Final Report on
Application and Refinement of
Assessment Tools for the
CSIRO Urban Water Program
Feasibility Study

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Urban Water Program

This report is one of the outcomes of the feasibility stage of the CSIRO's Urban Water Program.

The Urban Water Program is a multi-divisional project, sponsored by CSIRO's Executive, involving the Divisions of Building, Construction and Engineering, Land and Water and Molecular Science.

The vision for the Urban Water Program is "in the face of economic, social and climatic change, enable Australia's urban water systems to improve services to the community and improve economic performance while achieving ecological sustainability".

This report stands alone, but information included within it has been used within the wider Urban Water Program. Readers wishing to obtain more information about the Urban Water Program could contact Andrew Speers on 612 9490-5437 or at andrew.speers@dbce.csiro.au.

The Urban Water Program website can be visited at www.dbce.csiro.au/urbanwater.
ACKNOWLEDGEMENTS

Contributors

All members of the team contributed to this report, either directly or through incorporation of documentation written during the course of the project. Chris Zoppou, principal research scientist on this project, designed the report format and compiled the first draft. Shiroma Maheepala, senior research scientist, contributed to the sections on TAWS and Scenarios. Susan Cuddy, contract manager, and John Coleman were joint editors.

In addition, the modelling team worked closely with other members of the Urban Water Program, particularly in the provision of the contaminant balance model and the provision of data on treatments, pipe specifications and life cycle costing.

Acknowledgement of the roles of team members in providing documentation or material for the various sections in this report are as follows:

<table>
<thead>
<tr>
<th>Section</th>
<th>Contributor</th>
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<tbody>
<tr>
<td>UVQ Flow Balance Model</td>
<td>Grace Mitchell</td>
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<tr>
<td>UVQ Contaminant Balance Model</td>
<td>Steve Gray and Trevor Farley</td>
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<td>TAWS</td>
<td>Shiroma Maheepala, Mike Rahilly, Chris Zoppou, Michael Reed</td>
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<td>TAWS Simulated Annealing</td>
<td>Mike Rahilly, Bertil Marksjö, Shiroma Maheepala, Leorey Marquez</td>
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<tr>
<td>TAWS Batch processing</td>
<td>Leorey Marquez</td>
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<td>Scenario Manager</td>
<td>John Coleman</td>
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<td>Network Designer</td>
<td>Michael Reed</td>
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<td>Life Cycle Costing</td>
<td>Selwyn Tucker, Mike Rahilly, Shiroma Maheepala, Grace Mitchell</td>
</tr>
<tr>
<td>Case study description</td>
<td>Shiroma Maheepala, Grace Mitchell, Susan Cuddy, Robert Shipton</td>
</tr>
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<td>Climate</td>
<td>Neil Viney, Bryson Bates (Land and Water, Perth)</td>
</tr>
<tr>
<td>Scenarios</td>
<td>Shiroma Maheepala, Michael Reed, Chris Zoppou</td>
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<td>Future Directions</td>
<td>Chris Zoppou</td>
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</table>

Data and Model Providers

All agencies who were approached to provide data, or assist with data collection and interpretation, were co-operative and extremely helpful. We thank them for their contribution and good will. In particular, the Western Australian Water Corporation, the Western Australian Ministry for Planning, Western Australia Water and Rivers Commission, Agriculture Western Australia and the Bureau of Meteorology contributed significant resources to preparing the data used in the project.

Special reference must be made to the assistance of members of other teams within the Urban Water Program. In particular, we wish to thank Dhammika de Silva (CSIRO Building, Construction and Engineering) for collection and formatting of the pipes specifications data, Prem Mathes (CSIRO Molecular Science) for collection and formatting of the treatments data, and Norm Becker (CSIRO Molecular Science) for collection of contaminants data.

We would also like to acknowledge the generosity of the Co-operative Research Centre for Catchment Hydrology and Dr Grace (V.G.) Mitchell in permitting the Urban Water Program to use AQUACYCLE source code to develop the water and contaminant balance model (i.e. the UVQ model).
EXECUTIVE SUMMARY

At the commencement of the Urban Water Program, it was agreed that there was a need to use models to provide rigour and flexibility to the scenario development. Within the group, there was already one model available which dealt with water infrastructure and supply, namely the Integrated Water Resources Decision Support System (IWR DSS), developed by CSIRO Building, Construction and Engineering for a regional study of water allocation in the Spencer Gulf. This model provided the basic components upon which scenarios could be developed and assessed: namely methods to represent the case study water transport infrastructure, to cost alternative configurations of infrastructure and supply, and to include water treatment options, while providing hydraulic and hydrologic integrity. This model provided a firm foundation for the development of an integrated urban water model suitable for the type of scenarios that the UWP would be investigating. However, to achieve these objectives the following enhancements were required to IWR DSS and were written into the task contracts:

♦ incorporate wastewater infrastructure and costing
♦ improve the water treatment component
♦ incorporate stormwater infrastructure and costing
♦ enable recycling and reuse of water between the potable, waste and storm water networks
♦ improve the costing functions to incorporate life cycle costing
♦ incorporate an interface to manage scenarios descriptions and data files, running of models, and storage and analyses of results.

The enhancements to the IWR DSS were scheduled in two phases:

♦ Phase 1 which incorporated the life cycle costing of the potable water infrastructure
♦ Phase 2 which incorporated the waste and storm water infrastructures and their costings.

A major objective of this project was the ability to investigate scenarios that were independent of spatial and temporal scales. As the spatial and temporal scales of the IWR proved to be incommensurate with the choice of scenarios, it was necessary to include an urban water balance model. An existing model, AQUACYCLE, which operates at a time scale of a single day, was chosen to model the water cycle. This model was enhanced by modifying a number of flow paths. A contaminant balance model was developed as part of this model. While these extra models were tasked under other contracts, they form part of the UWP model suite.

To manage the integration of these models, the selection of various components for each scenario, the presentation of results and manage the data, these components were encapsulated within a modelling framework. The Scenario Manager was developed for this purpose.

To test the modelling framework and to demonstrate the feasibility of effectively incorporating models at different spatial and temporal scales, it was applied to a hypothetical case study based on a real site. This case study provided the opportunity to also examine a number of scenarios. Contract 4.1 undertook the description of the case study in a format suitable for modelling.

PERFORMANCE AGAINST MILESTONES AND DELIVERABLES

Milestones and deliverables were revised during the project to reflect the changed nature of the modelling requirements and the development of the TAWS (Tool for Assessing Water Systems) DSS which integrated the storm and waste water networks with the IWR DSS.
MILESTONES

- IWR DSS running for case study - achieved by April 1999
- TAWS Stage 1 running for case study - achieved by July 1999 though costing functions constantly being enhanced
- TAWS Stage 2 running for case study - not yet achieved.

DELIVERABLES

The delivery of software was accompanied by a series of review and/or design documents. These were written as a series of internal working papers, some of which are referenced below. Many of these papers are being incorporated into reports. A complete list of working papers is in an Appendix to this report.

- Review of computer tools and models available for planning of alternative urban water systems completed (UWP Working Paper T4-1)
- Review of storm water models completed (UWP Working Paper T4-20)
- Data Specifications prepared and distributed to contract managers for collection and formatting of data (UWP Working Papers T4-33, T4-35)
- Description of case study land uses, potable water network and supply and demands for inclusion in IWR/TAWS completed for both 199x and 2020 (UWP Working Papers T4-32, T4-34)
- Life cycle costing specifications completed and implemented (UWP Working Paper T4-29)
- Application of IWR model to study area in Perth documented (UWP Working Paper T4-32)
- Specifications to include storm and waste water within IWR completed and link with urban water and contaminant balance models completed (UWP Working Papers T4-17 and T4-19)
- Specifications for contaminant balance model (UWP Working Paper T4-47)
- Specifications for Scenario Manager (UWP Working Paper T4-42)
- Review of alternative methods on improving optimisation process within IWR DSS (UWP Working Paper T4-18)
- Analyses of alternative scenarios of the case study (UWP Working Papers T4-39, T4-40, T4-41, T4-45).

MAJOR PUBLICATIONS

In addition to the working paper series, and this report and its companions, the work has been reported to the wider community through:


# Table of Contents

- **Acknowledgements** ii
- **Executive Summary** iii
  - Performance Against Milestones and Deliverables iii
  - Milestones iv
  - Deliverables iv
  - Major Publications iv
- **Introduction** 1
  - Background 1
  - Objectives 2
  - Associated reports 2
  - Report Format 3
- **Modelling Framework (CUWPID)** 4
  - Scenario Manager 5
    - Urban Water System Representation 5
  - UVO Flow and Contaminant Balance Model 8
    - Flow Balance Model 8
    - Contaminant Balance Model 9
  - TAWS Model 12
    - Main Components 13
  - Scenario Designer 18
    - Estate Designer 18
    - Cluster Designer 19
    - House Designer 20
    - Network Designer 22
  - Other Models 28
    - Treatment Process Selector 28
    - WWTreat 29
    - Flash Flooding 29
    - Externalities 29
  - Scenario Reporter 29
- **Application** 30
  - Description of Perth North-East Corridor Study Area 30
    - Estates 31
    - Climate 32
    - Population 33
    - Land Use 33
    - Inflows 34
    - Water Supply, Waste and Storm Water Networks 34
  - Assessment of Scenarios 36
    - Issue 1 - Implications of Levelling of Peaks for an Existing Development 38
    - Issue 2 - Implications of Levelling of Peaks for a Greenfield Development 38
    - Issue 3 - Implications of the Adoption of Polyethylene Pipes 39
    - Issue 4 - Implications of Reducing Pressure Class of Pipes 40
    - Issue 5 - Can the Optimisation Find a More Cost-Effective Transport Option? 41
  - Issue 6 - Implications of Elevated Atmospheric CO₂ Concentrations 42
- **Conclusions** 44
- **Future Directions** 45
  - Model Enhancements 45
  - Research Opportunities 46
- **References** 48
- **Appendix A** The Contaminant Balance Model A-1
Contaminant Flows and Contaminant Profile Operations.......................................................... A-1
Indoor Scale .......................................................................................................................... A-2
Unit Block Scale .................................................................................................................. A-4
Cluster Scale ....................................................................................................................... A-5
Estate Scale .......................................................................................................................... A-7

♦ Appendix B  Simulated Annealing Algorithm
B-1

♦ Appendix C  Hydraulic Feasibility Analysis in Taws
C-1

Water Supply Network ........................................................................................................ C-1
Waste Water and Storm Water Networks ............................................................................. C-2
Pressurised Flows ................................................................................................................ C-3
Open Channel Flows ........................................................................................................... C-3

♦ Appendix D  Contract 4 Working Papers
D-1

List of Tables

Table 1. The spatial and temporal scale of UVQ and TAWS in the UWP feasibility study ........6
Table 2. Symbols used in flow and contaminant paths in the UVQ diagrams ......................... 10
Table 3. Contaminant profiles required for the contaminant balance ........................................ 11
Table 4. Contaminants included in a contaminant profile in UVQ ............................................. 11
Table 5. Symbols used in the Network Designer ....................................................................... 23
Table 6. A sample of entries in the Treatments Specifications Table in TAWS ......................... 28
Table 7. Estates of the Study Area showing total area and number of clusters ......................... 32
Table 8. Average temperature and rainfall in Perth and the Study Area .................................... 33
Table 9. Populations within Estates .......................................................................................... 33
Table 10. Land use categories used for modelling ................................................................... 33
Table 11. Details of potable water supply for clusters in each estate ......................................... 35
Table 12. Residential households in each estate served by the water supply system .............. 35
Table 13. Issues explored using TAWS (v1.0) .......................................................................... 36
Table 14. Scenarios developed for exploring issues identified in Table 13 ............................... 36
Table 15. Cost implications of adopting polyethylene pipes for pipe sizes <300 mm over traditional pipes .......................................................... 40
Table 16. Cost implications of adopting polyethylene pipes with pressure class 6.3 over polyethylene pipes with pressure class 16 for the reticulation system .......................................................... 40
Table A-1. Description of the symbols used in the flow and contaminant paths in the UVQ diagrams .......................................................... A-1
Table A-2. Identification of input and output flows and contaminant paths in UVQ .................... A-2
Table A-3. Location of contaminant profile operations at indoor scale .................................. A-3
Table A-4. Location of contaminant profile operations at unit block scale ............................ A-4
Table A-5. Location of contaminant profile operations at cluster scale ................................. A-6
Table A-6. Location of contaminant profile operations at estate scale .................................... A-8
Table C-1. Values of the Hazen-Williams coefficient C for different conduit materials and age of conduit ........................................... C-3
Table C-2. Average values for the Manning resistance coefficient, n for various channel material type ...................................................... C-3
Table C-3. Hydraulic properties of various channel shapes ....................................................... C-4
Table D-1. Set of Contract 4.1 final reports ............................................................................. D-1
Table D-2. Cross-reference of Contract 4.1 working papers to final reports ......................... D-1
List of Figures

Figure 1. The conceptual structure of CUWPID................................................................. 4
Figure 2. Diagram of nested view of estates, clusters and houses.......................................... 5
Figure 3. Diagram of network view of estates........................................................................ 6
Figure 4. Diagram of indoor contaminant and flow paths in UVQ........................................... 10
Figure 5. Sequence of steps in the execution of TAWS............................................................ 15
Figure 6. The conceptual structure of the Scenario Designer.................................................... 18
Figure 7. Estates View in the Scenario Designer...................................................................... 19
Figure 8. Estate Designer in the Scenario Designer................................................................. 19
Figure 9. House Designer - General Properties...................................................................... 20
Figure 10. House Designer - Water Use Behaviour................................................................. 20
Figure 11. House Designer - Garden Properties..................................................................... 21
Figure 12. House Designer - Contaminant Specifications......................................................... 21
Figure 13. Household Contaminant Specifications................................................................. 22
Figure 14. The Network Designer’s view of an urban water system....................................... 22
Figure 15. Diagram of a TAWS logical network in the Network Designer................................. 23
Figure 16. Diagram of a TAWS physical network in the Network Designer.............................. 24
Figure 17. Attributes of a storage node................................................................................... 25
Figure 18. Attributes of a pipe............................................................................................... 26
Figure 19. Attributes of a water quality profile...................................................................... 26
Figure 20. Attributes of a treatment option............................................................................. 27
Figure 21. Life cycle cost functions....................................................................................... 28
Figure 22. Topographic map of Study Area............................................................................ 31
Figure 23. Map of Study Area Estates.................................................................................. 32
Figure 24. Schematic diagram of the water supply system in the study area............................. 34
Figure 25. Monthly demands for Bullsbrook cluster during the simulation period.................... 37
Figure 26. Cost savings offered by peak levelling in the current water supply system in Perth NEC 38
Figure 27. Diagram of simplified physical network showing the location of the failed pipes...... 41
Figure 28. Cumulative rainfall for different levels of CO2........................................................ 42
Figure A-1. Diagram of indoor contaminant and flow paths in UVQ....................................... A-3
Figure A-2. Diagram of unit block contaminant and flow paths in UVQ................................... A-4
Figure A-3. Diagram of cluster contaminant and flow paths in UVQ........................................ A-6
Figure A-4. Diagram of estate level contaminant and flow paths in UVQ................................. A-8
Figure B-1. Pseudo code for simulated annealing algorithm................................................... B-1
Figure C-1. Characteristics of pressurised pipe flow.............................................................. C-1
Figure C-2. Characteristics of a partially full pipe flow............................................................ C-4
Figure C-3. Characteristics of a trapezoidal channel............................................................... C-5
Figure C-4, Flow in a partially full circular pipe....................................................................... C-5
INTRODUCTION

BACKGROUND

By the year 2000, it is estimated that one-half of the world's population will be living in urban areas. The high concentration of human activity in urban areas has significantly stressed water resources in the urban environment. The scale of human activity in urban areas has now reached such proportions that the impact on one single generation is comparable with the impact of all preceding generations.

In the past the solution of water resources problems has led to (Jermar 1987):

♦ the separate development of surface and ground water resources,
♦ the use of high quality water for low quality requirements and visa versa,
♦ the excessive use of water for certain purposes thus inhibiting or excluding more valuable uses,
♦ neglecting water re-use, water re-cycling and waste material recovery possibilities and other water saving practices,
♦ the loss of nutrients or raw material from place of immediate or potentially easy utilisation, and
♦ neglecting important secondary aspects, constraints and hazards of many water and other development projects.

This has led to:

♦ excessive use of natural resources,
♦ the increase in deterioration of the natural environment, and
♦ the economic failure of many water development projects.

The origins of this predicament stem from traditional thought processes for tackling resource problems. In the past, resource problems were addressed by maximising economic benefits only. This was sufficient when resources were in abundance and there was no need to account for any secondary consequences of the decision process. The increasing pressure for water is forcing the development of marginal projects, which would not have been considered a few years ago. If current levels of development are to remain sustainable, they must be planned with more care and thought than was required for the more obvious projects in the past.

