CHAPTER 2

REVIEW OF LITERATURE

2.1 GENERAL

Review of earlier studies carried out by many researches provides knowledge of past approaches and helps one to identify the research gap and thereby helps to adopt, modify and improve the conceptual framework for solving any problem. In the present study, review of literature related to wastewater treatment, disposal and management in urban and peri-urban areas using GIS is done. This helps to propose a methodology for selection of suitable sites for decentralized wastewater treatment system and the reuse options. In addition, the earlier studies related to the effective use of treated wastewater and advanced method of artificial recharge using Soil Aquifer Treatment System are also reviewed. Thus the review of literature enhanced the knowledge of GIS capability in sustainable management of wastewater in urban and peri-urban areas.

2.2 GIS BASED MULTICRITERIA ANALYSIS

2.2.1 Geographical Information System

A fully functional Geographical Information System (GIS) is an integration of several components and different subsystems. It is devoted especially to collect, store, retrieve and analyze spatially-referenced data (Burrough and McDonnell 1998).
Jacek Malczewski (1999) and Laaribi (2000) defined GIS is a powerful tool of acquisition, management and analysis of spatially-referenced data. GIS is used as a tool in solving complex spatial problems involving several factors with conflicting objectives/criteria.

### 2.2.2 Multicriteria Analysis

GIS based multicriteria analysis for solving spatially related complex problems was introduced during 1960. Roy (1996) defined multicriteria analysis as a decision-aid and a mathematical tool allowing the comparison of different alternatives or scenarios according to many criteria, often conflicting, in order to guide the decision maker towards a judicious choice. Jacek Malezewski (1996) described that multicriteria decision analysis involves a set of feasible alternatives that are evaluated on the basis of multiple, conflicting and noncommensurate criteria by a group of individuals. Malezewski (1999) described about the types and frame works of multicriteria which are presented below.

#### 2.2.3 Types of Multicriteria Analysis

**(a) Multi Attribute Decision Making**

Multi Attribute Decision Making is a procedure about incorporating multiple conflicting criteria into the management planning process.

An Attribute is a measure or quality of a geographical entity or a relationship between geographical entities. Multi Attribute Decision Making (MADM) methods obtain preferences usually in the form of function and weights.
Multi Objective Decision Making (MODM)

Objectives are functionally related to or derived from a set of attribute. MODM methods derive these from the preferences among objectives and the functions relating attribute to objective.

Framework of Multicriteria Analysis

Decision-making is a process. It involves a sequence of activities that starts with decision problem recognition and with recommendation. It is argued that the quality of the decision-making depends on the sequence in which the activities are undertaken.

(a) Problem Definition

A problem is defined when there is a lack of knowledge between the expectation and the present situation. Such situation could be turned to expected situation when it is resolved by proper solutions. Thus decision making is selecting a set of criteria from available alternatives. Hence GIS offers major support in the problem definition stage and the capabilities for data storage, management, manipulation and analysis.

(b) Evaluation Criteria

Once the decision problem is defined the spatial multicriteria analysis focuses on the set of evaluation criteria (objective and attribute). To be more specific, this step involves specifying a comprehensive set of objectives that reflect all concerns relevant to the decision problem and measures for achieving those objectives. Such measures are called attribute. A measurement scale must be established for each attribute.
The degree to which the objectives are met as measured by the attributes is the basis for comparing alternatives. The evaluation criteria are associated with geographical entities and relationships between entities and therefore can be represented in the form of maps. There are two types of criterion maps. An evaluation criterion map is a unique geographical attribute of the alternative decisions that can be used to evaluate the performance of the alternatives. A constraint map displays the limitations on the value that attributes and decision variables may assume. Evaluation criterion maps are also referred to as attribute maps. GIS data handling and analyzing capabilities are used to generate inputs to spatial multicriteria decision making.

(c) Alternatives

As suggested earlier, the process of generating alternatives should be based on the value structure and be related to the set of evaluation criteria. To each alternative a decision variable is assigned. Variable are used by the decision maker to measure the performance decisions.

(d) Criterion Weights

At this stage the decision maker’s preferences with respect to the evaluation criteria are incorporated into the decision model. The preferences are typically expressed in terms of the weights of relative importance assigned to evaluation criteria under consideration. The following are the methods of criterion weights: (i) Ranking methods, (ii) Rating methods, (iii) Pair-wise comparison method (or) Analytical Hierarchy Process (AHP).

(i) Ranking Method

The simplest method for assessing the importance of weights is to arrange them in rank order i.e. every criteria under consideration is ranked in the order of the decision makers preference.
Either, Straight ranking --- (The most important = 1, second important = 2…) or
Inverse ranking --- (The least importance = 1, next least important = 2…).

(ii) Rating Method

The rating method requires the decision maker to estimate weights on the basis of a predetermined scale. A scale of 0 to 100 can be used. One of the simplest rating methods is the point allocation approach.

(iii) Analytical Hierarchy Process (AHP)

One of the most promising would appear to be that of PAIRWISE comparisons developed by Saaty (2002) in the context of a decision making process known as the Analytical Hierarchy Process (AHP). This method involves pair-wise comparisons to create a ratio matrix. It takes the pair-wise comparisons as an input and produces the relative weights as output.

2.3 GIS BASED SITE SUITABILITY ANALYSIS

During nineteenth century the use of land suitability analysis using GIS was started (McHarg 1969). Land suitability map helps the planners to solve complex problems in a better fashion of way (Dueker and Barton 1990). Selection of appropriate location and to map the suitability index by considering all the possible best alternatives is termed as land suitability analysis (Senes and Toccolonies 1998).

De la Rosa (2000) explained that land suitability is a component of sustainability evaluation of a landuse. Suitability together with vulnerability defines the sustainability of a landuse. The sustainable landuse should have maximum suitability and minimum vulnerability.

