Final Report for APN LCI PROJECT
Project Reference Number: LCI2013-02CMY(R)-Dhakal

Understanding and Quantifying the Water-Energy-Carbon Nexus for Low Carbon Development in Asian Cities

Low Carbon Initiatives Framework

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http://www.wec-nexus.ait.asia

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ABBREVIATIONS

AC	Activated Carbon
AD	Anaerobic Digester
AF	Anaerobic Fermentation
AIT	Asian Institute of Technology
ASP	Activated Sludge Process
BFP	Belt Filter Press
BIOFOR	Attached Growth Biological Filtration
BMA	Bangkok Metropolitan Administration
BMR	Bangkok Metropolitan Region
BOD	Biological Oxygen Demand
BT	Biological Treatment
BTU	British Thermal Unit
CAACO	Chemo-Autotrophic Activated Carbon Oxidation
CEA	Central Electricity Authority
Cf	Centrifuge
CF	Conversion Factor
CH_4	Methane Emission
CL	Chlorination
CSE	Centre of Science and Environment
CSO	Combined Sewer Overflows
DAF	Dissolved Air Flotation
DJB	Delhi Jal Board
DWB	Delhi Water Board
EA	Extended Aeration
EB	Biogas energy
Ech	Embodied energy of chemicals
Ed	Diesel energy
El	Electrical energy
Emt	Embodied energy of construction material
En	Net energy
ET	Equalization tank
FBR	Fluidized bed reactor
FM	Flash mixer
FST	Final settling tank
Gbiogas	Carbon emission due to biogas flaring
Gch	Emissions embodied in chemicals
Gd	Carbon emission from use of diesel
Ge	Carbon emission from use of electricity
Gfugitive	Carbon emission due to fugitive gases
GgCO2-e/day	Giga gram carbon dioxide equivalent per day
GHG	Green House Gases
Gmt	Emissions embodied in construction materials
GNCTD	Government of National Capital Territory of Delhi
GWh	Gega Watt Hour
HIG	High Income Groups
IPCC	International Panel of Climate Change
ISBR	Improved Sequential Batch Reactor
JJ	Jhuggi Jhopri
kWh	Kilo Watt Hour
LCA	Life cycle analysis

LIG	Low Income Groups
lpcd	Litre per capita per day
M1 to M6	Large-scale municipal sewage treatment options
MB	Membrane Bioreactor
MCM	Million Cubic Meter
MG	Million Gallons
MGF	Multi Grade Filter
MIG	Medium Income Groups
ML	Million Litres
MLD	Million Liter per Day
MT	Metric Tonnes
MW	Mega Watt
MWA	Metropolitan Waterworks Authority
MWh/day	Megawatt hour per day
N_2O	Nitrous Oxide emission
NCT	National Capital Territory
NCTD	National Capital Territory of Delhi
NRW	Non-Revenue Water
NT	Not-for-treatment
OD	Oxidation ditch
OT	Ozonation tank
PST	Primary settling tank
PT	Primary treatment
PWA	Provincial Waterworks Authority
R_2	Coefficient of Co-relation
RBC	Rotating biological contractor
RBD	Rate of BOD degradation
RCC	Reinforced cement concrete
SBR	Sequential batch reactor
SC	Screen chamber
SD	Standard Deviation
SDB	Sludge-drying beds
SF	Sand filter
Sld. H	Sludge treatment
ST	Secondary treatment
STP	Sewage treatment plant
STPs	Sewage Treatment Plants
TF	Trickling filter
TMG	Tokyo Metropolitan Government
TS	Tube settler
TSD	Treated sewage disposal
TT	Tertiary treatment
UASB	Up-flow anaerobic sludge blanket
USEPA	United States Environmental Protection Agency
UWC	Urban water chain
WEC	Water-energy-carbon
WSP	Waste stabilization pond
WTP	Water Treatment Plant
WWPS	Wastewater pumping station
WWTP	Waste Water Treatment Plant

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OVERVIEW OF PROJECT WORK AND OUTCOMES

1. Non-technical summary

Water and energy are, separately, key priority agendas; they are being planned and managed as separate entities. Yet, it is not common to look at their linkages and optimize them. As, water and energy are becoming limited resources, water footprints in energy sectors and energy footprints in water sectors are increasing being a concern in development and planning processes. In the context of cities, energy is of primary importance to urban water system management. The water infrastructures rely on energy throughout each elements of the system, source abstraction, conveyance, treatment, distribution, wastewater collection, treatment and recycle/disposal. Typically, fossil fuels are also the primary sources of energy which produce considerable amount of carbon dioxide and other Green House Gases (GHGs) and release into the atmosphere. This gives rise to the concept of nexus where water, energy and carbon can be managed under the same domain. Cities are significant place to study this nexus because of several reasons including, high population density, complex agglomeration of infrastructures, economy, industries, technologies and its overall dynamics. Cities are also major emitter of GHGs with the share of 71% of global energy related CO_2 emissions. Urban water sector could utilize 1 to 18% of total energy use in the city. Urban water sector is complex and diverse which involves processes of water services delivery to different economic sectors. The high energy demand for water utilities is one of the issues in sustainable management of water and sanitation services in developing and developed countries. This research looks into case studies in four Asian cities: Bangkok, Tokyo, Delhi and Kathmandu.

Keywords: Water, Energy and Carbon Nexus, Water footprint, Energy Footprint, Urban Water, Carbon Footprint

2. Objectives

The WEC-Nexus project was aimed to achieve following objectives:

- Characterizing nature of WEC Nexus through comparative case studies in Bangkok, Delhi, Tokyo and Kathmandu.
- Quantifying the nexus to determine the extent of the direct and indirect importance and to exemplify the potentials of the nexus to the low carbon development in cities.
- Gauzing the extent and relevancy of addressing the barrier and opportunities for optimizing the nexus, as well as influence the policy for low-carbon development.

3. Amount received and number years supported

The Grant awarded to this project was: US$ 37,450 for Year 1 and US$ 35,600 for Year 2

4. Activity undertaken

4.1 Research Framework and Case Study Protocol

The research protocol of water, energy and carbon (WEC) nexus was developed with the aim to apprehend the major linkages, key indicators and drivers of water, energy and carbon in urban context.

The urban water system from water supply source to disposal of waste water shall be considered for nexus. The urban water system's elements comprise abstraction, conveyance, treatment, distribution, end use, collection, treatment, recycle and disposal. The case studies at selected cities developed broad common research framework that can be applied to other cities. These case studies also guide to clarify the similarities and differences in the linkages, drivers and indicators of nexus in different spatial characteristics. The knowledge through this project is expected to be useful to policy makers to attain low carbon development.

4.2 Workshops

The project organized four workshops, first and second workshops were organized among the project collaborators to plan the research activities to methodologies and synthesizing progress of case studies respectively, third workshop involving stakeholders from local governments (Metropolitan Waterworks Authority, Bangkok Metropolitan Administration, Ministry of Environment – Japan and Delhi Water (Jal) Board) was organized to highlight on policies in three cities and identify where the gaps and issues are in order to plan quantification of nexus, and final workshop was organized to compile all the activities, plan for final report preparation and discuss additional research needs.

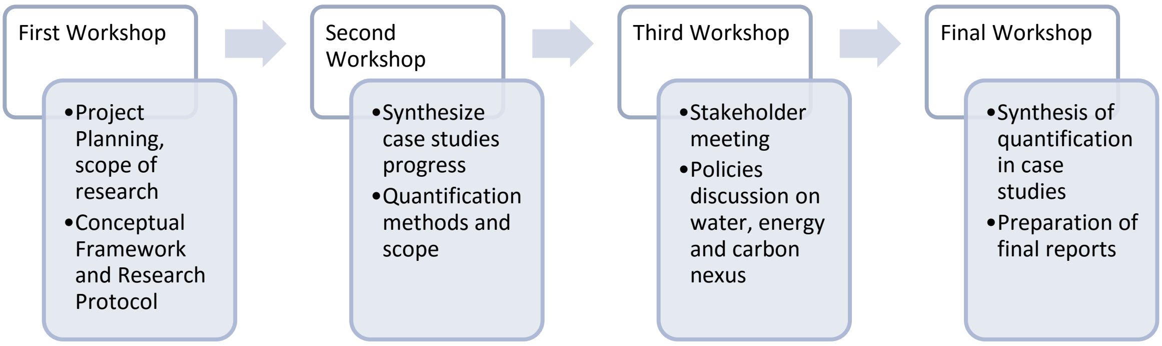

Figure 1: Highlights on outcomes of workshops

Some of the photographs from the project workshops are attached below:

WEC-Nexus's second workshop to synthesize city case studies

Stakeholder workshop on policies discussion of water, energy and carbon (WEC) nexus in Asian cities

4.3 Case Studies

Case studies of four cities namely, Bangkok, Tokyo, Delhi and Kathmandu (Kathmandu was additional city) were done throughout this project period. The case studies followed the common framework while in some cities several extensions were done capturing unique components. Case of Delhi has focused also on end-use water consumption and the water required for Energy production. In other case studies, the energy production systems are located outside the city boundaries and hence only focused on energy for water systems. While all the cities cases focused on municipal urban water and wastewater sectors, the consumption of bottled water was beyond the scope of this project, it was undeniably important aspect of water-energy-carbon nexus in cities, mainly in the cities like Bangkok, where individual's carbon footprint is well above cities of other developed countries. As many cities have been voluntarily committing to reduce their GHG emission, this research into water and waste water sectors and their energy-carbon footprint in crucial. Our research will help planner and policy makers to optimize water and energy systems in achieving low carbon urban sustainability goals.

5. Results

The case studies presented the status of current water-energy-carbon nexus in four cities. Although the data analysis have been done mostly for few previous years, the results are presented generally in average numbers. The results also present the commonalities and differences among cities which provides avenue to learn from cities. Each cities has potential to optimize nexus and make water infrastructures sustainable. With this research project it tries to fill the gap in knowledge and guide policy makers and decision makers of city government. The outcomes of the project has scientific contributions in this area from our published journal articles, policy brief and presentations. We also established network of researches and practitioners from city government for any future synergetic activities or research. Number of students in all our collaborated institutions had opportunities to work and learn from this project and few carried out their masters' and doctoral research inline to this project scope.

6. Relevance to the APN Goals, Science Agenda and to Policy Processes

This research took up a new research frontier in the low carbon city research in Asia. It hopes to stimulate a new thread of research in the region through producing conceptual framework of an integrated research and quantification for others to follow. Collectively, the project utilized the outcomes of this research methods and learning to mobilize students and local researchers to conduct more case studies and refine integrated concepts and methods. This research contributes to the several goals of APN as outlined in the above mentioned document. It takes up integrated research agenda and promotes regional cooperation amongst the researchers and institutions. Given importance of each of the topics (water, energy, and climate change mitigation) in the region, such integrated agenda which is place-based, for cities in developing country, and involvement of key scholar from scholars from developing country assist not only in research capacity building but also pushes the research frontier itself. This research also tried to provide a new insight to decision makers who are otherwise tackling water, energy and carbon separately. Moreover, one of the key APN Goal is to improve the scientific and technical capabilities in the region for which this proposal hopes to kick-start a new stream of research in Asia and make the involved institutions Center of Excellences in this area for more work to commence in the future. One of the key Science Agenda of APN in its Third Strategic Plan is 'Resources Utilization and Pathways for Sustainable Development' to which this proposal directly contributes. For APN's Institutional Agenda, this project will aid to the agenda of Future Earth's several core projects and the knowledge networks such as De-carbonization and Urban Futures. This project also directly contributes to the Urban and Regional Carbon Management Initiative of the Global Carbon Project (GCP), Urbanization and Global Environmental Change (UGEC) and several others.

Energy security, climate change mitigation and water security are three key contemporary policy agenda globally related to the sustainable development. In cities' context, many of these are interlinked and addressing them in an integrated fashion is useful for local decisions makers and also to maximize the benefits from global support mechanisms tailored to each issue. The policy dialogue among stakeholders from three cities have helped us organize our research and also establish a network to pursue future research and development. This project hoped at creating better knowledge of integrated approach that are relevant to the decision makers and even show potential opportunities there.

7. Self-evaluation

- The first objective of our study was to characterize the nature of water-energy-carbon nexus in cities. We completed characterizing nexus and synthesizing case studies on Bangkok, Delhi and Tokyo. We had additionally considered case study of Kathmandu.
- The key highlights of first year activities include establishment of project website, organizing numbers of stakeholder workshops, publish document on conceptual framework, collecting information in cities.
- Second year project activities highlighted on case studies in different cities focusing on different elements of urban water system, their energy and chemical uses, final workshop on synthesizing case studies.
- Number of findings have been published in different journals, policy briefs and number of presentations have been delivered in different conferences and forums. At the time this final report was prepared, a scientific paper in the form of peer-reviewed journal paper is on progress.

8. Potential for further work

The planning process in two entities of water and energy have been focused primarily on securing water and energy securities. Sustainable design of water systems with net zero emission shall be future aim. Technologies will be having the important role in maintaining environmental balance and adapting to the changing environment. Capacities of the water and energy planner shall also be enhanced to understand the need for low carbon goals and transform policies and management towards net zero emission. As we understood water, energy and carbon footprints there are knowledge gaps on multiple other dimensions linked to this nexus, for e.g., changing climate, socio-economic interrelations etc. City planners, policy makers and researcher should work closely to generate knowledge and make legitimate application. If we look into broader picture beyond city, water-energy-food nexus is also one of the vital area that need further research.

9. Publications

9.1 Policy Brief

- Dhakal, S., Shrestha, S., Shrestha, A., Kansal, A., and Kaneko, S. (2015). Towards a better water-energy-carbon nexus in cities (APN Global Change Perspectives Policy Brief No. LCD-01). Kobe: Asia-Pacific Network for Global Change Research.

9.2 Papers

- Ruchira Ghosh, Arun Kansal, Sakshi Aghi (2016). Implications of end-user behavior in response to deficiencies in water supply for electricity consumption – A case study of Delhi. Journal of Hydrology 536, 400–408.

- Pratima Singh, Arun Kansal, Cynthia Carliell- Marquet (2016).Energy and carbon footprints of sewage treatment methods. Journal of Environmental Management 165, 22-30.

9.3 Presentations

- Dhakal, S., Shrestha, A., Shrestha, S., Kansal, A., and Kaneko, S. (2015). Water-Energy-Carbon nexus in cities. Presented at APN side event at Regional Forum on Climate Change (RFCC). Asian Institute of Technology (AIT) Conference Center in Thailand, 2 July 2015.

- Dhakal, S., Shrestha, A., Shrestha, S., Kansal, A., and Kaneko, S. (2015). Water-Energy-Carbon nexus in cities- Cases from New Delhi and Bangkok. Presented at International Expert Workshop on Water Energy Food Nexus: Challenges and Opportunities in Mekong Region. Organized by SEA-EU-Net and Asian Institute of Technology, Thailand. 22-23 January 2015.

- Shrestha, S. Dhakal, S., Shrestha, A., Kansal, A., and Kaneko, S. (2015). Water-Energy-Carbon Nexus in Cities: Cases from Bangkok, New Delhi, Tokyo. Presented at workshop on "Water Energy Food Nexus: International Cooperation and Technology Transfer", Paris, 18 March 2015.

- Shrestha, A., Dhakal, S., Shrestha, S., Kansal, A., and Kaneko, S. (2014). Understanding and Quantifying the Water, Energy and Carbon Nexus for Low Carbon Development in Asian Cities. Presented at APN's Low Carbon Initiative (LCI) session in 3rd Annual Meeting of Low Carbon Asia Research Network, Indonesia, 24-26 November 2014.

10. Acknowledgments

We heartily acknowledge Asia-Pacific Network for Global Change Research for financial support to accomplish this important collaborative research by binding three educational institutions together. Through support from APN we were able to achieve our project goals, create a network of stakeholders from different countries and our research outcomes could further guide future research and development needs in Asia. Our projects would not have been possible without the role and interests from our partner stakeholders and policy makers. We would like to thank Bangkok Metropolitan Administration, Ministry of Environment- Japan, Delhi water board (Delhi Jal Board), Kathmandu Upatyaka Khanepani Limited (KUKL) for their kind support in providing us required data.

1. Preface

Many cities are setting greenhouse gases reduction targets voluntarily or as the commitment to address global climate change and implementing plans to reduce these greenhouse gas emissions. Cities are the major contributor of climate change, and they are also most affected by the impacts of climate change. Despite less than 2% coverage of the earth’s surface; cities consume 78% of the world’s energy and produce over 71% of global energy related CO_2 emissions and more than 60% of total greenhouse gas emissions combining energy generation, vehicles, industry, and biomass use (UN-Habitat, 2012).World’s urban population expected to double up to 6.3 billion from 3.48 billion now (in 2014) by 2050, and urban areas currently already responsible for over 71% of global energy related CO_2 emissions. Water and energy sectors are two crucial systems in the cities. Water security, energy security and climate mitigation being three important contemporary policy issues, understanding the linkages between water and energy systems helps policy makers and city planners to build efficient urban water infrastructures for future. As these two entities, currently being perceived and planned separately, their significant bonding cannot be overlooked while planning sustainable development. There are significant energy and water footprints in water sector and water footprints in energy sector. In both of this interlinkage there are significant amount of carbon emission. This gives rise to the concept of Water-Energy-Carbon Nexus to explore optimization of energy use and carbon emission while securing water and energy demand. The range of energy use in water/wastewater sectors by cities can be 1 to 18 % of the total energy used by the whole city.

On the other hand there are significant knowledge gaps and limited researches were being done in Water-Energy-Carbon Nexus in cities, especially in Asian cities. We tried to look into four Asian cities: Bangkok, New Delhi, Tokyo and Kathmandu, focusing on their urban water and waste water sectors to quantify their energy and carbon footprints. The general conceptual framework was developed to cover all elements of urban water system from source water abstraction, water conveyance, water treatment, water distribution, wastewater collection, wastewater treatment and disposal.

2. Introduction

Water, Energy and Carbon (WEC) nexus is central to the interaction of natural, social and economic environments. Past researches and our understanding of drivers, processes and implications of this nexus in cities are very limited, while cities are key places to analyze this nexus given the present context of speed and scale of urbanization. Today the Asia's urban population is 44 percent which is expected to reach 64 percent at the middle of the century (UN, 2012). Water and energy are inherently linked, with added challenges due to population growth, climate change, urbanization, increasing consumption pattern of energy and water. Hence, there should be integrated approach in decision making and planning processes. This is the novel research in the emerging field and highly relevant in Asian context due to very limited research done in Asia but of high policy relevance.

Our selected cities characterize different stages of development with distinct differences in geographical, social and climatic environments.

2.1 Participating countries

Following project collaborators and researchers have worked for this joint collaborative project.

- **Thailand**,	Dr. Shobhakar Dhakal, AIT, *Email: shobhakar@ait.asia*
	Dr. Sangam Shrestha, AIT, *Email: sangam@ait.asia*
	Mr. Ashish Shrestha*,* AIT*, Email: ashish@ait.asia*
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- **India**,	Prof. Arun Kansal, TERI University, Email: *akansal@teri.res.in*

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- Gauzing the extent and relevancy of addressing the barrier and opportunities for optimizing the nexus, as well as influence the policy for low-carbon development.

2.3 Overview of Water-Energy-Carbon Nexus in Cities

Water footprints in energy sectors and energy footprints in water sectors are increasing being a concern in development and planning process. Since both of this resources, water and energy are becoming limited, it underscore the need to understand this inter relationship in a coherent way. The overall goal of understanding this nexus is to optimize the energy and water use for maximum benefit and sustainable growth while reducing carbon emissions. Cities or urban spaces are significant area to study this water, energy and carbon nexus because of several reasons including, high population density, complex agglomeration of infrastructures, economy, industries, technologies and its overall dynamic nature. Cities are the major consumers of water and energy. Urban water sector is complex and diverse which involves processes of water services delivery to different economic sectors. Urban areas utilize 1 to 18 % of electrical energy to treat and transport water and waste water, which account for 2 to 3 % of world's energy being utilized for water and sanitation purposes (Olsson, 2012). In California 19 % of electricity used in the state was for water related services including agriculture (Stokes and Horvath, 2009). The high energy demand for water utilities is one of the shortcoming in sustainable management of water and sanitation services in developing and developed countries. Usually fossil fuels are the primary sources of energy which produce considerably amount of carbon dioxide and other GHGs in the atmosphere. Hence, it is necessary to comprehensively and quantitatively understand the urban water cycle and urban energy processes to estimate interlinked water, energy and carbon footprints.

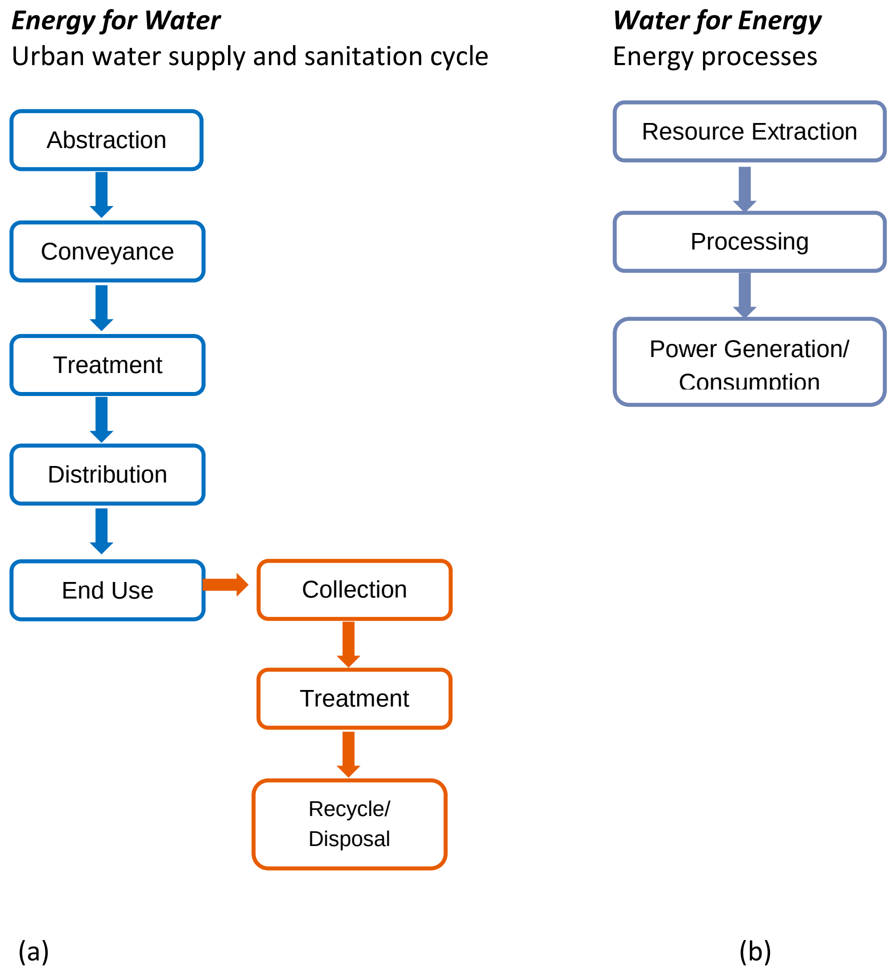


Figure 2: Water and Energy Cycle/Process

Urban water cycle can be described through the processes of source water abstraction, conveyance, treatment, distribution, end uses, waste water collection, treatment, and recycle/disposal. Energy use cycle can be described through the processes of extraction, processing and power generation/consumption (Figure 2).

2.3.1 Quantifying Water, Energy and Carbon Nexus

Energy for Water or Energy Footprint in Water/Wastewater Sectors

Energy required to deliver water varies greatly between water utilities influenced by geography, topography, climate and available infrastructures. The source and water quality have a significant impact on overall energy uses in urban water system. For wastewater treatment process, energy requirement is influenced mostly by treatment standards and regulations. Primary and secondary treatment processes in both water and waste water consumes less energy compared to their tertiary treatments. Electric loads at urban water and wastewater utilities involve application of pump motors, air blowers, injection equipment, controls, lighting, also use of energy intensive treatment technologies like ultraviolet light disinfection and ozonation.

The average figures for energy footprints in water utilities based on various references on different country scale are summarized below:

Table 1: Energy footprints of water service delivery in different countries

Countries	Aspect	Energy Intensity		Units	Source
		Range	Average		
Australia	Energy: Water Utilities	0.09 – 1.92	0.82	kWh/m^3	Kenway *et al.* (2011)
	Energy Waste Water Utilities	0.45 – 1.13	0.76		
	Waste Water treatment: Primary	0.36 – 1.34	0.80	GJ/ML	Kenway *et al.* (2008)
	Waste Water treatment: Secondary	0.93 – 2.96	1.65		
	Waste Water treatment: Tertiary	1.14 – 39.6	3.25		
United States	Surface water treatment plants	1407 - 1483	-	kWh/MG	GWRC (2013)
	Wastewater treatment	-	2500.00	kWh/MG	CEC (2005)
	Production & distribution of potable water in Western US	5000 - 15000	-	kWh/MG	Wilkinson (2000)
	Production & distribution of potable water in Eastern US	1800 - 2500	-	kWh/MG	U.S. Department of Energy (2006)
	California – Water conveyance	0.00 – 1.06	-	kWh/m^3	CEC (2005), Valentina *et al.* (2012)
	California – Water Treatment	0.03 – 4.23	-	kWh/m^3	
	California – Water Distribution	0.18 – 0.32	-	kWh/m^3	
	California – Waste Water collection & treatment	0.29 – 1.22	-	kWh/m^3	
Canada	Water treatment	-	280.00	kWh/ML	GWRC (2013)
	Water distribution pumping	-	300.00	kWh/ML	
	Wastewater pumping	-	100.00	kWh/ML	
	Wastewater treatment	-	450.00	kWh/ML	
Germany	Water conveyance & treatment	0.12 – 1.13	-	kWh/m^3	Valentina *et al.* (2012)
	Water Distribution	0.03 – 0.58	-		
	Waste Water collection & treatment	0.39 – 0.83	-		
Singapore	Water conveyance	-	100.00	kWh/ML	GWRC (2013)
	Water treatment (pumping)	-	240.00	kWh/ML	
	Water treatment (process)	-	220.00	kWh/ML	
	Waste water conveyance	-	70.00	kWh/ML	
	Waste water treatment (pumping)	-	90.00	kWh/ML	
	Waste water treatment (process)	-	54.00	kWh/ML	
UK	Total energy use by all water sectors (2009/10)	-	9012.00	GWh	GWRC (2013)
Norway (Oslo)	Electricity use in Water treatment (in 2007)	-	22.80	GWh	Venkatesh and Brattebo (2011)
	Diesel fuel (in 2007)	-	180.20	MT	
	Electricity use in Waste Water treatment (in 2007)	-	39.17	GWh	
	Heating oil	-	1.11	GWh	

In wastewater treatment process, the most energy consuming processes are aeration for biological treatment, and pumping, mechanical treatment and ventilation for odor control. The typical breakdown of energy consumption for French conventional wastewater treatment plants with nutrient removal are presented in Figure 3.

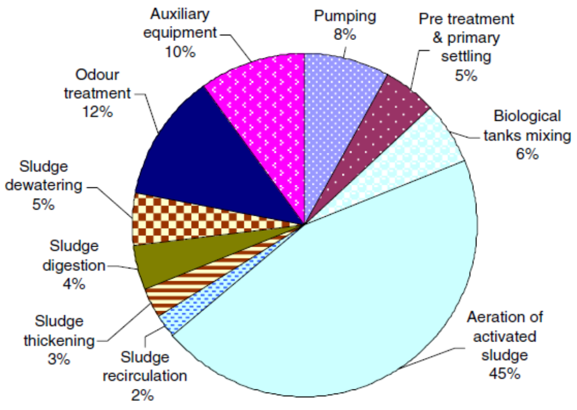


Figure 3: Typical energy consumption breakdown of a conventional WWTP in France. Source: Valentina *et al*. (2012), Martin and Aguilera (2011)

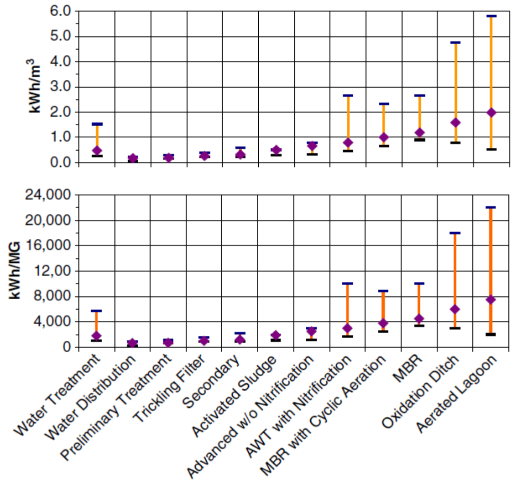


Figure 4: Energy use range in different elements of water and waste water treatment processes. Source: Valentina *et al*. (2012)

The tertiary treatment such as membrane processes, aeration of activated sludge utilizes maximum amount of energy in conventional wastewater treatment facilities. The range of typical energy consumption values and its average are presented in Figure 3 and 4.

Water for Energy or Water Footprint in Energy Sectors

Even in 20th century where fossil fuel is extracted in tremendous quantity, the water footprint of energy is still not comprehensively understood and documented. Water is the major component of energy production and future of water availability plays crucial role in energy security and sustainability. Energy sector utilizes water and specifically energy production process consume freshwater than any other sector after agriculture. Worldwide freshwater water withdrawal for energy sectors accounts up-to 8% while in developed countries it is up-to 40%. The water used in the energy sector also pollute the water sources. The consumption of water for producing coal only accounts for 20% of water consumed. In USA water consumption in energy sector is growing rapidly which will account for 125% increase in water use for energy production by 2025 (Olsson, 2012).

The energy processes involves extraction, processing and power generation. In city scale only the consumption process occurs within the boundary in general. But it is important to consider upstream implications of water and carbon footprints to quantify the nexus.

- *Extraction*: Oil (Primary, Secondary, Tertiary recovery), Natural gas, Shale gas, Coal
- *Processing*: Crude oil refining, Coal to liquids, Liquids to gas

- *Power generation/ consumption*: Fossil fuel/biomass steam turbine, combined cycle gas turbine, nuclear thermoelectric power plant, Wind power, Solar PV, Concentrating solar power, geothermal, hydropower.

A study by Mielke *et al.* (2010), in U.S. to quantify water footprint in energy sector presents typical figure of water footprint for each processes of energy production. Although these data varies within countries the information provides general portrait of water used by energy sector.

Table 2: Water footprints of energy processes in U.S.

Processes	Elements	Water Uses (gal/MMBtu)	
		Range	Average
Oil extraction	Oil (Primary- Secodary)	1 - 62	61.0
	Oil sands	9 - 34	22.0
	Shale Oil	6 - 38	22.0
Natural gas extraction and transportation	Conventional natural gas		0.1
	Shale gas extraction	0.6 – 1.8	1.4
	Pipeline transportation	0 – 2	1.0
Coal extraction and transportation	Mining	1 - 6	2.6
	Washing	0 - 2	0.9
	Mining + Washing	1 - 8	3.5
	Slurry Pipeline	3.2 – 7.2	5.3
Fuel processing	Crude oil refinery	9 - 14	10.0
	Corn ethanol dry mill	0 - 130	35.0
	Cellulosic biorefinery	24 - 120	70.0
Coal-to-liquids and gas-to-liquids	Coal production	0 - 9	4.0
	Coal to liquids	39 - 60	51.0
	Coal + Coal to liquids	40 - 69	54.0
	Natural gas production	0 - 5	3.0
	Gas to liquids	19 - 86	42.0
	Natural gas + Gas to liquids	19 - 90	45.0
Uranium fuel	Mining	1 - 6	3.5
	Enrichment	4 - 8	6.0
	Mining + enrichment	5 - 14	9.5

2.3.2 Drivers for Nexus

People have developed infrastructures and technologies for water services, which are also constantly being influenced by factors such as availability of natural resources, climate change, water demand and environmental regulations. The approach and nature of water abstraction and use within cities are dynamic with many external influencing factors. In general, urban fresh water could be abstracted from rivers basins or ground water aquifer. The sources for urban water supplies varies even within cities. Water security has become significant issues, which are driven by many environmental factors, as a result policy makers regard the inter-basin large scale transport of water as feasible and already in plans for eg. in China, India, South Africa and Spain (Hoekstra, 2011). Huge infrastructure are required to abstract, transport, treat/collect, distribute/dispose, freshwater and wastewater. By 2000, there were more than 50,000 large dams (with storage capacity over 3 million m^3) in operation. In 2006, 54 % of world's population had piped drinking water connection with considerably progress in East Asia having coverage up to 88% (World Water Assessment Programme, 2009).

The emerging challenges and drivers that affects the nexus are:

- **Climate change –** The implications of climate change are understood in volume of water availability and frequency of extreme events such as floods, droughts, heat waves etc. It creates uncertainty about trends, extremes of future climate variables. The normal climate trend alters as a result some basin receives excess water while other basins suffers drought. The groundwater table, river discharges are all affected hence creating pressure on water services management. Climate change is one of the contributing factor that drives change in technology and infrastructure in water utilities. The future changes in climate might make our current and old models of water supply obsolete.

- **Increase in population -** World's population doubled; from 1 billion in 1800 to 2 billion in 1930, and 6 billion in 1999 from 3 billion in 1960. Today the world's population exceed 7 billion. UN population division projects that the population will surpass 9 billion by 2050. Population growth is not only directly related to increased water and food demand. The consequences are linked with many indirect impacts including contribution to GHG emissions and use of high quantity of fossil fuels. The urban population are also increasing due to migration and increased urbanization.

- **Increase in urbanization -** Today the Asia's urban population is 44 percent which is expected to reach 64 percent at the middle of the century (UN, 2012). For developing world, it is expected that by 2030, 56 % of their population will live in cities. The major challenge involved with urban areas is the unpredictability and migration trend, in order to ensure proper water and energy services.

- **Change in technologies –** The advanced technologies are being implemented in water utilities which are generally energy intensive. Technology such as membrane based reverse osmosis consumes higher amount of energy compared to conventional system using coagulation and flocculation and rapid sand filtrations. Most of the cities are now conveying water from inter-basin sources over the long distance. The decrease in fresh water availability is also one of the factor for shifting towards alternate source for e.g. desalination. Different desalination techniques involves different intensities of energy uses: single stage evaporation (650 kWh/m^3), multistage flash (55-80 kWh/m^3), multi-effect distillation (40-65 kWh/m^3) and reverse osmosis (3.7 kWh/m^3) (Semiat, 2008). One particular study in California showed that if water supply from desalination is implemented the electricity consumption would be 52% of total electricity used in the state (Stokes and Horvarth, 2009).

- **Ageing infrastructures –** The asset management in water utilities have been the growing priority as well as area of increasing research and development. The ageing infrastructure have consequence on water leakage at cost of both water and energy. The water pricing mechanism plays major roles in controlling the water losses. The water losses in some developing countries exceed 40 %. The prevention of physical water loss means reducing energy and carbon footprints in water services.

