DESIGN OF SUSTAINABLE WATER DISTRIBUTION SYSTEMS IN DEVELOPING COUNTRIES

Kalanithy Vairavamoorthy*, Ebenezer Akinpelu*, Zhuhai Lin*, Mohammed Ali*

*Water Development Research Unit, Faculty of the Built Environment South Bank University, 202 Wandsworth Road, London SW8 2JZ, UK. PH +44 (0)20 7815 7382; FAX +44 (0)20 7815 8390; emails: vairavk@sbu.ac.uk; akinpeeo@sbu.ac.uk; zhuhail@sbu.ac.uk; alime@sbu.ac.uk.

ABSTRACT

This paper concerns the development of international guidelines for the design of urban water distribution systems in developing countries where intermittent supplies are unavoidable for the foreseeable future, in order to sustain adequate and safe supplies. The development of these guidelines has been funded by the Department for International Development (UK).

The available water sources throughout the world are becoming depleted and this has brought into focus the urgent need for planned action to manage water resources effectively for sustainable development. The problem of water scarcity in urban areas of developing countries is of particular concern and as the water quantity available for supply generally is not sufficient to meet the demands of the population, water conservation measures are employed. One of the most common methods of controlling water demand is the use of intermittent supplies, usually by necessity rather than design. It is evident from literature surveyed that the design of distribution networks operating intermittent supplies has in general been based on the assumption of continuous supply; the concepts and methods used are identical with those used in developed countries. This has resulted in severe pressure problems and great inequities in the distribution of water. Clearly there is a need to develop more appropriate design tools which recognise the particular features of intermittent systems.

This paper describes a novel approach to the design of water distribution systems in developing countries. An alternative approach to design has been developed which employs a modified network analysis procedure and utilises formal optimisation techniques to ensure the maximum uniformity in supply. The conventional approaches to network analysis will be described and discussed with respect to their suitability for simulating conditions of water shortage. The modifications required to model such conditions have been identified and incorporated into a modified network analysis simulation tool. The simulation tool has been verified using data obtained during extensive field surveys performed in Kerala, India.

In addition to the simulation tool, optimisation techniques to identify the least cost design of distribution systems, while achieving the most equitable distribution of water have been developed. These optimisation routines in combination with the simulation tools, have been applied to the design of an urban network in Kerala, India, and construction of this network is to begin in the next few months.

1.0 INTRODUCTION

At the launch of the International drinking water supply and sanitation decade (in November 1980), Dr H.T.Mahler, Director-General of the World Health Organisation (WHO), stated that: "*. . the number of water taps per 1000 population is a much better indicator of a country's health status than the number of hospital beds*", (Development Forum, 1987). The importance of water supply is acknowledged by all governments in developing countries who have and are giving priority to this provision. Providing a water supply for a community involves tapping the most suitable source of water, ensuring that it is safe for domestic consumption and then supplying it in adequate quantities.

The World Health Organisation,(WHO Study Group, 1987), defines:

- safe water as ". . *water that does not contain harmful chemical substances or micro-organisms in concentrations that cause illness in any form*";
- and adequate waters supply as " . . *one that provides safe water in quantities sufficient for drinking, and for culinary, domestic, and other household purposes so as to make possible the personal hygiene of members of the household. A sufficient quantity should be available on a reliable, year-round basis near to, or within the household where the water is to be used* " .

The available water sources throughout the world are becoming depleted and this problem is aggravated by the rate at which populations are increasing, especially in developing countries. This has brought into focus the urgent need for planned action to manage water resources effectively. The problem of water scarcity in urban areas is of particular concern. Migration of the rural population to urban centres has resulted in towns and cities expanding rapidly. Such situations place a strain on existing public services and result in chaotic conditions in many towns and cities throughout the developing world. Since the water quantity available for supply generally is not sufficient to meet the demands of the population, water conservation measures are employed. One of the most common methods of controlling water demand is the use of intermittent supplies, usually by necessity rather than design. It is of interest to note that 91% of systems in South East Asia are intermittent as reported by a WHO survey, (Pickford, 1987); practically all Indian cities are reported to operate intermittent systems, (Kumar and Abhyankar, 1988).

2.0 INTERMITTENT SUPPLY

An important component of a water supply system is the distribution network which conveys water to the consumer from the sources. These systems constitute a substantial proportion of the cost of a water supply system, in some cases as much as half the overall cost of the system.

The design of water distribution systems in general has been based on the assumption of continuous supply. However, in most developing countries water supply is not continuous but intermittent, and this could have been foreseen at the design stage. This has resulted in severe supply pressure losses and great inequities in the distribution of water.

