likewise the source control elements at Figtree Place provided small construction cost savings over traditional stormwater practices. The existing design details of the Figtree Place project can be further improved with consequent lower costs.

Chapter 3 examined the design, construction and performance of the dual water supply system (rainwater and mains water) at a house in Maryville, an inner city suburb of Newcastle. Using knowledge from the Figtree Place experiment a design was developed for the installation of a rainwater tank to supply rainwater for toilet, hot water and outdoor uses. The rainwater supply is supplemented with mains water via a trickle top up system when water levels are low in the tank. An air gap is used for backflow prevention in accordance with Australian Standards.

Monitoring of the performance (during a 169 day period) of the dual water supply system at the Maryville house revealed that use of the rainwater tank reduced stormwater volumetric (36%) and peak discharges (84%), and mains water peak daily (80%), the one peak instantaneous (93%) and volumetric (52%) demands. The installation of the rainwater tank at the Maryville house has substantially reduced impacts on the mains water distribution, water supply headworks and stormwater infrastructure. The presence of the rainwater tank also encouraged water conservation in the household.

The dual water supply system was installed at a cost of $1,851, which was considerably less than the commonly assumed cost of over $4,000. The cost of rainwater varied from $0.30/kL to a benefit of $0.39/kL when a rates rebate and savings in the construction of water cycle infrastructure were considered. This is significantly less than the $1 - $14 cost per kL reported by industry. The cost of rainwater at the Maryville house was also considerably less than the price of mains water in the Lower Hunter region. Rainwater collected from roofs and stored in tanks appears to be a genuine economic alternative to mains water supplies. It is stressed mains water supply is necessary for drought security and fire fighting purposes. Thus the use of rainwater tanks to supply hot water, toilet and outdoor uses appears to be an economically viable compliment to mains water supplies.

Monitoring of water quality from the rainwater tank and from an instantaneous hot water service with the temperature set at 55°C at the Maryville house revealed that the rainwater was acceptable for hot water, toilet and outdoor uses. Similar to the water quality results from the Figtree Place experiment (Chapter 2) water quality was found to improve in the rainwater tank and the hot water service.

A mistake commonly made by researchers and engineers is to assume that rainwater can only be used to supply outdoor uses. The mismatch between seasonal rainfall and outdoor water use patterns can result in poor utilisation of rainwater resulting in long periods when the tanks are either empty or full. The results from the Figtree Place and Maryville experiments show that this problem can be remedied by using rainwater to supply constant indoor uses such as toilet flushing and hot water (representing about 60% of total indoor water use) that will consistently draw down the rainwater storage tank allowing the rainwater to refill the storage more often. Combinations of different water use frequencies from rainwater tanks such as toilet flushing, hot water and outdoor uses can result in substantial reductions in mains water use and stormwater discharges.

11.2.1.2 Rainwater Quality and Public Health Issues

In Chapter 4 the literature describing water quality that can be expected from rainwater tanks and health risks attributed to drinking rainwater stored in tanks was discussed. The human digestive system and common water borne diseases were examined to develop an understanding of the health risks that may result from using rainwater for household uses.

It was found that the quality of rainwater stored in tanks can be degraded by poor maintenance of the rainwater tank and in rare and unusual cases this has resulted in the transmittal of pathogens from human, animal or birds via fecal contamination of stored water to humans causing disease. In general the majority of water borne diseases were found to originate from fecal contamination of drinking water by humans, animals and birds.

The elements of the rainwater treatment chain, namely the roof, first flush device, rainwater tank and hot water service and the human gastrointestinal tract, play significant roles in reducing the risk of disease caused by pathogens. A number of processes are believed to operate to improve water quality in a rainwater tank including accumulation of microorganisms at the surface air-water interface (the water surface microlayer), flocculation of contaminants and settlement to the bottom of the tank, and the action of biofilms. Bacterial indicator organisms Total Coliforms and Fecal Coliforms are used to indicate recent fecal contamination of drinking water supplies indicating the possible presence of pathogens. Coliforms occur naturally in the environment. Therefore their presence in rainwater may not indicate the possibility of contamination of rainwater by pathogens.

It is often stated that water supply from rainwater tanks is not acceptable for potable uses. However, over 3 million Australians drink water from rainwater tanks and there are only a handful of cases reported where water from a rainwater tank has caused illness. The risk of contracting an illness from a rainwater tank appears to be very small. Indeed the use of rainwater for non-drinking purposes is likely to produce negligible health risks. It appears that the quality of rainwater and the efficacy of the rainwater treatment chain will allow the widespread introduction of rainwater tanks to supply toilet, hot water and outdoor uses.