- **Regulations**

  Pollution -The waste water generated through the water consumption process are treated up to the safe disposal threshold limit for each and every pollutants. The regulations are maintained by the city authorities normally under guidelines of World Health Organization (WHO). The regulation is very important in order to prevent: water sources contamination, soil salinization, ground water pollution and health related hazards. Furthermore, pollution charges for discharging wastewater to water bodies can drive innovation in recycling or additional treatment.

Environmental Consideration- Environmental flows during water abstraction and its associated impacts on ecosystems are well addressed in some nations while in some places it is still neglected. Research in Asia and the Pacific showed that 23 out of 48 countries are undertaking activities to integrate environmental flows into local, regional and state level planning processes (World Water Assessment Program, 2009).

2.4 Methodology

The overall project methodologies can be summarized into:

- Conceptual framework and protocol for case studies (Delineation of boundaries and scoping)
- Data collection (Every elements of urban water systems) – Primary & secondary data, Survey, modelled data.
- Conceptualizing the framework and case studies, identifying important drivers and issues in each cities.
- Quantification of energy and carbon footprints and synthesis of case studies.

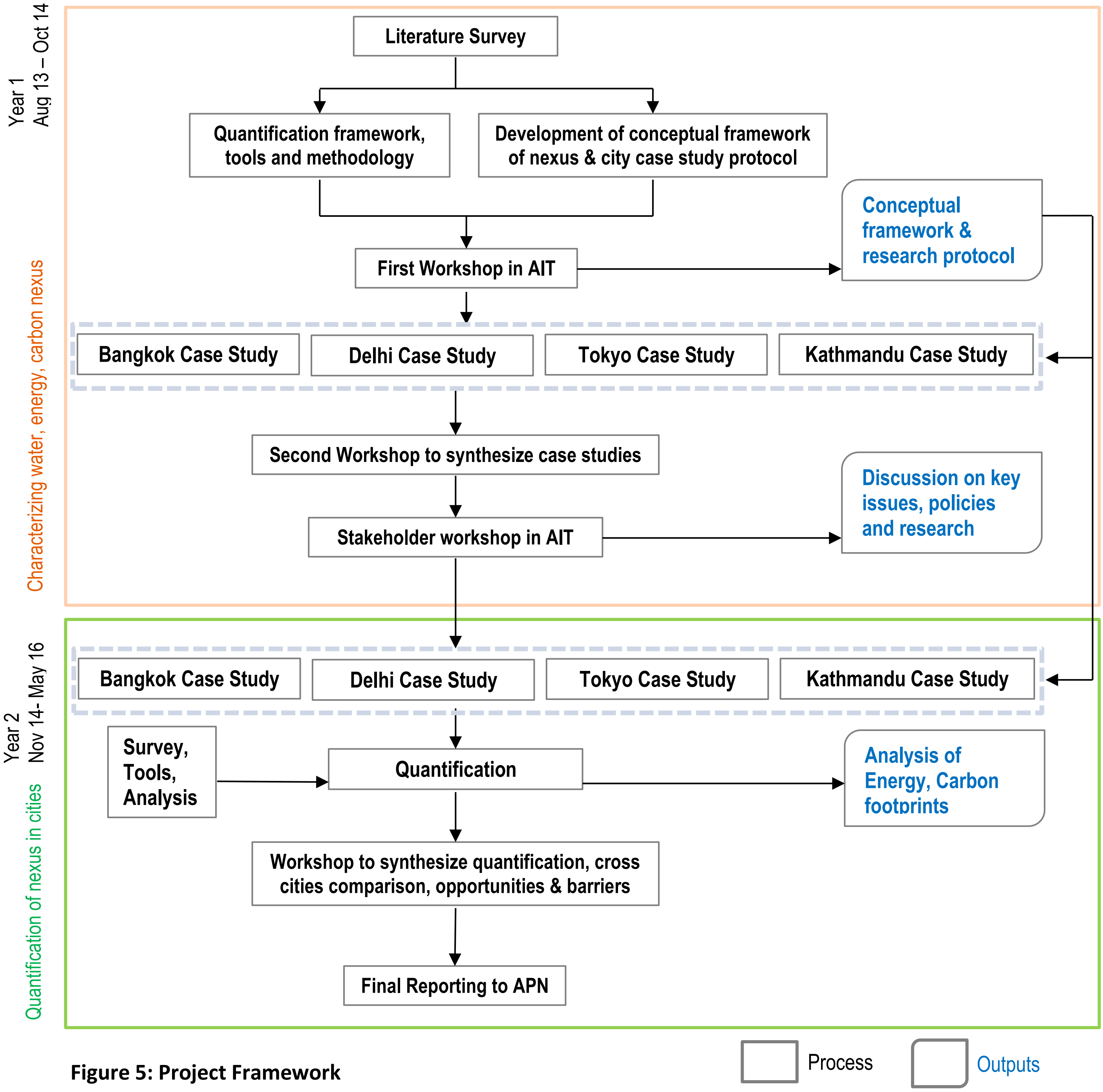
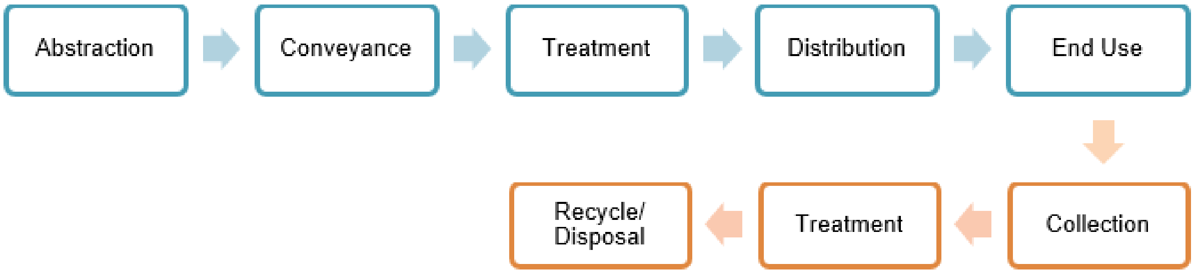


Figure 5: Project Framework

2.4.1. Overall framework

The whole cycle of water abstraction, transport, treatment, distribution, consumption and then collection and treatment of waste water requires energy. The process of the urban water supply and sanitation can be divided into elements as shown in figure below for nexus study.



In each of the elements of the cycle we traced what are the energy linkages. This will give us better portrait for quantification.

- **Abstraction** – Water sources in the cities are mainly from surface and groundwater. Historical trend shall be presented which shows historical data on share in total energy abstraction, distance and depth (of surface water and ground water).

  Surface water – River and lake them pumping but could be gravity flow too. Furthermore there is direct GHG (Carbon dioxide, Nitrous Oxide etc.) emission especially when barrage is constructed

  Ground water - There are public and private sectors extracting water. For the scope of the study we will consider only large private players and public sectors. While individual pumps in households can be clustered together. Sample survey can provide this required information. Carbon footprint can be further linked with the pumping. Groundwater is considered mainly for Delhi and Kathmandu.

- **Conveyance** – Conveyance is transport of water from source to treatment plant. Conveyance system is considered mostly for surface water while for groundwater it is not the big issue. Perhaps conveyance system in groundwater is highly variable and will not be included in the study. There are generally two systems of conveyance I.e. Open canal system (losses could be more) with barrage and piped (loss will be less) with pumps or intermediate pumps. Embodied energy is considered in Delhi, for the pipes, concrete in canal and other materials used.

- **Treatment (embodied, direct, construction, operation)** – Energy footprint in highly variable in water treatment plant (WTP) based on water quality standards, technology choice, scale of treatment and degree of automation. Highly automated system has high energy footprint and good reliability of water quality. Whenever there is low reliability in the water quality, domestic purifier is used intensively. Operational energy is considered for all the cases and specific embodied, direct and construction are considered for Delhi.

- **Distribution** – Essentially booster pumping at centralized or household sector contribute to the energy footprint. It is now known there are public or private sector; piped distribution and tanker supply by public/private sector. Tankers have high energy and carbon footprints (Delhi Jal board has 4,000 tankers) while investment in water distribution infrastructure has energy implications. Design life is also important as it is allied with embodied energy, reliability, quality and others. Design life of pipe lines and other infrastructure determine the condition of the infrastructure related to quality, reliability, pressure. In general, it is also known that when reliability is poor then more energy is used to compensate low pressure and poor water quality.

- **End use** – Energy use related to the use of domestic purification for drinking and cooking (purifier or bottled water). Energy footprint for bottled water can be considered in the end use.

  Sample survey can be done in household if they use no treatment, ultraviolet filter, reverse osmosis or purchase bottled water. The energy footprint data is available for these devices and we can calculate the total energy footprint of the household to city level. Our case study in Delhi has considered end use side to study energy-water-carbon interrelations.

- **Collection of wastewater** – Collection infrastructures are generally more for centralized system. The types of collection system is linked to direct GHG emissions. Climate conditions for e.g. temperature as well as conveyance distance affects the GHG emissions from sewers. In combined sewer system storm water are collected together with the waste water. Storm water is considered within the wastewater.

- **Wastewater treatment** – Energy footprint again depends on the types of system, technology choices, water quality output (disposal standards) etc. which is highly variable. Biogas production is included in the waste water treatment as it is common in the waste water treatment plants. Energy recover shall be considered wherever there are those systems. There are also methane recovery from treatment and using as energy, cogeneration and CHP system in practice to manage energy demand. Energy footprint can be reduced when energy is recovered. The study shall give city planners various opportunities to reduce their energy and carbon footprint.

- **Recycle/Disposal** - Water recycling and reuse is term which is used in the context of industries. In the context of municipal system only recycle term is used. Sludge produced from treatment process is used as a fertilizer in general case while it is also used for landfill materials. Wherever the plants is recycling waste water, energy footprint will be different and shall be considered. Some studies are being done for combination of different treatment options and disposal.

Each cities case studies follow the common research protocol, however research methodologies are to some extent unique due to specific issues, data availability and different types of water and wastewater systems existing in diverse conditions. Below are further details on research methodologies and data.

2.4.2 Summary of data

Summary of data used for each case studies

Table 3: Data summary

City	Data Type	Source	Details	Remarks
Bangkok	Water Treatment	MWA, MWA Reports	Water abstraction, transport, treatment, distribution's volume, energy use, chemical	• Raw data and secondary data from MWA, PWA, BMA and the published report and articles were utilized.

			use data from 2004 to 2015.	• Water treatment data from four water treatment plants (Bangkhen, Samsen, Mahasawat and Thonburi) of MWA and (Pathumthani, Bangsue) of PWA were utilized to obtain energy intensity for each unit of water processing every elements of water supply system. • Waste water treatment data were collected from seven waste water treatment plants (Si Phraya, Rattanakosin, Dindaeng (BMA-1), Chong Nonsi, Nong Khaem, Thung Khru and Chatuchak) to obtain energy intensity for treatment and pumping systems. • Carbon footprints were generated by obtaining emission factor for each unit of electricity consumed and multiplying emission factor with energy intensity.
	Water treatment and Waste water treatment policies	MWA, BMA	Plans, policies and strategies	
	Waste Water Treatment	BMA	Waste water treatment, pumping systems volume, energy use data from 2005 to 2015.	
	Emission factors	EPPO, EGAT	Data of 2010 to 2011	
Tokyo	Water Treatment	Bureau of Waterworks, TMG	Water abstraction, transport, treatment, distribution’s volume, energy use, chemical use data from 2000 to 2013.	• Secondary data from Bureau of Waterworks and Bureau of Sewerage Tokyo Metropolitan Government were utilized. • Water treatment data from eleven water treatment plants (Kanamachi, Misato, Asaka, Misono, Higashi-Murayama, Ozaku, Sakai, Kinuta, Kinuta-shimo, Nagasawa and Suginami Purification Plants) were utilized to obtain energy intensity for each unit of water processing every elements of water supply system. • Waste water treatment data were collected from seven waste water treatment plants (Shibaura, Mikawashima, Sunamachi, Ariake, Nakagawa, Kosuge, Kasai, Ochiai, Nakano, Miyagi, Shingashi, Ukima and Morigasaki) to obtain energy intensity for treatment and pumping systems. • Carbon footprints were generated by obtaining emission factor for each unit of electricity consumed and multiplying emission factor with energy intensity.
	Water treatment and Waste water treatment policies	TMG	Plans, policies and strategies	
	Waste Water Treatment	Bureau of Sewerage, TMG	Waste water treatment, pumping systems volume, energy use, chemical use data from 2000 to 2013.	
	Emission factors	Tokyo Electric Power Company (TEPCO).		
New Delhi	Water Treatment	Delhi Water Board, Central Ground Water Board, Primary Survey, Secondary sources, Government publications, Interviews	Water abstraction, transport, treatment, distribution’s volume, energy use, chemical use data.	• Raw data and secondary data from Delhi Water Board and the published report and articles were utilized. • Data from Haiderpur, Nangloi, Dwarka, Okhla II and Bawana Water Treatment Plants (WTPs) • Wastewater treatment data from large-scale - municipal STPs to decentralized small-scale - institutional STPs • End Use data are collected through primary survey of sample households. • Energy footprint and carbon footprints were generated by emission factor.
	Water treatment and Waste water	Delhi Water Board, Secondary sources	Plans, policies and strategies	

	treatment policies			• Data collected for Rajghat Power House, Badarpur TPP, Gas Turbine Power Station (GTPS), Pragati-I Power Station, Pragati-III Power Station
	Waste Water Treatment	Delhi Water Board, Primary Survey, Secondary sources	Waste water treatment, pumping systems volume, energy use, chemical use data	
	Thermal Power Plants	Secondary sources	Energy production, Water Uses	
	Emission factors	Secondary sources	Energy emission factor, Carbon emission factor	
Kathmandu	Water Abstraction, Volume	KUKL, KUKL reports	Water abstraction, treatment, volume of distribution	• The study used raw data and secondary data from KUKL annual reports and news articles. • Water treatment data was also retrieved from sources alike. • Energy for abstraction was calculated using the data on extraction volume and depth of water table. • Energy intensity for treatment was calculated using a standard provided by AwwRF for low-range treatment plants considering Kathmandu's treatment plants were at a primitive stage. • Energy and Energy Intensities for Distribution were generated by simple physics formula as indicated. • Carbon footprints were generated by obtaining the emission factor for each unit of electricity consumed and multiplying the EF with energy intensity.
	Water Treatment	KUKL, KUKL reports, AwwRF report	Water treatment data from KUKL's presentation files and official reports	
	Emission factors	International Energy Agency (IEA)	From year 2014	

2.4.3 Workshops

Various workshops were conducted during the project periods to collect information from cities. Summary of the project meetings, in the form of workshops and policy dialogue, conducted between project collaborators and also with participation of representatives of the local government of the case study cities are presented below:

Table 4: Highlights on different project meetings

	Dates	Meeting Participants	Discussions/ Outcomes
First Workshop	1st September 2013	AIT project teams (Dr. Shobhakar Dhakal, Dr. Sangam Shrestha, Mr. Ashish Shrestha), Collaborator from Hiroshima University (Prof. Shinji Kaneko)	▪ Project planning, scheduling, scope of research was finalized. ▪ Cities specific challenges, nature of nexus was deliberated. ▪ Framework of the WEC Nexus have been developed.
	9th -11th September 2013	AIT project teams (Dr. Shobhakar Dhakal, Dr. Sangam Shrestha, Mr. Ashish Shrestha), Collaborator	▪ Delineation of boundary conditions for cities while studying water for energy and energy for water was deliberated.

		from TERI University (Dr. Arun Kansal)	▪ Worked out on detailed framework to develop protocol for case studies. ▪ Conceptual framework and research protocol was prepared
Second Workshop	16th – 19th June 2014	AIT project teams (Dr. Shobhakar Dhakal, Dr. Sangam Shrestha, Mr. Ashish Shrestha), Collaborator from TERI University (Dr. Arun Kansal, Hiroshima University (Dr. Yuki Yamamoto)	▪ Synthesize case studies progress ▪ Planning of additional surveys and data requirements. ▪ Quantification method.
Third Workshop	4th – 5th November 2014	AIT project teams (Dr. Shobhakar Dhakal, Dr. Sangam Shrestha, Mr. Ashish Shrestha), Hiroshima University (Dr. Yuki Yamamoto),Delhi Water Board (Mr. Radheshyam Tyagi), Tokyo Metropolitan Government, Japan (Mr. Kenji Yasuno), Metropolitan Waterworks Authority (MWA), Thailand (Mrs. Chatsinee Surasen, Ms. Parichat Punthong), Bangkok Metropolitan Administration (BMA), Thailand (Mr. Wiruch Tanchanapradit, Dr. Pathan Banjongproo, Ms. Thanapon Kemdaeng)	▪ Policies discussion on water, energy and carbon nexus in three cities. ▪ Roles of local government in formulating policies in urban water sector. ▪ Quantification methodologies and contribution/participation from local government in our study.
Final Workshop	2nd and 3rd February 2016	AIT project teams (Dr. Shobhakar Dhakal, Dr. Sangam Shrestha, Mr. Ashish Shrestha), Collaborator from TERI University (Dr. Arun Kansal, Dr. Ruchira Ghosh), Hiroshima University (Prof. Shinji Kaneko)	▪ Synthesis of quantification in case studies

3. Description of cities

3.1 Bangkok

Bangkok, the capital of Thailand, is the urbanized commercial and industrial hub of South Asia and is situated in flat deltaic plain of Chao Phraya River. Thailand has international border with Myanmar (Burma), Laos, Cambodia and Malaysia. Thailand is divided into 5 regions: Central, East, North, Northeast and South. The study area lies in central region that has 5 major river basins: Chao Phraya, Tha Chin, Mae Klong, Lower Pasak and Sakae Krung. The study area covers Bangkok and adjacent provinces normally known as 'Greater Bangkok' or 'Bangkok Metropolitan Region (BMR)' as shown in Figure 6. BMR is urban agglomeration of Bangkok Metropolis and 5 adjacent provinces of Nakhon Pathom, Pathum Thani, Nonthaburi, Samut Prakan and Samut Sakhon. The area is flat and low-lying, with an average elevation of 1.5 metres above mean sea level. BMR has tropical wet and dry climate which is classified into three main seasons rainy (May–October), cool (November–January), and hot (February–April). The average annual rainfall is approximately 1,500 millimeters (mm). The temperatures are generally hot year-round, ranging from an average low of 20.8 °C (69.4 °F) in December to an average high of 34.9 °C (94.8 °F) in April. BMR covers an area of 7,761.50 km².

The residential and industrial water supplies in BMR are provided by a combination of surface water and groundwater, the latter being mainly used in the outskirts of the Bangkok metropolis. Piped water systems began in Bangkok in 1909. Metropolitan Waterworks Authority (MWA), the state owned enterprise, supplies water to Bangkok Metropolis, Nonthaburi and Samut Prakan; and Provincial Waterworks Authority (PWA) supplies water to Nakhon Pathom, Pathum Thani and Samut Sakhon. MWA and PWA is governed under Ministry of Interior. In 2006, MWA supplied piped water in total 4.66 million cubic meters mcm/day (equivalent to 91% of total demand) to residential, industrial, and commercial sectors from surface water sources. The remaining 9% of the water demand (about 0.5 mcm/day) was met by abstracting water from deep wells (Polprasert, 2007). This was largely done by industries, which prefer and are allowed by the Department of Groundwater Resources to use groundwater. Now MWA has the capacity of 5.9 million cubic meter per day and serves the total area of 2,596 km² which is 81 % of their total serviced area. The main sources of raw surface water (in MWA) are the Chao Phraya and Mae Klong rivers.

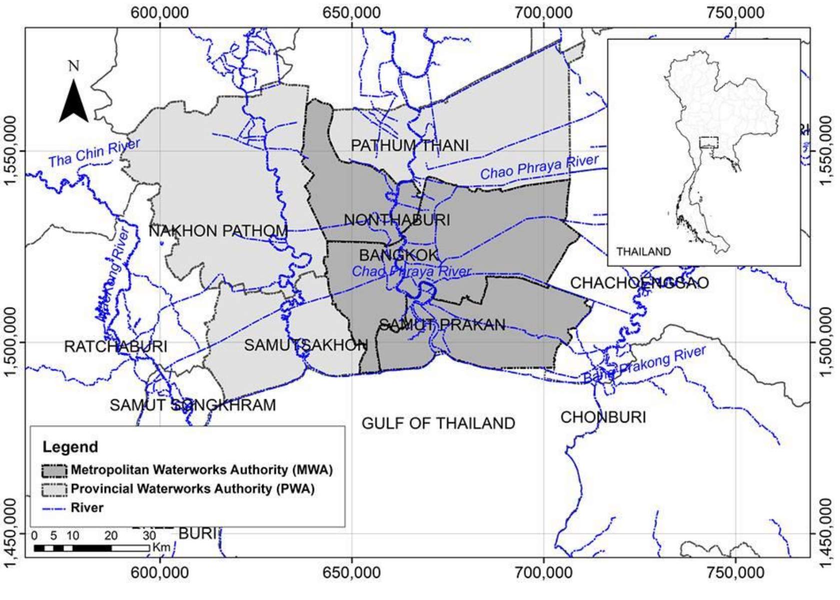


Figure 6: Map of Thailand and Bangkok Metropolitan Region showing six provinces

The most recent census in 2010 puts the population of the Bangkok Metropolis at about 8.2 million, and that of the BMR at about 14.5 million, up about 30 percent from 2000 in the city and about 43 percent in the BMR as a whole.[1] These numbers include the large unregistered population, mostly composed of rural migrants, which makes up about one third of the total population. The formal registered population of Bangkok city peaked at 5.84 million in 2003 and decreased gradually to 5.7 million in 2013, at the same time that population was increasing in the neighboring provinces (BMA 2013). Reasons for higher population growth in vicinity provinces (both for registered and unregistered populations) are the increasing economic activities there as the city expands outwards, and heavier in-migration from other provinces due to increasing employment opportunities. Population density in the city was 5,259 persons per km^2 and 1,877 in the BMR in 2010 (Census 2010).

Table 5: Demographic information of BMR

Provincial Boundary	Area (km^2)	Population	Population Density (Per Km^2)
Bangkok Metropolis	1,568.74	8,249,117	5,258.60
Nakhon Pathom	2,168.30	942,560	434.70
Nonthaburi	622.30	1,333,623	2,143.10
Pathumthani	1,525.90	1,326,617	869.40
Samut Prakan	1,004.50	1,828,044	1,820.60
Samut Sakhon	872.30	885,559	1,015.20

Bangkok Metropolitan Administration (BMA) has initiated Bangkok master plan on climate change 2013-2023, under support from Japan international Cooperation Agency (JICA). The program focus on key issues relevant to water, energy and nexus like efficient solid waste management and wastewater management, energy efficiency and alternative energy, green urban planning and adaptation planning.

3.1.1 Institutional Settings, Legislation and Practices

- ***Drinking water*** - On 16 August 1967, Metropolitan Waterworks Authority (MWA) was established as a state enterprise in accordance with Metropolitan Waterworks Authority Act of 1967. MWA has divided its service area in 16 branches to manage water provision, customer service, pipe and valve repairs, meter replacement, meter recording, bill collection, and other related services. MWA operates with close coordination among several other institutions of Thailand, namely, Office of National Economic and Social Development Board, Ministry of Interior (MOI), Royal Irrigation Department (RID) and Ministry of Public Health. In 1979, as demand for better service increased, the water delivery services to cities and municipalities became the responsibility of a state enterprise called the Provincial Waterworks Authorities (PWA) through a cabinet resolution in 1978. The aim was to increase flexibility and enhance efficiency by having everything under the responsibility of Department of Public Works, the Ministry of the Interior, and the Department of Health (DOH) within the Ministry of Public Health (MOPH).

  Several national policies, acts, legislations direct the water supply management in BMR. Conservation of Public Water Supply Canals Act of 1913 (amended in 1983) regulates pollution in canals. Groundwater Act of 1977 (amended in 1992 and 2003) regulates abstraction of groundwater. The Cabinet Resolution on “Remedial Measures for the Mitigation of the Groundwater Crisis and Land Subsidence in Bangkok” issued in 1983, which instructed the MWA to terminate its abstraction and use of groundwater for tap water supply.

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[1] http://www.citypopulation.de/php/thailand-prov-admin.php?adm1id=B

As MWA is the major responsible body to supply clean drinking water to increasing city demand, recent policies include increasing their capacity, connections, water pressure in distribution networks and reduce the non-revenue water losses. Some of the measures they have followed for water loss reduction are fundamental, symptomatic and preventive. MWA's water loss reduction project aims to improve distribution system efficiency improvement and automated control standards improvements. MWA aims to reduce water loss to 20% and to ensure the water pressure is no less than target 10 meters by 2017. The organization is also looking forward for optimizing energy conservation in production and distribution and application of renewable energy such as solar and mini hydro in water systems. MWA further has focus on long-term improvement framework for water supply infrastructure for the 30 year period (2018-2047) and preparing MWA plan to be completed in 2017.

- ***Wastewater and Storm water*** – The wastewater and storm water management in BMR falls under the responsibility of Bangkok Metropolitan Administration (BMA). Department of Drainage and Sewerage (DDS), which is one of the 14 departments of BMA, manage both storm water discharge and wastewater and sludge disposal (Chiplunkar *et al.*, 2012).

  The Enhancement and Conservation of National Environmental Quality Act (NEQA) (passed in 1975, amended 1978, 1979 & 1992) regulates environmental quality and protection. The effluent standards and treatment are regulated through this act. Industrial Estate Authority Act (1979). Other relevant acts for water quality management are Factories Act (1992), Hazardous Substances Act (1992) and Public Health Act (1992, amended in 2007).

  Some of the measures BMA are undertaking include promoting reduction of water usage at households and collect wastewater tariff. They are launching different campaigns in collaboration with DDS, Sanitation Dept. of District Offices, Community, Private sector (water saving devices manufacture, Advertising), NGO and private WWTP operators. The long term goals of the BMA is to expand their service areas and implement separate collection systems for waste water and storm water. Some of the measures also include replacing inefficient equipment, use more energy efficient equipment and construct more WWTPs.

3.1.2 Water Supply Management

The service area of MWA is 2,477 square kilometers divided into 16 branches. The number of customers totaled 2,017,531. A total of 1,716 million m^3 or 4.7 million m^3 per day was distributed through the pipe network along 27,485.3 kilometers to serviced areas. MWA covers 93% of the population in MWA service area.

The MWA has two major source of water abstraction with two major water conveyance channels. The groundwater extraction has been prohibited since few years for public water supply. The other provinces are supplied by PWA. Table 6 below shows the capacity and water production from WTPs of MWA.

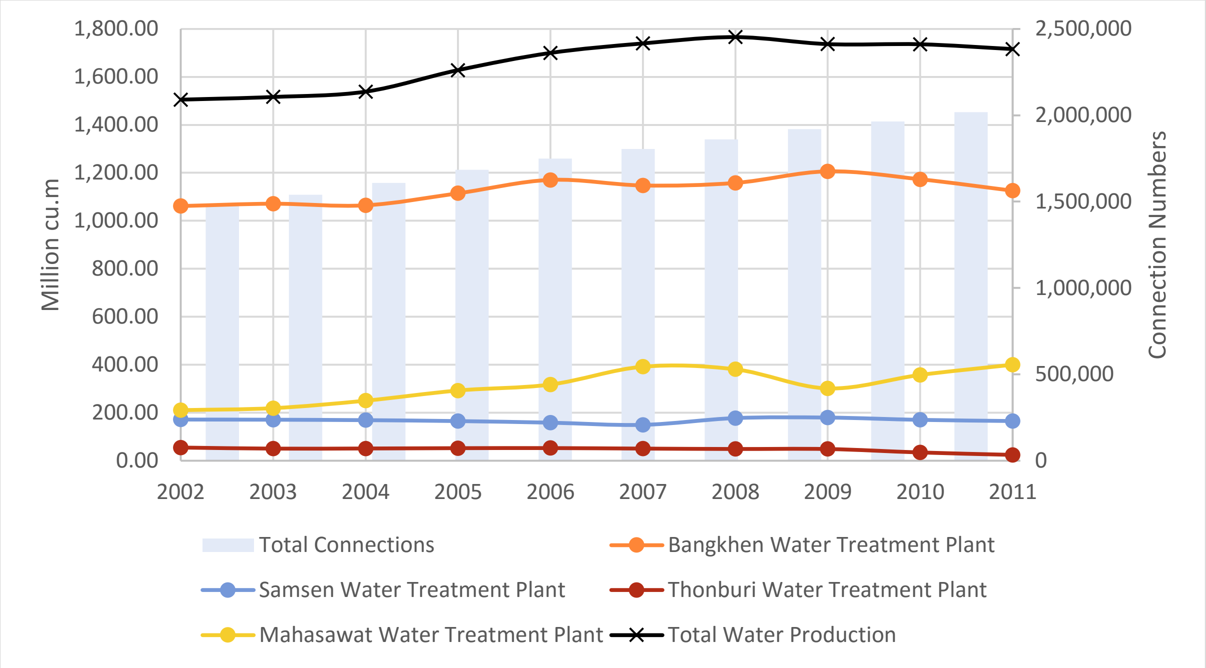


Figure 7: MWA water production and connections (Data source: MWA, 2012)

Figure 8: Raw water resource map showing WTPs and river networks within BMR (Source: MWA, 2012)

Table 6: Water Treatment Plants of MWA and PWA

Water Treatment Plant		Production capacity/day (Million m^3)	Water Production/ day (in 2014 -2015) (Million m^3)
MWA	Bangkhen WTP	3.60	3.640
	Samsen WTP	0.55	0.378
	Thonburi WTP	0.17	0.092
	Mahasawat WTP	1.60	1.450
PWA	Pathum Thani WTP	0.048	(Including supply from private company) 0.367
	Banglen WTP	0.44	0.359

Data source: MWA (2014), MWA (2016), PWA (2016)

The map showing river networks, water sources and treatment plant location are shown in Figure 8. The major raw water sources for MWA are Chao Phraya river and Mae Klong river. Bangkhen, Samsen and Thonburi WTPs receive water from Chao Phraya river through East water canal conveyance system and Mahasawat WTP receive water from Mae Khlong river through west water canal conveyance system. There are 44 pumping stations with pumping capacities from 0.002 to 0.453 Million m^3/day.

The total water consumption per capita in MWA service area is very high, in 2008, it was around 430 lpd, total domestic water consumption is 1.5 M m^3/day, total non-domestic water consumption is 1.7 MCM/day (Babel *et al.*, 2010).

PWA water sources are also Chao Phraya river and Tha Chin river. Water abstraction unit at Pathumthani WTP has operating pumping capacities of 0.37 to 0.395 Million m^3/day and Banglen WTP has operating pumping capacities of 0.340 Million m^3/day.

3.1.3 Waste Water Management

Bangkok Metropolitan Administration (BMA) manage the waste water treatment and disposal in BMR. The municipal waste water management system was not present in Bangkok until 1990. Currently, BMR has seven central WWTP in operation to treat almost a million m^3/day of domestic wastewater and serve an area of 196 km^2 (Figure 9 and Table 7). There are also 12 small community WWTPs with a treatment capacity of 24,800 m^3/day.

In 1998, the service area of BMA was 4.15 km^2 with 2.34 % of population access to centralized urban sanitation access in Bangkok. In 2008, the service area of BMA was 196 km^2 with 54.49 percent of population having access to centralized urban sanitation access (Chiplunkar *et al.*, 2012). Figure 10 shows the sectors contributing to water pollution in BMR and as a whole in central Thailand.

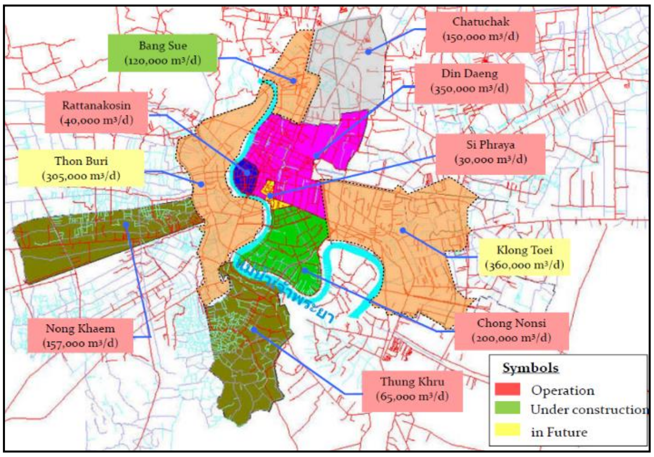
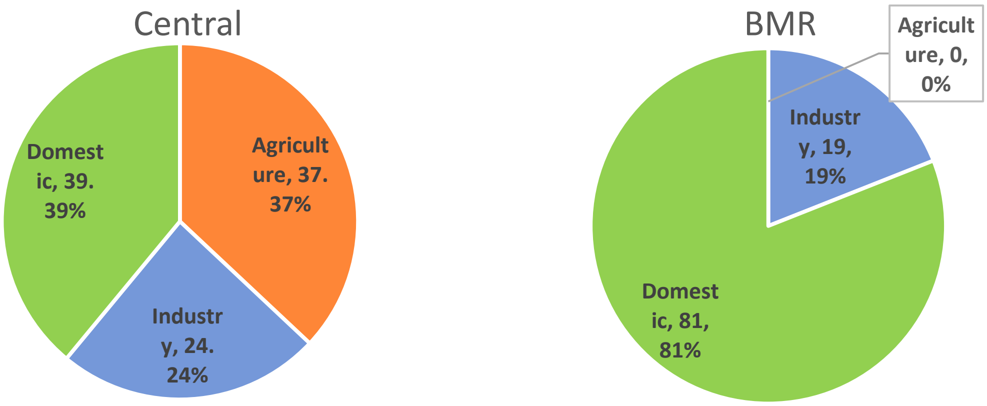


Figure 9: WWTPs of Bangkok Metropolitan Administration (Source: Wijarn and Somchai, 2011)

Table 7: Waste Water Treatment Plants of BMA within BMR

WWTPs	Capacity (cu.m./day)	Area Served (km^2)	Population	Year of operation
Current BWA's WWTPs				
Si Phraya	30,000	2.7	120,000	1994
Rattanakosin	40,000	4.1	70,000	2000
Dindaeng (BMA-1)	350,000	37.0	1,080,000	2004
Chong Nonsi	200,000	28.5	580,000	2000
Nong Khaem	157,000	44.0	520,000	2002
Thung Khru	65,000	42.0	177,000	2002
Chatuchak	150,000	33.4	432,500	2005
Future plans (as per 2011)				
Bang Sue	120,000	21.0	250,000	2012
Klong Toei	360,000	56.0	485,000	
Thon Buri	305,000	59.0	704,000	

Sources: World Bank (2000); Wijarn and Somchai (2011)



(a)

(b)

Figure 10: Sectors contributing to water pollution in central region and BMR. (Data source: World Bank, 2000)

World Bank, (2000), studied the various sectors contributing to water pollution in different regions of Thailand. It showed that in domestic and agricultural sector are major polluter in central region and domestic sector is major polluter in BMR. It is still prevalent that majority of waste water are disposed to canals around BMR without sufficient treatment. The average performance of the wastewater treatment plants from 2010 to 2015 can be summarized in tables 8 and 9 below.

