LINKING URBAN LAKES: Assessment of Water Quality and its Environmental Impacts

AKSHAY ANAND
February, 2014

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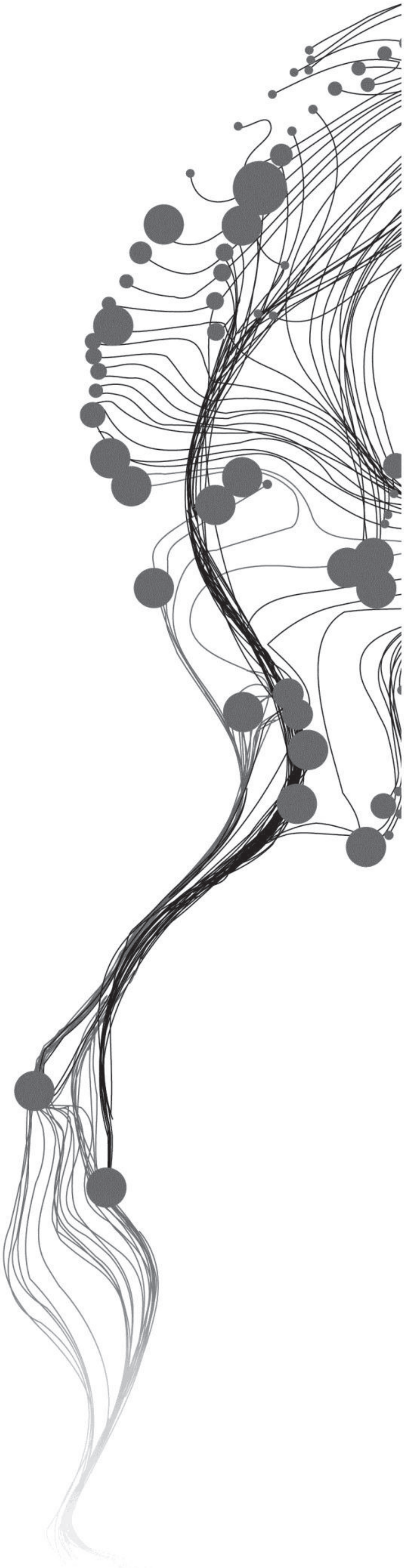

LINKING URBAN LAKES:
Assessment of Water Quality and its Environmental Impacts

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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Urban Planning and Management

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ABSTRACT

Lakes in urban and peri-urban areas are an important interface between planning and ecology, which demands environmentally responsive strategies, acknowledging problems like flooding, water pollution, and water quality with their complexities in design and engineering. The present study attempts to investigate the impacts of hydrological planning interventions on lake ecosystems.

The research highlights the issues in experimental projects like 'lake linking project' carried out by Ahmedabad Urban Development Authority (AUDA). The integration of storm water infrastructure and lake ecosystem creates adverse pressure on lake water quality which is subsequently also transferred to other connected lakes. Such hydrological interventions generate potential irreversible impacts on the lake ecosystem and receiving waters. In order to avoid water logging in urban areas the excess storm water is discharged into lakes, by considering storm water as a potential resource and justifying the need to harvest storm water. The research focuses on evaluation of impacts by linking urban lakes in lake ecosystems in terms of water quality.

Water quality assessment of 6 interlinked urban lakes of Ahmedabad was carried out, to evaluate the degree of pollution in lakes. The pollutant loading from untreated storm water is discharged via storm drainage from urban subcatchments. In order to identify the sources of pollutant loadings, the storm water drainage and the lakes were modeled in EPA-SWMM. In EPA-SWMM model the hydrological properties of subcatchment, the hydraulic network of storm water, and the quality parameters are defined for the catchment. Pollutograph generated from model simulation showed that the cumulative inflows in interconnected lakes from subcatchment entering subsequent lakes increase the pollutant concentration in lakes. It was found that the condition is compounded when the inflows reach outfall downstream, where accumulated heavy pollutant loadings are discharged in the receiving waters.

It was concluded from the research that experimental projects like linking of lakes have considerable impacts on the water quality on lakes and disrupt the balance of not only lake ecosystems but also pollute receiving waters. Thus it was recommended that a prior environmental impact assessment study is essential for maintaining the balance and sustainability of lakes. It was noted that environmental impact assessment studies have larger scope, but case specific hydrological impact assessment and cumulative impact assessment framework can be explored with respect to local context.

Keywords: Urban lakes, water quality, interlinking of lakes, urban hydrology, experimental approaches, impact assessment.

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AMC – Ahmedabad Municipal Corporation
AUDA - Ahmedabad Urban Development Authority
BOD - Biochemical Oxygen Demand
CEE - Centre for Environmental Education
CWC - Central Water Commission
COD - Chemical Oxygen Demand
CPCB - Central Pollution Control Board
CPHEEO – Central Public Health and Environmental Engineering Organization
CGWB – Central Ground Water Board
DO - Dissolved Oxygen
DP – Development Plan
DPR – Detailed Project Report
EIA – Effective Impervious Area
EIA – Environmental Impact Assessment
EPA - Environmental Protection Agency
EPA – Environment Protection Act
EMC - Event Mean Concentration
GPCB - Gujarat Pollution Control Board
GEMI - Gujarat Environment Management Institute
GTPUDA - Gujarat Town Planning and Urban Development Act
IMD – Indian Meteorological Department
MOEF – Ministry of Environment & Forests
MOUD - Ministry of Urban Development
MOUAF – Ministry of Urban Affairs
NTU - Nephelometric Turbidity Units
NLCP – National Lake Conservation Plan
SEAC – State Level Environmental Appraisal Committee
SPM - Suspended Particulate Matter
SWMM - Storm Water Management and Modeling
TDS – Total Dissolved Solids
TPS – Town Planning Scheme
TSS - Total Suspended Solid
TIA – Total Impervious Area
UDPFI – Urban Development plans Formulation and Implementation

1. INTRODUCTION

1.1. Background and Justification

Ahmedabad is the one of the fastest growing cities of Gujarat, India. The city of Ahmedabad has more than 204 lakes, amongst which the lakes around the old city are of historical importance. As the city is expanding rapidly, it engulfs satellite villages into the urban area; hence the village ponds or lakes are subject to re-development in an urban context.

In the context of Ahmedabad, lakes with urban parks associated with it, have acquired a significant importance as generators of urban development. Lakes contribute to provide a better quality of urban landscape throughout the city. On the contrary increasing population density, impervious surfaces and subsequent runoff- inflow from natural drains from polluted areas and untreated storm water drainage discharge in lakes has disrupted the hydrological balance of the urban water cycle.

Urban water and the city with anthropogenic interactions, interference and intervention with natural processes call for a comprehensive understanding of urban water cycle as an independent system. Various attempts to balance human interference have niched out 'specialised modern approaches' like Water Urbanism, Greenbelt, Ecological corridors and Eco-city. These 'specialised modern approaches' are a result of growing interest in neo-organic landscapes theories and its analogies applied in urban planning emphasising the significance of scientific inquiry (Gandy, 2004). However present and future challenges dealing with urban water and systems with transfer and dissemination of experiences and new knowledge gained has to be addressed in the context of sustainable coexistence of human and natural environments (Niemczynowicz, 1999).

The urban water body – 'Lake' - is an integral part of the urban ecosystem with recreational and environmental attributes. Besides acting as a breather, lakes benefit cities in a multitude of ways. Generally in the context of urban development, lakes are accompanied with parks which also harbour variety of flora and fauna forming a potential ecological network within the city (Shah, 2005). The benefits from lakes offered to society are intangible and they are vulnerable to developments and short sightedness of the governing bodies in defining these ecological elements for recreational use only. Environmental assets like lakes are an important part of the ecosystems. They provide services to society having an economic value attached based on the benefits human being receive from lake ecosystem (Pearce, Atkinson, & Mourato, 2006).

"The social, economic, political, and cultural association of the lake in urban areas is referred to the urban systems. Researchers justify the values of urban lakes linked to ecological, economic, social, cultural, and even political values to be the driving force behind the sustainability of lakes. These urban components add aspects such as appraisal or neglect towards the lake systems which directly or indirectly affects the lake sustainability of lakes" (Bal, Ast, & Bouma, 2011, p. 3). As suggested by Bal et al. (2011), the values are redefined by change in definition, as in case of Ahmedabad, water bodies from - village ponds; lakes; urban lakes; to storm water detention ponds reflects the economic, political and cultural transition of association which have greatly affected the 'sustainability' of lakes in Ahmedabad.

1.2. Study Area

The study area is situated in Ahmedabad which is the most important city of Gujarat in India and has a population of around 5.6 million. The city evolved with time at the banks of river Sabarmati and lies between 220 56' & 230 08' North Latitude and 720 30' & 720 42' East Longitude. The Ahmedabad Urban Development Authority (AUDA) which is responsible for urban development in the city with many of its projects also include a 'hydrological project' called interlinking of lakes which focuses on harvesting storm water management and avoiding water logging in urban areas hence becoming an essential segment under the comprehensive strategy 'infrastructure development'.

Sr. No	Name of the Lake	Present Area (Sq. Mt)	Depth (Mt)	Past Use	Present Use
1	Memnagar	36624	-3	Village Tank; Domestic Water Supply	• Bore wells for domestic supply in the periphery of lake. • Dumping of household waste and waste water • Storm Drain • Recreation
2	Vastrapur	62500	-4		
3	Thaltej	57124	-4		
4	Bodakdev	31050	-1		
5	Prahladnagar	18568	-3		
6	Sarkhej – Makarba	93920	-2.5	Palace Complex	Site of Archaeological importance

Table 1: Selected Lakes for interlinking

In 1960, Ahmedabad had at least 204 lakes, which was reduced to 137 by 2000. These lakes were encroached upon by slums and haphazard development or left to disuse. The lake linking project was initiated by the Ahmedabad Urban Development Authority in 2004 to interlink 8 lakes in the first phase with the development of 44 lakes in the western part through a piped network. In the first phase 6 lakes mentioned in Table 1 were interconnected and as the new lakes were developed they were designed with the provision of interlinking. The linked network has its outfall downstream in Sabarmati River.
The individual lakes are linked with storm water channels, envisioned to increase the catchment of storm water network coverage to avoid water logging in urban areas and considering lakes as detention ponds or storage units (Jagani, 2004).
Integration of the storm water network with the lakes and further interconnecting the lakes, were two distinct and disparate infrastructures. The storm water conveyance and transport was built for the low

lying and water logged areas of Ahmedabad during heavy monsoons. While the functional purpose of the lakes was recreational use, anticipating increase in land values along the lake-front and harvest water, as the region of Ahmedabad falls under water scarce region. Thus understanding the potential of storm water harvesting and diverting excess storm water from water logged urban areas, a 'techno-planning' solution to integrate storm water network and lakes was undertaken and implemented.

Such experimental projects, integrating infrastructures; interlinking of lakes, giving partial pragmatic solutions dealing with issues of water logging in urban areas overlooked the irreversible impacts in terms of runoff water quality discharged in lakes. Also considering lakes as detention ponds contradict primary purpose of its recreational and ecological importance.

Integration of storm water network with lake ecosystem significantly alter the natural cycle of lakes, hence prior to the inception of the interlinking project, environmental impact assessment should be carried out. In the case of interlinking of lakes project no such impact assessment studies were found done, in spite of Government of India already having a provision under Environment Protection Act (EPA), 1986 to carry out environmental impact assessment on large scale projects. However in a recent advisory on 'Conservation and restoration of urban water bodies' by Central Public Health and Environmental Engineering Organization (CPHEEO, 2013), published by Ministry of Urban Development (MOUD) emphasize the importance and conservation of urban lakes. But in spite of existing manuals and advisories on conservation and restoration of lakes, urban local body of Ahmedabad pays limited attention to potential irreversible impacts which can disrupt the balance of urban hydrological cycle.

1.3. The Case: Linking Urban Lakes – *An experimental approach.*

The interlinking of lake project initiative is seen as a techno-planning solution for water resource conservation (Jagani, 2004) by the local urban authority of Ahmedabad. The conceptual design of interlinking of lakes and its conveyance is shown in Figure 1.The concept of interlinking lakes is not new, as from a geological perspective they are connected either by confined or unconfined aquifers. In urban environments due to intensification of urbanization, increased impervious surfaces hinder the natural recharge of groundwater and fragment the natural linkage, making lakes independent functional entities. Attempts to unify these lakes and form a functional whole for hydraulic simplicity through alternative approaches and experimental infrastructural projects generate an impasse, if the impacts of forming the new unity are not preconceived or underestimated.

Alternative approaches and experimental projects require decision making by scientific and technical expertise based on rational, objective science and ethics. The project carries uncertain impacts and engineering complexity dealing with various issues from storm water quality to lake water quality and its consequential effects on receiving waters.

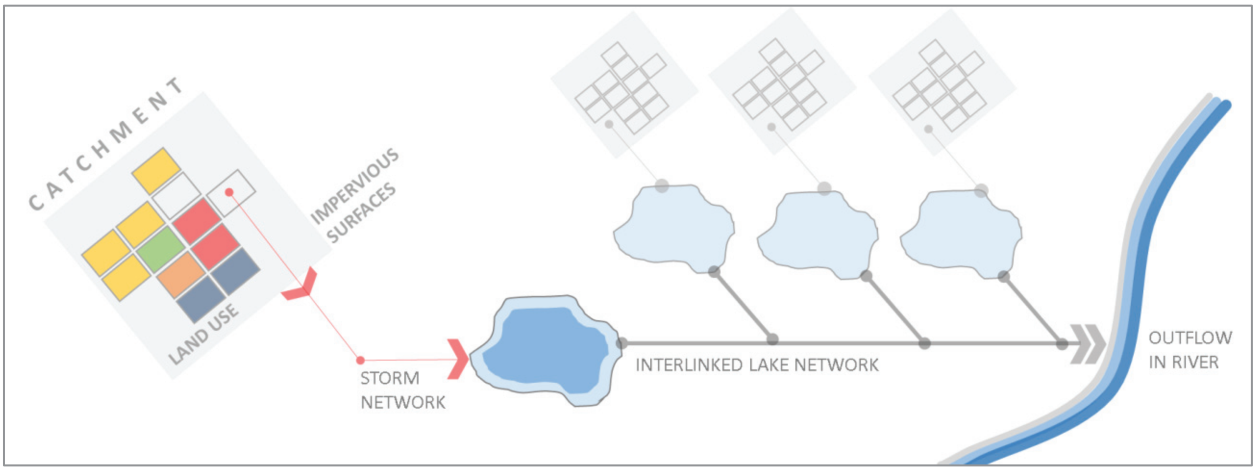


Figure 1: Conceptual design of interlinked lakes and its conveyance

Thus to deal with this complexity it is important to analyse the system in parts; from catchment to lake through storm water; lake through interconnected lakes and outfall at receiving waters to assess the impacts. The impacts on receiving waters come as a consequence of rapid changes in urbanisation in terms of hydraulics, failing to deal with variables of urban hydrology such as 'water quality' which gave rise to so called terms 'urban stream syndromes' (Fletcher, Andrieu, & Hamel, 2013).

A variety of approaches to mitigate storm water have been implemented (e.g. distributed network, combined storm sewer networks) in Indian cities where issues of urban hydrology still remain complex and challenging. Also there is much focus given on consideration of storm water as a potential resource for harvesting at parcel level which eventually reduces excessive surface runoff.

1.4. Lakes and Governance

The urban local bodies like AUDA in Ahmedabad play an important role in developing and framing the future prospects of urban water systems in the city. One of the key barriers in the interlinking of lakes approach is the conventional 'rule of thumb' practice, which states that if the problem is caused by a 'technological solution' then we apply new 'technological fixes' to solve the problem rather than questioning the solution itself. The city needed storm water management via storm water networks as a solution to the prevalent water logging problems but it was unable to work because of the problems emerging in the network distribution, which resulted in flooding of the low lying areas in western Ahmedabad during heavy rainfall (Jagani, 2004). Hence the new 'technological fix' applied by linking storm water network with lakes and further interlinking lakes caused uncertain impacts on receiving waters. Moreover direct or indirect pollution from urban areas discharged through storm network channels in lakes disrupt the original balance of the lake ecosystem, making them as mere detention ponds. Storm water harvesting is increasingly considered as a potential resource, and it is also often confused with rain water harvesting. The expression 'ecological storm water[1]' coined by Lindholm and Nordeide (2000), gives a misleading potential of storm waters allowed to be discharged in the name of harvesting without being treated in the sewage, receiving waters, ground water, soil and ecological systems such as lakes may have adverse effects. The technical means to solve a local problem and expecting benefits with so called 'water harvesting' justification is a overestimation of the attempts which further compounds the problem if looked at a larger context of the region (Stafford, 2006).

The nature of local-scale experiments like interlinking of lakes poses a significant challenge for decision makers beyond primary issues of feasibility and technology. The complexity here arises when alternative local scale projects foresee benefits from pragmatic solutions at local, meet the mandate at national scale, but may not be beneficial at the regional scale. For instance the pollutant concentration from subcatchments discharged in Sabarmati River through interlinked lakes may affect agriculture in rural areas downstream.

In the current trends of urban hydrology there is need for transition towards more sustainable urban water management practices involving complexity, uncertainty and other direct-indirect externalities. Such transitions require new governance policy framework and organizational cultures accommodating new experimentation and learning from large scale to local scale projects (Farrelly & Brown, 2011). Farrelly and Brown (2011) identified four areas which influence experimental projects; stakeholder, critical success factors, key drivers and key aspects of resistance as shown in Table 2. In the four influencing factors identified by Farrelly and Brown (2011) it is argued that implementation of such experiments should be

[1] Defined by (Lindholm & Nordeide, 2000) – Let the water be in contact with sunlight air, soil, plants and micro-organisms, utilize the processes that occur in the natural water cycles , slow runoff, source control of quantity and quality, local infiltration and detention, central detention is open water courses and ponds.

subjected to policy-reformulation, regulatory, structural and efficiency mechanisms. Moreover alternative experimental approaches should be perceived in a systematic manner taking account of social, environmental, and economic externalities. Overlooking such externalities can cause direct-indirect irreversible impacts, thus in order deal with local scale experimental projects it requires a strategic and integrated approach encompassing societal, environmental and governance perspectives (Farrelly & Brown, 2011).

Stakeholder	Critical Success Factors
• Water Utility • Land Developer • Local Government • Non-Government Organization • Consultants • Academia • Environment Authority • Industry council • State government • Users-Groups of people	• Persistent and dedicated individuals • Approaching the project with rational and objective science • Engineering of project • Mechanisms for risk sharing • Funding, costs and investment tenure • Iconic project status
Key Drivers	**Key Aspects of Resistance**
• Environmental and/or social sustainability • Confidence in technology and project • Commitment and Scientific evidence • Responsibility and Ethics • Innovative technologies and approaches	• Regulatory approval • Capacity and skills • Sustaining stakeholder commitment • Distribution of costs • Unclear future management responsibilities • Unexpected technical feasibility outcomes • Lack of broad stakeholder engagement • Enrolling extended stakeholders in vision.

Table 2: Influencing factors in experimental projects (Farrelly & Brown, 2011).

Moreover forming boundaries of expectations of such experimental projects should be clearly defined rather than considering them as 'techno-planning' solutions. While expectations attract attention and resources which may lead to overestimation of benefits from the project and avoid learning and technical understanding of the project. In a positive sense such experimental local projects provide space for learning and articulation processes considering user preferences, regulation, and infrastructure requirements. Thus it should be looked as development perspective where local experimental projects such as lake linking cut across through micro-macro-meso scales (Geels & Raven, 2006).
The process of managing interlinked urban lakes starts with identification of an environmental problem, such as urban lake water quality, which requires a clear understanding of importance of lakes in an urban landscape with more holistic conception of water resources is crucial in a hydrological system (Sorensen, 1996).

1.5. A note on experimental approaches

In order to understand the nature of experimental approaches, experiences from three examples were studied:

The first example expresses the systematic sustainable practices in Malmo, Sweden in storm water management since the late 1980s. The central idea was to focus on source control points and local small scale solutions within the city area. It is considered more effective to target sources of storm water

generation at smaller units of impervious surfaces which causes urban runoff where it is mixed with pollutants from several sources (Niemczynowicz, 1999).
The city surrounds a chain of ponds and constructed wetlands created along the stream. This chain constitutes an ecological zone, parks with recreational uses. Before the water enters these larger infiltration facilities, runoff from larger roads goes through permeable pavements and other temporary storage such as tree box filters and bio-swales networked in the area (Stahre, 2002). Here the above described system is added to the previously existing system to avoid flooding in urban areas and to mitigate pollution release in the receiving waters.

Inference:

The point which needs emphasis here is that two types of solutions discussed in the case of Malmo are complementing each other for achieving different goals, showing no contradiction between old and new solutions. In a process of continuous development in urban hydrology, where parallel technological inputs are added through experiments should accommodate previous goals and offer minimum contradictions to avoid uncertain impacts.

Another example from Sweden, from the city of Stockholm describes the disparity within the urban water cycle; biological cycle and technical cycle. The interactions between these cycles and for the fact they are perceived separately puts the emphasis on the main reason why the urban water systems are in state of problem (Malmqvist, 2000). The surrounding waters of the city of Stockholm were considered among the cleanest in any large city. But water quality investigations showed that sediments of these waters had toxic organic and heavy metals contamination and urban storm water runoff was identified as a major source of these pollutants, coming from newly developed residential areas.

Inference:

It was found from the example of Stockholm that, after considering several alternatives that there were only two effective ways to reduce the impacts of storm water discharges; either to treat the storm water and/or to reduce storm water pollutant at source. Aptly said by Malmqvist (2000) that "the solution to pollution is dilution" is far behind 'a solution'.
Second example is from Taoyuan Metropolitan Area, Taiwan where the city upgrades three century old irrigation system of manmade ponds into storage for rain-water and purification of domestic and industrial water. Figure 2 shows how Taoyuan city utilizes the ponds as tool to connect the dispersed urban tissue within the metropolitan area. Further they were interconnected through canals to complete the hydrological network and used for transportation, water harvesting and irrigation purposes. Due to rapid sprawl in the area irrigation has diminished and these ponds were degraded into fishing and recreational uses (Shannon, 2008).

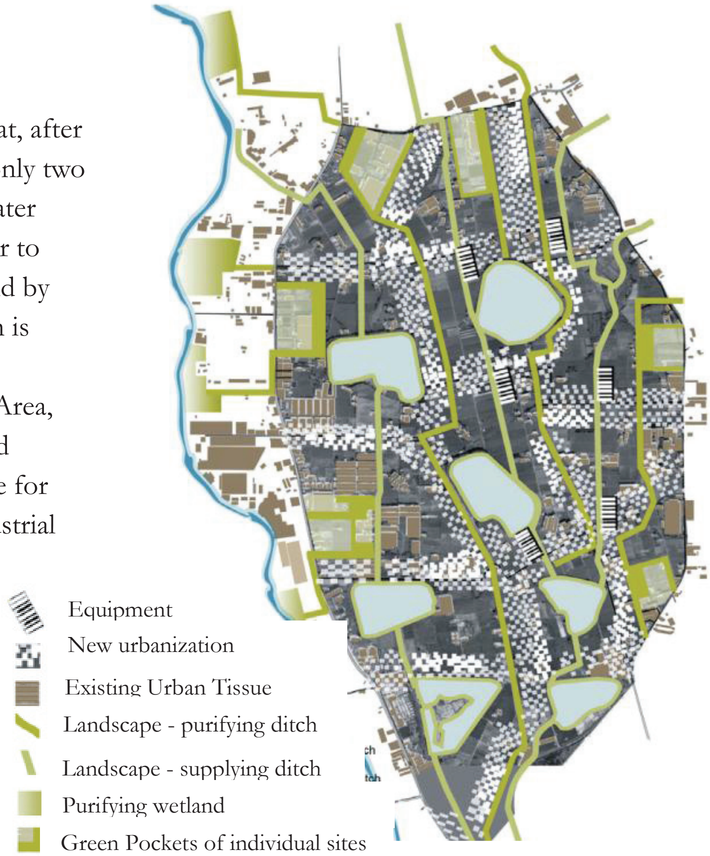


Figure 2: Pond City, Taoyuan Metropolitan Area, Taiwan
Source 1: Water Urbanism (Shannon, 2008)

Inference:
An experimental approach was undertaken to rejuvenate these ponds by reclaiming the pond areas and with densification of new urban areas. The use of canals as waterways was reinstated with new perspective of public spaces around these ponds. The approach highlights minimum intervention to the hydrological system, maximizing new potential for lakefront as public spaces in an urban landscape.

Conclusion from examples
The examples discussed above were used to highlight issues and approaches which are relevant to understand the solutions derived from the urban hydrological system. The conclusion drawn from these experiences is that of interventions to urban hydrological systems should be defined with the boundary condition taking account of ecological boundaries of environment. While in urban areas the boundaries of ecological assets like lakes are not defined, it is essential to demarcate the boundaries of intervention for the sustainability of lakes. Also constant incremental changes in approaches, practices towards lake ecosystem should consider technical, social, socio-technical, transformative capacity and resilience of the lakes (Ernstson et al., 2010). Technical intervention is seen as the part which deals with improvements in urban landscape such as lakefront, riverfront developments, but also influences the sustenance of ecosystem in and around urban areas. Thus there exists a delicate balance where the boundary conditions should be understood and interventions should have the capacities to respect these boundaries, as described by (Rockstrom et al., 2009) that although boundaries are defined in terms of individual quantities and separate processes, they are tightly coupled so as to say if one boundary is overstepped there is considerable impact on other ecological systems. Experimental projects juxtapose themselves on the thresholds of these boundaries where, there is a potential for uncertain, unforeseen and irreversible impacts. Hence there emerges the necessity to check the developed policy framework and the stakeholders involved at various levels and the related sectors which generate experimental approaches to engage and deal with the socio-ecological dynamics within the given governance framework. Consequently if fetches an immediate task to analyse ecosystem services and uncertainty linked with it such that it can be incorporated into the practice of urban planning. (Ernstson et al., 2010).

2. URBAN LAKES

2.1. Classification of Indian lakes

"A lake may be defined as an enclosed body of water (usually fresh water) totally surrounded by land and with no direct access to the sea. A Lake may be totally isolated, with no observable direct water input and, on occasions, no direct output" (Chapman, 1996, p. 317).

India is always known for its lakes and the variety it demonstrates but there is no authentic data set which can be referred like 'census of lakes'. The study lacks data on the typology of lakes though there is some background of the classification of lakes into natural and manmade reservoirs and distinction between northern and southern lakes and fresh water and salty water lakes (Reddy & Char, 2006).