11.2.1.3 Institutional Resistance

In Chapter 5 social and institutional resistance to the use of rainwater tanks was discussed. This resistance often manifests itself in the guise of health and economic concerns. In Chapters 2, 3 and 4 it was shown that the health and economic concerns are probably overstated. Institutional resistance to the use of rainwater tanks was developed by the NSW Government and water authorities in the late 1800s to recover the debt incurred in the construction and maintenance of mains water supplies because citizens refused to connect to or pay for mains water preferring to source rainwater from household tanks and community wells.

Social and institutional resistance to the use of rainwater tanks has been fostered to ensure the economic viability of the new centralised water supply paradigm in colonial Australia. The operation of the water supply paradigm and enduring normative values that rainwater tanks are a health hazard and that rainwater is more expensive than mains water have served to exclude the use of rainwater tanks in urban areas that have a mains water supply. The evolution of the centralised control and pipe paradigm for water supply, stormwater and sewage disposal has created further resistance to the use of source control measures such as rainwater tanks.

Paradigms change when the evidence accumulates that the current paradigm is no longer tenable. However the engineering community has accepted that the pipe paradigm is adequate for water supply, stormwater and sewerage management. Therefore better solutions are not examined or required. The thinking of engineers has been constrained by adherence to the pipe paradigm. It is argued that institutions such as water authorities and local government resist changes to the pipe paradigm because such institutions require centralised control of infrastructure and the revenue that this control generates.

11.2.1.4 A Probabilistic Behavioural Model for Simulation of Outdoor Water Use

The comprehensive monitoring program of domestic water use at individual dwellings throughout the Lower Hunter region by the Hunter Water Corporation has provided unique insight into the patterns of domestic water use and allowed the development of a probabilistic behavioural outdoor water use model.

The probabilistic behavioural outdoor water use model developed in Chapter 6 shows improved predictive ability in comparison to traditional models currently in use. The model was able to simulate the strong seasonal outdoor demand trends experienced in the Lower Hunter region. The model differs from traditional models that rely on linear regression to physical parameters in that it simulates behavioural reaction to climate variables (including rainfall and temperature) using a probabilistic framework.

The model uses daily rainfall depth, maximum daily temperature and historical monthly average daily outdoor water use to simulate daily outdoor water use. Outdoor water use is shown to be most likely on days without rain. On days without rain the volume of water used is influenced by normal water use habits and temperature. There is also a small probability of outdoor water use on days with rainfall; however, the volume of water used is limited by the depth of rainfall. When the rainfall depth is large there is no outdoor water use for several days regardless of rainfall. The outdoor water use model was combined with the SCE-UA global optimisation method to determine the parameters that achieve the best fit to observed outdoor water use.

11.2.1.5 Development of a Model to Simulate the Performance of the First Flush Device

In Chapter 6 the development of a model to simulate the performance of a first flush device is described. Many authors describe the first flush as a fixed amount of roof runoff requiring separation. Design and modelling of the performance of first flush devices has been dominated by this belief. However the number of dry days preceding a rainfall event, rainfall intensity and rainfall depth are indicators of roofwater quality. Design of first flush separation devices and simulation of their performance will need to reflect the dynamic nature of roofwater quality and quantity.

The design of first flush separation devices needs to maximise conservation of roofwater and minimise contaminant transport to the rainwater tank whilst accounting for variation of roofwater quality and quantity from all storms. The first flush model developed in Chapter 6 continuously simulated the performance of a first flush device over a long time period. This enables the design of a first flush device to account for the variable nature of rainfall events and is a significant improvement over the traditional assumption that the first flush device will separate a fixed quantity of rainfall. The first flush model was combined with the SCE-UA global optimisation method to determine the key hydraulic dimensions required to separate the first 1 mm of roofwater from inlet to a rainwater tank whilst maximising water conservation.

In Chapter 4 it was shown that a first flush device will not remove all contaminants from inflow to a rainwater tank and in Chapter 2 it was revealed that contaminants could be transported to the tank from roofs throughout a rainfall event. However a first flush device can be designed to remove a large proportion of contaminates from entry to a rainwater tank making it an important part of the rainwater supply treatment chain.

11.2.1.6 Development of the Allotment Water Balance Model

In Chapter 6 a water balance model was developed that will allow long-term simulation, at short time steps, of dual water supply systems and source control measures on allotment or cluster developments. The performance of the Allotment Water Balance model was partially verified against monitoring data from the Maryville Experiment (Chapter 3) providing excellent agreement to the observed data for the performance of the rainwater tank.

The Allotment Water Balance model includes the new and improved methods for the simulation of outdoor water use and the performance of first flush devices that were developed in this thesis. The water balance model was used to analyse the long-term performance of the Figtree Place unit clusters (Chapter 2) and the Maryville house (Chapter 3). In both cases the analysis revealed that the use of rainwater tanks in a dual water supply system provided significant reductions in mains water use, stormwater discharges and stormwater peak discharges. The use of a mains water trickle top up scheme at the Maryville house resulted in substantial reductions in 1-year ARI peak daily and instantaneous water use. The analysis also revealed that the use of rainwater tanks was likely to significantly reduce the impact of urbanisation on stormwater quality.