For examples the results of a field studies performed by the authors in South India, identified the following problems of intermittent systems:

- Overall shortage of water.
- Insufficient pressure in the distribution system (several areas had zero pressure).
- Inequitable distribution of the available water.
- Very short duration of supply (e.g. in the outskirts of Chennai water is usually supplied for one hour each day).

A serious problem arising from intermittent supplies, which is generally ignored, is the associated high levels of contamination. This occurs in networks where there are prolonged periods of interruption of supply due to negligible or zero pressures in the system. By establishing the factors that are most related to contamination, (i.e. duration of supply), it may be possible to develop control measures to minimise this risk. Such control measures might themselves lead to modifications in the design concept. In this paper control measures to minimise contamination will not be discussed.

As a result of discussions with the relevant authorities in India, some interesting points emerged. The design engineers stated that although it was known at the design stage that a system would operate intermittently, it was designed as a continuous system. They acknowledged that this was not the correct approach, but argued that they had no alternative since there were no proper guidelines and design tools developed specifically for intermittent systems. This results in larger than expected flows rates in the pipelines, the consequence of which is large pressure losses in the network with those consumers furthest away from supply points unable to collect sufficient quantities of water. During the initial hours of supply when everyone is drawing water, this problem is particularly acute.

Clearly there are serious problems related to designing intermittent systems as continuous systems. From discussions with the authorities, it was apparent that there was a need to develop more appropriate design tools which recognise the particular features of intermittent systems. It might be expected that the development of such design tools would ultimately find extensive application.

3.0 DESIGN TOOL FOR INTERMITTENT WATER SUPPLY SYSTEMS

In response to the findings of discussions with engineers in India, a major research project began to develop new approach to the design and analysis of intermittent water distribution systems. The project funded by the Department for International Development (UK), was led by South Bank University in collaboration with Indian Institute of Technology, Madras and Kerala Water Authority. The results of this research project will be disseminated by mean of international guidelines made available in March 2001.

A major component of this new approach is a modified mathematical modelling tool specifically developed for intermittent water distribution systems. This modified tool combined with optimal design algorithms with the objective of providing an equitable distribution of water at the least cost forms the basis of the new approach. A brief description of these components will be given below.

In addition to the above, another research project will begin in April 2001 (subject to funding approval), to develop guidelines for the effective monitoring and management of water quality in intermittent water distribution systems. However, details of this additional project will not be presented here.

3.1 MODIFIED ANALYSIS TOOLS

The overall shortage in water availability, that is a fact of life in most developing countries, necessitates intermittent supply at a low per capita supply rate. These conditions force consumers to collect water in storage vessels. Storage is an important feature of such systems since it is the storage facilities that provide water during non-supply hours. Because of the low supply rate of water and the intermittent nature of supply, the demand for water at the nodes in the network are not based on notions of diurnal variations of demand related to the consumers behaviour (as with networks in developed countries), but on the maximum quantity of water that can be collected during supply hours. The quantity of water provided to the consumers often drops well short of their requirements. In such systems it is logical to assume that consumers will draw water from the distribution system for the total duration of supply and the quantity they collect will be dependent totally on the driving pressure heads at the outlets.

There is a fundamental problem in the assumption made by most methods of network analysis, in that the analysis is demand driven, i.e., the demands of the network will be met irrespective of the conditions in the network. As stated above, in intermittent water networks the quantity of water collected by consumers will be dependent on the driving pressure heads at the outlets and hence the relationship between the pressures in the system and the demands are important, and it cannot be assumed that demand will be met under all conditions. Therefore, the application of standard methods of network analysis to intermittent flow conditions is inappropriate.

A modified network analysis program has been developed that incorporates pressure dependent outflow (PDO) functions to model the demand (or outflow). The model consists of four main innovative components:

1. <u>Demand Model:</u>

   Using queuing theory and reservoir routing, this model forecasts the end-users demand profile (intensity and distribution of usage over a given period of supply), for use with the secondary network model. Data used by this model includes: type of connection time of supply; duration of supply; pressure regime.

2. Secondary Network Model:

Obviously it is impractical to model networks as far an individual house connection, and therefore methods must be developed to establish lumped PDO functions for a single node (primary node), for a group of nodes (secondary network). Such methods have been developed and take into account the hydraulic behaviour of the secondary network (Vairavamoorthy, 1994). This model initially assumes a primary node to be a constant head (or reservoir) node, supplying water to the secondary network. By performing a series of simulations, varying the pressure at the primary node, flows out of the primary node into the secondary network for these different pressures can be calculated.

3. Network Charging Model (prior to pressurised flow)

Using a pressure head iterative method, a mathematical model for complex networks has been developed that simulates the charging up of the network after supply resumes. By introducing an equivalent outlet technique (incorporating the PDO functions), the node numbers in the network can be reduced and real networks simulated. This model predicts the time at which different users receive water after supply resumes and highlights the time lag experienced by tail-end users in the network (it is anticipated that this model will be used to predict contaminant movement in intermittent networks during the first flush (as part of the forthcoming research project mentioned above)).