According to Reddy and Char (2006) there is no unique or rigid classification of lakes in India, which instead depends on the context of the classification and the classifier. The commonly perceived classifications are the following;

- Geographical classification – Himalayan, peninsular, coastal, etc.
- Limnological classification – Freshwater, brackish water, etc.
- Functional classification – Irrigation, water supply, hydropower, etc.
- Water quality classification – The category based on water quality.
- Management classification – Conserved and Protected lakes.
- Urban lakes – The water bodies falling in urban areas.
- Non-urban lakes – which includes inland freshwater, inland brackish water and sacred lakes/tanks
- Coastal estuarine lakes – The lakes formed from estuaries in coastal areas.
- Ephemeral lakes – intermittent water bodies, formed during precipitation also called rain ponds.

2.2. Urban Lakes

Urban lakes are considered only a subset of all freshwater bodies, such as reservoirs, lakes, ponds and tanks. Urban lakes are essential elements of urban water systems as well as ecological networks. But due to rapid urbanization and development lakes are experiencing varying degree of environmental degradation related to encroachments, eutrophication (from domestic and industrial effluents) and siltation. Increase in impervious surfaces in urban areas and excess water flow in lakes have resulted in urban lakes becoming contaminant sinks (Reddy & Char, 2006).

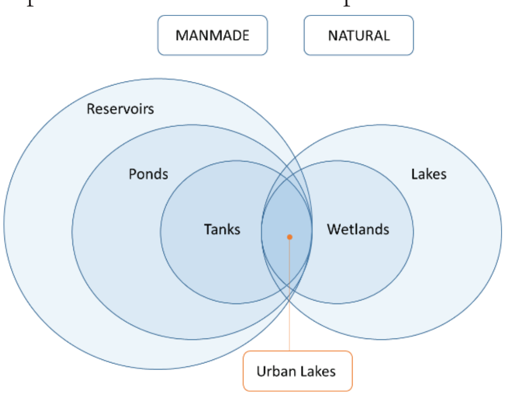


Figure 3: Urban Lake Systems
Source 2: Reddy and Char (2006)

Lakes provide a variety of uses and are prime regions of human settlement and habitation (Chapman, 1996). On the other hand lakes and reservoirs are traditionally under-valued resources to human society. It is not surprising, given the extensive changes to both hydrology induced by urbanisation and its consequences for the water quality and hydraulic regime, that water bodies in catchments that contain even small areas of urbanisation end up highly degraded (Fletcher et al., 2013). Although owning a lake front property has societal prestige, it also causes intense shoreline urban development along the lake front, thereby increasing anthropogenic pressure on lakes and adversely impacting lake water quality. Furthermore, anthropogenic pressures lead to degradation of lake catchment such as discharge of storm water from polluted sources, municipal wastes and overexploitation and excessive usage vitiates the quality of lake water. Infrastructure development, housing pressure and encroachments have caused many urban lakes to become hyper-eutrophic and as a result most urban and rural lakes in India have vanished under this pressure (Reddy & Char, 2006).

2.3. Water quality in urban lakes

Water quality in lakes is a complex subject, which involves physical, chemical, hydrological and biological characteristics of water and their complex and delicate relations. From the user point of view "the term water quality is defined as those physical, chemical or biological characteristics of water by which the user evaluates the acceptability of water" (CPCB, 2007-2008, p. Annexure 1).

Urban lake water quality management is necessary for rational urban development and conservation of water resources, there has been a steady evolution in procedures for designing a system to obtain information on the changes in water quality. Lakes in urban areas are categorised for ecological importance and recreational use, but water quality criteria of recreational use are given inadequate consideration. Recreational water quality criteria are used to assess the safety of water to be used for swimming, bathing and other water recreation activities. The primary concern is towards human health by preventing water pollution from faecal material or from contamination by micro-organisms that could cause gastro-intestinal illness, ear, eye or skin infections (Helmer et al., 1997). The central Pollution control board (CPCB) is an apex body in the field of water quality management in India. CPCB is responsible for carrying out water quality management and monitoring programme which was first started in 1976 and focused mainly on rivers. The programme was gradually extended and currently there are a total of 1032 monitoring stations across the country (CPCB, 2007-2008).

Designated-Best-Use	Class of water	Criteria
Drinking water source without conventional treatment but with chlorination	A	Total Coliform organisms (MPN*/100 ml) shall be 50 or less pH between 6.5 and 8.5 Dissovled Oxygen 6 mg/l or more Biochemical Oxygen demand 2 mg/l or less
Outdoor bathing (organised)	**B**	**Total Coliform organisms (MPN*/100 ml) shall be 500 or less** **pH between 6.5 and 8.5** **Dissovled Oxygen 5 mg/l or more** **Biochemical Oxygen demand 3 mg/l or less**
Drinking water source after conventional treatment and disinfection.	C	Total Coliform organisms (MPN*/100 ml) shall be 5000 or less pH between 6 and 9 Dissovled Oxygen 4 mg/l or more Biochemical Oxygen demand 3 mg/l or less
Propogation of wildlife and fisheries	**D**	**pH between 6.5 and 8.5** **Dissovled Oxygen 4 mg/l or more** **Free ammonia (as N) 1.2 mg/l or less**
Irrigation, industrial cooling and controlled disposal	E	pH between 6.0 and 8.5 Electric conductivity less than 2250 micromhos/cm Sodium absorption ratio less than 26, and Boron less than 2 mg/l

Table 3: Designated best use classification of surface water.
Source 3: Guidelines for Water Quality Management CPCB (2007-2008).

As shown in Table 3, CPCB (2007-2008) has identified 5 classes under which surface water bodies are used. Water bodies used for drinking purposes without any treatment but with disinfection with chlorine are categorised in class 'A'. Urban lakes in India are also used for bathing purpose with daily chores which are categorised in class 'B' with the suggested pollutant criteria. Other water bodies which are used for drinking purposes with treatment are classified as class 'C'. And water bodies which are conserved for aquatic ecosystem and irrigation purpose are classified as class 'D' and 'E' respectively.

Below are the list of parameters that shall be considered for analysis of samples provided in the "Protocol for Water Quality Monitoring" under 'surface water quality' notified by Central Pollution Control Board (CPCB).
Parameters for water quality assessments in the guidelines as prescribed by CPCB (2007-2008) are:
1. General: Colour, odour, temperature, pH, EC, DO, turbidity, TDS
2. Nutrients: NH3-N, NO2 + NO3, Total Phosphorous
3. Organic Matter: BOD, COD
4. Major ions: K, Na, Ca, Mg, CO3, HCO3, SO4
5. Other inorganics: Fluorine, Bromine and other location specific inorganic parameters.
6. Microbiological: Total and Faecal Coliforms.

2.4. Urban Lake Pollution and its effects

In urban areas lakes, are the natural collectors of water runoff from pervious and impervious surfaces, and the direct or indirect discharge from residential and industrial areas, thus making lakes sensitive receivers and prone to eutrophication which is the most common and serious problems they face. According to Landner and Wahlgren (1988) 'eutrophication' is defined as the enrichment of nutrients that cause a stimulation of a large number of symptomatic changes, among which are the augmentation of the production of algae and macrophytes. The degradation of the lake water quality due to negative physical interference, affect the usage of lake waters.

2.4.1. Sources of contaminants to urban lakes

The source of contaminants to lakes is largely derived from anthropogenic activities and through the urban catchments which discharge excess water to urban water bodies. Especially in urban areas, where variety of wastes can generate high toxic levels when in stream with surface runoff can directly contaminate the lakes.
In general, lakes are exposed to multiple sources of toxic substances which are vulnerable for disturbing the balance in the lake systems (Chapman, 1996):

- Direct point sources, municipal and industrial effluent discharges.
- Diffuse urban sources, surface runoff from streets, surface wastes from residential and commercial areas.
- Diffusion from surface water flowing through waste disposal areas
- The cumulative inputs from different areas as surface runoff flowing through natural or manmade storm drains.
- Slum inhabitation around the lakes, which cause lake waters to come in direct contact with human excreta through illegal sewage connection dump.
- Excessive recreational use, unregulated use of lakes with human activities around the lake may harm the lake systems.

2.4.2. Contaminant loads to urban lakes

Exposure to various sources of contamination forms various chemical, nutrient, organic and microbiological concentrations either in surface or sediments. The lake concentration, is a result of the contaminant load (mass per unit time) distributed in the lake, which is termed as loading (mass per unit volume or area per unit time). Thus it is important to differentiate between contaminant loads and loading while forming water management guidelines and policies based on allowable concentrations (Chapman, 1996).

***1. Heavy metals, pesticides and other inorganic and organic substances*:** Proximity to industrial areas and disposal of effluents in significant quantities can constitute a problem. Moreover land uses in the catchment area including domestic effluent sources can affect the influx rates.

2. Total Suspended Solids (TSS): Suspended solids are present in domestic and industrial effluents and additionally they carry organic and nutrient loads which exert harmful effects on lake ecosystem. In suspension they reduce the penetration of sunlight affecting species sensitive and dependent on sunlight, and when settled, they clog the spawning grounds inhibiting the reproduction of species. In extreme conditions runoff entering lakes either through piped drainage or natural drainage transport particulate matter, clay, silts and mineral particles, which by settling in lake, gradually fill it and transform it into a swamp, which is irreversible and requires huge costs in de-silting.

3. Dissolved Oxygen (DO) and Biological Oxygen Demand (BOD): The presence of dissolved oxygen in lake water is essential for the survival of aquatic species. Organic materials entering the lake also consume oxygen as they decompose. BOD is a measure of total amount of oxygen required to oxidise organic matter at a specific temperature and time.

4. Microbial Pollution: This is a critical parameter for the beneficial use of lake water. The abundant and easily identified coliform bacteria are widely used as an indicator of the possible presence of pathogens and viruses. As lake waters are often used for bathing and recreational purposes, such pollution can be the root source for water borne diseases in the surrounding population.

5. Nutrients (mainly nitrogen and phosphorous): In case of excessive nutrients, nitrification may take place which may cause an additional oxygen demand and reduce the oxygen levels in the lake.

6. Chemical Pollution: It downgrades the quality of water for recreational uses, it reduces the species diversity, while toxic substances such as heavy metals accumulate in the food chain and can affect human health through coming in direct contact or indirect. The allowable concentrations of various pollutants depend on the lake water purpose.

6. Coliforms: The presence of coliforms indicates the pathogenic bacteria like faecal coliforms and steptococcal. The major source of these bacteria is sewage, animal wastes, and bird excreta which causes various health hazards to the people in contact (Zoppou, 2001).

2.5. Management of urban lake pollution

There are various exogenous and endogenous factors which are responsible for pollution in urban lakes, thus to control the extent of pollution there can be several approaches. The most direct approach is to reduce the influx of point source pollution; diversion of effluents from industrial, municipal and domestic sources and control on solid waste dumped by the recreational use of lakes. Since the pollutant also travel through storm network channels identification of polluted urban catchments is essential for pollutant load reduction in the storm drainage network. Other methods include altering the state of hydraulics by siphoning fresh water from reservoirs, underground sources and harvesting which can have positive effects if done selectively preferably at the end of the stratification period (Economopoulus, 1993). However this approach of 'solution through dilution' (Malmqvist, 2000) depend on the context of the lakes and the source of the siphoned water. Urban lakes require due maintenance by removal of accumulated sludge around storm water inlets which helps lakes to regain its equilibrium.

2.6. Modelling lake water quality

Integration of urban storm water with lake systems for flood protection and harvesting storm water as a resource raises several questions on lake water quality in terms of public health and environmental effects. This is due to the fact that urban storm water which was once regarded as a nuisance is now increasingly considered as a potential resource for water harvesting and revitalising urban water bodies (Shah, 2005), hence it is important to model the water quality in storm water entering in lake systems.

Urban hydrological modelling, in terms of water quality and its impacts on receiving waters depend on being able to measure, and understand rainfall-runoff relationships at spatial and temporal scales. Changes in rainfall-runoff behaviour and generation of pollutants from the subcatchments and activities result in degradation of overall water quality within the urban hydrological systems. According to Fletcher et al. (2013) intensive urbanization in these subcatchments affect water quality of receiving waters by two primary mechanisms (Fletcher et al., 2013):

1) Increased generation of pollutants through land use and human activities.

2) Increased mobilization and transport as a result of increased surface runoff and hydraulic efficiency of the network.

It is therefore important identity water quality model package which can investigate above mentioned mechanisms. Urban hydrological models can vary from simple conceptual models to complex hydraulic models. Variables regarded as random variables having a probabilistic distribution those models are considered stochastic otherwise it is deterministic, which produces identical results for the same input parameters (Clarke, 1973). Further stochastic and deterministic models may be further classified into conceptual or empirical. The spatial variability and distribution are important to be able to described in a model, and thus most urban runoff models are deterministic-distributed models as lumped models take no account on spatial distribution of the input (Nix, 1994).

Approaches to storm water quality models are similar to those used to model water quantity, for instance in deterministic models the transport of pollutants is modelled using single equation of the conservation of mass, including two fundamental transport processes, advection[2] and diffusion[3].

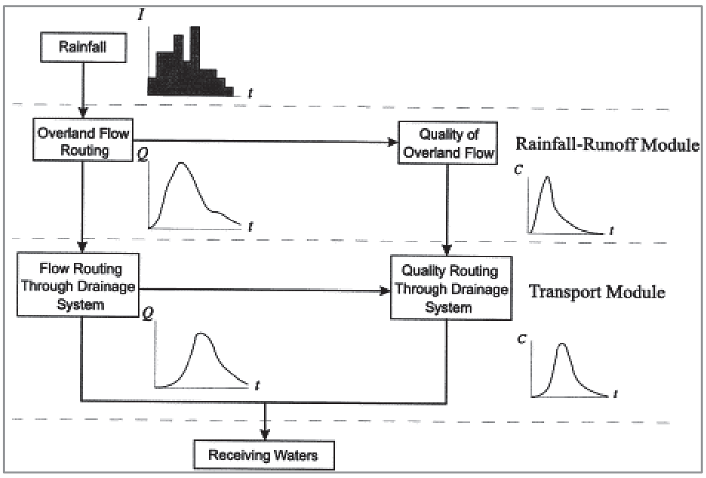


Figure 4: Overview of processes incorporated in urban storm water model
Source 4: Zoppou, C. (2001). Review of urban storm water models.

The basic components of an urban storm water model are:

(i) Rainfall-Runoff modelling (buildup and washoff through impervious surfaces in a catchment)

(ii) Transport modelling (routing of pollutants within the network).

The processes are illustrated in Figure 4: Overview of processes incorporated in urban storm water model (Zoppou, 2001).

There are variety of urban storm water models classified based on modelling scales capable of simulating single or continuous events, water quantity and quality components with ability to model various pollutants and other models based on their characteristics to undertake uncertainty analysis, optimization and design. A comparative table of various urban storm water models is show in Appendix A.

[2] Advection describes the process of conveyance of pollutants in moving waters.
[3] Diffusion is the transport of pollutants in the direction of decreasing gradients.

There are five basic processes which affect the movement and transformation of pollutants in an urban catchment: chemical, physicochemical, biological, ecological and physical. Modelling these processes require specialised packages developed earlier in 1970s primarily by US government agencies, such as Environment Protection Agency (EPA). Since then number of models has been developed. These models include very simple conceptual model to complex hydraulic models (Zoppou, 2001)

The Environmental Protection Agency developed Storm Water Management and Modelling (SWMM) which is used in the present study to model surface runoff based on rainfall intensities and land use in urban catchments. Figure 5 shows the model characteristics of SWMM, in which structures information on atmospheric data like rainfall intensities, hydrological characteristics of catchment, hydraulics and the pollutant quality parameters. The model was used to measure the pollutant build-up in urban catchment during the dry season which is flushed during the precipitation in the storm water channels.

Lakes studied in the thesis are considered as storage units as they receive water from storm water network. And in EPA-SWMM pollutants in storage systems can be modelled as either complete mixing or plug flow (Zoppou, 2001).

In assuming lakes as storage units or storm water ponds there are various other factors based on residence time of pollutants in lake, basin configuration, and inflow and outflow hydraulic states. Given the residence time distribution for all inflow events to a lake, it should be possible knowledge of pollutant decay processes and relationships to model the effectiveness and performance of the lake (Walker, 1998).

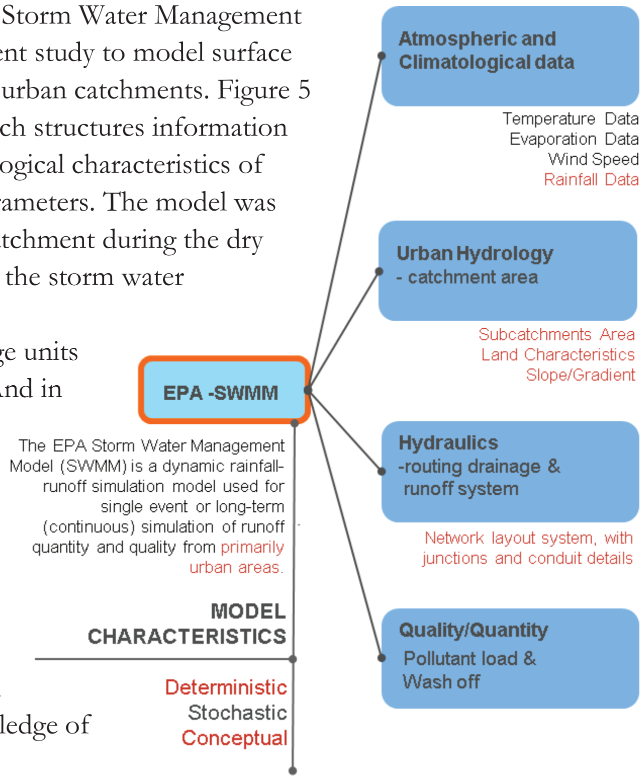


Figure 5: EPA-SWMM Model characteristics

3. RESEARCH DESIGN

3.1. Research Problem

Lakes in urban and peri-urban areas are an important interface between planning and ecology, which demands environmentally responsive strategies, acknowledging problems like flooding, water pollution, and water quality with their complexities and severity in design and engineering. Much emphasis is given to planning due to land value potentials with preference of lake-front recognized as catalysts for development (Chapman, 1996).Through time human settlements have always been in vicinity to water as the necessity of life, intensification of urban development have engulfed the satellite rural areas and generated an influx of demand of development with several layers of networked systems, like road networks, water supply and storm water networkwith a constant pursuit to understand the processes which forms the urban systems (Eckbo, 1964).

The networked hydrological systems are interdependent and governed by the spatial boundaries of the urban development. These interdependencies form the basis of integrating infrastructure systems, for instance a typical road network section will be inclusive of drainage systems, storm water network and water supply. Even though each infrastructure systems have a different function and time span, they are integrated for spatial and operational feasibility. Hence it is important to identify the nuances of integrating or linking systems when they can influence ecological balance in larger context.

Urban areas are composed of a multitude of systems; environmental, economic, hydrological and societal. Their interactive responses form a balance of a system of its own. Any interventions within these systems have impacts. There is need to acquire knowledge of these impacts is necessary to avoid irreversible effects which creates imbalance in urban environments. To assess the impacts of interlinking of lakes in terms of water quality is the focus of the research. Every lake is part of a larger hydrological system that normally comprise of catchment areas, inlet and outlet of the lake and the associated ecosystems and biodiversity (Reddy & Char, 2006). Thus there is need to evaluate the present conditions of the lakes with unknown parameters which are investigated in the research.

Present Conditions:

1. The lakes recharge the ground water aquifers through bore-wells and harvest rainwater and receive quantifiable waters from the storm channels, also acting as detention ponds.
2. The interlinking of lakes distributes the excess water quantity amongst other lakes via piped network which is discharged in Sabarmati River.

Unknown Parameters:

1. The water quality in the lakes.
2. The pollutant loadings from the storm channels conveyed to the lakes.
3. The characteristics and types of the pollutants present in lakes
4. The degree of contamination of interlinked lakes.
5. Impacts at receiving waters.

The research problem is how to measure the possible impacts of linking lakes in terms of water quality and the factors influencing the lakes in urban hydrological system.

3.2. Research objectives and questions

Main Objectives

1. The research objective is to evaluate and model the impacts of lake linking project on water quality of lakes.

Sub Objectives

1.1 Discuss issues in experimental approaches and evaluation of lake linking project.
- 1.1.1 Investigation in integration of water infrastructure in urban areas.
- 1.1.2 Identify influencing factors in experimental projects.

1.2 To carry out water quality assessments in urban lakes.
- 1.2.1 To know the presence and level of pollutants.
- 1.2.2 To inquire the sources of pollutants from subcatchment.

1.3 To characterise and evaluate the degree of pollution in lakes.
- 1.3.1 To identify the extent of anthropogenic pressures on lake.
- 1.3.2 Evaluation of lakes based on water quality assessment.

1.4 To model the transport of pollutants within the interlinked lakes.
- 1.4.1 Impact of urban subcatchment washoff in lakes.
- 1.4.2 The estimation of inflow of pollutants from urban subcatchments.
- 1.4.3 The transport of pollutants in storm events through network.
- 1.4.4 Estimation of pollutant loadings in lakes through simulation
- 1.4.5 Impacts on outfall loadings in receiving waters.

3.3. Conceptual framework

The above conceptual framework shows the schematic representation of the linking of lakes and individual lake as a unit of analysis. The water quality assessment with 2-3 samples for per lake was done and the level of pollutants in lakes were analysed according to the permissible limits prescribed by national standards. The characteristics of lakes were studied in order to know the degree of pollutants in lakes. Further the lakes were modelled in EPA-SWMM to investigate the impacts of interlinking on lakes and receiving waters. Finally the pollutant loadings in lakes from simulated results were calibrated with the measured values. The research was concluded with the evaluation of results and future recommendations.

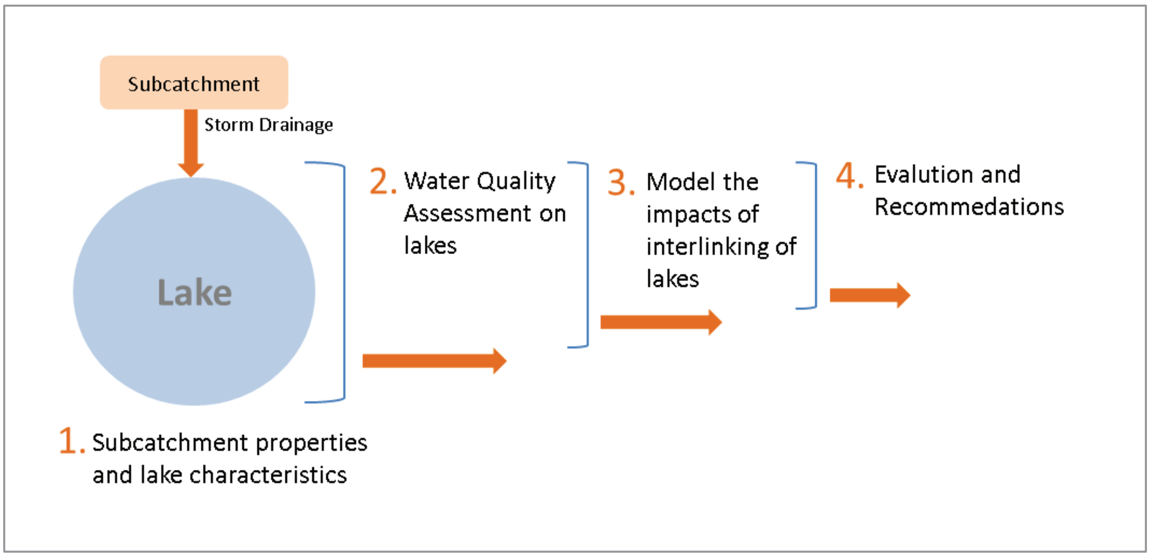


Figure 6: Conceptual Framework

3.4. Research Methodology

The research method was aimed to sequentially answer the research questions and tried to formulate the impacts of interlinking of lakes. The research was carried out in four phases mentioned in Figure 7 and described as below.

Phase 1: ***Formulation of research and literature review***
In this phase the case of interlinking of lakes was analysed in terms of experimental approaches of the urban local government. Literature review of important publication on integrated water governance and infrastructure was studied. Similar experiences on water infrastructure and lake management were investigated and research problem was identified with research questions. Also literature on urban hydrology and urban hydrological modelling was studied and methods to model the interlinking of lakes were discussed.

Phase 2: ***Field work and data collection***
In this phase the field visit was carried out for gathering data on urban subcatchments and lakes. The water quality assessment was done with the help of Gujarat Environment Management Institute (GEMI) and water quality report was produced in institute's in house laboratory. Rainfall data of Ahmedabad for the year 2013 was obtained from the Indian Meteorological Department (IMD) with field observations on the lakes. Along with the data gathering process, various experts and environmentalists were interview to get the holistic idea of the hydrological system of Ahmedabad. The land use data of 2011 was used in the study for calculating impervious surfaces in the subcatchment provided by Ahmedabad Urban Development Authority.

Phase 3: *Analysis and Modelling*
In this phase review of water quality assessment in lakes were done and the lakes were studied according to its independent characteristics. Further the lakes were summarised based on their concentration of pollutant found during the assessment. The modelling of interlinked lakes with their respective urban subcatchment was done in EPA-SWMM 5.0. For modelling simplicity and unavailability of data on certain parameters system default values were assumed with justification. Total suspended solids pollutant was selected for the modelling. Parameters required to define the pollutants were derived through manuals and literature. While a detailed description of the modelling of pollutant decay processes was beyond the scope of the thesis, thus pollutant build-up and washoff in a rainfall event on subcatchment and its inflow in lakes was measured in the model. Pollutograph of subcatchment and lakes were generated and were calibrated with the measured values of TSS during field sampling. The outfall loadings were also analysed and compared with the water quality data of the receiving waters.

Phase 3: *Conclusion and Recommendations*
This phase concludes the study, and sequentially tries to answer the research questions. The conclusion also highlights points of discussion regarding the nature of projects like interlinking of lakes. Finally a recommendation for further area of research which could not be encompassed in the research but are important is mentioned.