Present-day water management problems are inter-disciplinary and as such include complex phenomenon with complicated inter-relationships. These must be considered in order to cope with increasing demands for water. The solution of such complex and interdisciplinary problems calls for an integrated water resources management approach that includes ecological, economic, social and political aspects.

CSIRO has identified the inter-disciplinary management of water resources in the urban environment as a priority area for research and has initiated the Urban Water Program (UWP). The objective of this program is to identify and develop technologies which are commercially valuable, scientifically robust, and improve the cost effectiveness of urban services while achieving ecological sustainability. This Program is intended to integrate urban drainage, water supply and waste water transport systems in an urban environment and to evaluate these systems in terms of hydrological, hydraulic, ecological, social and economic impacts.

Water resource managers in the near future will be involved with new technologies and emerging strategies. With these, managers will be able to conceptualise ingenious methods of improving the efficiency of and improving the environmental outcome from their water assets, as well as develop alternative strategies for addressing water resources problems.

Unfortunately, there are very few methods available for a water resource manager to assess the benefits and implications of innovative ideas. The most flexible and cost effective approach for examining these scenarios is with the use of a computer model. In general, computer models focus on one aspect of the
urban water cycle. To adequately assess the implications of various management strategies, a holistic approach to the urban water cycle must be considered. Integrating water supply, waste water and storm water systems, into a single modelling framework, represents a more realistic approach than the traditional approach, where water supply, waste water and storm water systems are considered as separate entities in the urban water cycle. The major advantage of the integrated approach is that it enables consequences of management decisions to be assessed by considering interactions among the three urban water streams.

OBJECTIVES

The objective of this project within the Urban Water Program feasibility study was to develop tools to provide rigour and objectivity in the evaluation of alternative urban water systems scenarios. These tools were to be developed within a modelling framework which should be flexible enough to allow the user to examine and evaluate existing and new water management practices. Another requirement of the modelling framework was that it should be suitable for application to any urban area in Australia and therefore it must be generic.

While this report describes a full implementation of the modelling work, only a prototype was built during the feasibility study. Those components which have been implemented are identified within the various sections in this report.

The objectives of this report are twofold:

♦ to document the modelling work undertaken within Contract 4.1 of the Urban Water Program; and
♦ to convey to the reader an understanding of the breath of the modelling work and its application.

ASSOCIATED REPORTS

This report is accompanied by six technical reports. These reports provide detailed information on the technical specifications of the TAWS model (stages 1 and 2), the contaminant balance component of the UVQ model, the characterisation of the Perth North East Corridor Study Area, and the Scenario Manager. These reports are:

♦ Integrated Water Resource Model - Methodology, Implementation and Application (Maheepala et al. 2000a)
♦ Tool for Assessing Water Systems (TAWS) - Methodology (Maheepala et al. 2000b)
♦ Tool for Assessing Water Systems (TAWS) - Design, Implementation and Data Specification (Maheepala et al. 2000c)
♦ The Scenario Manager - Functionality and Implementation (Coleman et al. 2000)
♦ Contaminant Balance component of UVQ Model - Technical Specification (Farley 2000)
♦ Characterisation of the Perth North-East Corridor Study Area (Cuddy et al. 2000)

Reports describing complimentary modelling work in other UWP contracts, which are directly relevant to the modelling work described in this and its associated reports, are:


In addition, a series of working papers were prepared during the life of the project. While many of these have been used as source for the technical reports listed above, many have remained as internal working papers. These are listed in Appendix D.
REPORT FORMAT

This report has four sections:

♦ modelling framework
♦ application
♦ conclusions
♦ future directions.

The first section introduces the modelling framework and the models contained therein. It includes an overview of the way in which the urban water system is represented as that representation strongly influences the interface design and modelling capabilities. The interface and models are described in some detail, with further technical information contained in Appendices.

The Application section describes the case study, which is based on data collected for a real site in Perth, and the use of the tools for the assessment of a range of scenarios for that case study. These alternative scenarios are subject to water quality, hydrologic and hydraulic constraints, and they are evaluated using infrastructure life cycle costs. This section demonstrates the capability of the modelling.

The report concludes by identifying model enhancements and research opportunities.
MODELLING FRAMEWORK (CUWPID)

CUWPID is a collection of software applications designed to provide an easy-to-use interface to applications that evaluate alternative urban water systems. The modelling framework provides for the description, analysis and comparison of alternative urban water system configurations, called scenarios.

CUWPID demonstrates that it is possible to develop an integrated water supply, waste water disposal and treatment, and storm water quality and quantity model. It is flexible and facilitates the exploration of opportunities for improving the provision of urban water services. It relies on data collected as part of the Urban Water Program, which characterises Australian urban regions.

While the methodology for the modelling framework and models was developed during the feasibility study, full implementation was not realised due to the time constraints of such a study. The inclusion of storm and waste water proved to require major enhancements and its implementation may expose the need for further refinement.

![Figure 1, The conceptual structure of CUWPID](image)

The major components of CUWPID are shown in Figure 1. It includes; (i) a scenario designer, (ii) the Urban Volume and Quality (UVQ) model, (iii) the Tool for Assessing Water Systems (TAWS) model, (iv) Other Models and (v) Scenario Reporter. These components are accessed through a scenario manager. Each of these components is described in detail in the following sections.

The Scenario Manager controls the type of models that can be accessed, the input of data, the presentation of results (via the Scenario Reporter) and enables the user to specify an integrated water supply, waste water and storm water infrastructure (via the Scenario Designer). In the current version of CUWPID there are two models that can be accessed. These are UVQ and TAWS.

UVQ is based on the AQUACYCLE water balance model developed by V.G. Mitchell, CRCCH1 (Mitchell 1998). UVQ performs a water volume and water quality balance. It can be executed independently of the other models and has the additional benefit that it can be used to provide data for TAWS. Since UVQ is a balance model it ignores the spatial variability of the problem.

TAWS is based on the Integrated Water Resources Decision Support System (IWR DSS) developed by CSIRO Building, Construction and Engineering (Maheepala and Gibert 1997). TAWS extends the capabilities of the IWR DSS by allowing the assessment of the cost-effectiveness of alternative integrated water supply, waste water and storm water networks, using full life cycle costs.

Models that are thought to be valuable in assessing urban water scenarios, such as urban water infrastructure design models, would reside in the Other Models component of CUWPID. A method for

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1 Co-operative Research Centre for Catchment Hydrology
selecting treatment process alternatives, known as the treatment process selector, was designed, but not implemented, during the feasibility study and is described in this report.

**Scenario Manager**

The scenario manager is the interface between the user and the scenarios. It facilitates the design of networks and provides and validates data for the various models. The user selects a region, then a scenario, to either create, edit, delete or run. It is also intended that scenarios can be compared to other scenarios. The scenario manager also decides which models are executed and if necessary the sequence in which the models should be executed.

To allow the Scenario Manager to run the underlying models, interfaces were written that allow the models to be run in 'batch mode'. For the TAWS model, a unique command language was developed by Marquez (Maheepala, Rahilly and Marquez 2000) to automate the running of the model via a series of instructions stored in a comma delimited text file. The instructions follow a simple syntax and consist of English-language keywords that mirror the menu options used in the interactive version of the model. Interfaces to run the UVQ model in various modes were less complicated and rely on creating and passing text files to the program.

**Urban Water System Representation**

In this modelling framework, a study area is referred to as a region. Within a region there are a number of estates that consume water and produce water of various qualities. Estates are used to represent a collection of residential, industrial and agricultural areas. An individual area within an estate is referred to as a cluster. A cluster can only contain houses of the same type, or represent an industrial area or an agricultural area that consumes water of a particular quality. These spatial distinctions lend themselves to a nested structure and the interface has been designed in this way (see Figure 2). The user can thus create and link objects (region, estate, cluster, house). Once created and linked, the properties of each object are accessible for editing and viewing. Some of these properties are described in this report, in the sections on the models or the interface component (Estate Designer, Cluster Designer, House Designer, Network Designer) which creates the data for the model.

![Figure 2, Diagram of nested view of estates, clusters and houses](image)

There is a further view, the network view, which visually shows the linkages between the various estates and water supplies. This view cannot be built until the estates have been described in the nested view. Figure 3 is a illustration of the network view.
Modelling of water movement and transport is done at all scales. UVQ performs a water volume and water quality balance at household level through to estate scale. In this framework, TAWS operates at estate and regional scales only.

UVQ and TAWS also operate at different temporal scales (see Table 1). TAWS operates on a monthly time step, whereas UVQ operates on a daily time step. Therefore TAWS is appropriate to evaluate infrastructure between clusters (i.e. estate level) and estates (i.e. regional level) using monthly time steps. These temporal and spatial scales are consistent with the scales used to make planning decisions. Thus, CUWPID is best classed as a planning, not a design, tool.

Table 1, The spatial and temporal scale of UVQ and TAWS in the UWP feasibility study

<table>
<thead>
<tr>
<th>Scale</th>
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<tr>
<td>Spatial</td>
<td></td>
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<tr>
<td>House</td>
<td>✔</td>
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<td>Unit Block</td>
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Nested View

The spatial hierarchy of regions, estates, clusters and houses (or unit blocks) allows for the ready identification of input, output and flow paths through urban areas. The representation used here (based on AQUACYCLE (Mitchell 1998)) integrates the potable supply-wastewater disposal network with the rainfall-runoff network to provide a more holistic view of the urban water system. Thus it incorporates the land phase of the hydrological cycle, as modified by urbanisation, and the constructed water supply and wastewater disposal systems.

The 'naturally occurring' processes of interception, depression storage, soil infiltration, evapotranspiration, interflow, soil drainage, and pervious surface runoff occur alongside the 'urban' processes of pipe infiltration and exfiltration, unplanned stormwater inflow, and impervious surface
runoff. Inputs into the stormwater drainage network are not derived solely from rainfall, but also include contributions from the reticulation system through outdoor water use.

Imported water leaks to the groundwater and is applied to parks and gardens as well as being used indoors for residential, commercial, industrial, and municipal purposes. In addition to draining wastewater from indoor water uses, the wastewater disposal system receives additional input due to unplanned stormwater inflow, and infiltration of soil moisture into the pipe network; and on the outflow side sewer overflows and pipe leakage (exfiltration) may be factors.

This representation and the above terms are used in describing the UVQ model and the Estate, Cluster and House Designer components.

Network View

The water system representation and terms introduced here are used in the sections on the TAWS model and the Network Designer. They provide an elegant representation of the supply, transport and demand system that characterises urban water systems.

The network view has in fact two views: a logical network and its associated physical network. The logical network defines conceptual flow paths of water supply, waste water and storm water in an urban area. The physical networks define the actual physical paths that the water can travel.

Logical Network

The logical network shown in Figure 15 page 23 consists of logical links and logical nodes. Logical links represent conceptual flow paths between logical nodes. Logical links have a direction and carry water of a particular quality (potable water, grey water, black water, storm water, etc.) from one logical node to another.

There are two types of logical links:

- **Supply link** - A supply link carries water to satisfy a demand of an end node;
- **Disposal link** - A disposal link carries away surplus water from a node. There are 3 types of disposal links: a wastewater disposal link which carries away wastewater; a stormwater disposal link which carries away stormwater; and a spillage disposal link which carries spilled water of any quality (note that the spillage disposal link is not yet implemented).

There are five types of logical nodes which match the nodes of the same names described in the Network Designer:

- **Demand node** - A demand node consumes a particular quality of water and produces water of a particular quality that cannot be kept within the node. Storage is not provided at a demand node. Examples of demand nodes are residential indoor water use, residential outdoor water use and non-residential water uses such as industrial, commercial and agriculture.
- **Source node** - A source node is an independent water source that supplies water of a particular quality. A source node may have a storage facility. Examples of source nodes are reservoirs in the headwaters of a catchment, storm water runoff from a drainage catchment, rainwater tanks and groundwater aquifers.
- **Storage node** - A storage node is a dependent water source (i.e. a storage node can receive or demand water from other nodes) that stores water and supplies water of a particular quality. Examples of storage nodes are retarding basins and Aquifers with Storage and Recovery facilities (ASR).
- **Receiving node** - Water sent to a receiving node leaves the system. This may represent discharging into the environment. Examples of receiving nodes are ocean outfall and inland waterways.
- **Treatment node** - A treatment node provides a series of treatment processes for changing the quality of the water. During the treatment process there may be some loss of water. There are two types of treatment nodes depending on whether the treatment node can also store water. The first type, *direct*
transfer treatment nodes, have no facility to store water within the node (e.g. water supply treatment plant). The second type, storage transfer treatment nodes, have facilities to store treated effluent within the node (e.g. a sewage treatment plant with holding ponds).

Physical Network

The physical network defines the actual physical path that water can travel between logical nodes. The physical network will generally consists of pipes, open and natural channels. Mixing of water of different qualities is not permitted in the physical network. Therefore, the physical network may consist of a number of sub-networks, each transporting water of different quality. Currently, TAWS is restricted to only three qualities of water and therefore only three types of networks are considered:

- Water Supply Network transports potable water. It is assumed that this network carries pressurised flows and consists of circular pipes.
- Waste Water Network transports waste water produced by the nodes. It is assumed that this network carries pressurised or non-pressurised flows and consists of circular pipes.
- Storm Water Network transports storm water. It is assumed that this network carries non-pressurised flows and consists of either circular pipes or open channels.

The physical network consists of physical nodes and physical links. The physical nodes represent pipe junctions, service reservoirs, or logical nodes, see Figure 16, page 24. The physical links may consist of a single pipe, a number of parallel pipes or an open channel. Flow may be conveyed in either direction in a reversible physical link, however, a network cannot have closed loops. Reversible physical links are sized to convey the greatest flow required in the link.

The physical links may have associated pumping stations to provide additional head for delivering water in the physical network. Only one pumping station is permitted per physical link. However, this assumption produces problems for reversible physical links if pumping is required in both directions. To avoid such problems, it is further assumed that for reversible physical links, pumping stations can deliver the maximum discharge in both directions.

A pumping station usually consists of a number of pumps. It is assumed that all the pumps in a pumping station are of the same type. Pumps may be arranged in parallel, series or a mixture of parallel and series. The configuration is determined by the model according to the discharge and pressure head to be delivered.

Thus the physical network provides for the modelling of the hydraulics of transporting water and this enables estimation of the hydraulically feasible infrastructure requirement for calculation of infrastructure costs.

UVQ FLOW AND CONTAMINANT BALANCE MODEL

UVQ is used to estimate a time series of water demand and storm water and waste water production for urban estates and to model the flux of contaminants through urban estates. UVQ combines two models - a flow balance model, and a contaminant balance model. These are described below.

FLOW BALANCE MODEL

To provide a means of describing the flow of water through the existing urban water, waste and storm water systems, from source to discharge, at a local scale, a conceptual urban water balance was required. A generic urban water balance model called AQUACYCLE developed by Mitchell (1998) was selected after a review of available models. The model operates on several spatial scales (unit block, cluster, and catchment) and receives input from both precipitation and imported water, which pass through the system and exit in the form of evapotranspiration, stormwater, or wastewater. AQUACYCLE can "store" stormwater and wastewater separately and utilise them as supply sources for water applications according to the users
specifications. AQUACYCLE was enhanced for CUWPID to effectively handle waste water disposal using septic tanks and leachfields; stormwater disposal using spoungdrains and infiltration basins; exfiltration from the sewerage system; and, overflow from the waste water system. Although exfiltration and overflow from the wastewater system involve comparatively small water flows, they are important for the transportation of contaminants within the urban water system.

The development and implementation of the flow balance model in the UWP feasibility study is fully described in Mitchell and Maheepala (1999).

**CONTAMINANT BALANCE MODEL**

The contaminant balance model utilises the flows calculated by the flow balance component. The movement of contaminants is calculated immediately after the flows have been calculated for each daily time step.

Both the contaminant and flow balance components in UVQ solve the continuity equation given by

\[
\frac{DS}{Dt} = I - O
\]

in which \( I \) is the inflow, \( O \) is the outflow, \( S \) is the storage and \( t \) is the time. It simply states that the change in storage, \( \Delta S \), is equal to the difference between the inflow and outflow over the time interval, \( \Delta t \).

UVQ represents an urban area at several spatial scales. These are the (i) house/indoor, (ii) unit block, (iii) cluster, and (iv) estate. The house scale will generally represent water use within a residential house. However, it could also represent a factory, hospital, school, shopping centre or an airport. In these cases, a unit block represents a single property that can contain buildings, paved areas, and pervious areas such as gardens. A cluster is a number of homogeneous unit blocks as well as roads and public open spaces. An estate consists of a number of clusters that may or may not have the same land use.

Within each spatial scale a number of water sources, storages, demands, treatments and connecting flow paths have been identified. These are the only paths available for the transport of contaminants and flow through UVQ’s representation of the urban system. They cannot be changed, only switched on or off.