Prakesh (2003) had done land suitability analysis for sustained agricultural production. It involves the evaluation of various criteria such as soil topography, irrigation, socio-economic and market. Multicriteria decision making techniques like ranking, rating etc. are employed for the analysis. Three approaches AHP, Ideal Vector Approach (IVA) and Fuzzy AHP are followed. All the three approached are implemented to analyze the suitability of the rice crop in the Doiwata block of Dehradun district.

Ceballos-Silva and Lopez-Blanco (2003) used matrix pairwise comparison for land suitability. This method overcomes the problems of determining the weights. But they have not taken into consideration the hierarchical organization of the criteria, which is the basic principle of Analytical Hierarchy Process (AHP). Hence it shows that they have just used the matrix pairwise comparisons as tool to derive weights. They have not implemented the AHP as a whole for decision making.

Jacek Malczewski (2004) listed two important considerations of spatial multicriteria decision analysis namely (i) the GIS capabilities of data acquisition, storage, retrieval, manipulation and analysis, and (ii) the MCDM capabilities for combining the geographical data and the decision maker’s preferences into one-dimensional values of alternative decisions.

Jacek Malezewski (2006) incorporated the concept of fuzzy quantifiers into the GIS based land suitability analysis via Ordered Weighted Averaging (OWA). OWA is multicriteria evaluation procedure or combination operator. The nature of the OWA procedure depends on some parameters which can be specified by means of fuzzy quantifiers. By changing the parameters, OWA can generate a wide range of decision strategies or scenarios. The quantifier-guided OWA procedure is illustrated using landuse suitability analysis in a region of Mexico.
Hamadi Kallali et al (2007) identified suitable sites for SAT system using a single-objective multi-criteria analysis for groundwater recharge of Hammamet–Nabeul aquifer located in Cap Bon peninsula in North East of Tunisia. The author developed a decision hierarchy and also identified different criteria such as technical, environmental and economic for the selection of best suitable sites for SAT systems. The author concludes that GIS and Multicriteria Analysis plays major role in solving difficult problems and in finding suitability area faster.

Anagnostopulous et al (2007) stated that the use of conflicting objectives and decision making preferences in any land suitability analysis provides the best and valuable solutions to the expected problem. The author proposed a procedure for finding out suitable locations to implement natural systems for the wastewater treatment in the Evros Prefecture-Northeast Greece. The author applied multicriteria suitability analysis for ordering alternatives using decision rule of Weighted Linear Combination.

Makram Anane et al (2008) used multicriteria analysis to locate and rank suitable sites for Soil Aquifer Treatment (SAT) in Jerba Island (South Tunisia) by integrating a single-objective AHP method into a GIS model. The author in his work concludes that the result obtained by using multicriteria analysis (MCA) showed that a large area, covering 1489 ha, is suitable for SAT, which exceeds the required area to infiltrate the total treated wastewater produced by all the island wastewater plants.

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Greece. The author applied multicriteria suitability analysis for ordering alternatives using decision rule of Weighted Linear Combination.

Mahamid and Thawaba (2010) described that integration of GIS and multicriteria analysis plays a vital role in development and planning process of an area by spatial analysis and there by driving new geographic information. Authors handled spatially related maps in GIS in order to find the best location for landfill site based on scientific standards and measurements.

2.4 WASTEWATER RECLAMATION AND REUSE

Asano (1996) described that wastewater reclamation and reuse is a type of wastewater treatment system and its quality is attained after treatment process. Application of wastewater for various level of reuse purpose purely depends on the characteristics of wastewater attained after treatment.

Asano and Levine (1996) clearly stated that the level of wastewater treatment required for a particular purpose purely depends on the quality of the end-use. The factors which mainly govern the wastewater reuse are the flow rate, quality of wastewater generation, quantity of water supply for domestic and industrial purpose in urban areas and rural needs such as agriculture and irrigation. Rose (1999) recommended that sustainable manner of wastewater treatment must be given attention in domestic and industrial wastes. Nhapi et al (2002) stated that, wastewater reuse is an approach to turn the useful component of wastewater into a resource. Great care must be exercised when reusing the reclaimed wastewater which may contain chemical and biological substances that may create some harmful effects on public health.
MetCalf & Eddy (2005) included rainwater and storm-water collected by urban sewer system was also considered as wastewater. Raw wastewater contain organic matters, toxic compounds and nutrients which results in eutrophication and release of harmful gases. Massoud et al (2009) defined the wastewater reclamation as a treatment process which treats wastewater to predetermined levels of water quality, further facilitating its reuse. Wastewater includes wastewater discharged from urban water consumption sources such as residential, commercial, institutional and industrial sources. Water reuse includes the use of treated waste water for all beneficial purpose, including agricultural, irrigation, industrial cooling and other non potable or potable applications.

2.4.1 Integrated Wastewater Planning

Pinkham et al (2004) discussed that integrated wastewater planning improves upon conventional wastewater facility planning by representing whole system costs and benefits of wastewater management systems. Integrated wastewater planning is a more comprehensive method of planning which gives decentralized systems adequate consideration as alternatives to centralized systems. Integrated wastewater planning is an attempt to broaden the scope of planning activities for wastewater management systems by considering the true implications of wastewater management planning decisions.

2.4.2 Ecological Sanitation, EcoSAN

GTZ (2009) and Werner et al (2010) developed, EcoSAN which promotes the extraction of water, energy and nutrient resources found in wastewater for beneficial reuse locally in agriculture and to increase sustainability of wastewater management. EcoSAN does not promote specific wastewater treatment technologies. Rather, an interdisciplinary approach is
taken to provide a wastewater management solution that addresses issues including local reuse of end products, cultural acceptance and appropriateness, and community planning contributing largely to integrated management of natural resources. Technologies such as urine-diversion dehydration (UDD) toilets, composting, rainwater harvesting, constructed wetlands, vacuum sewers, anaerobic digestion are often incorporated into EcoSAN projects. Source separation and preventing dilution of flow streams are two principles which optimize cost efficiency, treatment quality, and promote nutrient, energy, and water extraction and reuse in EcoSAN projects.