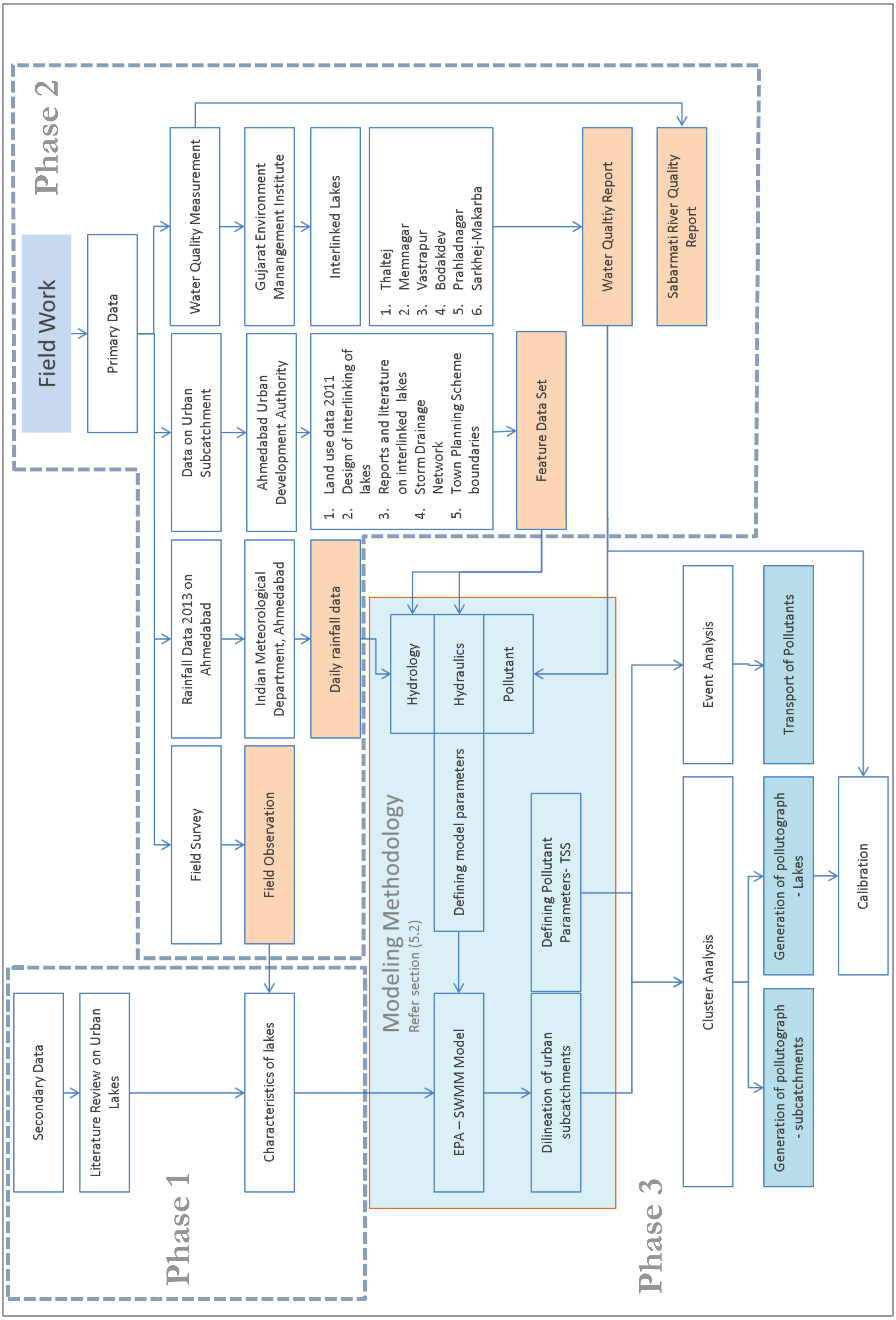


Figure 7: Research Methodology

3.5. Sampling Design and Data Collection

3.5.1. Sample Design

The sampling design is described in relation to a number of precise water quality objectives. In addition to the water quality issue being addressed, the number of samples to be taken is related to lake size and morphology (Chapman, 1996).

The sample size is considered to be 3 samples per lake. The collection of the samples were done manually and submitted to the laboratory for water quality assessment reporting. The selection of the laboratory for the water quality assessment is based on the capacity to perform chemical, general, ecological and bacterial analysis according to notified CPCB standards.

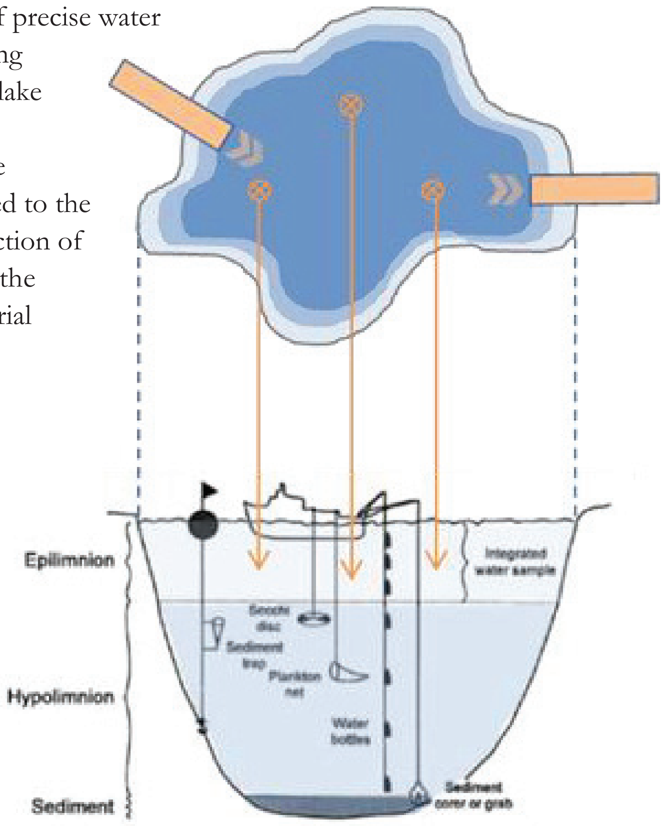


Figure 8 - Sampling location criteria
Source 5: (Chapman, 1996, p. 353)

LAKES	NO OF SAMPLE
THALTEJ	2
MEMNAGAR	3
VASTRAPUR	3
BODAKDEV	3
PRAHALADNAGAR	2
SARKHEJ	3

Table 4: Sample size from lakes

The water quality laboratory assessment was done by GEMI, as per the sampling procedure laid down by CPCB. In sampling procedure, 3 samples per lake were taken from 4 lakes while 2 samples were taken from the remaining 2 lakes. Thus, 16 samples were collected in total, due to laboratory processing limitation of 8 samples per day, 2 samples were taken from Thaltej and Prahladnagar as shown in Table 4. The sample classification for various tests is shown in Figure 9. From collected samples of each lake, a composite sample was made for the bioassay test and to measure the toxicity of the lake. The preservative acids were added to samples on site with some preliminary tests and for microbial tests the 30ml samples were taken in sterile bottles. Thus one sample consisted of 7 sets of sample bottles for testing. The sampling location on lake were taken from the shore as shown in Figure 8, with an average distance of 7 to 8 meters, proximity to the inlet of the lakes, outlet of the lakes and the storm water inlets respectively.

The sampling procedure was carried out in two phases, covering Memnagar, Vastrapur and Thaltej on 15th Oct. 2013 and Sarkhej, Bodakdev and Prahladnagar on 17th Oct.2013.

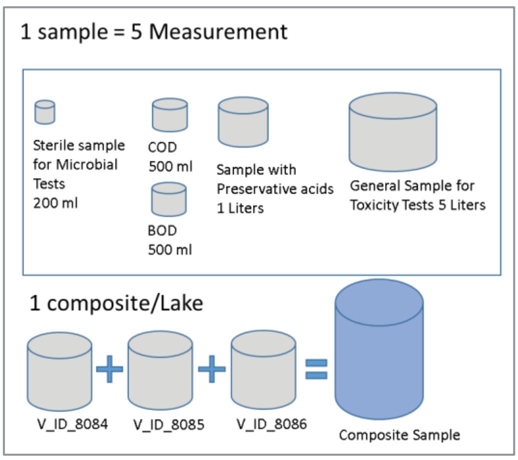
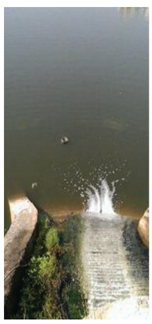


Figure 9 - Sample classification and measurement



All the samples were collected between 9:00 am to 1:00 p.m. as the dissolved oxygen content varies throughout the day. Due to limitation of budget heavy metals and other specialised tests was not done, the selected parameters on which the tests were performed are:

1.	pH	12.	Alkalinity
2.	Colour	13.	Total Hardness
3.	Odor	14.	Calcium Hardness
4.	Flavour Threshold Test	15.	Magnesium Hardness
5.	Conductivity	16.	Ammonical Nitrogen NH3-N
6.	Total Solids	17.	Chemical Oxygen Demand COD
7.	Total Dissolved Solids	18.	Dissolved Oxygen
8.	Total Suspended Solids	19.	Biochemical Oxygen Demand
9.	Choride as CL	20.	Toxicity Test
10.	Turbidity	21.	Total Coliform
11.	Oil & Grease	22.	Fecal Coliform

Table 5: Selected parameters for water quality measurements

In addition to the above parameters mentioned in Table 5 other general parameters include, temperature, colour, odour and taste was taken in the laboratory. The lake quality measurements for the selected parameters is shown in Table 6, in which Sample Identification (SIDs) of outlet for lakes were considered the detailed water quality measurements of total samples in respective lakes is shown in Appendix E.

Parameters	Units	Permissible Limits - WHO and CPCB	Thaltej	Memnagar	Vastrapur	Bodakdev	Prahladnagar	Sarkhej
			SID - 8090	SID - 8088	SID - 8084	SID - 8143	SID - 8139	SID - 8137
pH	-	6.5 to 8.5	8.28	8.39	8.28	8.75	8.30	8.26
Conductivity	mS/cm	2000	10.00	1162.00	537.00	1840.00	226.00	506.00
Total Solids	mg/l	-	500.00	533.00	416.00	850.00	284.00	396.00
Total Dissolved Solids	mg/l	2000	476.00	503.00	412.00	868.00	282.00	392.00
Total Suspended Solids	mg/l	600	24.00	30.00	4.00	18.00	4.00	4.00
Chloride as Cl	mg/l	1000	139.00	199.90	119.90	420.00	59.90	139.90
Turbidity	NTU	10	39.00	19.20	2.50	21.70	34.60	23.30
Oil & Grease	mg/l	10	BDL	6.90	2.00	1.40	BDL	0.05
Alkalinity	mg/l	200	180.00	360.00	160.00	380.00	100.00	120.00
Total Hardness	mg/l	600	150.00	190.00	100.00	320.00	100.00	110.00
Calcium Hardness	mg/l	100	90.00	100.00	70.00	130.00	60.00	70.00
Magnesium Hardness	mg/l	200	60.00	90.00	30.00	190.00	40.00	40.00
Ammonical Nitrogen NH3-N	mg/l	50	1.68	11.20	2.24	7.84	0.50	0.50
Chemical Oxygen Demand (COD)	mg/l	250	85.36	85.36	44.92	87.29	62.89	47.17
Dissolved Oxygen (DO)	mg/l	3	8.20	0.30	7.00	3.60	9.40	6.20
Biochemical Oxygen Demand	mg/l	30	7.40	BDL	5.90	BDL	0.70	BDL
Total Coliform	MPN/100ml	0	1600.00	1600.00	1600.00	1600.00	80.00	1600.00
Fecal Coliform	MPN/100ml	0	2.00	2.00	2.00	2.00	2.00	2.00

Table 6: Lake water quality measurements for selected parameters

The water quality measurement done in interlinked lakes receive contributing storm water through inlet from diverse land uses. The samples considered for analysis were taken near the outlet of lakes as primary measurement assuming that the water flowing from one lake to another must be tested before it enters another. Table 6 shows the samples Ids (SID) of lakes from the outlet of the lakes.

3.5.2. Data Collection

The data collection also included expert interviews from three critical segments – the Ahmedabad Urban Authority itself, Academia, and Environmental Institution including a brief video interview with a veteran environmentalist on interlinking of the lakes. Other data includes the actual design of the interlinking of lakes, land use information for 2011, reports on urban health, and various datasets of infrastructure including roads, administrative boundaries and water bodies. Moreover general observations were made on each lake in terms of noting the frequency of visitors in the lake as shown in Figure 10, purpose of the visit and preferred time of their visit. The data overview of data collected during field visit is mentioned in Appendix B.

3.5.3. General Observation

Parks are developed alongside the lake from the reclaimed land from the relocated slums. It was observed that lakes in high density areas were visited often, twice during a day by the people living in surrounding areas. Lakes are used for recreation by the surrounding inhabitants, also lakes are a centre for social congregation gatherings. Lake development has also an impact on the urban development and land values other than recreational and environmental values; in fact lake developments have triggered development and densification of the area.

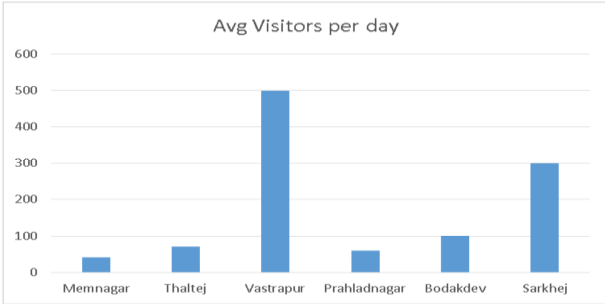


Figure 10 - Frequency of visitors in lakes

3.5.4. Selection of Catchment

The selection of catchment was based on considering Town Planning Schemes as basic units from which the storm water channels transport water to the lakes. In Gujarat, the process of city development is governed under the provision of Gujarat Town Planning and Urban Development (GTPUDA) Act, 1976. The local urban development authorities develop Town Planning Schemes (TPS) and Development Plans

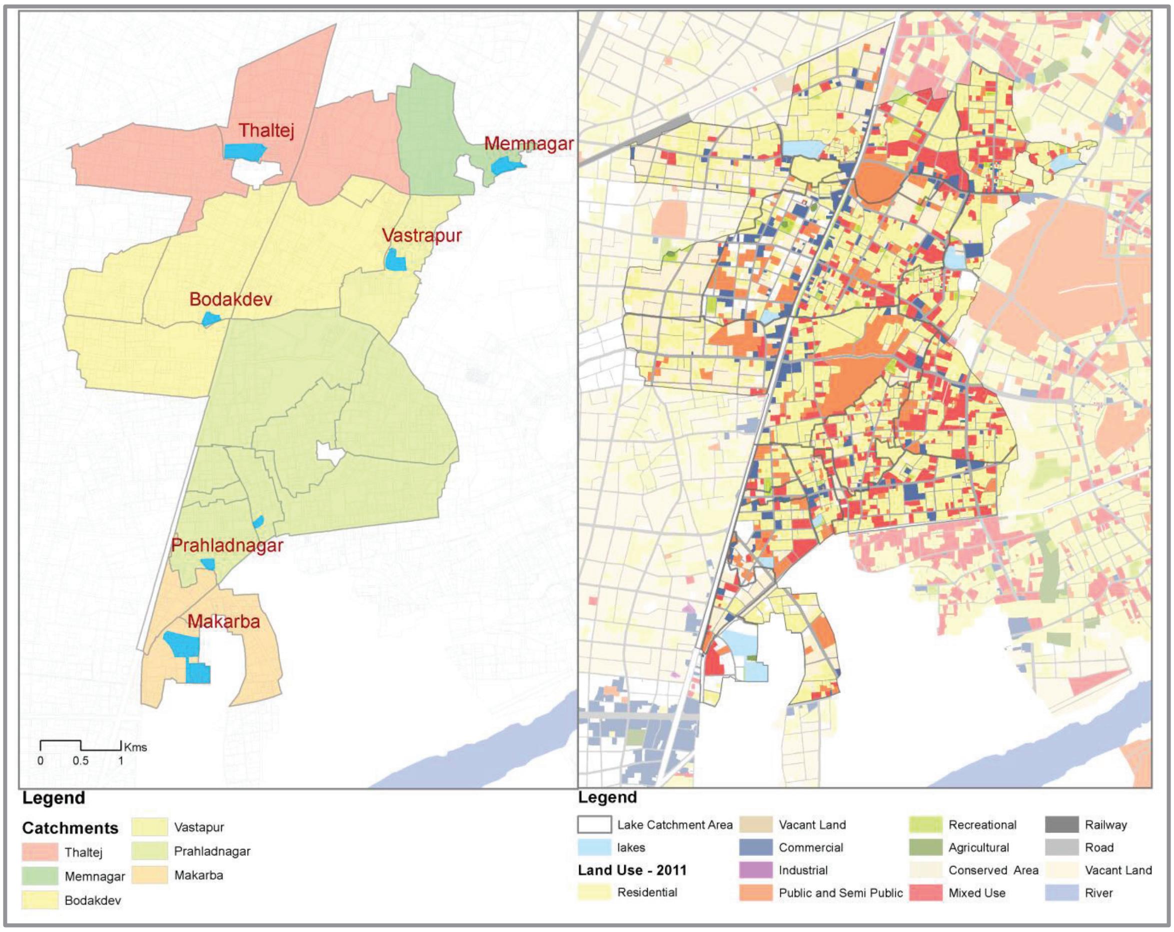


Figure 11: Catchments and Land Use

(DP) for integrated spatial development of the entire urban area (AUDA, 1997). The selected catchments in the interlinking of lakes cover an area of 5780 acres including 21 TPS, ranging from low density to high density residential and commercial developments as shown in Figure 12.

The analysis of the urban area can be done at various scales, ranging from building footprint, unit block, cluster and catchment. Total imperviousness of the catchment is commonly used to derive the hydrological impacts of urbanisation. Based on the land use in these catchments the total impervious areas of the catchment were derived. The determination of total yield of storm water from catchment was considered as input to these lakes.

These lakes were developed for recreational use but some lakes like Sarkhej and Thaltej still had traditional usage like bathing, washing and other daily chores.

Catchment	Population	Area_Acre	No of TP Schemes
Memnagar	37290	332.61	1
Thaltej	42699	1120.86	3
Vastrapur	24438	284.85	1
Prahladnagar	118580	1983.80	8
Bodakdev	20776	1626.18	5
Sarkhej-Makarba	51964	432.15	3

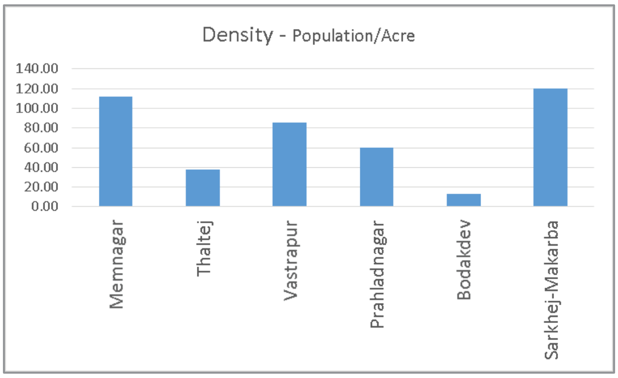


Figure 12: Population density and catchments characteristics
Source 6: Ahmedabad Municipal Corporation and Census Report 2001

4. CHARACTERISTICS OF LAKES

4.1. Thaltej

Figure 13: Characteristics of Thaltej Lake

Thaltej lake has a catchment area of 1120.86 acres forming 20.27 % of total catchment. It comprises chiefly residential areas, mixed used and public spaces. Thaltej lake was used as main source of water by the inhabitants of surround village and it received waters through natural drains during monsoon seasons. Later Thaltej lake was developed by the urban development authority, and the lake area was reclaimed from the slum settlements and illegal encroachments.

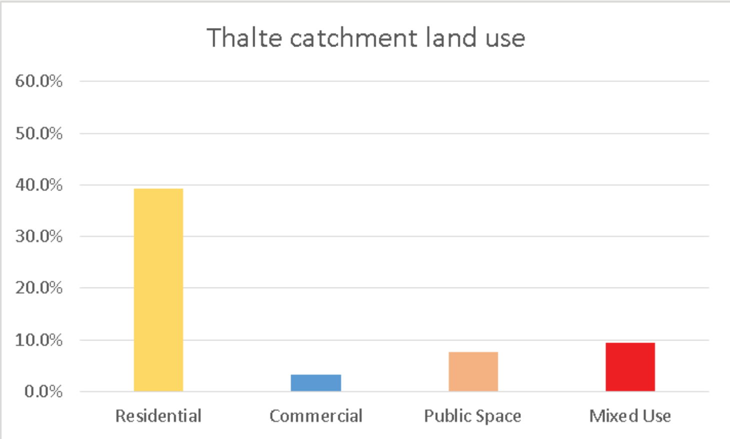


Figure 14: Thaltej catchment land use

Figure 15: Thaltej lake - Top (2000), Bottom (2013)
Source 7: Google Earth Imagery

The reclaimed land further was developed by assigning land uses like religious, recreational and open space in the surrounding periphery of the lake. In spite of efforts done by urban authority to develop and maintain the lake, it can be seen from Figure 15 that the illegal encroachments have increased and have fragmented the lake since the year 2000.

The water quality measurements show a presence of high amount of coliforms, suspended solids and dissolved solids which consequently increases the turbidity of the water. The Thaltej lake water receives water from multiple sources, like storm water channels and also natural drains from the surrounding areas. In monsoon season high amount of solid wastes is also accompanied by the storm water, which gets dumped into the lake.

The permissible limits according to CPCB for calcium hardness and alkalinity is 100 mg/l and 200mg/l respectively, which in the case of Thaltej it was measured 90mg/l for calcium hardness and 180mg/l for alkalinity. Alkalinity and hardness both are important components of water quality and have indirect effects on growth of phytoplankton. Higher alkalinity indicates the quantity of base present in water; bicarbonates, carbonates, phosphates, hydroxides etc. and govern the pH. Although most aquatic organisms can live in broad range of alkalinity concentrations, fluctuations in pH values can cause stress, and poor growth of these organisms. (Wurts, 2002)

Photo 1: Thaltej lake surface pollution and surrounding.

4.2. Memnagar

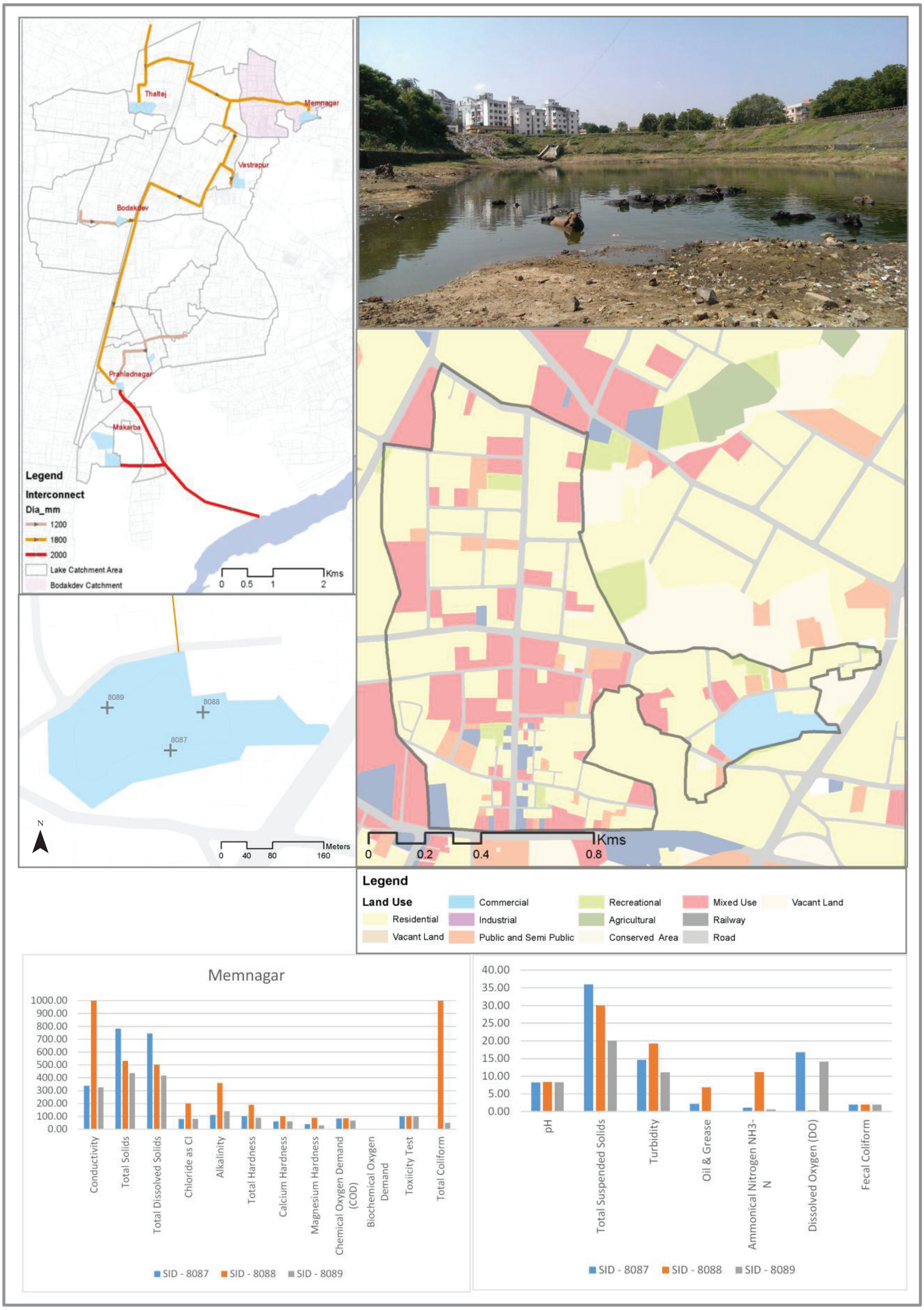


Figure 16: Characteristics of Memnagar Lake

Memnagar Lake has a catchment of 134.60 hectares chiefly comprising of residential area, mixed used and public spaces. The city of Ahmedabad was formed by clusters of villages which eventually became the part of the city and each of these villages had their independent lakes which are being still used for many purposes. Due to the lake development initiative carried out by Ahmedabad Urban Development Authority, t lakes and gardens were developed by reclaiming the lake area.

There are existing slum settlements around Memnagar Lake, slum dwellers use lake waters for bathing, and cattle wash off purposes. Memnagar lake was observed to be the most polluted lake from field visit observation. The lake is abused by the slum dwellers and the park developed within the lake area was also found dysfunctional centre to unsocial activities. The population in slums of Memnagar are mainly migrants from surrounding villages, having no or limited access to surface water and sewage they have practically occupied the lake area. The delay in relocating slums from the lake area by the government has kept the lakes in a vulnerable situation, making them a dump yard for various toxic wastes.

A total of three samples were taken from Memnagar Lake;

1) Inlet of storm water channels
2) Outlet to another lake
3) Shore of the Lake

From field observation it was noted that sewage waters enter the lake through storm water channels and contaminating the water quality and visual appearance of the lake. A complete neglect in terms of maintenance of lake Infrastructure and precincts by the local authority was the primary reason for abuse of Memnagar lake.

