A modern water supply system may include facilities for collection, storage, transportation, pumping, treatment and distribution. Of the total expenditure incurred on different facilities of a water supply system, the expenditure incurred on transportation and distribution of water is quite large and may even exceed 70% (Bhave 2003). A drinking water distribution system must be able to supply water to all consumers at their delivery points throughout the design period. Water distribution systems deteriorate over time. Surveys conducted by the United States Environmental Protection Agency, reveal that 35 – 60% of the water is wasted in leakages in the pipelines and that about 65% of the total maintenance expenditure is dedicated only for the repair and rehabilitation of the existing pipelines (AWWA 1996). It is not economically viable to replace all deteriorating pipelines in aging water distribution systems. Therefore, careful planning of maintenance activities for water distribution systems is essential. Optimal rehabilitation and maintenance strategies will not only save money but also will improve the level of service, increase the satisfaction of customers, enhance the life and reliability of the water distribution systems (Tabesh et al 2010).

1.1 SCOPE OF THE STUDY

The study of Water Distribution System (WDS) refers to the distribution of treated water through the distribution network to the consumers. In the literature, the research has addressed two aspects in the
water distribution system: (i) the optimal design of new water distribution networks, and (ii) the maintenance of the existing ones. This study considers the second aspect. Water distribution systems deteriorate with time, and usually function at severely reduced levels of efficiency, and therefore they have to be maintained periodically. Water distribution system maintenance is a complex task encompassing a wide range of alternatives like rehabilitation, replacement, and/or expansion of an existing system. The costs associated with the maintenance of water distribution systems are very high, and account for a large proportion in municipal maintenance budgets. Most municipalities make maintenance decisions using experience and intuition, and do not select the minimum cost strategy (Restrepo et al 2009). A decision model that evaluates various maintenance strategies can assist water management expert in selecting a cost-effective maintenance strategy that maximizes the system availability.

In this study, a maintenance decision model for a water distribution system has been proposed. The objective of the study is to determine the best maintenance strategy which would minimize the total discounted maintenance cost of the water distribution system over a specified maintenance planning horizon subject to the WDS availability constraint. Many possible maintenance alternatives such as repair, rehabilitation or replacement of a pipe are chosen as examples for demonstrating the application of the proposed decision model. The use of Stochastic Search Algorithms such as Simulated Annealing, Tabu Search and Genetic Algorithms in order to evaluate the various water distribution system maintenance strategies and thereby assist the management to determine the best maintenance strategy has been demonstrated. The search effectiveness of these algorithms has been compared and evaluated. A real-life water distribution system in Velachery, Chennai, India has been considered in the study. Monte-Carlo simulation technique has been employed to evaluate the infrastructure availability of the
water distribution system. A failure study of water distribution system is conducted to identify the potential failure modes. WDS performance assessment is carried out taking into account the failure behavior of the pipes and junction joints in the water distribution network, as well as the electro-mechanical components of the pumping station in the water distribution system.

1.2 DEFINITIONS

1.2.1 Water Distribution System

The American Water Works Association defines a water distribution system as one “including all water utility components for the distribution of finished or potable water by means of gravity storage feed or pumps through distribution-pumping networks to customers or other users” (Mays 2000).

1.2.2 Maintenance

According to the classical view, the role of maintenance is to fix broken items. Taking such a narrow perspective, maintenance activities will be confined to the reactive tasks of repair actions or item replacement triggered by failures. Thus, this approach is known as reactive maintenance or corrective maintenance. A more recent view of maintenance is defined as “all activities aimed at keeping an item in, or restoring it to, the physical state considered necessary for the fulfillment of its function” (Jardine and Tsang 2006). Obviously, the scope of this enlarged view also includes proactive tasks, such as preventive maintenance. If the strategic dimension of maintenance is also taken into account, it should cover those decisions taken to shape the future maintenance requirements of the organization. The Maintenance Engineering Society of Australia (MESA) recognizes this broader perspective of maintenance and defines the function as “the
engineering decisions and associated actions necessary and sufficient for the optimization of specified capability” (Jardine and Tsang 2006).

1.2.3 Maintenance Management

Maintenance management refers to the application of the appropriate planning, or organization and staffing, program implementation, and control methods to a maintenance activity. This may pertain to the management of a sustaining maintenance and support activity responsible to ensure that the system being utilized by the consumer is effectively and efficiently maintained throughout its design life (Blanchard et al. 1995).

1.2.4 Reliability

Reliability is defined as the probability that a system will perform its intended function for a specified period of time when used under designated operating conditions (Ebeling 2007). It is the probability of a non failure over time. For a large system, with many interactive subsystems (such as a water distribution system), it is extremely difficult to compute the mathematical reliability analytically. Accurate calculation of a mathematical reliability requires knowledge of the precise reliability of the basic subsystems or components and the impact on accomplishing the mission caused by the set of all possible subsystem (component) failures (Mays 2000).

1.2.5 Maintainability

Maintainability is defined as the probability that a failed component or system will be restored or repaired to a specified condition within a period of time when maintenance is performed in accordance with the prescribed procedures (Ebeling 2007). While reliability is concerned with the ability of a
system to survive, maintainability is related to the repairability of the system. Combining the two, we have a measure called availability.