2.4.3 Direct and Indirect Reuse

Vigneswaran and Sundaravadivel (2004) explained that the reuse of treated wastewater for specific direct or indirect reuse purpose is mainly depends on the standard of treated wastewater attained after treatment. Direct reuse of reclaimed wastewater is a planned one where the treated wastewater is transported directly to the reuse location or spot. Indirect reuse of reclaimed wastewater is not a planned one where the treated wastewater is transported directly into near by receiving waters bodies like surface water or groundwater for recharge purpose.

2.4.4 Reuse Options

- Agriculture (Irrigation) and gardening
- Aquaculture (Fish ponds)
- Service water (toilet flushing, cooling water, cleaning)
- Groundwater replenishment
- Drinking water after additional treatment

2.5 CENTRALISED WASTEWATER TREATMENT SYSTEM

Parkinson and Tayler (2003) pointed out that the view of conventional or centralized wastewater treatment systems involve advanced collection and treatment processes that collect, treat and discharge large quantities of wastewater. In urban areas large community of people offers greater opportunities for centralized approaches to the provision of infrastructure and services, which may also reduce the per capita cost of service provision. Centralized systems are out of sight and hence, require less public participation and awareness. It requires high investment cost for construction and operation and maintenance. Further centralized systems for wastewater collection and disposal require disproportionately large investments which are unaffordable to the majority of the peri-urban poor people (Seidenstat et al 2003 and USEPA 2004).

2.6 DECENTRALISED WASTEWATER TREATMENT SYSTEM

The ultimate goal of Millennium Development Goals (MDGs) for the year 2015 is to provide improved sanitation to the people and to access 100% sanitation for the year 2025. Such improved sanitation will be attained through the concept of treatment of municipal wastewater using decentralised wastewater treatment system.

BORDA (1998) proposed that the decentralized wastewater treatment system is an approach for treatment of municipal and industrial wastewater flow from 1 to 500 m$^3$/day for community level. Decentralized wastewater treatment system is a compactable approach and provides local control of wastewater (Kalbermatten John 1999).
Decentralized wastewater treatment system offers potential benefits relating to increased responsiveness to local demands and needs and hence, increased willingness of communities to pay for improved services (Hordijk and Michaela 1999).

Fraganol et al (2001) suggested that decentralized wastewater treatment system is an effective technique in planning and decision-making, design of physical infrastructure and management arrangements for operations and maintenance. Decentralized or cluster wastewater treatment systems are designed to operate at small scale. It is more suitable for communities with improper zoning such as scattered, less populated peri-urban and rural areas. The main objective of decentralized treatment system (Figure 2.1) is to meet treatment goals and address environmental and public health protection requirements (USEPA 2004).


Figure 2.1 General Objectives of Wastewater Management Versus Decentralized Systems Characteristics
Decentralized Wastewater Treatment System (DEWATS) developed by BORDA (2009) promotes the most appropriate solution for developing countries in management of wastewater flow less than 1000 $m^3$/day with a sustainable sanitation. The principles of DEWATS include low maintenance, state of the art technologies constructed with materials found locally that are designed to meet local treatment standards. Four basic technical treatment elements are used for the fundamental basis of DEWATS systems (BORDA 2009):

- Primary treatment using sedimentation and flotation
- Secondary treatment in anaerobic fixed bed reactors
- Tertiary aerobic treatment in sub-surface flow filters and
- Tertiary aerobic treatment in polishing ponds

Thus the selection of decentralized treatment system depends on important factor such as:

1. Quantity of wastewater generated in the area
2. Quality of wastewater or the level of pollutants present in the wastewater
3. Availability of space
4. Investment cost for construction and maintenance and
5. Water quality level in the surface and groundwater system etc.

2.6.1 Benefits of Decentralized Approaches

Scholzel & Bower (1999) listed the benefits of decentralized treatment approaches as follows:
• Establishing of multi-stakeholder networks to combat water pollution
• Building up implementation capacity on various levels
• Providing treatment for both, domestic and industrial wastewater at affordable price
• Fulfillment of discharge standards and environmental laws
• Wastewater pollution reduced by up to 90%
• Providing treatment for wastewater flows up to 1000 m$^3$/day
• Reliable and long lasting applications
• Tolerant towards inflow and load fluctuation
• Materials / inputs used for construction are locally available
• Minimum maintenance and long de-sludging intervals
• Low operation and maintenance costs and non dependence on energy and
• Resource recovery through wastewater re-use and biogas generation

2.7 DECENTRALIZED WASTEWATER TREATMENT SYSTEMS

Allison et al (1998) listed a range of decentralized wastewater treatment technologies which are less dependent on power for operation than more advanced technologies. Option of decentralised wastewater technologies for a particular site basically depends on the quality of wastewater source and land. Land requirement is more for decentralised treatment system and reuse, where most of the lands in urban and peri-urban areas are privately controlled
which obstructs effective planning. For domestic wastewater or communal institutions, decentralized wastewater treatment system is highly suitable. The system is not restricted to merely managing individual user system they can close the gap between on-site systems and the conventional centralized system (GTZ 2001).

Choukr-Allah and Hamdy (2004) defined that a technology which is affordable to and operable by the user provides the degree of purification needed for the wastewater’s end use. The definition includes:

(i) Affordable : Both in capital, operation and maintenance costs
(ii) Operable : Within an affordable operation & management cost the user can operate the system with available labour and infrastructure and
(iii) Reliable : The system should meet the effluent quality requirements recommended by the regulatory agency.

The main objective of decentralized wastewater management system is to conserve the environment by selection of sustainable treatment and sanitation before the effluents are discharged or reused. The sustainable sanitation comprises of three major process (Zaini Ujang and Mogens Henze 2006).

(i) separation of pollutants at source
(ii) decentralization of facilities and
(iii) reuse of by products
Ajit Seshadri (2009) recommended that the success of concept of decentralised wastewater treatment system for developing country like India depends on the community interest and their active participation. Therefore decentralized treatment system are more suitable for semi arid climatic condition as it works using simple process, less maintenance, low cost and efficiency have proven to be successful. Some of the treatment technology options that could work well for rural and peri-urban level are anaerobic treatment, baffled septic tank, waste stabilisation ponds, up flow anaerobic sludge blanket, constructed wetlands and soil treatment systems. The mentioned treatment technologies are discussed below.