Table 8: Operating parameters of WWTPs in BMR

WWTPs	Treatment System	Design Capacity (m^3/d)	Actual water treated (m^3/d)	BOD in (mg/L)	BOD out (mg/L)	SS in (mg/L)	SS out (mg/L)	Sludge (m^3/d)
Chatuchak	Cyclic Activated Sludge	150,000	131,386	32.95	8.24	46.39	8.82	8.14
Din Daeng	Biological nutrient removal activated sludge	350,000	197,058	31.93	4.92	37	10	15.74
Si Phraya	Contact stabilization activated sludge	30,000	18,255	54.25	5.22	82.93	6.22	1.05
Chong Nonsi	Cyclic Activated Sludge	200,000	122,472	33.29	5.54	56.32	9.49	12.73
Thung Khru	Vertical loop reactor activated sludge	65,000	51,845	32.20	4.25	52.93	7.80	7.63
Nong Khaem	Vertical loop reactor activated sludge	157,000	118,924	39.89	4.83	73.06	7.78	45.81
Rattanakosin	Two Stage Activated Sludge	40,000	30,084	71.84	10.76	62.85	13.47	2.60

Table 9: Operating parameters of small WWTPs in Bangkok (2015 Data)

Small WWTPs	Treatment System	Design Capacity (m^3/d)	Actual water treated (m^3/d)	BOD in (mg/L)	BOD out (mg/L)
Klongchan	Activated Sludge	6,500	2,976	108.58	8.42
Rom Klao	Activated Sludge	3,800	1,187	74.17	8.25
Tungsonghong 1	Aerated Lagoon	3,000	1,400	32.78	11.63
Tungsonghong 2	Activated Sludge	1,100	957	50.17	8.65
Hua Mak	Stabilization Pond	1,500	1,365	74.83	8.67
Huai Khwang	Activated Sludge	2,400	1,100	87.33	10.71
Tha Sai	Activated Sludge	1,400	1,528	30.87	5.98
Bangbua	Activated Sludge	1,200	1,130	_	_
Bangna	Oxidation Ditch	1,500	1,218	87.50	3.67
Khlong Toei	Activated Sludge	1,200	769	141.50	8.25
Ram Inthra	Activated Sludge	800	600	63.29	11.42
Bonkai	Activated Sludge	400	350	179.58	4.42

Thailand electricity consumption of national grid in 2010 was 149,320 GWh, which increased by 10.4 % from 2009. The total installed capacity in 2010 was 31,485 MW. Electricity consumption in BMR was 45,061 GWh or 30.2 % of total consumption for the whole country in 2010.

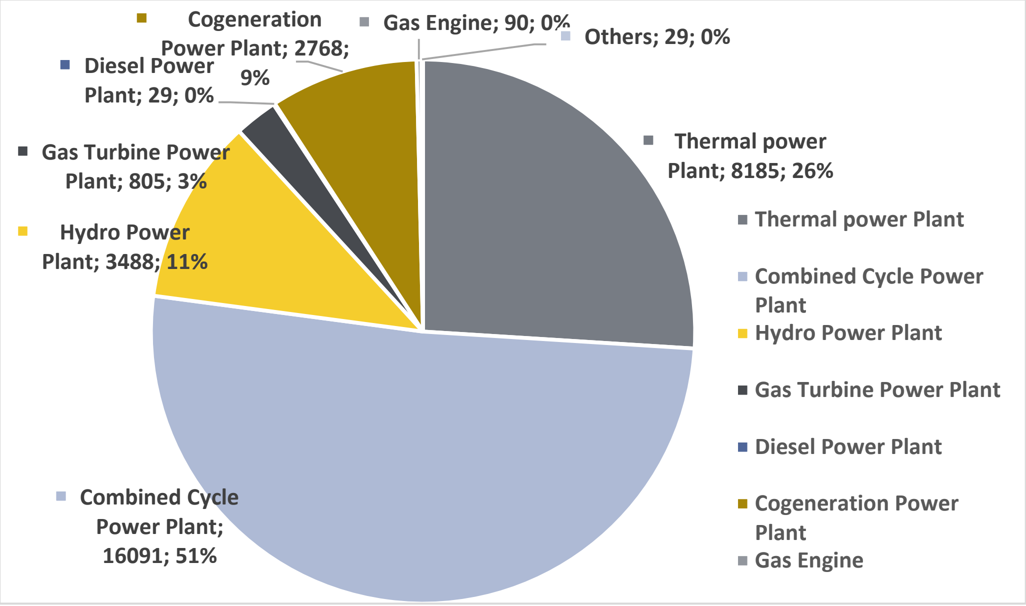


Figure 11: National Grid Installed capacity (MW) by types of power plants in 2010

Of the total electricity consumption in Thailand, industrial sector is the major consumer, followed by commercial sectors. While residential sector also contribute in the major share of electricity use up-to 22%.

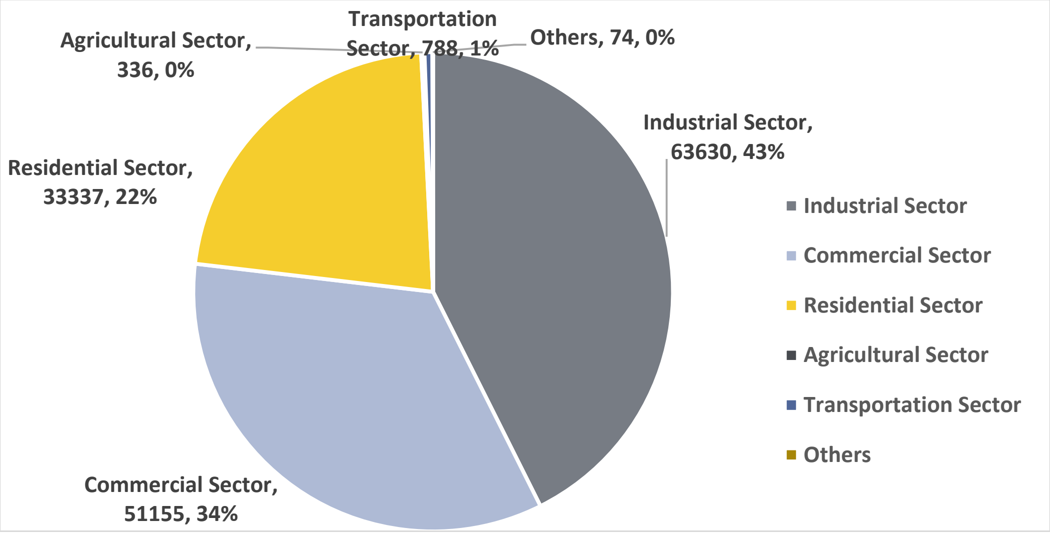


Figure 12: Electric consumption (GWh) by economic sector in 2010

Electricity Generating Authority of Thailand (EGAT) is responsible for providing electric energy for the whole kingdom by generating, transmitting and selling electricity to Metropolitan Electricity Authority (MEA), Provincial Electricity Authority (PEA), a number of direct customers prescribed by law, and neighboring countries. The MEA share of electricity supply responsible for supply in BMR is 29.9 % in 2010 and 29.5% in 2011. The total CO_2 generation from the power generation sector was 220.4 million tons and 224.4 million tones in 2010 and 2011. The CO_2 emission factor in kg/kWh was 4.7 and 4.9 in 2010 and 2011 respectively.

3.2 New Delhi

Delhi also known as National Capital Territory of Delhi (NCTD) is located from 28°24'17" to 28°53'00"(N) and from 76°50'24" to 77°20'37" (E). The total area is 1483 km^2. In 2001, the population was 13.85 million and with annual exponential growth rate of 1.92%, the population today is more than 16.8 million (Statistical Abstract of Delhi, 2012). NCTD is surrounded by states of Uttar Pradesh, Harayana, Rajasthan, Punjab, Uttaranchal and Himanchal Pradesh. The region lies in Yamuna flood plain and foot hill of Aravali ranges. Apart from Yamuna, which is the main river of the city, there are three canals- Agra Canal, Western Yamuna Canal and Hindon Canal. Delhi experiences the extremes of weather (temperature ranges from 4^{o}C - 45^{o}C) and is influenced by western disturbances from Himachal Pradesh during winters and SW monsoon during June-September months and heat waves from Rajasthan during summer months. The climatic conditions of Delhi are thus similar to that of temperate grasslands with hot, dry summers, and cold winters.

Figure 13 shows change in land-use of the city during past three decades. Similar to the pattern of urbanization in any other emerging economy, Delhi also has witnessed tremendous increase in the built-up area and commensurate decrease in agriculture area. Population growth and density increase in the city clearly indicates that the city has grown more horizontally and less vertically. This pattern of city growth has implication on ground water recharge and urban flooding. Figure 13 also shows a marginal increase in area occupied by water bodies. This is due to the accumulation of rainwater and untreated sewage resulting from lack of adequate drainage and sewerage systems (Sharma and Kansal, 2011).

Delhi has two major satellite towns –Noida and Gurgaon. Both these cities are in their exponential growth phase (Figure 15) and competing with Delhi for demand of all natural resource including water. Tables 10 shows key indicators for understanding water-energy nexus of NCTD.

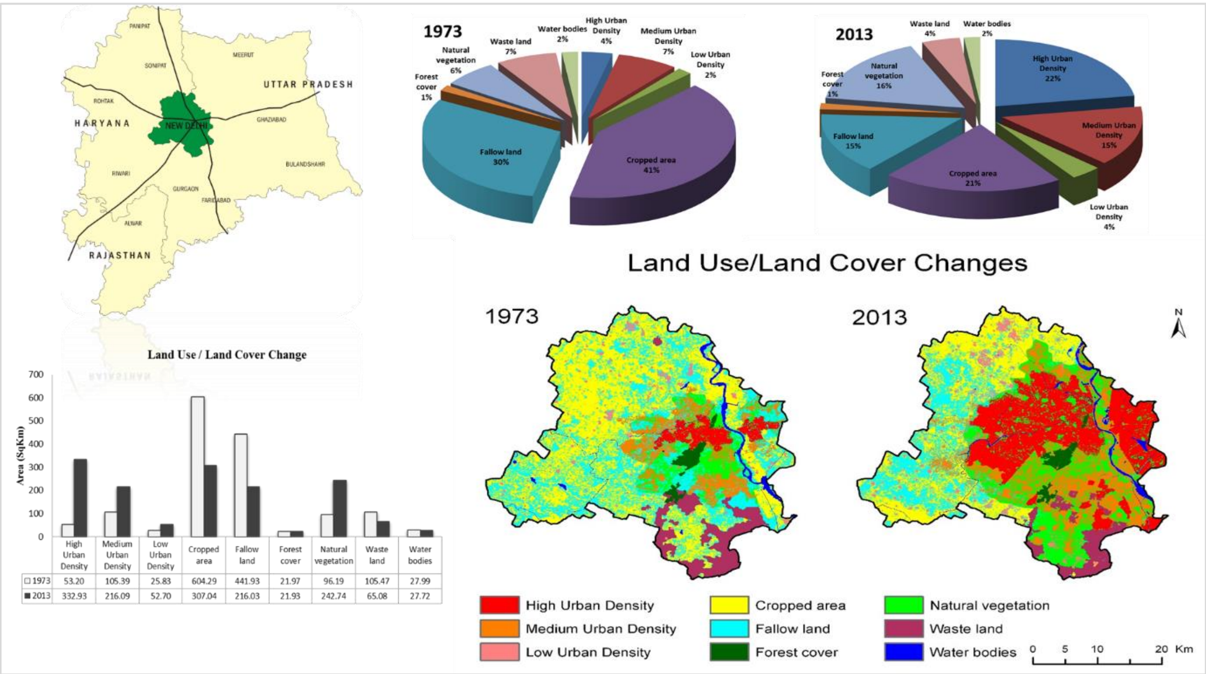
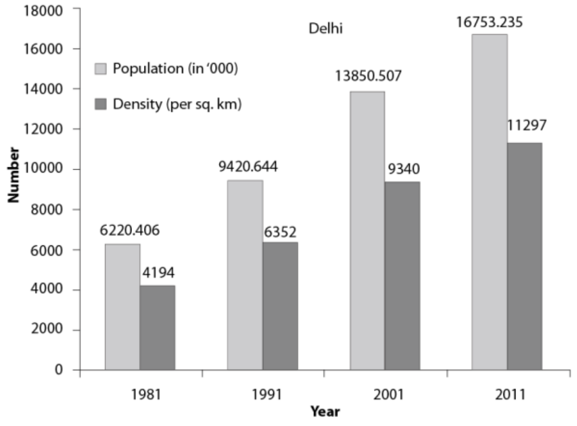


Figure 13: Land use pattern in Delhi (1973–2013) (Source: Landsat image compilation)



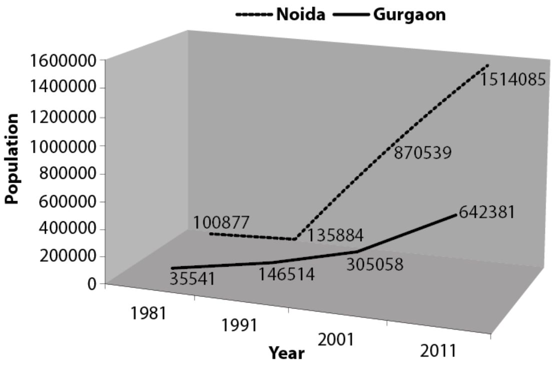


Figure 14: Population growth and density in NCTD[2]

Figure 15: Population growth in satellite towns of NCTD -Noida and Gurgaon[1]

Table 10: Biophysical characteristics of NCTD

Biophysical Characteristics	Details
Population (2001)	13,850507 (total) annual exponential growth is 1.92% and decadal growth rate is 20.96 (2001-2011) [a]
Population (2011)	16,753,235 [a]
GDP (2010-11)	INR 2644.95 billion at current price [a]
Coordinating bodies between constituent cities in the megacity?	There is National Capital Region Planning Board that coordinates a mega region consisting of Delhi and adjoining cities in neighboring states.
Names of constituent cities (i.e. local municipalities)	Local Municipalities Municipal Corporation of Delhi (MCD) (1397 Sq. km); New Delhi Municipal Corporation (NDMC) (42.74 sq.km); Delhi Cantonment Board (DCB) (42.97 sq. km) [a]
Land area (sq. km)	1483[a]
Urbanized area (sq.km)	1113.65[a]
Annual precipitation (mm)	708.1 mm in 2011 [a]
Annual solar radiation (kWh/m^2)	4.91[d] (Nov 2010- Nov 2011)
Building gross floor areas (m^2) Residential Commercial & Institutional Industrial	Total 67.85 million Sq.m (Residential= 55.41 million Sq.m + Commercial & Institutional= 8.52 million Sq.m, Industrial= 3.92 mllion Sq.m) b, c also see the note below

[a] Statistical Abstract of Delhi 2012, Directorate of Economics and Statistics, Government of National Capital Territory of Delhi, Delhi (PDF can be supplied, if required)

[b] Master Plan for Delhi-2021, Delhi Development Authority 2010, Delhi

[c] City Development Plan Delhi 2006, JNNURM, Department of Urban Development, Government of Delhi, IL&FS Ecosmart Limited, New Delhi

[d] Data gathered from India Meteorological Department, Pune

Note: There are no clearly assessed figures available for building floor area in Delhi. We have therefore arrived at these figures through multiple consultations with senior officials in the planning and property department of MCD, NDMC, DCB and Delhi Development Authority (DDA).

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[2] **Data Sources**: <indiastat.com>, Census of India; Data Sources: <http://urbanindia.nic.in/theministry/subordinateoff/tcpo/DMA_Report/CHAPTER_3.pdf>

3.2.1 Water Resources: Stakeholders and practices

The institutional framework of water regulatory authorities in India is given in Figure 16. At the Central level, the Ministry of Water Resources (MoWR) is the nodal ministry responsible for water. It was set up in 1985. It is responsible for developing, conserving and managing water as a national resource. It covers areas as diverse as irrigation, multi-purpose ground water exploitation, and Command Area Development, drainage and flood control. It also tackles issues related to waterlogging, soil erosion, dam safety, and creation of structures for navigation and hydropower. It also oversees the development and regulation of inter-state rivers.

Under this ministry, three principal technical organizations have been created. The Central Water Commission is responsible for developing surface water. The Central Ground Water Board monitors and develops ground water resources. The National Water Development Agency was set up to assess possibilities for inter-basin water transfers.

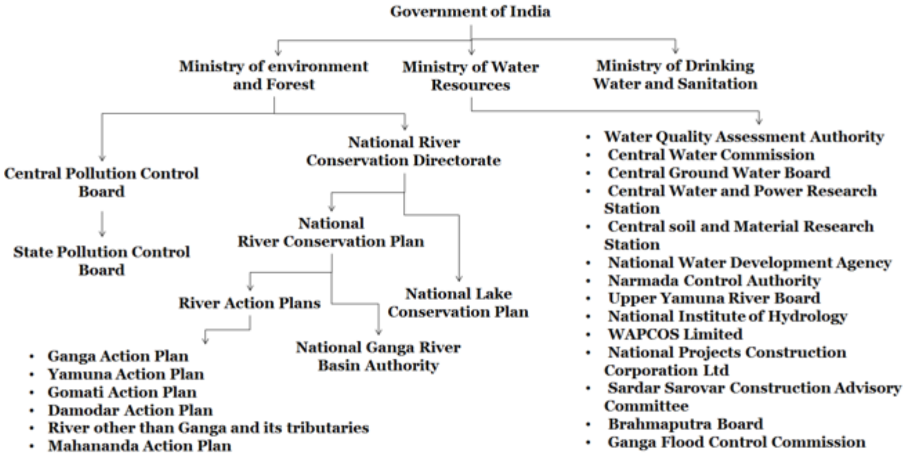

Figure 16: Institutional framework of water regulatory authorities in India

Water Quality and environmental matters come largely under the Ministry of Environment and Forests (MoEF). The MoEF coordinates India's Environmental Action Plan and has also launched a number of other programs including the Wetlands Conservation Programme and The National River Conservation Plan.

The Ministry of Urban Development coordinates projects in urban water supply and sanitation. The Rajiv Gandhi National Drinking Water Mission handles rural water supply and sanitation. This is under the Ministry of Rural Areas and Employment. The Ministry of Power and the Central Electricity Authority handle water for power generation.

Water is also a subject of several other ministries and departments; such as the Ministry of Agriculture (irrigation), Health and Family Welfare, Ministry of Surface Transport, Inland Waterways Authority of India, and for Financing and Planning, the Ministry of Finance, the Planning Commission and the Finance Commission.

The measurement of water quality is conducted by the Central Water Commission, which operates more than 300-water quality monitoring stations in the major and medium river basins. The CPCB (Central Pollution Control Board), in collaboration with the SPCBs (State Pollution Control Boards), in several states, has been separately monitoring aquatic resources at selected locations since 1977.

In NCTD, the Delhi Jal Board (DJB) or Delhi Water Board (DWB) is the agency responsible for procurement, treatment, transportation and distribution of water and collection and treatment of sewage in region. The Delhi Water Board Act, 1998 provides for the establishment of a Board to discharge the functions of water supply & sewage disposal within the National Capital Territory of Delhi and for matters connected therewith. Water and waste water utility for about 18 million people (supplies bulk water to NDMC and Delhi Cantonment Board).

3.2.2 Water Supply Management

Figure 17: Water supply zones in Delhi (black text) and location of water treatment plants (blue text) (personnel interaction with DJB)

Figure 17 shows the water supply zones in Delhi and corresponding WTPs locations. Further details of water supply sources and overall water resources availability are summarized in tables 11 and 12.

Table 11: Present sources of water utilized by Delhi Jal Board (DJB) in NCTD[3]

S No.	Source of raw water	Quantity (MGD)
1	Yamuna River	330
2	Ganga River	207
3	Bhakra Storage	218
4	Ranney wells/Tube wells[4] (Groundwater)	85

Table 12: Present potential of water resources for Delhi

S No.	Present resources	Quantity (MGD)
1	Surface water resources[5]	820
2	Ground water resources[3]	100
3	Rain water runoff potential[3]	140

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[3] GNCTD, 2015. Economic Survey of Delhi 2014-15. Chapter 13 Water Supply and Sanitation. Directorate of Economics and Statistics. Government of National Capital Territory of Delhi, Delhi

[4] Central Ground Water Board, 2011. Groundwater Information Booklet. Ministry of Water Resources, State Unit Office, New Delhi http://cgwb.gov.in/District_Profile/Delhi_districtprofile.html

[5] Delhi Development Authority, 2010. Master Plan for Delhi 2021, Delhi Development Authority, Delhi.

4	Recycled wastewater potential[3]	565
	Potential Future Fresh Water Resources[1]	
5	Renuka dam	275
6	Kishau Dam	372
7	LakhwarVyasi Dam	135
8	Sharda-Yamuna Link	4085

Surface water

Surface water sources to Delhi are Yamuna, Bhakra and Ganga reservoirs. The water is abstracted from the River Yamuna at Tajewala Barrage through Western Yamuna Canal traversing to Haryana. This water is supplied through Delhi Tail Distributary to Haiderpur, Nangloi, Dwarka, Okhla II and Bawana Water Treatment Plants (WTPs). Recently, additional release of 80 MGD water by Haryana through Munak canal is received by Okhla II, Bawana and Dwarka WTPs. Further, water is also abstracted at Wazirabad Barrage for Wazirabad and Chandrawal WTPs. Moreover, Delhi also receives water from Satluj and Beas through Narwana branch Karnal link, which further joins Yamuna canal in Karnal. The Ganga River system supplies water from the Upper Ganga Canal (Muradnagar offtake) to the Bhagirathi and Sonia Vihar WTPs.

Table 13: Surface water and groundwater sources, tapping point and corresponding WTPs[6]

Original source	Tapping source	Location	WTP
Yamuna river	Direct tapping	Wazirabad barrage (674.5 ft (205m) above mean sea level)	Chandrawal
			Wazirabad
Yamuna river + Bhakra storage	Indirect tapping	Western Yamuna canal (WYC)	Haiderpur
			Nangloi
		Additional supply in WYC carrier lined channel (munak canal)	Bawana
			Okhla II
			Dwarka
Tehri dam	Indirect tapping	Upper Ganga Canal (Muradnagar offtake)	Bhagirathi
			Sonia Vihar
Ground-water		Ranney Wells + Tubewells	Okhla I
			Bhagirathi, Chandrawal, Wazirabad & Haiderpur
Recycled water			

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[6] JICA, 2011. Study on improvement of water supply system in Delhi in the republic of India. Jointly prepared by JICA, GNCTD, MoUD and DJB. Delhi

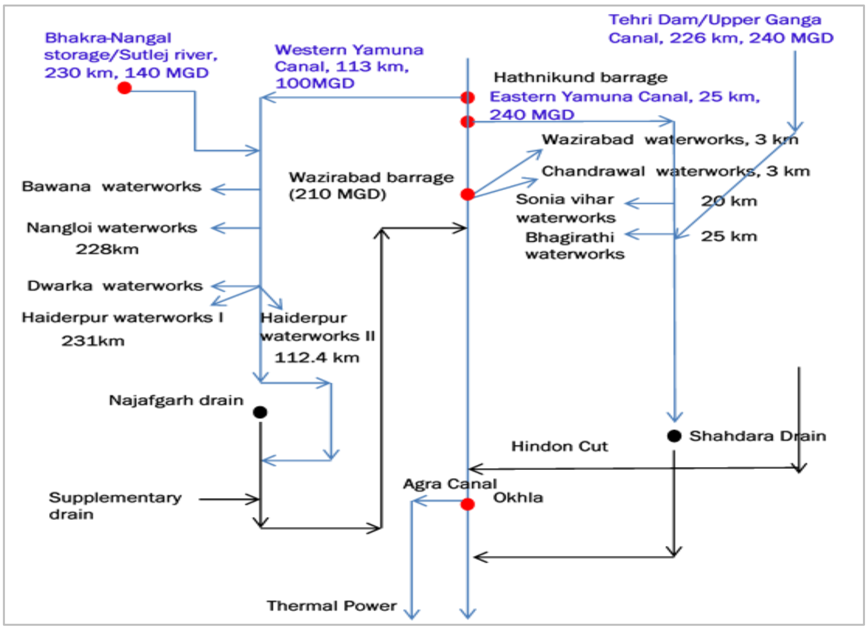

Figure 18: Surface water sources of Delhi[7]

Groundwater (GW)

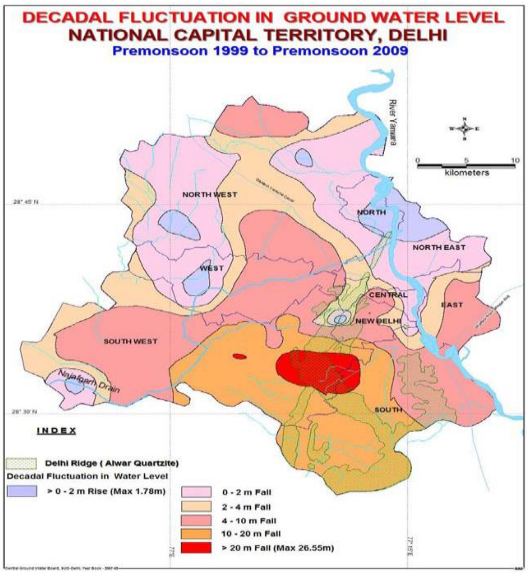

Figure 19: Ground water exploitation in Delhi[8]

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[7] DHI. 2010 Integrated water resources management and water quality modelling of River Yamuna basin-draft final report. Yamuna action plan: phase II. National River Conservation Directorate, Ministry of Environment and Forests, Government of India, India.

[8] Shekhar Shashank., Raja Ram Purohit & Y. B. Kaushik. 2006 Hydrogeological Framework & Groundwater management Plan for NCT Delhi, Central Ground Water Board 2006 report, CGWB http://www.cgwb.gov.in/documents/papers/incidpapers/Paper%2015-%20Kaushik.pdf

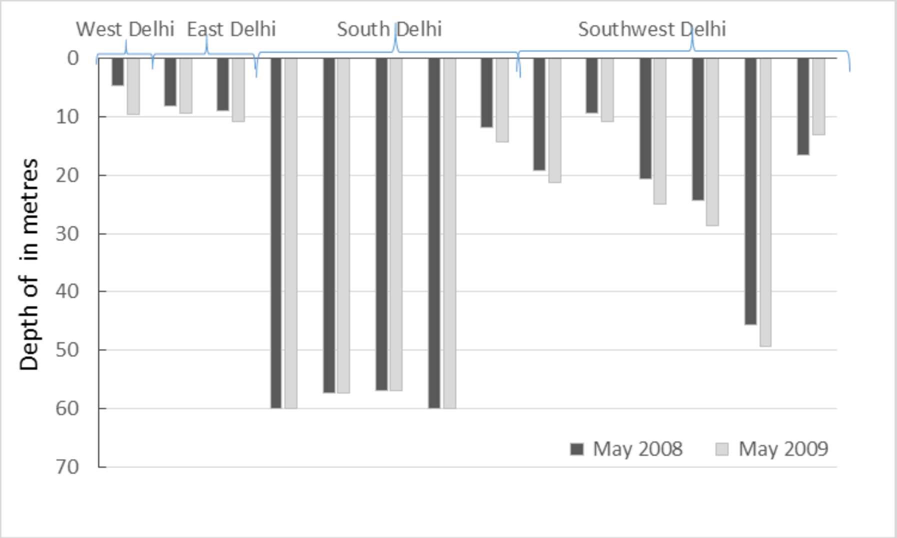

Figure 20: Ground water depths in various parts of NCTD[9],[10]

Most parts of Delhi showed implications of overuse of groundwater extraction due to which groundwater depth has increased just within one year between 2008 to 2009 (Figure 20).

Table 14: Annual GW status of Delhi (as of July 2011)[11]

Attributes	Quantity
Total Replenishable GW Resource/ GW recharge (MCM)	310
Net GW Availability (MCM)	290
Total GW Draft (MCM)	390
Stage of GW development (%)	137

Net annual ground water availability has been assessed as 290 MCM and total annual ground water draft for all uses has been estimated as 390 MCM (Table 15). Out of 8 districts, 5 fall in over exploited category.

Table 15: Annual GW development and sector wise uses for Delhi in MCM (as of 2011)[2]

District	GW recharge	Net GW availability	Gross GW draft for irrigation	Gross GW draft for domestic and industrial uses	Gross GW draft from all uses	Stage of GW development (%)	Category
Central	3.84	3.45	0.51	2.40	2.92	84.45	Semi Critical
East Delhi	12.84	1.18	8.44	12.80	21.24	178.87	Over- exploited
New Delhi	7.97	7.17	5.53	0.95	6.49	90.40	Critical
North East	12.55	11.35	3.28	9.69	12.99	114.36	Over- exploited
North West	86.31	80.23	32.81	57.33	90.15	112.36	Over-exploited
North	15.55	13.99	1.38	8.30	9.68	69.18	Safe
South West	97.52	91.27	64.59	63.17	127.78	139.99	Over-exploited
West	28.11	26.52	4.73	35.77	40.51	152.73	Over-exploited

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[9] GNCTD, 2010. State of Environment Report for Delhi 2010. Chapter 2, Water Supply, Department of Environment and Forests. Government of NCT of Delhi, Delhi

[10] Water Policy for Delhi, 2012, Ministry of Water Resources, Government of National Capital Territory of Delhi, Delhi. http://www.downtoearth.org.in/dte/userfiles/images/draft_20130503.pdf

[11] Central Ground Water Board, 2014. Dynamic Ground Water Resources of India. Ministry of Water Resources, River Development & Ganga Rejuvenation. Government of India. http://www.cgwb.gov.in/documents/Dynamic-GW-Resources-2011.pdf

Total	**264.69**	**235.16**	**121.27**	**190.41**	**311.76**		

Delhi Jal Board (DJB) owns 4043 functional tube Wells (TW) and 14 Ranney Wells (RW) in Delhi. Total groundwater production from these TW's and RW's is 85.49 MGD (388979.5 m^3/d)[12]

Table 16: Zone wise number of TW and RW with their water production capacity

Division	DJB zone	Tube wells (TW)		Ranney wells (RW)		Ground water production (MGD)
		No. of TWs	Capacity of TWs (MGD)	No. of RWs	Capacity of RWs (MGD)	
South	South & South-West	2782	26.7	0	0	26.7
WW-III	Yamuna flood plain	3	0.198	4	3.6	3.798
East	East & North-East	37	1.459	5	2.23	3.689
WS-II	Central & North	523	15	0	0	51.3
	West	426	6.52	0	0	
	North-West	272	21.37	5	6.4	
Total		**4043**	**73.26**	**14**	**12.23**	**85.49**

3.2.3 Waste Water Management

Wastewater infrastructure of the NCT is managed by Delhi Jal Board (DJB; jal means water in Hindi and Sanskrit), which is an autonomous department of the Government of Delhi. NCT is divided into 12 drainage zones with 35 wastewater treatment plants (WWTPs), 105 wastewater pumping stations (WWPS), and 13 common effluent treatment plants (CETPs). The boundaries of drainage zones are not based on topography; the zones are essentially administrative units. Two drainage zones are new, and work related to transport and treatment infrastructure in these two is yet to be completed. The wastewater is ultimately discharged into the river Yamuna, which is amongst the most polluted river stretch of India. About USD, 203.97 million has been invested for the restoration of river water quality of river Yamuna since the year 1993 (NRCD-MoEF, 2012). Despite huge investment in infrastructure for water pollution control, the city still has a huge gap with respect to the needs for domestic wastewater management, warranting more investments in near future. Only 50% area of NCT of Delhi is covered by underground sewerage (DJB, 2014). The infrastructure for transporting wastewater comprises 7200 km (GNCTD, 2012-2013) of sewer lines and 350 km of open drains (personal communication with DJB) and mainly carries domestic wastewater. Open drains are mostly unlined, and wastewater flows under gravity towards the sink. The sewerage network comprises pipes of reinforced concrete cement with diameters varying from 250 mm to 2500 mm. Sewerage facilities are provided in planned colonies, Jhuggi Jhopri (JJ) resettlement colonies, slums, and urban villages but not in rural areas and unauthorized colonies, slums, and JJ clusters.

Domestic wastewater generated in NCT of Delhi is estimated at 2573 million litres a day (MLD) (GNCTD, 2012-2013), 30% (personal communication with DJB) is transported through the underground sewer network and the remaining through open drains. The average pollution load by NCT of Delhi in river Yamuna in terms of BOD is about 270 tonnes/day (CSE, 2011). Two drains, namely Najafgarh and Shahdara, contribute about 67% of the load by volume and nearly 20% in terms of BOD to the river Yamuna (DJB, 2004). The wastewater treatment capacity is about 2,285 MLD but only 1,520 MLD reaches the WWTPs. WWTPs in one zone may treat wastewater generated in other zones also. For instance, the WWTPs at Okhla treats wastewater from South Delhi, Outer South Delhi, and Kanjhawala- Bawana as well. The existing WWTPs are underutilized because the collection system is deficient, the sewers – trunk – are choked at many places, and the pumps are often out of order. Of the 35 WWTPs, four WWTPs are not in operation; 22 WWTPs do not run to their full capacity; and two are overloaded—only seven run to their full capacity (DJB, 2014). Twenty-three WWTPs use the ASP and are plagued frequently with operational problems. The average efficiency of WWTPs in lowering

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[12] Primary data collection from Interviewing DJB officials, Delhi Jal Board, Delhi, 6 October 2015

BOD is about 85%. In recent years, a few decentralized wastewater systems have been installed by DJB for recycling wastewater.