An example of the flow and contaminant paths at the house/indoor level is shown in Figure 4. Most of the characteristics of water utilisation in a building are included in this diagram. Diagrams depicting the unit block, cluster and estate levels are provided in Appendix A.

In these diagrams stars indicate that a mass of contaminant is added to the flow. For example, the kitchen, bathroom, laundry and toilet add a mass. The output from treatment processes can be specified by either a fixed contaminant concentration profile, indicated by a cross, or from calculated values. Examples of the former in Figure 4 are tap and tank water.

The symbols used to describe flow/contaminant paths in Figure 4 are listed in Table 2.

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2 This section is adapted from Farley et al. (2000).
Figure 4, Diagram of indoor contaminant and flow paths in UVQ

Table 2, Symbols used in flow and contaminant paths in the UVQ diagrams

<table>
<thead>
<tr>
<th>Flow/contaminant path</th>
<th>Symbol</th>
<th>Symbol Style</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain / Tap Water</td>
<td></td>
<td>solid blue line</td>
</tr>
<tr>
<td>Tank Water</td>
<td></td>
<td>solid teal line</td>
</tr>
<tr>
<td>Black Water</td>
<td></td>
<td>solid black line</td>
</tr>
<tr>
<td>Grey Water</td>
<td></td>
<td>solid grey line</td>
</tr>
<tr>
<td>Storm Water</td>
<td></td>
<td>solid green line</td>
</tr>
<tr>
<td>Ground Water</td>
<td></td>
<td>solid red line</td>
</tr>
<tr>
<td>Link at this level</td>
<td></td>
<td>solid black arrowed line</td>
</tr>
<tr>
<td>Link at another level</td>
<td></td>
<td>dashed black arrowed line</td>
</tr>
<tr>
<td>Located at this level</td>
<td></td>
<td>solid black border box</td>
</tr>
<tr>
<td>Located at another level</td>
<td></td>
<td>dashed black box</td>
</tr>
<tr>
<td>Loads specified</td>
<td>⭐️</td>
<td>red star</td>
</tr>
<tr>
<td>Concentrations specified</td>
<td>⚫️</td>
<td>yellow cross</td>
</tr>
<tr>
<td>Sludge calculated</td>
<td>⬅️</td>
<td>black wide arrow</td>
</tr>
<tr>
<td>Input</td>
<td>⬤️</td>
<td>clear circle</td>
</tr>
<tr>
<td>Human contribution</td>
<td>♂️♀️</td>
<td>people</td>
</tr>
<tr>
<td>Flow path</td>
<td>⬤️</td>
<td></td>
</tr>
</tbody>
</table>
Contaminant Profiles

Contaminant profiles required for the contaminant balance are listed in Table 3. Profiles depend on land use and source characteristics. For example, contaminant profiles for roof runoff were characterised according to the residential, industrial and commercial land uses. These were further characterised by roof type, such as inert and galvanised roofs. These data were collected for a number of urban regions throughout Australia. Further details of the contaminant data collected for use in this model are detailed in Becker and Gray (1999).

Table 3, Contaminant profiles required for the contaminant balance

<table>
<thead>
<tr>
<th>Location</th>
<th>Contaminant Source/Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>House</td>
<td>Tap, Tank, Estate Waste Water Store, Estate Storm Water Store,</td>
</tr>
<tr>
<td>Unit Block</td>
<td>Cluster Storm Water Store</td>
</tr>
<tr>
<td>Cluster</td>
<td>Other Cluster Waste Water Store, Other Cluster Storm Water</td>
</tr>
<tr>
<td>Estate</td>
<td>Store</td>
</tr>
</tbody>
</table>

The complete list of modelled contaminants included in a contaminant profile is shown in Table 4. All contaminants are treated as conservative.

Table 4, Contaminants included in a contaminant profile in UVQ

<table>
<thead>
<tr>
<th>Contaminants included in a Contaminant Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu (total) Total Copper</td>
</tr>
<tr>
<td>Zn (total) Total Zinc</td>
</tr>
<tr>
<td>Cd (total) Total Cadmium</td>
</tr>
<tr>
<td>Pb (total) Total Lead</td>
</tr>
<tr>
<td>N (total) Total Nitrogen</td>
</tr>
<tr>
<td>NH$_3$–N Nitrogen in the form of Ammonia</td>
</tr>
<tr>
<td>P (total) Total Phosphorus</td>
</tr>
<tr>
<td>Suspended Solids Suspended Solids</td>
</tr>
<tr>
<td>Diss. Solids Dissolved Solids</td>
</tr>
<tr>
<td>COD Chemical Oxygen Demand</td>
</tr>
<tr>
<td>Coliforms Coliforms</td>
</tr>
<tr>
<td>Pesticides Pesticides</td>
</tr>
<tr>
<td>PAHs Poly Aromatic Hydrocarbons</td>
</tr>
<tr>
<td>Oil and Grease Oil and Grease</td>
</tr>
<tr>
<td>Gross Litter Gross Litter</td>
</tr>
</tbody>
</table>

Contaminant Profile Operations

The contaminant profiles are manipulated in one of three ways: a "use" operation, a "mix" operation, or a "sludge" operation. The 'use' operation copies one profile to another. The 'mix' operation combines
multiple contaminant profiles to produce an output contaminant profile. The ‘sludge’ operations allow for both a mixing of multiple input contaminant profiles to produce multiple output contaminant profiles and the removal of contaminant as sludge. These operations are more fully described in Farley et al. (2000). Their use at each spatial scale is tabulated in Tables A-3, A-4, A-5 and A-6.

**TAWS MODEL**

TAWS is used to assess the cost-effectiveness of alternative urban water systems. Alternative water systems are evaluated using infrastructure life cycle cost subject to water quality, hydrologic and hydraulic constraints. The hydrological constraints ensure that the demands for various qualities of water are available from the source nodes. Hydraulic constraints ensure that physical infrastructure exists that is capable of conveying the flows required to satisfy demands. TAWS allows for upgrading of existing infrastructure and installing new infrastructure for transporting water and waste water and assesses the capacity of the storm water infrastructure.

TAWS builds on the IWR model (Maheepala and Gibert 1997, Maheepala et al. 1999a). The upgrade was in two stages:

- the inclusion of life cycle costing to IWR (known as IWR + LCC, or TAWS Stage 1). The description of life cycle costing and its implementation in IWR is documented in Tucker et al. (1999) and Maheepala et al. (2000a).
- the inclusion of waste and storm water networks.

The methodology of TAWS is described below (and more fully in Maheepala et al. (2000c)) and the design and implementation in Maheepala et al. (2000b).

**Water Quality**

The quality of water is expressed in terms of a water quality profile, which describes concentrations of different constituents (e.g. salinity, turbidity, total bacteria count, etc.) to suit individual circumstances. Water quality is considered as simply a label for identification of a particular type of water with its associated profile. For example, 'QP1' may be a label for potable water, and 'QP2' may be a label for storm water.

At a demand node the quality of water that it can receive or be supplied with and the quality of water that it can produce must be specified. If water of the specified quality is not available, then the user can specify a list of other water qualities that are acceptable.

**Water Treatment Selection**

TAWS can simulate the operation of treatment plants in order to convert polluted water to a better quality water for reuse. To do this, TAWS has a treatment node which specifies the input and output qualities, and the treatment process to be used for the conversion. There are a number of treatment processes available to choose from, each with appropriate flow ranges and water qualities. For the feasibility study, treatment plants and other treatment processes are manually described and are not determined by TAWS during run time. An alternative method has been designed and is described in [Treatment Process Selector](#) page 28.

**Data Requirements**

TAWS requires data to describe the logical and physical network. As well as describing the infrastructure and network, TAWS requires data describing the physical environment such as rainfall, evaporation, and inflows. Data specifications for TAWS Stage 1 and Stage 2 are described in Maheepala et al. (2000a, 2000c). These reports identify the data structures and their contents.
**Main Components**

The four main components of TAWS which are used to assess water supply and disposal scenarios, that is, ways of supplying water and disposing of surplus water in an urban area, subject to constraints of capacity, sources, transport systems and treatments, are:

1. Hydrologic analysis
2. Hydraulic analysis
3. Cost estimation
4. Optimisation.

TAWS uses configurations to represent scenarios which are defined as a set of flow rates and quality profiles assigned for all links in the logical network.

TAWS can be used for 'what-if' evaluation of configurations using the first 3 components. Alternatively, TAWS can be used to search for an optimal configuration, i.e. a configuration that minimises the life cycle cost of the infrastructure. To do this, the first three components sit as steps within the optimisation component. The components are generally described below.

**Hydrologic Analysis**

This component checks the hydrological feasibility of a configuration, using the logical network. It checks whether critical demands are satisfied and all surplus water is removed from the system, under a set of specified hydrologic conditions (e.g. rainfall and evaporation), according to a set of priority rules for both the nodes and links of the logical network. For example, the node priorities represent the preference order for satisfying demand nodes; and the link priorities represent the preference order each demand node has for supply sources. During this process, shortfalls of demand and removal are estimated. These are then evaluated against a user defined acceptance criterion for the hydrologic feasibility.

**Hydraulic Analysis**

This component checks the hydraulic feasibility of a configuration, using the physical networks. It checks whether the current infrastructure is adequate to carry the peak flows while satisfying pressure requirements. If insufficient, the quantity of new (or the expansion of existing) infrastructure needed to carry the peak flows of the configuration is determined.

A more complete description of the approach used to assess the hydraulic feasibility of the physical network is presented in Appendix C.

**Life Cycle Cost Estimation**

The implementation of life cycle costing within the TAWS model was carried out by Rahilly (see Section 6 in Tucker et al. 1999). Under this method, components of the physical and logical networks are described using quite complex cost functions from which dollar values are calculated during TAWS runs.

This component performs the life cycle cost analysis and estimates the Net Present Value of the total life cycle cost of infrastructure provided for a configuration. The net present value of a configuration includes:

- the capital cost of each infrastructure item, being the cost of providing some new item of infrastructure or the inflated value of an existing item.
- the operating cost of each infrastructure item, being the discounted cost of operating and maintaining the item.
- the replacement cost, which is the discounted cost of removing an item of infrastructure and replacing it with an identical item if its service life expires during the planning period.
- the residual value, which is the value of the infrastructure item at the end of the planning period.
If an item of infrastructure in the physical network is unused due to the configuration of flow in the logical network and its service life expires during the planning period, the cost of replacement of the item is not included in the estimation of the net present value of the physical network.

Optimisation

Optimisation is used to search for the solution that minimises the total life cycle cost of infrastructure provided for water supply and disposal, subject to hydrologic and hydraulic constraints, ie it searches for an optimal network configuration of the logical network with associated hydraulically feasible physical network that has the lowest Net Present Value (NPV) estimated over a user specified planning period. TAWS implements the simulated annealing algorithm described by Kirkpatrick et al. (1983) and Goffe et al. (1994), together with heuristic rules, in pursuit of an optimal network configuration.

Until recently, simulated annealing has seldom been applied to water resources problems (Cunha and Sousa 1999). TAWS is one of the very few attempts to implement simulated annealing in a practical water resource assessment model and to develop an integrated urban water resources model.

The simulated annealing algorithm is based on the analogy with a physical annealing process. In this process the temperature of a material is increased sufficiently so that the molecules are random. The high mobility of molecules at the initial temperature enables them to reach different quasi-equilibrium states during a cooling process. After slow cooling, these molecules will form a crystalline structure where the energy of the system is minimal, which corresponds to an ordered crystalline structure. If the temperature is lowered too fast, the resulting crystal may have many defects or even lack all crystalline order.

In the optimisation problem, solutions are equivalent to quasi-equilibrium states in the physical system, cost of a solution corresponds to the energy of a state and the control parameter is equivalent to temperature. A more complete description of the simulated annealing algorithm is presented in Appendix B.

A simplified description of the sequence of steps performed during the execution of TAWS is shown in Figure 5. The description focuses on the water supply network. Similar logic applies to the integrated logical network of potable, waste and storm water systems.
Step 1 - Initial Valid Configuration

The first step in TAWS is to determine an initial valid configuration that is both hydrologically and hydraulically feasible.

For each demand node, TAWS determines the monthly demand during a simulation period. The simulation period should include extreme climatic conditions, since the water system needs to be able to cope with periods of low rainfall. TAWS then allocates flow to the logical links serving the demand node according to a set of heuristic rules. These include:

- priority rules that specify the preferred order for satisfying the water demand of the node.
- priority rules that specify the preferred order each demand node has for supply sources.

Assuming that sources are not limiting, this process will determine a hydrologically feasible configuration for the logical network.

Once flow has been allocated to each logical link in the network, TAWS checks the capacity of the physical network to carry the allocated flows. If a pipe is shared by two or more logical links, the flow used to test the pipe is the sum of the flow in the logical links. If a pipe is incapable of withstanding the pressure associated with the required flow, TAWS selects a suitable replacement pipe that is capable of withstanding the pressure associated with the flow. Similarly, TAWS will add pumps if required to ensure adequate pressure is maintained at the demand nodes.

Situations may arise where TAWS cannot determine an initial valid configuration. Such situations include cases of either hydrological or hydraulic infeasibility. Hydrological infeasibility arises when the sources are limiting indicating that the demands are not satisfied by the available sources. Hydraulic infeasibility arises when the pipe specification data doesn't include a suitable replacement pipe to handle the required flow and pressure in a physical link.
Step 2 – Calculate Life Cycle Costs

Once a valid initial configuration has been determined, TAWS undertakes life cycle costing of the physical infrastructure defined in the configuration. The cost of the infrastructure and its operation is expressed in terms of net present value (NPV) over a user specified planning period. The discount rate applied to expenditures is also user specified. The calculation of NPV of a configuration is described in the previous section on Life Cycle Cost Estimation.

Step 3 – Perturb Current Configuration

Perturbation is a change in the allocation of flows in the logical network. A single logical link is selected at random for perturbation and a new flow allocated to the link. This new flow is chosen from a normal distribution with its mean value being the flow used during the previous successful hydrologic simulation. The user specifies the variance of this normal distribution. This is the first step inside the optimisation loop.

Step 4 – Re-assess Hydrological feasibility

Once a single link in the logical network has been perturbed, the logical network is re-assessed for hydrological feasibility.

For each demand node, the sum of the allocated monthly flows in all logical links reaching the demand node is compared with the time series of monthly demands for the node. This is to ensure that the node can be supplied with the required quantity of water throughout the simulation period. Similarly, for each source node, the sum of the allocated monthly flows in the logical links leaving the source node are compared with the time series of monthly availability in the source node. If all demand nodes can be satisfied, and all source nodes are capable of supplying the allocated flows throughout the simulation period, the new configuration is assessed to be hydrologically feasible.

In the event of hydrological failure, the configuration is rejected, and TAWS returns to step 3 to undertake an alternate perturbation of the logical network using the previous valid configuration.

Step 5 – Re-assess Hydraulic Feasibility

Once the configuration of the logical network has been assessed as hydrologically feasible, TAWS evaluates the hydraulic feasibility of the physical network. For each logical link, TAWS assesses whether the associated physical link is capable of conveying the flow.

If a pipe is incapable of withstanding the pressure associated with the required flow, TAWS selects a suitable replacement pipe that is capable of withstanding the pressure associated with the flow. Similarly, TAWS will add pumps if required to ensure adequate pressure at the demand nodes. In effect, TAWS re-configures the physical network to convey the allocated flows.

If the user has not specified a sufficient range of pipes for TAWS to identify a pipe capable of conveying the allocated flow, then the configuration is assessed to be hydraulically infeasible. In such an event, TAWS returns to Step 3– Perturb Current Configuration to generate an alternative logical network configuration by perturbing the previous valid configuration.

A more complete description of the approach used to assess the hydraulic feasibility of the physical network is presented in Appendix C.
Step 6 – Calculate Life Cycle Costs

This step is identical to Step 2. TAWS calculates the Net Present Value of the hydraulically feasible physical network that has been re-configured, to convey the hydrologically feasible allocated flows in the logical network.

Step 7 – Evaluate Metropolis Criterion

The perturbed configuration of the logical network and the appropriately re-configured physical network will only be accepted if it satisfies the metropolis criterion.

The metropolis criterion is of the form $e^{-\Delta c/t} \geq p$, where $\Delta c$ is the difference between the cost of the perturbed configuration and the previous configuration, $t$ is the temperature applying to this iteration of the loop, and $p$ is a uniformly generated random probability.

Obviously a lower cost perturbed configuration will be accepted in all cases since $-\Delta c/t$ will be greater than zero, and hence $e^{-\Delta c/t}$ will be greater than or equal to 1.

The probability of a higher cost perturbed configuration being accepted depends on the ratio $-\Delta c/t$. Perturbed configurations with large increases in Net Present Value have a higher probability of being accepted when $t$ is large.