The installation of rainwater tanks with mains water trickle top up to all domestic dwellings in the Lower Hunter region was examined using the water balance model. Very significant average reductions in mains water use, 1-year ARI peak daily mains water use and stormwater discharges were demonstrated for each zone in the region.

11.2.2 The Subdivision Scale

In Chapter 7 a method to determine the retention storage available in a rainwater tank prior to a design storm event with a given ARI was developed. The method used continuous simulation results from the Allotment Water Balance model developed in Chapter 6 to calibrate antecedent conditions for use in design storms to ensure consistency with peak stormwater discharges derived by continuous simulation. The performance of a subdivision that includes rainwater tanks on domestic allotments for hot water, toilet and outdoor uses was evaluated using knowledge of the retention storages available in each tank prior to design storm events in the WUFS stormwater management model.

Stormwater peak discharges, mains water demand and the requirement for stormwater infrastructure in the subdivision were substantially reduced. This resulted in cost savings that ranged from $210 to $511 per allotment in the provision of street stormwater drainage infrastructure. These savings will vary with climate, soil types and economic conditions in different regions. Nonetheless the savings in the provision of stormwater infrastructure will only partially pay for the installation of rainwater tanks. The reduced impact on the environment and water distribution infrastructure that may result from the installation of rainwater tanks was not evaluated in this thesis. Nor was the impact of a full water sensitive urban design (WSUD) approach (including rainwater tanks) evaluated.

The installation of rainwater tanks in subdivisions was also shown to provide significant lifecycle benefits to the community that are derived from a reduction in the requirement for street drainage infrastructure that subsequently results in decreased depreciation and maintenance costs.

11.2.3 The Regional Scale

The assessment of the impact of the widespread installation of rainwater tanks at the regional scale required analysis of regional mains water demand, water supply headworks infrastructure and the community's economic welfare.

11.2.3.1 Development of a Regional Water Demand Model Using Non-parametric Aggregation

In Chapter 8 a regional demand model was developed that can simulate the impact of domestic rainwater tanks on regional water demand thereby enabling analysis of the impact of rainwater tanks on water supply headworks infrastructure. The model differs from traditional methods of predicting regional water demand that rely on regression relationships using historical total regional water use. The spatial variation of mains water use is captured in the model by using the expected mains water use in dwellings in selected climatic and socio-economic zones throughout a water supply catchment.

The regional demand model uses the water balance model (Chapter 6) to create reference files of mains water use in different dwelling types in selected climate zones within a water supply catchment. Water demand for every dwelling in each climate/socio-economic zone at each time step is selected by matching the values of climate variables used to generate mains water use in the dwellings with climate variables that coincide with streamflow and evaporation in the water supply catchment. The concurrent generation of climate and streamflow data at urban and water supply catchment sites preserves the spatial dependence that associates drought (low streamflow and rainfall) with high outdoor water demand and vice versa.

The simple model by Kuczera and Ng [1994] was used to estimate regional non-domestic demand in the regional demand model. The non-domestic demand model may be calibrated to past demand trends or alternatively it may be assumed that non-domestic demand will form a given proportion of total mains water demand. The regional demand model was calibrated to historical regional demand for the Lower Hunter and Central Coast regions. Calibration was achieved by altering the parameters in the non-domestic component of the model. The annual demands for both regions were reproduced with a fair degree of accuracy by the model.

Replicates of future climate data were used in the regional demand model to predict water demand from the year 2000 to 2099 in the Lower Hunter and Central Coast regions. The impact of different rates for installation of rainwater tanks on regional water demand was examined for both regions. The widespread installation of rainwater tanks to supplement mains water supplies for domestic hot water, toilet and outdoor uses was shown to produce substantial reduction in regional mains water demand for the Lower Hunter and Central Coast regions.

11.2.3.2 Analysis of the Water Supply Headworks Systems for the Lower Hunter and Central Coast Regions

In Chapter 9 the demand scenarios developed in Chapter 8 were used in the WATHNET water supply headworks model to determine the impact of the installation of rainwater tanks on the provision of water supply headworks infrastructure. It was demonstrated that the use of rainwater tanks to supply outdoor, hot water and toilet flushing demand will delay construction of new water supply headworks infrastructure from 8 to 34 years in the Lower Hunter region.

The installation of rainwater tanks to all new domestic dwellings would delay the requirement for a new dam by 8 years and the installation of rainwater tanks to all new and redeveloped domestic dwellings will delay the requirement for a new dam by 26 years. The installation of rainwater tanks to meet Local Government requirement for additional stormwater management on new and redevelopment sites will significantly defer the requirement for new dams.