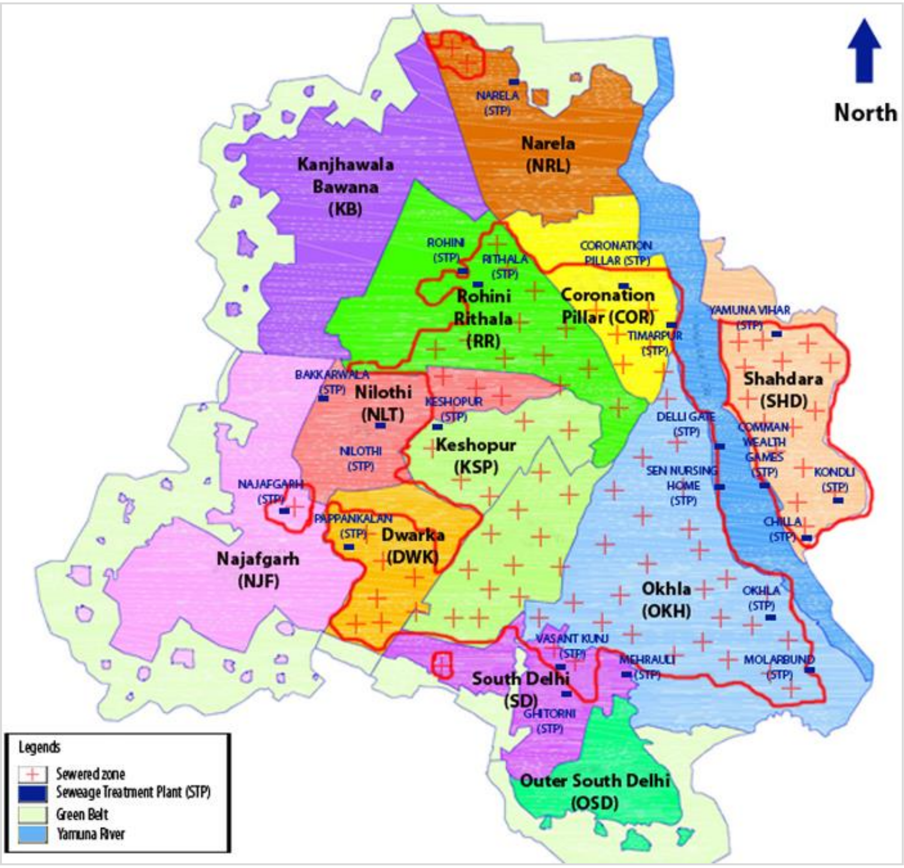

Figure 21: Location of sewage treatment plants and drainage zones in Delhi (DJB, 2014)

The large-scale STPs are predominantly based on ASP, submerged attached-growth biological reactor (SBR), EA, and up-flow anaerobic sludge blanket (UASB) (CPCB, 2005) to achieve biological oxygen demand (BOD) of less than 30 mg/L in the discharge; whereas the small-scale STPs mainly rely on physicochemical processes followed by biological treatment to reach a discharge BOD of less than 20 mg/L. In the present study, STPs in India were selected from two states, namely Delhi and Gujarat. It was ensured that the proportion of different treatment technologies used in the selected STPs is nearly the same as that for the whole of India based on a report published by the Central Pollution Control Board (CPCB, 2005). Initial visits were made to ensure that the selected STPs were fully functional and meeting the discharge standards; STPs that were found under-performing or non-functional were excluded. Finally, 25 large-scale STPs and 12 small-scale STPs were surveyed for the detailed study. In addition, data on electrical energy use in 13 STPs run by Severn Trent Company in England were obtained to compare energy use in STPs in the UK and India. Table 17 presents the details of the municipal and institutional STPs.

Table 17: Types of STPs

Type of TP	Treatment method	No. of STP	Operating capacities (m³/day)	BOD removed (kg/day)	Outlet BOD (mg/L)
Municipal STP					
M1	SC, GC, PST, ASP, AD, SDB	17	15 140–13 2475	1741–20 627	20–30
M2	SC, EA, FST, SDB	3	5677–9463	968- 2392	12–23

M3	GC, ASP, TF, DAF, AD, SDB	1	75 700	10 870	25
M4	SC, GC, FM, CF, 2stage - SBR, BFP	2	8327- 9462	1082- 1698	10–16
M5	SC, GC, UASB, FST, Cl, BFP	1	62 459	19 237	17
M6	SC, GC, FBR, FST, AD , Cl, BFP	1	12 491	1923	20
Institutional STP					
I1	SC, ET, AF, MGF,CAACO, AD, SDB	1	135	39.3	18
I2	SC,ET, GC, SBR, MGF, Cl, SDB	3	700–4164	122 –1229	5–18
I3	SC, ET, SBR, FST, MGF,AC, Cl, BFP	2	300 –700	114 –182	16 –20
I4	SC, ET,EA,FST, SF, AC, Cl, SDB	2	250–12 000	95–3168	16-17
I5	SC, ET, FBR, TS, MGF,AC, Cl, Cf	1	700	267	18
I6	SC, ET, PST, FBR, MGF, OT, SDB	1	45	12.69	18
I7	SC, FM, PST,RBC, SST, SF, AC, SDB	1	24	6.5	19
I8	SC, ET, GC, PST, ASP, SF, Cl, SDB	1	83	19.55	20

Inlet BOD of large-scale STPs ranged from 150 mg/L to 275 mg/L. Of the large-scale STPs, 17 use the conventional treatment, namely primary treatment followed by a biological treatment consisting of ASP for the liquid and anaerobic digester (AD) for the sludge. Sludge is dewatered in sludge-drying beds (SDB), and biogas is generally flared or used for electricity generation. The generated electricity is used in the respective STPs. The operating capacities of the conventional STPs were 45–204 million litres per day (MLD) and they achieved outlet BOD of less than 30 mg/L. The other three surveyed STPs used EA without any extensive primary and tertiary treatments. These plants are used for smaller areas of a city and their capacities ranged from 10 MLD to 22.7 MLD. One of the surveyed municipal STPs had a two-stage biological treatment consisting of ASP and TF. Sludge is thickened by using dissolved air flotation (DAF), treated in an AD, and finally dried on SDB. Biogas is scrubbed using a biological process and is used for electricity generation. Another large-scale STP used the UASB process and disinfected the treated sewage by chlorination before disposal. Some biogas in this plant was used for electricity generation and the rest was flared, and the sludge was dewatered using a belt filter press (BFP). The outlet BOD was less than 20 mg/L. Two small STPs were designed for recycling treated sewage and their treatment method consisted of extensive physicochemical treatment using alum and a polyelectrolyte in a flash mixer (FM) and a clariflocculation (CF) unit. Biological treatment in these STPs involved a SBR. The sludge was dewatered using BFP, and the plant was designed for reusing the treated sewage for cooling in thermal power plants and for irrigating gardens and orchards. Another medium-size STP used a fluidized bed reactor (FBR). Treated sewage after chlorination had BOD of less than 30 mg/L. It was observed that 90% of the surveyed large-scale STPs were operating at 40% to 60% of their designed capacity because of choking of feeding sewer lines and several other reasons. The results are reported and analyzed based on the actual operating capacities of STPs instead of their designed capacities.

The surveyed small-scale STPs primarily used physicochemical processes and biological filters. The small-scale STPs chosen for the survey served population equivalent up to 10,000 and had sewage conveyance lengths of less than 500 m. Of the twelve small-scale STPs surveyed, 3 STPs used SBR and used chlorine to disinfect treated water. These STPs have outlet BOD of less than 18 mg/L and uses polyelectrolyte for sludge dewatering. Two STPs used the EA process (capacities of 0.27 MLD and 14 MLD) and used chlorine to disinfect treated sewage after sand filtration (SF) and activated carbon (AC). The STPs achieved outlet BOD of between 16 mg/L and 17 mg/L. Two other STPs also used the SBR process followed by AC, chlorination, and BFP for sludge dewatering. Their outlet BOD was less than 20 mg/L, and the treated sewage was used for cooling thermal power plants. Other STPs used chemo-autotrophic activated carbon oxidation (CAACO), a rotating biological contractor (RBC), ASP, a FBR followed by AC and chlorination and used a centrifuge for sludge dewatering. Another STP with FBR process used an ozonation tank and SDB. The outlet BOD of all the treatment methods ranged from 18 mg/L to 20 mg/L.

3.3 Kathmandu

Kathmandu Valley covers the capital city, Kathmandu and two surrounding metropolitan cities known as Lalitpur and Bhaktapur. Kathmandu Valley is the largest urban settlement of Nepal, having an area 49.45 km^2 which is home to 2.5 million inhabitants (9.1 % of total country population). Other municipalities within the valley are Kirtipur and Madhyapur Thimi. The valley consists of major rivers like Bagmati, Bishnumati and Manohara with Bishnumati, Manohara, Dhobikhola, Nagmati and Balkhu rivers being the main tributaries of the Bagmati River. Kathmandu Valley lies in the Warm Temperate Zone (elevation ranging from 1,200–2,300 meters (3,900–7,500 ft), where the climate is fairly temperate. Under Köppen's climate classification, portions of the city with lower elevations have a humid subtropical climate (Cwa), while portions of the city with higher elevations generally have a subtropical highland climate. In the Kathmandu Valley, the average summer temperature varies from 28–30 °C (82–86 °F). The average winter temperature is 10.1 °C (50.2 °F). Rainfall is mostly monsoon-based about 65% of the total concentrated during the monsoon months of June to August. Rainfall has been recorded at about 1,400 millimeters (55.1 in) for the Kathmandu valley, and averages 1,407 millimeters (55.4 in) for the city of Kathmandu. On average humidity is 75%.The annual amount of precipitation was 1,124 millimeters (44.3 in) for 2005, as per monthly data.

3.3.1 Water Demand and Supply

The present population of the Valley water supply service area is estimated to be 2.7 million with a water demand of 370 MLD. The total water production in the wet and dry seasons is about 142 and 98 MLD, respectively (KUKL, 2015).

Given the above numbers, the water supply operator, Kathmandu Upatyaka Khanepani Limited (KUKL) is clearly not being able to meet the demand with its water supply. Added to the supply has 38 percent of leakage, which is one of the biggest challenge for the supply. However, KUKL has considered on addressing this problem with a fifteen-year long project for replacing old pipes in the valley with new ones for leakage control, estimated to be complete in 2025 (Manandhar, 2013). This can help replace improve the water supply and reduce waste likewise. However, the un-met demands have led to adding pipelines beyond KUKL's systems as per request of communities. This has led to an unplanned distribution of water that does not follow the plan, making Kathmandu's water distribution network more complex

3.3.2 Institutional Settings, Legislations and Practices

Table 18: Legislation regarding water resource management in Nepal

S.N.	Legislation	Features
1	Local Self Governance Regulation 1999	• Sets out the powers, functions and duties of local authorities in relation to water and sanitation. • Establishes the procedure for the formulation of water related plan and project implementation.
2	Local Self Governance Act 1999	• Establish decentralized governance structure. • Sets out the powers, functions and duties of local authorities in relation to water and sanitation. • Sets out which natural resources are assets of local bodies and empowers local bodies to levy a natural resource tax.
3	Drinking Water Regulation 1998	• Regulates the use of drinking water.

		- Provides for the formation of Drinking Water User Associations and sets out the procedure for registration. - Deals with licensing of use drinking water. - Deals with the control of water pollution and maintenance of quality standards for drinking water.
4	Environment Protection Regulation 1997	- Lists the water related projects required to conduct an Environmental Impact Assessment (EIA) or Initial Environmental Examination (IEE). - Deals with the control of water pollution and pollution control certificate.
5	Environment Protection Act 1996	- Requires certain persons/bodies to conduct an EIA or IEE. - Deals with the prevention and control of pollution.
6	Water Resource Regulation 1993	- The umbrella Regulation governing water resource management. - Sets out the procedure to register a Water User Association and to obtain a license. - Establishes the District Water Resource Committee.

Source: WaterAid Nepal, 2005

3.3.3 Water Supply Management

Supply from Ground Water and Surface Water

Kathmandu receives its water supply from surface sources and groundwater sources. Out of total water supplied by the water supply operator Kathmandu Upatyaka Khanepani Limited (KUKL), surface water counts for 80% in wet season and 54% for Dry season (KUKL, 2015).The remaining of the supply is through the ground source i.e. wells and tube wells which are mostly situated at the northern area of Kathmandu Valley. Thus, most of the surface sources are being tapped for the water supply in Kathmandu Valley (Manandhar, 2013). Surface water accounts for 116 MLD during wet season and 64 MLD during dry season. KUKL is using 35 surface sources including small tributaries. KUKL, in its 10 systems, gets water from surface sources like Shivapuri, Bishnumati, Alley, Boude, Nagmati, Shyalmati, Doodhpokhari, Lunhkot, Nakhu, Sesh Narayan, Nallu, MahadevKhola and Devki rivers.

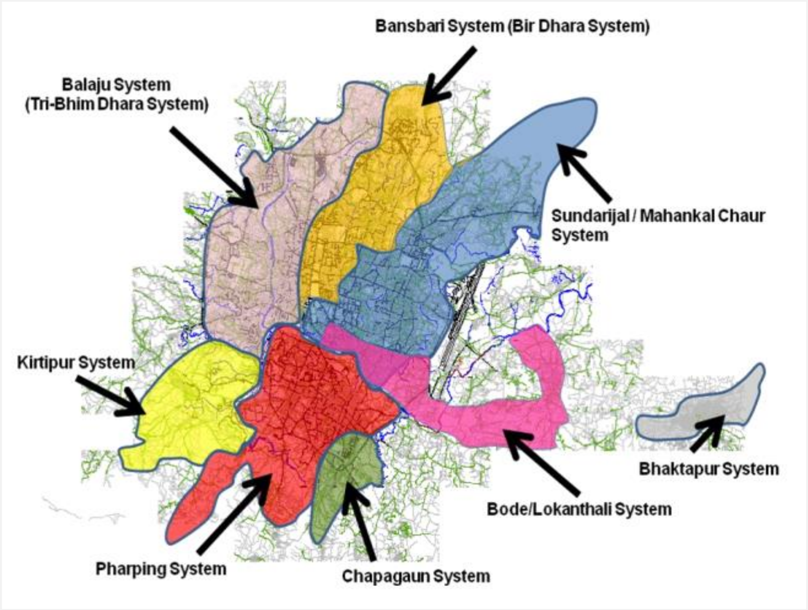

Figure 22: KUKL's Water distribution systems. Source: GRDB

The groundwater aquifers of the Kathmandu Valley have been divided into 3 districts: Northern (157 km^2 with 59 km^2 recharge area), Central (114 km^2 with about 6 km^2 recharge area) and Southern (55 km^2 with about 21 km^2 recharge area) (Dixit and Upadhyaya, 2005).

These aquifers however have remained in a bad condition as the extraction of groundwater to meet the domestic and commercial demands has been increasing at a distressing rate. When JICA (1990) conducted the modeling of deep aquifer system to estimate sustainable withdrawal of water, the study suggested a safe withdrawal of 0.027 million m^3/day. However, with the current recharge being up to 15 mm/year (0.04 to 1.2 million m^3/year); extraction rate is 20 times of this amount; and reserves will be used up within 100 years at current rate of extraction (Pradhanang, 2012). Moreover, estimations are that groundwater has been decreasing at an average rate of 2.5 meters per year. A study by Guthi mentions that if the groundwater will be continuously extracted at this rate, it will be sufficient only until the next 90 years. According to ADB, this kind of un-sustained extraction of groundwater can cause land subsidence problems as already evident in many cities.

Groundwater abstraction started in 1980 A.D. and became the most reliable sources for water consumption. However, the abstraction rate has been exceeding the recharging rate lately, thereby depleting the groundwater level considerably. While unmet demands have been one of the major concerns in water supply system of Kathmandu, the quality and quantity of water have been equally problematic.

Also, the valley’s distribution network, which has been developed for over more than 100 years now has a very complex and ad-hoc network system. The system is being managed by 10 branch offices of KUKL, with six of them for the Kathmandu Metropolitan City area and adjoining VDCs, one for Lalitpur and adjoining VDCs, one for Bhaktapur and adjoining VDCs, one for Kirtipur and adjoining VDCs and one for Madhyapur Thimi and adjoining VDCs (ADB, 2006).

Other temporary populations and VDCs are able to obtain water from sources without treatment like traditional waterspouts, ground water wells, rivers, streams, etc.

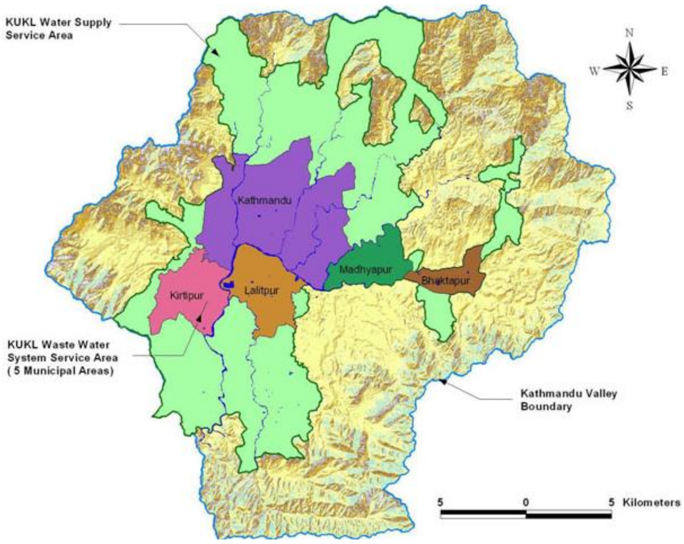

Figure 23: Kathmandu Valley and KUKL Service area Source: KUKL (2011)

Supply from Private Tankers

Private tankers provide water during peak demand as requested by individual households or communities based on their needs. Usually, the tankers collect water from source and supply it to the communities without treatment (Joshi, 2015).

As of 2013, there are 216 water tanker entrepreneurs registered, who are operating 370 tanker trucks of different sizes (9000-12000 liters) (Manandhar, 2013). About 21 percent of water consumption of Kathmandu is supplied by around 700-800 tankers that are delivering water in Kathmandu Valley from different locations like Balaju, Matatirtha, Godavari, Swayambhu, Chobhar, and Jorpati. Exact numbers have not yet been recorded by the government for the amount of water supplied in Kathmandu Valley through private tankers but a study by Dibesh Shrestha has shown that in average 25.58 MLD and 15.36 MLD of water is supplied in dry season and wet season respectively (Manandhar, 2013; Shrestha, 2011).

Supply from Registered Wells

According to KVWMSB, there are altogether 265 registered wells that supply water for commercial, industrial and residential use. These sectors are mainly comprised of banks, housing, hotels and other industries. An estimate of 20 million liters of water is permitted to be extracted by these sectors as licensed by KVWMSB (Joshi, 2015).

Water extraction from Households

In city core areas, road networks are planned usually for pedestrian movements, hence big trucks and private tankers who supply water as city pipelines are not enough and cannot pass through. As a result of lack of municipal water supply and costly water transport from private tankers, households have opted for private dug wells and tube wells in their respective land areas. This is also one of the main source of water for household construction purposes, which can easily serve the homes after construction of their dwelling (Manandhar, 2013). These dug wells have not been monitored by the government, but according to Manandhar, there are about 10,000 dug wells in the valley.

However, in every household, dug wells or tube wells are being used for household activities. Water supply from KUKL or private tankers are first collected in underground water tankers with the capacity of about 9000 - 12000 liters, from which they pump the same water to their roof-top water tankers which has the capacity of about 500 - 2000 liters. Water is then accessible through gravity flow. As per the need, households also pump water from their dug wells to separate rooftop water tankers for other purposes.

Melamchi Water Supply Project

In a bid to address these issues and combat water scarcity, whilst reducing pressure stress in groundwater resources, Melamchi Water Supply project (MWSP) is underway. The MWSP is set to bring 510 MLD water to Kathmandu Valley from off-the valley sources. It is expected to be completed in three stages (Stage I: 170 MLD from the Melamchi River, Stage II: 170 MLD from the Yangri River, and Stage III: 170 MLD from the Larke River) (MWSDB, 1998). The rivers flow through Indrawati basin, a sub-basin of Koshi river basin.

The project, which is estimated to be completed in 2016 aims to serve a population of 722,053 in an area of 1700 hectares with a minimum supply of 2 hours/ day (ADB, 2006). Its infrastructure development comprises construction of a 26 km diversion tunnel (70% completed to date), roads, water treatment plant, bulk distribution system, distribution network improvement and water source improvement in Kathmandu. It also considers the potential negative social impacts into consideration.

Water Treatment in Kathmandu

The treatment process carried out in Kathmandu is conventional treatment with following processes:

- Biofiltration to treat impurities from groundwater
- Screening of raw water using chlorine
- Sedimentation to remove suspended impurities like silk, clay, etc.
- Alum feeding
- Flocculation and sedimentation to remove finer particles
- Aeration to dissolve gases, taste, iron and odor
- Permutit method for softening and
- Disinfection to kill pathogenic bacteria

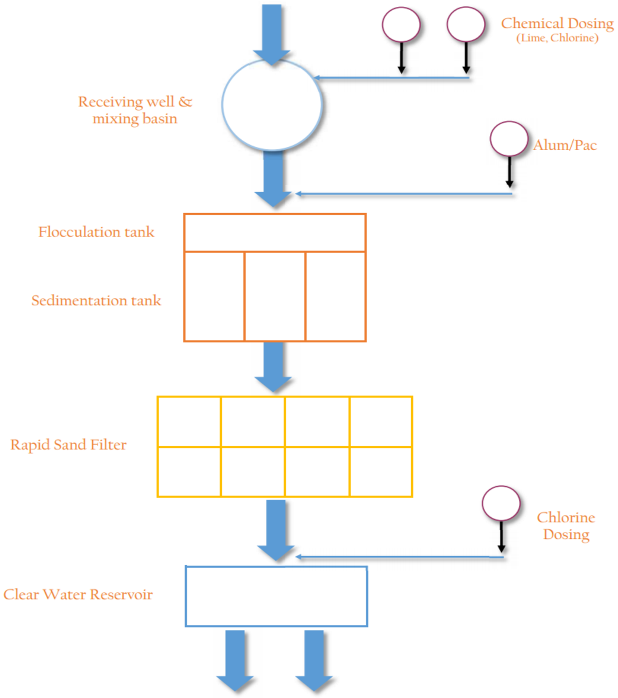

Figure 24: Flow diagram of a typical water treatment plant in Kathmandu. Source: Joshi, 2015

After water is treated, in Kathmandu's case, 90% of water treated is distributed to households by gravity. Hence, only a minimal amount of energy is consumed during distribution phase. MahankalChaur, Bode Manohara and Basbari branch of KUKL system have two reservoirs in their schematic. After water is treated, it first goes to a clear water reservoir by gravity. The water is then pumped to distribution reservoirs for distribution to the respective areas.

3.3.4 Waste Water Management

Combined storm water and sewer system in Kathmandu Valley are 50–70 years old connected to 17% of total households. The sewage system has a capacity to serve 40%. There are 4 treatment plants with total capacity of 17 million liters per day to treat wastewater produced.

The insufficient wastewater treatment infrastructures are resulting in pollution of major rivers, namely the Bagmati and Bishnumati Rivers. Agricultural runoff and industrial discharge without pretreatment contribute to the detrimental effects on water quality, not to mention public and environmental health.

Kathmandu Valley currently has five municipal wastewater treatment plants (WWTP): an activated sludge plant at Guheshwori, non-aerated lagoons at Kodku and Dhobighat, and aerated lagoons at Sallaghari and Hanumanghat. Of the five, the only wastewater treatment plant in operation as of January 2003 is the activated sludge system at Guheshwori (Green and Richards, 2003).

In brief, Urban Water Supply services in Kathmandu valley are governed mainly by two sources of water- Surface water and ground water. These sources are used by water supply authorities, private tankers to transport water for areas with demand, and households themselves to extract water for their convenience. Amongst the two sources, the water supply authority of Kathmandu, Kathmandu Upatyaka Khanepani Limited (KUKL) uses both surface and ground water in their system to undergo the urban water cycle stages like abstraction, conveyance, treatment and distribution (Joshi, 2015).

On the other hand, the private tankers use both surface and ground water, but without going through any treatment process, they distribute water to parties upon request. Similarly, households extract groundwater and undergo treatment as desired.

Kathmandu is assumed to have changes in its water energy and carbon nexus following the MWSP project. This report will also give an outlook of estimated energy consumption and carbon emissions from water supply after Melamchi is operational.

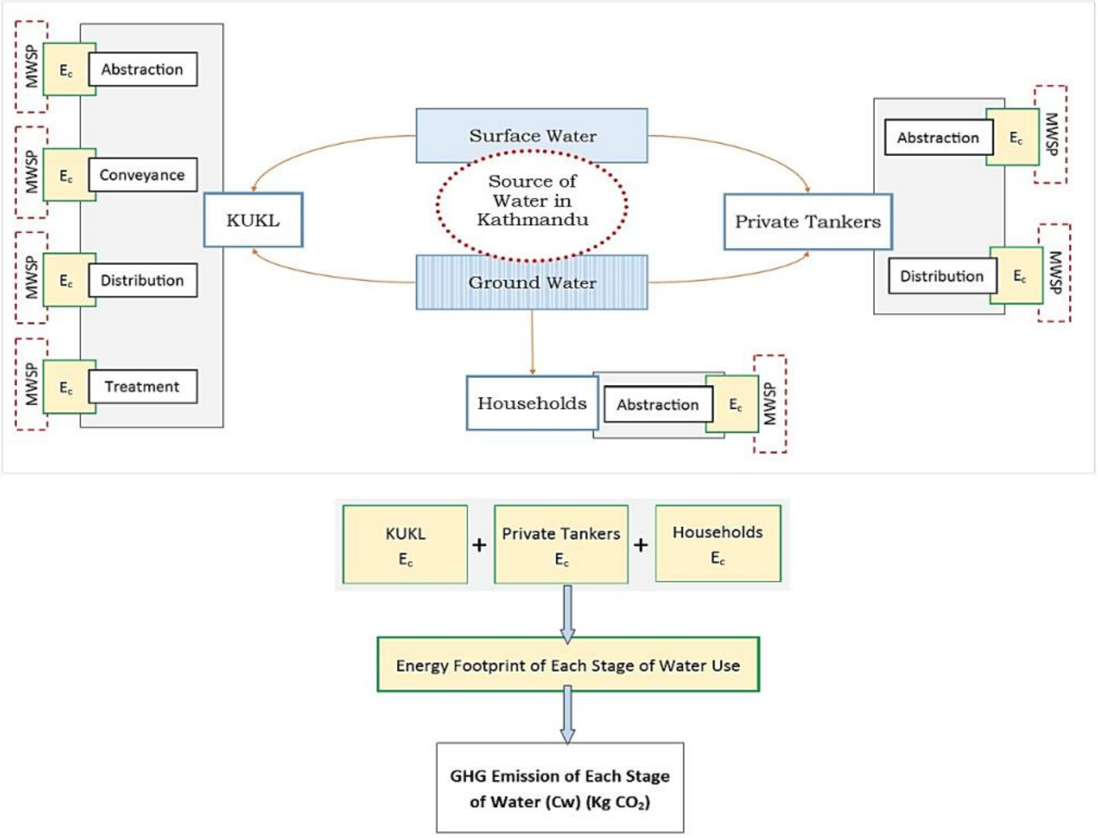

Figure 25: Water Supply Management in Kathmandu Valley

3.4 Tokyo

Tokyo, the capital of Japan is the center of Greater Tokyo area which administers 23 special wards of Tokyo. Tokyo metropolis covers total area of 621.81 km^2 out of 2,188.68 km^2 Greater Tokyo area. Tokyo had been the most populated city in the world since 1955 with the population of 13.71 million, in 2010 its population was 36.83 million and it is predicted that by 2030 the population will reach 37.19 million. Tokyo has the humid subtropical climate with average summer temperature of 27.5 °C and average winter temperature of 6 °C. The average annual rainfall is approximately 1,530 millimeters (mm).

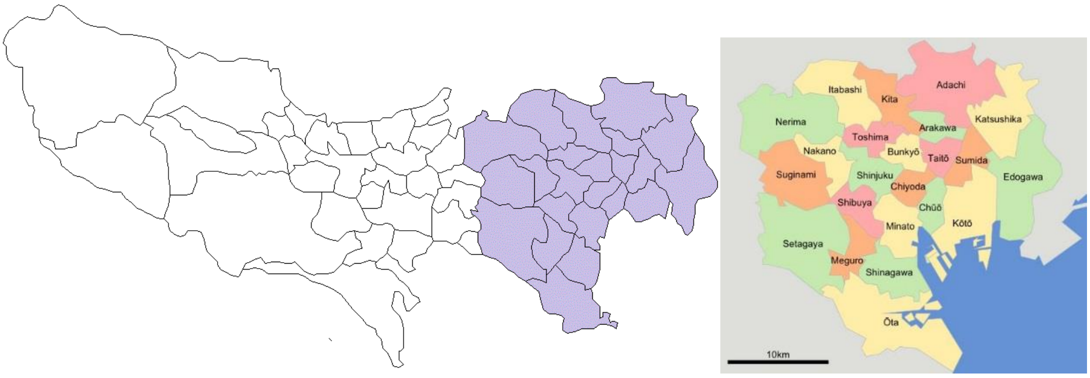

Figure 26: Map showing the total area of Greater Tokyo Area and Tokyo Metropolis (23 special wards) (Source: Wikipedia)

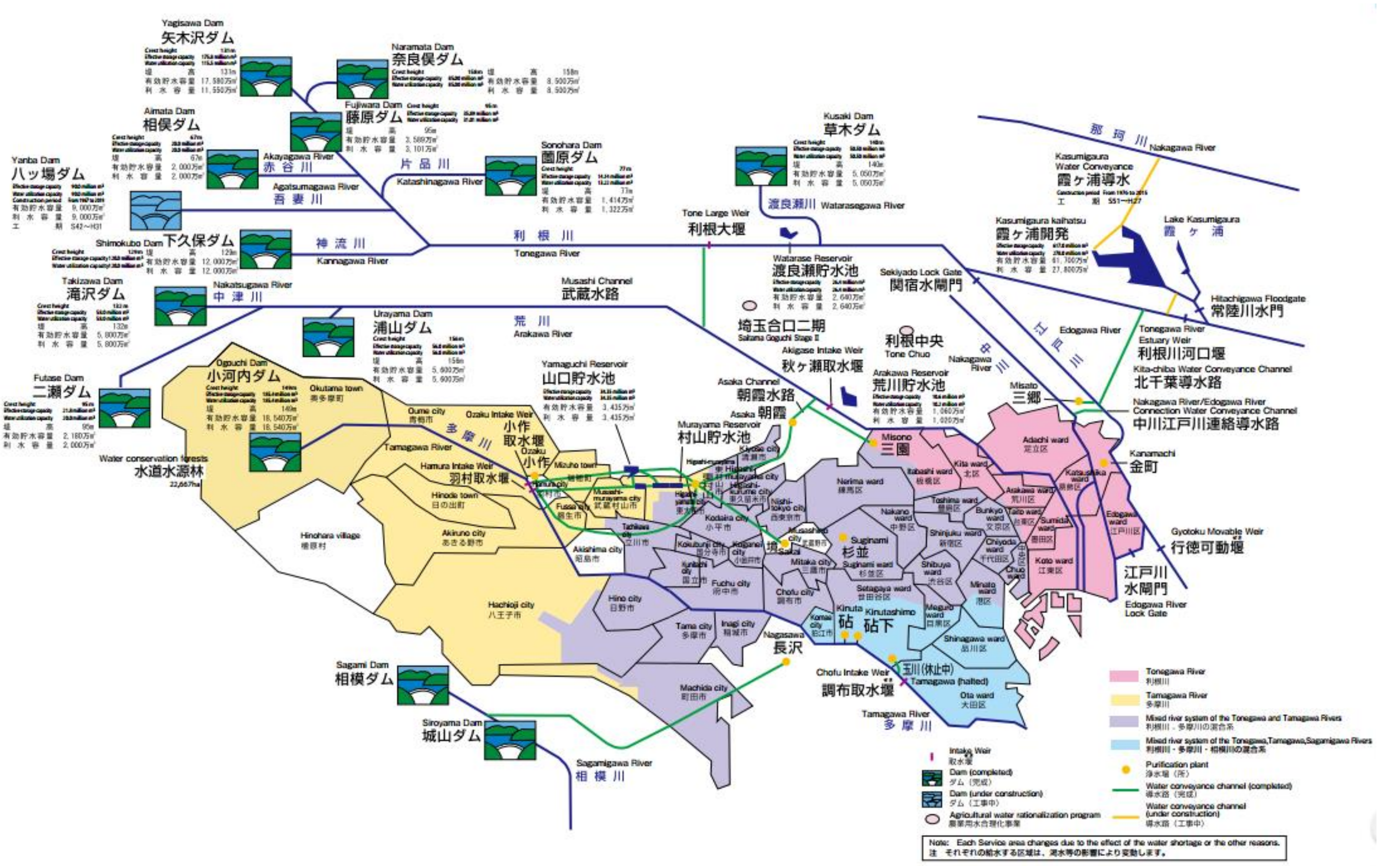

Figure 27: Location of Water Purification plants. Adopted from: Water Supply in Tokyo (2015)

3.4.1 Institutional Settings, Legislation, Policies and Practices

Drinking water - Bureau of Waterworks, Tokyo Metropolitan Government is the responsible body to supply clean drinking water within the city. The formulation of international standard for water supply service by the International Standardization Organization (ISO), had led Japan Water Works Association (JWWA) to formulate the "Waterworks Guideline", a domestic standard for water supply services in 2005. The Guideline is composed mainly of 137 items of service indexes ranging widely from facility capacity, operation and maintenance, water supply service level, cost, finance, personnel plan and consignment to environmental problems. Bureau of Waterworks set up numerical goals/targets as part of their management plan, which addresses the issues of improving efficiency, reinforcement of financial foundation, long term goal for facility installation. The achievement status are then evaluated at regular interval based performance assessment of different index (Bureau of Waterworks, 2007). Furthermore the index also address the total power consumption in water treatment in overall facilities within Tokyo. In 2003, the average power consumption was 0.5 kWh/m^3. Also, seismic measures for the distribution pipelines are included in the index to improve the safety and crisis response of waterworks system to earthquake and disaster. The ratio of earthquake resistant pipelines (which is combination of material seismic resistance of pipe and earthquake-resistant joint) to total extension of pipelines was 9.8 in 2000 and 16.8 in 2003. Other important index include utilization rate of sludge after water purification in term of environmental consideration. In 2000 this index value was 50.4% while in 2003 it increased to 68.4% demonstrating their effectiveness.

In 2013, Bureau of Waterworks Tokyo have prepared, "Tokyo Waterworks Management Plan 2013" with the overall goal of effective management as lifeline to support the everyday life of Tokyoites and the urban activities of the capital to provide safer and steadier supply of water services. Some of the crucial area that Bureau of Waterworks have focused are stable water supply- by securing water resources; countermeasures against earthquakes- by enhancing disaster response capabilities such as reinforcement of transmission networks, electric power facilities and improving emergency response systems such as fire hydrants, drainage valves; safe and better tasting water- by introducing advanced water treatment and addressing water quality issues; promoting communication with the customers by enhancing customer convenience; energy and environment related measures – by effective use of sustainable energy and environmental action, implementing environment management plans, improving water treatment efficiency.

Some of the Tokyo has emphasized on energy generation within treatment facilities.

Emphasize on the water leakage detection techniques and prompt repairs of leakages, with application of leak detection and leak prevention technologies.