If TAWS rejects a perturbed configuration under the metropolis criterion, it returns to Step 3 to undertake an alternate perturbation of the allocated flows in the logical network using the previous valid configuration. Otherwise, the perturbed configuration is accepted as the new valid configuration on the path toward identifying a network configuration that minimises life cycle cost.

Step 8 – Metropolis Loop Completed

TAWS increments the metropolis loop counter and then compares it to a user-specified value. If the counter is less than the user-specified value, TAWS returns to Step 3 without adjusting the temperature parameter used in the metropolis criterion.

Otherwise the counter is set to zero and TAWS adjusts the temperature parameter, $t$. The current temperature is scaled by a user-specified cooling coefficient to produce a new lower temperature. The cooling coefficient, $\alpha$, must satisfy $0 < \alpha < 1$.

Step 9 – Termination Parameters Satisfied

If the new temperature is still greater than the minimum temperature specified by the user, TAWS returns to Step 3 to undertake an alternate perturbation of the logical network using the new configuration accepted in Step 7.

Step 10 – Report on Least Cost Solution Found

If the new temperature set in Step 9 is less than or equal to the user-specified minimum temperature, TAWS regards the current configuration as its estimate of the configuration with the lowest Net Present Value.

The quality of the "optimal" network configuration identified by TAWS is highly dependent on a number of user-specified parameters employed in the implementation of the simulated annealing algorithm described above. These include the initial temperature, the minimum temperature, the cooling coefficient, and the metropolis loop control value.
Implementation

Only the water supply system is implemented (TAWS v1.0). Waste and storm water systems are in progress. Assessment of scenarios is done using the water supply system only. TAWS is presently implemented as a Windows application in C++.

SCENARIO DESIGNER

The Scenario Designer enables the user to specify and select the attributes of the urban water system or scenario to be analysed.

A Scenario includes:

- a time series of climatic data,
- the network of water supply mains, connecting sources of water to demands for water of a particular quality, and the network of storm water and waste water mains and channels connecting sources of storm water and waste water and treatment plants and or disposal points,
- the attributes of estates, which represent demands for water of various quality and the sources of storm and waste water,
- the attributes of the individual clusters of homogenous houses, one or more of which together constitute an estate, and
- the attributes of gardens and houses and their occupants that affect water use within each cluster.

All these data are provided using the four components of the Scenario Designer. These are the: (i) Network Designer, (ii) Estate Designer, (iii) Cluster Designer and (iv) House Designer (see Figure 6). The Scenario Designer is more fully described in Coleman et al. (2000).

The design of the components of the Scenario Designer is heavily influenced by the data needs and urban process representations of the underlying models (UVQ and TAWS). However, it is independent of the underlying models and the design allows for linking to alternative models with relative ease.

![Scenario Designer Diagram]

Figure 6, The conceptual structure of the Scenario Designer

ESTATE DESIGNER

An Estate is essentially a collection of Clusters. An estate can include both storm water and waste water storages from which water may be re-used within the estate. The Estates View (see Figure 7) displays the Estates available for use within the scenario. The user can design as many estates as required for use in an urban network.
From the Estates View, the user can add new estates and edit existing estates. The storm water and waste water storage properties of an estate can be edited. Clusters can be included in an estate simply by drag and drop from the Clusters View, or selection from the shortcut menu in the Estate Designer (see Figure 8).

Analysis of the contaminant flux within an estate requires the user to provide the water quality specification of precipitation and tap water entering the estate and a quality specification for any storm water and waste water reuse within the estate.

**CLUSTER DESIGNER**

A *Cluster* is a collection of identical houses sitting on a particular soil type, attributes of which are specified using the Cluster Designer.

The Clusters View displays all the clusters that the user has designed for use in the scenario. Clusters can be added to an estate by dragging them from the Clusters View and dropping them onto the Estate Designer for an estate.

The Cluster Designer allow users to specify the attributes of a cluster, such as storm water and waste water storages within the cluster, and Aquifer Storage and Recovery (ASR) facilities. The type and
number of houses that exist within a cluster, the occupancy rate for individual house types and areas of roads and public open space within the cluster can also be specified. A range of soil physical properties is required to ensure that the water balance model can adequately simulate the behaviour of the water stored in the soil profile within the cluster. The irrigation requirement for any public open space within the Cluster can be sourced from either tap water, bore water or both. It is also possible for clusters to source reuse water from other cluster’s storm water and waste water storages and to drain water to other clusters within the estate. The user can also specify contaminant paths for the cluster.

**HOUSE DESIGNER**

With the House Designer, the user can specify the attributes of a house, the parcel of land on which it sits and the behaviour of the occupants that affect the daily water consumption of the house and garden. These include internal appliances (see Figure 9), the nature of surface areas within the parcel of land on which the house sits, the presence of a rainwater tank and the pattern of usage of water stored in such a tank, the presence of on-site waste water treatment and any re-use of water from such a facility.

![Figure 9, House Designer - General Properties](image)

The **Water Use Behaviour** tab of the House Designer (Figure 10) enables the user to provide estimates of the consumption of water by the occupants within the house. Default data are provided whenever the user designs a new house type. These default usage data were obtained from the 1982 Perth Domestic Water Use Study (Metropolitan Water Authority 1985).

![Figure 10, House Designer - Water Use Behaviour](image)
Grey water re-use for garden irrigation, the proportion of garden area irrigated, the proportion of soil field capacity maintained by the householder and the available sources of irrigation water are specified on the Garden Properties tab of the House Designer (see Figure 11).

![Figure 11, House Designer - Garden Properties](image)

The House Designer also enables the user to specify the quantities and in some cases the concentrations of contaminants that join the waste water and storm water streams, see Figure 12. The Scenario Designer provides default data for all contaminants, see Figure 13.

![Figure 12, House Designer - Contaminant Specifications](image)
The Network Designer allows users to layout their water supply and disposal networks, see Figure 14. This integrated network can be manipulated to include new or redundant networks. As well as providing an intelligent interface for describing the network, The Network Designer builds, imports and exports TAWS data files. A more complete description of the Network Designer is in Coleman et al. (2000).
Table 5, Symbols used in the Network Designer

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logical link</td>
<td></td>
<td>supply or disposal link</td>
</tr>
<tr>
<td>Demand node</td>
<td></td>
<td>residential, industrial, agricultural</td>
</tr>
<tr>
<td>Source node</td>
<td></td>
<td>reservoir, groundwater, rivers, lakes</td>
</tr>
<tr>
<td>Storage node</td>
<td></td>
<td>reservoir, ASR, retarding basin, water supply tanks</td>
</tr>
<tr>
<td>Receiving node</td>
<td></td>
<td>ocean, lakes, rivers</td>
</tr>
<tr>
<td>Estate node</td>
<td></td>
<td>city, town, suburb</td>
</tr>
<tr>
<td>Tank node</td>
<td></td>
<td>balancing storage service reservoir</td>
</tr>
<tr>
<td>Pipe junction node</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumping Station</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment node</td>
<td></td>
<td>wetlands, sewage treatment plants</td>
</tr>
</tbody>
</table>

An example of a logical network is given in Figure 15. The corresponding physical network for this logical network is given in Figure 16.

Figure 15, Diagram of a TAWS logical network in the Network Designer
The Network Designer plays an important role in imposing restrictions on how the user links the networks and provides the links between the output of UVQ and the demand inputs of TAWS.

Some examples of the in-built restrictions and data aids are:

- A logical link from a source to a demand is defined by dragging with the mouse a link from the source object to the demand object. This is entirely visual. Having defined the link, the user then edits the properties of that link to specify which physical pipes make up the link. Without the Network Designer, pipes would need to be listed in the order in which they are laid in the ground, identifying each end of the link. This manual method is both slow and subject to a high probability of error. Now, with the click of a button the Network Designer will generate the whole list by automatically traversing the pipe network.

- Previously there were no checks on how links are connected. With the Network Designer, the user is prevented from making invalid links. For example, physical pipes can only be defined to or from a pipe node, and not an actual demand or source. Each demand and source is associated with a single pipe node, and only logical links can be drawn between these logical nodes.

- Most of the TAWS data are stored in the form of lookup tables (e.g. pipe specifications, pump specifications, water qualities, etc). Properties of objects which link to lookup data have been integrated with that data. Even though TAWS stores the lookup tables in separate text files, the Network Designer provides the list of data at any point where it is necessary. For instance, when configuring a pipe the user does not need to remember the full name of a pipe because the Network Designer provides a drop down list of all the pipes from which the user can choose one. Similar drop down lists are used for selecting pipe nodes, treatment plants, rainfall stations, evaporation stations, catchment areas, pumps, life cycle costs etc. As well as streamlining the design process, this prevents incorrect references from occurring.

- The management of the lists mentioned above is handled by the Network Designer. Thus the user has a structured interface to navigate the list and modify the properties of any item in the list.

- The structured approach of data entry also lends itself to providing hints/tips/limits on data values. For example, when the user is defining parameters of waste water treatment plants they can have some expert advice or limits built into each field.

- Although spatial data such as positions of sources and demands are not used by TAWS, those data are stored in the TAWS files. Previously this information was difficult to generate unless a GIS was used. Now the Network Designer maintains all the spatial locations of nodes, even when nodes are dragged around the region.
Editor Functionality

Using this functionality and in-built constraints, the user can add and edit nodes such as source, demand, treatment, pipe, tanks and output nodes. These nodes can be joined using drinking water, waste water or storm water pipes. The links that join these nodes can be given physical pipe characteristics such as diameter and construction material. Each node and link has a specific editor, which is initiated by a double click on the node or link after the Edit tool has been selected. Figure 17 is an example of the editor for storage nodes.

![Figure 17, Attributes of a storage node](image)

Global Data Management

There are a number of tables of data that are either local to the current scenario, or global to all scenarios. Four which are of central importance describe:

- pipe specifications
- water quality profiles
- treatment options
- life cycle costing.

The Network Designer provides useful tools for managing and editing these tables.

Pipe Specifications

The pipe specifications table contains attributes of physical pipes. Each pipe description includes diameter (inner and outer), bursting pressure, roughness, and cost (establishment, operating and replacement) functions. Three flags are used to specify the physical networks (drinking, waste, storm) for which the pipe may be used (see Figure 18).
Water Quality Profiles

The quality profiles table defines the available water qualities and their contaminant profiles. Each logical link can transport water of a particular profile. Demand nodes require water of a minimum quality, or better quality if available. Some of the contaminant profiles listed in this table could be generated by UVQ runs.

Treatment Options

The treatment options table contains all the treatment processes available for treatment nodes. Each option converts water of one quality to another, and cost functions describe the associated costs. Treatment options may describe a sewage treatment plant, a wetland system, or even a commercial or industrial process that degrades water quality.
Treatment types has been provided by Booker and Mathes (1999). Each treatment type has been keyed with an unique ID, eg CATO-1. The full list of treatments available for the feasibility study are available in Coleman et al. (2000). An example of the description of a treatment option is given in Figure 20.

**Figure 20, Attributes of a treatment option**

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Description</th>
<th>Inflow Quality</th>
<th>Outflow Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CATO-1</td>
<td>Screen Clarifier, Rapid sand filter, Disinfection, Storage</td>
<td>QP1</td>
<td>QP2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outflow Percent</th>
<th>Construction Year</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>1970</td>
<td>85</td>
</tr>
</tbody>
</table>

Life Cycle Costing

Life cycle cost are described by mathematical equations. Each component of the establishment, operation and replacement cost for a piece of equipment (pipe, treatment plant, storage etc) is stored in the life cycle table and used in TAWS when costing the infrastructure. Each cost function has a cost type (combinations of Establishment, Operating, and Replacement), a function type predefined in TAWS (such as constant, linear, power, quadratic, and custom pipe functions), and for each function type there are up to four parameters required. Extra information like fraction, design life and year cost determined is also recorded (see Figure 21). The cost types and cost functions have been developed within the UWP feasibility study (Tucker et al. 1999).
OTHER MODELS

This component is a repository of other programs that might be useful to urban catchment planners. These programs are not essential for providing data for UVQ or TAWS and they are stand-alone tools. At least four programs - Treatment Process Selector, WWTREAT, a flash flooding model and modelling externalities - have been identified for the Other Models component of TAWS. The Other Models component of CUWPID has not be implemented during the feasibility study.

TREATMENT PROCESS SELECTOR

The treatment process selector may be implemented within TAWS, or as an external module. The method was developed during the feasibility study (Booker et al. 1999), but not implemented. Treatment processes for the different combinations of scale, input quality and output quality have been provided by Booker and Mathes (1999). A treatments specifications table associates the potential treatment processes with water quality transformations. A sample of entries in this table for treatments at regional, cluster and household scale is given in Table 6.

Table 6, A sample of entries in the Treatments Specifications Table in TAWS

<table>
<thead>
<tr>
<th>No</th>
<th>Scale</th>
<th>Input Water Quality</th>
<th>Output Water Quality</th>
<th>Potential Treatment Options**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regional</td>
<td>Surface water</td>
<td>Potable water</td>
<td>RATO-1, RATO-2</td>
</tr>
<tr>
<td>10</td>
<td>Regional</td>
<td>Stormwater</td>
<td>Livestock</td>
<td>RATO-7, RATO-8</td>
</tr>
<tr>
<td>28</td>
<td>Cluster</td>
<td>Ground water</td>
<td>Potable water</td>
<td>CATO-5, CATO-6</td>
</tr>
<tr>
<td>37</td>
<td>Cluster</td>
<td>Stormwater</td>
<td>Aquifer recharge</td>
<td>CATO-3, CATO-4, CATO-21</td>
</tr>
<tr>
<td>66</td>
<td>Household</td>
<td>Rainwater (tank)</td>
<td>Potable</td>
<td>not yet defined</td>
</tr>
</tbody>
</table>

** Treatment ID key in the Treatments Specifications Table. An example of the description of the treatment identified as CATO-1 is shown in Figure 20, Attributes of a treatment option.
From each treatment option, parameters such as flow limits, capital cost, operating cost, replacement cost and footprint area are recorded in a database. The editor for this is already available through the Network Designer (refer Figure 20, Attributes of a treatment option). This information is necessary to determine life cycle cost within TAWS.

When the user has specified the input and output water qualities of a treatment option, TAWS will list a number of suitable treatments to choose from. At this stage, the capacity of the treatment process cannot be considered because flow volumes through the treatment are not yet known. Once TAWS is run with the treatment in place, it will become evident how large the treatment must be to cope with the maximum simulated flows. This makes treatment selection a two-step process.

In the future a more automated selection process may be used where TAWS makes the selection during optimisation based on water quality, maximum flows, and minimum cost.

**WWTREAT**

WWTreat is an alternative approach to treatment selection which considers particle size of contaminants when selecting appropriate technologies. A discussion paper on the design for such an expert system has been described (Cuddy 1998). This method differs from the Treatment Process Selector in that it would be capable of selecting combinations of treatment processes. The final choice of treatment processes would depend on user-defined critical constraints, such as life cycle costs and externalities. An expert system is an appropriate technique because different treatment processes may be more effective in reducing different water quality pollutants.

**FLASH FLOODING**

Flash flooding is caused by the inability of storm water infrastructure to safely convey runoff. The destructive force of fast flowing water from storm water or water supply infrastructure failure can cause damage to property and is a risk to life. The risks and costs associated with flash flooding can be high. The costs associated with flash flooding or flooding resulting from the collapse of a retarding basin or from a burst water supply main or service reservoir should be included in the costs of any infrastructure design. Models for assessing the impacts of flash flooding have been recently developed (see Zoppou and Roberts 1999).

**EXTERNALITIES**

Externalities include factors that affect public acceptance, impact on environments outside the urban water system, social well being, national security, regional growth and stability, preservation of natural areas and risk management costs. A method for valuing externalities has been developed as part of the Urban Water Program (Bowers and Young 1999). These need to be encapsulated into a modelling framework.

**SCENARIO REPORTER**

The scenario reporter facilitates the review of model results and the comparison between model results for different scenarios. While the report facility has not been well developed during the feasibility study, examples of its capabilities are included in the section on Assessing Scenarios.
APPLICATION

The models have been applied to a study area in the Perth Region to assess the cost-effectiveness of various ways of providing water services.

DESCRIPTION OF PERTH NORTH–EAST CORRIDOR STUDY AREA

The criteria set for selecting the study area were (Speers, 1998):

- a catchment containing developed areas and potential for greenfields development
- less than 100,000 equivalent population
- a single sewage catchment.

A study area of about 422 square kilometres was selected in the North-East Corridor of the metropolitan region of Perth. The boundary of the study area is shown in Figure 22. The main localities included in the study area are Midland, Guilford, Swan Valley, Ellenbrook and Bullsbrook.