Domestic water demand is only 43% of total water demand in the Lower Hunter region and the region has a moderate population growth rate of 0.9% per annum. In areas with domestic demand that is a greater proportion of total demand and with similar climate even greater impacts on deferral of the requirement for new dams would be expected. The Central Coast region has an annual population growth rate of 1.37% and domestic water demand is 64% of total water demand for the region. In the Central Coast region it was demonstrated that the use of rainwater tanks to supply outdoor, hot water and toilet flushing demand will delay construction of new water supply headworks infrastructure from 28 years to over 100 years. The installation of rainwater tanks to all new domestic dwellings will delay the requirement for a new dam by 28 years and the installation of rainwater tanks to all new and redeveloped domestic dwellings will delay the requirement for a new dam by over 100 years.

11.2.3.3 A Community Based Investment Model to Determine the Economic Benefits of Rainwater Tanks

Chapter 10 described the creation of an investment model that allows economic comparisons between a traditional base scenario and alternative scenarios that include rainwater tanks. The base scenario assumes further exploitation of rivers to meet growth in urban water demand and additional pipe drainage systems to manage increasing stormwater runoff.

In the investment model each alternative scenario starts with enough funds to ensure economic viability of the base scenario. In each year expenses are deducted, income is added and interest is earned on the balance. The analysis considers comparative costs and benefits using the base scenario as the reference. The investment model includes costs and benefits that differ from the traditional base scenario. The financial balances from each scenario in any year are compared to provide an annual equivalence and the initial investments required to maintain a surplus financial balance in each scenario provide a present equivalence.

Two investment cases were evaluated for the Lower Hunter and Central Coast regions. In each investment case the scenarios for different rates of installation of rainwater tanks were used from Chapters 8 and 9. The regional water demands (Chapter 8) and delays in requirement for augmentation of water supply headworks infrastructure for each scenario (Chapter 9) were used in the investment analysis.

The first investment case used the results from the thesis to analyse the economic efficiency of different rates of installation of rainwater tanks in the Lower Hunter and Central Coast regions. The reduced requirement for stormwater infrastructure leading to construction, depreciation and maintenance cost savings that result from the installation of rainwater tanks (Chapters 2 and 7) was used in the analysis. The installation, operation, maintenance and replacement costs of the rainwater tank systems (Chapters 3 and 7) were also included in the analysis.

The scenario that includes rainwater tanks for all new dwellings and for all redeveloped dwellings (G+0.9%) was shown to be the most economically efficient for the Lower Hunter region with present value savings (relative to the traditional base scenario) ranging from $37 million to $78 million. The use of rainwater tanks for all new dwellings and 0.9% of existing dwellings per year (G+0.9%) were the most economically efficient solution for the Central Coast region with present value savings ranging from $11 million to $47 million. The economic benefits to the community are derived from mains water savings, construction and depreciation savings resulting from a reduced requirement for stormwater infrastructure and interest earned on community savings due to the deferral of new water supply dams. All scenarios that involved installing rainwater tanks to new or redeveloped dwellings showed considerable economic benefits to the community. This is caused by the reduced requirement for stormwater infrastructure leading to construction, depreciation and maintenance cost savings that results from the installation of rainwater tanks to new or redeveloped dwellings.

The second investment case makes some additional assumptions. It is assumed that the installation of rainwater tanks to new and redeveloped dwellings will reduce the requirement for new water distribution infrastructure resulting in cost savings. The creation of considerable growth in the market place for rainwater tanks and pumps is assumed to create economies of scale and increased competition between firms resulting in lower costs. The scenario that includes rainwater tanks for all new dwellings and for all redeveloped dwellings (G+0.9%) was shown to be the most economically efficient for the Lower Hunter and Central Coast regions. All of the alternative investment scenarios that include rainwater tanks were shown to provide considerable benefits to the Lower Hunter region of $83 million to $139 million and to Central Coast region of $64 million to $100 million and to be more economically efficient than the traditional base scenario.

A sensitivity analysis that varied real interest rates and the magnitude of stormwater savings resulting from the use of rainwater tanks showed that the magnitude of the economic benefits accruing from the use of rainwater tanks was dependent on real interest rates and the value of stormwater savings that result from the use of rainwater tanks.

However, these findings need to be tempered by the limitations of the study. This study has not valued the environmental benefit associated with delaying the construction of dams to augment water supply and from reduced stormwater discharges to the receiving environment. Also the impacts of the use of rainwater tanks on the mains water distribution system have not been properly evaluated. Moreover, the construction and lifecycle costs of alternative scenarios have only been assessed, albeit conservatively, using data from a small number of case studies and demonstration sites. Therefore, the benefits of the alternative approaches that include rainwater tanks have most likely been understated for the Lower Hunter and Central Coast regions.