Waste water and storm water - Bureau of Sewerage, Tokyo Metropolitan Government is responsible for waste water management. The construction of sewer systems and treatment systems, sewerage mapping in Tokyo dates back to early 19th century. The Bureau of Sewerage was founded in April 1962. In 1908, "The Tokyo City Sewerage Plan" was announced to begin treatment of waste water in District 2, in 1964 "The Tokyo Urban Sewerage Plan" was changed so sewer planning includes all 23 Wards. In the same year Ochiai WWTP started operations which included World's first park on top of a treatment facility. Sewerage Mapping and Information System (SEMIS) was initiated in 1986. In 1987 waste water heat recycling system was started in one of the treatment plants. In July 1992, "The Master Plan for the Second-Generation Sewerage" was enacted. In 1998 sewerage service charges was revisited. In February 2010, "Management Plan 2010" and "Earth Plan 2010"are enacted. TMG aims to reduce greenhouse gas emitted by the sewerage industry by 25% or more by 2020 and 18% or more by 2014, based on 2000 levels. That could provide positive contribution to the "10-year Project for a Carbon-Minus Tokyo," which is Tokyo City's initiative to reduce global warming.

The key management policies of Bureau of Sewerage, Tokyo Metropolitan Government are:

Policy 1: **Ensure a safe and comfortable living environment** – It includes plan of reconstructing facilities, adaptation and mitigation to floods and disaster management.
Policy 2**: Contribute to a hospitable and environmentally beneficial water environment** – It includes plan to countermeasure global warming, improvement of combined sewer systems, advanced treatment etc.
Policy 3: **Provide the best service at the lowest cost**

Some of the important practices for effective waste water management includes:

- Reconstructing facilities that have exceeded their designed service life in order to improve the energy efficiency. Inspection of sewer system by using TV camera and strengthening of poor condition sewer by lining with vinyl chloride material. It is one of the low cost and effective rehabilitation process.
- Construction of pumping stations to countermeasure floods, maintenance of rainwater infiltration systems and construction of storm water regulating reservoirs.
- Protection of the public water bodies and rivers from the Combined Sewer Overflows (CSO) and emphasizing advanced and semi advanced treatment. Construction of the sewerage system has greatly improved water quality of rivers and the sea, but red tides still occur for 90 days of the year at Tokyo Bay. Therefore, advanced treatment facilities were established to eliminate large amounts of nitrogen and phosphorus.
- Utilization of sludge as the resources by reusing its chemical energy. The amount of reclaimed water excluding stream restoration work has increased by 1.8 times in the past 10 years (from 5,000 m^3/day in 1999 to 9,000 m^3/day in 2009). Furthermore, in Tobu Sludge Plant, Carbide products manufactured from sludge are being used as fuel in coal-fired power plants.
- Repair and improvement of deteriorating equipment to reduce operation cost and overall GHG emissions have been emphasized. Their plans include use of sludge gasification incinerators that are highly efficient in reducing greenhouse gas emissions; furthermore, the heat generated from the sludge incineration will be used for air conditioning and Ash materials as the byproduct will be used for producing construction materials. Bureau of Sewerage Tokyo, have estimated that the amount of heat generated (about 120,000 GJ per year) by gas produced from sludge gasification is the equivalent to the amount of city gas used by 8,500 households during an entire year.

3.4.2 Water Supply Management

Waterworks in Japan have been successful in covering entire service area since 2003. The major source of drinking water in Tokyo are surface water from Edogawa, Tonegawa, Tamagawa, Sagamigawa rivers. These rivers originate from the upstream of the central Tokyo and drains into Tokyo Bay. Small portion of drinking water are extracted from the confined groundwater aquifers. In water supply sector the monthly average water supply temperature have increased in both winter and summer, probably due to heat exchanges between water utilities and shallow ground as the effect of urban heat island effect (Tsuyoshi, 2007). Water utilities are extracting solar and small scale hydro power within their facilities, with the estimated target to increase generating capacities to 10,000 kW by 2016 from 6,803 kW in 2006. The Non-Revenue Water in Tokyo is 3.3 %.

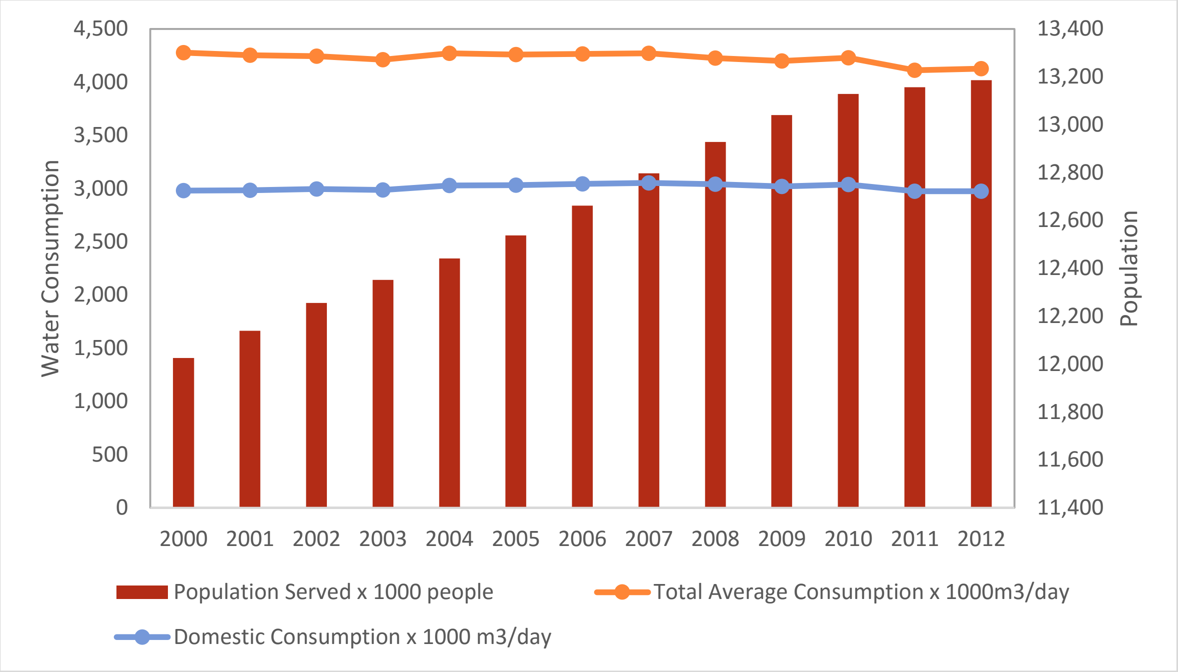

Figure 28: Daily water consumption and population served in Tokyo. Data Source: Bureau of Waterworks, TMG

Table 19: Water Treatment Plants of Bureau of Waterworks in Tokyo

Water Treatment Plant	Water Sources	Production capacity/day (Million cu.m.)	Treatment Technologies
Kanamachi Purification Plant	Tonegawa/ Arakawa River Systems	1.5	Rapid sand filtration, Advanced water treatment
Misato Purification Plant		1.1	Rapid sand filtration, Partially Advanced water treatment
Asaka Purification Plant		1.7	Rapid sand filtration, Partially Advanced water treatment
Misono Purification Plant		0.3	Rapid sand filtration, Advanced water treatment
Higashi-Murayama Purification Plant	Tonegawa, Tama River System	1.26	Rapid sand filtration Tonegawa/ Arakawa River advanced water treatment
Ozaku Purification Plant	Tama River System	0.28	Rapid sand filtration
Sakai Purification Plant		0.315	Slow sand filtration
Kinuta Purification Plant		0.114	Membrane filtration, Slow sand filtration
Kinuta-shimo Purification Plant		0.07	Membrane filtration, Slow sand filtration
Nagasawa Purification Plant	Sagamigawa River	0.2	Rapid sand filtration
Suginami Purification Plant	Ground water	0.015	Chlorine injection only

Data source: Bureau of Waterworks in Tokyo, 2013

3.4.3 Waste Water Management

Bureau of Sewerage, Tokyo Metropolitan Government manages all the waste water collection, storm water collection and treatment responsibility within Tokyo. Their major roles are improving living environment through sewage treatment, preventing flooding through rainwater drainage, preservation of water quality of public water bodies and ensuring efficient use of the resources and energy provided by the reclaimed water and the sewers through the versatile use of sewer facilities.

The sewerage system within Tokyo is divided in three components:

i. *Sewers* – Sewers supply water to water reclamation centers or waste water treatment plants. The total sewer line is 15,800 km within the 23 Wards. The material of the sewers are mainly of concrete, polyvinyl chloride (PVC), and tiled pipes, and their diameter ranges from 25 cm to 8.5 m.
ii. *Pumping Stations* - Sewers have designed gradient to ensure gravity flow that makes the depth of sewers deeper. Pumping stations have the role of pumping up wastewater to transport it water reclamation center. It also plays major role in preventing flooding by promptly discharging rainwater that has flowed into the sewers to rivers and the sea.
iii. *Water reclamation centers* – The two major functions of water reclamation centers are to-treat wastewater and to treat sludge generated as a result of treatment processes. Tokyo Metropolitan Government Sewerage Bureau manages 20 centers that treat around 5.56 million cubic meters of wastewater per day within Tokyo and Tama region. As the area required to treat such large volumes of water is very huge, the centers are designed to make the most efficient use of space using feature of double-decker sedimentation tanks and deep reaction tanks. In a joint effort between the Tokyo Metropolitan Government and individual local Ward and city administrations, the roofs covering the water reclamation centers are also used for parking space.

The total volume of waste water effluent from treatment plants is larger than the total amount of consumed water as drainage system collects storm runoff too. The total amount of water consumption in the Tokyo metropolis (of source area 621 km^2) was 1805 mm in 2000 compared to annual precipitation of 1467 mm during 2000 (Tsuyoshi, 2007). Most of the Tokyo have combined sewer systems. All area of the Tokyo are linked with the sewer system. Tokyo metropolis catchment is divided into 10 small catchments and each of the sub basin have one to more wastewater treatment facility. The approximate percentage share of waste water volume from residential sector is 71% and surface runoff is 21% and groundwater leakage is 8%. The ward area is divided into 10 treatment districts which are serviced by 13 water reclamation centers (Figure 29). 4.64 million m^3 of wastewater is treated daily in Tokyo. The total length of sewers in 15,830,225 m (Trunk: 1,074716 m and Branch: 14,755,508 m), total number of manholes are 479,598 m and total number of public house inlets are 1,878,639. There were 83 numbers of pumping stations as per 2010 with annual pumped volume of 828,695,340 m^3 and daily average of 2,270,400 m^3.

Figure 29: Overall plan of sewer system in Tokyo (23 Wards)

Table 20: Performance of WWTPs in Tokyo

Waste Water Reclamation Centers	Water Treatment/ year	Water Treatment/ Day	Area Served (Ha)	Population	BOD in (average in 2012)	BOD out (average in 2012)
Shibaura	231,858,880	2,554,185	6,433	684,000	190-240	2-4
Mikawashima	155,069,925	1,715,281	3,936	811,000	130-270	2-5
Sunamachi	131,745,951	1,878,120	5,687	960,000	100	7
Ariake	5,221,815	21,240	6,153	906,900	130	1
Nakagawa	64,465,618	787,850	4,442	521,500	160	7
Kosuge	77,451,415	1,579,590	1,633	265,700	140	7
Kasai	117,532,406	1,696,228	4,893	792,900	160-180	1
Ochiai	135,849,138	1,235,175	3,506	679,800	140-190	3-12
Nakano	10,336,483	70,376	3,506	679,800	140	3
Miyagi	78,237,711	899,115	1,687	301,800	120-160	3-4
Shingashi	190,964,535	2,229,046	10,474	1,632,900	190	7
Ukima	34,338,846	626,668	10,470	1,632,900	94	3
Morigasaki	429,899,098	5027,018	19,065	2,605,900	110-130	4

4. Results & Discussion

4.1 Bangkok

4.1.1 Energy and Carbon Footprints Water Supply System

The energy footprints in water supply cycle within MWA are documented in the MWA Annual reports. The range of energy footprints in different process from 2004 to 2011 are presented in Table 21 and Figure 30.

Table 21: Energy and carbon footprints of water utilities in MWA

Process	Comparison	2010	2011	2012	2013	2014	2015
Abstraction & Conveyance	Water Volume (m^3/year)	1887.31	1925.89	1986.94	2028.99	2076.36	2164.12
	Energy Footprint (Energy use) (kWh/ m^3)	0.01	0.01	0.01	0.01	0.01	0.01
	Carbon Footprint (Energy Use) (kg/ m^3)	0.03	0.03	0.03	0.04	0.03	0.04
Water Treatment	Water Volume (m^3)	1785.72	1781.21	1844.20	1877.42	1934.66	2029.54
	Energy Footprint (Energy use) (kWh/ m^3)	0.56	0.59	0.58	0.60	0.60	0.59
	Carbon Footprint (Energy Use) (kg/ m^3)	2.70	2.83	2.79	2.89	2.88	2.85
	Carbon Footprint (Chemical) (kg/m^3)	0.011	0.015	0.013	0.019	0.014	0.012
Water Distribution	Water Volume (m^3/year)	1735.91	1715.78	1763.55	1804.54	1797.81	1835.13
	Energy Footprint (Energy use) (kWh/ m^3)	0.05	0.05	0.05	0.04	0.04	0.05
	Carbon Footprint (Energy Use) (kg/ m^3)	0.22	0.22	0.22	0.21	0.21	0.23

The maximum energy use is observed in water transmission system followed by water distribution system. The majority of the energy is utilized in pump stations.

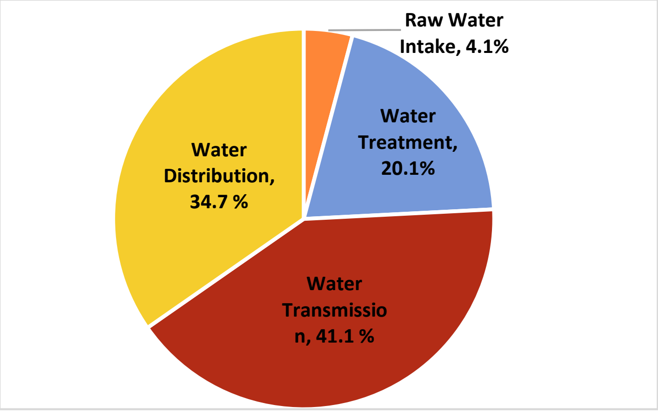

Figure 30: Energy utilization by water supply process in MWA (Data source: MWA, 2012)

Energy use in waste water management can be divided into two parts: Energy consumed by WWT units and Energy consumed by pumps in the collection system. The figure 31 below shows the month variation in total kWh of energy consumption in different treatment plants from 2010 to 2013. Energy consumed by WWT Units is 97 to 99 % and 1 to 3 % is consumed by pumping stations.

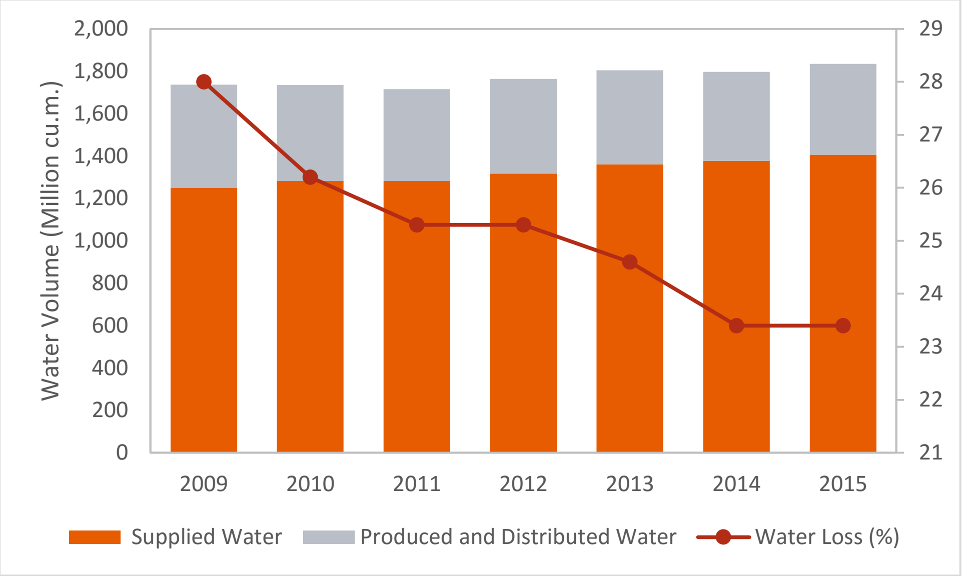

Figure 31: Water loss in MWA's water supply system

Average NRW water loss of MWA water have been decreasing substantially from 28 percent in 2009 to 23.4 percent in 2015. This water loss has significant implications on energy loss and carbon footprints which could be further avoidable.

Average water abstraction and conveyance volume in Bangkok Metropolitan Region, combining MWA and PWA during 2010 to 2015 was 2242 Million m^3 (figure 32), while treated water volume was 2096 Million m^3 and distributed water volume was 1995 Million m^3. The maximum energy is consumed in treatment, which averaged out to 330.5 MWh/year, while abstraction/conveyance and water distribution system has the share of 23.5 MWh/year and 126.2 MWh/year. However, energy footprint related to direct electricity use during treatment process constitute maximum share with the value of 1.1 kWh/m^3 of treated water, while abstraction/conveyance and water distribution system have energy footprints of 0.1 kWh/m^3 and 0.4 kWh/m^3 respectively.

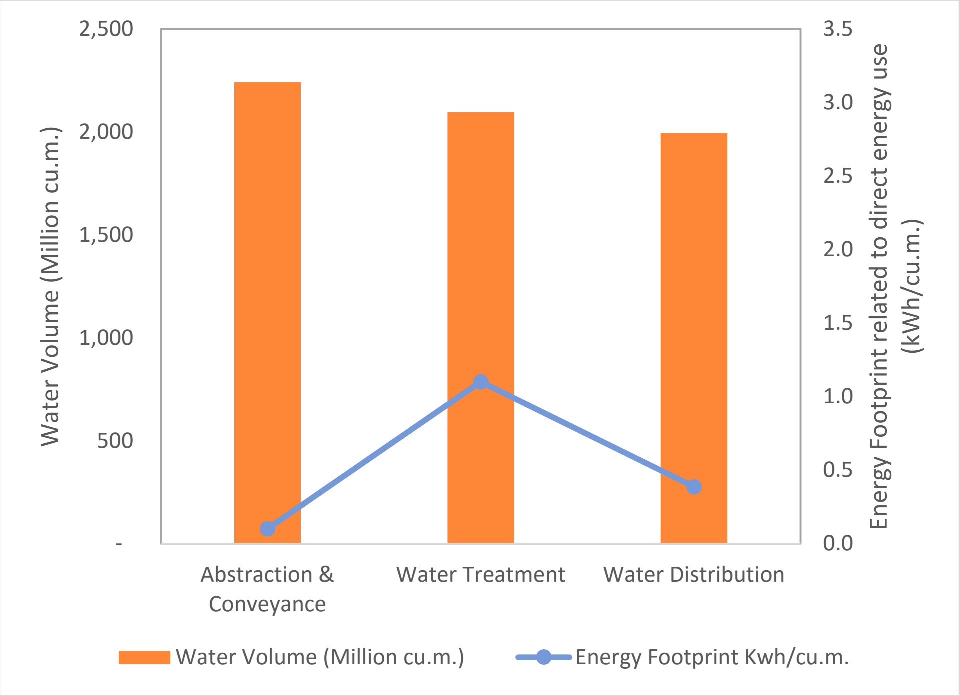

Figure 32: Average (2010 - 2015) of water volume and energy footprint related to direct energy use in BMR water supply system

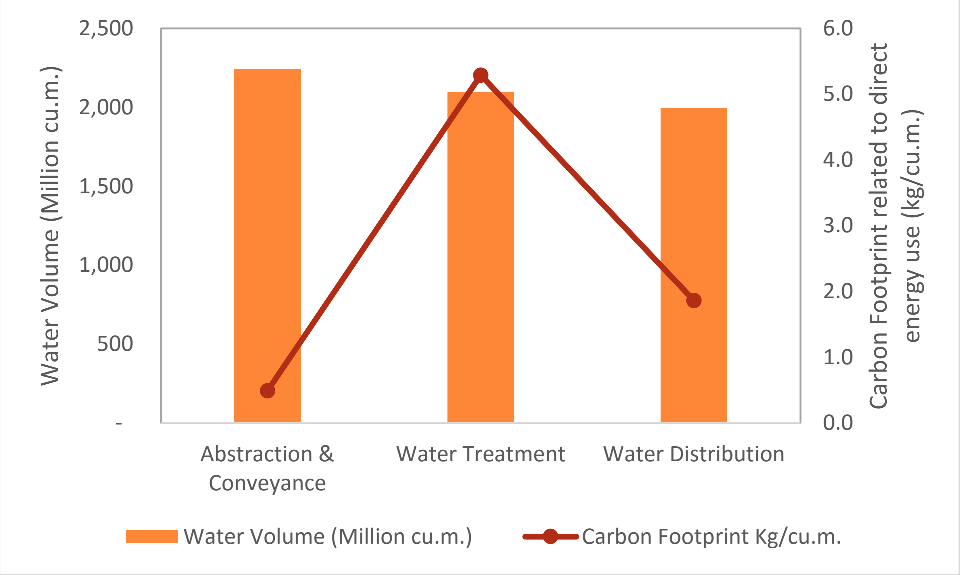

Figure 33: Average (2010 - 2015) of water volume and carbon footprint related to direct energy use in BMR water supply system

Likewise abstraction/conveyance, water treatment and water distribution system have similar pattern of carbon footprint (figure 33) as of energy footprint with the values of 0.5 kg CO_2/m^3, 5.3 kg CO_2/m^3 and 1.7 kg CO_2/m^3.

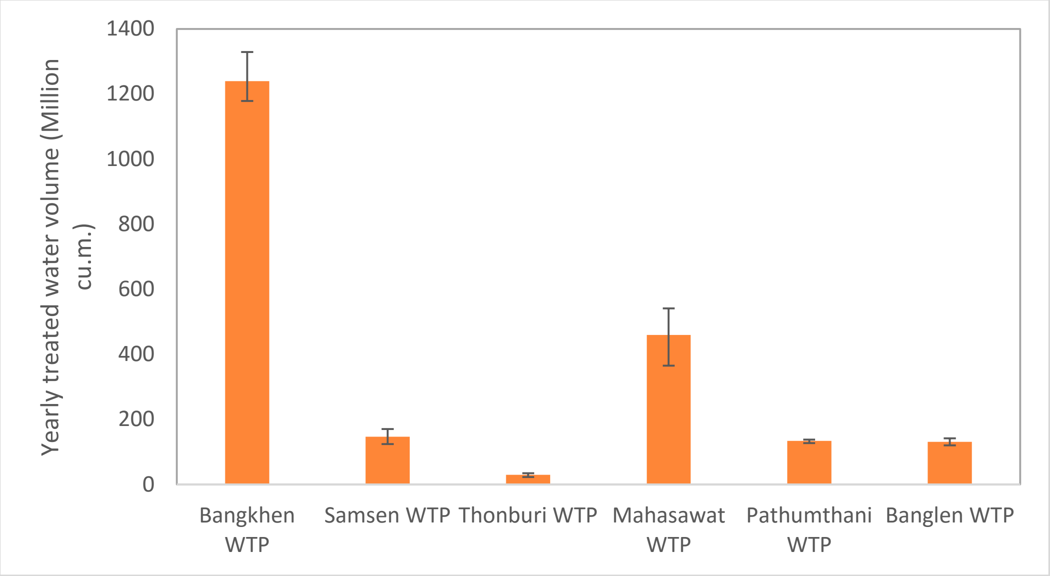

Figure 34: Average of yearly treated water volume of MWA and PWAs' WTPs from 2010 to 2015, showing maximum and minimum values

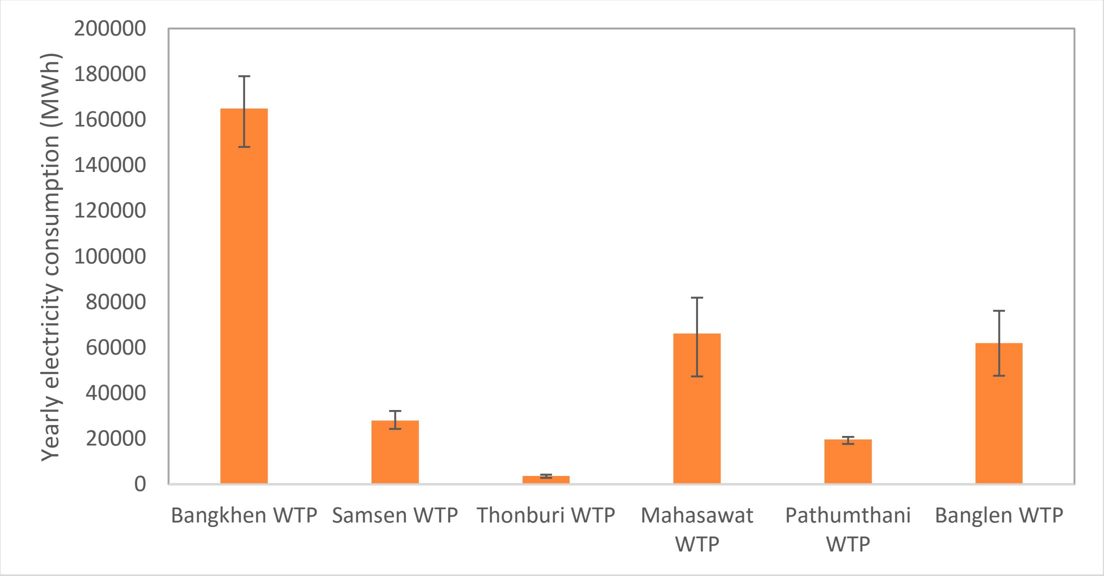

Figure 35: Average of yearly electricity consumption in water treatment by six WTPs of MWA and PWA from 2010 to 2015, showing maximum and minimum values

Out of six WTPs of BMR, Bangkhen WTP is of the largest capacity, therefore, has the maximum energy use among other WTPs (figure 34 and 35). However, its energy intensity (figure 37) is not the highest. Bangkhen WTP has lesser carbon and energy footprints compared to its capacity with other treatment plants. Capacity utilization and design of systems has significant links to its operational energy footprints. Bangkhen WTP operates at comparatively highest capacity utilization of 94%, while lowest is among Thonburi WTP of just 30%, also Thonburi WTP has lowest capacity, but its energy intensity is almost as of Bangkhen WTP. Maximum energy and carbon footprints of WTPs within MWA is of Samsen WTP, which has only 51 percent utilization of its overall capacity. Of the two WTPs of PWA, Banglen WTP has maximum energy and carbon footprints, with capacity utilization of 64 percent.

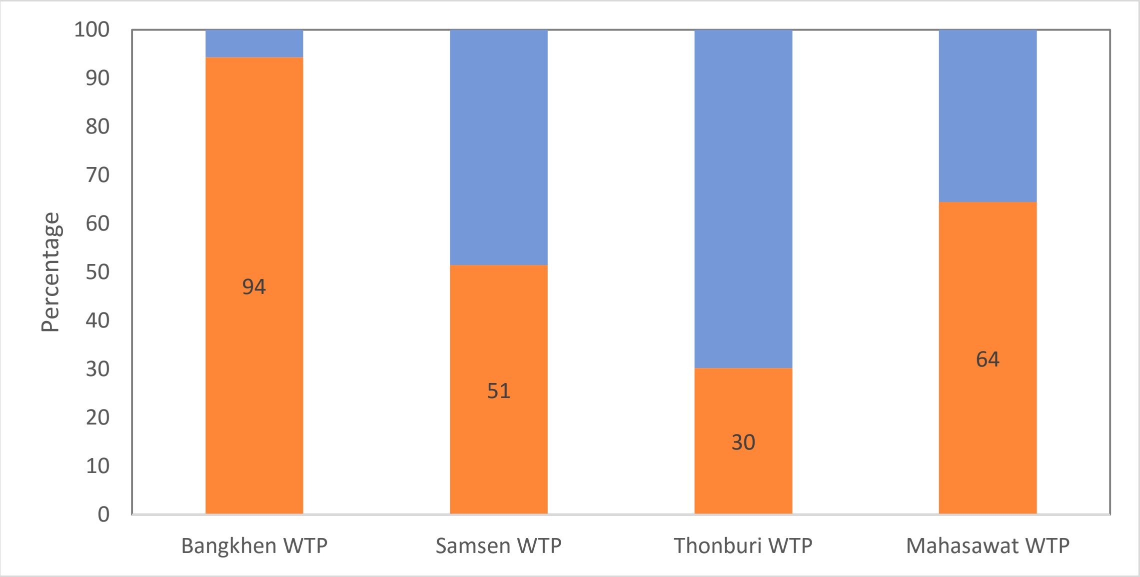

Figure 36: Average capacity utilization of 4 WTPs of MWA from 2010 to 2015, showing designed vs actual operating capacity

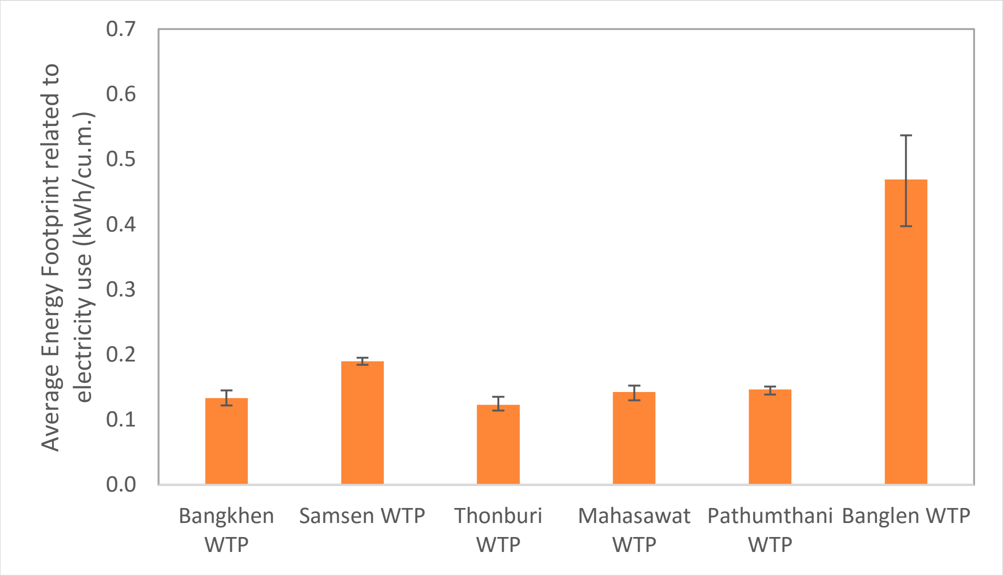

Figure 37: Average of energy footprint related to electricity use in water treatment by six WTPs of MWA and PWA from 2010 to 2015, showing maximum and minimum values

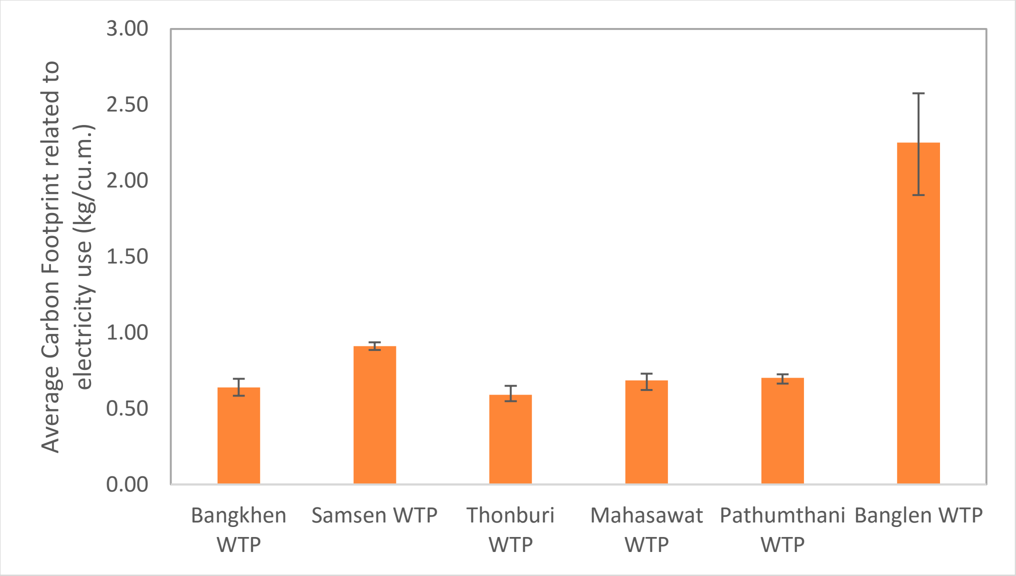

Figure 38: Average of carbon footprint related to electricity use in water treatment by six WTPs of MWA and PWA from 2010 to 2015, showing maximum and minimum values

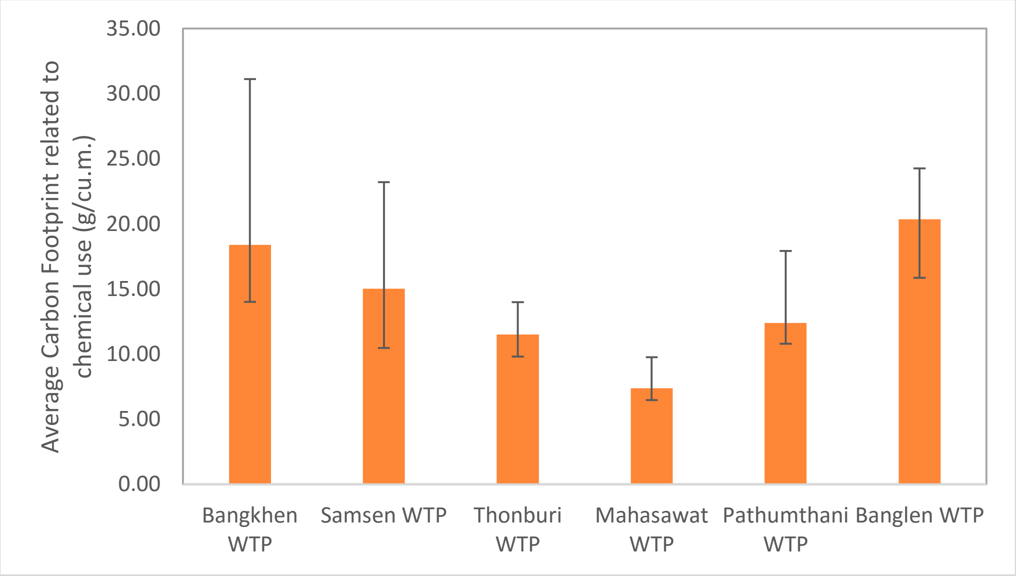

Figure 39: Average of carbon footprint related to chemical use in water treatment by six WTPs of MWA and PWA from 2010 to 2015, showing maximum and minimum values

Carbon footprints related to chemical use were obtained by multiplying emission factor of each chemical types with the quantity of chemicals used by the treatment plants. Please see Annexure V for details on chemicals. Figure 39 shows the range of average carbon footprints for each WTPs along with maximum and minimum carbon footprints.