The main topographical features in the study area are the large sand dunes in Ellenbrook, the State Forest, the Swan River running through the centre of the study area and the Darling Scarp to the east. The sand dunes in Ellenbrook and the State Forest are approximately 45 to 75 metres above the sea level. The land within the areas of Bullsbrook, Henley Brook, West Swan and Caversham is about 10 to 45 metres above the sea.

The main watercourses in the study area are the Swan River, Helena River, Jane Brook, Susannah Brook, Bennett Brook, Henley Brook and Ellen Brook.

The study area has been characterised for two time periods. The 'base case', referred to as 'Year 199x', describes the 'current' state of the study area. Note that 'current' reflects a range of collection periods for the data, from the 1980s for the stormwater infrastructure to 1998. This is simply a reflection of the availability of data. The 'Year 2020' is a hypothetical characterisation of the study area in the Year 2020 and uses data on future land use zoning, population trends, and infrastructure upgrade proposals to describe a more highly urbanised study area.

---

3 This section is adapted from Cuddy et al. (2000).
For modelling purposes (water balance, contaminant balance and water related infrastructure), the study area was divided into 11 estates (see Figure 23 and Table 7). In general, estates represent the main localities in the study area. These estates were further divided into clusters for the purposes of describing different water use patterns.
Table 7, Estates of the Study Area showing total area and number of clusters

<table>
<thead>
<tr>
<th>Name</th>
<th>ID</th>
<th>No of clusters</th>
<th>Area (sq kms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullsbrook</td>
<td>1</td>
<td>7</td>
<td>205</td>
</tr>
<tr>
<td>Upper Swan</td>
<td>2</td>
<td>6</td>
<td>59</td>
</tr>
<tr>
<td>Vines</td>
<td>3</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>Ellenbrook</td>
<td>4</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>Henley Brook</td>
<td>5</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>Herne Hill</td>
<td>6</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>West Swan</td>
<td>7</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>Middle Swan</td>
<td>8</td>
<td>9</td>
<td>23</td>
</tr>
<tr>
<td>Caversham</td>
<td>9</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>Midland</td>
<td>10</td>
<td>7</td>
<td>25</td>
</tr>
<tr>
<td>Guilford</td>
<td>11</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>75</strong></td>
</tr>
<tr>
<td><strong>Total Area</strong></td>
<td></td>
<td></td>
<td><strong>422</strong></td>
</tr>
</tbody>
</table>

Figure 23, Map of Study Area Estates

**CLIMATE**

The climate in the study area is Mediterranean, with hot dry summers and mild wet winters. The average temperatures and rainfall of Perth, Upper Swan and Bullsbrook are given in Table 8.
Table 8, Average temperature and rainfall in Perth and the Study Area

<table>
<thead>
<tr>
<th></th>
<th>Perth</th>
<th>Study Area</th>
<th>Upper Swan</th>
<th>Bullsbrook</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average daily maximum</td>
<td>23.6</td>
<td>25.4</td>
<td>24.8</td>
<td></td>
</tr>
<tr>
<td>Average daily minimum</td>
<td>13.5</td>
<td>10.9</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>Average rainfall (mm)</td>
<td>869</td>
<td>737</td>
<td>688</td>
<td></td>
</tr>
</tbody>
</table>

(Source: North-East Corridor Structure Plan, Dept of Planning and Urban Development, 1994)

POPULATION

Two sets of population data were calculated for each estate - as at 1996 for Year 199x, and as projected for the Year 2020. These are listed in Table 9.

Table 9, Populations within Estates

<table>
<thead>
<tr>
<th>Name</th>
<th>199x Scenario</th>
<th>UWP 2020 Scenario</th>
<th>2020:/ 199x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullsbrook</td>
<td>2,625</td>
<td>4,682</td>
<td>1.7</td>
</tr>
<tr>
<td>Upper Swan</td>
<td>1,660</td>
<td>2,344</td>
<td>1.4</td>
</tr>
<tr>
<td>Vines</td>
<td>985</td>
<td>1,909</td>
<td>1.9</td>
</tr>
<tr>
<td>Ellenbrook</td>
<td>694</td>
<td>13,233</td>
<td>19</td>
</tr>
<tr>
<td>Henley Brook</td>
<td>492</td>
<td>12,749</td>
<td>26</td>
</tr>
<tr>
<td>Herne Hill</td>
<td>1,542</td>
<td>7,890</td>
<td>5</td>
</tr>
<tr>
<td>West Swan</td>
<td>1,153</td>
<td>11,268</td>
<td>9.8</td>
</tr>
<tr>
<td>Middle Swan</td>
<td>8,914</td>
<td>15,479</td>
<td>1.7</td>
</tr>
<tr>
<td>Caversham</td>
<td>1,967</td>
<td>6,358</td>
<td>3.23</td>
</tr>
<tr>
<td>Midland</td>
<td>17,141</td>
<td>27,299</td>
<td>1.6</td>
</tr>
<tr>
<td>Guilford</td>
<td>1,742</td>
<td>3,061</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Total Population</strong></td>
<td><strong>38,915</strong></td>
<td><strong>106,272</strong></td>
<td><strong>2.8</strong></td>
</tr>
</tbody>
</table>

LAND USE

Two sets of land use distribution were prepared for each estate - as at 1996 and as projected for the Year 2020. A land use classification was used which matched the needs of the models and the scale of the data provided by state agencies. The final set is given in Table 10.

Table 10, Land use categories used for modelling

<table>
<thead>
<tr>
<th>Land use category</th>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban residential</td>
<td>urp</td>
<td>Houses, flats, boarding houses, units, retirement villages</td>
</tr>
<tr>
<td>Rural residential</td>
<td>rr</td>
<td>Dwellings on land used for rural activities</td>
</tr>
<tr>
<td>Commercial business</td>
<td>cb</td>
<td>Retail &amp; professional offices, shops, cinemas, hotels/motels, airports, service stations, function centres; Institutions e.g. Comm /State /Local Government &amp; civic offices, utilities, hospitals, churches, prisons, schools, health centres, aged care centres, museums, public art galleries, zoos</td>
</tr>
<tr>
<td>Commercial horticulture</td>
<td>ch</td>
<td>Market gardens, vineyards, orchards, plant farms, nurseries, etc.</td>
</tr>
<tr>
<td>General light industry</td>
<td>gli</td>
<td>Low water users (rural industry, noxious industry, waste disposal)</td>
</tr>
<tr>
<td>Parks &amp; gardens</td>
<td>pág</td>
<td>Parkland, botanic gardens, recreation grounds, sports arenas, public/private clubs with or without recreation areas, golf courses, public open space</td>
</tr>
<tr>
<td>Roads and open spaces</td>
<td>ros</td>
<td>Roads and parking areas; Rural open space, eg Natural open grassland, forests, rural road reserves, rubbish disposal, nature reserves, National parks, State forests</td>
</tr>
<tr>
<td>Waterways</td>
<td>ww</td>
<td>Waterways (buffered drainage lines)</td>
</tr>
</tbody>
</table>

Year 199x land use is largely rural (about 86%) and covered with either natural grassland, reserves, State Forests, rural residential hobby farms or intensive horticultural land uses. The horticultural land uses are in the Swan valley between Great Northern Highway and West Swan Road. A small proportion of the study...
area (about 14%) is urban and covered with urban residences, parks and gardens, industries or commercial premises. By the Year 2020, large increases in rural residential and urban, at the expense of rural open space, are predicted.

The occurrence of these land uses formed the basis for ascribing clusters within each estate.

**INFLOWS**

From the point of view of infrastructure, the study area is a 'closed' system. However it is not a closed hydrologic system and has inflows from the north and east. Historical data were provided by the relevant agencies and predicted inflows under elevated CO₂ conditions, required for storm flow modelling, were modelled by Evans and Schreider (1999) for Brockman River, Avon River, Susannah Brook and Jane Brook. Inflow from Ellen Brook was not modelled as historical flow data were not available during the life of the project.

**WATER SUPPLY, WASTE AND STORM WATER NETWORKS**

**Water Supply**

The Greenmount reservoir and the Yokine reservoir are the primary sources of water supply, with the urban developments of Ellenbrook and the Vines recently linked to Wanneroo reservoir. The latter is a temporary measure until the Gnangara Water Supply Scheme is commissioned (possibly in 2001/01 summer). This Scheme will ultimately supply the West Swan and Upper Swan areas. A schematic diagram of the basic configuration of the water supply system of the study area is presented in Figure 24.

Table 11 shows the number of clusters in each estate that are supplied with reticulated water. Note that several clusters are supplied exclusively with groundwater (mainly commercial horticulture water use and rural residential outdoor water use).
Table 11, Details of potable water supply for clusters in each estate

<table>
<thead>
<tr>
<th>Estate</th>
<th>No. of clusters supplied with reticulated water</th>
<th>No. of clusters supplied with groundwater</th>
<th>Total no. of clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullsbrook</td>
<td>6</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Vines</td>
<td>5</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Ellenbrook</td>
<td>5</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Upper Swan</td>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Henley Brook</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Herne Hill</td>
<td>6</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>West Swan</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Middle Swan</td>
<td>7</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Caversham</td>
<td>7</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Midland</td>
<td>6</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Guilford</td>
<td>6</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>57</strong></td>
<td><strong>18</strong></td>
<td><strong>75</strong></td>
</tr>
</tbody>
</table>

Within each estate, the number of residential households was established. This was used to estimate housing densities in different clusters.

Table 12, Residential households in each estate served by the water supply system

<table>
<thead>
<tr>
<th>Estate</th>
<th>No. of h’holds in 199x</th>
<th>No. of h’holds in 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullsbrook</td>
<td>367</td>
<td>2317</td>
</tr>
<tr>
<td>Vines</td>
<td>581</td>
<td>1191</td>
</tr>
<tr>
<td>Ellenbrook</td>
<td>865</td>
<td>5184</td>
</tr>
<tr>
<td>Upper Swan</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Henley Brook</td>
<td>0</td>
<td>4000</td>
</tr>
<tr>
<td>Herne Hill</td>
<td>151</td>
<td>2215</td>
</tr>
<tr>
<td>West Swan</td>
<td>0</td>
<td>2858</td>
</tr>
<tr>
<td>Middle Swan</td>
<td>2982</td>
<td>5462</td>
</tr>
<tr>
<td>Caversham</td>
<td>444</td>
<td>1485</td>
</tr>
<tr>
<td>Midland</td>
<td>6138</td>
<td>10048</td>
</tr>
<tr>
<td>Guilford</td>
<td>655</td>
<td>1134</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12183</strong></td>
<td><strong>35894</strong></td>
</tr>
</tbody>
</table>

Waste Water Infrastructure and Treatment

The urban developments in Midland and Guilford are served by the Beenyup regional wastewater treatment plant, which is external to the study area. Wastewater produced in the Ellenbrook area is collected via a series of sewers and trucked to the Beenyup plant. Bullsbrook and the Vines have small, local treatment plants. The rest of the population in the study area use septic tanks. Pressurised and gravity pipes are used throughout the urban areas, with 28 Pumping Stations identified.

By the year 2020, most of the sewage from the urban areas, including that previously trucked from the Ellenbrook area, will be piped to a central plant, outside the study area. The local plants at Bullsbrook and Vines will still be operational, with onsite disposal. Any new urban developments will be on sewer as septic is being phased out.

Storm Water Infrastructure

With the exception of pipes under roads, most of the infrastructure is ‘natural watercourse’. By the Year 2020, planning documents indicate that all urban development will follow best management practices, including retention of all natural drainage lines throughout the urban areas as open space strips. Minor ponds will be incorporated at intervals along the natural water courses and major retention basins/nutrient
stripping ponds will be located at the eastern extremity of natural drainage lines. Thus, water from new urban areas will run firstly through one or more minor ponds, and then through a major pond.

**ASSESSMENT OF SCENARIOS**

The urban water system assessment tools developed during this feasibility study were designed to analyse certain of the planning issues facing urban water authorities. This section describes analyses undertaken using the assessment tools. A number of typical issues were selected for analysis (see Table 13). The issues were selected to demonstrate both the strengths of the tools and to identify limitations in the tools where scope exists for future enhancement.

<table>
<thead>
<tr>
<th>No</th>
<th>Issue to be explored</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Implications of levelling of peaks on water supply transport costs for an existing development</td>
</tr>
<tr>
<td>2</td>
<td>Implications of levelling of peaks on the water supply transport costs for a greenfield development</td>
</tr>
<tr>
<td>3</td>
<td>Cost implications of the adoption of polyethylene pipes over the pipes currently used</td>
</tr>
<tr>
<td>4</td>
<td>Implications of reduction in pressure class used in water supply reticulation pipes from PN16 to PN6.3</td>
</tr>
<tr>
<td>5</td>
<td>Can the optimisation find a more cost-effective transport option?</td>
</tr>
<tr>
<td>6</td>
<td>Implications of elevated atmospheric CO2 concentrations on the water supply transport costs</td>
</tr>
</tbody>
</table>

The analysis process involved the development of a number of scenarios, the collection of data for each scenario to meet the data requirements of the underlying models, the running of the models for each scenario, and the analysis of results. All these scenarios focussed on assessing the cost implications of planning and operational changes to the water supply system in the Perth North-East Corridor (NEC) study area. The scenarios developed to test the issues described in Table 13 are given in Table 14.

<table>
<thead>
<tr>
<th>No</th>
<th>Pop'n</th>
<th>Development type</th>
<th>Planning period (yrs)</th>
<th>Materials to be used for water supply pipes</th>
<th>Pressure Class to be used for water supply pipes</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>199x</td>
<td>Existing</td>
<td>1</td>
<td>Traditional</td>
<td>Any Class</td>
</tr>
<tr>
<td>S2</td>
<td>2020</td>
<td>Greenfield</td>
<td>20</td>
<td>Traditional ♦ Polyethylene pipes for diameter up to 300 mm ♦ Traditional pipes for diameter greater than 300 mm</td>
<td>Any Class ♦ Any class for traditional pipes ♦ PN16 pipes for diameter up to 300 mm in trunk mains ♦ PN16 pipes for reticulation pipes within clusters</td>
</tr>
<tr>
<td>S3</td>
<td>2020</td>
<td>Greenfield</td>
<td>20</td>
<td>Polyethylene pipes for diameter up to 300 mm ♦ Traditional pipes for diameter greater than 300 mm</td>
<td>Any class for traditional pipes ♦ PN16 pipes for diameter up to 300 mm in trunk mains ♦ PN6.3 pipes for reticulation pipes within clusters</td>
</tr>
<tr>
<td>S4</td>
<td>2020</td>
<td>Greenfield</td>
<td>20</td>
<td>Polyethylene pipes for diameter up to 300 mm ♦ Traditional pipes for diameter greater than 300 mm</td>
<td>Any class for traditional pipes ♦ PN16 pipes for diameter up to 300 mm in trunk mains ♦ PN6.3 pipes for reticulation pipes within clusters</td>
</tr>
</tbody>
</table>

A schematic diagram of the water supply system used in these analyses is presented in Figure 24. Note that the 18 clusters supplied exclusively with groundwater are not included in these analyses.

The following assumptions were made in the analysis of scenarios:

1. A supply reliability of 100% was required for a given configuration to be hydrologically feasible. To check the supply reliability of the water system, supply and demand dynamics of the water supply system were simulated from 1976 to 1995 on a monthly basis using historic rainfall and evaporation data. The UVQ model was used to generate water demand of each cluster as a time series. For example, irrigation water demand of Bullsbrook cluster from 1976 to 1995 is shown in Figure 25.
2 A peak demand of 243 litres/hr per household was used for all clusters. For the study area, this peak demand was 2.55 times the maximum daily demand and 3.5 times the mean-day maximum monthly demand. The peak demand used was a global parameter, i.e. all pipes in the network were subject to the same peak demand or peak factor.

3 A planning period of one-year commencing in 1999 was used to evaluate the existing water supply system (i.e. base case). A planning period of 20 years, commencing from 1999 was used for the future water supply system evaluation (see Table 13).

4 Layout of the physical infrastructure of the water supply system in both existing and greenfield developments was the same. However, physical infrastructure for the greenfield development was newly installed at the beginning of the planning period. Also, for the greenfield development, the TAWS model determined sizes of pipes and pumping stations. The TAWS model required sizes of headwork, treatment and service tank infrastructure to be given as input data.

5 A 7% discount rate was used for calculating life cycle costs of all the infrastructure items, which included headwork infrastructure, treatment plants, pipes, storage tanks and pumping stations.

6 As the TAWS model cannot handle loop water supply networks, it was used to explore the water supply infrastructure at estate level only (i.e. between clusters). Water supply infrastructure within the clusters (i.e. reticulation system) was analysed manually. The following assumptions were made when designing the water supply infrastructure within the individual clusters:

- There was no existing infrastructure for supplying water within the individual clusters. Therefore, new reticulation infrastructure was provided at the beginning of the planning period.