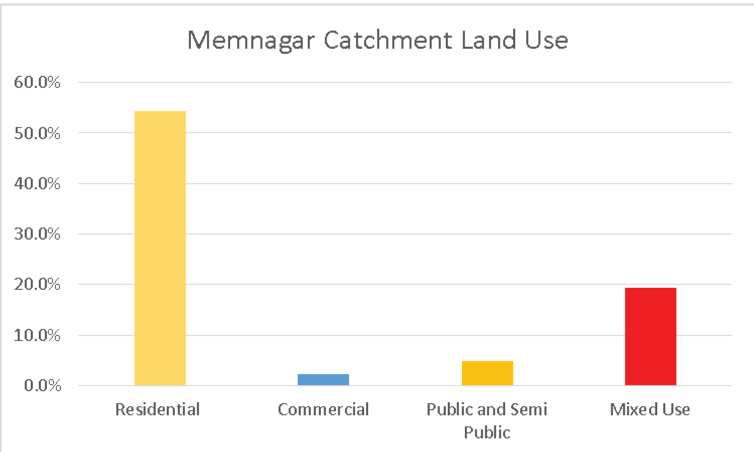


Figure 17: Memnagar catchment Land Use

Photo 2: Memnagar lake and surround slum use.

The residential areas in Memnagar catchment largely consist of low rise apartments, the commercial areas and mixed use.
As we can see from Figure 16: Characteristics of Memnagar Lake the samples (SID_8088) taken from the inlet of the storm water channel shows high amount of coliforms and high amount of suspended solids, which consequently makes the lake a breeding ground for insects and thereby increasing health hazards to the population in catchment.

4.3. Vastrapur

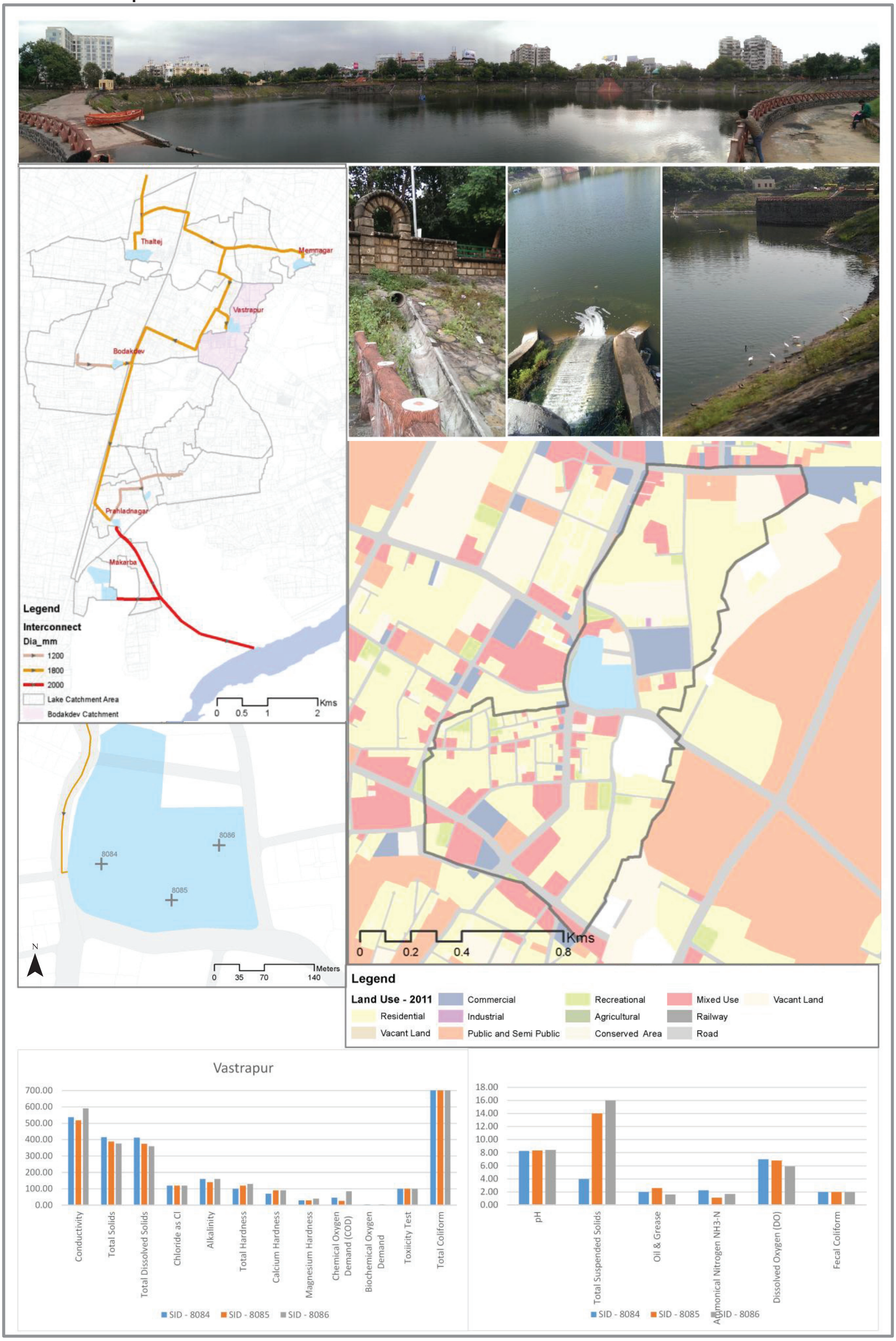


Figure 18: Characteristics of Vastrapur Lake

Vastrapur lake has a catchment area of 284.85 acres forming 4.68 % of total catchment. Vastrapur lake was developed as a model lake under 'Vastrapur Lake Development Project' by AUDA and is a major recreational attraction, central to cultural and public gatherings. Prior to the development of Vastrapur lake, encroachment from all sides by slum dwellers blocked the natural drainage and storm water entering the lake, as a result the catchment of Vastrapur faced severe water logging problems during high rainfalls (Brar, 2004).

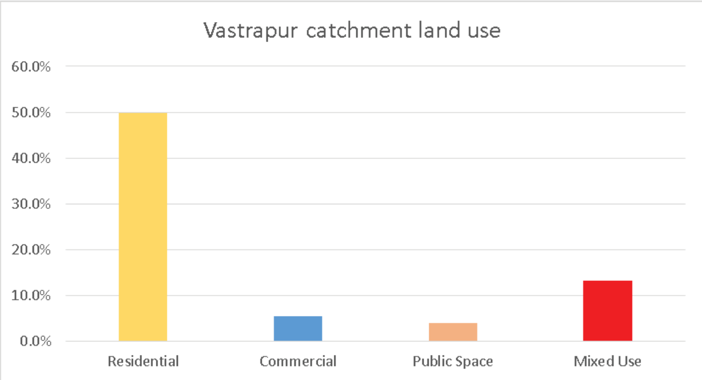


Figure 20: Vastrapur catchment land use

Figure 19: Vastrapur Lake, - Top (2000), Bottom (2013)
Source 8: Google Earth Imagery

Vastrapur lake lies amidst of dense residential areas, commercial areas with shopping malls and seasonal markets, and used regularly by local and other inhabitants of the city. Over exploitation of lake by people generates wastes, adding to polluted storm water draining to lake. The water quality samples taken from Vastrapur Lake showed high amount of coliforms, high amount of suspended solids and low dissolved oxygen. Storm waters contain organic materials from wastewater and sewage and that are decomposed by microorganisms which use oxygen in the process, thus DO levels should be above 8.5 mg/l in order to support aquatic life in lake waters (Franson, 1995). Large commercial complexes result into higher impervious surfaces and increase surface runoff during rainfall, causing water logging in the catchment and overflow of sewers which is then diverted to Vastrapur lake. The urban authority and the municipality see Vastrapur lake as a potential rain water harvesting pond and ignore the environmental impacts in lieu of pragmatic solutions.
Vastrapur Lake also has percolating wells which recharge groundwater and is vulnerable to pollutants from the storm water inflows and direct contamination through over exploitation. The lake also supports various flora and fauna around its precincts, hence proper maintenance and monitoring will ensure the healthy environmental balance.

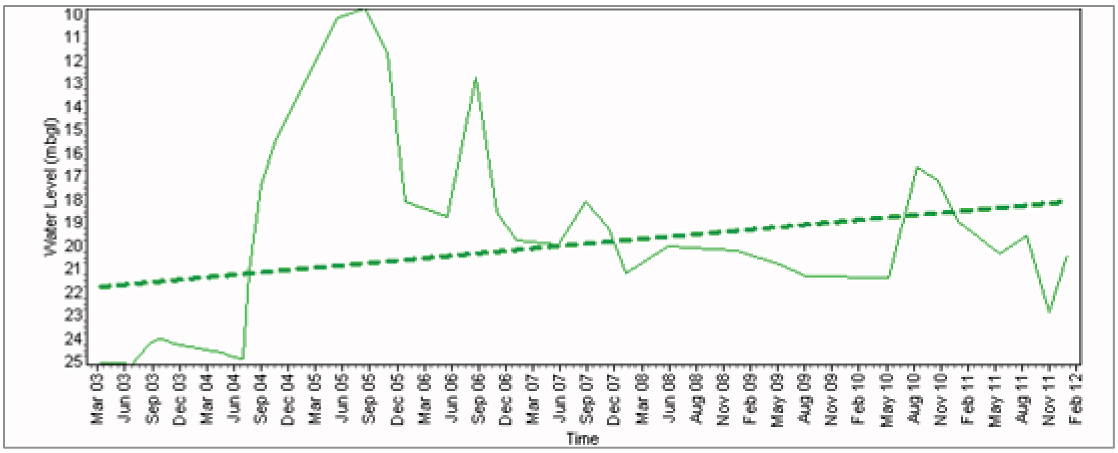


Figure 21: Vastrapur Lake recharge well hydrograph, Aquifer 9 - 38 m depth; rising trend 0.414 Mt/yr.
Source 9: Central Ground Water Control Board, Ahmedabad

4.4. Bodakdev

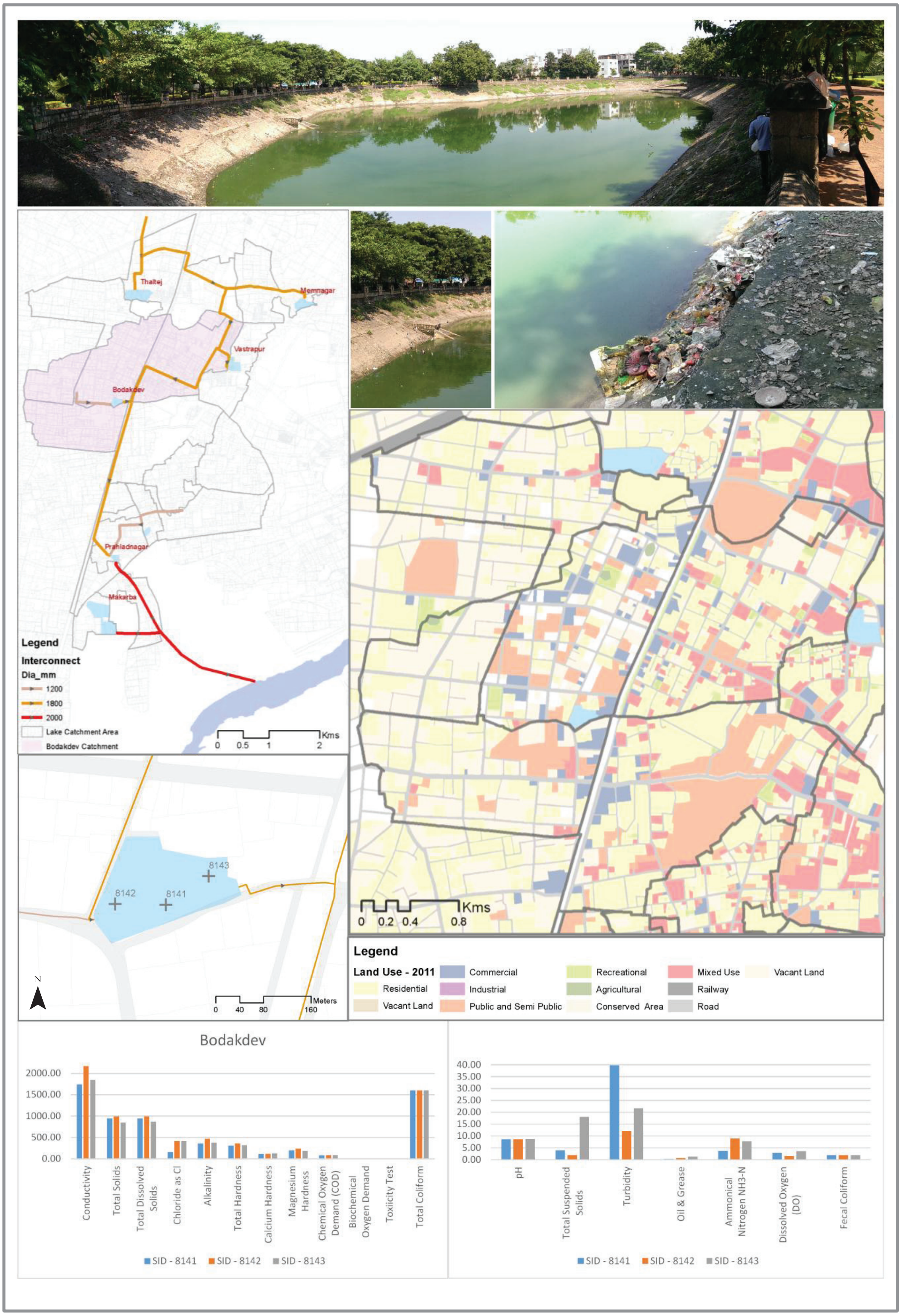


Figure 22: Characteristics of Bodakdev Lake

Bodakdev lake has a catchment area of 1626.18 acres forming 27.57 % of total catchment. The catchment of Bodakdev has 27.27% of vacant land, and 11.83 % of public spaces Bodakdev catchment was predominantly agricultural, and located on the western fringe of the city. Proximity to national highway along the catchment prompted commercial and low rise and dispersed residential development in through the catchment. Bodakdev catchment consisted of many small village ponds which were considered seasonal rain puddles, and the region is notified as water scarce region. Lakes were developed as a part of lake development initiatives.

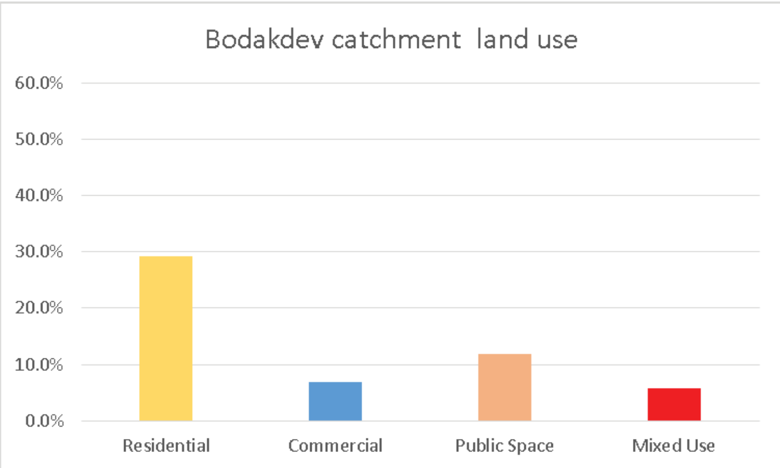


Figure 24: Bodakdev catchment land use

Figure 23: Bodakdev Lake - Top (2003), Bottom (2013)
Source 10: Google Earth Imagery

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The water quality assessments show high conductivity in all measure samples, conductivity is a directly related to the total dissolved salt content of the water. Aquatic organisms require a relatively constant concentration of the major dissolved ions in the water; major fluctuations may limit survival, growth. Also conductivity is temperature sensitive and increases with increasing temperature.(Hounslow, 1995)

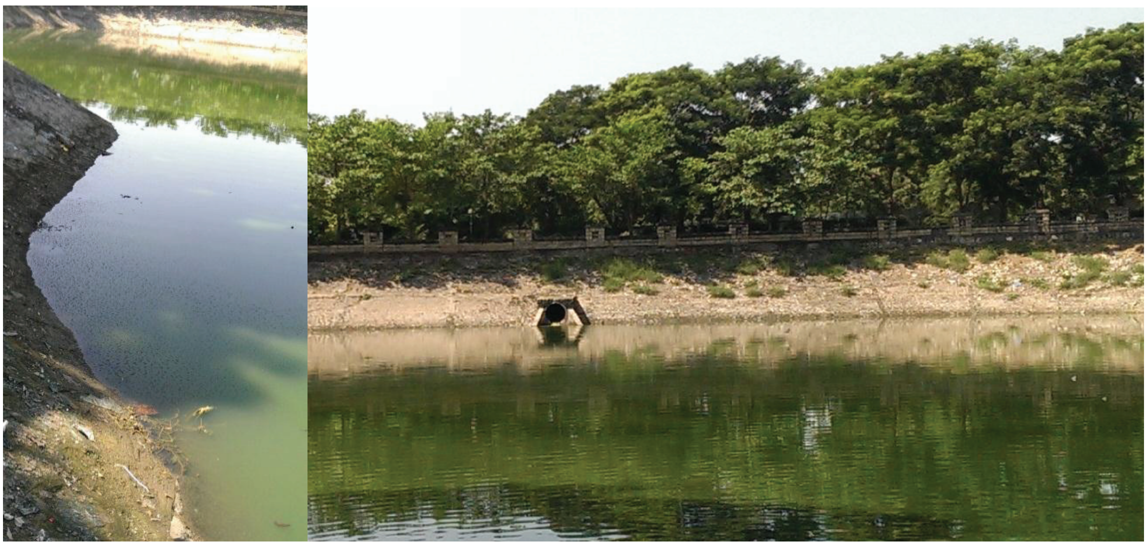

Photo 3: Bodakdev Lake shore

4.5. Prahladnagar

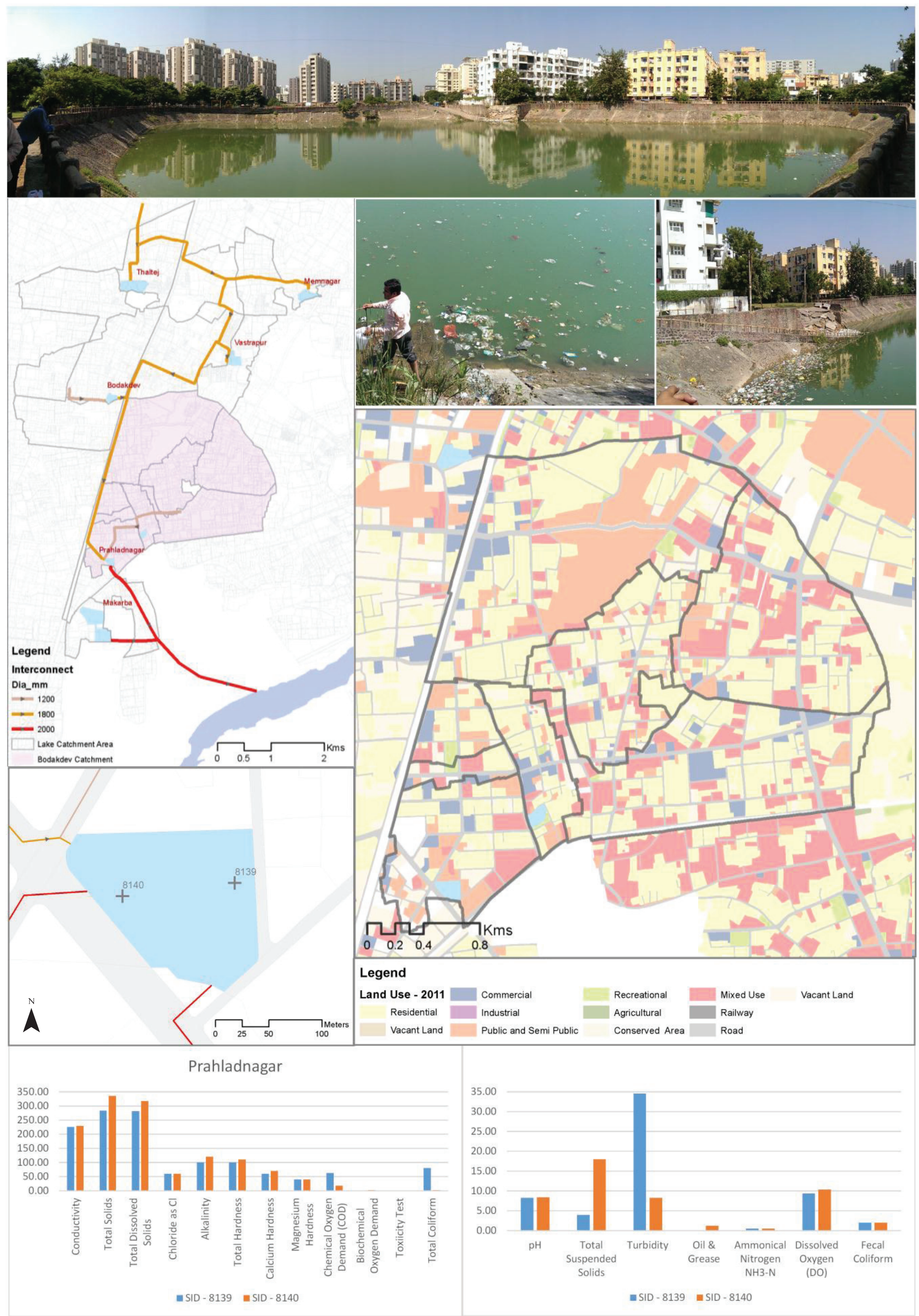

Figure 25: Characteristics of Prahladnagar Lake

Prahladnagar lake has a catchment area of 1983.80 acres forming 34.79 % of total catchment. Prahladnagar catchment chiefly comprises of high rise residential, mixed and institutional land use, and being close to the industrial areas nearby Prahladnagar lake is vulnerable to effluents released from industrial estates. The catchment is located on the southern fringe of Ahmedabad, and as the overall gradient of the city is from north to south, the catchment also receives the cumulative runoff from higher and surrounding catchments.

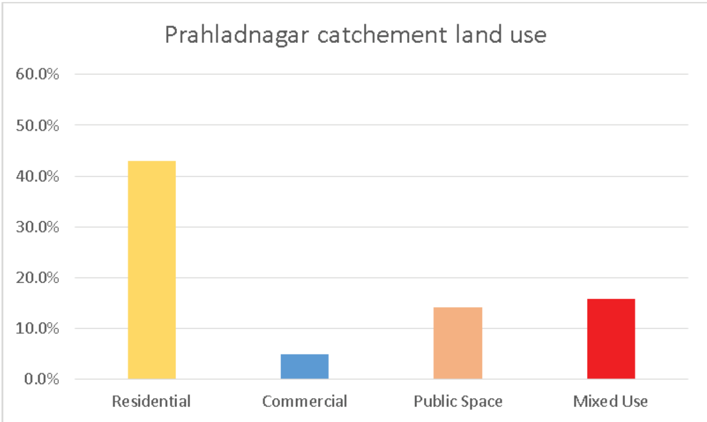

Figure 27: Prahladnagar catchment land use

Figure 27: Prahladnagar Lake - Top (2003), Bottom (2013)
Source 11: Google Earth Imagery

Water quality measurements carried out in Prahladnagar show high amount of turbidity, total dissolved solids and suspended solids. The storm water network distribution in this catchment is unorganised and dispersed, and also illegal connections to storm water networks for sewage discharge has led to high pollutant loadings at the receiving waters. The lakes developed in Ahmedabad follow Vastrapur lake model; to reclaim partial land from lake area and develop as a public garden. The inhabitants of the area visit the garden and due to improper maintenance, of garden and lake periphery, people throw plastic wastes and food wastes which are difficult to clean from the lake and further transported downstream via interconnected link.

Photo 4: Solid waste pollution in Prahladnagar Lake

4.6. Makarbar-Sarkhej

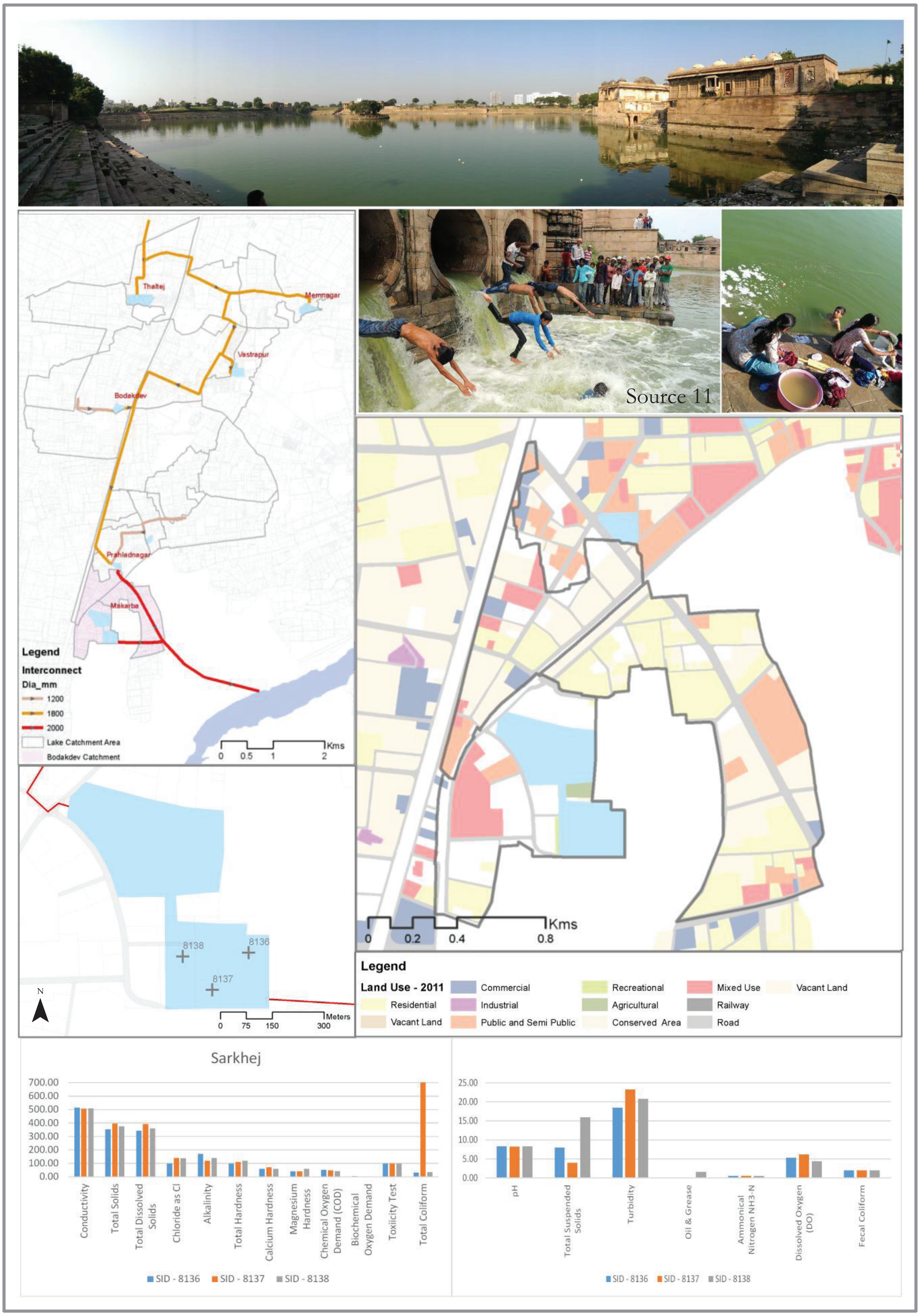

Figure 28: Characteristics of Makarba-Sarkhej Lake

Source 12: Getty Images published on www.bbc.com under 'FUTURE' – *"Just add water", 19 July 2013*

Sarkhej-Makarba lake has a catchment area of 432.15 acres forming 5.92 % of total catchment. The Sarkhej lake is a part of a palace complex designed with a mosque during Islamic rule between 1451 and 1458. The Sarkhej lake holds an historical importance and conserved by the archaeological survey of India, traditionally water bodies used for rainwater conservation was known as '*tankas*' (Desai, Desai, Mani, Bafna, & Vamadevan, 1990). The rulers in sultanate period had a good understanding of the sub-surface topography of aquifer flow in the region, as water is central component in Islamic architecture.