4.1.2 Energy and Carbon Footprints – Waste Water System

BMR has combined sewer system for storm water and wastewater. BMR waste water sector suffered 2011 great flood in Thailand, due to which their performance in pumping systems was in much higher degree than in other years. Hence, 2011 was not considered in calculating average figures for collection systems. In this case study for waste water systems in BMR, energy and carbon footprints are presented as combined for collection (pumping) and treatment.

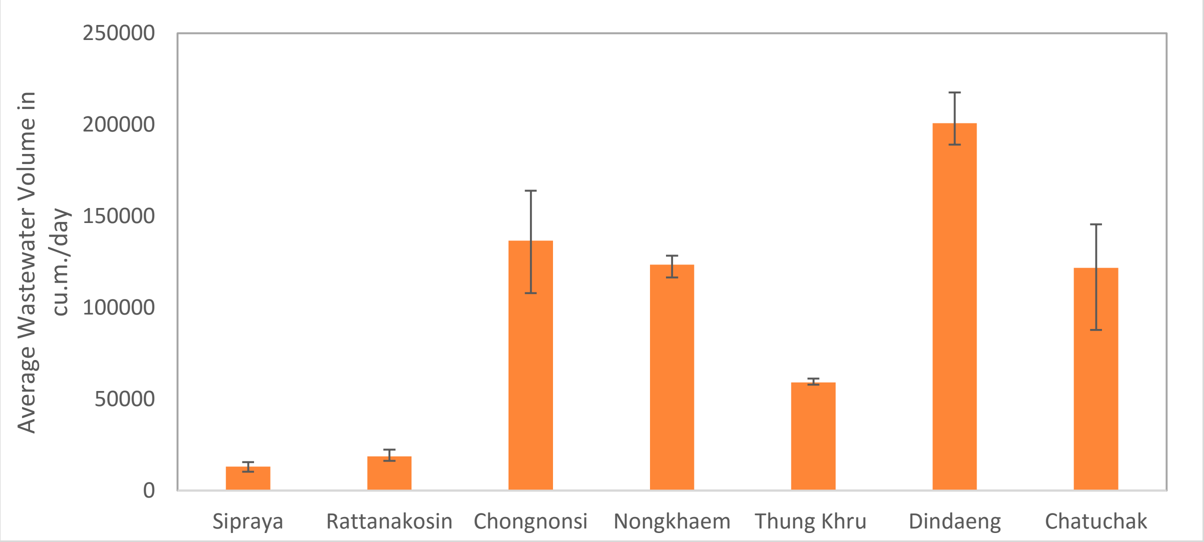

Figure 40: Average wastewater volume treated by six WWTPs in m^3/day from 2012 to 2015 and bars showing maximum and minimum range

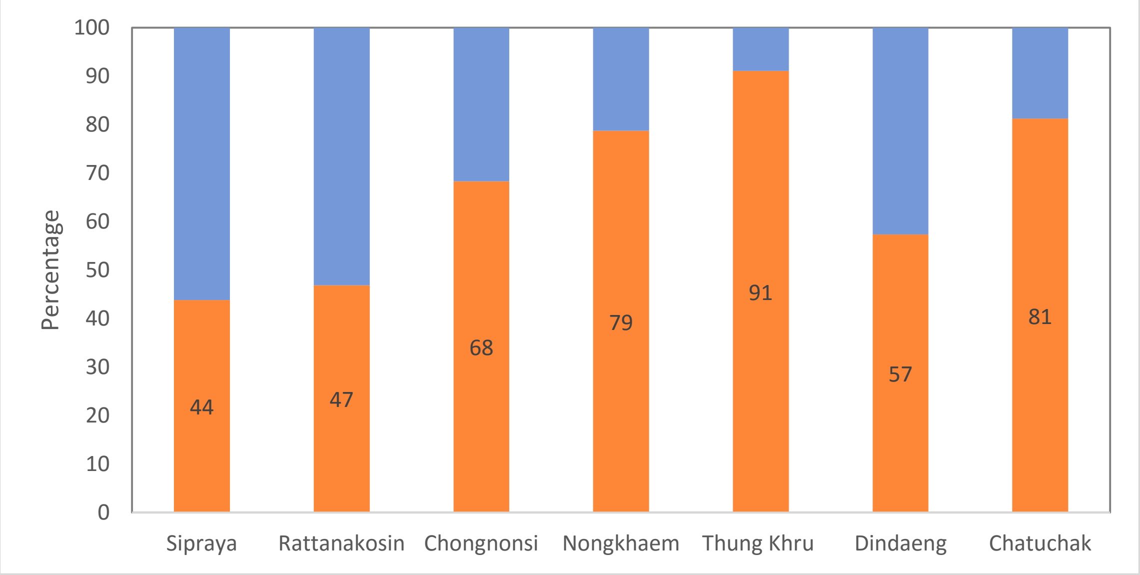

Figure 41: Average capacity utilization of 7 WWTPs from 2012 to 2015, showing designed vs actual capacity

Chongnonsi, Nongkhaem, Chatuchak and Dindaeng WWTPs are the larger plants in BMR and Sipraya, Rattanakosin, Thung Khru are comparatively small plants. Their average energy consumption are presented in figure 42. There further are several small community WWTPs in different provinces of

BMR. The average capacity utilization of Thrung Khru and Chatuchak WWTPs are higher among other WWTPs (figure 41).

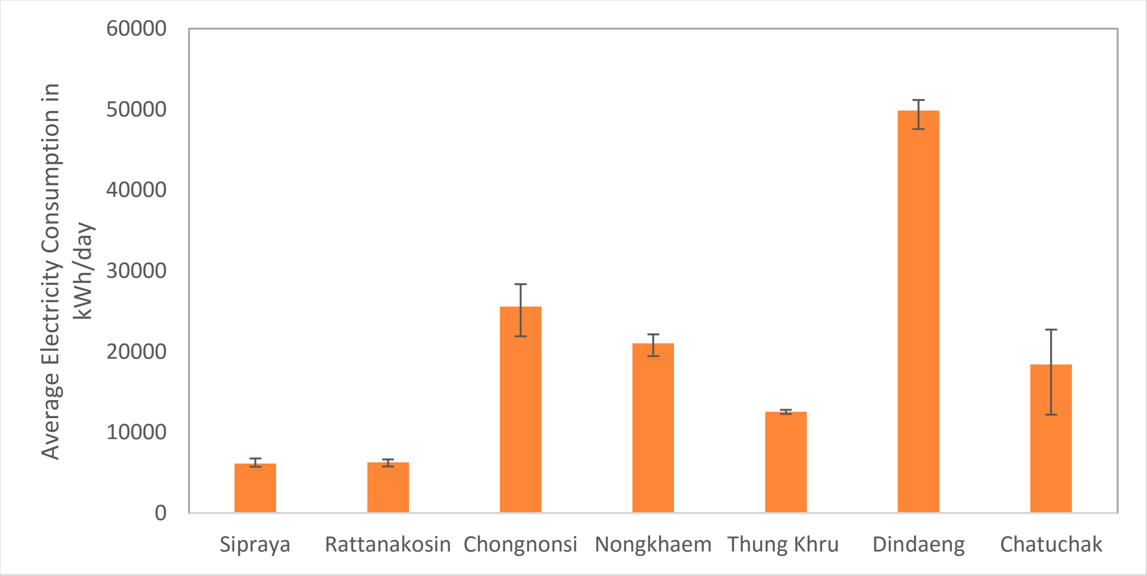

Figure 42: Average electricity consumption by six WWTPs in m^3/day from 2012 to 2015 and bars showing maximum and minimum range

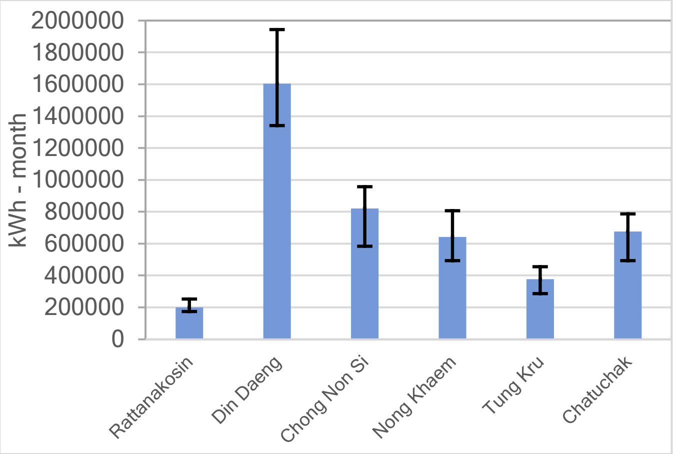

Figure 43: Variation of monthly electricity consumption kWh at six WWTPs showing Average, Maximum and Minimum values

Above figure 43, showed monthly electricity consumption per month with the combined data from 2011 to 2014.

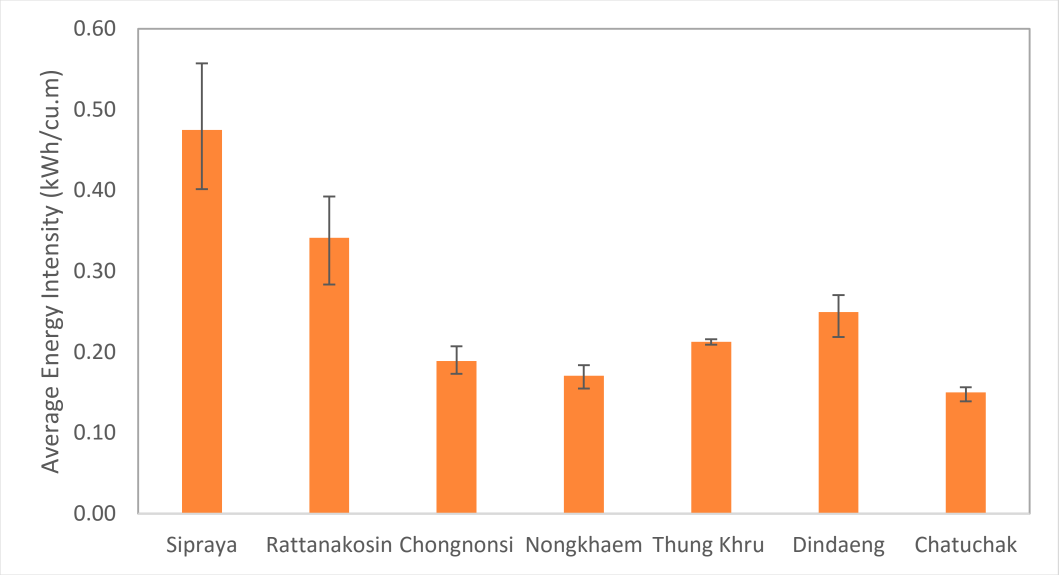

Figure 44: Average energy footprint (energy intensity) of six WWTPs in kWh/m^3 from 2012 to 2015 and bars showing maximum and minimum range

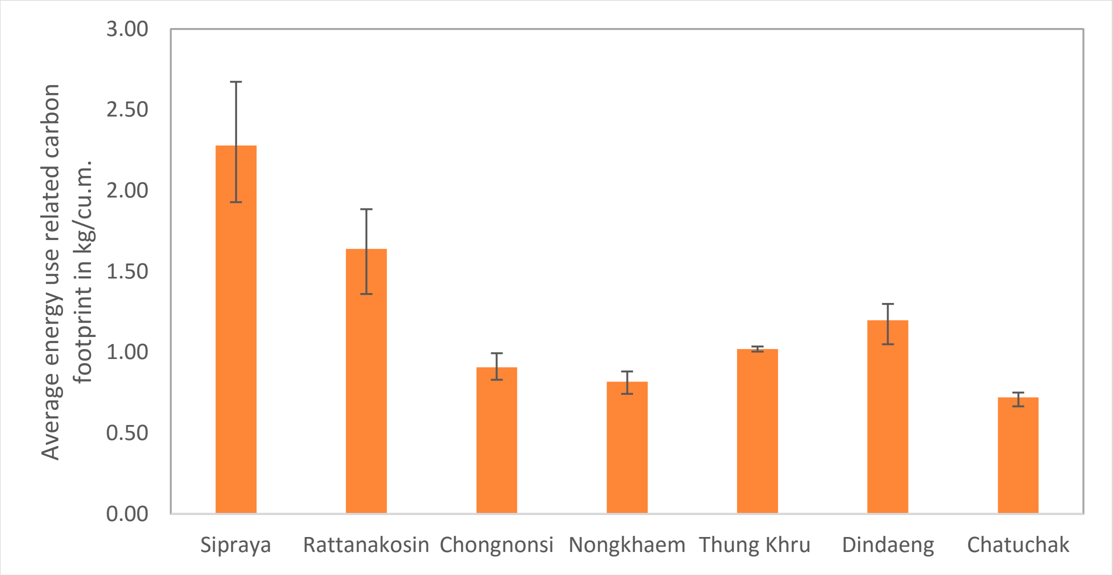

Figure 45: Average carbon footprint related to energy use of six WWTPs in kWh/m^3 from 2012 to 2015 and bars showing maximum and minimum range

Sipraya WWTP has maximum energy and carbon footprint which also has least capacity utilization among 7 WWTPs.

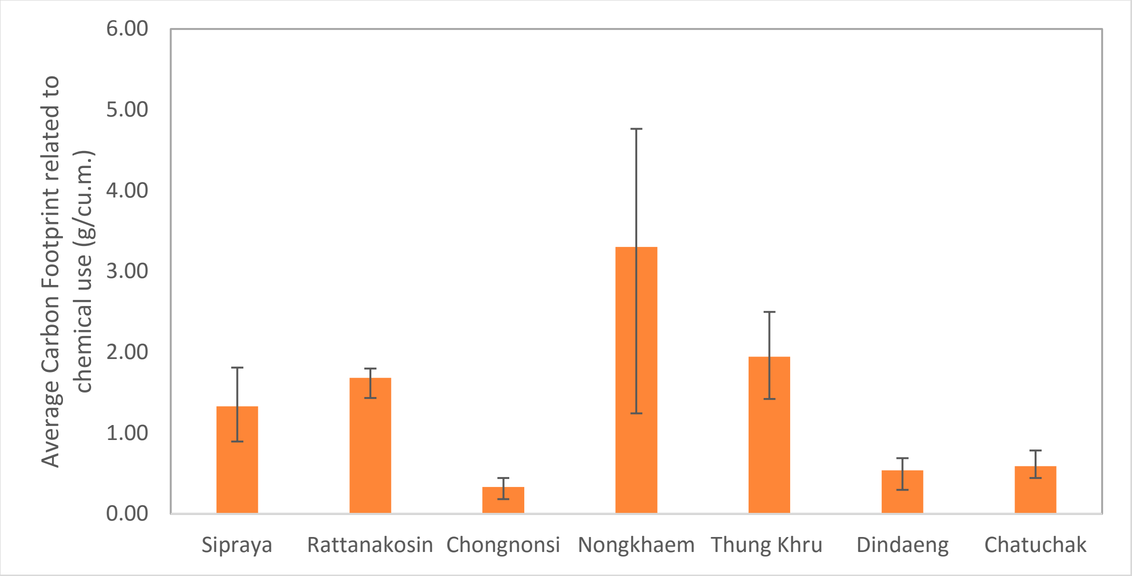

Figure 46: Average carbon footprint related to chemical use of six WWTPs in kWh/m^3 from 2012 to 2015 and bars showing maximum and minimum range

The water and waste water sector currently contribute 3 % of total GHG emission in BMR, while transportation and electricity are the major sources. However, considering the embodied energies, fugitive emissions and increasing capacity and demand on water/wastewater sector the number could be higher.

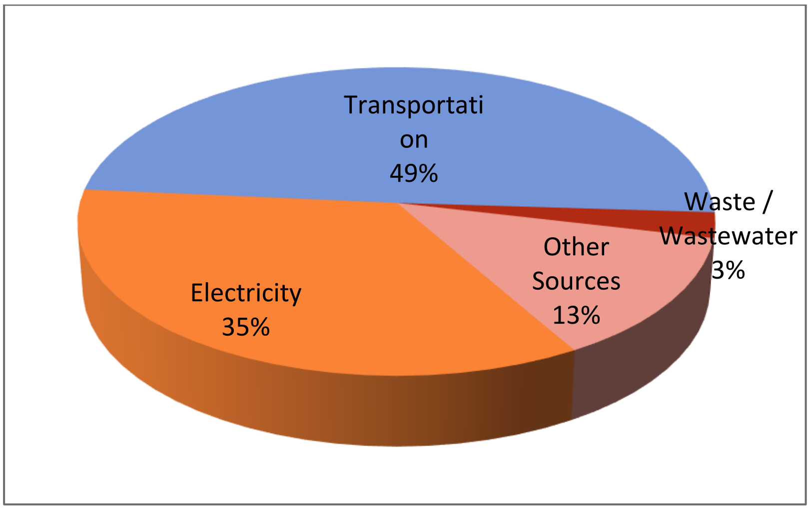

Figure 47: GHG Emission in BMR by sectors (million ton per annum) (Source: BMA Action Plan on Global Warming Mitigation 2007-2012)

Furthermore, the GHG emission source identified for wastewater sector are: emission from canal, emission from septic tank, electricity consumption, transportation of excess sludge and anaerobic digestion of excess sludge. As per BMA, septic tank contribute to largest emission share with the release of 524,286 Ton CO_2/ year. The total emission from wastewater source is 649,719 Ton CO_2/year. The total carbon footprints from energy use, chemicals use has been quantified for this comparative analysis.

4.1.3 Major findings

Following the research protocol and framework this study was divided into water supply, waste water management, energy consumption under the framework of energy for water. From perspective of city boundaries and scope of our research, energy for water is more important in city perspective rather than water for energy. This is because all the power are transported in to BMR from different power plants outside the provinces.

In water supply sector, majority of energy use are observed in water transmission. MWA were able to reduce NRW losses considerably in the recent years. The further plans to increase pressure and reduce further water losses will help in minimizing energy and carbon footprints. Some of the major issues in BMR are the pollution of the canals due to inadequate waste water treatment; CSO overflows into canals and rivers.

The total energy footprint for water supply sector is 1.59 kWh/m^3 and carbon footprint, combining emission related to energy and chemical use is 7.65 kg-CO_2/m^3. The total energy footprint for waste water sector is 2.16 kWh/m^3 and carbon footprint, combining emission related to energy and chemical use is 10.36 kg-CO_2/ m^3.

The energy footprint in waste water treatment system is quite higher, which account to use of activated sludge system, pumping systems and lesser utilization of treatment plants than its capacity. There are opportunities to reduce waste water related energy footprints.

4.2 New Delhi

Tables 22 and 23 give estimates of energy used in various stages of urban water cycle. Energy is estimated for- (1) embodied in materials of built infrastructure; and (2) operational phase. Operational phase energy is further classified into direct energy use (electrical and diesel) and embodied in consumable materials. These estimates have been made based on the primary and secondary sources of information, personal interviews and access to the records of the relevant government departments and by conducting primary survey wherever the data is not monitored/ documented. Table 22 also explains estimation method, data source and our assessment on the reliability of the values thus obtained. Further, the estimation is done only for municipal water supplies and do not include industrial sector.

In term of data availability it is found that data on water sourcing is difficult to access due to long distance inter-state transport of water and involvement of many agencies such as State Irrigation Departments, Central Water Commission, Central and State Ground Water Boards etc. Water being a state subject in India, the data on surface water flows is classified for access to general public even though it is not explicitly stated by these agencies. Similarly, access to *water treatment plants* is more difficult compared to *sewage treatment plants* due to security concerns in the former case. Therefore, Zoom-in studies have been conducted on wastewater infrastructure by doing a detailed inventory and use of mathematical models. This is done to understand the influence of various drivers on WEC nexus (annexures II and III). Similarly, primary survey has been done to understand WE nexus at the end consumer stage (annexure IV).

Table 24 gives estimate of carbon emissions from urban water cycle.
Tables 25 and 26 give estimates for TPPs in Delhi.
Annexure I: Gives supporting information for energy and carbon estimation for water sourcing, conveyance and treatment.

Annexure II: Gives detailed analysis of WEC nexus for wastewater infrastructure of Delhi.
Annexure III: Gives details on WE nexus at household consumer level.
Annexure IV: Gives supporting information related to estimates for TPPs.

Table 22: Energy estimates in various stages of urban water cycle

Stage of Urban water cycle	Energy (MWh/day)			Method of estimation	Data source	Reliability of the estimation/ Remarks
	Embodied in built Infrastructure	Operational Phase				
		Direct	*Embodied Chemicals*			
Water sourcing						
Surface	Not estimated	956	0 (NA)	Using a factor of 0.002 kWh/m^3/km[13]	Secondary data from government publication for surface flows which is reliable.	Poor reliability since the information about actual electricity consumption is not available.
Ground	Not estimated	75	0 (NA)	Using a factor of 0.004 kWh/m^3/m^1	Secondary data from government publication which is for the year 2011. Data for average depth of GW is estimated by Government officials during personal discussions.	Poor reliability and underestimation since the information about actual electricity consumption by DJB is not available and the data on private ground water abstraction is not available.
Water conveyance						
Centralised WT	Not estimated	564.30	1485.24	Direct electricity is actual given by DJB Embodied in chemicals is using the method (Annexure II & III). Data for chemicals consumed is the actual from the DJB	DJB records (unpublished)	Good
Bottling plants of DJB	Not estimated	1.20	Not estimated	Actual data given by DJB	DJB records (unpublished)	Underestimation since large number of private RO based bottling plants are not included in the estimates
Water distribution						
Pipeline supply	0.47	260.68	0 (NA)	For embodied, using the method (Annexure II & III) Direct electricity is actual given by DJB	Pipeline material data from unpublished DJB records. DJB records (unpublished)	Good. **Electricity consumption for conveyance of water to WTPs is subsumed in this estimation.**
Tanker supply	Not estimated	258.84 (Diesel)	0 (NA)	Using the method (Annexure II & III)	Data on tankers from DJB records (unpublished)	Underestimation since large number of private

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[13] Plappally, A.K and Leinhard J.H.V. 2012. Energy Requirement for Water Production, Treatment End Use, Reclamation and Disposal, Renewable and Sustainable Energy Reviews, 16: 4818-4848

						tankers are not included in the estimates
End use (Domestic)	Not estimated	1670	0 (NA)	Using the method (Annexure IV)	Data from primary survey	Good to very good. Estimates do not include energy used for heating water.
Wastewater conveyance	116.55	86.66 (Elect.) 0.46 (Diesel)	0 (NA) 0 (NA)	Mathematical model, (Annexure II & III)	DJB records (both published and unpublished)	Good to very good. Published in peer reviewed journal
Wastewater treatment and disposal	21.12	160.31 (Elect.) 16.21 (Diesel)	48.36	Mathematical model, (Annexure II & III)	DJB records (both published and unpublished)	Good to very good. Published in peer reviewed journal

Table 23: Energy in urban water cycle, New Delhi

Stages of urban water cycle	Energy (MWh/day)				Total Energy (MWh/day)
	Direct		Indirect		
	Electricity in operational phase	*Diesel in operational phase*	*Embodied in built Infrastructure*	*Embodied Chemicals in operational phase*	
Water sourcing					
Surface	956	0 (NA)	Not estimated	0 (NA)	956
Ground	75	0 (NA)	Not estimated	0 (NA)	75
Water treatment					
Centralised WT	564.30	0 (NA)	Not estimated	1485.24	2049.54
Bottling plants of DJB	1.20	0 (NA)	Not estimated	Not estimated	1.20
Water distribution					
Pipeline supply	260.68	0 (NA)	0.47	0 (NA)	261.15
Tanker supply	Not estimated	258.84	Not estimated	0 (NA)	258.84
End use (Domestic)	1670	Not estimated	Not estimated	0 (NA)	1670
Wastewater conveyance	86.66	0.46	116.55	0 (NA)	203.67
Wastewater treatment and disposal	160.31	16.21	21.12	48.36	246
Total	**3774.15**	**275.51**	**138.14**	**1533.6**	**5721.40**

Table 24: Carbon emission in urban water cycle

Stages of urban water cycle	Direct emissions (ton CO_2-e/day)		Indirect (off-site) due to electricity use (ton CO_2-e/day)	Total carbon emission (ton CO_2-e/day)
	Fugitive	Fuel combustion		
Water sourcing				
Surface	Negligible	Negligible	775	775
Ground	Nil	Negligible	61	61
Water treatment				
Centralised WT	Nil	Negligible	458	458
Bottling plants of DJB	Nil	Negligible	1	1

Water distribution				
Pipeline supply	Nil	Negligible	211	211
Tanker supply	Nil	48	Nil	48
End use (Domestic)	Nil	Nil	1355	1355
Wastewater conveyance	1043	Negligible	5838	6881
Wastewater treatment and disposal	360	Negligible	887	1247
Total	**1403**	**48**	**9586**	**11037**

Table 25: Water requirement in TPPs of New Delhi

Name of power station	Ash handling; cooling system	Estimated Energy production*	Estimated Water Requirement		Estimated Wastewater released	
		MWh/day	m^3/MW	m^3/day	m^3/MW	m^3/day
Rajghat Power House	Wet ash disposal; wet cooling tower	1860.084	3	5580.252	0.363***	669.63024
Badarpur TPP	Wet ash disposal; wet cooling tower	8989.596	3	26968.788	0.363***	3236.25456
Gas Turbine Power Station (GTPS)	Wet cooling tower	2911.464	2	5822.928	NA, nearly 20%	-
Pragati-I Power Station	Wet cooling tower	5300.856	2	10601.712	NA, nearly 20%	-
Pragati-III Power Station, Bawana	Wet cooling tower	4807.975	2	9615.95	NA, nearly 20%	-
Total water consumption (m^3/day) = 58589.63 (32549=coal) + (26041=gas)						
Total wastewater released (m^3/day)= 3905.9 (coal)						

* Energy estimated (MWh/d)= (MW×LF)×24

* *Water requirement (m^3/day)= [(m^3/MW) × 24× (MW× LF)]

Wastewater released (m^3/day)= [(m^3/MW)×24× (MW× LF)]

NA- Not available

Table 26: CO_2 emission from thermal power plants in ton CO_2-e per day

Name of power station	Estimated Carbon emission
	ton CO_2-e/day
Rajghat Power House	1953.0882
Badarpur TPP	9439.0758
Gas Turbine Power Station (GTPS)	1310.1588
Pragati-I Power Station	2385.3852
Pragati-III Power Station, Bawana	2163.58875
Total emission (ton CO_2/day)= 17251.3 [11392.2 (coal) + 3137.7 (gas)]	

Emission factor coal based TPP=1.05 and Gas based TPP=0.45

4.2.1 Key findings of the study

I. General observations and remarks from literature

Key challenges: The National Capital Territory of Delhi (NCTD) both as an urban agglomeration and as an independent state is significantly constrained for access to water resources. It has high dependence for water on hinterland and hence depends on interstate agreements and their application by other states. Long distance conveyance of water exerts its hydrological footprint on distant basins. As water demand increases, so will be the increase in wastewater generation and energy demand. Conflicts may increase in future between states (over interstate river water use), socio-economic strata, ecological vs economic goals, financial prudence vs social goals. There is uncertainty in dam based resource augmentation, declining groundwater output and reduced water availability for environmental flows.

Inequitable and unreliable water supply**:** Water supply is not uniform across the city and significant amount of population is using water from private water tankers and underground sources. Given the increasing trend of water quality deterioration of both surface and groundwater, there is lack of access to safe water which increases financial burden on people (either in the form of use of domestic purifiers, purchase of water from private vendors or in the form of medical treatment cost). Lack of trust in the quality of DJB water supply has led to the widespread use of bottled water consumption. Zerah (2000)[14] estimated coping strategies adopted by people had costed them INR 3 billion whereas operation expenses of the DJB on the same year were INR 1.6 billion. Mishra and Goldar (2008)[15] estimated that coping cost of households in authorized colonies is INR 10 per kl of water consumed, they pay INR 6 per kl to DJB as tariff and thus bears a cost of INR 16 per kl of water consumed. Coping cost of households is high in underserved colonies. Similarly coping cost borne by commercial, industrial and institutional consumers are INR 42, 47 and 18 per kl, respectively.

Absence of unified planning: The Delhi Development Authority (DDA) is under the administrative control of Central Government and the DJB is under state government. DDA ascertain water demand projections from population projections and water supply norms promulgated by Union government (MoUD) and look for supply-led solutions to meet the demand supply gap, instead of demand-side solution which would require involvement of all urban utilities in the planning process.

Abysmal state of groundwater: Groundwater of Delhi is bad both in terms of quality and quantity[16]. Still, there is a large-scale private groundwater abstraction. Though it is regulated by CGWB but the enforcement is very limited. Less than one-third of the tube well owners have registered with CGWB and in some areas the groundwater table is declining at the rate of 0.1 to 0.2 meter per year on an average (West, Northwest Delhi and New Delhi districts of Delhi), whereas, central Delhi records decline of 0.4 m per year[17], [18]. Another policy response to this situation is promotion of rainwater harvesting[19], [20]. However, it is estimated that even if this is implemented diligently, the outcome would not be higher than 10% of city's water uses[21].

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[14] Zerah M H (2000). Water: Unreliable supply in Delhi. Manohar Publisher.

[15] Smita Misra & Bishwanath Goldar (2008) Likely Impact of Reforming Water Supply and Sewerage Services in Delhi, Special Article, Economic & Political Weekly

[16] Maria, A. 2008. Urban water crisis in Delhi. Stakeholders responses and potential scenarios of evolution, Institut du développement durable et des relations internationals (IDDRI), Paris http://www.iddri.org/Publications/Collections/Idees-pour-le-debat/Id_0806_Maria_Urban-Crisis-Water-Delhi.pdf

[17] MoUD, 2013. Chapter 8 Water, Draft Revised Regional Plan 2021 (Approved in 33rd Meeting of the NCR Planning Board held on 1st July, 2013). National Capital Region Planning Board, Ministry of Urban Development, Govt. of India

[18] Shekhar Shashank., Raja Ram Purohit & Y. B. Kaushik. 2006 Hydrogeological Framework & Groundwater management Plan for NCT Delhi, Central Ground Water Board 2006 report, CGWB http://www.cgwb.gov.in/documents/papers/incidpapers/Paper%2015-%20Kaushik.pdf

[19] GNCTD, 2013. Economic Survey of Delhi 2012-13. Chapter 13 Water Supply and Sewarage. Directorate of Economics & Statistics, Government of National Capital Territory of Delhi, Delhi

[20] http://www.mdws.gov.in/hindi/sites/upload_files/ddwshindi/files/pdf/pdf/Recharge_0.pdf

[21] Soni V 2003. Water and carrying capacity of a city: Delhi, Economic and Political Weekly, Vol 38. (45).

Invisible subsidy to industry: No reliable information is available about industrial use of groundwater but it well known that most industry abstract groundwater privately to meet their requirements. The tariff by DJB for industries are much higher than that of domestic water supply and thus industry find it profitable to use groundwater than the water from public supply networks.

Development of parallel water market: During 1990s, informal settlements have started sourcing water from private water tank operators. These operators own deep tube wells on city outskirts. Huge profits that these operators derive have led to cartelization and emergence water mafia[22]. In some unauthorized colony, a new form of water market has emerged. Some local people have developed small water supply networks who pump water from deep tube wells and supply to some cluster of households for 2 hours a day[23]. Users pay fixed monthly charges to such service providers. These systems are leading to unsustainable use of groundwater.

Under-recognized importance to water-energy nexus: Water and electricity demand in NCTD peaked simultaneously during summer months (April-June) every year. There are increasing instances where water distribution in Delhi is affected adversely due to unavailability of electricity, and power generation companies have to reduce power generation during summers as they have to shut down their boilers due to unavailability of water. Water and energy shortage together affect public welfare and environment adversely due to use of coping strategies such as use of tanker water supply, discharge of untreated sewage and use of diesel generators by commercial and industrial establishments. There is no evidence that city government plans these infrastructures as a unified system. Energy considerations in water sector are limited to its impact on operational cost and there is an undeclared tendency to cope up these expenses through tariff restructuring, subsidies and grants-in-aid only. They do not recognize that energy shortage can play a pivotal role for water sourcing in future and cripple operation of entire water infrastructure, if to achieve the goal of 24x7 water supplies. Energy planners view water sector as minor consumer of energy since much of the energy share is on account of domestic and industrial demand. Energy demand forecasting thus consider only such demand as major determinants for future energy needs of the city. Unmet gap in existing urban water infrastructure and future needs can peg the electricity demand for water sector upto 12% of the total. Further, design period, material and technology choice by water utilities do not consider the energy locked in these infrastructure. The current mechanism of incorporating energy considerations in water sector as merely an operational cost favors centralized systems of water treatment as they enjoy economy of scale. This study points out that energy and environment impacts when analyzed from a system analysis, the decentralized form of urban water infrastructure and wastewater recycling has advantage over current practice of centralized urban water treatment systems.

Mainstreaming of local water entrepreneurs: Weak financial strength of urban utilities for expansion of piped water services to uncovered communities and unattractiveness of investments in peri-urban areas (including slums) have prompted urban utilities to start contracting to local water players as alternate delivery mechanism. Evaluation of this model using life cycle cost analysis (LCCA) will be useful to plan future governance structure of this sector and planning for appropriate public-private-partnership (PPP) model.

II. Observations from this study

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[22] The 71 Cities, Indo-Gangetic Plains, Volume II, CSE's 7th State Of India's Environment Report 2013, Centre for Science and Environment, Delhi http://www.cseindia.org/userfiles/delhi_20130314.pdf

[23] Raghupati U (2003). Small private water providers: An alternate solution for the poor. Shelter, 6(3).