11.3 The Continuing Research Agenda

This thesis makes a number of significant contributions. Most of this thesis has been devoted to demonstrating that a source control technology such as a rainwater tank can produce considerable economic benefits to the community as well as benefits to ecosystems that support the urban water cycle. In the context of the water industry in Australia these findings are significant and deserve serious consideration. However, this thesis makes an additional significant contribution by casting serious doubt on some of the assumptions used in the urban water industry. Industry claims that rainwater tanks are a health hazard, unreliable and are not economically competitive with the price of mains water supplies are at odds with the findings in this thesis. It is suggested that the urban water industry is operating within a constrained solution space created by questionable assumptions resulting in sub-optimal benefits to the community. The reasons for this are complex reflecting historical developments, institutional arrangements and current engineering paradigms. There is much work to be done to evaluate the efficacy of the currently held assumptions about the value of source control measures. An agenda for future work is proposed below in the context of allotment, subdivision and regional scales.

11.3.1 Future Research at the Allotment Scale

There are significant gaps in knowledge about the performance of the urban allotment and source control technologies in the context of the entire urban water cycle.

11.3.1.1 Design of the Rainwater Treatment Chain

The rainwater treatment chain includes roofs, first flush devices, rainwater tanks, pumps, filters and domestic appliances. This thesis has shown that the operation of the rainwater treatment chain can improve rainwater quality. It is important to develop an understanding of the performance of each of the elements within the rainwater treatment chain. A greater knowledge about the performance of the elements in the rainwater treatment chain will lead to improved designs that can maximise water quality and water conservation.

11.3.1.2 Water Quality in Rainwater Tanks

Over 3 million Australians drink rainwater from tanks [ABS, 1994] and many studies report the presence of bacterial indicator organisms Fecal Coliforms and Total Coliforms in tanks. Yet very few instances of human illness have been reported. The presence of bacterial indicator organisms may not indicate contamination of rainwater by pathogens. A detailed understanding of water quality in rainwater tanks and the development of indicators of poor water quality in tanks are required.

The quality of roof runoff improves in rainwater tanks. It appears that a number of processes operate to improve water quality in a rainwater tank including accumulation of microorganisms at the surface air-water interface (the water surface microlayer), flocculation and settlement in the tank, and the action of biofilms. However there is little scientific understanding of the microbial and biochemical processes involved in this treatment chain. Further research is needed to understand the processes that operate to improve water quality in rainwater tanks.

The Figtree Place and Maryville experiments (Chapters 2 and 3) showed that a treatment train exists for rainwater involving gutters, first-flush separation devices and hot water systems as well as the rainwater tank itself. Air-borne microbes and chemicals can enter rainwater tanks via the water collection process during periods of rain either directly from the atmosphere or indirectly by leaching of materials from water collection surfaces. Organic materials and microbes may also be derived from accumulated debris and excreta from animals and organisms colonizing or traversing the water collection surfaces.

When the concentration of dissolved organics falls below 25mg/L, there is an advantage for microorganisms to form attachments to the containment surfaces leading to the formation of biofilms. These biofilms have been extensively investigated in conduit systems for their impact on drinking water quality, by removal of chlorine and contribution to bacterial counts. However, literature searches did not reveal any research on biofilm activity in rainwater storage systems. Biofilms develop in complexity with time and deposit aggregates as part of a physical support and protection structure. As a consequence, these biofilms can become extremely efficient at removal of dissolved organics and can also remove potential contaminating metal ions. Rainwater storage tanks may therefore provide an effective mechanism for removal of dissolved organic and inorganic molecules. The low dissolved nutrient content would ensure that bacterial numbers do not proliferate in the water column.

Future research is needed to gain sufficient understanding of the distributions and functions of the microbial flora as well as the associated chemical dynamics in situ, which both affect water quality. This will provide the necessary information to facilitate the development of guidelines to ensure appropriate public health standards are maintained with the introduction of source control technologies. Without such guidelines the use of source control technology may not go ahead.

11.3.1.3 Outdoor Water Use

Monitoring of domestic water use at individual dwellings has provided unique insight into the patterns of domestic water use and allowed the development of the probabilistic behavioural outdoor water use model. Little is known about the spatial variation of domestic water use from different dwelling types and in response to a variety of socio-economic and climatic conditions over a range of time periods. How will the spatial, socio-economic and climatic variation in domestic water use impact on water distribution systems and demand management programs? Monitoring of the outdoor and indoor water use of domestic dwellings with different occupation rates subject to a variety of socio-economic and climatic conditions may improve planning for demand management programs and water distribution systems.

The probabilistic behavioural outdoor water use model was developed in this thesis using monthly monitoring data from the Lower Hunter region. The model simulates daily outdoor water use. The performance of the model should be verified using daily monitoring results in the Lower Hunter region and from a variety of other climatic zones.