2.7.1 Anaerobic Treatment

Ludwig Sasse (1998) recommends anaerobic treatment of wastewater is more suitable for treatment of black water and faecal sludge from household latrines. This system requires less land area, cheaper in construction and no external power is required. During hot climate the system may be able to remove more than 60% of organic load from the sewage, but very less reduction of pathogen. The simplest form of anaerobic treatment system is presented in Figure 2.2.

Bernd Gutterer et al (2009) introduced and developed an alternative treatment technology similar to anaerobic sludge blanket reactors(Figure 2.3) called “baffled reactors”. It consists of a series of narrow chambers. The wastewater is allowed to pass through the bottom of each chamber and has to pass through the sludge that has accumulated before passing through the chamber. After passing out from the top of the chamber, it is piped to the bottom of the next chamber. Introduction of series of chamber in baffled reactor is quite similar to anaerobic filters (Figure 2.4) and up flow anaerobic filters.
Source: Ludwig Sasse (1998)

**Figure 2.2 Anaerobic Sludge Blanket Reactors**


**Figure 2.3 Anaerobic Baffled Reactor**
2.7.2 **Up Flow Anaerobic Sludge Blanket**

Up Flow Anaerobic Sludge Blanket (USAB) is an anaerobic treatment process or technology where biodegradable organics and suspended solids will get biologically decomposed by the organic matter by the bacteria. UASB consist of series of reactors, in which the organic matter is destroyed and stabilized by anaerobic bacteria is known as Anaerobic biological units which may consists of anaerobic lagoons, septic tanks, Imhoff tanks etc (Kansal 2003). Systematic view of UASB reactor is presented in Figure 2.5.

**The major advantages and disadvantage of a UASB are :**

- It is an economic and effective treatment method.
- No external power is required and work for long period with low maintenance.
- It requires less percentage of nutrients for effective aerobic treatment.
- It results in the BOD range of about 5 to 10% after treatment
- It produces odourless sludge.
- The released biogas from the reactors can be used as source of energy.
- Reactors perform slowly due to hydraulic flow of effluent and
- It requires experts knowledge to construct and operate.


*Figure 2.5. Up Flow Anaerobic Sludge*
2.7.3 Waste Stabilisation Ponds

Waste Stabilization Ponds is a treatment system which treats the primary level naturally. The schematic view of waste stabilization pond is presented in Figure 2.6. Choukr-Allah and Hamdy (2004) listed three types of waste stabilization ponds which are widely used all over the world depend on their treatment requirement, namely (1) anaerobic, (2) facultative and (3) aerobic or maturation. The main advantage of waste stabilization ponds is that the reduction of pathogens and high concentration of algae growth, due to long retention time. The removal efficiency depends on the toxic and inhibitory substances, consistency of volumetric and surface loading and the temperature of the water should be preferably more than 15°C. The system works simple, low operation cost is required, no external energy is required, free of odour and mosquito breeding. The disadvantage of stabilization pond is that it requires large area for construction (Bernd Gutterer et al. 2009).

![Diagram of waste stabilization ponds](image)

Source: Bernd Gutterer et al. (2009)

Figure 2.6 Waste Stabilization Ponds

2.7.4 Constructed Wetlands

WaterAid Nepal (2006) and Bhushan Tuladhar (2007) explained that the Constructed Wetlands (CW) is a biological wastewater treatment
technology designed to mimic processes found in natural wetland ecosystems. These systems use wetland plants, soils and their associated micro-organisms to remove contaminants from wastewater. Constructed wetlands treatment is suitable for municipal, industrial and agricultural wastewater as well as storm water. Wastewater treated using Constructed Wetlands (CW) and recycling has major advantages:

1. Use of natural processes
2. Simple construction (can be constructed with local materials)
3. Simple operation and maintenance
4. Cost-effectiveness (low construction and operation costs)
5. Process stability
6. Applicable for rural level households where large area is required.

2.8 MANAGED AQUIFER RECHARGE

Managed Aquifer Recharge (MAR) is the purposeful recharge of water to aquifer for subsequent recovery or environmental benefit. Normally, this is achieved through injection well, infiltration basins and galleries for rainwater, storm water, reclaimed water, main water and water from other aquifers that is subsequently recovered for all types of uses (Dillon et al 2009).

CGWB (2010) of India listed the essential criteria for implementation of MAR in the field is:

a. Groundwater level are declining on regular basis
b. Drastic variation of groundwater table in lean months
c. Aquifer shows saline intrusion

d. Aquifer contains poor quality of water especially in semi-confining layer.

Aharoni et al (2011) listed different types of MAR systems used for groundwater recharge which are more efficient for unconsolidated rocks e.g., sandstone, gravel.

1. Dune filtration
2. Infiltration ponds
3. Bank filtration
4. Percolation tank
5. Soil Aquifer Treatment (SAT)
6. Underground Dam
7. Sand Dam and
8. Recharge release

2.9 AQUIFER RECHARGE USING SAT METHOD

Bouwer (1978) initially developed the SAT system. SAT is a simple and low cost MAR technology which helps in augmenting groundwater sources by introducing reclaimed water into the aquifer system.

Bouwer and Rice (1984) stated that SAT is suitable where the top soil and aquifer conditions are favorable for artificial recharge of groundwater through infiltration basins, a high degree of upgrading can be achieved by allowing partially treated sewage effluent to infiltrate into the soil and move down to the groundwater. The unsaturated or vadose zone then acts as a
natural filter and can remove essentially all suspended solids, biodegradable materials, bacteria, viruses and other microorganisms. Significant reductions in nitrogen, phosphorus and heavy metals concentrations can also be achieved during SAT process.