4. Modified Network Analysis Method (pressurised flow).
A modified network analysis program has been developed that incorporates pressure dependent outflow (PDO) functions to model the demand (or outflow). The network governing equations are solved using the gradient algorithm of Todini and Pilati (1987). The program applies sparse matrix methods to improve the computational efficiency of the overall method.

Network analysis was performed for a network in South India (Figure 1), incorporating the developed PDO functions. The results of the simulation corresponded well with the observations made in the field. Poor pressure conditions and the resulting inequities of supply were highlighted by the analysis (Figures 2 to 5).

Figure 2 indicates that most of the above network experiences pressures below 3 metres (and in many areas pressures are less then 1 metre). Figure 3 shows that it takes approximately 30 minutes for users at the tail end of the network to receive any water at all. In addition to this delay, Figure 4 indicates the tail-enders also experience the lowest pressures (when water finally arrives at their node), which means that the discharge rate from their standpipes is very low. Therefore the total quantity collected by the tail-enders is low compared to others in the network (this is shown in Figure 5). This network provides a highly inequitable distribution of water!

It is clear from the analysis that the present conditions in the network studied are unsatisfactory and that if a conventional network model had been applied, such conditions would not have been identified. By definition, demand driven models would have supplied all the nodes a quantity of water equal to that allocated to the nodes in the construction of the model. The model would have supplied this quantity of water irrespective of the pressures at the node. Hence, PDO functions are essential when analysing intermittent systems; only by the inclusion of PDO functions can the true extreme conditions that exist in intermittent systems be reproduced.

3.2 DESIGN APPROACH

The design approach for intermittent systems has received little or no attention. In the literature available for the design of distribution systems in developing countries, for example, Borjesson and Bobeda, (1964), Dangerfield, (1983), Hofkes, (1981), Sridharan and Datta, (1987), Taylor, (1967), and Thorley and Wood, (1987), the concepts and methods used are identical with those used for developed countries. The only differences are the criteria adopted, such as the per capita consumption allocation, minimum pipe sizes, residual heads, etc. (Haukland, 1991; Herbert and

Yniguez, 1986). It is obvious from the literature studied that there is an implicit assumption that the design procedure used in developed countries is appropriate for developing countries.