- The terrain was flat and the water reticulation system was gravity-fed. The maximum reticulation pressure was 25 m head and the minimum reticulation pressure was 15 m head. The average head gradient available from the supply reservoir to the most distant part of the reticulation system was 5 m/km. It should be noted that these conditions were similar to those in the study area.

7 To determine capital cost of reticulation systems in different clusters, firstly a capital cost curve was derived for cluster sizes of 100, 1000, 4000 and 16000 houses for a housing density of 16 houses per hectare, assuming the reticulation system consisted of polyethylene pipes. Then, a series of such cost curves were derived for peak demand flow rates ranging from 1 to 500 litres/hr per household and pipes that vary in pressure class from PN4 to PN16. A scaling factor was used to adjust costs for clusters with housing densities other than 16 houses/net ha. Information on the number of residential households served by the water supply system in year 199x and year 2020 (Table 12) was used to estimate housing densities in different clusters. Also a scaling factor was used to adjust the PE pipe costs to give equivalent traditional pipe costs.

The operation and maintenance costs of the reticulation systems were calculated by taking average length of water main per house block as the main parameter.
ISSUE 1 - IMPLICATIONS OF LEVELLING OF PEAKS FOR AN EXISTING DEVELOPMENT

To assess the implications of levelling peaks on the existing water supply transport costs, the TAWS model was executed for scenario S1 with a peak factor (hourly demand to maximum daily demand) of 2.55 (i.e. peak demand of 243 litres/hr per household). This peak factor was then reduced incrementally to 1.0.

The TAWS model was used to calculate life cycle cost of water supply infrastructure for each value of the peak factor. This analysis did not take into account the cost of provisioning infrastructure for levelling of peaks such as on-site storage tanks.

Figure 26 shows the impact of changing the peak demand from 243 litres/hr per household to 95 litres/hr per household (i.e. peak factor of 1.0) on the current water supply transport cost in Perth NEC. As infrastructure is already in place and the planning period used for this analysis is a year, cost savings can only be achieved through reduction in operation costs of infrastructure (i.e. pipes, pumping stations and service tanks).

![Impact of peak levelling on water supply transport cost](image)

Figure 26, Cost savings offered by peak levelling in the current water supply system in Perth NEC

The cost function used to estimate operation cost of pumping stations is based on the discharge delivered by the pumping station. However, the operation cost of pipes is based on the pipe length rather than the discharge through the pipe. Also, the operation cost of service tanks is constant. Therefore, within this analysis, changes in the peak demand have little effect on the operation cost of pipes and service tanks. This should be viewed as a limitation of the availability of data for estimating the operating cost of the transport system.

This analysis suggests that peak levelling may result in annual savings of the order of 4% in the water supply transport cost for an existing development. It should be noted that more cost savings could be demonstrated if the operating cost of pipes were based on the diameter of the pipes. Furthermore, more savings could be obtained if the planning period used in the analysis was more than a year (e.g. 20 years) and the current infrastructure was due for replacement during that planning period.

ISSUE 2 - IMPLICATIONS OF LEVELLING OF PEAKS FOR A GREENFIELD DEVELOPMENT

To assess the implications of levelling peaks on the water supply transport costs for a greenfield development, the TAWS model was executed for the scenario S2 with a peak factors of 2.55 (i.e. peak demand of 243 litres/hr per household). As in the previous analysis, the peak factor was reduced incrementally to 1.0.
This analysis assumed that there was no existing water supply infrastructure that could be used to supply water for year 2020 population in Perth NEC. The average annual water demand of the study area in year 2020 was predicted at about 12,800 megalitres (about 2.5 of the current average annual water demand). It was assumed that the current sources were adequate to meet water demand of year 2020. The headwork infrastructure was assumed to be newly installed for calculation of life cycle costs. The TAWS model was used to determine new transport infrastructure (i.e. pipe sizes and pumping stations) that was hydraulically feasible. It should be noted that this analysis did not take into account provisioning of infrastructure for levelling the peak demand such as on-site tanks.

Figure 35 shows impact of changing peak demand from 243 litres/hr per household to 95 litres/hr per household (i.e. peak factor of 1.0) on water supply transport costs for a greenfield development in Perth NEC. This analysis suggests that peak levelling may result in savings of the order of 34% in the transport cost of water for a greenfield development.

This analysis used a planning period of 20 years. Results showed that only about 1% cost reduction could be obtained in the operation cost over the 20-year period by reducing peak factor from 2.55 to 1.0. This was mainly because of not including flow (or diameter) as a parameter in the cost function used to calculate operating costs of pipes. Results also showed that no infrastructure items were due for replacement during the 20-year period. Therefore, in this analysis, capital cost was the main driver for reducing the total transport cost of the water supply system with the reduction in peak demand.

Once again, this should be viewed as a limitation of the availability of data for estimating the operating cost of water supply pipes and ‘true’ lifetime instead of ‘manufacturer supplied’ lifetime of infrastructure items.

**ISSUE 3 - IMPLICATIONS OF THE ADOPTION OF POLYETHYLENE PIPES**

To assess the implications of using polyethylene pipes over the pipes currently used, the transport costs of scenarios S2 and S3 were compared. In scenario S2, traditional pipe materials were used such as reinforced concrete, steel, PVC, etc. In scenario S3, polyethylene (pressure class 16 - 160 m head) pipes were used for pipe sizes below 300 mm. However, because operation and capital cost data for polyethylene pipes greater than 300 mm were not available, traditional pipe materials were used for pipe sizes above 300 mm. In both S2 and S3, population of year 2020 and a 20-year planning period were used. [Table 15](#) shows a comparison of capital, operation and total transport costs of scenarios S2 and S3.
Table 15, Cost implications of adopting polyethylene pipes for pipe sizes <300 mm over traditional pipes

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Comparative cost: traditional pipes as base case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Traditional pipes</td>
</tr>
<tr>
<td>Operation cost</td>
<td>100%</td>
</tr>
<tr>
<td>Capital cost</td>
<td>100%</td>
</tr>
<tr>
<td>Total transport cost</td>
<td>100%</td>
</tr>
</tbody>
</table>

Results suggest that the operation cost of the water supply system with polyethylene pipes (only up to 300 mm) is about 49% cheaper than of the water supply system with traditional pipes. However, capital costs of polyethylene pipes are slightly greater than that of the traditional pipes. About 96% of the total transport cost are capital costs for the water supply system with polyethylene pipes, whereas about 92% of the total cost are capital costs for the water supply system with traditional pipes. Hence, reduction in operating costs has little impact on the total transport cost of adopting polyethylene pipes over the traditional pipe materials. Consequently, reduction in the total transport cost due to the adoption of polyethylene pipes up to 300 mm pipe size over the traditional pipe materials is minimal, about 0.8%.

As mentioned above, this analysis used polyethylene pipes up to 300 mm diameter due to lack of capital and operation cost data on polyethylene pipe sizes greater than 300 mm as such pipes were usually especially manufactured according to requirements. Therefore, to see full implications of using polyethylene pipes, this analysis should be repeated by using polyethylene pipes for all pipe sizes and comparing costs with traditional pipe materials.

### ISSUE 4 - IMPLICATIONS OF REDUCING PRESSURE CLASS OF PIPES

To assess the implications of reducing pressure class of pipes over the pressure class of pipes currently used, the reticulation costs of scenarios S3 and S4 were compared.

Polyethylene pipes with pressure class 16 (i.e. working pressure of 160m head) were used for the reticulation system in scenario S3, whereas polyethylene pipes with pressure class 6.3 (i.e. working pressure of 60m head) were used for the reticulation system in scenario S4. The same types of pipes were used for the trunk main systems of scenarios S3 and S4, i.e. polyethylene pipes with pressure class 16 were used up to 300 mm pipe sizes, and the traditional pipe materials were used for pipe sizes greater than 300 mm. It should be noted that the trunk main system represented water supply network between clusters and the reticulation systems represented water supply network within the clusters.

Table 16 shows cost implications of using polyethylene pipes with pressure class 6.3 (PN6.3) over the polyethylene pipes with pressure class 16 (PN16) for the reticulation pipes of water supply system in Perth NEC over a 20 year time period.

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Comparative cost: polyethylene PN16 as base case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polyethylene PN16 pipes</td>
</tr>
<tr>
<td>Operation cost</td>
<td>100%</td>
</tr>
<tr>
<td>Capital cost</td>
<td>100%</td>
</tr>
<tr>
<td>Total transport cost</td>
<td>100%</td>
</tr>
</tbody>
</table>

Results suggest that up to 35% of cost savings can be obtained by adopting PN6.3 pipes instead of PN16 pipes for water reticulation. However, it should be noted that when demand was very low, all pipes in the reticulation system were subjected to the maximum pressure available to the system. Therefore, lower pressure rated pipes, such as PN4, PN6.3 or PN8, would need to be protected by pressure reducing valves. The cost of the pressure reducing valves was not included in this analysis.
ISSUE 5 - CAN THE OPTIMISATION FIND A MORE COST-EFFECTIVE TRANSPORT OPTION?

This scenario demonstrates that it is possible to drive assets harder by selecting an alternative more cost-effective water transport path using optimisation.

For this assessment scenario S1 was used. Scenario S1 represents the current water supply system. Firstly, infrastructure costs were calculated for the current peak demand of 243 litres/hr per household (i.e. peak factor of 2.55). Then the peak demand was increased to 380 litres/hr per household (i.e. peak factor of 2.92) in order to stress the water supply system. The TAWS model was then run in two modes: firstly, it was run in simulation mode to size infrastructure for the increased peak demand; then it was run in optimisation mode to determine whether there was an alternative path for delivering the water.

In the first case, i.e. not using optimisation, it was necessary to replace two pipes (see Figure 27). A 150mm diameter cast iron pipe, with a working pressure of 61m failed and was replaced by a 180mm diameter polyethylene pipe, with a working pressure of 80m. The second pipe to fail was a 100mm diameter asbestos cement pipe with a working pressure of 61m, which was replaced with a 100mm diameter PVC pipe with a working pressure of 120m. One pipe failed due to water flow and pressure limitations, and had to be increased in size and strength as a result. The other failed due to increased pressure, and a stronger material of the same diameter had to be chosen to replace it.

This compares with the optimised network, where no pipes were replaced and an alternative more efficient route was found to deliver water.

Figure 27. Diagram of simplified physical network showing the location of the failed pipes
In summary, the results show that, without optimisation, two pipes will fail when the peak demand is increased to 380 litres/hr per household, even though they are adequate for a peak demand of 243 litres/hr per household. By optimising the water allocation within the network, all demands can still be met without having to replace any pipes, thereby allowing the assets to be driven harder.

ISSUE 6 - IMPLICATIONS OF ELEVATED ATMOSPHERIC CO₂ CONCENTRATIONS

To examine the effect of elevated atmospheric CO₂ concentrations on water supply infrastructure, modified rainfall and climatic data were used for scenario S1. The modified rainfall and climate data for three levels of CO₂ concentrations were obtained from climate simulations performed within the Urban Water Program by Bates and Viney. The three different CO₂ concentrations considered were current CO₂ level and twice and three times the current CO₂ levels. The implications of elevated CO₂ concentrations on rainfall are shown in Figure 28. There is a slight increase in rainfall as a result of increased CO₂.

![Cumulative Rainfall](image)

Using the modified rainfall and climate data as inputs to UVQ, modified demands were generated by UVQ for TAWS for the clusters within the study area. These demands were then used in TAWS to establish the impact that elevated CO₂ levels will have on the water supply infrastructure. The planning period of scenario S1 was modified to 20 years to assess the implications on the operation costs.

Unfortunately, the prediction of monthly demands by UVQ could not capture the differences in the elevated CO₂ rainfall sequences. All sequences have dry periods of longer than a month, usually during summer and late autumn. During dry months, UVQ assumes a constant (ie maximum) daily irrigation rate. Since the surface area and soil properties for a cluster do not change during the simulation period, the monthly demand is simply a function of the number of days in the month and the cluster area. As a consequence, cluster types have identical maximum monthly demands over the simulation period.

Identical maximum demands for each cluster type, irrespective of the rainfall pattern, result in the use of similar transport infrastructure for the two elevated CO₂ rainfall sequences and the scenario with the current CO₂ concentration. Therefore, this analysis could not show that changes in rainfall have a significant effect on the total transport costs (change in the total transport cost was only about 1%).

A similar result is obtained for ongoing cost of infrastructure. The cost functions used in the TAWS model to calculate the operation costs of all the infrastructure components except pumping stations do not use flow as a parameter. The operating cost of pumping stations is based on the flow, but the flow represents steady peak flow over the planning period, rather than the actual flow. Therefore, there is
very little change in the ongoing cost of the infrastructure for the two elevated CO₂ scenarios and the scenario with the current CO₂ concentration.

This highlights two areas that need attention in the TAWS model. The first is that more work is required to derive appropriate cost functions to calculate operation costs of infrastructure components. The second is the ability to select appropriate flows for calculating the ongoing costs. The simulated flows, which reflect the behaviour of demands to external influences, such as elevated CO₂ levels, would be a better choice for calculating operating costs. This could be done by selecting a project planning period that overlaps with the simulation period that is being used to check the reliability of water supply in the system.
CONCLUSIONS

A modelling framework has been developed that can be readily used by managers to compare scenarios which integrate water supply, waste water and storm water infrastructure. Two models have been developed to operate within this modelling framework. They are the UVQ model for water and contaminant balance in urban areas and the TAWS model for assessing the cost-effectiveness of alternative urban water systems. Both models adopt the integrated approach for modelling of water supply, waste water and storm water services in urban areas. The models have been designed to be readily transferable between sites and to provide flexibility in specifying various ways of handling waste, waste water and storm water services.

Both UVQ and TAWS models (assessment tools) have been applied to a sample problem based on an actual site to test their functionality. The preliminary results demonstrate that both UVQ and TAWS models are valuable tools in developing hydrologically and hydraulically feasible and cost efficient alternative urban water systems.

In particular, the TAWS model has been used to analyse a number of scenarios focusing on alternative ways of planning and operation of the water supply system in Perth North East Corridor study area. For example, current design standards may be very conservative in their estimation of peaking factors. The model provides the opportunity to examine the impact of reducing the peaking factor and delay the augmentation of infrastructure as demand increases. It may be possible that by simply reducing the peaking factor, the existing infrastructure can cope with the predicted demands, for say the year 2020. In other words, with the TAWS model it has been possible to identify aspects of the urban water supply system where there is a potential to provide considerable savings for the water industry.

The TAWS model has the capability of automatically selecting from a wide range of pipe materials, which satisfy hydraulic constraints. Alternative and emerging pipe technologies may have desirable properties, such as reduced infiltration and exfiltration, and reduction in maintenance and longer life. The ability to select efficiently from a comprehensive list of pipe types, subject to minimising life cycle costs has the potential to reduce rehabilitation and infrastructure costs.

The assessment tools are suitable for assessing the consequences for urban water supply systems of changes in rainfall patterns, which may result from elevated atmospheric CO2. Deficiencies in existing infrastructure can be identified and the cost of infrastructure augmentation quantified. The cost estimates so produced may prove useful in policy development with respect to greenhouse gas emissions.

In summary, the integrated modelling framework incorporating the TAWS and UVQ models is a useful computer tool for water resource managers, urban planners and environmental regulators to assess the cost-effectiveness and the ecological sustainability of alternatives to the traditional method of providing water services in urban areas.
FUTURE DIRECTIONS

The feasibility stage of the project has identified a number of limitations in some components of the modelling approach. It has also demonstrated a number of strengths of the framework that has been developed. For example, the modelling framework is feasible and flexible and provides for the integration of models with different spatial and temporal scales. This is demonstrated with UVQ providing time series data to TAWS. The models can be run independently or they can be linked. This philosophy will continue with the next generation of CUWPID.

The feasibility stage has also identified modelling components that need to be enhanced. Some enhancements which will enable CUWPID to analyse a wider range of scenarios with greater accuracy are outlined below.

MODEL ENHANCEMENTS

Many of the enhancements to CUWPID could be developed in-house or acquired from other packages. In both cases, the scenario manager will provide an interface to and between these models. For example, the hydraulic analysis performed by TAWS is not state-of-the-art. There are a number of models available that could be used to perform detailed hydraulic analysis. This would improve the flexibility of the modelling system and enhance its commercialisation potential. Users of the modelling system may be reluctant to purchase the system if they have to adapt existing data to suit our model. This would not occur if an interface is provided to a number of popular models.

Enhancements to CUWPID and the models that could provide these enhancements to CUWPID have been identified as:

1. Hydraulic Analysis in TAWS
   ♦ implement unsteady flows (FEQUTL, Franz and Melching 1997)
   ♦ implement looped pipe system (EPANET, Rossman 1994)
   ♦ interface with other popular hydraulic models

2. Contaminants in TAWS
   ♦ track individual contaminant profiles through pipe system (EPANET, Rossman 1994)
   ♦ automatic selection of treatment processes based on contaminant profiles and desired outcomes (Treatment Process Selector, Booker et al. 1999; WWTREAT, Cuddy 1998)

3. Removal of spatial and temporal restriction
   ♦ ensure that models within CUWPID are spatially and temporally independent

4. Externals
   ♦ include the modelling of externalities in TAWS. A method for valuing externalities has been developed by Bowers and Young (1999).