- Public water supply in Delhi is 840 MGD[24]. Total energy use in entire water infrastructure of Delhi is 5721.40 MWh/day, which is a conservative estimate.
- About 70.8% of energy use is direct (in the form of electricity and diesel) and the remaining is in the form of embodied energy. Electricity alone has significant share (about 66%) of the total energy use.
- 97.6% of energy is used during the operational phase of the infrastructure. Of the operational phase energy use, electricity has a share of 67.6%; followed by embodied energy in chemicals which has a share of 27.5%. Diesel energy has about 5% share which is majorly due to inadequacy of pipeline infrastructure that necessitates the use of motorized tanker supply.
- Total electricity use in Delhi during 2014-15 is 25111[12] GWh. Electricity energy consumption in the entire water infrastructure of the city is about 5.5% of the total electricity consumed by the city and it is nearly 10% of the electricity consumed by domestic sector. The estimates of this study is more than the value given in GNCTD report [12] which states that the electricity consumption in Public water works (including street lighting) is 4.8%[12] of the total. This has happened since their estimate do not consider electricity used by end-user for coping strategies for inadequacy in water supply and the energy used for surface water sourcing.
- In the urban water cycle; water treatment for public supply has maximum share (about 35.8%); followed by energy use at household (29.2%) and then for water sourcing (18%). However, when the data is seen in terms of electricity energy alone, household sector has a maximum share (44.3%) followed by water sourcing (27.3%). The observation that household energy share is maximum in terms of electricity use is in consonance with the findings of other studies given in the literature[1]. However, our estimate of 44.3% is much lower than the value of 72% reported in the literature (ibid). This is due to the reason that in our estimation for water heating is not included since heating is required only for few months in a year due because of climatic conditions.
- Energy consumption for water sourcing will have an increasing trend due to declining trend of water stock of the city. Similarly, energy share of water treatment is likely to have an increasing trend in future due to increasing trend of pollution of both surface and ground water sources. Embodied energy of chemical use will contribute significantly to this energy trend.
- For water conveyance diesel energy use by water tankers is nearly the same as electricity used in pipelines. Although tankers water supply has only 1% share in the total water supply. Therefore, inadequate pipeline infrastructure increases energy consumption significantly.
- Energy share of wastewater infrastructure is low in Delhi since much of the wastewater is conveyed through open drains under gravitational force and treatment is not 100%.
- Delhi generates 6226 MWh electricity daily from TPPs which uses 1.6 MGD of water. However, Delhi draw significant electricity (86.8%) from the national grid to meet its total annual electricity requirement of 37484 GWh (or 102.7 GWh/d)[12]. This indicates that Delhi's energy related water footprint is trans-boundary.
- GHG emissions from fugitive sources (mainly in wastewater system) has significant share in total GHG emissions from water infrastructure. Fugitive emissions are generally ignored in studies reported in the literature.
- Total carbon emission is estimated as 11037 ton CO_2-e/day, of which 12.7% is in the form of fugitive emission (in-boundary) and 86.8% is off-site emission due to electricity use.
- Majority of fugitive emissions is from wastewater conveyance system (74.3%) since about 70% of wastewater is conveyed through open drains that contribute to these emissions. Similarly, fugitive emissions from wastewater treatment system are high in Delhi as much of the biogas is not utilised.

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[24] GNCTD, 2015. Economic Survey of Delhi 2014-15. Chapter 13 Water Supply and Sewarage. Directorate of Economics & Statistics, Government of National Capital Territory of Delhi, Delhi

III. Observations from “Zoom-in” studies

A. WE nexus at the end-user level (household/domestic sector)

- Changing lifestyles and greater use of technology by urban households have impacted both water and electricity consumption. Number of households switching to electrical appliances such as dishwashers and washing machines to save time continues to rise, although this trend reduces water consumption, it also increases electricity consumption at the same time.
- People use variety of coping strategies to cope with inadequacy in water supply. This includes use of rooftop water tanks for storing water to use during non-supply period, use of booster pumps to draw water from supply lines and lift to fill rooftop tanks, use of domestic water purifiers to enhance the water quality for drinking and cooking, provisioning of private source of water supply such as ground water withdrawal and/or purchase of packaged water bottles.
- Approximately, 83% of households in organized housing and 8% households in Slums uses booster pumps of 0.5–1 hp capacity and run them for about 50 minutes a day. Households that use bore-wells as an additional source of water use 1 hp motors and run them for 10 minutes a day (averaged over a week).
- The average water consumption is 75.9 lpcd in organized housing but only 45.2 lpcd in Slum dwellers. The lower per-capita water use by slum dwellers is at the cost of sanitation and hygiene. These estimates do not account for water lost in leakages. The largest share (approximately 32%) is claimed by bathing, followed, in that order by toilet flushing, washing dishes and pots and pans, and washing clothes. Bathing by the bucket-and-mug method and using dishwashers and fully automatic washing machines reduces water consumption; however, the machines consume more electricity.
- The average monthly electricity consumption per capita was 2.6 kWh and that of residents of organized housing alone was 3.25 kWh. A family of four living in organized housing consumes 10–16 kWh/month. More than 50% of this electricity was used in coping with low pressure in the water distribution network and in augmenting inadequate supply by pumping groundwater from bore-wells. Using water purifiers to make up for the unreliable water quality consumed about 15% of the total electricity spent on water-related activities, and remaining electricity consumption was for activities that have the potential to save water.
- Households in organized housing spent on average INR 355 a month and slum dwellers spent INR 213 on water respectively. Approximately 93% households reported payments to DJB as the principal expense on water. In general, respondents does not perceive the money spent on measures to compensate poor water quality (domestic purifiers) and for inadequate supply (booster pumps, rooftop tanks, and bore-wells) as a part of the cost of water. The cost of coping with inadequate water supply and unreliable water quality is approximately INR 172 a month in organized housing, INR 60 on electricity and INR 112 on maintenance of domestic water purifiers and rooftop water tanks.
- In the best-case scenario for water savings i.e. if all residents use dishwashers and washing machines, bathe using bucket and a mug, and give up using domestic water purifiers – the basic water needs reduces to 70.6 lpcd, although it would mean that monthly per-capita electricity consumption increases by 4.28 kWh. Therefore, a family of four can save as much as 1 kL of water a month, at the cost of increasing its electricity consumption by 1.75 kWh a month—which can be avoided if water supply is adequate, reliable, and safe, making it possible to do away with booster pumps, overhead tanks, bore-wells, and water purifiers. Thus, water-saving measures are negatively correlated to electricity consumptions at the level of end users.

B. Impact of choice of wastewater treatment method on WEC nexus

- Total energy use of sewage treatment plant (STPs) in India ranged from 0.09-8.33 kWh/m^3, which corroborates that energy use is a function of operating capacity, treatment method, and disposal standards (BOD).

- Within large-scale municipal STPs, total energy use is 0.09–1.32 kWh/m^3, the average being 0.40 kWh/m^3 (σ=0.46 kWh/m^3) and in small-scale institutional STPs, the range is 1.5– 8.3 kWh/m^3 (Av. 4.87 kWh/m^3; σ=2.73 kWh/m^3).
- In large STPs, on an average, embodied energy of materials accounts for 46% of the total energy footprint followed by electrical energy (44%). However, shares of diesel consumption and biogas recovery are insignificant (about 3% and 7% respectively). In contrast, shares in small STPs of electrical, embodied and diesel energy uses are 64%, 33% and 2% respectively.
- There are two reasons for such a disparity between large-scale and small-scale STPs. First, large-scale STPs face 4–6 hours of load-shedding a day without any power back-up during these hours. Therefore, effectively, the large-scale STPs surveyed in India operates for only 18 hours a day. Moreover, the effect of load-shedding is not reflected in the effluent BOD values since enough buffer capacity is available in large-scale STPs as the sewage flows is less than the designed capacity. Secondly, the layout of large-scale STPs is spacious, resulting in longer pipes. Nearly 100% spare capacity in large-scale STPs also contributes to the higher embodied energy per unit of sewage treated.
- Further, the share of diesel energy in large-scale STPs is higher than that in small-scale STPs because large-scale STPs uses diesel in vehicles to dispose dried sludge.
- Average carbon intensities estimated for large and small scale STPs are 2.6 kgCO2-e/m^3 and 3.1 kgCO2-e/m^3 respectively. The carbon emissions from the study is high and contrary to the conventional understanding due to the inclusion of carbon emission resulting from energy use, fugitive emissions and energy use from embodied materials. Higher carbon intensity of small-scale STP is due to greater energy consumption in the direct operational phase in form of electricity and diesel. Off-site and indirect carbon emissions together accounts for 13% of the total in large-scale STPs but is as high as 90% in small-scale STPs. On-site carbon emissions are higher in large-scale STPs because they use biological treatment systems for lowering BOD. Carbon emissions from flaring of unused biogas also have significant impact on the carbon footprint of large-scale STPs. Hence, the study determines that the probable long term impact caused by fugitive emissions due to higher degree of treatment to achieve lower BOD values and biogas flaring would be profound.
- Secondary treatment accounts for 70%–80% of electrical energy used in STP. Use of diffused aerators (in EA, SBR, and FBR, common in small-scale STPs) increase electrical energy use by about 2.5 times required for other biological treatment processes. However, wherever diffused aerators are used, BOD of the effluent is less than 20 mg/L as against 30 mg/L with other methods. Further, anaerobic process i.e., Upflow Anaerobic Sludge Blanket (UASB) also consumes energy significantly to achieve the elevation head of tall reactor through use of pump and for maintaining automation process.
- Primary treatment in small-scale STPs consumes greater electrical energy because the variable sewage flow warrants installation of an equalisation tanks with mixing devices.
- The analysis of 17 activated sludge process (ASP)-based large-scale STPs clearly indicates that energy use falls as the operating capacity of the STP increases. The relationship between energy use and operating capacity is log-linear ($y = -0.044\ln(x) + 0.5604$) with the coefficient of correlation of nearly 0.8.
- The energy footprint nearly doubles if the outlet BOD value decreases from 30 mg/L to 15 mg/L. To achieve a given value of outlet BOD, choice of technology also influences energy and carbon footprint. Technologies that decrease the pollution load (effluent BOD) increase energy consumption on a significant scale. There is thus a clear trade-off between pollution control and energy footprint of a city waste infrastructure.

C. WEC nexus in wastewater infrastructure of Delhi

- Total energy consumed by wastewater infrastructure in NCT of Delhi is about 450 MWh/day. The share of energy used during the operational phase (electrical, diesel, and the energy embodied in the chemicals) is 70% and the share of energy embodied in construction materials is 30%. Of the energy used in the operational phase, 79% is electrical and 5.4% is diesel. Electrical energy thus accounts for 55% of the energy consumed by the wastewater infrastructure.
- Wastewater treatment accounts for 54.7% and wastewater transport accounts for 45.3% of the total energy used in a day. Of the energy required for treatment, electricity accounts for 65.5%, diesel for 6.7%, and the embodied energy of materials for 27.8%. Of the energy used for transport, electricity accounts for 43% and the energy embodied in construction materials for 57%.
- On an average, the net energy footprint of wastewater infrastructure in NCT of Delhi was 0.26 kWh/m^3, which is conservative given the fact that only 30% wastewater is transported through underground sewers and only about 59% wastewater is treated. The energy intensity of wastewater transport is 0.09 kWh/m^3 (SD 0.05 kWh/m^3), and that of wastewater treatment is 0.19 kWh/m^3 (SD 0.092 kWh/m^3).
- There is substantial variation among various administrative zones in unit energy use (SD 0.096 kWh/m^3); higher values are observed in drainage zones in which the amount of wastewater handled is low and in drainage zones in which treatment capacity utilization is more than 80%. Operational energy use in transport infrastructure was the lowest in drainage zones having their location on the foothills of the Aravalli range of mountains, which ensures a gentle slope towards the WWTPs. It is high in drainage zones, which are on the flood plains of the river Yamuna because those require more pumping stations. The topography of a region therefore influences the operational energy of transport infrastructure; the energy consumption is 0.01–0.03 kWh/m^3. The area of a drainage zone and its energy consumption are positively correlated ($R^2 = 0.62$): as the area increases, so does energy consumption. Similarly, the energy embodied in the materials of transport infrastructure is influenced by the share of open drains in total wastewater transport and by population density. In drainage zones with low population density material energy use is higher than that in high population density zones, and population density influenced energy use by a factor 2.7 times the average value. Energy use in treating wastewater is influenced largely by the use of chemicals in the treatment process and by biogas recovery. Chemicals for dewatering and disinfection constitute approximately 28% of the total operational energy. Biogas recovery in Shahdara, Okhla, and Rohini-Rithala decreases the energy footprint by 33% of the total energy used for wastewater infrastructure.

- The energy intensity of decentralized systems is 0.42 kWh/m^3, which is about 40% more than that of the centralized systems despite the fact that energy use in decentralised plants for wastewater transportation is negligible. This is because the decentralised treatment systems use energy-intensive methods such as membrane bioreactors, which use less land, attain high treatment standards but consume more chemical and electrical energy. However, when the data are viewed in terms of pollution reduction, expressed per kilogram of BOD removed, the decentralized systems consume only 69% of the net energy consumed by the centralized systems, the average values being 0.51 kWh and 1.67 kWh respectively.
- Total GHG emissions from the wastewater network are estimated at 9.52 GgCO2-e/day, which is equivalent to 1.046 kgCO2-e/m^3 (SD 0.17 kgCO2-e/m^3).
- Net GHG footprints of underground sewers and open drains were 0.56 kgCO2-e/m^3 and 0.38 kgCO2-e/m^3 respectively. Open drains have a carbon burden lower than that of underground sewer lines because wastewater transported through open drains does not require electrical

energy for pumping, and the unlined drains in NCT of Delhi have not used any construction materials.

- In the present study, the GHG footprint of WWTPs is higher than reported in the literature (Cornejo et al. 2013, Lorenzo-Toja et al. 2015,) because it took into account all biogenic GHG emissions (CO2, N2O, and CH4).
- Biogas is used only in three zones; in other zones, it is allowed to escape into atmosphere after flaring and in some cases without flaring. Okhla and Rohini-Rithala drainage zones, which generate electricity from biogas, have total GHG emissions equal to 1.23 kgCO2-e/m^3 and 0.93 kgCO2-e/m^3 respectively whereas in Najafgarh drainage zone the total GHG emissions is 1.42 kgCO2-e/m^3.

The study provides some other useful information. Energy due to material use is affected by the designed lifetime of the infrastructure, which, in turn, influences the total energy footprint significantly. Therefore, longer designed lifetimes for WWTPs and the corresponding choice of materials increase the energy footprint in the initial years of operation of a treatment plant. Hence, it will be appropriate to design WWTPs in a modular format where capacity additions are carried out in stages to keep pace with the increase in population. The scenario analysed in the present study clearly shows the trade-offs between energy savings, pollution reduction, and GHG emissions reduction, and these trade-offs influence the decisions related to the choice of infrastructure. Unlined open drains have less GHG emissions and negligible energy use but a negative impact on groundwater, public health, and city aesthetics. The study also shows that decentralized systems, although more energy intensive in terms of the volume of wastewater handled, are energy efficient when analysed in terms of the amount of pollutants removed. Therefore, the choice between centralized and decentralized system is a matter of what the systems are intended to achieve: if lowering the degree of pollution from urban wastewater is the sole objective, centralized systems offer higher energy savings; however, if urban wastewater infrastructure is to be designed for recycling and reuse locally, decentralized systems are energy efficient because wastewater does not have to be transported over long distances. Adoption of resource recovery methods in WWTPs (such as generating biogas) has a significant impact in reducing the energy and GHG footprints of wastewater infrastructure (30%-40%), which is often an ignored area in the developing countries, due to lack of funds and inadequate maintenance of wastewater systems

4.3 Kathmandu

There were not disaggregated data available for the Kathmandu and data for various elements of water system, therefore we needed various approaches to calculate right figures. For case of Kathmandu, only the drinking water sector was considered, due to limitation in data availability for waste water treatment systems.

4.3.1 Energy Footprints and Energy related Carbon Footprints

Abstraction

The energy footprints for abstraction was calculated by taking the following parameters:

- Pump Horsepower (PHP)
- Average Daily Operation hours (n)
- Efficiency of the Pumps (e)

Hence, Energy Consumption was given by,

$$E = \frac{PHP \times 746 \times n}{e \times 1000}$$

Where E is in kWh.

The pumps were assumed to have efficiency from 65% to 85%.

KUKL (Kathmandu Upatyaka Khanepani Limited)

The general schematic of KUKL water supply system is shown in figure 48. Both surface water and ground water are used in Kathmandu drinking water sector.

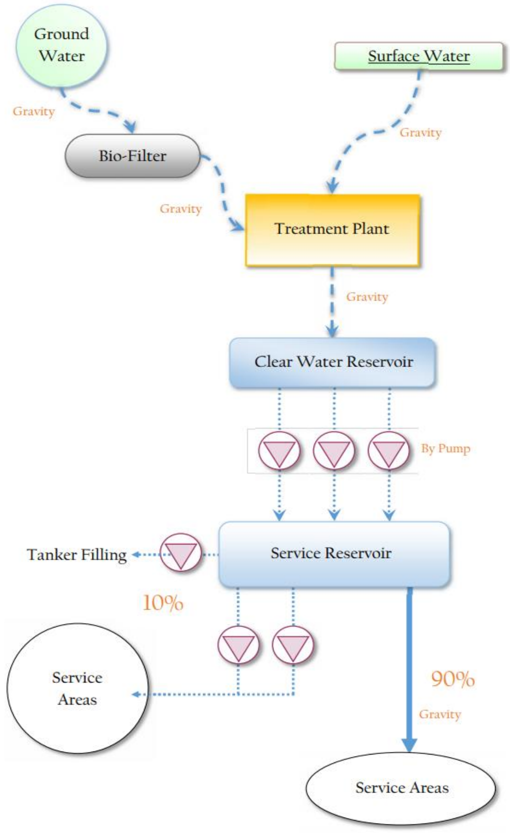


Figure 48: Flow diagram of KUKL's urban water supply cycle. Source: Joshi, 2015

Table 27: Energy Consumption for abstraction by KUKL's service branches

Branch	Range of Energy Consumption (kWh/yr)
MahankalChaur	5434.00-4160
Maharajgunj	10100-9130
Tripureshwor	1660-1980
Madhyapur	3100-2370
Baneshwor	925- 1200
Kirtipur	1032-1053
Chhetrapati	163-253

Lalitpur	470-620

There are 8 different branches within KUKL where water is abstracted from its source (table 27). The total energy consumed for abstraction is in the range of 18,800 kWh/yr – 22810 kWh/yr. With total volume for water extraction of KUKL being 78.8 MLD, the energy intensity of abstraction from KUKL amounts to 0.26 kWh/m^3 – 0.30 kWh/m^3.

The carbon emissions were calculated using the following formula:

$$Emissions\ (CE) = EF \times Energy\ Consumption$$

The emission factor for Nepal from electricity generation is 0.003 kgCO_2/KWh. Hence, carbon emissions from water abstraction from KUKL is calculated as 22 tCO_2e/ yr – 26 tCO_2e/ yr (Joshi, 2015).

Private Tankers

The total energy consumption by private tankers with 65% efficient pumps was found to be 1081.5 kWh/yr. The total volume of water extracted is 9056 m^3.

The energy intensity for abstraction by private tankers (65 percent pump efficiency) is 0.12 kWh/m^3.

Similarly, the total energy consumption by private tankers with 85 percent efficient pumps was found to be 827 kWh/yr. The total volume of water extracted is 9056 m^3. The energy intensity for abstraction by private tankers (85 percent pump efficiency) is 0.09 kWh/m^3.

Carbon Emissions from Groundwater extraction for private tankers varied from 1 tCO_2e/year to 2.5 tCO_2e/yr.

Registered Wells

The industrial, commercial sectors and housing consumes 4805 kWh/yr - 6283.7 kWh/yr. Given that the total volume of water extracted is 25844.5 m^3, the energy intensity for abstraction by registered wells varied from 0.19 kWh/m^3 – 0.24 kWh/m^3.

Carbon emissions varied from 5 –7 tCO_2e/yr.

Households

Although the KUKL pipeline is reported to be available to most of the households in Kathmandu, many households cannot acquire the connection due to lack of connectivity and functionality. According to KUKL, water supply is delivered at an average of 2-3 days a week. However, this number is due to vary with location and availability.

As the water is served by KUKL to households, according to KUKL, households are able to pump water for about 30 minutes with 1 HP pump capacity. But, households are not confined to KUKL as their only source of water and hence they rely on alternative sources too.

Also, most of the households although have a private connection to the piped water system, many households only receive water scantily suffering from negative pressures and chronic contaminations. To combat this problem of water scarcity, households engage in several coping behaviors like collecting water from public taps, purchasing it from vendors and neighbors and investing in storage tanks, etc.

The household water abstraction is also complex due to problems like leaking pipes, sharing with neighbors and community, stealing from the system and performing illegal pumping from distribution mains. Households are also not able to pump water when the electricity is down. The figure below gives a typical schematic of household water extraction:

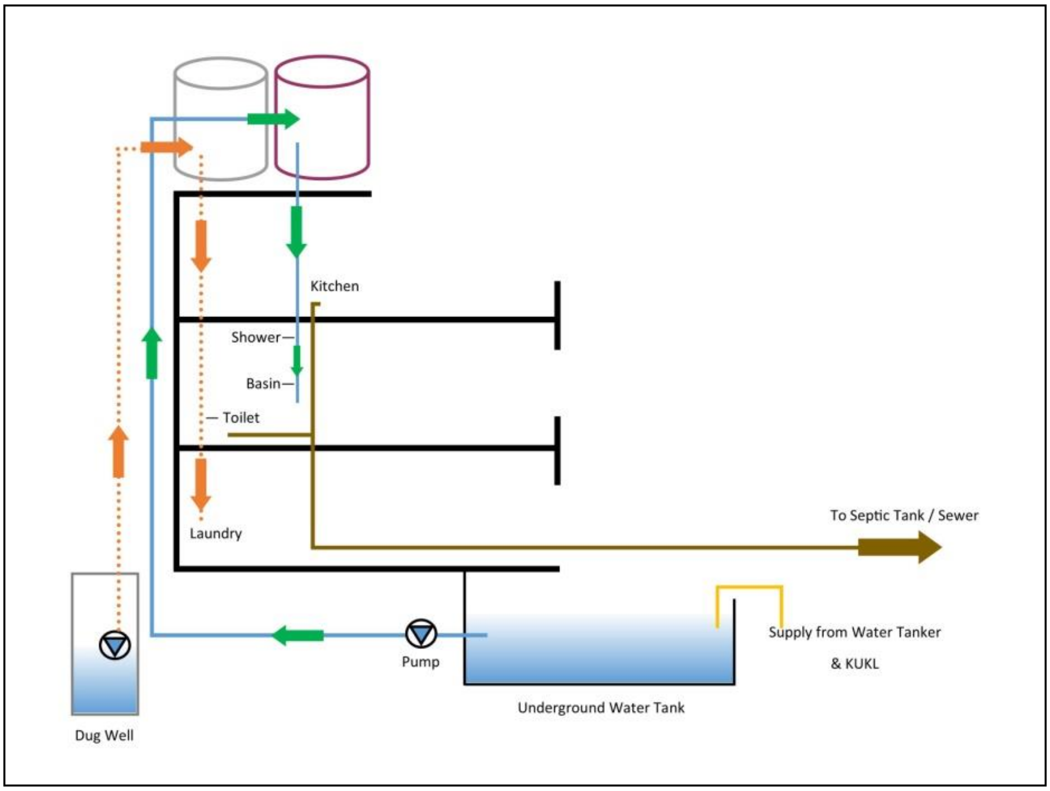


Figure 49: Typical Household water pumping characteristics

Only accounting for legal practices, Joshi (2015) calculated total energy consumption to be 25.8 kWh/yr – 128.5 kWh/ yr. The energy intensity was found to vary from 0.37 kWh/m^3– 1.86 kWh/m^3. Carbon emissions varied from 78 ktCO2e/yr – 385 ktCO2e/yr. The high and low estimations account for households extracting water through use of pumps with 1 HP capacity 2 – 7 days in a week.

The range of energy intensities for abstraction varies from **0.92 kWh/m^3 to 2.52 kWh/m^3** and carbon emissions vary from **105 tCO$_2$/year to 418 tCO$_2$/yr** for water abstraction in Kathmandu Valley (Joshi, 2015).

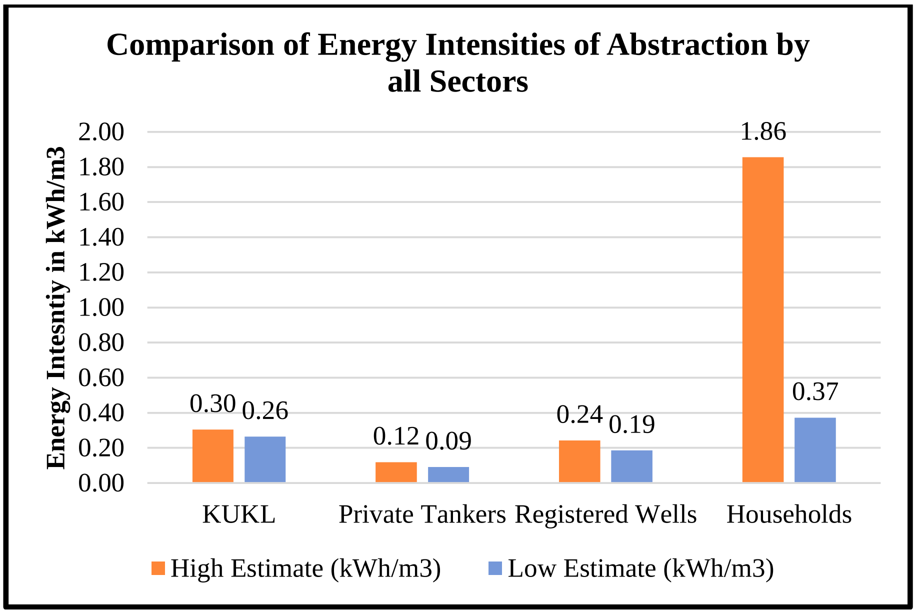


Figure 50: Comparison of Energy Intensities of Abstraction by all sectors

Source: Joshi, 2015

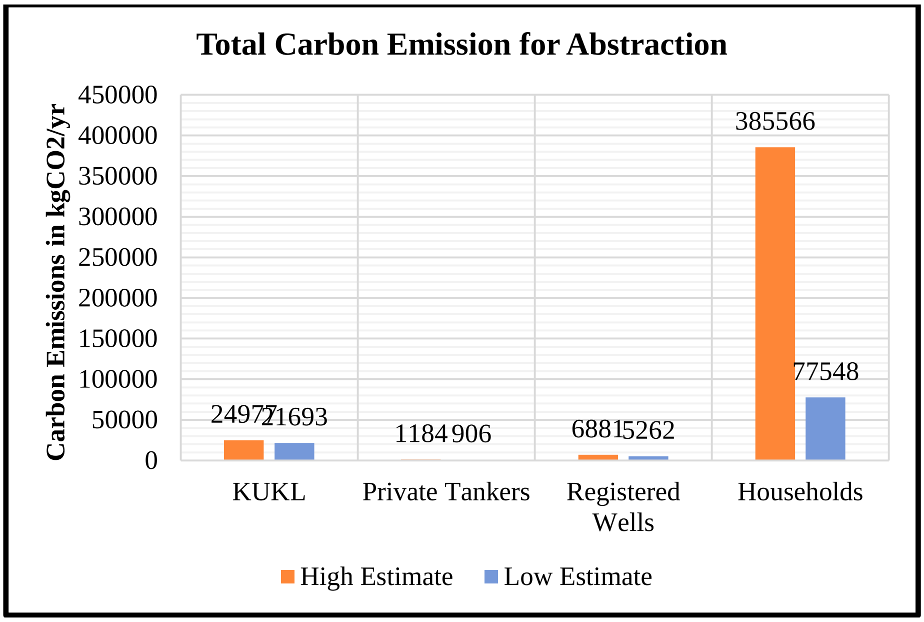


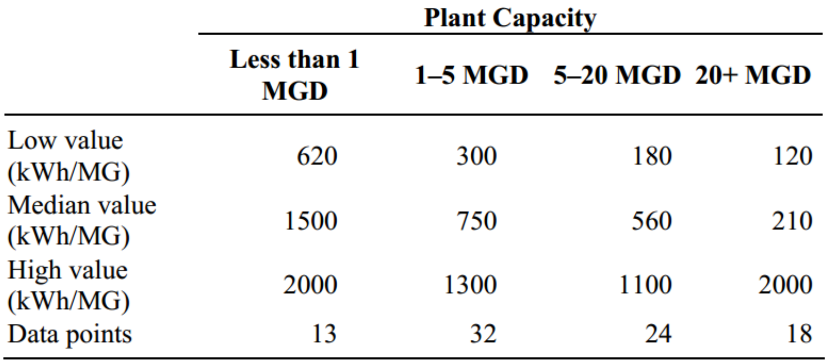
Figure 51: Comparison of carbon emissions from Abstraction by all sectors

Source: Joshi, 2015

Treatment

In order to calculate the energy intensity by treatment, Joshi (2015) reviewed AwwRF's high and low estimates of intensity for a specific volume of water treated. Because the treatment technologies in Nepal are comparatively very primitive and the total amount of water treated is low, the study took low value range of AwwRF's data into consideration.

Table 28: Energy Intensity of Conventional Water Treatment Plant by Plant Capacity



	Plant Capacity			
	Less than 1 MGD	1–5 MGD	5–20 MGD	20+ MGD
Low value (kWh/MG)	620	300	180	120
Median value (kWh/MG)	1500	750	560	210
High value (kWh/MG)	2000	1300	1100	2000
Data points	13	32	24	18

Using the lower range of values, Joshi (2015) came with the following estimations for energy intensities in treatment.

Table 29: Energy Intensity of KUKL's Water Treatment Plants

WTPs	Capacity (m^3/day) (GW+SW)	5% Backwash (m^3)	Capacity in MGD	Low Value (kWh/MG)
Balajau	10000	500	2.64	300
Basbari	21000	1050	5.55	180
Bhaktapur	4500	225	1.19	300
Bode Manohara	20700	1035	5.47	180
Jagati	500	25	0.13	620
Jwagal	1000	50	0.26	620
Kuleswor	1000	50	0.26	620
Lokanthali	1500	75	0.40	620
MahankalChaur	26000	1300	6.87	180
Ratnapark	1000	50	0.26	620
Shankar Park	1000	50	0.26	620
Sinamangal	1000	50	0.26	620
Sipradi	500	25	0.13	620
Sundarijal	19600	980	5.18	180
Tahakhel	500	25	0.13	620
Tripureswor	500	25	0.13	620

The total energy intensity for treatment (EI_{trt}) was 520.87 kWh/MG, corresponding to **0.14 kWh/m^3**. The total energy consumption was **5,800,000 kWh/yr** given that the total volume of water treated was **113500 m^3/day**. This meant that carbon emissions from treatment amounts to **17.4 tCO_2e/yr** (Joshi, 2015).

However, as the plant runs in 50% capacity during dry seasons, Joshi (2015) found that the total energy intensity for treatment (EI_{trt}) with 50% capacity of the plants was **0.15 kWh/m^3**, corresponding to a total energy consumption of **8270 kWh/day (3,018,500 kWh/yr)** and a total carbon emission of **9050 $kgCO_2$/yr**.

Distribution

KUKL

In Kathmandu's case, 90% of water treated is distributed to households by gravity. Hence, only a minimal amount of energy is consumed during distribution phase. MahankalChaur, Bode Manohara and Basbari branch of KUKL system have two reservoirs in their schematic. After water is treated, it first goes to a clear water reservoir by gravity.

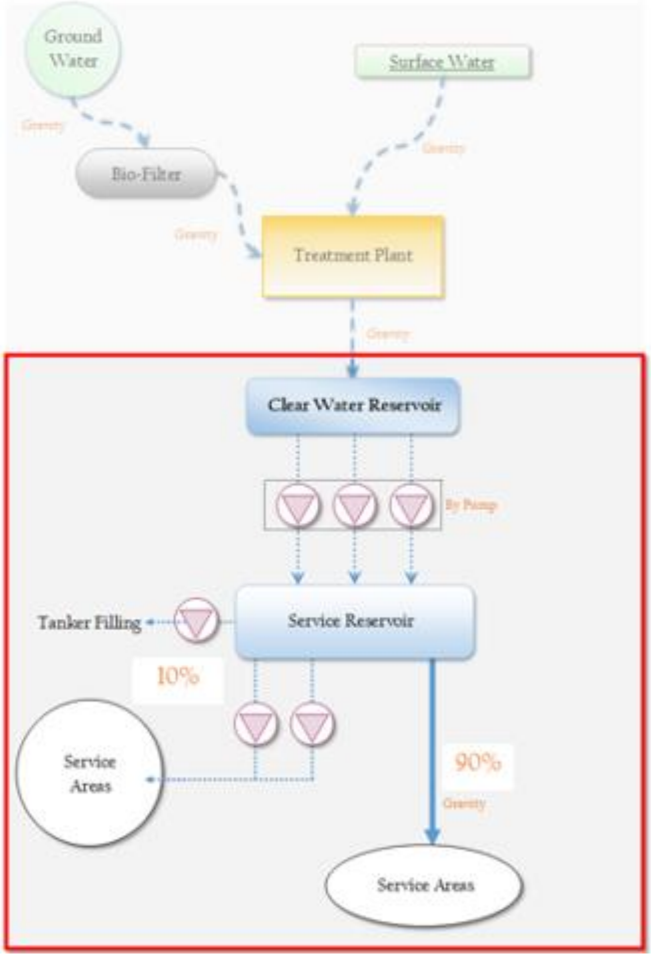


Figure 52: Schematics of MahankalChaur, Bode Manohara and Basbari Branch distribution of KUKL System

Joshi (2015) found that the energy intensity for water supply distribution by KUKL from three of these branches varied from **0.053 kWh/m^3 to 0.42 kWh/m^3** with different loss and pump efficiency scenarios. The study considered 0 - 35% loss scenario.

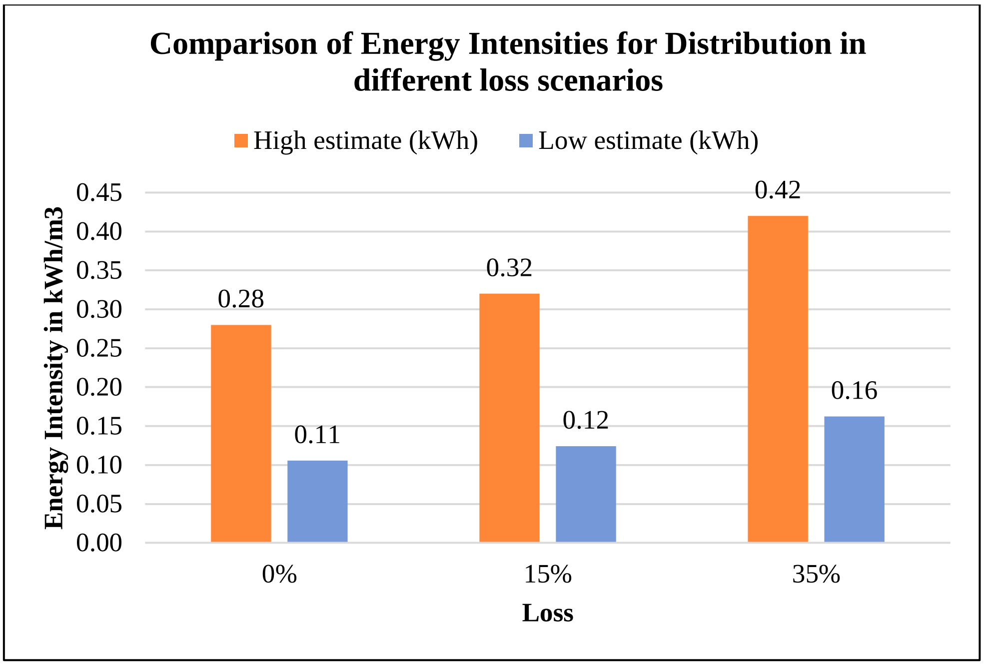


Figure 53: Comparison of Energy Intensities for Distribution in different loss scenarios. Source: (Joshi, 2015)

Private Tankers

The total diesel consumption by Private Tankers was found to be 13,082,512.50 liters per year. The total water supplied by private tankers is 13,961,250,000 liters (Joshi, 2015). The energy intensity for distribution by private tankers in Kathmandu is **9.97 kWh/m^3**.