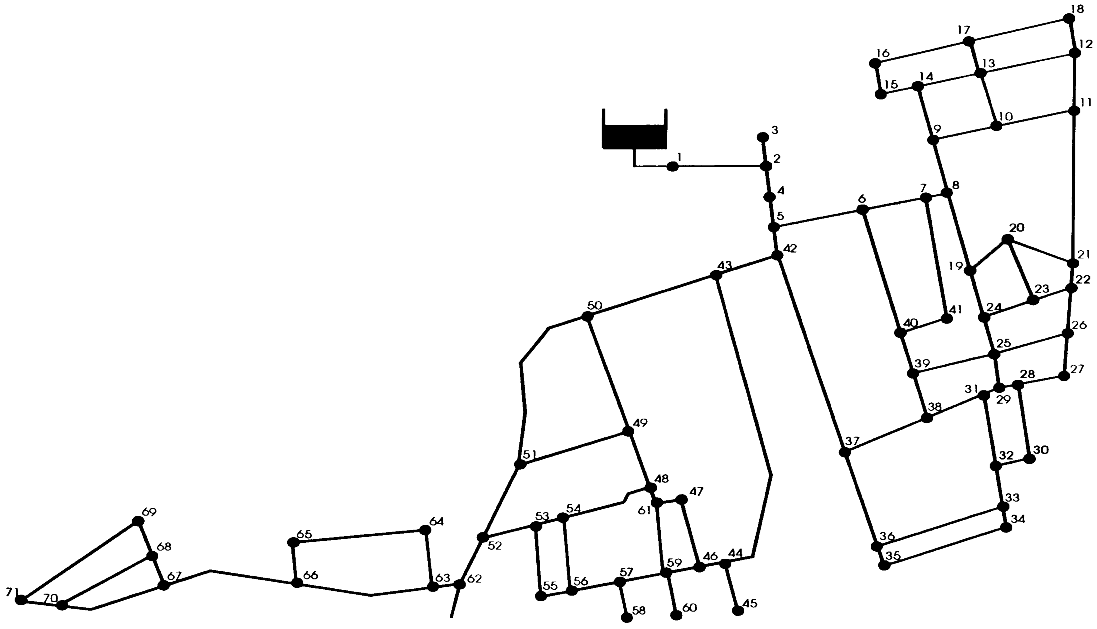

Figure 1: Schematic of network in South India

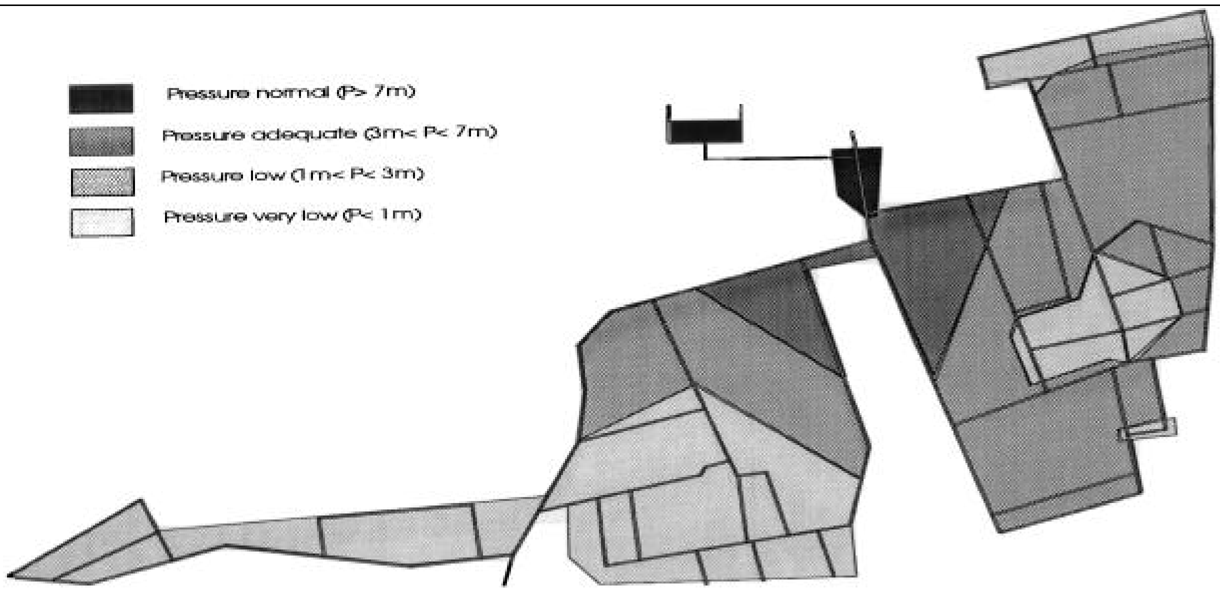

Figure 2: Pressure distribution in the network (End of Supply)