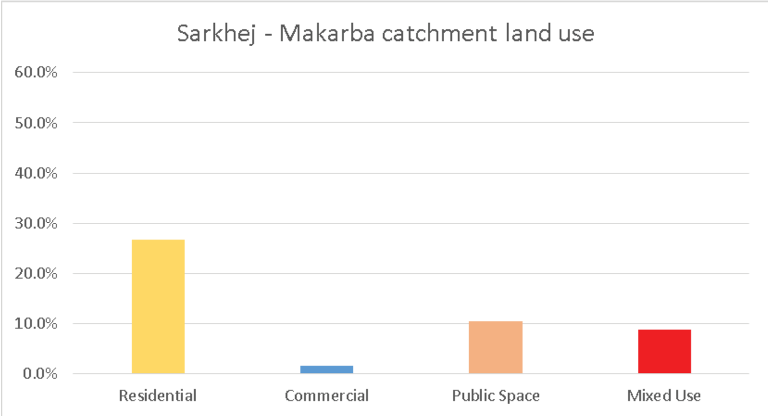

Figure 30: Sarkhej - Makarba catchment land use

Figure 29: Sarkhej-Makarba Lake - Top (2000), Bottom (2013)
Source 13: Google Earth Imagery

The lake waters of Sarkhej-Makarba due to its religious importance and community dependence is used extensively for daily bathing as well as other chores. Water quality measurements done at Sarkhej lake, show high levels of coliform, suspended solids and low dissolved oxygen as per (CPCB, 2007-2008) water quality use for recreational purpose. Communities living in the area had limited or no access to municipal water supply so they had to rely on Sarkhej lake as central water resource.

The hydrological system of Sarkhej lake had several inflow gates and inlets for natural drains during rainy season and diverted overflow waters to river as a part of the original design. The interlinking of the lakes project accommodated Sarkhej lake in its design adding waters from the upstream lakes before they discharge water to Sabarmati river.

Photo 7: Inlet for natural drains

Photo 7: Outlet gate to river

Photo 7: Intlet gate from adjoining water body - '*tanka*'

4.7. Summary of Lakes

Urban development particularly housing and infrastructure greatly affect the urban lake systems, the natural drains routes based on topography is ignored which allowed storm water to percolate and recharge the ground waters. Instead the water is collected from impervious surfaces like roads, building premises and slum areas which carry high pollutant loadings affecting the lake ecosystems.

The urban development authority approach is that the smallest spell of monsoon should divert the surface waters directly to lakes via storm channels to avoid water logging, breeding time for mosquitoes and insects to mitigate health hazards (AUDA, 2004; Bal et al., 2011).

The lake systems compliment the open space consideration of urban development in Ahmedabad. The open spaces allocation within AUDA area is 3.56% and 0.89% for open and recreational spaces respectively. The inclusion of urban lakes as public open spaces adds to the already low open space provision according to national standards, Urban Development Plans Formulation Guidelines. (MOUAF, 1996)
There are various efforts done by urban development authority to develop lakes but at the same time ignorance in understanding, maintaining and monitoring of the lake ecosystems was observed. Water quality measurements done at 6 lakes; Memnagar, Vastrapur, Thaltej, Bodakdev, Prahladnagar and Sarkhej were analysed and lakes were studied independently in order to know the level, extent and possible sources of pollutant contamination.

pH
The pHs of lakes in the interlinked project, varied between 8.26 to 8.75, and were noted to be alkaline due to various salts that are deposited through wastewater. The daily fluctuations in the lake pH are dependent on the temperature of the lake. Low alkaline lake waters are likely to fluctuate more than high alkaline water during 24 hour period (Wurts, 2002).

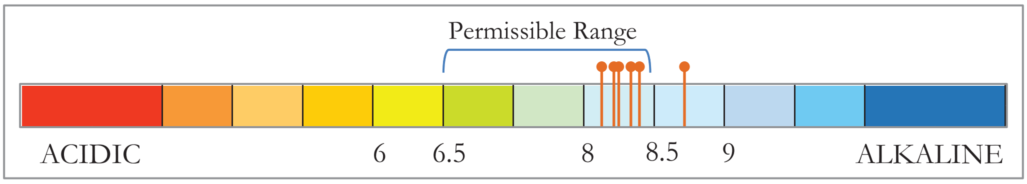

Figure 31: pH Scale of Lakes

Drastic fluctuations in the pH levels and alkalinity can put microorganisms and other phytoplankton's under stress and can affect the overall lake productivity.

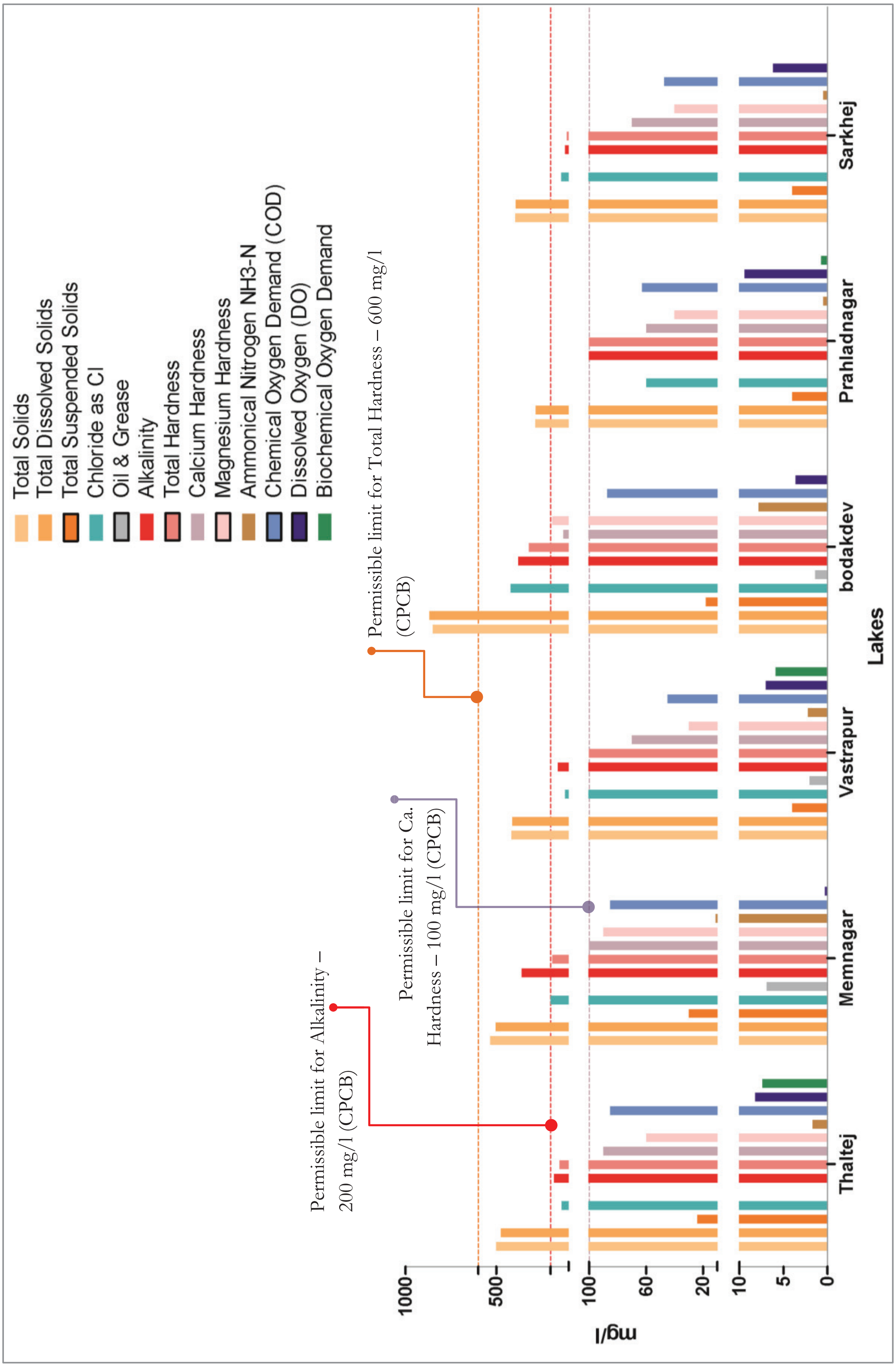

Figure 32: Comparison of Lakes
Note 1: The split bar chart was prepared in GraphPad Prism 5 due to large bandwidth of data.

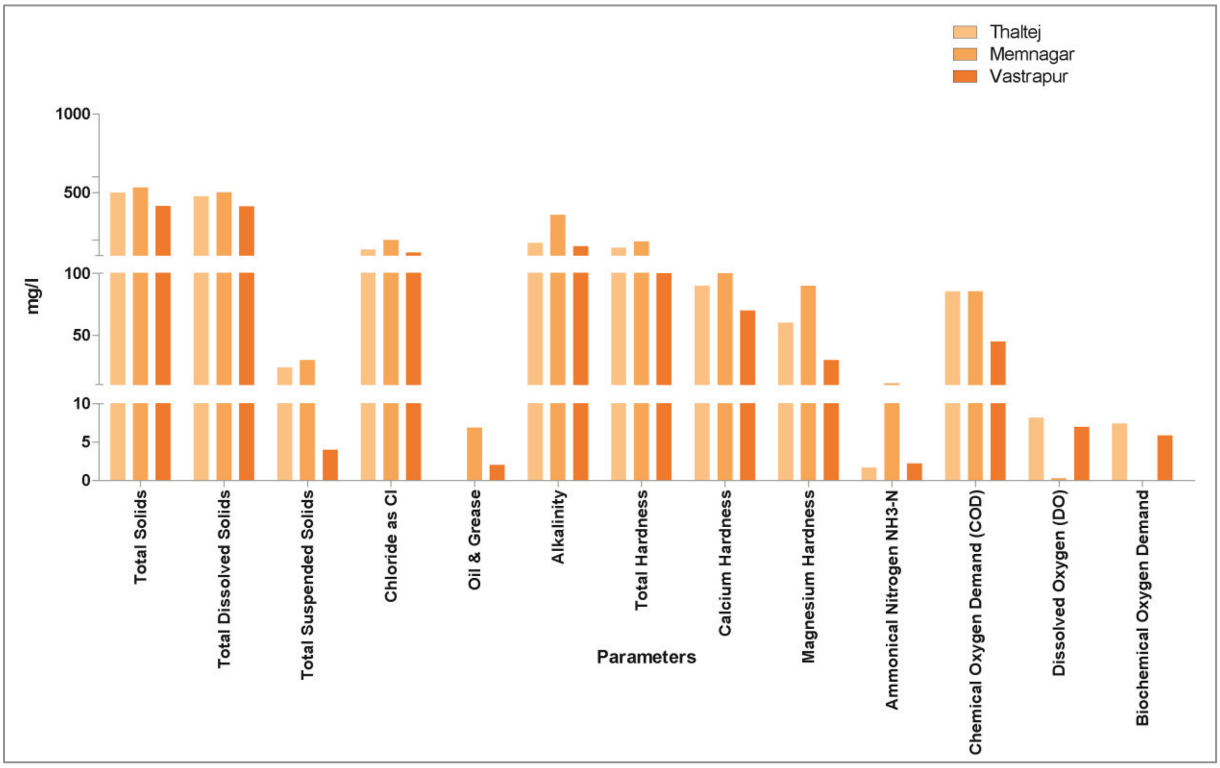

Figure 33: Cluster 1 Lakes - Thaltej, Memnagar, Vastrapur

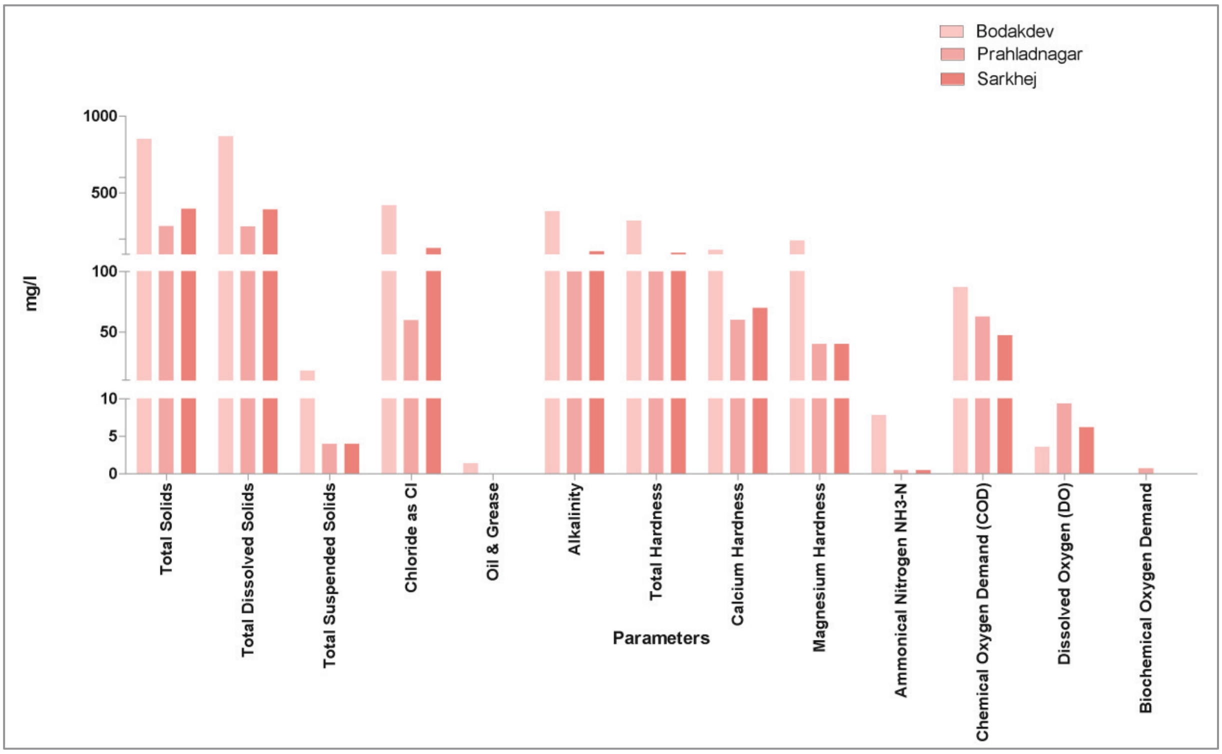

Figure 34: Cluster 2 Lakes - Bodakdev, Prahladnagar, Sarkhej

Alkalinity and Hardness levels

Alkalinity and hardness both are important components of water quality, alkalinity measures the base present in the water and hardness represents the overall concentration of salts like calcium, magnesium, etc. All the lakes measured were found highly alkaline and showed direct relation to hardness as shown in Figure 35. Alkalinity levels were found between the range 120 – 380 mg/l. The desirable limit for alkalinity is 200 mg/l (CPCB, 2007-2008), as lower alkalinity levels affect the daily fluctuations on pH have indirect effects on growth and sustenance of aquatic organisms as certain nutrients are unavailable to aquatic plant life. Calcium and magnesium are the most common sources of water hardness and are essential in the process of biological processes of aquatic organisms. Although aquatic organisms can tolerate broad range of

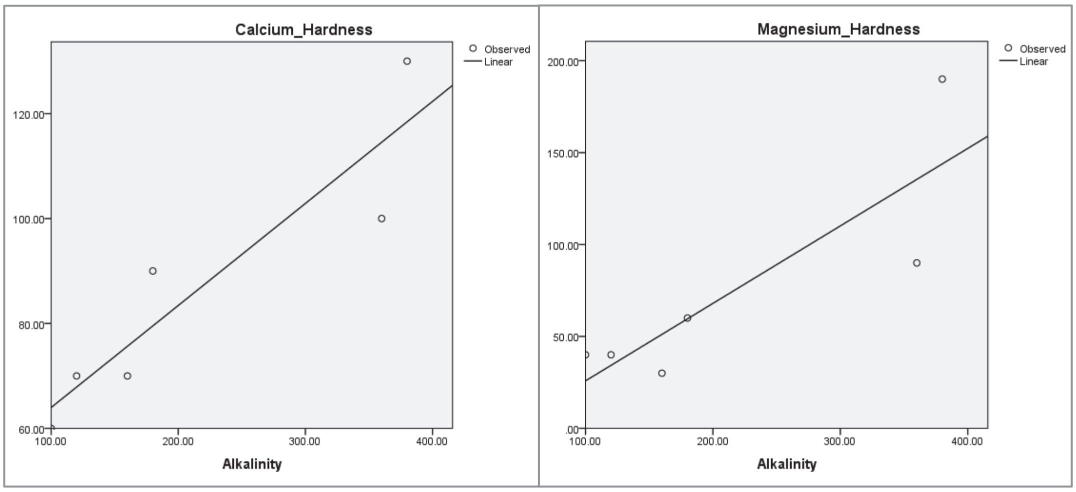

Figure 35: Alkalinity and Hardness

hardness concentrations (Wurts, 2002), salinisation of lakes is becoming a widespread water quality issue (Meybeck, Chapman, & Helmer, 1990). Especially in urban areas where wastewater contains high salt contents from residential areas, also lakes used for washing and bathing purpose can subsequently increase the salt contents of the lake.

Conductivity levels

Conductivity is significantly dependent on the amount of dissolved salt present in the lake. Conductivity is attributed to high salinity levels, mineral content and the presence of major cations (Na, Ca, Mg) and major anions(Cl and SO_4) in lake waters (Kazi et al., 2009). The Lakes in cluster 1 and 2 as shown in Figure 33 and Figure 34, namely Bodakdev and Memnagar recorded high Chlorine content and salts which consequently show relatively higher conductivity levels as shown in Figure 36.

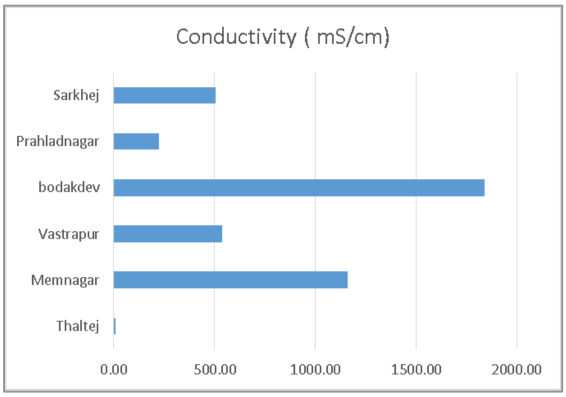

Figure 36: Conductivity levels in lakes.

DO levels

Dissolved oxygen in the lakes is essential for the sustenance of aquatic organisms in lake and the overall health of lakes. Dissolved oxygen measured in the lake Memnagar and Bodakdev were found to be 0.30 and 3.60 mg/l and for all lakes ranged between 0.30 to 9.40 mg/l. Low DO levels are due to high levels of sewage and solid waste present in the lakes which prevent air-water interaction leading to decomposition of organic matter (Samal et al., 2011). The desired level of DO for the a healthy lake as discussed in **Error!**

eference source not found. is prescribed to be 5mg/l or above if it is used for recreational and bathing purpose and 4mg/l or above for growth of lake ecosystem (CPCB, 2007-2008).

BOD and COD levels

Larger values of COD and BOD are attributed to presence of variety of nutrient present and are favourable for microbial activity. COD helps to estimate the carbonaceous factor of the organic matter essential for aqueous ecosystem in lakes (Samal et al., 2011). COD values measured in lakes range between 44.92 mg/l to 87.29 mg/l, amongst those, Vastrapur (44.92 mg/l) in cluster 1 and Prahladnagar (62.89mg/l) and Sarkhej (47.17 mg/l) in cluster 2 recorded relatively low COD values than desired limit of 250 mg/l. BOD values measured in lakes show some unexpected results and thus could not be summarised with insufficient information and limited number of samples.

Turbidity levels

Turbidity measures the clarity and ability of light to penetrate in lakes, essential for survival of microorganisms. Turbidity is measured in Nephelometric Turbidity Units (NTU). Lakes can have clear water state with aquatic vegetation or a turbid state of high algal biomass. The particulate matter that suspend on the surface include, organic and inorganic matter which have various natural and man-made sources. High levels of turbidity can be used as a surrogate measure to high amount of suspended solids in the lake (Bilotta & Brazier, 2008). Turbidity measured in the lakes range from 2.5 to 40 NTU out of which some lakes show unexpected results with respect to the visual observation in lakes.

Total Coliforms and Faecal coliforms levels

The measure levels of total coliforms recorded extremely high 1600 MPN/100ml and faecal counts more than 2 MPN/100ml exceeding (WHO, CPCB) standards for outdoor and recreational use. The high coliform levels signify organic contamination by sewage and waste water discharge in lakes.

Lakes in the present study showed varied degree of pollution from multiple sources of pollution from anthropogenic activities in the subcatchment. With all the lakes interlinked, there is a constant inflow and outflow of nutrients and toxic substances within the lakes, which restrict the natural cycle of the lake purification and disrupt the balance of lake ecosystem. During precipitation constant exchange of lake waters within lake and inflow from storm channels greatly affect the residence time of the lakes waters. Further it is also important to know the decay processes of various nutrients, organic wastes and their relationship knowing the residence time distribution of all inflow events in lake (Walker, 1998).

Due to the limited number of samples per lake, analysis on dependence and relationship between the parameters with correlation and regression was considered beyond the scope of the thesis.

5. SIMULATION ANALYSIS AND RESULTS

Understanding the urban hydrological cycle is primary to represent, model and manage the transport of water in the urban environment. The urban hydrological cycle consists of water supply, wastewater, and stormwater runoff systems. Lakes and reservoirs are a part of hydrological cycle and are closely entwined with urban hydrological cycle. This part of the thesis is aimed at modelling the relationship of urban storm water runoff from catchment to interlinked lakes in terms of water quality. In order to achieve that, it required a detailed study of sub components of the urban storm water runoff system (Newell, Cameron, Lant, Von Meunch, & Olsson, 1999).
There are various processes like chemical, physiochemical, biological, ecological and physical processes which affect the transport and conveyance of pollutant concentrations in urban catchment. Modelling these processes require specialised packages developed earlier in 1970s by Environment Protection Agency (EPA-USA). Since then number of models has been developed. These models include very simple conceptual model to complex hydraulic models (Zoppou, 2001).

5.1. The Model

The model EPA-SWMM 5.0 is used in this section which simulates both water quality and quantity of urban storm water runoff and combined sewer overflow. This is both continuous and single event model. Surface runoff is based on rainfall intensities, antecedent moisture conditions, land use and topography. Primary purpose of using this model is to identify the inflow of pollutant loadings from the catchment source from various land uses (EPA, 2010). EPA-SWMM is a deterministic model, which models water quality as direct function of hydrologic and hydraulic phenomena. Deterministic models include pollutant build-up and washoff with mobilization and transport mechanism depending on factors such as time, rainfall intensity, duration and the depth of runoff (Fletcher et al., 2013). The accumulation of pollutant loadings from the catchment via storm water inflow in the lakes will be evaluated, considering TSS pollutant. Here lakes are assumed as storage unit, which act as detention ponds since the storm water network from each catchment discharge water to its respective lakes which are interlinked.

5.2. Modelling Methodology

There are variety of approaches to model sub-components of urban storm water runoff system depending on appropriate spatial and temporal scales; unit block, cluster, subcatchment and catchment. In urban areas with the provision of surface water infrastructure the natural boundaries of catchment have blurred. The typical town planning unit, 'Town planning scheme' was used as subcatchment, and a group of sub-catchments through which storm water is discharged via storm water channels to the same lakes were considered single catchment. There are 6 catchments considered within the interlinked lakes consisting 21 TP Schemes as stated Figure 12, pg.29.
Modelling methodology followed here is in accordance with the input data required by the EPA-SWMM model and is divided into in three segments; hydrology, hydraulics and quality parameters.

5.2.1. Hydrology Parameters

The primary components in SWMM for defining hydrological parameters are subcatchment and rain gages.

5.2.1.1. Subcatchment

Total Imperviousness

Total imperviousness is a common predictor of hydrological characteristics of a catchment. The impervious areas were calculated that represent the proportion of impervious surface runoff that drain surface runoff in storm water drainage system. In calculating impervious surfaces there are two basic approaches (Sahoo & Sreeja, 2013), total impervious area (TIA) which is the area which prevents infiltration into the soil and effective impervious area (EIA) is the area connected directly to storm water network. However calculating EIA requires high resolution satellite imagery and field measurements for accuracy and for large catchments it is difficult to estimate hence TIA is most commonly used measure to model urban runoff in a model.

The method employed to calculate TIA was based on land use data of Ahmedabad 2011, in which residential, commercial, mixed use and road were considered as impervious surface whereas land use classes like recreational areas, open spaces, parks and vacant land were taken for pervious surfaces.