Asano (1996) listed several advantages of SAT systems in storing water underground via groundwater recharge. They are as follows:

(i) Water stored in surface reservoirs is subject to evaporation, taste and odor problems due to algae and other aquatic productivity, and may be avoided by soil-aquifer treatment (SAT) and underground storage.

(ii) Suitable sites for surface water reservoirs may not be available or may not be environmentally acceptable.

(iii) The inclusion of groundwater recharge in a wastewater reuse project may provide psychological and aesthetic benefits as a result of the transition between reclaimed municipal wastewater and groundwater. This aspect is particularly significant when a possibility exists in the wastewater reclamation and reuse plans to augment substantial portions of domestic or drinking water supplies.

Houston et al (1999) explained that ground-water recharge using fresh water or treated wastewater is most often accomplished by infiltration from surface basins. Thaer Abushbak (2004) defined SAT as a process where the applied wastewater moves down through the vadose zone, during the wetting time and drainage time, improvements in its quality can occur as a result of different physical, biological, and chemical mechanisms including filtration, biological degradation, physical adsorption, ion exchange, and precipitation.
Amy and Drewes (2006) defined soil aquifer treatment (SAT) as a process of purification of wastewater when it flows through unsaturated soils and the aquifer and the purified water is recovered by means of recovery wells. Figure 2.7 describes the SAT process during wetting of the basin.

Aharoni (2011) stated that SAT systems are natural, inexpensive, simple to operate, reliable systems and also allows seasonal storage of the water to be stored in periods of low demand and used in periods of high demand.

![Diagram of Soil Aquifer Treatment System](source)

Source: Amy and Drewes (2006)

**Figure 2.7** A Schematic View of Soil Aquifer Treatment System

### 2.9.1 Types of Soil Aquifer Treatment Systems

Bouwer (1985, 1996) explained the three different ways for achieving SAT system namely
(i) Surface spreading infiltration basins which are suitable in coarse and fine sandy soils.

(ii) Vadose zone wells which are suitable in hard aquifers and

(iii) Direct injection wells which are suitable in confined aquifers.

Bouwer (1987) illustrated various soil aquifer treatment (SAT) systems and recharge process as shown below in Figure 2.8.

(a) Natural drainage of treated water into nearby surface water bodies
(b) Natural drainage of treated water by subsurface water bodies
(c) Recovery of SAT treated water through wells situated between parallel infiltration basins
(d) Recovery of SAT treated water through wells situated around the infiltration basin

Source: Bouwer (1987)

Figure 2.8 A Schematic Diagram Showing Various SAT Systems
Bixio et al (2006) explained the function of SAT system in the field was depicted in Figure 2.9 and the recovery of SAT treated water through recovery wells situated parallel to the SAT basin.

Disadvantages of SAT system are that introducing not sufficiently pretreated wastewater and polluted water into the aquifer may affect natural water bodies. Further percolation of polluted water into the groundwater may change the soil and hydrogeological properties (JIMENEZ 2008).

![Schematic Diagram Showing the Layout of the Soil Aquifer Treatment System and Wells](image)


**Figure 2.9** Schematic Diagram Showing the Layout of the Soil Aquifer Treatment System and Wells

Advantage of SAT method is that reclaimed water such as treated black water, grey water or storm water is not just discharged into surface waters, but reused as water for irrigation in agriculture or to intentionally recharge groundwater aquifers via MAR (Melin 2009).
2.10  SOIL AQUIFER TREATMENT STUDY

Understanding of SAT with respect to its hydraulic behaviour and water quality improvement using various soil type has been done by many research work previously. The hydraulic behaviour and water quality results obtained by using short term SAT soil columns studies and in the field investigations carried out by many researchers are discussed below.

2.10.1  Operation of SAT System

Lance et al (1973) conducted soil column study by operating 3 days wetting and 3 days drying cycles. The author observed that during wetting period using the reclaimed water in a day perform a molecular diffusion through the infiltration surface where a negligible amount of oxygen will get renewed. Longer period of drying will vary based on the temperature or climatic condition of the environment, type of the soil, depth of the soil (Bouwer et al 1973) and size of the basin or the size of the soil column. During drying period the top layer of the soil which is the main layer for the formation of clogging will break and the passage of atmospheric oxygen through the soil will take place (Quanrud et al 1996).

Longer the drying period higher the infiltration rate (Kopchynski et al 1996). The residence time depends on the bed's depth and permeability and on the flooding rate (Brissaud et al 1989) and the number of wetting days depends on the wastewater clogging capacity, soil porosity and its permeability. As stated in the USEPA (1981) manual on land application of wastewater, it depends on the objective of treatment seeked as maximize infiltration and maximize nitrification or maximize denitrification.

Li et al (2000) defined cycle time or wetting drying schedule as the sum of total time of wetting and total time of drying (drainage time and true drying time).
CT = X + Y + Z  \hspace{1cm} (2.1)

where,

CT : cycle time
X : wetting time
Y : drainage time and
Z : true drying time

The anaerobic condition of soil is converted into aerobic condition and thus nitrification process will result (Westerhoff and Pinney 2000). During a field study of Avi Aharoni (2011) found that the anaerobic condition in the vadose zone can be reduced by a maximum drying period of about 2 to 4 days.

2.10.2 Hydraulic Characteristics of SAT System

The hydraulic behaviour of a SAT system mainly depends on the geological characteristics of the unsaturated aquifer, infiltration rate and the level of pretreated waste water quality standard before SAT application. The geological layer of the aquifer instructs us about the least permeable layer of the log, basin sizing depends on percentage of permeability. To achieve a good SAT result the recommended soils given by Bouwer (1985) are sandy loam, loamy sand, and fine sand. Infiltration – percolation is rustic and extensive purifying technique of converting the SAT system into an oxidizing and decontaminating wastewater (Brissaud et al. 1989).

Bouwer (1991) observed that infiltration loading rates of secondary effluent through different types of soils were actually dependent on the soil characteristics and the effluent quality, especially its suspended solid content. The reduction of infiltration rates in the soil columns was due to formation of
clogging layer at the top surface, which is formed due to the accumulation of suspended solids during infiltration of the effluent.