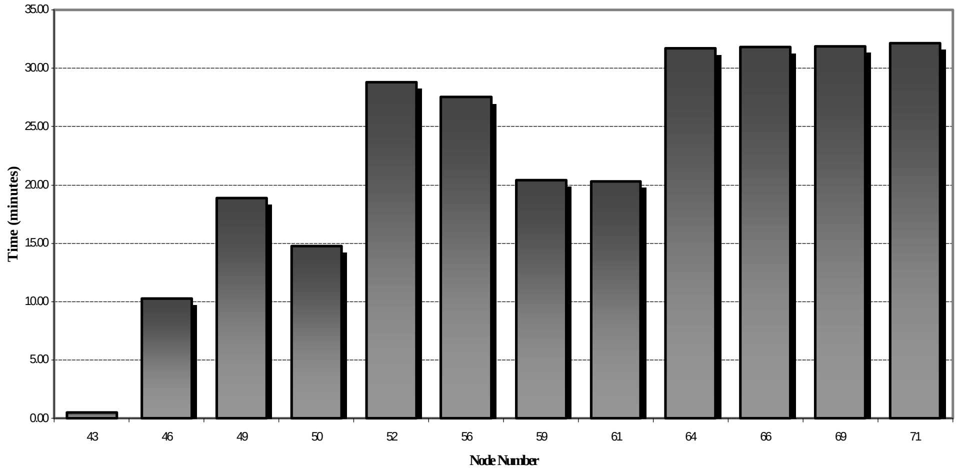

Figure 3: Predicted time for water to arrive at selected nodes

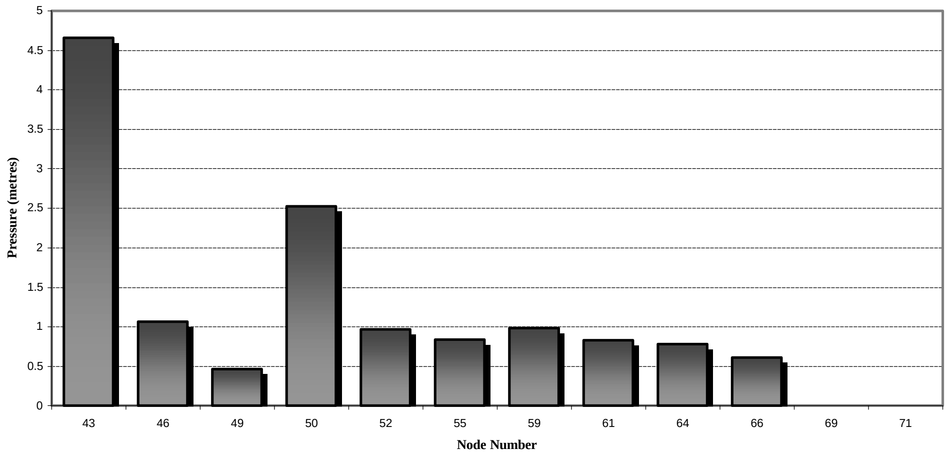

Figure 4: Pressure distribution for selected nodes (End of Supply)

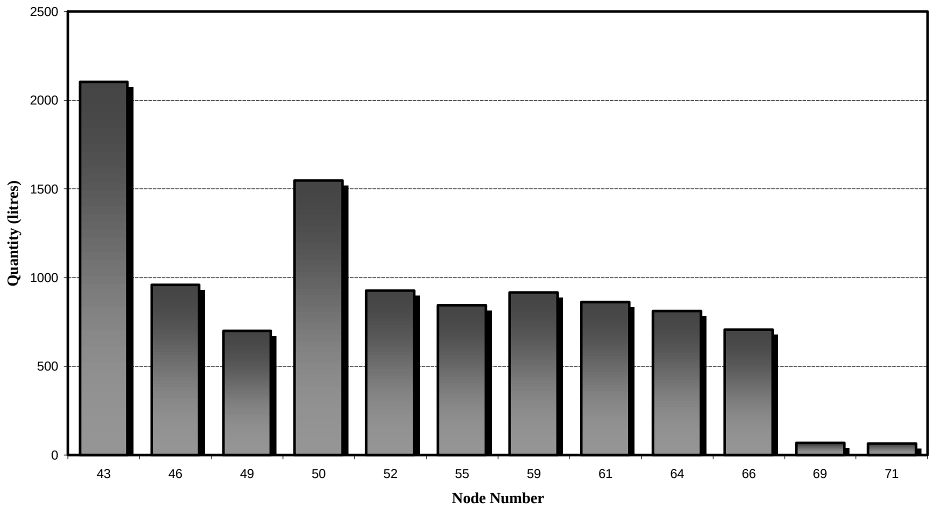

Figure 5: Total volume of water delivered to selected standpipes

As mentioned in Section 2.0, interviews performed in South India, indicated that new systems were being designed assuming continuous supply and using demand patterns that represented a 24 hour diurnal variation in demand. However, it was known by the engineers that the systems would operate at best for one hour a day and that this could be reduced to an alternate day supply.

Although, it is recognised that most distribution systems in developing countries are water starved, (Kalbermatten, 1989; Pickford, 1987), and operate intermittently, (Kumar and Abhyankar, 1987; Unvala, 1989; WHO Study Group, 1987), the need to rethink the design procedure has received little or no attention. In developed countries the importance of the effects of pressure on demand is not critical in the design of water distribution systems, except during periods of drought or under crisis conditions, whereas in developing countries it is a fundamental factor. Hence, in general conventional network analysis techniques are inappropriate in such situations. The modification in the design process for developing countries requires not only the inclusion of PDO functions to model the demand but also a re-definition of the objectives of design. The question should be asked: "what constitutes an optimal design ?".

In general an optimal design is thought of as being one that can supply sufficient quantities of water to the consumers at adequate pressures at least cost. In developed countries where there is sufficient quantities of water the objective of design is to find the least cost system which provides pressure above a specified minimum, (e.g. pressures above 15 metres head of water). However, in water starved systems, such an objective is not appropriate. In this case the objective might be that the limited quantity of water be distributed as fairly and equally as possible. It was argued in Section 3.1 that pressure dictates the quantity of water collected by the consumer. Therefore the obvious means of achieving equity is to maintain an equal pressure throughout the network. The optimisation problem can be viewed as having dual (multiple), objectives, i.e., to minimise the diversity in pressure at minimum cost.

It may not be possible however, to address the problem of achieving an equitable pressure distribution when sizing the network, since systems are often sized to meet a future forecast demand and therefore will always have excess capacity until the design conditions are realised. To accommodate these conflicting requirements a two part design approach is proposed.