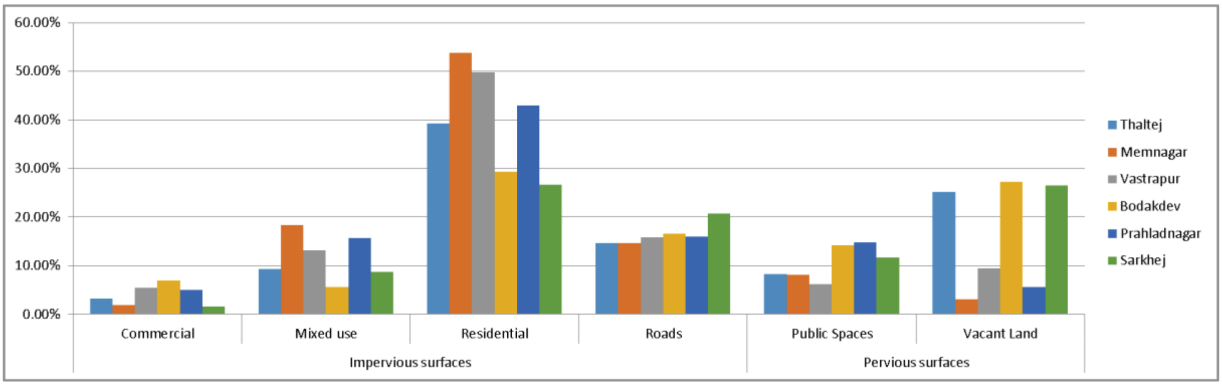

Figure 37: Land use classification of impervious and pervious surfaces

As shown in Figure 37, residential areas and roads chiefly account for impervious surfaces in the lake catchments. Moreover all catchments were found to be above 50.0% impervious surfaces and relatively low pervious surfaces. However there is an overestimation of impervious surfaces, calculated from land use data (Brabec, 2009), since at parcel level some pervious surfaces might get included as pervious surfaces. Lakes are strongly linked to these catchments as transport of pollutants has increased due to direct connectivity through storm water network. Thus predicting pollutant concentration and loads from catchment through model help us understand catchment-lake relationship (Soranno, Hubler, Carpenter, & Lathrop, 1996).

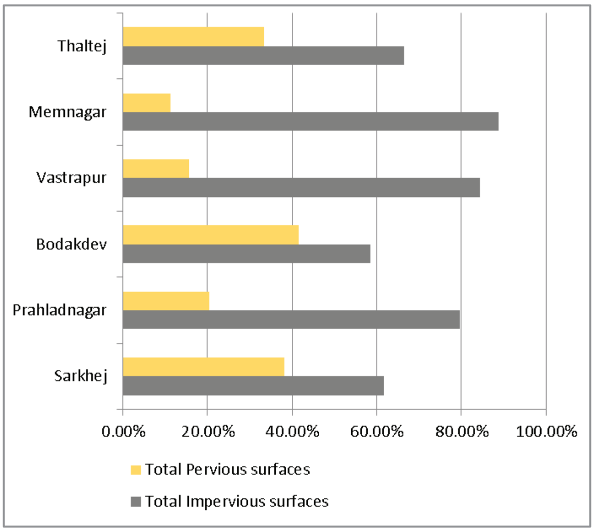

Figure 38: Total Impervious/pervious surfaces

Area and Width

The dimension of catchment suggests that shape factor can be used to estimate width by correlating the storm water runoff length within the catchment. Table 7 shows the calculated width of catchment. "As a rule of thumb the width can be approximated to be twice the length of storm waterway" (Guo & Urbonas, 2009)

Catchment	Hectares (Ha)	Width (Mt)
Thaltej	453.59	2000
Memnagar	134.60	1500
Vastrapur	115.27	1200
Bodakdev	658.09	1800
Prahladnagar	802.81	2000
Sarkhej	174.89	800
Total Area	**2339.26**	-

Table 7: Area and width of catchments

Slope

The slope of the city has downward slope from north to south and is relatively flat, thus same slope values were applied to all catchments which is 0.13 % (1.750) approx. (AUDA, 1997).

Infiltration Model

Infiltration is a process of rainfall penetrating in pervious surfaces of catchment. In SWMM model there are three methods namely; Horton's Equation, Green-Ampt. Method and Curve Number Method. Horton's equation were used, which is based on empirical observations showing that infiltration decreases exponentially from maximum to minimum rate over long rainfall event (EPA, 2010). According to Mishra, Tyagi, and Singh (2003) comparison done with several infiltration models for various soil types at varying moisture content found Hortan infiltration model accurate in steady state. The input parameters were assumed as system defaults (Max. Infiltration Rate - 3 mm/hr. and Min. Infiltration Rate – 0.5 mm/hr.), due to absence of the soil characteristics data required to calculate the values of minimum and maximum infiltration rates. The Horton infiltration equation states that:

$$f = f_0 + (f_0 - f_c)e^{-kt}$$

"where f_c is the steady state value of f, f_0 is the value of f at $t = 0$, and k is the infiltration decay factor. The Horton equation is derived from the assumption that infiltration capacity of soil is directly proportional to the rate of infiltration during precipitation and is only applicable when the effective rainfall intensity is greater than f_c." (Mishra et al., 2003).

Manning's N for impervious and pervious surfaces

Manning's N represent the roughness co-efficient that describes the resistance to runoff in channels and in subcatchment. Table 8 shows the suggested Manning's 'n' coefficients for various land use in Indian cities. The catchments are directly connected to storm water drainage thus manning's coefficients for overland storm water flow was considered 0.75 and manning's coefficient for conduit storm water flow was considered 0.013 for concrete pipe. The manning's coefficient of pervious surfaces was considered 0.05, for earth partially obstructed by debris and weed.

Coefficients of Imperviousness for various land uses in Indian cities	
Residential	0.60 to 0.75
Roads, paved surface of footpaths	1.00
Commercial	0.70 to 0.90
Paved markets	1.00
Unpaved markets	0.40 to 0.70
Mixed type markets	0.40 to 0.90
Mixed Development	0.60 to 0.90
Industrial	0.60 to 0.90
Institutional	0.60 to 0.90
Large establishments	0.60 to 0.90

Table 8: Co-efficient of imperviousness adopted for various land uses for Indian cities.
Source 14: DPR Manual – Storm water Drainage (MOUD, 2012)

Depression storage for impervious and pervious surfaces

Depth of depression storage for pervious and impervious surfaces was considered as 0.05 inches respectively and the percentage of impervious areas with no depression storage was considered 25 % as system default (EPA, 2010).

Subarea Routing

SWMM offers three choices of subarea routing; impervious – runoff from pervious area flows to impervious area, pervious – runoff from impervious area flows to pervious area and outlet – runoff from both areas flow directly to outlet (EPA, 2010). The runoff in urban catchments both from pervious and impervious areas flow directly to the inlet of storm water runoff thus outlet was selected for subarea routing and the percentage of routing was considered 100 % as system default.

Land Use

The three prominent land uses assigned to each of the catchments were residential, commercial and mixed use and the initial build-up of pollutants was considered 'none' as system default.

Table 9 shows the summary of hydrology parameter inputs in SWMM.

Hydrological parameters for subcatchments

No.	Catchment	Thaltej	Memnagar	Vastrapur	Bodakdev	Prahladnaga	Sarkhej	Remarks/Source
1	Rain Gauge (Intensity - mm/hr)	AHD_RF	AHD_RF	AHD_RF	AHD_RF	AHD_RF	AHD_RF	Rainfall data - 2013 Ahmedabad (IMD, 2013).
2	Outlet	Thaltej lake	Memnagar lake	Vastrapur lake	Bodakdev lake	Prahladnagar lake	Sarkhej lake	Storm water discharge to lakes.
3	Area (Ha)	453.59	134.60	115.27	658.09	802.81	174.89	Area of the catchment.
4	Width (Mt)	2000	1500	1200	1800	2000	800	Width of the catchment (Guo & Urbonas, 2009)
5	% Slope	0.13	0.13	0.13	0.13	0.13	0.13	Average slope - North to South
6	Percent Impervious	66.51%	88.78%	84.37%	58.47%	79.63%	61.75%	Calculated from land use (Sahoo & Sreeja, 2013), (Soranno et al., 1996).
7	N- Impervious	0.75	0.75	0.75	0.75	0.75	0.75	Coefficients for pervious/impervious surfaces (MOUD, 2012).
8	N- Pervious	0.05	0.05	0.05	0.05	0.05	0.05	
9	Dstore-Imperv (inches)	0.05	0.05	0.05	0.05	0.05	0.05	Assumed System Default (EPA, 2010).
10	Dstore-Perv (inches)	0.05	0.05	0.05	0.05	0.05	0.05	
11	Zero-Imperv	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	
12	Subarea Routing	OUTLET	OUTLET	OUTLET	OUTLET	OUTLET	OUTLET	-
13	Percent Routed	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	-
14	Infiltration	HORTON	HORTON	HORTON	HORTON	HORTON	HORTON	(Mishra et al., 2003).
15	Groundwater	-	-	-	-	-	-	-
16	Snow Pack	-	-	-	-	-	-	-
17	Land Uses	3	3	3	3	3	3	Residential, Commercial, Mixed.
	Residential	39.23%	53.77%	49.85%	29.29%	42.92%	26.66%	Percentage of Total Catchment Area.
	Commercial	3.23%	1.99%	5.51%	6.88%	4.96%	1.61%	
	Mixed	9.35%	18.41%	13.20%	5.67%	15.70%	8.70%	
18	Initial Buildup	NONE	NONE	NONE	NONE	NONE	NONE	Initial pollutant build-up in catchment.
19	Curb Length	0	0	0	0	0	0	-

Table 9: Hydrological parameters for subcatchments

5.2.1.2. Rain Gages

Rainfall measurement and data is crucial for understanding many applications in urban hydrology. Rainfall data for the year 2013 as shown in Figure 39 was used as rainfall input in the model. The modelling of rainfall series can be modelled with longer and shorter time steps thus to avoid the overestimation of antecedent dry days the rainfall even between (June – October, 2013).

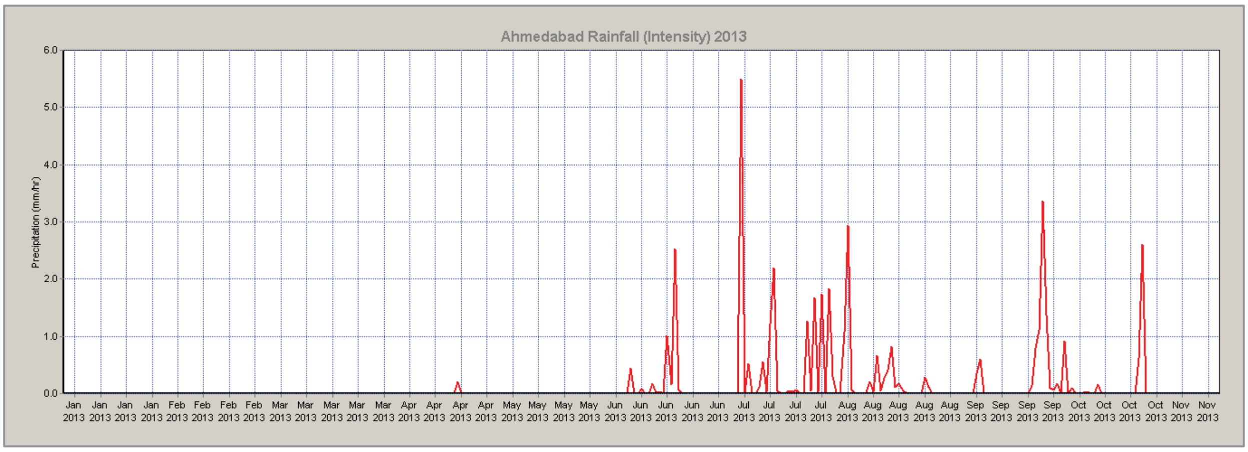

Figure 39: Rainfall Intensity - Ahmedabad 2013 (IMD, 2013)

The summary of precipitation statistics as shown in Table 10 was calculated based on selected term of annual rainfall event for 153 days with the time interval of 24 hrs. The time series in rain gage module was given in intensity and the antecedent dry days were calculated as a ratio of total number of days to the number of events. The maximum value was noted to be 131 mm for 5, July 2013 with the return period of 6 months. It can be seen from **Error! Reference source not found.** that the frequency of events with lower rainfall intensities are higher for the year 2013.

The presence of impervious surfaces in the catchment influences the rainfall patterns by reducing the infiltration, decrease in the annual precipitation and increasing the peak runoff flows and eventually decreasing the recession time.

Precipitation Statistics summary (mm/hr)	
Event Period	Daily
Event Statistic	Total (mm)
Event Threshold	Precipitation > 0.0000 (mm/hr)
Period of Record	06/01/2013 to 10/31/2013
Number of Events	63
Event Frequency*	0.412
Minimum Value	0.200
Maximum Value	131.700
Mean Value	15.771
Std. Deviation	24.219
Skewness Coeff	2.524
Total Days	153
Antecedent Dry days - Total days/Number of Events	3 approx.
*Fraction of all days containing an event	

Table 10: Summary of Precipitation Statistics

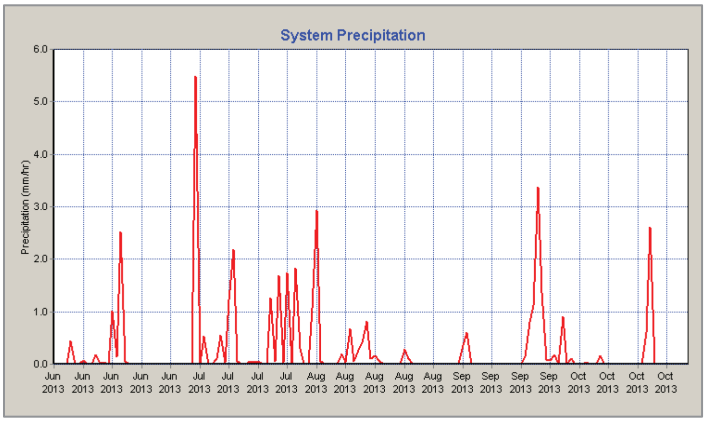

Figure 41: System precipitation

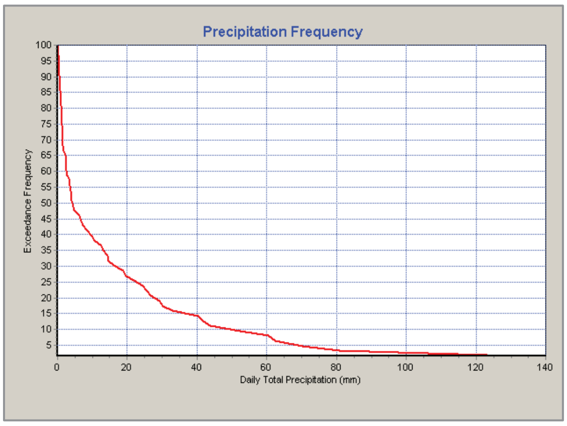

Figure 41: Precipitation Frequency

5.2.2. Hydraulics

The nature and spatial network of storm water drainage plays a crucial role in determining the hydrological characteristics of catchment. While considering that the catchments are connected to lakes via storm water network it is essential to justify the routing method. SWMM offers steady flow, kinematic wave and dynamic wave. Steady state represents the simplest type assuming each computational time step flow is uniform and steady with no delay or change in shape. Whereas kinematic wave routing prevents backwater effect and dynamic flow considers the acceleration and storage under backwater profiles. The rule of thumb is to select shorter time step for dynamic wave routing (1-60 sec.) and longer time step for kinematic wave routing (1-300 sec) (EPA, 2010). Kinematic wave routing and the SWMM suggested time step was considered for modelling storm water conduit flow from subcatchment to lakes.
The primary components in SWMM in defining hydraulic parameters are Nodes and Links.

5.2.2.1. Nodes

Storage Units

It is important to mention here the assumption of lakes as storage units, as the hydrological function of these lakes is to store excess storm water from urban catchments; these lakes are treated as detention ponds. Thus in orders to model the inflow stormwater quality and peak inflow, the lakes here are considered as storage units with no pollutant treatment.

Storage Unit	Thaltej	Memnagar	Vastrapur	Bodakdev	Prahladnagar	Sarkhej
Inflows	NO	NO	NO	NO	NO	NO
Treatment	NO	NO	NO	NO	NO	NO
Invert Elevation (Mt)	46.600	46.360	45.989	44.657	38.91	37.43
Max. Depth (Mt)	4	3	4	1	3	2.5
Initial Depth	0	0	0	0	0	0
Ponded Area (Sq. Mt)	134241	61040	52811	8650	22803	110379
Evaporation Factor	1	1	1	1	1	1
Inflitration	NO	NO	NO	NO	NO	NO
Storage Curve	FUNCTIONAL	FUNCTIONAL	FUNCTIONAL	FUNCTIONAL	FUNCTIONAL	FUNCTIONAL

Table 11: Lakes - Storage unit properties

The above Table 11 shows the storage unit properties derived from the interlinking of lake design of AUDA, due to no treatment done at present it is considered none. The lakes in the design serve as interlinking nodes, and in kinematic wave routing ponded water are simply stored excess volumes (EPA, 2010), thus pond area of lakes were used in the model.

Junctions

The junctions are drainage system nodes where links join together within the catchment to divert storm water to the storage units (lakes). External inflows can enter the system at junctions during flooding in the catchment.

Outfall

Outfalls are terminal nodes, which define the boundary conditions downstream, through which the system discharges storm water to receiving waters which Sabarmati in this case. The invert elevation level of the outfall was considered as 35.535 Mt with no tidal gate due to insufficient data.

5.2.2.2. Links

Links are the transport components of a storm water drainage system represented by conduits in SWMM. Depending on the shape and cross sectional area the parameters of conduits are defined according the data in the interlinking of lake design. The parameters are explained in detail in Appendix C. Figure 42 shows the layout of conduits and subcatchments in the model connected through underground piped network connection. The storm water collected from the subcatchment is discharged in the lakes through

storm water drainage and the water in lakes is transported further downstream with an outfall in the Sabarmati River. The inflow from catchment to stormwater drainage in SWMM is described by Manning's equation: [$Q = W/n * (d - d_p)^{5/3} \cdot s^{1/2}$] (EPA, 2010)
where Q = subcatchment outflow, W = subcatchment width, n = Manning's roughness co-efficient, d = water depth, d_p = depth of depression storage and s = slope. The width and slope are considered uniform within the catchment. Manning's coefficients were used as same through the network (0.013) for concrete circular section piped network prescribed by (MOUD, 2012).
The interlinking was done in phases and for modelling purpose, the catchments were grouped based on their interconnections; cluster 1 included Thaltej Lake - subcatchment, Memnagar Lake- subcatchment and Vastrapur Lake-subcatchment and cluster 2 included Bodakdev Lake- subcatchment, Prahladnagar Lake- subcatchment and Sarkhej Lake-subcatchment.

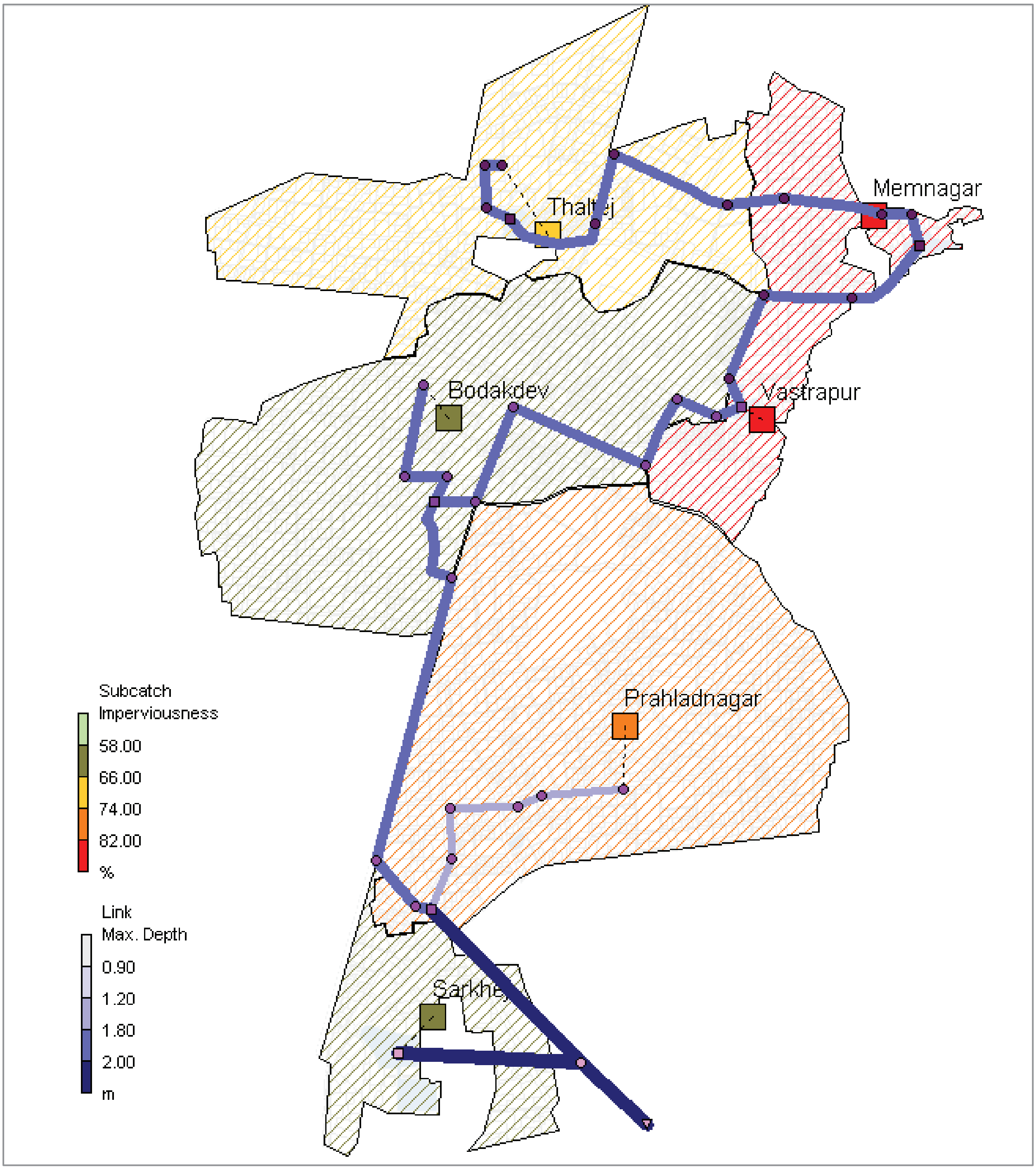

Figure 42: Hydraulic network representation of linked lakes

5.2.3. Quality Parameter

Pollutant – Total Suspended Solids

Amongst the water quality parameters measured as stated in Table 6, Total Suspended Solids (TSS) was selected to model the transport and deposition of TSS from urban catchments in the lake. Suspended solids are immensely important cause for water quality degradation leading to issues of visual and recreational values of lakes and decline of aquatic ecosystems. Suspended solids comprise of particulate matter and are mostly transported in cohesive sediments primarily as flocculated material. The so called ‘floc’ formed of cohesive suspended solids is in a continues state of change as the medium in which it is transported provides further build-up mixing with other nutrients, organic and chemical substances (Droppo, 2001).

Suspended solids can influence and alter various physical, chemical and biological properties of the water bodies. Physical alterations include higher levels of turbidity, reducing the penetration of light and affecting the visual and recreational value of lake. Chemical alterations caused by suspended solids include the inflow of pollutants such as oil & grease, heavy metals, and other toxic wastes generated by human interaction. The biological effects include restricted growth and survival of aquatic organisms and microbial activities (Bilotta & Brazier, 2008). One of the major sources of inflow of suspended solids in lake is generated from surface runoff and storm water drainage and there has been and increasing focus to study suspended solids amongst the so called ‘emerging priority pollutants’(Fletcher et al., 2013).

In SWMM model, pollutants are defined by its concentration in rain, groundwater and inflow/infiltration sources. Depending on the land use classes, build-up and wash off functions of these pollutants are specified. The pollutant build-up at impervious surfaces are affected by dust, human activities, traffic, wind and erosion from unpaved areas and during rainfall the contaminants enter the storm water network system by wash-off of pollutants caused by runoff from catchment. Subsequently the polluted water is discharged in the lakes where it is mixed with other pollutants undergoing toxic transformation.

In the present study three primary land uses were used; residential, commercial and mixed designated to each catchments using land use editor in quality module. The land use assigned to each catchment represents the spatial variations of pollutant concentration within the catchment. There are primarily two functions which define the pollutant concentrations in residential, commercial and mixed use areas discussed below:

Build-up of TSS at catchments

The contribution of each catchment in TSS build-up increases the cumulative loads in the system hence it is important to understand the mechanism of pollutant build-up at catchment level. “*There exists an exponential relationship between the amount of solids on the surface*, M, *and the duration of antecedent dry weather period*, t_{dry}”. .(Sartor, Boyd, & Agardyand, 1974) .

$$[\, M(T) = M_0 \,(1 - e^{-k\,(t_{dry} + t')}) \,]$$

where,

M (g/m^2) is the amount of solids on the surface.

T [days] is the time elapsed from the start of the first rainfall in the series.

t_{dry} [days] is the duration of antecedent dry weather period.

t’ [days] is the virtual time – calculated by assumption that deposition is zero at t’

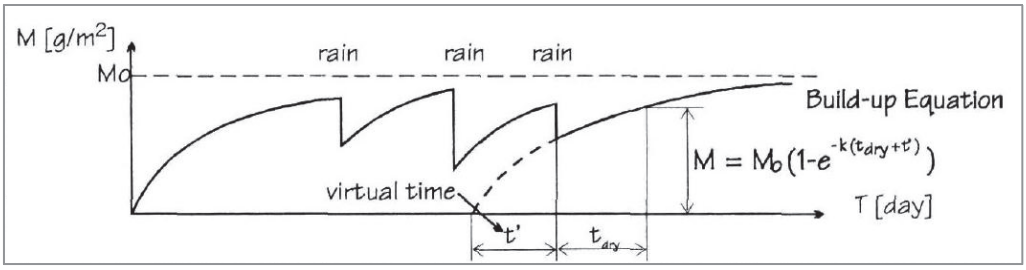

Figure 43: Solids build-up at the surface
Source 15: (Deletic, Maksimovic, & Ivetic, 1997)

There are two main parameters which are to be determined in each particular catchment as described by (Deletic, Maksimovic, & Ivetic, 1997)

1. Maximum amount of expected solids at the surface
2. K [day^{-1}] - accumulation constant.

Due to unavailability of data on TSS (EMC) estimation on impervious surfaces in urban catchment of Ahmedabad system default values were chosen with 1 day accumulation constant. For reference an international matrix for storm water pollutant concentrations developed by (Göbel et al., 2007) for the land use in urban areas was used.