5. Make UVQ more flexible
   ♦ removal of hierarchy in flow paths
   ♦ introduce a plug and play approach to allow the user to construct their own network
   ♦ enhanced generation of contaminants off surfaces
   ♦ including processes in storages
   ♦ use a simultaneous equation solver for contaminant and flow calculations
6. Multi-objective optimisation
   ♦ optimisation of cluster size
   ♦ minimise externalities
   ♦ optimise environmental outcomes
   ♦ optimise infrastructure staging
   ♦ optimisation of treatment processes
   ♦ optimisation of resource allocations
   ♦ optimisation of the selection of replacement pipes within TAWS

7. Presentation of Results
   ♦ using key indicators which have been identified by Gomboso (1999)
   ♦ the effective comparison of alternative scenarios

8. Online help and documentation
   ♦ It is essential to produce a comprehensive user manual and on-line help facility. The user manual
   will explain each screen within the scenario manager and will also give the user an overview and
   explanation of the use of the Scenario Manager. It will also form the basis of an on-line help
   system that would be produced as a result of processing the user manual through a commercial
   help development software packages such as RoboHelp or .HDK. The resultant Windows or HTML
   help file will then form the on-line help facility of the scenario manager.

9. Interrogation / Interpretation
   ♦ A fundamental part of a the scenario manager is to provide the user with a flexible method for
     interrogating and understanding the results produced. This will allow users to delve deeply into
     scenario results and to define reports in terms of content and form (text or graphical). Further,
     users will be able to interpret results obtained from multiple scenarios. The interpretation
     system will identify those key factors that have had the greatest impact on scenario results and
     quantify these impacts in an objective manner. It will also assist users to develop an
     understanding of scenario behaviour.

With the above enhancements, it will be possible to identify emerging technologies that would produce the
 greatest benefit, with a user-friendly and commercially attractive package. Efficient assessment of
 opportunities that can be exploited will be valuable to the water industry. For example, minimisation of
 off-site, nutrient rich discharges to receiving waters not only has environmental and social benefits, the
 trading of emission permits is an alternative revenue source for the water industry. The model can be
 used to investigate alternative approaches of recycling of waters, thereby reducing emissions to receiving
 waters.

RESEARCH OPPORTUNITIES

This study represents a significant advancement in urban water models. The IWR/TAWS model
represents one of the very few attempts to implement simulated annealing in a practical water resource
assessment model and to develop an integrated urban water resources model. A number of other research
opportunities have been identified from this study.

1. Infrastructure Failure

There are very few models available which examine the impact of infrastructure failure. For example,
flash flooding is a major community expense. Insurance companies would benefit from the ability to
predict the cost flash flooding may cause and those areas that are prone to flash flooding. This is another
potential client for modelling products, other than the water industry.
2. Rainfall Interpolation

Rainfall is extremely variable. There are few efficient and robust techniques for interpolating rainfall in both space and time. Traditional techniques average the rainfall data. The averaging process conserves the rain but it reduces the intensity of the rainfall. This can significantly underestimate extreme rainfall events and rare flood events. This is a critical process in urban areas which has implications for estimating rare flood events and pollution runoff.

3. Risk Analysis

In the existing modelling approaches, all the model parameters, such as costs and infrastructure variables are known with certainty. This is not the case, all model parameters contain some variability. Life cycle costs should also reflect the variability in the model inputs. There are a number of reliability techniques that could be employed, for example Monte Carlo method, point estimate method and moment methods. Due to the complexity and computational requirements of CUWPID's components, the most suitable candidates are mean value first-order-second-moment and point estimate methods.

These research opportunities and model enhancements are achievable in the modelling framework.
REFERENCES


4 Internal working papers were prepared during the course of the project to document approaches, designs and their implementation. They are not peer reviewed and are therefore not publicly available. These documents may be made available by the authors, on request. Refer to Appendix D for a complete list.


Metropolitan Water Authority (MWA) (1985) Domestic Water Use in Perth, Western Australia, Metropolitan Water Authority, Perth.


Appendix A  THE CONTAMINANT BALANCE MODEL

CONTAMINANT FLOWS AND CONTAMINANT PROFILE OPERATIONS

UVQ uses several spatial scales to represent the components of an urban area. Four nested spatial scales have been selected, indoor water use, unit block, cluster and estate. Each of these scales is described below and the diagrams reproduced. The diagram of the house flow and contaminant paths is also reproduced in the main report (Figure 28). The symbols used in the diagrams are given in Table A-1. The diagrams are reproduced from Farley et al. (2000).

Table A-1, Description of the symbols used in the flow and contaminant paths in the UVQ diagrams

<table>
<thead>
<tr>
<th>Flow/contaminant path</th>
<th>Symbol</th>
<th>Symbol Style</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain / Tap Water</td>
<td></td>
<td>solid blue line</td>
</tr>
<tr>
<td>Tank Water</td>
<td></td>
<td>solid teal line</td>
</tr>
<tr>
<td>Black Water</td>
<td></td>
<td>solid black line</td>
</tr>
<tr>
<td>Grey Water</td>
<td></td>
<td>solid grey line</td>
</tr>
<tr>
<td>Storm Water</td>
<td></td>
<td>solid green line</td>
</tr>
<tr>
<td>Ground Water</td>
<td></td>
<td>solid red line</td>
</tr>
<tr>
<td>Link at this level</td>
<td></td>
<td>solid black arrowed line</td>
</tr>
<tr>
<td>Link at another level</td>
<td></td>
<td>dashed black arrowed line</td>
</tr>
<tr>
<td>Located at this level</td>
<td></td>
<td>solid black border box</td>
</tr>
<tr>
<td>Located at another level</td>
<td></td>
<td>dashed black box</td>
</tr>
<tr>
<td>Loads specified</td>
<td></td>
<td>red star</td>
</tr>
<tr>
<td>Concentrations specified</td>
<td></td>
<td>yellow cross</td>
</tr>
<tr>
<td>Sludge calculated</td>
<td></td>
<td>black wide arrow</td>
</tr>
<tr>
<td>Input</td>
<td></td>
<td>clear circle</td>
</tr>
<tr>
<td>Human contribution</td>
<td></td>
<td>people!</td>
</tr>
<tr>
<td>Flow path</td>
<td>nnn</td>
<td></td>
</tr>
</tbody>
</table>

The following table shows system inputs and outputs of flows and contaminants. The tap at the indoor level (1), represents a source of potable water. The tap at the unit block level (66), however, may be of potable or lower quality water. This is also the case for the tap input at cluster level (120). The major outputs from UVQ are the stormwater flows and loads and the wastewater flows and loads and the inputs are the tap water of various qualities. It is assumed that the source of tap water is infinite and UVQ will simply calculate the amount of tap water of various qualities that are required within an estate.
Table A-2, Identification of input and output flows and contaminant paths in UVQ

<table>
<thead>
<tr>
<th>UVQ Inputs and Outputs</th>
<th>1, 50, 66, 120, 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Flows</td>
<td>91, 153, 175, 178</td>
</tr>
<tr>
<td>Output Flows</td>
<td>1, 33, 34, 35, 36, 50, 66, 100, 120</td>
</tr>
<tr>
<td>Input Contaminants</td>
<td>163, 164, 175, 178</td>
</tr>
<tr>
<td>Output Contaminants</td>
<td></td>
</tr>
</tbody>
</table>

A group of estates defines a region and the allocation of water resources within a region can be modelled using TAWS. To do this, TAWS requires the input demands and output supplies for each estate; these are furnished by UVQ.

The "use", "mix", "simple sludge", and "sludge with treatment" operations are fully described in Farley et al. (2000). This appendix identifies where these operations occur, within each scale and are derived from Tables 9-12 in Farley et al. (2000).

**Indoor Scale**

The indoor water use scale represents water utilisation and contaminant transport within a building. It distinguishes between water used in the kitchen, bathroom, laundry and toilet. Water supplied into the house can be sourced from a potable water supply, tank water or recycled wastewater or stormwater. Contaminant profiles represent both human and external inputs and are assumed to remain constant during a simulation. The contaminant loads from humans are proportional to the occupancy rate. Modelling at this level facilitates comparison between water demand techniques, such as low flow showerheads. The indoor water use can also be used to model water use within commercial and industrial buildings where the water demand in the indoor water use is specified using an equivalent occupancy rate.
Contaminant Profile Operations

Table A-3 identifies the locations of use and mix operations within the indoor scale. The numbers in brackets in the source column identify the flow paths in Figure A-1.

Table A-3, Location of contaminant profile operations at indoor scale

<table>
<thead>
<tr>
<th>Source</th>
<th>Used By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap (1)</td>
<td>Kitchen (3), Bathroom (5), Laundry (7), Toilet (9)</td>
</tr>
<tr>
<td>Tank (2)</td>
<td>Kitchen (4), Bathroom (6), Laundry (8), Toilet (10)</td>
</tr>
<tr>
<td>Kitchen (15)</td>
<td>Pervious soil store (19), On-site waste water treatment (24), Unit block sewerage system output (28)</td>
</tr>
<tr>
<td>Bathroom (16)</td>
<td>Pervious soil store (20), On-site waste water treatment (24), Unit block sewerage system output (26)</td>
</tr>
<tr>
<td>Laundry (17)</td>
<td>Pervious soil store (29), On-site waste water treatment (25), Unit block sewerage system output (30)</td>
</tr>
<tr>
<td>Toilet (18)</td>
<td>On-site waste water treatment (22), Unit block sewerage system output (23)</td>
</tr>
</tbody>
</table>

MIX Operation

<table>
<thead>
<tr>
<th>Location Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitchen, Bathroom, Laundry, Toilet</td>
</tr>
</tbody>
</table>
Unit Block Scale

A unit block represents a single property that can contain, in addition to the Indoor water use, paved areas, and pervious areas such as garden. Alternatively, a unit block in an industrial land use will, for example, contain a factory building and car parking areas. On-site supply and disposal practices can be investigated along with the effect of unit block characteristics such as size, occupancy, and water demands. Additional contaminant profiles are used to specify the contaminant contributions from pervious soil store, on-site wastewater treatment, runoff from impervious areas etc. Excess contaminant loads from pervious soil store and on-site wastewater treatment are assumed to be removed as sludge.

Contaminant Profile Operations

Table A-4 identifies the locations of use, mix and simple sludge operations within the unit block scale. The numbers in brackets in the source column identify the flow paths in Figure A-2.

<table>
<thead>
<tr>
<th>Use Operation</th>
<th>Source</th>
<th>Used By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (50)</td>
<td>Pavement (51), Pervious soil store (52), Roof (53)</td>
<td></td>
</tr>
<tr>
<td>Tank (62)</td>
<td>Unit block storm water output (63), Indoor (64)</td>
<td></td>
</tr>
<tr>
<td>Roof (58)</td>
<td>Pervious soil store (61), Unit block storm water output (77)</td>
<td></td>
</tr>
<tr>
<td>Pervious soil store (31)</td>
<td>Pervious soil store (67)</td>
<td></td>
</tr>
</tbody>
</table>
### Cluster Scale

A cluster comprises a number of identical unit blocks as well as roads and public open space. Typically a cluster contains a single land use type such as a suburb. These types of developments create an urban form that is made up of numerous groupings of unit blocks which have similar characteristics and share facilities such as public open space, stormwater drainage systems, and roads. A stormwater storage facility or wastewater treatment plant, for example. Additional contaminant profiles are used to specify the contaminant contributions from public open space (POS) pervious soil store, ground water store, runoff from impervious areas etc. Excess contaminant loads from public open space pervious soil store, stormwater and wastewater stores are assumed to be removed as sludge.

The cluster may act as an exit point for stormwater and wastewater, or may act as a store for stormwater and wastewater, recycling these for use in the indoor and unit block levels, or may divert its stormwater and wastewater to estate stormwater and wastewater stores if these exist.
Contaminant Profile Operations

Table A-5 identifies the locations of use, mix, sludge, simple sludge and sludge with treatment operations within the cluster scale. The numbers in brackets in the source column identify the flow paths in Figure A-3.

<table>
<thead>
<tr>
<th>USE Operation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (100)</td>
<td>Road (101), POS pervious soil store (103), Cluster storm water store (132), Cluster waste water store (139)</td>
</tr>
<tr>
<td>Road (104)</td>
<td>Cluster storm water store (131)</td>
</tr>
<tr>
<td>POS pervious soil store (114)</td>
<td>Cluster storm water store (116), Cluster sewerage system output (126), Cluster sewerage system output (44)</td>
</tr>
<tr>
<td>Unit block storm water output (90)</td>
<td>Cluster storm water store (123)</td>
</tr>
<tr>
<td>Cluster storm water store (151)</td>
<td>Cluster storm water store (14), Cluster storm water store (79)</td>
</tr>
<tr>
<td>Infiltration (72)</td>
<td>Infiltration (130)</td>
</tr>
<tr>
<td>Unit block storm water output (90)</td>
<td>Cluster sewerage system output (40, 41, 42)</td>
</tr>
<tr>
<td>Unit block sewerage system output (89)</td>
<td>Cluster sewerage system output (43), Cluster waste water store (133)</td>
</tr>
<tr>
<td>Cluster sewerage system output (155)</td>
<td>Cluster storm water output (46)</td>
</tr>
</tbody>
</table>
### MIX Operation

<table>
<thead>
<tr>
<th>Location Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sewer Infiltration</td>
</tr>
<tr>
<td>Storm Water Output</td>
</tr>
<tr>
<td>Sewerage System Output</td>
</tr>
</tbody>
</table>

### SIMPLE SLUDGE Operation

<table>
<thead>
<tr>
<th>Location Name</th>
<th>Flow Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>POS Pervious Soil Store 202</td>
<td></td>
</tr>
<tr>
<td>Cluster Waste Water Store 204</td>
<td></td>
</tr>
</tbody>
</table>

### SLUDGE WITH TREATMENT Operation

<table>
<thead>
<tr>
<th>Location Name</th>
<th>Flow Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster Storm Water Store 203</td>
<td></td>
</tr>
</tbody>
</table>

---

#### Estate Scale

An urban area containing several land uses will be represented as a number of separate clusters. This combination of separate clusters represents an estate. Additional storages for stormwater and wastewater may be present at this scale and water from these storages may be recycled for the indoor, unit block and cluster levels. Stormwater and wastewater flows from each cluster may be sent to these additional storages or may simply exit the estate.
Contaminant Profile Operations

Table A-6 identifies the locations of use and mix operations within the estate scale. The numbers in brackets in the source column identify the flow paths in Figure A-4.

Table A-6, Location of contaminant profile operations at estate scale

<table>
<thead>
<tr>
<th>USE Operation</th>
<th>Source Operation</th>
<th>Used By Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estate storm water store (173)</td>
<td>Storm water output (175)</td>
<td></td>
</tr>
<tr>
<td>Estate waste water store (176)</td>
<td>Sewerage system output (178)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MIX Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location Name</td>
</tr>
<tr>
<td>Evaporation</td>
</tr>
<tr>
<td>Storm Water Output</td>
</tr>
<tr>
<td>Sewerage System Output</td>
</tr>
</tbody>
</table>
Appendix B  SIMULATED ANNEALING ALGORITHM

The optimisation used by TAWS to obtain cost effective solutions is based on the simulated annealing algorithm developed by Kirkpatrick, Gelatt and Vecchi in the 1980s (Kirkpatrick et al. 1983).

A simulated annealing algorithm will generally include two nested loops, as shown in Figure B-1. It starts from an arbitrarily selected configuration, with an appropriate initial temperature and works to minimise a given cost function. For a given temperature, \( t_j \) the following three step inner loop operation is repeated \( L_j \) times. \( L_j \) represents the minimum number of metropolis loops that will be performed before decreasing the temperature, even if no improvement of the optimum of the average cost of current configurations takes place. This parameter will have a decisive influence upon the computation time and rate of convergence. A new configuration \( s'_j \), is constructed from the current configuration \( s_j \), by giving a random perturbation to a randomly selected components of the configuration. The corresponding cost function is evaluated. If the cost of the new configuration is lower than the current configuration the perturbed configuration is accepted and it becomes the current state. If the new configuration has a higher cost, and the new solution is given the probability of \( \min(1, \exp(-\Delta c / t)) \) where \( \Delta c \) is the cost change due to the perturbation. One of the characteristics of this probability function is that for very high temperatures each state has almost equal chances of being the current state. For low temperatures, only states with low cost functions have a high probability of being the current state.