11.3.1.4 The Allotment Water Balance Model

The allotment water balance model can be further developed to include wastewater disposal, water quality and lifecycle costs/benefits of the difference elements within the allotment water balance as shown in Figure 11.2. This will allow analysis of a wide range of integrated source control strategies including demand management, grey water reuse, water conservation, rainwater use and infiltration of stormwater.

The Allotment Water Balance can be used in the development and application of methodologies that optimise urban water cycle management at the allotment scale for a given climate and allotment scenario. In an optimisation problem it is necessary to define an objective, the constraints and a decision space within which the optimal decision is to be found. At the allotment scale the objective is to minimize the allotment owner's lifecycle costs associated with the provision of potable water supply and the disposal of storm and wastewater collectively referred to as water cycle services (shown as mains water, stormwater and wastewater charges in Figure 11.2). The need for provision of external water cycle services, namely mains water and off-site disposal of storm and wastewater, can be reduced by using source control technologies.

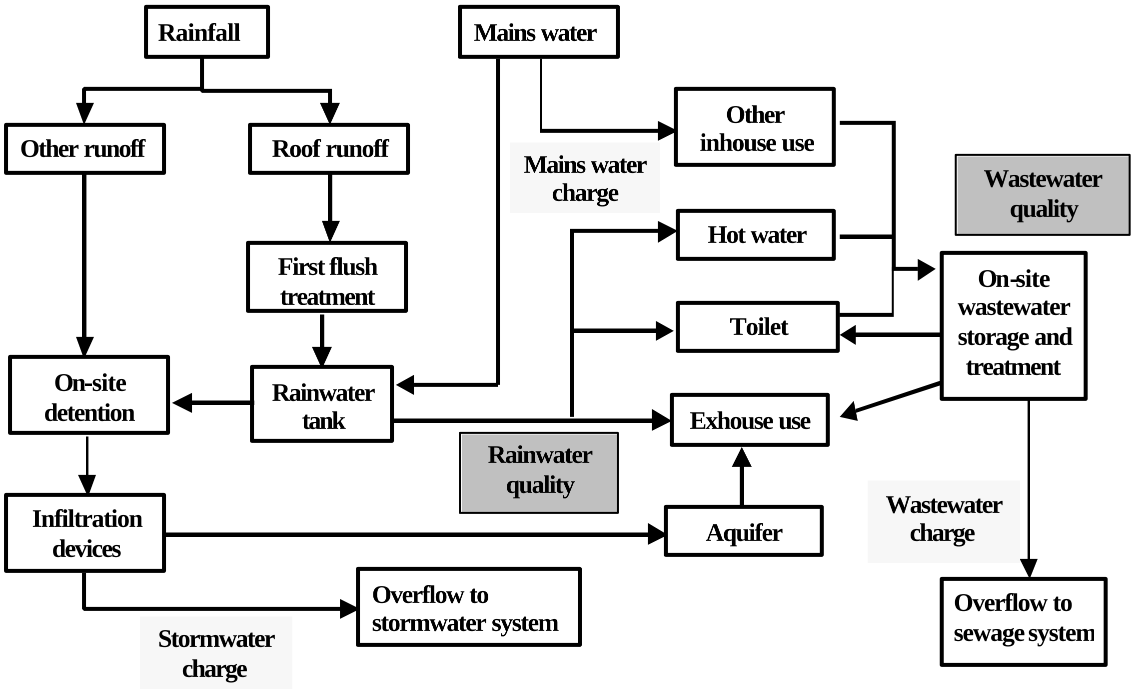

Figure 11.2: Schematic of the Allotment Water Balance model with further development

External water cycle services have a unit price ($/kL) payable to the agency responsible for providing the service. This price can be referred to as a shadow price, which represents the cost to community and environment for provision of water cycle services. In Australia unit pricing has been widely adopted in urban areas for mains water and sewage disposal. However, there are no similar pricing schemes for stormwater disposal, though it is noted such schemes have long been used in Germany. To minimize lifecycle costs on the allotment it is necessary to develop a simulation model of inhouse and exhouse water consumption, storm and wastewater disposal and all available source control technologies.

To be useful the model must be able to simulate a long (~100 year) rainfall history with 5-minute time steps. Unfortunately such long rainfall records are typically unavailable. This data limitation can be overcome by use of stochastic point rainfall models such as DRIP [Heneker et al., 2001]. DRIP can generate synthetic rainfall data at 5-minute resolution that is statistically indistinguishable from observed rainfall data. It can be applied to sites with little or no pluviograph data provided there is a daily rainfall record.