Houston et al (1999) explained that when the thickness of the clogging layer is small, relative to water depth and conductivity, the thickness of the saturated clogging layer remain constant. Hence the infiltration rate is directly proportional to the water depth. On this basis it is possible to compare the measured rate of infiltration at the deeper water depth, to a prediction made by multiplying the rate of infiltration observed at the lower water depth by the ratio of the deeper and shallower depths. And also, it is important to know the aquifer depth and its capacity of water transfer.

Bouwer (2002) during his field analysis of SAT found that permeable soils with high infiltration rates minimize land requirements.

Manuel Fernando (2009) listed following factors which broadly influence the performance of SAT and its infiltration rate (i) ponding depth (ii) effluent wastewater quality (iii) soil type and its permeability and (iv) the wetting and drying periods.

2.11 WATER QUALITY PERFORMANCE OF SAT SYSTEMS

Several studies in laboratory and field on water quality improvement and the behaviour of different soil types during SAT system were evaluated by Idelovitch and Michail (1986). The authors also found that there was no design specification of the soil columns used in SAT study. Wastewater effluents are usually applied to the top of the soil columns at a specific constant rate. Soil columns are usually packed with soil material from either a specific location where soil aquifer treatment is planned, or a material of similar characteristics. They can either be used to test the performance of soils in removing specific contaminants or to assess their clogging capacity.
Sobsey et al (1995) demonstrated that virus reduction can be extensively achieved in soil columns (up to 5.1 log10 virus reduction) depending on virus type, soil type and water quality. In their study using miniature soil columns filled with sand, viruses (Hepatitis A), enteroviruses and coliphage are removed as water percolates by interactions with anaerobic bacteria within the soil.

Fine textured soils are more efficient to retain viruses and bacteria (Sobsey et al 1995). The effluent pre-treatment also influence the removal of viruses and pathogens. For instance, a high DOC concentration at column inlet interferes negatively with the adsorption of viruses due to retention of soils. Temperature can also have an important role as higher reductions can be achieved with increasing temperatures (i.e. 25°C and above), however some viruses tend to be more resistant at such temperatures. If it is already known that the use of treated wastewater, independently of the reuse purposes, always involves risks associated with residual pollutants such as bacteria and pathogens. The ability to control these microorganisms is critical in order to protect public health and acceptance.

Significant reductions can be achieved whilst effluent passes through the soil columns. Dissolved organic matter can be removed from the wastewater with a combination of chemical, physical and biological processes. As the water percolates through the soil, degradation of the wastewater may occur which causes clogging at the soil surface, leading to reduced infiltration rate and therefore the effective removal of contaminants. A layer of biomass slows down infiltration rate which results in increase of local water retention time. Thus the purification process depends on the accumulation of suspended solids or bacterial growth, which rely on the effluent characteristics and hydraulic loading rate (Quanrud et al 1996).
Kopchynski et al (1997) during his soil column test demonstrated that the performances of SAT systems are widely affected by (1) the degree of the wastewater pre-treatment prior to recharge (2) the physical characteristics of the soil used in these systems such as groundwater depth and distance to recovery wells and (3) the operation of infiltration basins with flooding and drying period is defined by the NCSWS (2001) as well as (4) loading rate and temperature.

Cordy et al (2004) understood that removal mechanisms achieved by aquifer recharge are complex and therefore soil column experiments are performed in order to test how the quality of the wastewater effluent can be improved as well as to investigate how different type of soils can influence the removal of specific contaminants. The author showed that, some pathogens can still persist in the treated wastewater.

Fox (2005) achieved 80% DOC removal for chlorinated secondary effluent in 2.4 m length column fed over 475 days under various wetting and drying period. Various parameter removals are mainly achieved during the early stages of soil column tests due to biological degradation.

Smith and Hegazy (2006) used the soil columns varying in size from 5 cm to 2.4 m length. The study with soil columns using wastewater gives an understanding on how wastewater quality can be improved in SAT, depending on several parameters such as soil type, column dimensions, water characteristics and duration of the project. Generally, soil columns are saturated with the effluent under specific periods of time, depending on the purpose of the study such as removal of contaminants, clogging mechanisms or permeability of soils (Alimi-Ichola and Gaidi 2006). The temperature of the columns are usually maintained constant with values ranging from 10 °C to 45 °C depending on the climate conditions under which aquifer recharge is meant to take place.
2.11.1 Pollutants Removal

WAJ Paling (2001) has conducted the test for six months using secondary treated wastewater. Treated wastewater was stored in a 5 °C high level reservoir in a cooled environment. A constant head is maintained by overflow outlets at 50, 100 and 150 mm above the top of the soil column. Organic matter was broken down by the action of micro-organisms and inorganic matter converted into insoluble compounds, forming a thin coating around the sand grains. In nitrogen removal, initially a 100% reduction in ammonia was found. The degree of ammonia reduction is primarily a function of the length of the flooding and drying cycles.

Fecal bacteria like faecal streptococci and coliforms die off in the top meter of soil and most of the viruses were adsorbed in the top 5 cm of soil. Faecal bacteria and viruses reach the groundwater and travels a distance of 100 m in soil which seems to be sufficient to reduce their levels to essentially zero.

Nema et al (2001) carried out a pilot study in Sabarmati river bed (Figure 2.10) at Ahmedabad for six months and the results of the study are analyzed to assess the performance of SAT system. Two primary settling basins, two infiltration basins and two production wells were located in the centre of infiltration basin in order to carry out the reclaimed wastewater. Hydraulic loading ranged from 0.04 m / d to 0.12 m / d with a water depth of about 0.2-0.25 m. Reduction in organic pollutants was about 90%. Removals of organic materials were mainly depending on hydraulic loading. When the hydraulic loading rate was decreased the removal efficiency of pollutants increased.
Akber et al (2003) assessed the removal performance of SAT using six soil column study for Kuwait climatic condition. Different soil samples were collected and analysed for petrography and mineralogy under polarizing microscope. The collected samples were sieved and cumulative weight percentages were plotted against grain size to classify them. The influent applied to the soil column was the tertiary waste water. Soil samples were taken at a depths between 0.0 m and 0.5 m in one place and at depths between 0.5 m and 2.0 m at another place of same area.