First, the minimum cost design is obtained ensuring adequate pressures throughout the network for the duration of the specified design horizon. Next, the objective to minimise the variability in pressure is addressed by considering the strategic location and setting of valves in the network (Vairavamoorthy and Lumbers, 1998; Ali *et al.*, 1998). The inclusion of valves is considered progressively at time intervals between the outset of the operation of the network to its design horizon. The overall best valve locations are established for a case study network in which the valve settings will vary throughout its design life.

As part of the ongoing research project an optimisation method has been developed based on real-coded genetic algorithms (details can be found in Vairavamoorthy and Ali, 1998, 2000). The particular features of the program includes: least cost design objective; optimal pressure management routines (to ensure a more equitable distribution of water throughout the network); and multiple objective function routines.

The results of an example application of these methods to the network shown in Figure 1, are shown in Figures 6 and 7. The original network has been reinforced with additional pipes and flow reduction valves, strategically placed to minimise the deviation in pressure. Figure 6 and 7, shows that effective pressure management is possible in the early stages of the network but the magnitude of the improvement in pressure distribution diminishes as the design horizon is approached. This is related to the presence of excess capacity. In the early stages, the excess capacity is greatest and therefore there is room to reduce this excess capacity in a way that improves the pressure distribution. As the design horizon is approached, the excess capacity decreases and there is less potential for effective pressure management. However, the process has improved overall pressure distribution in the network and provided a more equitable distribution of water.

4.0 APPLICATION TO NETWORK IN KOCHI

The optimisation routines developed as part of this research project have been successfully applied to the design of networks in West Kochi, Kerala (an example shown in Figure 8). The proposed design (shown in Figure 8), has been approved for construction and tenders have been invited. It is interesting to note that the proposed design involves establishing four zones where previously there was only one. These zones where identified using the optimisation programs developed, where the objective of the design was to minimise the diversity in pressure in the distribution system (for equity in supply), at the least cost. An evaluation study of this network will be performed in approximately 24 months time to measure the success of designing for equity.

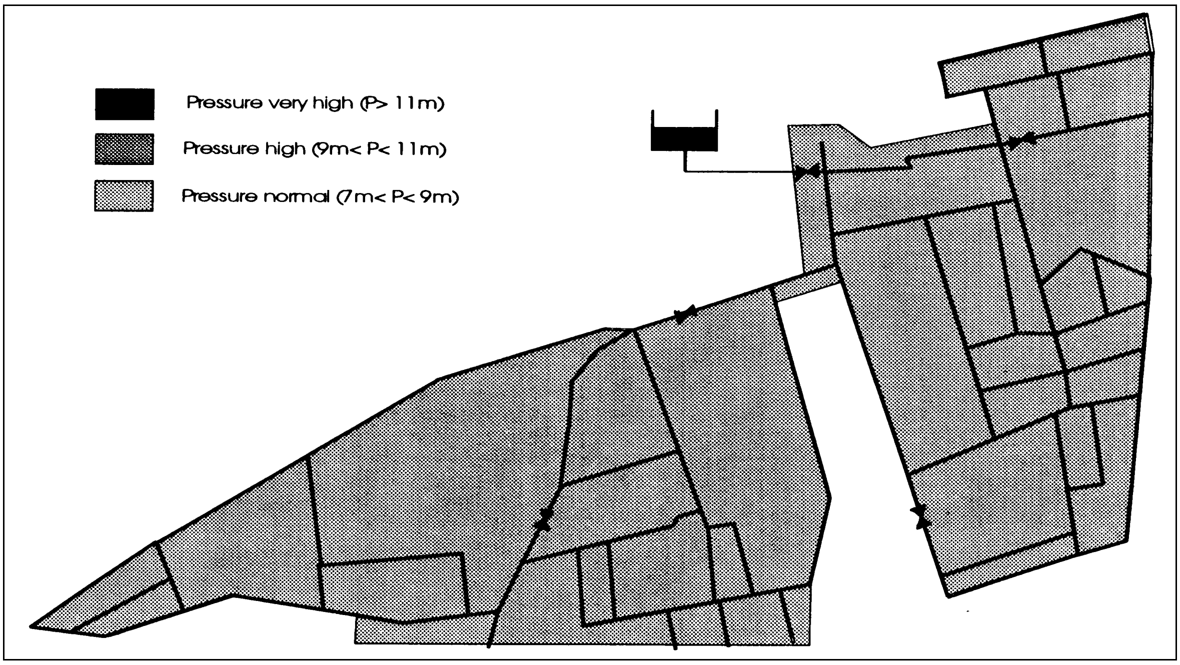

Figure 6: Pressure distribution after least cost design and optimal valve location (0 Year)

5.0 CONCLUSIONS

This paper presents details of new guidelines for the design and control of intermittent water distribution systems in developing countries. In these countries the availability of water is either inadequate or restricted due to difficulties such as power cuts. It is important to recognise these realities when designing and operating such networks. An alternative approach to design has been developed which employs a modified network analysis procedure and utilises formal optimisation techniques to ensure the maximum uniformity in supply.