The purpose of the optimisation is to search for the mix of source control measures (type and size) and external water cycle services that minimizes allotment lifecycle costs. The search could be conducted using genetic algorithms, a robust probabilistic search method that is widely used in many disciplines. The expected outcome would be a methodology that defines an optimum water management solution at the allotment scale for particular climate and site conditions. Case studies in the major urban centres can be used to demonstrate the benefits of the methodology. This approach would provide an unambiguous basis for defining best practice at the allotment scale and potentially provide a greater range of technical solutions that can be considered at the subdivision and regional scales.

11.4.2 Future Research at the Subdivision Scale

The use of design storm bursts to design stormwater drainage systems in urban subdivision developments is current practice in the stormwater industry. The design storm burst approach, which is dependent upon assumptions about initial conditions such as antecedent soil moisture, appears to have limited usefulness. Indeed the performance of the design storm burst approach will be uncertain for analysis of traditional drainage systems that include source control measures such as rainwater tanks, on-site detention and infiltration trenches. The volume of water stored in the source control devices immediately prior to a rainfall event is unknown. Thus the results of simulation using the design storm burst approach will be uncertain.

The use of continuous simulation using climate records of sufficient length will substantially reduce uncertainty about the initial conditions in the urban catchment and the status of source control measures prior to storm events. The use of continuous simulation will also allow analysis of water quality, and lifecycle costs and benefits of various stormwater drainage strategies. Future research could develop continuous simulation methods for stormwater management and determine optimum stormwater drainage strategies for urban subdivisions in terms of lifecycle costs and environmental impacts.

The impact of source control measures on water distribution and sewerage disposal infrastructure in urban subdivisions has not been evaluated in this thesis. Source control measures such as rainwater tanks, demand management and grey water reuse have the potential to impact on the entire urban water cycle. Determination of the impact of source control measures in urban subdivision developments may require a systems analysis of infrastructure in the entire urban water cycle (water supply, stormwater and sewerage disposal). Future research could develop systems analysis methods for management of the urban water cycle at the subdivision scale and determine optimum management strategies in terms of lifecycle costs and environmental impact.

The WUFS stormwater management program [Kuczera et al., 2000] could be combined with the DRIP rainfall model [Heneker et al., 2001] and the Allotment Water Balance model developed in this thesis to allow continuous simulation of the performance of subdivisions that include source control measures as well as pipe drainage approaches. The modified WUFs could be combined with genetic algorithms to search for combinations of source control measures and traditional approaches that will minimise lifecycle costs and maximise environmental benefits. The author acknowledges that this will be a computationally challenging task that will probably require the use of parallel processing techniques. It is noted that Cui and Kuczera [2001] have developed methods for using genetic algorithms in a parallel virtual machine using PC technology to search for optimum solutions for water supply headworks operation. This procedure could be adapted for use in the search for optimum solutions for the management of water cycle services at the subdivision scale. In this thesis it was shown from a small number of studies that did not seek optimum solutions that the use of rainwater tanks on domestic allotment could provide substantial benefits to the community. The environmental and economic benefits of defining best practice at the subdivision scale for a given soil type and climatic condition may be considerable.

The modified WUFS could also interface with water distribution software such as EPANET and wastewater software such as MOUSE to enable a systems analysis of the full urban water cycle in a subdivision.

11.3.3 Future Research at the Regional Scale

The regional demand model developed in this thesis was able to predict the regional demand in the Lower Hunter and Central Coast regions. The efficacy of the model would be improved by calibration to daily regional demands in different categories. Monitoring data at the allotment and regional scales will provide significant improvement in the performance of the model outside of the Lower Hunter region. Monitoring at the allotment scale has been discussed above. Monitoring data for domestic, industrial, commercial water use in different water supply zones and entire regions will allow the model to determine the impact of rainwater tanks on volumetric and peak water demands in different zones and regions.

This thesis has shown that the widespread installation of rainwater tanks will have significant impact on stormwater management and water supply in the Lower Hunter and the Central Coast regions. This result was found in the shadow of industry claims that the use of rainwater tanks will provide no benefits. The nation faces an urban water crisis! What benefits will rainwater tanks and other source control measures provide in other regions such as Perth, Adelaide and Melbourne? These are serious and pressing questions that can no longer be dismissed by the urban water industries. Future research programs must evaluate the impact of source controls including rainwater tanks in all Australian cities.

Future research could seek to determine optimal regional urban water cycle solutions for the community and ecosystems. Optimisation at the allotment and subdivision scale minimises developer and resident owner lifecycle costs for a given set of shadow prices. These optima may not achieve optimal outcomes for the wider community and/or the ecosystem. There is a pressing need to develop and demonstrate a methodology for setting shadow prices that will favour sustainable use of ecosystem services. The use of shadow prices is not new. For example, in the 1960s the Harvard Water Program investigated shadow pricing for pollution abatement [Kneese and Bower, 1972]. By incorporating (or internalising) the cost of pollution in a producer's accounting, a profit-maximizing producer is encouraged to be environmentally responsible. Shadow pricing has seen little practical implementation in urban water cycle management until now.