### 1.2.6 Availability

The term availability is generally used for repairable systems to indicate the probability that the system is in an operating condition at any given time ‘*t*’. Availability may also be interpreted as the percentage of time a component or system operates over a specified time interval or the percentage of components operating at a given time (Mays 2000). It differs from reliability in that availability is the probability that the component is currently in a non-failure state even though it may have previously failed and been restored to its normal operating condition. Availability may be the preferred measure when the system or component can be restored since it accounts for both failures (reliability) and repairs (maintainability). It is also the best parameter for any complex system that is required and depended upon on a continual basis. The availability of a system satisfies the following inequality relationship.

\[ 0 \leq A(t) \leq 1 \]

### 1.2.7 Failure

The transition process from the normal, working condition to the failed condition is termed as failure (Andrews and Moss 2002). The termination or the degradation of the ability of an item to perform its required function is called failure. The reverse process transforming the component to a working state is termed repair. The component life-cycle consists of a series of transitions between these two states.
1.2.8 Failure Mode

To understand the mechanism of system failures and in order to identify the potential weaknesses of a fail-safe concept it is necessary to perform a failure mode analysis. The mode of a failure is the symptom (local effect) by which a failure is observed. The effect by which a failure is observed on the failed system is termed the failure mode.

1.2.9 Mean Time To Failure

The time to failure for any component can not be predicted exactly. The failure can only be characterized by the stochastic properties of the population as a whole. The times to failure can be used to form a probability distribution which gives the likelihood that components have failed prior to some time. Components operated under different conditions or supplied by different manufacturers will have different time to failure distributions. Because of the presence of many uncertainties that affect the operation of a physical system, the time when the system fails to perform satisfactorily as intended is a random variable (Mays 2000).

1.2.10 Failure Rate

Failure rate (usually denoted as \( \lambda \)) is defined as the number of failures occurring per unit time. In terms of failure, the failure rate is a measure of the rate at which failures occur. Failure rate is an important function in reliability analysis because it provides a measure of the changes in the probability of failure over the lifetime of a component. The failure rate for many systems or components often exhibits a bathtub shape (Mays 2000). The failure rate is assumed to relate to the useful-life (constant failure rate) phase. For components with a constant failure rate, the mean time-to-failure is computed as the reciprocal of the failure rate.
1.2.11 **Mean Time To Repair**

Repair time, the key parameter required for the assessment of maintainability/availability, is the time required to reach the faulty component and to repair it or replace it with a new component. The mean time to repair (MTTR) is the expected time to perform a restoration task on a system after a malfunction, whether or not the system is down for all or part of the restoration. The MTTR measures the elapsed time required to perform the maintenance operation and is used to estimate the downtime of a system (Mays 2000). For repairable water resource systems, such as pipe networks and pumping stations, the failed components within the system can be repaired or replaced so that the system can be put back into service. The time required to have the failed system repaired is uncertain; consequently, the mean time required to repair the system from its failure to an operational status is a random variable (Mays 2000).

1.3 **AN OVERVIEW OF THE THESIS**

This thesis is a research effort on the failure analysis and simulation based availability assessment of a Water Distribution System (WDS) and on the application of stochastic search algorithms to determine a cost-effective maintenance strategy to be recommended in order to maximize the infrastructure availability for such a critical urban infrastructure.

i) A review of the literature related to the water distribution system management is presented in chapter 2. A survey of articles on the optimization models, techniques and heuristics used for the optimal design of water distribution systems is provided. The literature on topics such as failure analysis and prevention, reliability-based design, and risk assessment and control in water distribution systems is presented. The application of various optimization models for optimal
maintenance, rehabilitation, and replacement policies of water distribution systems is also included.

ii) The maintenance optimization study of the water distribution system is described in chapter 3. The need for the maintenance of the Water Distribution System, the objectives of the study, and the formulation of the WDS maintenance optimization problem are presented. The proposed methodology and the solution approach used in the study are also presented. The data related to the existing Velachery water distribution system in India, used in the study to demonstrate the application of the proposed maintenance decision model are also presented.

iii) In chapter 4, a systematic approach to identify the potential failure modes that have an influence on the failure of the water distribution system is presented. A real-life urban water distribution system is taken up for the study. The various undesirable failure modes and events which make the components in the water supply pumping system as well as the pipes in the water distribution network fail are considered in the study. The application of the Monte Carlo simulation model to evaluate the WDS performance is presented. The WDS infrastructure availability is considered as the measure of performance.

iv) The problem of determining the best maintenance strategy for WDS when the system parameters are altered is computationally hard. The various multiple maintenance alternatives in order to maximize the system availability are considered in the WDS maintenance optimization problem under study. Simulated Annealing (SA) is a randomized local
search method that has been used to derive near-optimal solutions for such computationally complex optimization problems. The application of Simulated Annealing algorithm to determine the least-cost maintenance strategy for the water distribution system is presented in chapter 5. Taguchi orthogonal experiments are used to determine the parameter settings of the Simulated Annealing technique.

v) Tabu Search (TS) is another search algorithm that can be applied to any search that works on the improvement principle. In chapter 6, a Tabu Search based algorithm is proposed to solve the WDS maintenance optimization problem. The parameter settings of Tabu Search algorithm are decided based on Taguchi orthogonal experiments.

vi) Genetic Algorithm (GA) is widely used currently to solve optimization problems, especially the combinatorial ones. In chapter 7, the use of Genetic Algorithms to obtain the cost-effective maintenance strategy for the WDS is presented. The parameter settings of this search algorithm are determined using Taguchi orthogonal experiments. Genetic Algorithms with an orthogonal array based crossover and a Monte Carlo technique based crossover schemes are proposed.

vii) The results obtained from the proposed stochastic search algorithms viz., Simulated Annealing technique, Tabu Search algorithm and Genetic Algorithms used to optimize the maintenance effort on the pipe network and the pumping system components of the water distribution system are presented in chapter 8. The Conclusions and suggestions for further study are also presented.