Details of a modified analysis (simulation) method suitable for simulating conditions of water shortage are given. The modified analysis consists of four main components: a demand model; a secondary network model; a network charging model; and a modified network analysis model. The simulation tool has been verified using data obtained during extensive field surveys performed in Kerala, South India.

In addition to the analysis method details of new optimisation methods based on real code genetic algorithms are given for the least cost design of distribution systems, while achieving the most equitable distribution of water are given. These optimisation routines in combination with the simulation tools, have been applied to the design of an urban network in Kerala, India, and construction of this network is to begin in the next few months.

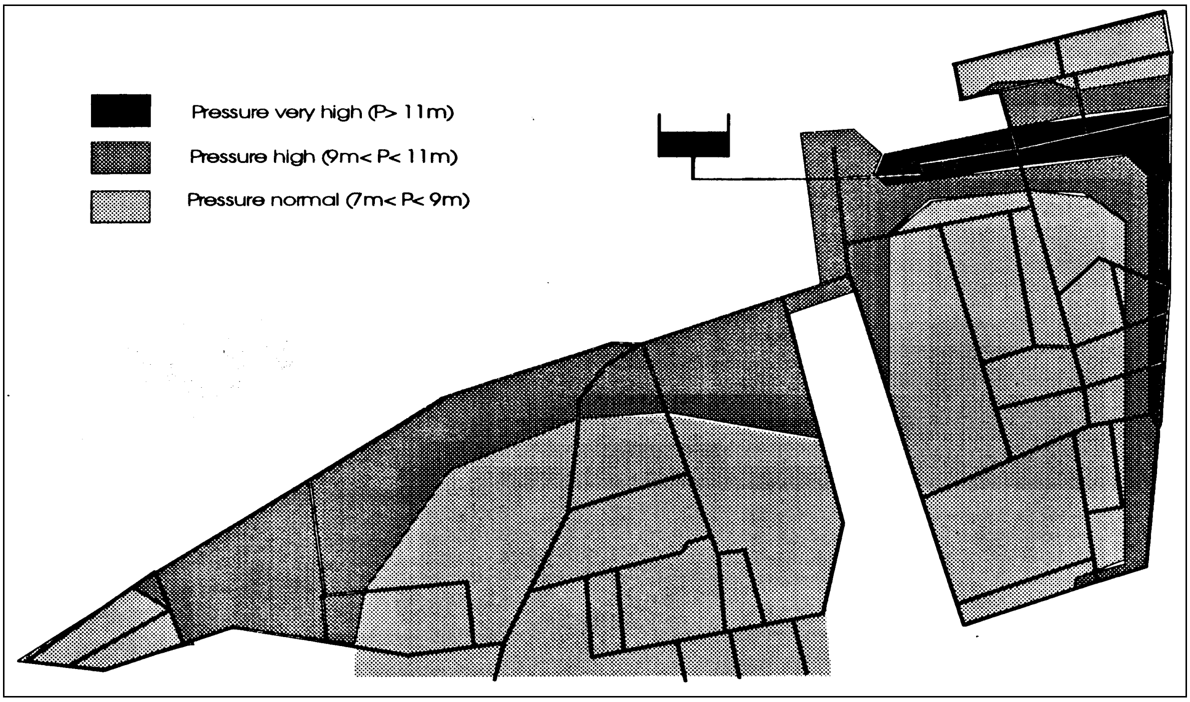

Figure 7: Pressure distribution after least cost design and optimal valve location (25 Year)