If the shadow price for external services is low it is not economical for allotment owners to utilise source control measures, thereby putting maximum demand on ecosystem services. As the shadow price for external services increases source control measures become economically attractive thus reducing the demand on ecosystem services. Figure 11.3

illustrates the role played by shadow prices in the quest for optimal community and environmental outcomes. The shadow price incorporates two components: One to cover the cost of the external water service infrastructure, and the second to pay for use of ecosystem services. It is the latter component which represents a major research challenge.

To ascertain the optimal installation of water supply infrastructure and source control measures the iterative approach described by the flowchart in Figure 11.3a could be used. Initial shadow prices for external water services are assigned. The next step in the flowchart would be to find the best source control solutions at the allotment and subdivision scales by minimising lifecycle costs given the shadow prices for external water cycle services. These source control solutions place a demand on external water cycle services and in turn on ecosystem services.

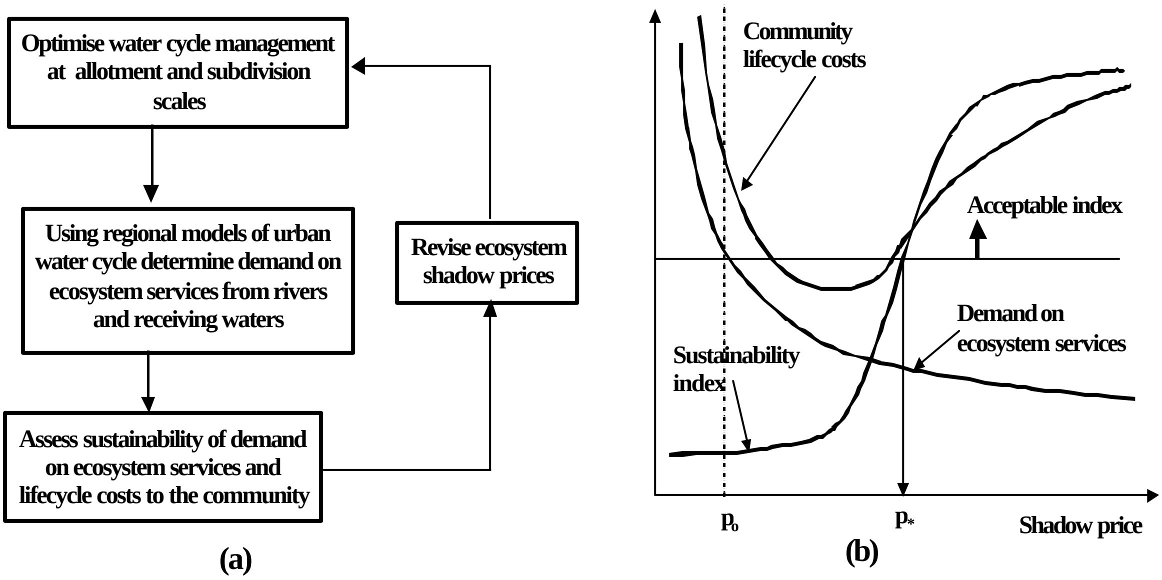

Figure 11.3. Flowchart for constructing demand/sustainability versus shadow price curves.

The next step in the flowchart would be assessment of the community infrastructure necessary to provide the external water cycle services. Such infrastructure may include new dams for water supply, extensions to water distribution networks, new stormwater drainage and treatment facilities and so on. The new and existing infrastructure puts a “demand” on ecosystem services: Rivers provide water supply; receiving waters assimilate urban pollutant loads; natural streams within urban catchments convey stormwater and so on. In providing these services the natural regime of ecosystems is modified: Rivers are dammed; receiving waters assimilate urban pollutant loads in excess of natural loads; streams receive frequent stormwater discharges; and so on. These changes to the ecosystem affect its sustainability and are characterised by a sustainability index worked out in the third step of the flowchart. Cycling through the flowchart of Figure 11.3a using different shadow prices could enable construction of the curves, shown in Figure 11.3b, relating shadow price to demand and sustainability.

There is no objective way of deciding what is an acceptable level for the sustainability index. It is a value judgement reflecting community values on modification and degradation of natural ecosystems and inter-generational equity. Once an acceptable index level is specified, the appropriate shadow price p_* is defined and, in turn, the "optimal" solutions for water cycle management can be found.

One of the curves in Figure 11.3b represents community lifecycle costs as a function of shadow price. In this example, the shadow price that minimises community lifecycle costs is not the same as the shadow price that provides acceptable environmental outcomes. Without this type of investigation, it is likely that the actual shadow price charged, for example p_o, is neither economic nor sustainable.

The significance of this future research is that it would provide a rational framework for the community to assess its water cycle management requirements at all three scales and would also provide an effective tool for government to set policy objectives.