Land use and pollutant concentrations		Residential	Commercial	Mixed
Build-up	Function	Exponential	Exponential	Exponential
	Max build-up (Kg/Ha)	0.15	0.15	0.15
	Rate constant (days)	1	1	1
	Normalizer	Area	Area	Area
Wash-off	Function	EMC	EMC	EMC
	Coefficient	200	180	200
Street sweeping interval (days)		1	1	1

Table 12: Land use and pollutant concentrations

Wash-off of TSS

TSS wash-off is in urban areas is caused by rainfall-runoff and the resultant overland flow. Wash-off can be categorised as; wash-off in the direction of natural slope (pervious surface) and wash-off in the storm drainage (impervious surface). According to Sargaonkar (2006) wash-off of pollutant loading during runoff can be determined by:

$$C_j = T_i / Q_j$$

Where,

C_j is the concentration of pollutant in runoff,

T_i is the total loading of pollutant i in the surface runoff in the catchment (kg/year),

Q_j is the amount of surface runoff from land use j (m^3/year)

The event mean concentrations (EMCs) for land use in Ahmedabad catchment could not be derived due to insufficient data on annual loading of TSS in the catchment, default values in SWMM were used as described in Table 12. Although the bandwidth of EMC suggested by (Göbel et al., 2007) for high and low density areas were used later in the model for sensitivity analysis. The detailed table of EMC bandwidth for various pollutant loadings is described in Appendix D.

5.3. Simulation and Results

Simulation was performed in SWMM with the hydrological, hydraulic and quality input parameters mentioned in respective sections. Overview of the model parameters is shown in Table 13. The simulation results are generated for various components; subcatchments, nodes, links and outfall.

The simulation results are categorized as:

1. Model Stability Results
2. Runoff Results
3. Wash-off Results
4. Node Depth
5. Node Inflows
6. Node Surcharging
7. Node Flooding
8. Storage Volumes
9. Outfall Loadings
10. Link Flows
11. Conduit Surcharging

Simulation summary	
Raingages	1
Subcatchments	6
Infiltration	HORTON
Junction Nodes	29
Outfall Nodes	1
Storage Unit Nodes	6
Conduit Links	35
Flow Units	CMS
Flow Routing	KINWAVE
Pollutants	1
Land Uses	3
Reporting Period	06/01/2013 - 10/31/2013

Table 13: SWMM Model Simulation summary

The underlined simulations results described above are consdered relevant for discussion and are within the scope of the research. The basic structure which the SWMM model follows is rainfall-runoff-inflow-loadings as shown in Figure 44. The subcatchments in the model were aggregated from clusters of town planning units, however segmentation of catchments into finer levels of spatial resolution can give varied resutls in terms of runoff generated from surface. Consequently the pollutant build-up on impervious surfaces, is also aggregated as the subcatchment consisting of various land uses. Thus it gave an overstimated values of pollutant loadings in lakes than the measured TSS values during field measurement.

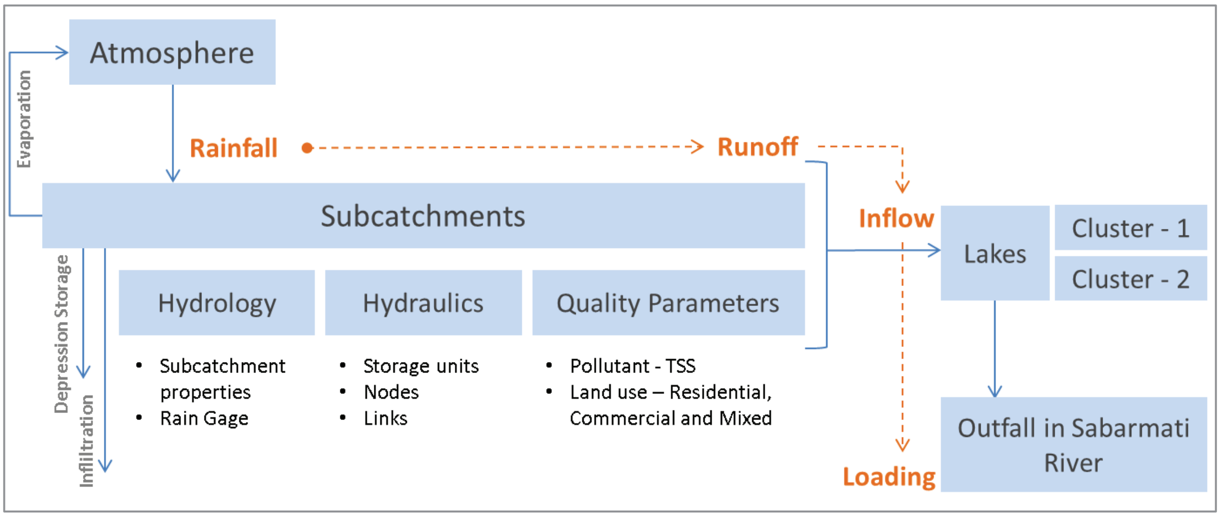

Figure 44: SWMM modelling structure

The primary purpose of using this model was:

1. To understand and the non point source generated pollutants from catchment through storm water runoff affecting the lakes.
2. The relationship of catchment runoff and lake inflow; which subsequently transport and discharge high amount of TSS in the lake.
3. The cummulative loading in each lake and outfall loadings in receiving waters.
4. Comparative pollutograph analysis of simulated levels of TSS for lakes.

5.3.1. Cluster Analysis

The result in Figure 45 shows the comparsion of subcatchment and lakes in terms of catchment runoff, lake inflows and TSS pollutograph (Figure 45 a-e). The SWMM runoff-inlfow hydrograph result showed direct relationship with surface runoff generated from subcatchments and discharge into the lakes which is dependent on the percentage of impervious surfaces in the subcatchment. The stormwater enters the system through Thaltej catchment and further donwstream Memnagar and Vastrapur are highly dense catchments with higher percentage of impervious surfaces. The inflow rate of storm water in the lake was observed highest in Thaltej catchement lowest at Memnagar catchment. In the pollutograph of TSS show in Figure 45 (e), Vastrapur lake shows the high amout of TSS deposited from the cummulative runoff with high pollutant loadings from Thaltej and Memnagar subcatchments and lakes respectively.

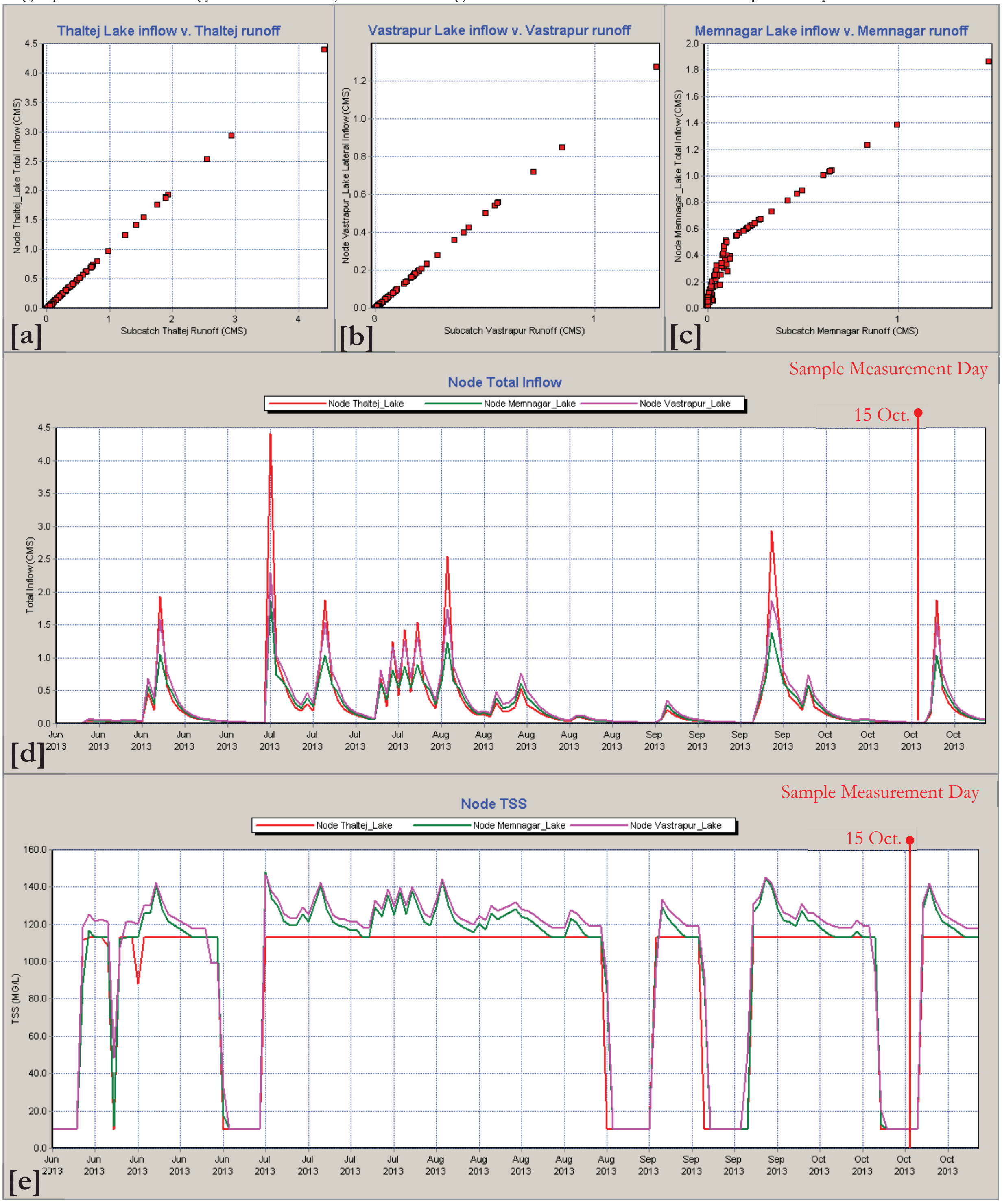

Figure 45: Analysis of Cluster -1 Lakes; Thaltej, Memnagar, Vastrapur

Further downstream in cluster 2 as shown in Figure 46 (a, b and c) the inlow in the lakes were recorded higher which received runoff from the catchment as well as from water from the lakes upstream. Amongst the lakes in cluster 2 ; Bodakdev, Prahladnagar and Sarkhej, Prahladnagar lake had the highest peak flows as shown in Figure 46(d) and discharging to the outfall with TSS loadings. The constant inflows and outflows during the rainfall event, retric t the possible removal of stormwater pollutants by decrease in resident time of storm water in the lake as it is transported further downstream . The pollutograph in Figure 46(e) shows that Prahladnagar catchment, discharge high amout of TSS pollutant in the lake. However the TSS levels in Sarkhej lake which has smaller catchment was observed comaparatively low which suggest that the size of catchment also plays a crucial role. Larger catchments having more impervious surfaces with various land use generate more pollutants which during rainfall are washed off and discharged in the storm water channels. It can be clearly seen that TSS pollutograph in lakes are sensitive to area, amout of inlfow and runoff generated from the catchment.

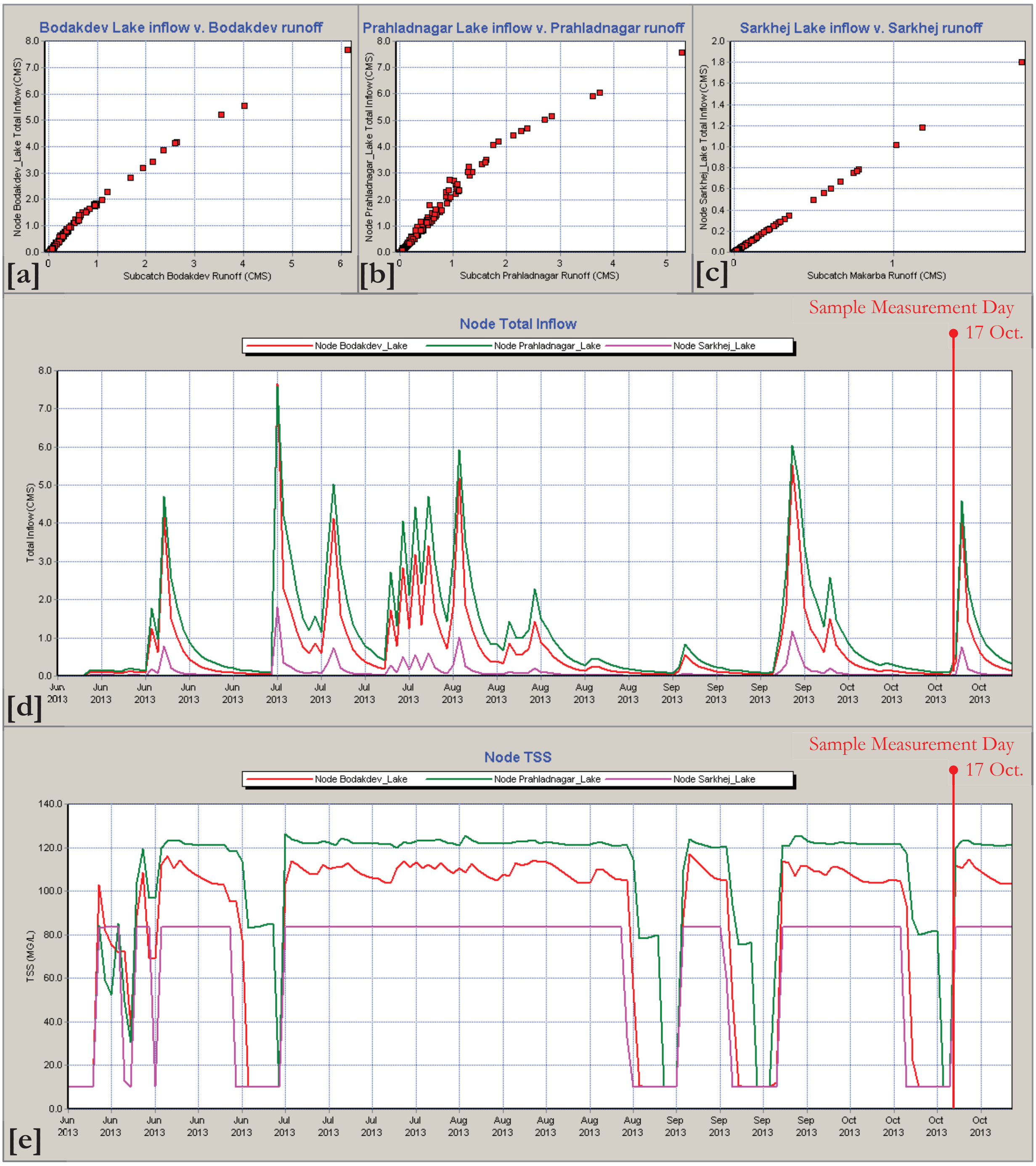

Figure 46: Analysis of Cluster -2 Lakes; Bodakdev, Prahladnagar, Sarkhej

5.3.2. Storm Event Analysis

The pollutograph in Figure 48 shows the TSS loading and transport in four events taken at monthly intervals. The TSS loading transport is subdivided in four segments; subcatchment, link, node (as lakes) and outfall. During the rainfall event cumulative contribution of TSS pollutant within these four segments discharge TSS with the inflow of storm water into the lakes from various subcatchments. The interlinked system can be studied in post development condition to know which subcatchments, links, and lakes contribute high amount of TSS in the system. In SWMM the complete TSS pollutant generation and transport process for the rainfall event (from June – October) for the year 2013 was visualised. The events which were significant for understanding variations of TSS pollutant loadings at outfall were selected for discussion.

The month of July recorded the highest rainfall (see Page 51 - Figure 39; **Error! Reference source not found.**; Table 10) in the rainfall event of the year 2013. The pollutograph in Figure 48 shows peak concentration of TSS loadings and enormous amount of TSS are discharged in receiving waters through outfall. Hence it can be derived that the TSS transport rate and its peak formation is influenced by rainfall intensity and subcatchment runoff. This phenomena is called as 'first flush' in which the concentration of pollutants in storm water is noted relatively higher than the later rainfall events (Lee, Bang, Ketchum Jr, Choe, & Yu, 2002). However the peak concentration of various pollutants in the so called 'first flush' phenomena may differ in the same storm event (Gupta & Saul, 1996). Understanding the 'first flush' and its relationship with other variables (impervious area; antecedent dry weather day; subcatchment area and rainfall intensity) can be used to evaluate the process in detail at outfall, by correlating the cumulative pollutant mass and cumulative runoff volume generated for the event (Bertrand-Krajewski, Chebbo, & Saget, 1998).

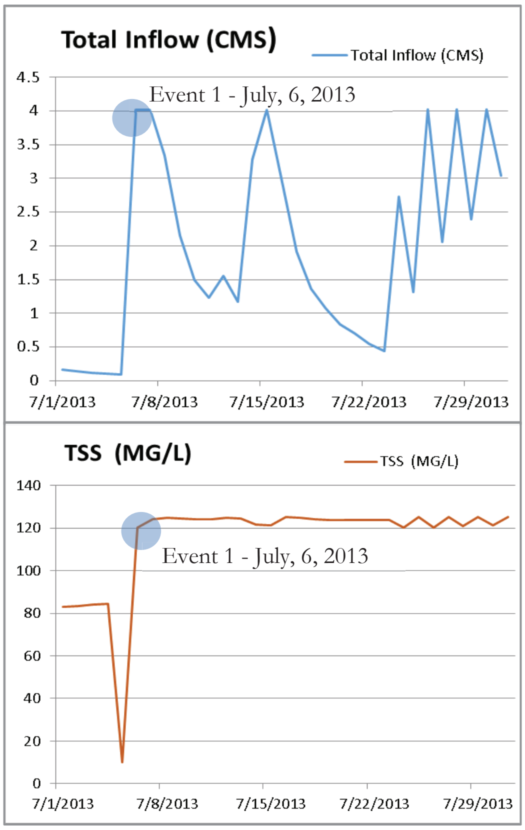

Figure 47: Inflow and Pollutant mass at outfall for Event -1('first flush')

In order to know degree of pollution in lakes which depend on the subcatchment characteristics, the peak of pollutant concentration in lakes were measured.

Although the results showed varied degree of pollutant concentration in lakes due to their interconnection, discharge at outfall with cumulative pollutant concentration were considered to evaluate the system. As mentioned in Table 9, Memnagar, Vastrapur and Prahladnagar have almost 80 % or above impervious surface with high density residential, commercial and mixed use. Although they differ in their area they are the chief contributors of pollutant loadings at outfall. Amongst mentioned Prahladnagar subcatchment accounts the most of the pollutant loading concentration at outfall. It is therefore important to investigate the parameters which are critical in generating pollutant loadings from the subcatchment. The event mean concentration (EMC) for TSS pollutant assigned in SWMM model in quality parameters (see Pg. 55, Table 12) plays an important role in generation and discharge of pollutant loadings from subcatchment during runoff. The evaluation of EMC is an appropriate for understanding the effects of subcatchment runoff on receiving lakes (Lee et al., 2002). Estimation of EMC in India is done on large watersheds of river basin with aggregated regional land cover (Sargaonkar, 2006) hence there is limited guidance for usage of EMC bandwidth in urban areas.

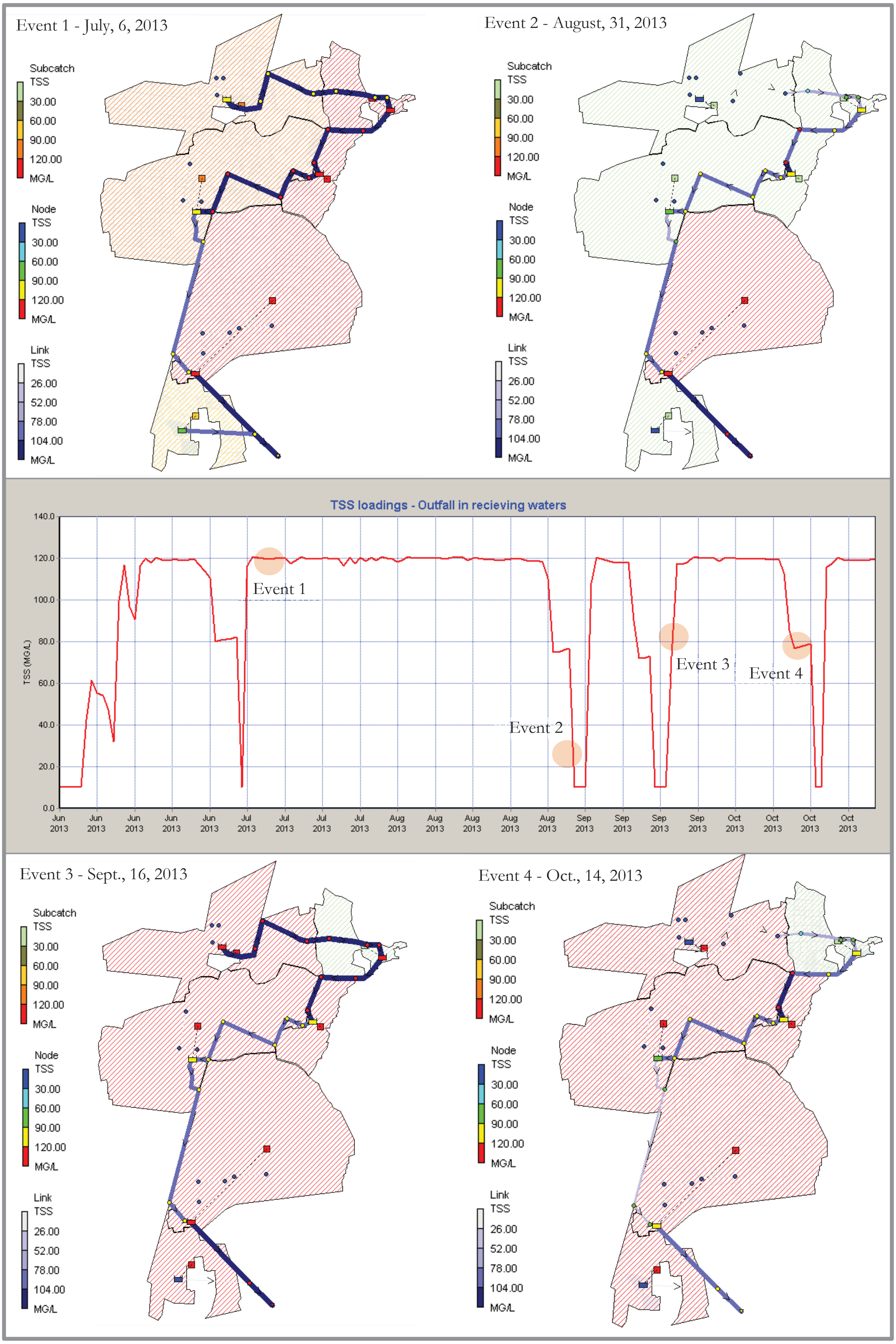

Figure 48: Outfall Pollutograph and pollutant transport in storm events

5.3.3. Calibration

The transport and conveyance of pollutants in the conduit system within lakes was considerd without pollutant modification or settling during transport which is described by simplified advection formulation and hence require no calibration (Gaume, Villeneuve, & Desbordes, 1998). However the subcatchment pollutant discharge through washoff and inflow in the lakes during a storm event is an essential to calibrate the measured TSS levels with the simulated TSS levels in the lakes.

Calibration parameters input values in models like SWMM is essential because there are uncertainties while using proxy or system default data. Interpretation of the results is based on acquired knowledge about the system, measured data and the fitted parameters values. It was found from the simulation analysis that event mean concentration (EMC) is a crucial parameter for generating pollutant loadings in subcatchments and its subsequent discharge in lakes.

Thus "EMC is an important analytical parameter, represents flow weighted average concentration and is computed by total pollutant mass divided by the total runoff volume" (Lee et al., 2002). This section of the study focuses on calibrating EMC values through several iterations to evaluate the pollutographs of lakes. As shown in Table 14, three simulation iterations was carried out with distinct EMC values. The first interation was conducted from the values suggested by SWMM (default values), second iteration was done according to Göbel et al. (2007) suggested bandwidth for EMC concentration values for urban areas and the third iteration was taken as an intermediate value between first and the second iteration.

Caliberation of EMC values			Residential	Commercial	Mixed	Pollutograph
Wash-off	No.	Function coefficients	EMC	EMC	EMC	-
	1	SWMM suggested values	200	180	200	Iteration 1
	2	EMC bandwidth in urban areas (Göbel et al., 2007)	74	66	74	Iteration 2
	3	Intermediate value (of 1 and 2)	137	123	137	Iteration 3

Table 14: EMC values used for calibration

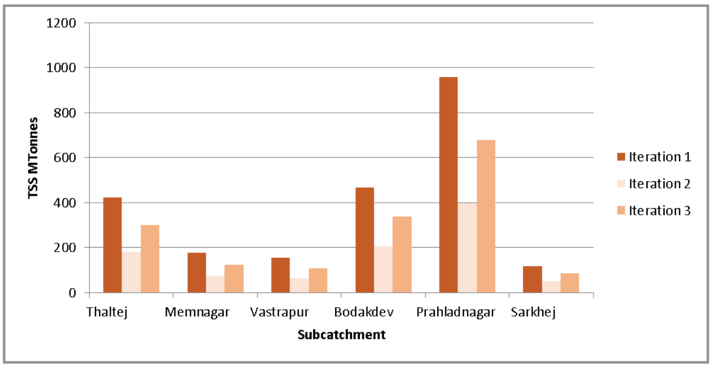

Figure 49: Pollutant wash-off from subcatchments

The caliberation was carried in two parts; generation of pollutants from subcatchments and pollutant concentration in the lakes. Since the water quality measurements were done in the lakes, subcatchment pollutant generation was only studied for proxy reference.
It was found that the Prahladnagar and Bodakdev subcatchment accounted for the higher TSS generation as subcatchment area is an influencing factor in pollutant generation and washoff process (Park, Lee, Park, & Ha, 2008). As shown in Figure 50 the cluster 1 (Thaltej, Memnagar, Vastrapur) and cluster 2 (Bodakdev, Prahladnagar, Sarkhej) lakes were calibrated in three iterations with EMC values mentioned in Table 14.

It was found that the calibration in iteration 1 gave overestimated TSS values for lakes; Vastrapur, Prahladnagar, and Sarkhej, and underestimated for Thaltej, Memnagar and Bodakdev as shown in Table 15. There was a noted difference between the simulated values and the measured values during calibration.