During the wetting period of the soil columns the author observed that the bacteria die off at the top of the soil and viruses are adsorbed in the top 5 cm. The removal percentage obtained after the SAT soil column study
of the parameters pH, total suspended solids (TSS), phosphate (PO$_4$), nitrate (NO$_3$), ammonia (NH$_3$), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total bacteria, Coliform, E. coli and S. Faecalis resulted in 90%, 99%, 90%, 99.6%, 99%, 99%, 100%, 100% and 100% respectively. The author observed that during continuous loading rate the conversion of ammonia to nitrates and low nitrification due to aerobic condition exist in the columns.

Fox et al. (2005) carried a comparative study of field and soil column test to determine the removal performance of DOC using different soils. Five soils were used in soil column using different sources of reclaimed water. Soil samples were obtained from the field and compacted in the soil columns by taking 10 cm diameter cores to a depth of 51cm. The collected soil samples were placed in tight bags and stored at 4°C. Initial percentage of total organic content was also determined.

The soil columns were connected with series of sampling ports to obtain liquid samples, had effluent weirs to control water levels, vacuum pump to the effluent lines to promote unsaturated flow conditions and operated using different wetting and drying periods. During wetting period the author observed that there was no significant change in the accumulation of organic matter during the field and soil column study below a depth of 8cm. The author also observed that biological activity at the soil-water interface resulted in an accumulation of biomass and associated organic matter.

During the column studies, less than 20% of the total organic matter was observed below 8cm soil depth. Therefore the author concludes that soil aquifer treatment can remove organic carbon without accumulation from adsorption that might eventually lead to breakthrough. The author also suggests that the soil percolation encompasses several processes such as soil
interface, the combined effects of sedimentation, filtration, aeration, microbial growth leading to the formation of a biologically active zone that may be impermeable and the oxygen is supplied from the unsaturated zone. Hence removal of organic carbon depends upon biological removal. SAT can remove organic carbon without accumulation from adsorption.

ZHAO Qing-Liang et al (2007) have investigated the removal and transformation of organic matter through laboratory-scale SAT soil columns over a 110-day period. They adapted soil-column system which simulated aquifer conditions in a series of three 55 cm-columns of diameter 10 cm was used (Figure 2.11).

The SAT columns were acrylic with top and bottom caps sealed with rubber gaskets. A screen was placed at the bottom of the column to support 2.5 cm of sand, 2.5 cm of gravel, plus 50 cm of soil. Each column was fitted with a sampling port at the bottom. A peristaltic pump recalculated water from the top of the first 55 cm vertically mounted column. It was equipped with a low volume constant head tank and the excess wastewater is fed back into the supply tank.

The soil-column system operated under gravity flow conditions with approximately 2 cm of hydraulic head. Columns were operated in 20 day cycles consisting of 10 day of flooding followed by 10 day of drying. During the wetting cycles, influents applied to the columns were changed every two days and effluents from the columns were sampled every two days. In this study, significant removal of TOC and DOC occurred in the initial 0.5m of soil infiltration. In SAT columns over a 110-day period, bulk organics were effectively removed.
Figure 2.11 Scheme of the Laboratory Scale SAT System

Source: ZHAO Qing-Liang et al (2007)
Sofia Figueiredo (2007) conducted a short term soil column study to identify the influence of soil columns configuration on permeability and removal of contaminants in secondary treated wastewater effluent and to assess their performance for the development of short term soil column tests for aquifer recharge applications. The results obtained after the SAT soil columns study showed significant improvement in the effluent quality after passage through different types of soils with turbidity dropping from 5.9 NTU to 1.1 NTU in each column effluent. The effect of clogging at the soil surface of each column showed the limitation of the three types of soil for the long term treatment of the secondary wastewater effluent used in this study. Infiltration rates range from 6 cm/day to 9.5 cm/day after 3 days of operation. With regard to nutrient removal, columns packed with Israel soil prove to be more effective with up to 57% adsorption of PO$_4$-P, and 64% removal of NH$_4$-N by nitrification and 90% removal of NO$_3$-N.

Sharma et al (2008) assessed the potential and suitability of SAT technology for removal of different contaminants from wastewater effluents in order to develop a framework or guidelines for its application under different conditions and also focused on the removal of organic matter in SAT systems. Removal of organic matter is a critical parameter in SAT as it governs and influences the removal of other contaminants by biodegradation namely traces organics, nitrogen species and microbes. A framework for analysis and prediction of the performance of SAT systems with respect to removal of organic matter under different water quality and process conditions was developed. Furthermore, effects of soil type and redox conditions on organic matter removal during SAT were also analyzed. The author recommends sandy loam soil for the recommendation of removal of DOC. Since the sandy loam soil showed a higher removal performance of 50% to 60% of DOC using secondary and primary treated wastewater in the field condition.
2.11.2 Organic Compounds

Bouwer and Chaney (1974) explained that SAT systems can handle high BOD-loadings, probably hundreds of kg / ha / day and BOD levels are generally reduced to essentially zero after a few metres of percolation through soil. However, the final product water from SAT systems still contains some organic carbon, usually a few mg / l. This is probably due to humic and fulvic acids but also the presence of synthetic organic compounds in the sewage effluent that do not break down in the underground environment. Bouwer and Rice (1989) observed that the halogenated hydrocarbons tend to be more resistant to biodegradation than non-halogenated hydrocarbons.

Drewes and Peter Fox (1999) performed a comparative study of laboratory and field test which indicates that biodegradation of organic matter during SAT is more dominant in adsorption. The BOD₅ of sewage varies from several hundred to about 1000 mg / l for raw sewage and from about 10 to 20 mg / l for good quality secondary effluent.