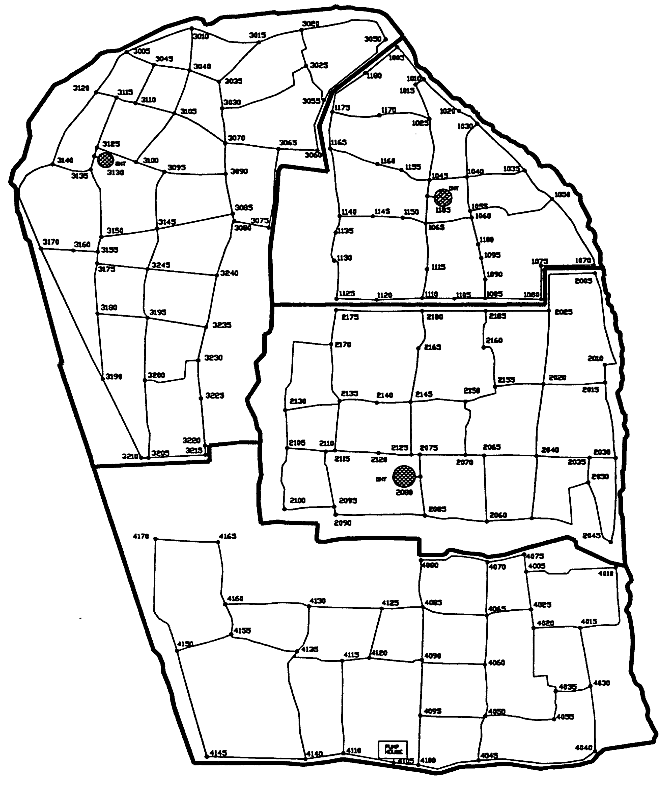

Figure 8: Proposed network design for West Kochi (using GA based optimisation)

6.0 REFERENCES

Ali, M., Vairavamoorthy, K., and Gunn, M. (1998). "*Leakage minimisation in water distribution systems using Genetic Algorithms.*" Proceeding of the Knowledge, Information and Data-Water Conference, Edinburgh, U.K. April 27 – 28, 169 – 183.

Borjesson, E.K.G., and Bobeda, C.M. (1964). “New concept in water service for developing countries.” *J. AWWA*, 56, July, 853-862.

Dangerfield, B.J. ed. (1983). *Water Supply and Sanitation in Developing Countries.* Inst. of Water Engrs and Scientists, London.

Development Forum (1987). *Water Decade Review,* United Nations, United Nations University, New York.

Haukland, S. (1991). “Water supply: Double standards.” *World Water and Environ. Engr.*, April, 61-64.

Hebert, V., and Yniguez, C. (1986). “Sensitivity of water distribution costs to design and service standards: A Philippine case study.” *Tech. Note No.16*, UNDP/World Bank Technical Advisory Group (TAG).

Hofkes E.H. ed. (1981). “Small community water supplies.” *Tech. Paper 18*, Inter. Ref. Centre for Community Water Supply and Sanitation (IRC), The Hague, Netherlands.

Kalbermatten, J.M. (1989). “Water Tech USA: A program for helping developing nations.” *J. AWWA*, 81(10), 39-44.

Kumar, A., and Abhyankar, G.V. (1988). “Assessment of leakages and wastages.” *Proc. 14th W EDC Conf. on Water and Urban Services in Asia and the Pacific*, 23-26.

Pickford, J.A. (1987). “Water and sanitation for underprivileged rural and urban communities.” *Proc. 1987 Asia-Pacific Conf. on Water Engrg*., 21-33.

Sridharan, K., and Datta, R.S.N. (1987). “An appropriate technology for operation and maintenance of urban water supply distribution systems.” *Proc. XIII National Conf. on Environ. Engrg and Appropriate Technology for Water Supply and Sanitation*, Inst. of Public Health Engrs (India), 1-12.

Talyor, F.B. (1967). “Functional design for effective operation of water supply systems in developing countries.” *J. AWWA*, February, 151-155.

Thorley, A.R.D., and Wood, D.J. (1987). “Applications of microcomputers in the design and optimisation of water supply and distribution systems in developing countries.” *Computer Applications in Water Supply: Volume 1 - Systems Analysis and Simulation.*, B. Coulbeck and C.H. Orr, eds., John Wiley and Sons, 219-245.

Todini, E., and Pilati, S. (1987). “A gradient algorithm for the analysis of pipe networks.” *Computer Applications in Water Supply: Volume 1 - Systems Analysis and Simulation*, B. Coulbeck and C.H. Orr, eds., John Wiley and Sons, 1- 20.

Unvala, S.P. (1989). “Bombay's water supply situation - Drought and migration wreak havoc on limited resource.” *World Water Inter*., February, 33-37.

Vairavamoorthy, K. (1994); *Water Distribution Networks: Design and Control for Intermittent Supply*: PhD Thesis, Imperial college of Science, Technology and Medicine, London UK.

Vairavamoorthy, K. and Lumbers, J.P (1998). *“Leakage reduction in water distribution systems: Optimal valve control.” J. Hydraulics Division, ASCE, 124 (11).* Nov 1998, 1146 – 1154.

Vairavamoorthy, K., and Ali, M. (2000) “*Optimal Design of Water Distribution Networks Using Genetic Algorithm*” Journal of Computer-Aided Civil and Infrastructure Engineering 15 (2000) 374-382.

Vairavamoorthy, K., and Ali, M. (1998). “*Least Cost Design of Water Distribution Networks*” Proceeding of the First International Conference on New IT for Decision Making in Civil Engineering, 11-13 October, Montreal, Canada.

WHO Study Group (1987). “Technology for water supply and sanitation in developing countries.” *Tech. Rep. Series 742*, World Health Organisation, Geneva.