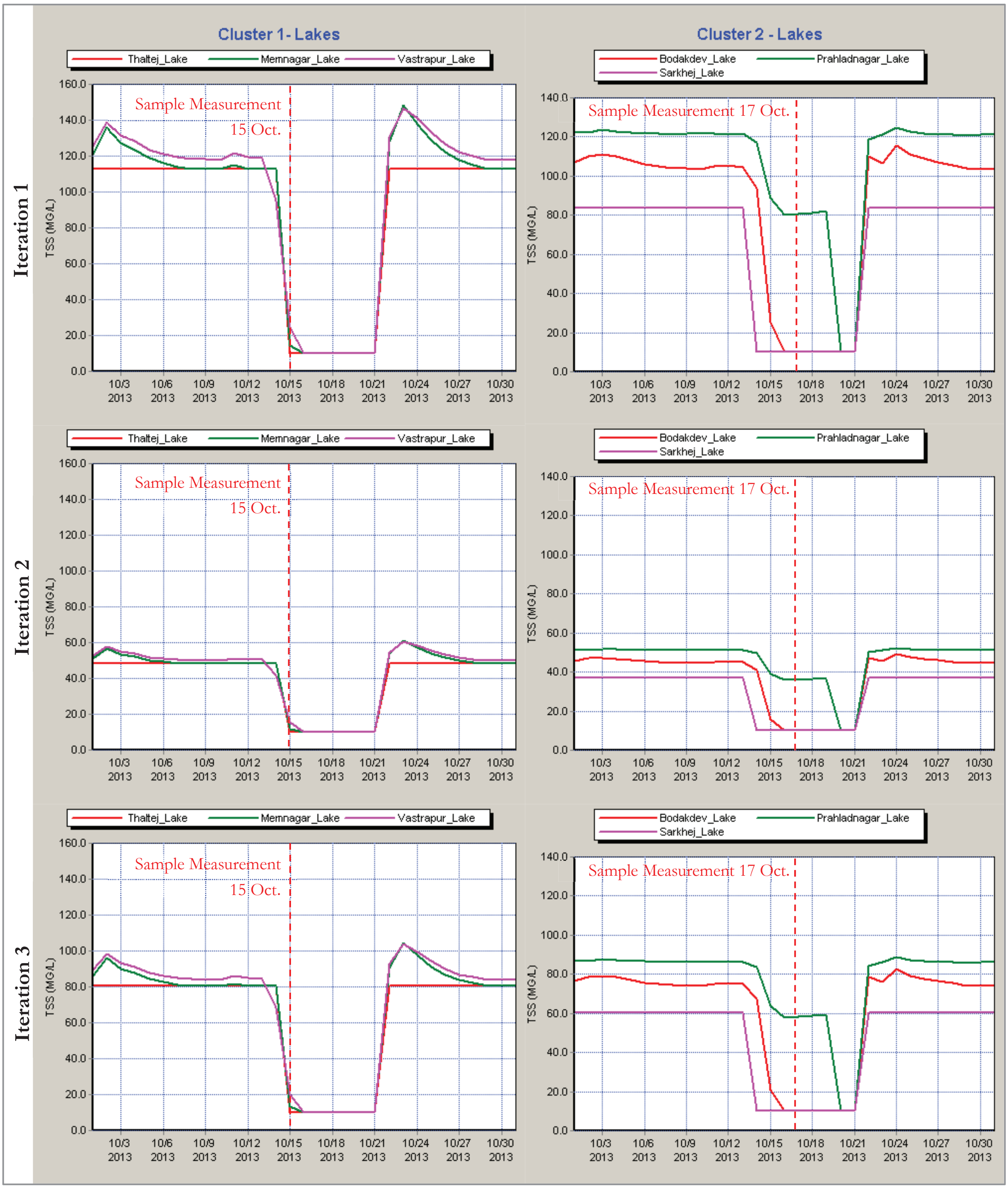

Figure 50: Calibration of EMC values for TSS pollutant in lakes

Caliberation - TSS (Mg/L)	Thaltej Lake		Memnagar Lake		Vastrapur Lake		Bodakdev Lake		Prahladnagar Lake		Sarkhej Lake	
	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured
iteration 1	10.00		14.70		24.44		10.00		80.76		10.00	
iteration 2	10.00	24.00	11.74	30.00	15.34	4.00	10.00	18.00	36.17	4.00	10.00	4.00
iteration 3	10.00		13.00		19.89		10.00		58.47		10.00	

Table 15: Simulated and Measured values in Lakes for TSS pollutant

One of the reasons behind the difference could be the duration of antecedent dry days from the last storm event, after which the inflows in the lake gradually reduce and the suspended particles start to settle in lake depths. Other reason which is more likely is the error in measurement taken during sampling procedure.

5.4. Discussion

The EPA-SWMM model simulation showed that the major source of pollutant concentration discharged in lakes is from urban subcatchments which are non-point sources. From the cluster analysis it was noted that subcatchment runoff and lake inlfow have direct relationship which is due to high impervious surfaces in the subcatchment. Pollutograph generated from model simulation showed that the cumulative inflows in interconnected lakes from subcatchment entering subsequent lakes increase the pollutant concentration in lakes. Comparison of pollutograph between cluster 1 and cluster 2 showed that the pollutant concentration gradually increased downstream.

The event analysis done with four storm events show the changes in pollutograph during varying rainfall intensities. The event analysis also explains the transport of pollutants in subsequent lakes.

The pollutant build-up during dry period is crucial as higher impervious surfaces generate high concentration of pollutants during washoff in a storm event. The 'event mean concentration' (EMC) determines the pollutant loadinds during washoff thus derivation of EMC for various land use is crucial. The varaition of EMCs in land use is giving according to the surface characteristics, and different EMCs bandwidth directly relates to change in pollutograph of loadings as shown in Figure 51. EMCs can also alter pollutograph depending on the rainfall intensity of storm events.

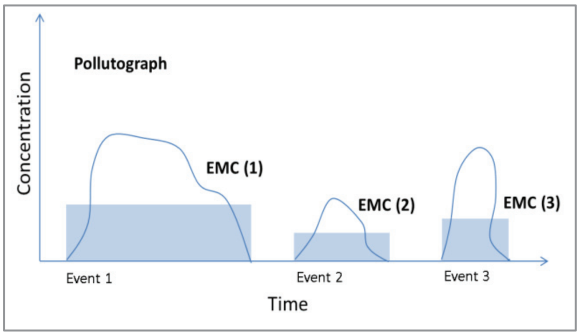

Figure 51: Pollutograph explaining the even mean concentration (EMC) for single events.
Source 16: Adopted from (Göbel et al., 2007), Fig. 1

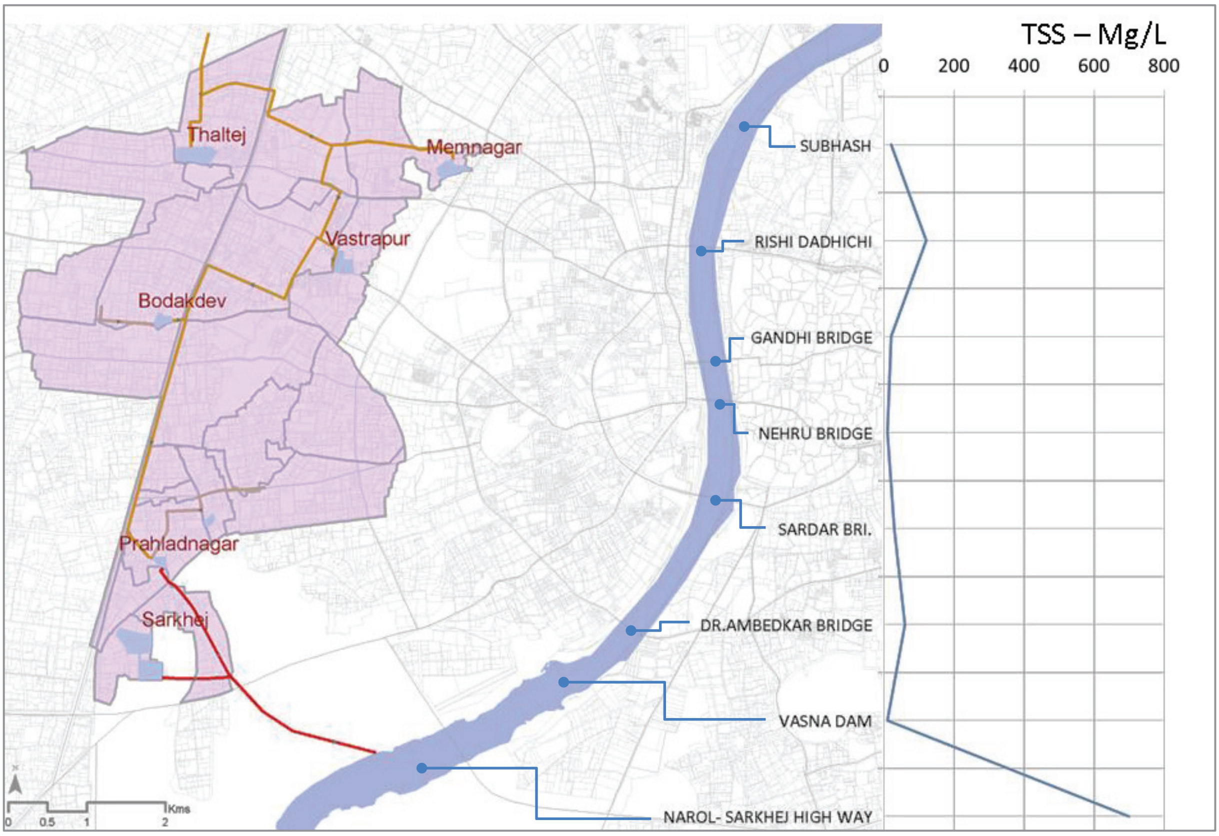

Figure 52: TSS levels in Sabarmati River
Source 17: Sabarmati river water quality data (July-August) 2013-Gujarat Environment Management Institute

From the Sabarmati River data quality report on (July-August, 2013) it was found that at the outfall of the hydrological model where it discharges pollutants in the river showed drastic increase in pollutant loadings of the river as shown in Figure 52. There can be various point/non-point sources discharging pollutant loadings through various subcatchments at different locations of river. Therefore it cannot be directly concluded from the river water quality data that the pollutant peak is due to the discharge of pollutants from the catchment. However outfall pollutograph as shown in Figure 53 from the catchment showed high amount of TSS discharged in Sabarmati River.

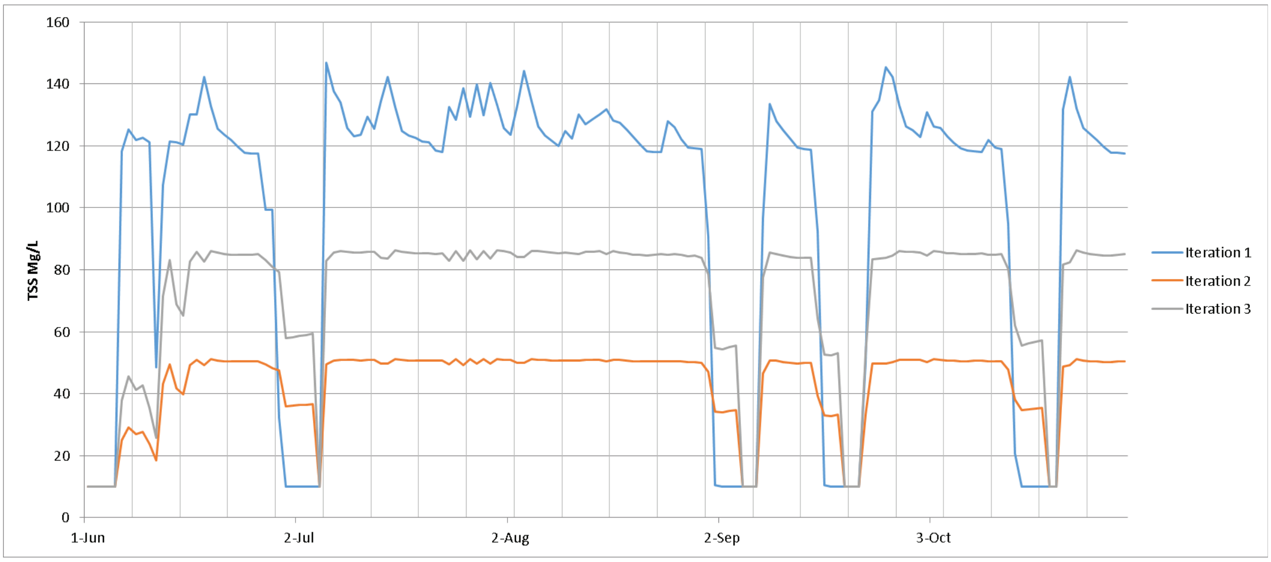

Figure 53: Pollutograph at outfall with calibrated EMC values

The EPA-SWMM model is very complex, with the limited hydrological data on urban subcatchments and storm network it is difficult to conduct the validation of the model. Also the availability and measurement was not consistent; urban lake water quality was done in the wet season, and it also requires dry weather measurement. Detailed analysis with several storm events for estimation of pollutant loadings in lake requires regular water quality monitoring. In this research, in spite of significant field measurement efforts on urban lake water quality the research could not fill the gaps of model requirements for complete understanding of linked lakes behaviour due to lack of reference water quality data on lakes. However through the research an attempt was made to model the linking of lakes and assess the impacts on urban lake water quality by highlighting key issues like estimation of EMC in urban subcatchment for various land use and surfaces.

6. CONCLUSIONS

In this research, evaluation and modeling of the impacts of lake linking project on water quality of lakes was carried out. Technical hydrological intervention as 'lake linking project' in the study alters the equilibrium of the lakes. But the local government perceives the project as 'techno-planning' solution to avoid water logging during high intensity rainfall. It was observed from the research that such interventions have considerable impacts on the water quality on lakes and disrupt the balance of not only lake ecosystems but also pollute receiving waters. It was learnt from the literature that in a continuous process of urban development, especially urban hydrology there should be no contradiction between old and new solutions, however there can be complementing solutions to achieve the same goals. Minimum intervention by accommodating previous approaches offer limited contradictions and avoid uncertain impacts.

In the second part of the research water quality assessment in urban lakes were carried out in 6 interlinked lakes, to know the presence and level of pollutants and to inquire the sources of pollutants from the subcatchment. It was found from the research that bacterial pollution was found beyond the permissible limits of water class 'B'. Moreover amongst the interlinked lakes, Prahladnagar and Bodakdev were found most polluted, however some parameters like dissolved oxygen was found extremely low in Memnagar Lake.
In general the interlinked lakes had higher salt content, also calcium and magnesium hardness contributed to high alkalinity of lakes. Memnagar and Bodakdev Lakes were found above the permissible limits of 200 mg/l prescribed by CPCB. The higher salt content in lakes suggest the grey waters and some portion of sewage from residential areas are discharged in lakes, it was noted in the field observation that discharging water was accompanied with foam at the inlet of the storm water channel in lakes. Each lake was analyzed and evaluated based on the selected parameters of water quality assessment and derive the lake subcatchment properties. It was also found the higher impervious areas generated high runoff and washoff, which eventually increased pollutant concentrations in the storm water channels.

Lakes in the present study showed varied degree of pollution from multiple sources of pollution from anthropogenic activities in the subcatchment. The final part of the research was model the transport of pollutants within the interlinked lakes. From the model simulations and event analysis it was found that during entire rainfall cycle there is a constant inflow and outflow of nutrients and toxic substances within the lakes. The natural cycle of the lake self-purification and the balance of lake ecosystem disrupted due to less residence time of lake waters.

During high intensity rainfall, the inflow between the lakes was observed higher. Residence time of lake waters is an important factor to achieve lake equilibrium. Due to constant exchange of waters with high pollutant concentrations the lakes do not achieve steady state. And since the lakes are linked, in hydrological sense they behave as a single entity and it takes a longer duration to achieve the steady state of the whole system. Further it is also important to know the decay processes of various nutrients, organic wastes and their relationship knowing the residence time distribution of all inflow events in lakes.

The transportation of pollutants was analyzed through series of events and was noted that subcatchments having large areas and high impervious surfaces were chief contributors of pollutant concentrations in lakes. It was observed from the research that lake linking projects have considerable impacts on water quality of lakes if the untreated storm water is siphoned in the lakes. Also redefining urban lakes as detention ponds disrupt the ecological balance of the lake ecosystems. Moreover interlinking of urban lakes also has substantial impacts on Sabarmati River.

Recommendations:

1. Environmental Impact Assessment of projects which have the tendency affect the environment and disturb the ecological balance should be prioritized, and done prior to the inception of the project.
2. In case of local scale projects specialized impact assessment like hydrological impact assessment should be also considered. Moreover anticipation of cumulative impacts in terms of societal, environmental, and economic is also essential.
3. In context of urban hydrology, land use classification and EMC estimation of various surfaces (permeable/impermeable) should be carried out at contextual level, in order to accurately model urban hydrological system.
4. There is need to develop a comprehensive and robust urban water quality monitoring program which monitors the permissibility of pollutant concentration in urban lakes, urban local bodies are centrally responsible to take such initiatives.
5. Management of urban lakes, by developing a lake census of urban lakes, and classifying the vulnerable lakes proximity to industrial or hazardous sources of pollution.

There is need to acquire knowledge of these impacts is necessary to avoid irreversible effects which creates imbalance in urban environments.

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7. APPENDICES

A - Comparative table of various urban storm water models.

Model	Water quality parameter																
	Temperature	Inorganic suspended solids	Organic sediment	Inorganic sediment	BOD	Total coliform	Total inorganic carbon	Ammonia	Total N	Total P	Dissolved oxygen	Alkalinity	pH	Suspended solids	Soil erosion	Total dissolved solids	Others
Urban models																	
DR3M-QUAL																	7.,9
HSPF	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes		yes	yes	yes	1,2,7,9,10
MIKE-SWMM	yes	yes	yes	yes	yes	yes		yes	yes	yes	yes			yes	yes		10
QQS					yes	yes			yes	yes					7		9
STORM					yes	yes			yes	6					7		
SWMM					yes	yes			yes	yes				yes	yes		3,7,8
SWMM Level 1					yes				yes	yes				5			
Wallingford Model					yes			yes	yes	yes	3			7			9
Non urban models																	
BRASS																	11
HEC-5Q	yes				3			yes	1	2	yes						9,10
QUAL2E-UNCAS	yes				yes	yes		4	1	2	yes						9,10
WQRRS	yes	yes	yes	yes	yes	yes	yes	yes	1	2	yes	yes	yes	yes			9,10

Source 18: (Zoppou, 2001)

B - Data collection overview

Data	Data type	Source
Land Use Information around selected lakes	shape files	AUDA
Storm water Network in the Catchment Areas	shape files	AUDA
Administrative Boundary of AUDA and AMC	shape files	AUDA
Details of the Lake Linking Project	Scan	AUDA
Data on lakes (depth, area, catchment)	Various	AUDA
Field survey Data (Frequancy of visit)	Record	Manual
Water Qualtiy Assessment Report on 6 lakes	Report	GEMI
Water Qualtiy data of Reciving waters - Sabarmati River (2013)	Spread sheet	GEMI
Interviews with environmental experts	Video	CEE
Rainfall Data (daily precipitation 2013)	Spread sheet	IMD, Local Station
Literature on Lake Development of Ahmedabad	Reports	CEPT, CEE, AUDA
Population Census Report 2001	Report	AMC

C - Manning's 'n'for coduit with various materials in Indian context.

Sr. No	Type of Material		n' as per manual
1	Salt glazed Stoneware Pipes	a) Good	0.012
		b) Fair	0.015
2	Cement Concrete Pipes (with collar joints)	a) Good	0.013
		b) Fair	0.015
3	Spun Concrete Pipes (RCC & PSC) with socket & spigot joints (Design value)		0.011
4	Masonry	a) Neat Cement Plaster	0.018
		b) Sand & Cement Plaster	0.015
		c) Concrete - steel troweled	0.014
		d) Concrete - Wood troweled	0.015
		e) Brick in good condition	0.015
		f) Brick in rough condition	0.017
		g) Brick in bad condition	0.020
5	Stone Work	a) Smooth dressed Ashlar	0.015
		b) Rubble set in cement	0.017
		c) Fine, well packed gravel	0.020
6	Earth	a) Regular surface in good condition	0.020
		b) In ordinary condition	0.025
		c) With stones and weeds	0.030
		d) In poor condition	0.035
		e) Partially obstructed with debris or weeds	0.050
7	Steel	a) Welded	0.013
		b) Riveted	0.017
		c) Slightly tuberculated	0.020
		d) With spun cement mortar lining	0.011
8	Cast Iron	a) Unlined	0.013
		b) With spun cement mortar lining	0.013
9	Asbestos Cement		0.011
10	Plastic		0.011

Source 19: Detailed Project Report (DPR) Manual – Storm water Drainage (MOUD, 2012)

D - Suggested EMC bandwith for urban areas.

Bandwidth of EMCs of parameters and pollutants: rainwater, runoff from roofs, and runoff from trafficked areas

Parameter		Unit	Rainwater		Roofs		Trafficked areas with low density		Trafficked areas with high density	
			Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Physico-chemical parameters										
1	EC	µS/cm	28	223	25	269	n.a.	n.a.	108	2436
2	pH	–	3.9	7.5	4.7	6.8	6.4	7.9	6.4	7.9
Sum parameters										
3	TSS	mg/l	0.2	52	13	120	74	74	66	937
4	BOD_5	mg/l	1.0	2.0	4.0	16.1	n.a.	n.a.	2.0	36.0
5	COD	mg/l	5	55	n.a.	n.a.	n.a.	n.a.	63	146
Nutrients										
6	P_{tot}	mg/l	0.01	0.19	0.06	0.50	n.a.	n.a.	0.23	0.34
7	NH_4	mg/l	0.1	2.0	0.1	6.2	n.a.	n.a.	0.5	2.3
8	NO_3	mg/l	0.0	7.4	0.1	4.7	n.a.	n.a.	0.0	16.0
Heavy metals										
9	Cd	µg/l	0.1	3.9	0.2	1.0	0.2	0.5	0.3	13.0
10	Zn	µg/l	5	235	24	4880	15	1420	120	2000
11	Cu	µg/l	1	355	6	3.416	21	140	97	104
12	Pb	µg/l	2	76	2	493	98	170	11	525
13	Ni	µg/l	1	14	2	7	n.a.	n.a.	4	70
14	Cr	µg/l	2	8	2	6	n.a.	n.a.	6	50
Main ions										
15	Na	mg/l	0.22	20.00	n.a.	n.a.	n.a.	n.a.	5.0	474.0
16	Mg	mg/l	0.03	0.33	n.a.	n.a.	n.a.	n.a.	1.0	1.4
17	Ca	mg/l	1.10	67.13	1.00	1900	n.a.	n.a.	13.7	57.0
18	K	mg/l	0.46	0.65	n.a.	n.a.	n.a.	n.a.	1.7	3.8
19	SO_4	mg/l	0.56	14.40	n.a.	n.a.	n.a.	n.a.	5.1	139.0
20	Cl	mg/l	0.20	5.20	n.a.	n.a.	n.a.	n.a.	3.9	669.0
Organic parameters										
21	PAH	µg/l	0.04	0.76	0.35	0.60	n.a.	n.a.	0.24	17.10
22	MOH	mg/l	0.29	0.41	0.108	3.14	n.a.	n.a.	0.51	6.50

Source 20: Bandwidth of EMCs of parameters and pollutants (Göbel, Dierkes, & Coldewey, 2007)

E - Detailed water quality measurements of total samples

Parameters	Units	Permissible Limits - WHO, CPCB	Vastrapur			Memnagar			Thaltej		Sarkhej			Prahladnagar		Bodakdev		
			SID - 8084	SID - 8085	SID - 8086	SID - 8087	SID - 8088	SID - 8089	SID - 8090	SID - 8091	SID - 8136	SID - 8137	SID - 8138	SID - 8139	SID - 8140	SID - 8141	SID - 8142	SID - 8143
pH	-	6.5 to 8.5	8.28	8.34	8.42	8.21	8.39	8.32	8.28	8.27	8.29	8.26	8.32	8.30	8.41	8.64	8.69	8.75
Conductivity	µS/cm	2000	537.00	517.00	591.00	339.00	1162.00	326.00	10.00	705.00	513.00	506.00	508.00	226.00	230.00	1741.00	2170.00	1840.00
Total Solids	mg/l	-	416.00	388.00	376.00	782.00	533.00	438.00	500.00	584.00	352.00	396.00	376.00	284.00	336.00	948.00	992.00	850.00
Total Dissolved Solids	mg/l	2000	412.00	374.00	360.00	746.00	503.00	418.00	476.00	560.00	344.00	392.00	360.00	282.00	318.00	944.00	990.00	868.00
Total Suspended Solids	mg/l	600	4.00	14.00	16.00	36.00	30.00	20.00	24.00	24.00	8.00	4.00	16.00	4.00	18.00	4.00	2.00	18.00
Chloride as Cl	mg/l	1000	119.90	119.90	119.90	79.00	199.90	79.90	139.00	159.90	99.90	139.90	139.00	59.90	59.90	159.90	420.00	420.00
Turbidity	NTU	10	2.50	5.90	3.10	14.60	19.20	11.10	39.00	37.50	18.50	23.30	20.80	34.60	8.30	39.80	12.10	21.70
Oil & Grease	mg/l	10	2.00	2.60	1.60	2.20	6.90	0.02	BDL	BDL	BDL	0.05	1.60	BDL	1.20	0.30	0.80	1.40
Alkalinity	mg/l	200	160.00	140.00	160.00	110.00	360.00	140.00	180.00	170.00	170.00	120.00	140.00	100.00	120.00	360.00	470.00	380.00
Total Hardness	mg/l	600	100.00	120.00	130.00	100.00	190.00	90.00	150.00	160.00	100.00	110.00	120.00	100.00	110.00	310.00	360.00	320.00
Calcium Hardness	mg/l	100	70.00	90.00	90.00	60.00	100.00	60.00	90.00	60.00	60.00	70.00	60.00	60.00	70.00	110.00	120.00	130.00
Magnesium Hardness	mg/l	200	30.00	30.00	40.00	40.00	90.00	30.00	60.00	70.00	40.00	40.00	60.00	40.00	40.00	200.00	240.00	190.00
Ammonical Nitrogen NH3-N	mg/l	50	2.24	1.12	1.68	1.12	11.20	0.56	1.68	1.12	0.50	0.50	0.50	0.50	0.50	3.72	8.96	7.84
Chemical Oxygen Demand (COD)	mg/l	250	44.92	25.83	85.56	84.24	85.36	66.36	85.36	84.24	51.66	47.17	42.68	62.89	17.97	85.36	88.30	87.29
Dissolved Oxygen (DO)	mg/l	3	7.00	6.80	5.90	16.80	0.30	14.10	8.20	7.30	5.30	6.20	4.40	9.40	10.40	2.90	1.60	3.60
Biochemical Oxygen Demand	mg/l	30	5.90	4.20	5.00	BDL	BDL	BDL	7.40	7.10	4.60	BDL	3.60	0.70	2.50	BDL	BDL	BDL
Toxiicity Test	percent (%)	90	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	TF1	TF1	TF1	TF1	TF1
Total Coliform	MPN/100ml	0	>1600	>1600	>1600	4.00	>1600	50.00	>1600	>1600	30.00	1600.00	35.00	80.00	2.00	>1600	>1600	>1600
Fecal Coliform	MPN/100ml	0	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2