2.11.3 Removal of Nitrogen

Akber (2003) studied the improvement of tertiary treated waste water quality before and after SAT soil column test using six different soil columns consisting of muddy sand and gravelly muddy sand. Significant changes such as the conversion of total ammonia to nitrate due to aerobic condition and less denitrification and low organic contents in the columns were observed. The removal percentage of about 99.9% nitrogen was obtained during the soil column study. Thus the author concludes that the use of tertiary treated wastewater for SAT system works good.

Kerem Gungor and Kahraman Unlu (2005) conducted a bench scale soil column experiment to observe the removal efficiency of nitrites and
nitrates during soil aquifer treatment using different soil types like sandy clay loam, loamy sand and sandy loam. Soil columns were operated with wet and dry cycles of 7 days wetting and 7 days drying and followed by 3 day wetting and 3 days drying with constant ponding depth of 2.5cm in the soil columns. During the laboratory study the author notified that the removal performance of SAT systems with respect to nitrogen depends on the wetting and drying periods, where the denitrification and nitrification process could occur constantly. The author also observed that 95% of nitrogen removal taken place in loamy sand due to denitrification and nitrification process, when compared with the other two soils. Desirable level of nitrogen removal during SAT system is attained by selecting wetting and drying periods and correct hydraulic loading rates. Under anaerobic condition the nitrate and organic carbon is essential for denitrification process (FAO 2005).

2.11.4 Bacteria and Viruses

Gilbert et al (1976) conducted a pilot study of SAT system at Flushing Meadows Wastewater Project in Arizona. During their research they used the secondary level treated wastewater effluent for recharge purpose. The water samples were collected from the near by four renovated wells located around the recharge well. During the quality analysis of renovated water samples showed that 99.9% of removal of total bacteria and faecal coliforms. It was also noted that there were no viruses present after the SAT.

Vecchioli et al (1980) in his research with SAT system observed that the faster rate of clogging in recharge wells is mainly due to the growth of bacteria. The author suggests that the potential growth of bacteria is minimized by removing the concentration of nutrients, biodegradable matter and further disinfection of water in recharge wells.
Less concentration of pH offers better adsorption of viruses which are present in the wastewater. 70% to 80% viruses are adsorbed at the top most layer of the soil and water interface. Most of the research reported that 80% to 90% of the viruses and bacteria are killed after percolation of 1m to a few meter depth of soil. The recommendation of coarse sand for SAT process should be avoided and well recommended standard of reclaimed wastewater free off pathogenic microorganisms results less clogging effects in the recharge structures (FAO 2005). Hence the recommendation of good SAT is done when a porous medium able to remove 100% of all chemical and biological concerns and results better infiltration rate. But so far no research study is done to recommend an ideal SAT system due to their limitation in their objectives such as maximization of infiltration rate, minimization of harmful constituents in the impaired water etc.

Presence of faecal coliform bacteria in the sewage effluent is the indicator for the presence of pathogenic organisms salmonella, shigella, mycobacterium and vibrio comma etc. Escherichia coli are the indicator to determine the presence of faecal contamination of water. Hence it is clear that the detection of faecal coliform bacteria and Escherichia coli the percentage of other pathogenic and virus can be determined in the effluent sewage (FAO 2005).

Jingjing Lian and Menggui Jin (2010) conducted an experiment on the transport and fate of the bacteria (Escherichia coli) in SAT system, a packed silt soil column under saturated conditions. The author applied a known concentration of bacteria of about $10^5$ Colony-Forming Units L$^{-1}$ in the secondary treated wastewater influents for the SAT columns. The results obtained after SAT column study showed that there was no detection of E. coli, and the electric conductivity, total nitrogen, permanganate index finally became the same between the influent and effluent. But significant
removal performance is observed in the solid phase from top to bottom of the columns. Hence the author conclude that simulation of recycling water recharge could make people understand the transport and fate of contaminants better, provided reference to practical projects.

2.12 CLOGGING BEHAVIOUR IN SAT SOIL COLUMNS

The development of clogging can be observed when the ability of porous media strains to transmit liquids when compared to its initial infiltration rate. This decrease of percolation rate is due to clogging (Gupta et al 1962). Clogging is a layer which is developed due to the accumulation of organic matter on the top layer of the filter media during wetting period of reclaimed wastewater. Breaking of clogging layer is achieved by allowing drying periods between the operating periods of the infiltrating beds. During infiltration the solid organic matters are eliminated at a very few depth of 1 to 2 cm of the soil. This is due to the pore size of the soil which allows the suspended solids to retain at the top of the inter surface between the water and the soil. The residence time and the oxygen available in the filtering medium are the factors which perform the oxidation of the organic matter and of the nitrogen (Brissaud et al 1989). For a given type of soil, the saturated hydraulic conductivity of that soil and aquifer materials remains a constant parameter (Philippe vandevivere and Philippe Baveye 1992). In Europe mainly in France and Spain wetlands are often used as a polishing step prior reuse (Bixio et al 2005). The use of secondary effluent is often associated with the possibility of soil clogging due to the suspended solids which may lead to surface clogging.
2.13 SUMMARY

Review of earlier studies for wastewater management problems using GIS based multicriteria method helped in framing decision hierarchy for selection of best suitable sites for decentralized treatment plants and their reuse options like domestic, industrial, recreational and groundwater recharge purposes. The selection of reuse option of groundwater recharge technique with advanced method called Soil Aquifer Treatment (SAT) was considered in the present study. SAT is a managed aquifer recharge system and the study of SAT performance conducted by many researchers in the laboratory and in the field, gives an idea about SAT system. The literature study also reveals the performance of SAT system for removal of specific contaminants with particular soil type, level of treated waste water quality and the climatic condition. The overall study shows that very few SAT related research studies have been carried out in India. Also the performance of SAT was studied using single layer soil column approach. Thus the study of research papers paved the way, how the SAT system could perform better for Chennai city using the secondary treated municipal waste water with two layer soil column study.