This basic step is known as the metropolis step. A main feature of the metropolis step is that, besides accepting improvements in cost, it can also accept deteriorations in cost. Initially, at large values of temperature \( t_j \), large deteriorations will be accepted. As \( t_j \) decreases, only smaller deteriorations will be accepted and finally, as the value of \( t_j \to 0 \), no deteriorations will be accepted at all. This feature of simulated annealing means that the simulated annealing algorithm, in contrast to other optimisation algorithms, can escape from local minimum. This is achieved in the step where \( \exp(-\Delta c / t) \), known as the metropolis criterion is compared with a uniform random number \( p \).

---

% Simulated Annealing

% set up initial parameter estimates and temperatures
choose \( s_i \) \{\( s_i \) is the initial configuration\}
choose \( t_i \) \{\( t_i \) is the initial temperature\}
choose \( t_f \) \{\( t_f \) is the stopping temperature\}
calculate \( c_i \) \{cost of initial configuration\}

\( j \leftarrow 0 \)
do until \( t_{j+1} \leq t_i \) or until \( j = M \) \{termination criterion\}

\( j \leftarrow j + 1 \)
%metropolis loop
for \( i = 1 \) to \( L_j \)

choose at random \( s' \in N(s_j) \) \{\( N(s_j) \) in the neighbourhood of \( s_j \), perturbation\}
choose at random \( p \in [0,1] \)
%metropolis criterion
if \( p \leq \min(1, \exp(-c(s_j') - c(s_j)/t_j)) \) \{\( c(s_j) \) is the cost of configuration \( s_j \)\}
then \( s_{j+1} \leftarrow s' \)
else \( s_{j+1} \leftarrow s_j \)
end
end for
choose \( t_{j+1} \leftarrow t_j \)
end do

---

Figure B-1, Pseudo code for simulated annealing algorithm
In the simulation algorithm, the temperature must be controlled. The metropolis loop is therefore embedded in an outer loop. The outer loop decreases temperature according to the rule, \( t_{j+1} \leftarrow \alpha t_j \), where \( \alpha \) is the cooling coefficient satisfying \( 0 < \alpha < 1 \). Kirkpatrick et al. (1983) used a factor between 0.8 and 0.99. Faster cooling would give sub-optimal results, but less computer time would be needed.

The simulation is terminated when \( M \), which represents the maximum number of temperature decreases, has been reached or when the control variable \( t_j \) is smaller than a user specified value \( t_f \). \( L_j \), \( M \) and \( t_f \) are known as termination parameters.

The above algorithm represents the basic simulated annealing algorithm. There are a number of variants developed in an attempt to improve the efficiency of the algorithm. Simulated annealing has many attractive features: it should converge to the global solution, it is versatile and is simple to implement. However, it requires the careful selection of various parameters.
Appendix C  HYDRAULIC FEASIBILITY ANALYSIS IN TAWS

Hydraulic feasibility analysis is performed to establish whether the existing infrastructure is adequate to convey the peak flows. Each physical link in the water supply network carries pressurised water flows and usually consists of closed pipes, whereas waste water and storm water systems usually carry non-pressurised flows. The waste water system normally consists of closed pipes, whereas the storm water system consists of closed pipes and open channels.

For pressurised closed pipes, Bernoulli’s equation is used to establish whether the pipe is capable of conveying the required flow without exceeding the pressure rating of the pipe. Manning’s equation is used to establish whether open channels have sufficient capacity to convey required flows.

If the existing infrastructure does not have sufficient capacity, then additional infrastructure is needed to convey the peak flows. The additional infrastructure can be either new or a duplication of the existing infrastructure.

The hydraulic analyses of the water supply, storm water and waste water networks are described below.

WATER SUPPLY NETWORK

Water supply networks are generally characterised by pressurised pipes, pumps, service tanks and pressure reducing valves. Bernoulli’s equation is simply the conservation of energy and can be written as

\[ p_1 \frac{\alpha_1 \nu_1^2}{2g} + Z_1 = p_2 \frac{\alpha_2 \nu_2^2}{2g} + Z_2 + h_L \]

for pressurised steady flow, where \( \alpha \) is the kinetic energy factor which lies between 1.03 and 1.3 for turbulent flow, \( p \) is the pressure, \( Z \) is the elevation at the centroid of the pipe section, \( v \) is the fluid velocity, \( g \) is the gravitational acceleration, \( h_L \) is the combined head loss, \( \rho \) is the density of water and subscripts 1 and 2 refers to the start and end nodes of the pipe section, see Figure C-1.

The combined head loss in the pipe generally consists of exit, entrance and friction losses. However, it is assumed that exit and entrance losses are negligible. The friction loss is estimated by using the Hazen-Williams equation. This equation in Metric units is given by:

![Figure C-1. Characteristics of pressurised pipe flow](image-url)
where \( L \) is the pipe length, \( D \) is the pipe diameter, \( Q \) is the discharge \((Q=Av)\), \( A \) is the cross-sectional area and \( C \) is the Hazen-Williams coefficient that varies with the type of pipe material.

Equation (2) is written between pipe junctions. The elevation of the pipe junctions, \( Z_1 \) and \( Z_2 \), the velocity of the flow through the pipe, between the pipe junctions is calculated using the pipe diameter and the flow the pipe is required to convey. The head loss \( h_L \) is also estimated using the pipe properties, flow velocity and \( (3) \). Either \( P_1 \) or \( P_2 \) are also given from calculations upstream of these pipe section. With these values the pressure, \( P_1 \) (or \( P_2 \)) can be estimated. This is compared with the pressure rating of the pipe to establish its ability to convey the flow.

The main assumptions of a hydraulic analysis of a water supply network are:

- existing pipes are duplicated only if additional capacity is required and they can withstand the pressure exerted within the pipe. Otherwise all the pipes in the physical section are replaced with pipes having higher pressure ratings.
- pipes in a physical section are replaced when the lifetime of a pipe has lapsed within the planning period. The replacement pipe is the same size, type and pressure rating as the current pipe.
- if existing pumping stations are not sufficient to supply the required head and flow rate required, additional pumping stations are provided. The new pumping station consists of at least two pumps of the same type, with one as a stand-by pump.

**WASTE WATER AND STORM WATER NETWORKS**

The waste water and storm water networks share many of the features of the water supply system, in that the waste water and storm water networks can operate under pressure and involve pipes, pumps and storages. However, both the storm water and waste water networks are more complicated than the water supply network. In addition to pipes under pressure, they can include a number of conveyance devices and other structures, including pipes, open channels, natural channels, gutters and roads. Many of these have very little influence on steady monthly flow that is used in TAWS. For example, manholes can have a significant influence on rapidly varying flows as temporary storage devices and increasing the energy loss of the flow. However, for steady flows at a monthly time scale they do not affect the behaviour of the flow. Therefore, only those components that influence steady average monthly flows are included in the hydraulic analysis of the waste water and storm water infrastructure. These include; pumps, pipes flowing partially full or under pressure and open channels operating under steady flows.

Both the storm water and waste water infrastructures should be capable of accommodating some variability in the flow. The temporal variability of the waste water flows is directly influenced by rainfall. The temporal variability in waste water is influenced by the infiltration into the sewer system and illegal storm water connections to the sewer system. A simple flow peaking factor is used to simulate the variability in the flow. The peaking factor can be selected by the user or alternatively, can be calculated from the daily values produced by UVQ.

Storm water infrastructure is designed to cope with extreme meteorological events. This is usually the 1 in 10 year recurrence flow event. Hydraulic analysis of the storm water network establishes whether the storm water infrastructure has sufficient capacity to convey the storm water peak storm water flows. The waste water infrastructure however, can be sized. In both cases flow in pipes can occur as either pressurised or as free surface (open channel) flow.
Pressurised Flows

The assumptions made in the hydraulic analysis of storm water and waste water infrastructures under pressurised flow or surcharging are the same as for water supply infrastructure. Pressurised flows in a pipe are calculated using (2) and (3). The Hazen-Williams coefficient for storm water and waste water pipes are given in Table C-1 for different pipe material and age. Storm water and waste water infrastructures are assumed to have failed if the hydraulic pressure exceeds the tensile capacity of the pipe material.

Table C-1, Values of the Hazen-Williams coefficient C for different conduit materials and age of conduit

<table>
<thead>
<tr>
<th>Conduit Material</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely smooth and straight pipes</td>
<td>New</td>
</tr>
<tr>
<td>Cast-iron pipe, coated (inside and outside)</td>
<td>140</td>
</tr>
<tr>
<td>Cast-iron pipe, lined with cement or bituminous enamel</td>
<td>130</td>
</tr>
<tr>
<td>Steel, riveted joints, coated</td>
<td>110</td>
</tr>
<tr>
<td>Steel, welded joints, coated</td>
<td>140</td>
</tr>
<tr>
<td>Steel, welded joints, lined with cement or bituminous enamel</td>
<td>140</td>
</tr>
<tr>
<td>Concrete</td>
<td>140</td>
</tr>
<tr>
<td>Cement-asbestos and plastic pipe</td>
<td>140</td>
</tr>
</tbody>
</table>

Both storm water and waste water infrastructure can be characterised by pipes and manholes. Overflow occurs when the capacity of a pipe is exceeded and the excess volume of flow can escape through manholes and becomes surface runoff. In TAWS, the volume of surcharge is not calculated, but the occurrence of surcharging is reported.

Open Channel Flows

Open channel flows can occur in pipes, man-made and natural channels. In many urban environments, natural channels have been replaced by well defined man-made channels or their banks stabilised. Both natural and man-made channels can be represented by rectangular, triangular, trapezoidal and circular shaped channels. TAWS is currently restricted to these channel types.

No head losses at pipe expansions, contractions, man holes, junctions, bends are considered. Pipe exit losses, and losses associated with transitions between pipe and open channel flows are also ignored. It is also assumed that only subcritical flow, where the Froude number \( F_v = v / \sqrt{gh} < 1 \) occurs in the storm water and waste water networks. Generally, supercritical flows, \( F_n \geq 1 \) should be avoided as these are associated with very high velocity flows, that can cause scour of channel linings, ultimately leading to the failure of the infrastructure. Considering only subcritical flows also avoids the necessity to consider hydraulic jumps in the network. Therefore, the capacity of an open channel is estimated by assuming steady normal flow. Normal flow is calculated using the Manning equation given by

\[
Q_n = Q_{max} = \frac{1}{n} AR^{2/3} S_0^{1/2}.
\]

in which \( A \) is the cross-sectional area, \( R = A/P \) is the hydraulic radius, \( P \) is the wetted perimeter, \( S_0 \) is the channel or pipe slope, \( n \) is the Manning resistance coefficient and \( Q_{max} = f(h_{max}) \). Values for the Manning resistance coefficient are given in Table C-2 for various channel material types. The parameters that are used to describe the circular channel are shown in Figure C-2 and in Figure C-3 for the trapezoidal channel, which also includes the rectangular and triangular channel. Expressions for the wetted perimeter \( P \), and the cross-sectional area \( A \), for these channels are given in Table C-3.
Table C-2, Average values for the Manning resistance coefficient, n for various channel material type

<table>
<thead>
<tr>
<th>Open Channel Type</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth cement lining</td>
<td>0.010</td>
</tr>
<tr>
<td>Lined cast iron</td>
<td>0.012</td>
</tr>
<tr>
<td>Average concrete pipe</td>
<td>0.013</td>
</tr>
<tr>
<td>Average clay sewer pipe and cast iron pipe, average cement lining</td>
<td>0.015</td>
</tr>
<tr>
<td>Earth canals, straight and well maintained</td>
<td>0.023</td>
</tr>
<tr>
<td>Dredged earth canals, average conditions</td>
<td>0.027</td>
</tr>
<tr>
<td>Canals cut in rock</td>
<td>0.040</td>
</tr>
<tr>
<td>Rivers in good condition</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Table C-3, Hydraulic properties of various channel shapes.

<table>
<thead>
<tr>
<th>Channel Shape</th>
<th>Channel Characteristic</th>
<th>Area (A)</th>
<th>Perimeter (P)</th>
<th>Data Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td></td>
<td>$\frac{D^2}{4} \left( \frac{\pi \theta}{360} - \sin \frac{\theta}{2} \right)$</td>
<td>$\frac{\pi D \theta}{360}$</td>
<td>$S_0, D, n$</td>
</tr>
<tr>
<td>Trapezoidal</td>
<td></td>
<td>$B h_{\text{max}} + \frac{h_{\text{max}}^2}{m}$</td>
<td>$B + \frac{2h_{\text{max}}}{\sqrt{1 + m^2}}$</td>
<td>$S_0, B, m, n, h_{\text{max}}$</td>
</tr>
</tbody>
</table>

1 Rectangular channel when $m = 0$; 2 Triangular channel when $B = 0$; 3 $\theta = \cos^{-1}\left(1 - \frac{2h_{\text{max}}}{D}\right)$

Figure C-2, Characteristics of a partially full pipe flow
For the open channel, such as a trapezoidal channel, establishing $h_{\text{max}}$ is straightforward. It simply represents bank full capacity, see Figure C-3. For pipe flow, the pipe is considered as full when $h = 0.95D$. Above this level, there is a decrease in flow capacity of a pipe because the wetted perimeter increases at a greater rate than the cross-sectional area, see Figure C-4.

In the model, $Q_{\text{max}} = f(h_{\text{max}})$ can be calculated for each channel and pipe. The discharge, $Q(h)$ that is to be conveyed by the channel will be compared with $Q_{\text{max}}$. The channel fails if $Q(h) > Q(h_{\text{max}})$, the channel does not have the capacity to convey the flow. For pipe flow $Q(h) > Q(h_{\text{max}} = 0.95D)$ does not necessarily mean that the pipe has failed. It only indicates that the pipe is not capable of conveying the flow as an open channel and surcharging occurs. The pipe may be able to convey the flow under pressure. This is confirmed using the energy equation, (2). If the pressure does not exceed the tensile capacity of the pipe there is no failure of the infrastructure, however, overflows may occur.
Appendix D  CONTRACT 4 WORKING PAPERS

A series of working papers were prepared during the life of the project to document thoughts, approaches, design and implementation. Many of these have been integrated into technical reports. Many have not. For the purposes of cross-referencing, the final reports have been numerically identified (see Table D-1).

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<tr>
<th>ID</th>
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<tbody>
<tr>
<td>1</td>
<td>Integrated Water Resource Model - Methodology, Implementation and Application (Maheepala et al. 2000a)</td>
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<td>2</td>
<td>Tool for Assessing Water Systems (TAWS) - Methodology (Maheepala et al. 2000c)</td>
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<td>3</td>
<td>Tool for Assessing Water Systems (TAWS) - Design, Implementation and Data Specification (Maheepala et al. 2000b)</td>
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<td>4</td>
<td>The Scenario Manager - Functionality and Implementation (Coleman et al. 2000)</td>
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<td>5</td>
<td>Contaminant Balance component of UVQ Model - Technical Specification (Farley 2000)</td>
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<td>6</td>
<td>Characterisation of the Perth North-East Corridor Study Area (Cuddy et al. 2000)</td>
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Table D-2 cross-refers the original working papers to the final reports.

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<td>T4-1</td>
<td>Models for assessment of alternative urban water systems</td>
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<td>T4-2</td>
<td>Integrated Water Resource Decision Support System - Preliminary Data Requirements</td>
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<td>Modelling of Stormwater in IWR DSS</td>
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<tr>
<td>T4-4</td>
<td>Modelling of Wastewater in IWR DSS</td>
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<td>T4-5</td>
<td>Overview of IWR Data Representations (2-page flier)</td>
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<tr>
<td>T4-6</td>
<td>Design Issues in Developing an Expert System for Selecting Appropriate Wastewater Technologies</td>
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<td>T4-8</td>
<td>A Method To Enhance The Current Handling Of Wastewater In The IWR DSS</td>
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<td>T4-9</td>
<td>A Method To Include Contaminant Balance in IWR DSS</td>
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<td>T4-10</td>
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<td>Batch Commands for IWR DSS</td>
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<td>Toward cost-effective and sustainable water resource development in the Spencer Region of South Australia</td>
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<td>A Method for using peak factors in the design of water supply distribution systems</td>
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<td>Waste Water Treatment in JAT</td>
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<td>Urban Water Program Study Area</td>
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<td>TAWS Methodology - A Tool for Assessing the Cost-effectiveness of Alternative Urban Water Systems</td>
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<td>Optimisation Model of TAWS</td>
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<td>Review of Storm Water Models</td>
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<td>The House Editor</td>
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<td>The Network Designer</td>
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<td>Study Area Potable Water and its Infrastructure - Data Processing</td>
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<td>T4-30</td>
<td>Alternative Treatment Options - Data Processing</td>
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<td>Matching Scenario Components with Modelling Capability</td>
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<td>Representation of the study area in IWR DSS</td>
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<td>Incorporating 'Key' Indicators of Quality, Quantity, Efficiency and Effectiveness of Urban Water Systems into Scenario Assessment</td>
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<td>Assessment of Scenarios</td>
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