United Nations Environment Program has mentioned that the emission factor for diesel for transportation is 3211 g/kg. Taking this number, the total carbon emissions from private tankers was found to be **34.9 kTCO$_2$/yr**, which is the most carbon and energy intensive sector in water distribution for Kathmandu.

4.3.2 Total Energy Intensity and Carbon Emissions from Kathmandu's Urban Water Supply

Study by Joshi, 2015 found that the total energy intensity for Kathmandu's Urban Water Supply ranges from **11.13 kWh/m^3 – 12.77 kWh/m^3**. Similarly, total carbon emissions amounted to **35kTCO$_2$e**.

Only considering the piped meter connection (excluding distribution by private tankers, but including household water extraction), the total energy intensity ranges from 1.16 kWh/m^3 – 2.87 kWh/m^3.

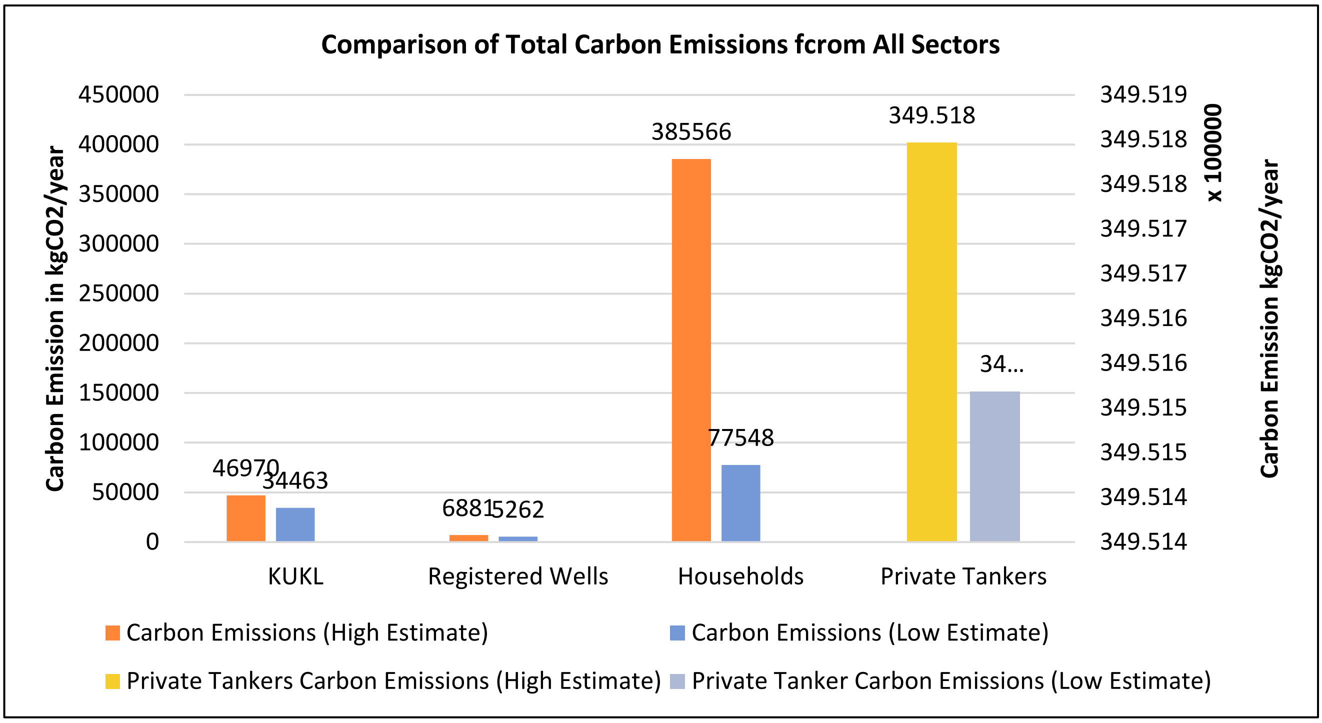


Figure 54: Total Carbon emissions from all sectors with different pump efficiencies

4.3.3 Implications after Melamchi Water Supply Project

Joshi (2015) assumed that private tankers will be eliminated after MWSP is served to the alley, but households would still extract water (from their underground tank or use dug wells and tube wells as desired). Private tankers and households' water extraction were found to be very energy intensive. Total energy intensity after eliminating Private Tankers can be reduced to 2.72 kWh/m^3. This is a significant reduction in energy intensity as private tankers that use diesel are assumed to be running no longer. On so doing, Kathmandu would be able to save about 140 GWh of energy per year and about 35 ktCO$_2$e of carbon emissions.

Joshi (2015) assumes that after Melamchi water is served, households can be very likely to decrease the water extraction from tube wells, hence reducing the energy usage by a certain amount.

4.3.4 Discussions and major Findings

In Kathmandu, water extraction mostly depends on the static depth of the groundwater table, head of pumps, efficiency of pumps, discharge of water through the pumps and number of hours of operation. Since the water is conveyed to treatment plants through gravity, no energy is consumed during this process, but treatment largely depends on the kinds of technologies used while chemical dosing. Around 90% of water is distributed through gravity in Kathmandu, but only 10% is distributed by the use of pumps.

Joshi's study found that Kathmandu consumes about 690 MWh/day- 784 MWh/day of energy for water supply and distribution. Similarly, the total energy intensity was in the range for Kathmandu is about 11.1 kWh/m^3- 12.8 kWh/m^3. The total carbon emissions are in the range of 35 kTCO$_2$e – 35.4 kTCO$_2$e per year.

Decision-makers can integrate the energy issues into water policy decision-making as looking at both these components can generate valuable insights that may not rise from separate policy analyses of water, energy and climate change. Kathmandu's policy makers can find better methods and ways to link decisions between water energy and carbon in order to maximize the benefits, address the increasing financial costs while also identifying new partnerships and ideas. For example, policy-makers can make their sustainability plans where they can make decisions like eliminating diesel-based transportation to serve water, improving water quality, managing leakage and reducing groundwater pumping to yield effective solutions.

Policy makers can also help to make improvements on management practices. On recognizing that energy considerations in managing water can lead to energy and cost savings, plans and policies that incorporate improvement of energy efficiency, and better technologies can bring about remarkable results. For example, leakage management practices if carried out by testing and benchmarking pump stations for water agency like KUKL to check their performance, a good amount of energy can be reduced throughout this good practice.

Clearly, transitioning to a sustainable water supply system needs cooperative and innovative policy-making which cannot happen overnight. However, on understanding the benefits incurred, policy makers can implement this integrated approach between the three components to reduce energy and water demand.

4.4 Tokyo

4.4.1 Energy and Carbon Footprints Water Supply System

The power consumption within the Tokyo for water intake, water storage and water supply in business offices, administration buildings and all other waterworks facilities by the annual water distribution volume, indicates that Tokyo's figure is comparatively worse than other cities, due to long distance between the water resource and the water supply area with ups and downs, to the poor quality of raw water, to the facilities needing excessively high consumption of power for water purification, etc. (Bureau of Waterworks, 2007). We looked into data from 2008 to 2012 for different water treatment plants and waste water treatment plants (or water reclamation centers).

Table 30: Average energy footprints in kWh/m^3 from 2008 to 2012 in 11 WTPs in Tokyo

	Kanamachi	Misato	Asaka	Misono	Higashi-Murayama	Ozaku	Sakai	Kinuta	Kinuta-shimo	Nagasawa	Suginami
Abstraction & Conveyance	0.148	0.162	0.303	0.200		0.182		0.321	0.304		0.162
Treatment	0.293	0.362	0.449	0.344	0.029	0.199	0.087	0.463	0.625	0.016	0.344
Distribution	0.144	0.191	0.151	0.153	0.009	0.015		0.184	0.291	0.000	0.135

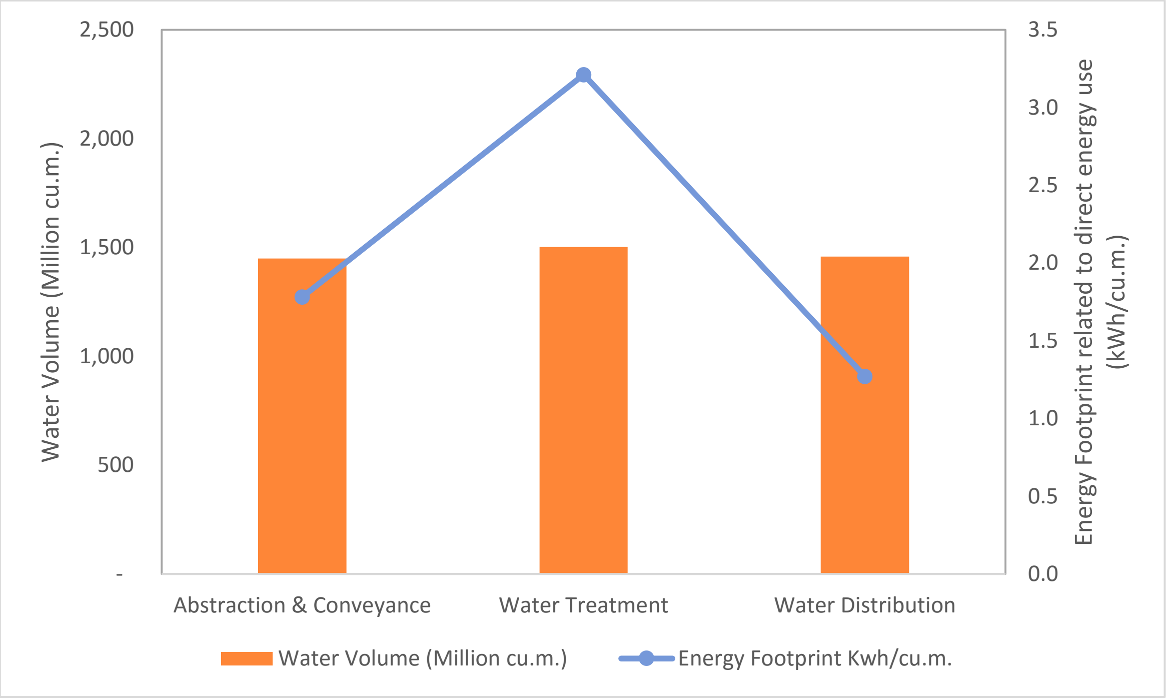


Figure 55: Average (2008 - 2012) of water volume and energy footprint related to direct energy use in Tokyo water supply system

Figure 55 shows that average energy footprints for water treatment is higher than abstraction and distribution.

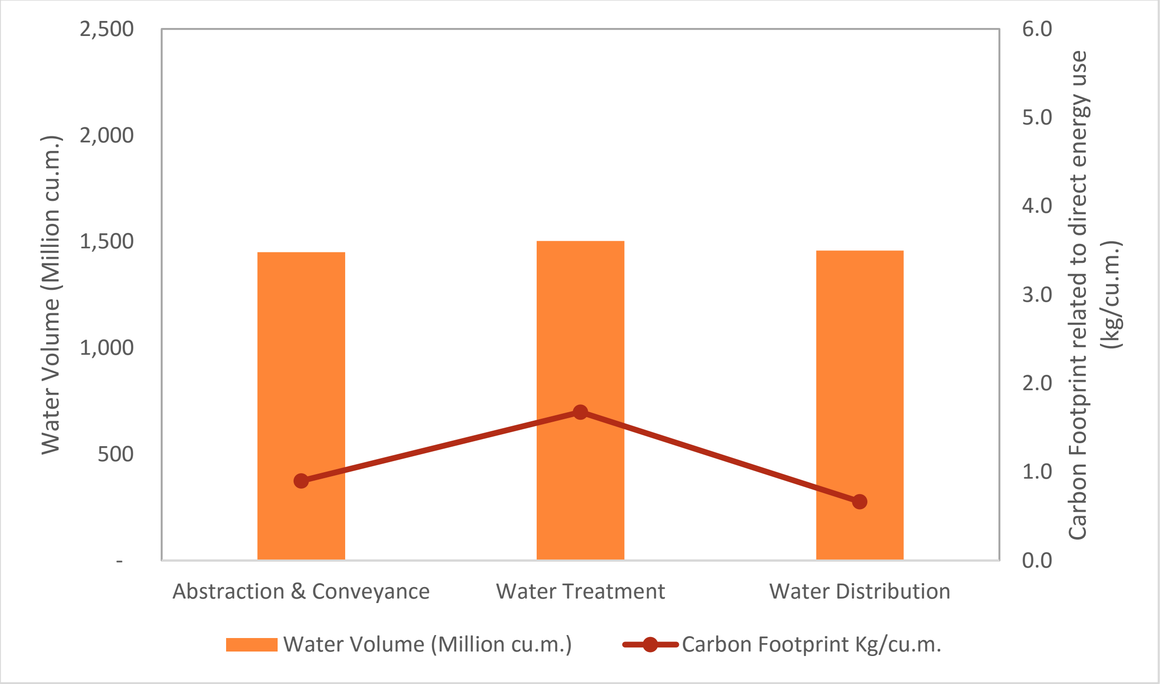


Figure 56: Average (2008 - 2012) of water volume and carbon footprint related to direct energy use in Tokyo water supply system

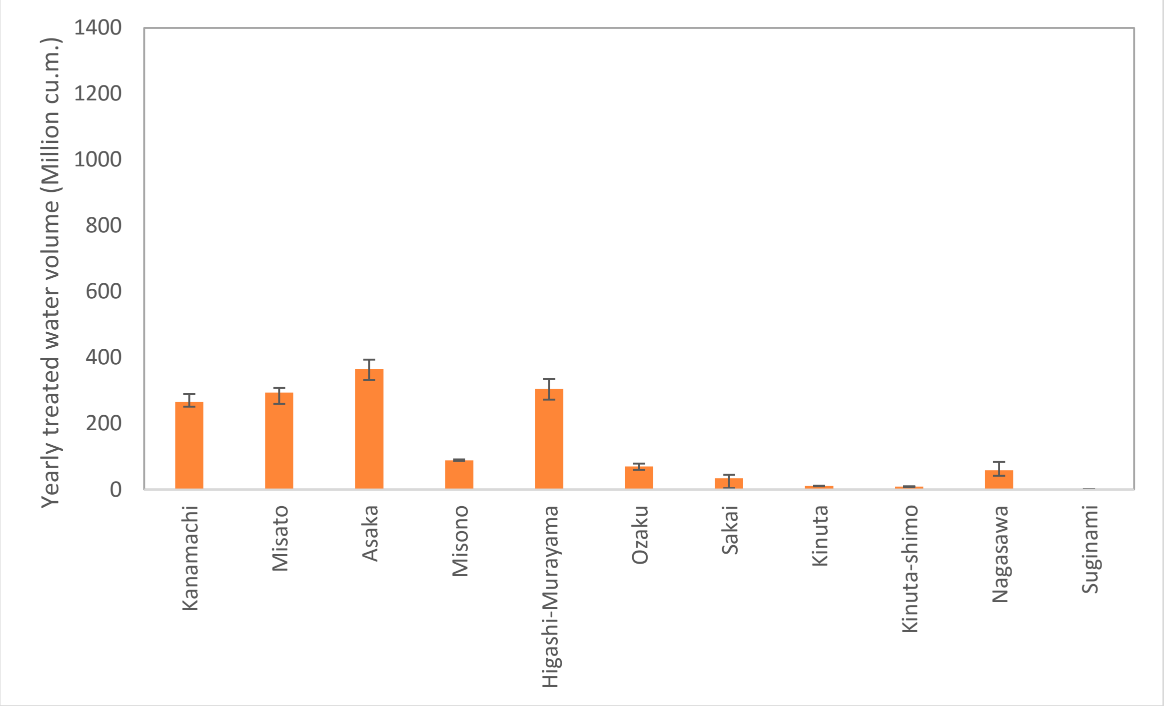


Figure 57: Average of yearly treated water volume of Tokyo' WTPs from 2008 to 2012, showing maximum and minimum values

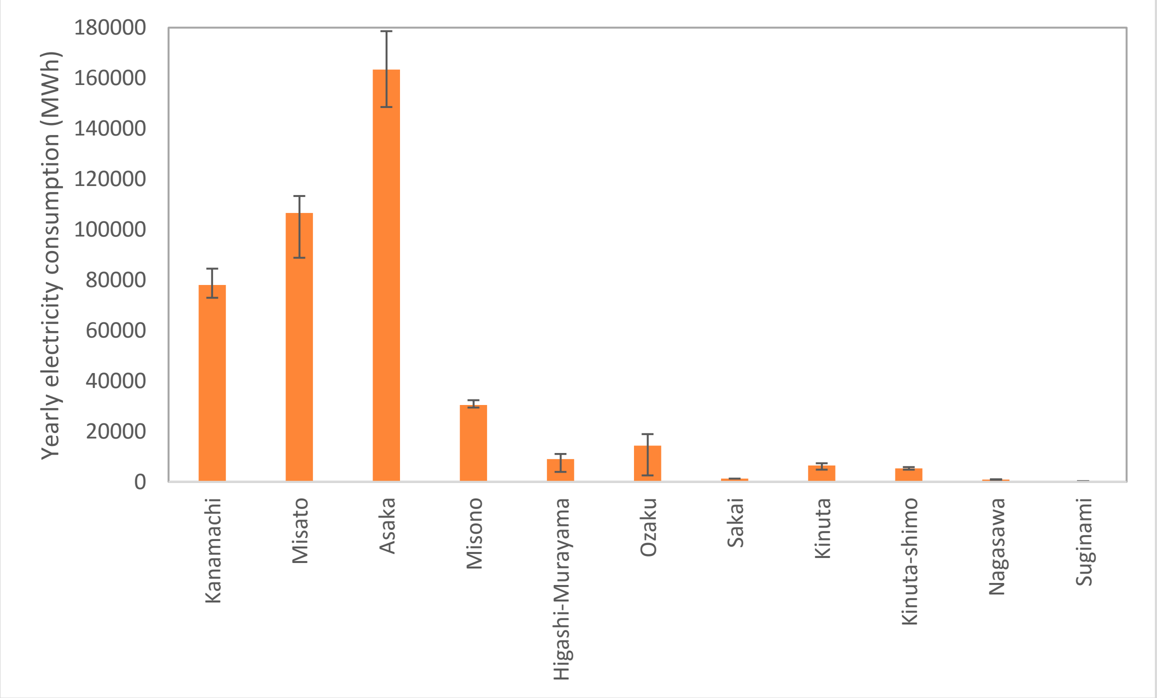


Figure 58: Average of yearly electricity consumption in water treatment by WTPs of Tokyo' from 2008 to 2012, showing maximum and minimum values

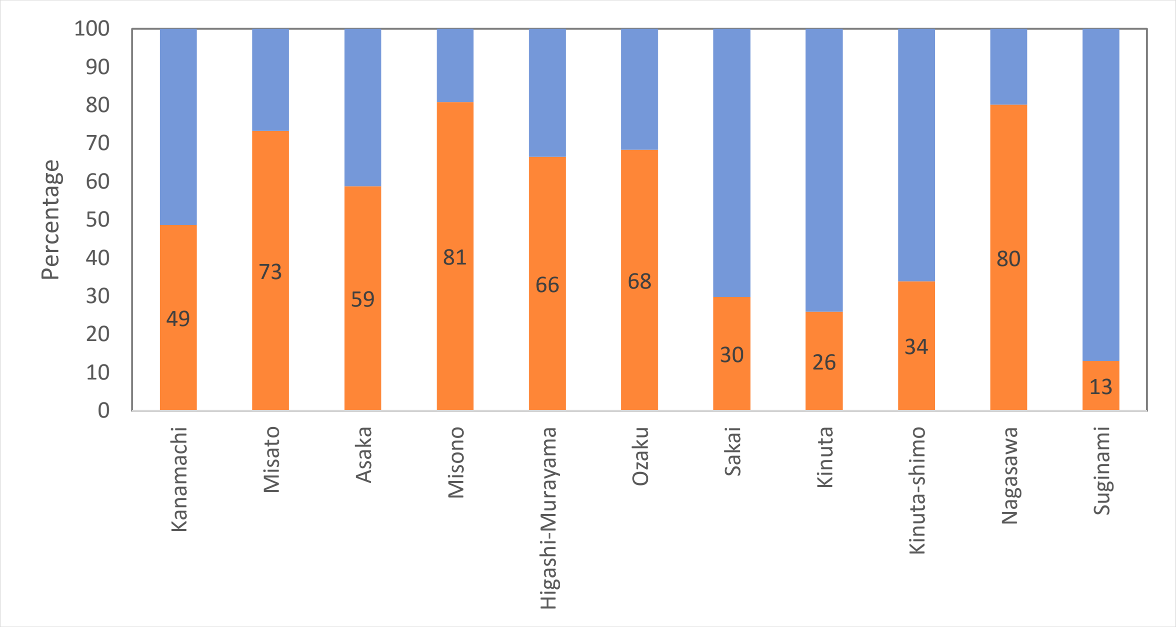


Figure 59: Average capacity utilization of 11 WTPs of Tokyo from 2008 to 2012, showing designed vs actual operating capacity

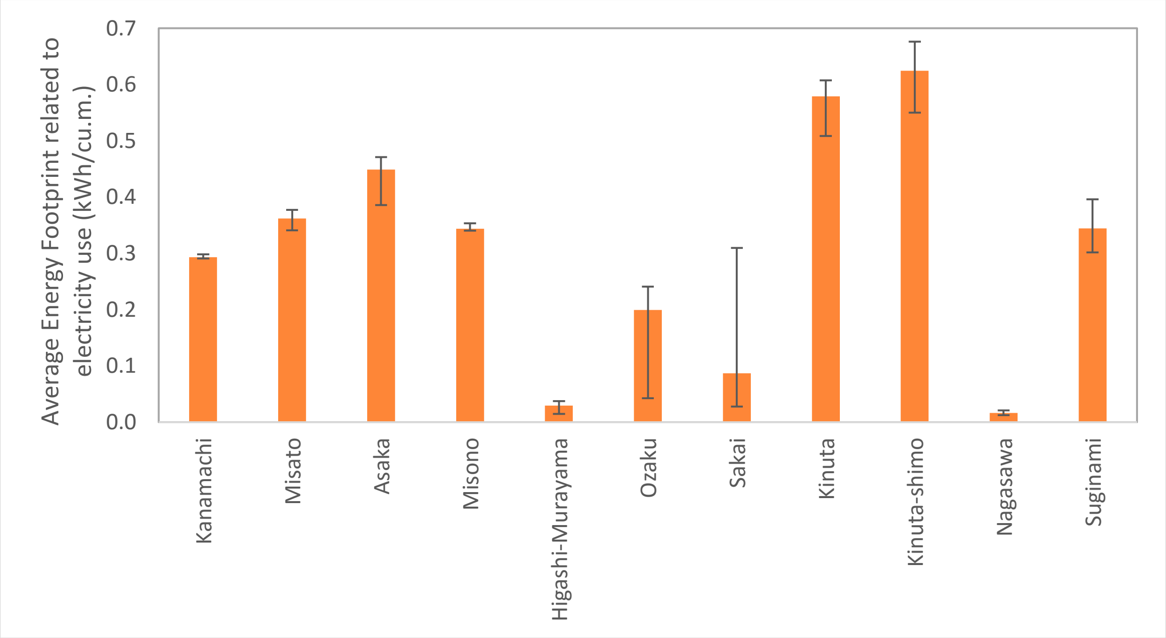


Figure 60: Average of energy footprint related to electricity use in water treatment by 11 WTPs of Tokyo from 2008 to 2012, showing maximum and minimum values

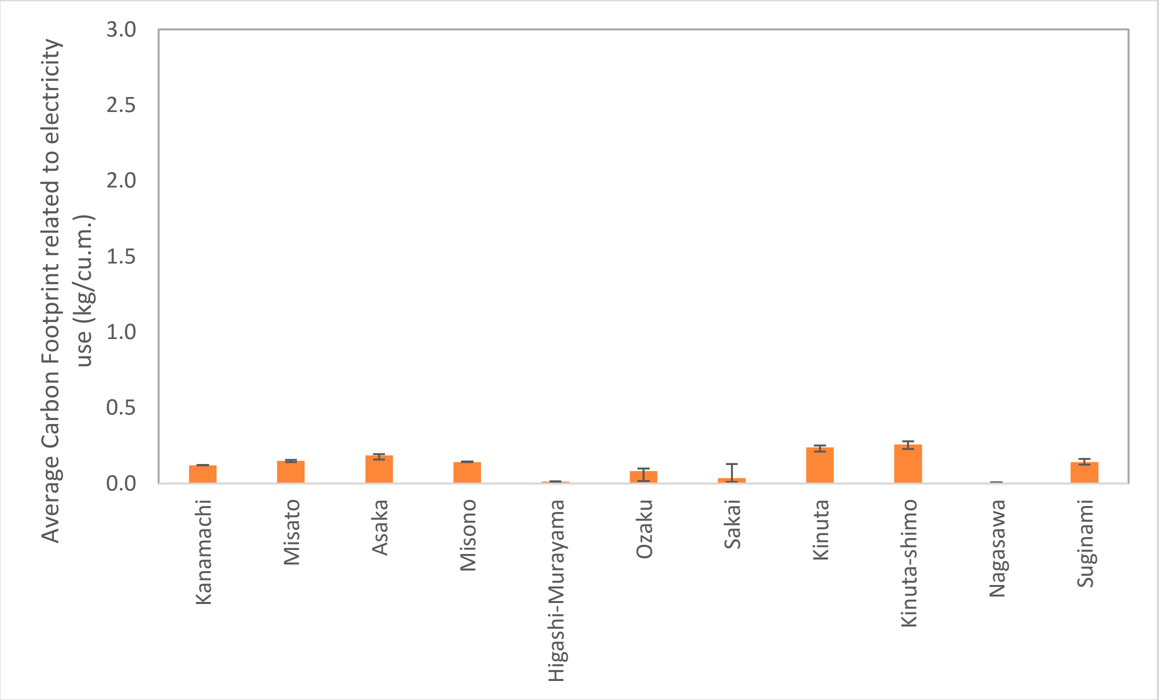


Figure 61: Average of carbon footprint related to electricity use in water treatment by 11 WTPs of Tokyo from 2008 to 2012, showing maximum and minimum values

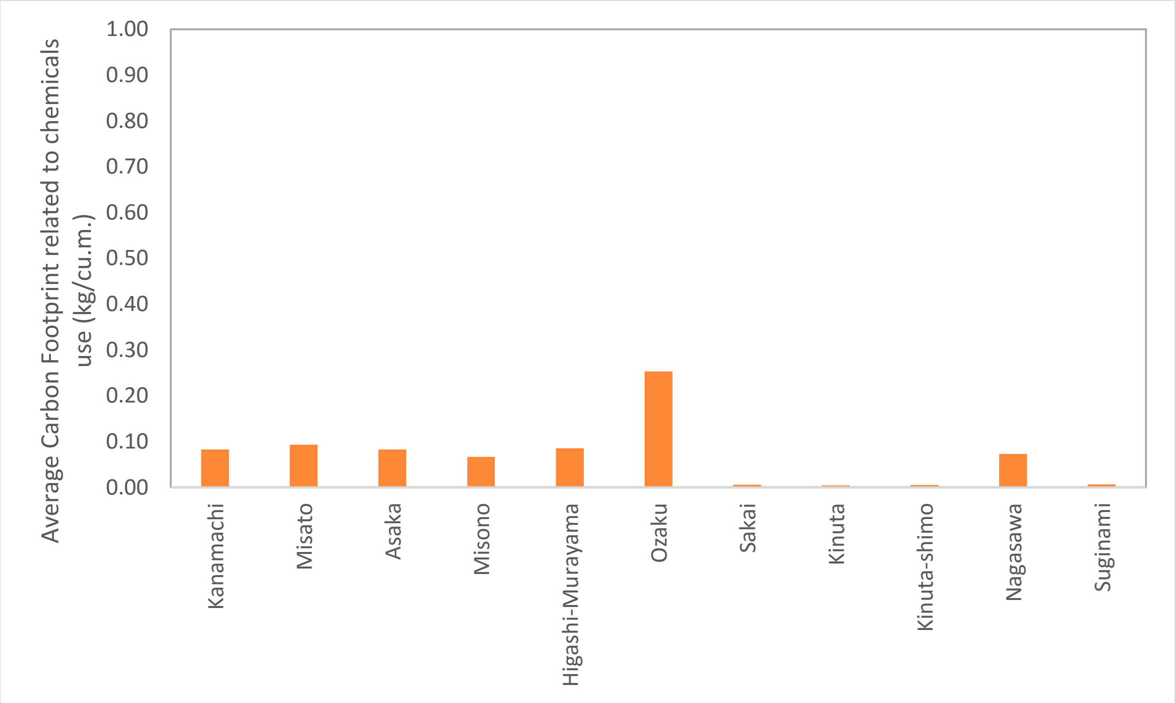


Figure 62: Carbon footprint related to chemicals use in water treatment by 11 WTPs of Tokyo in 2012

Kanamachi, Misano, Asaka and Higashi-Murayama are the larger drinking water treatment plants in Tokyo (figure 57), the yearly electricity consumption of Asaka is huge followed by Misano, Kanamachi and Misono. It is to be noted that Asaka's capacity was utilized to 59% in average, Kanamachi's 49%, Misato's 73% and

Misono's 81 %. The WTPs having lowest capacity utilization has comparatively higher energy and carbon footprints (figure 59 and 60).

4.4.2 Energy and Carbon Footprints – Waste Water System

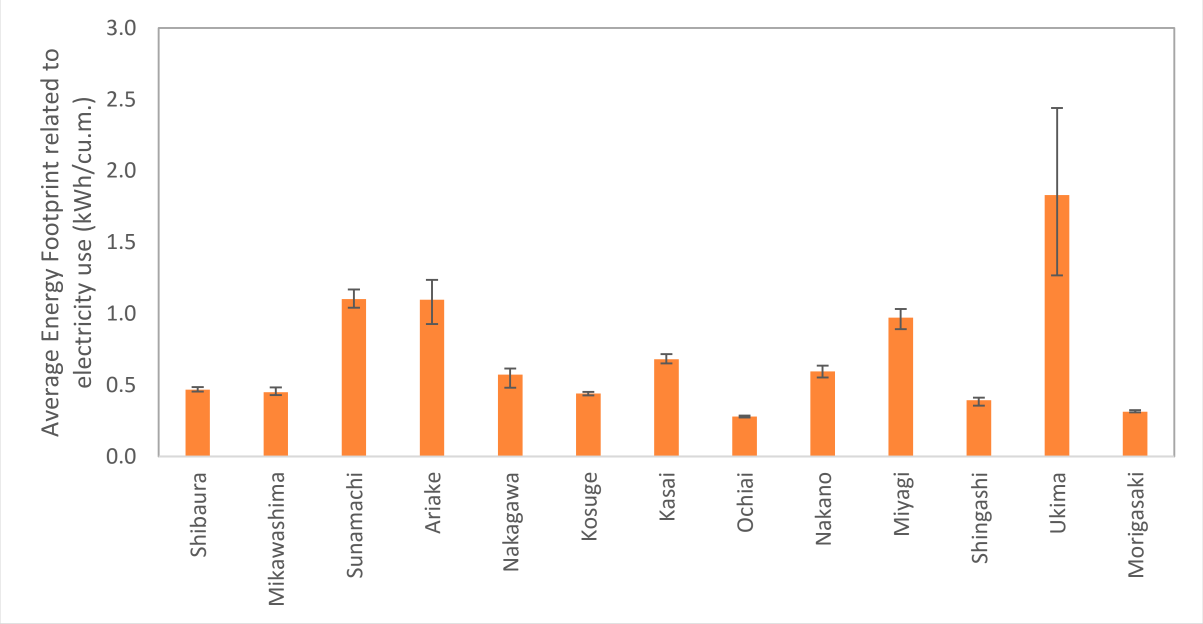


Figure 63: Average energy footprint (energy intensity) of 13 Water Reclamation center (WWTPs) in kWh/m^3 from 2008 to 2012 and bars showing maximum and minimum range

Energy footprints of 13 WWTPs are calculated from 2008 to 2012 (figure 63). Ukima, Sunamachi, Ariake and Miyagi WWTPs have comparatively higher footprints.

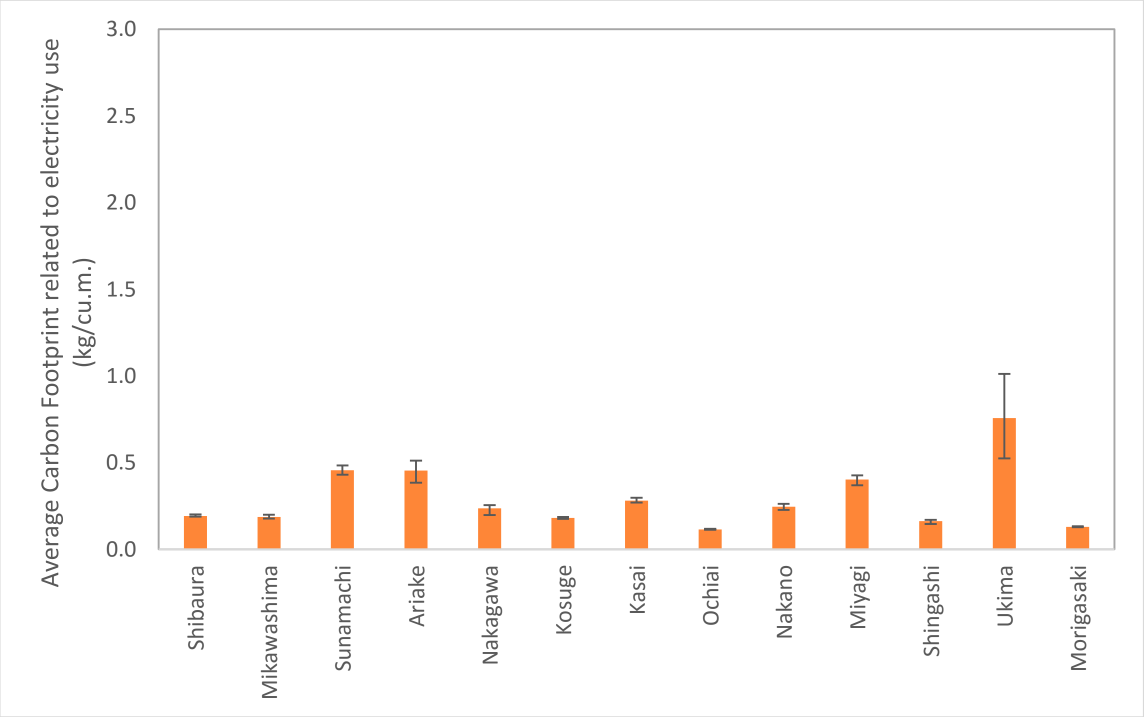


Figure 64: Average carbon footprint related to electricity use of 13 Water Reclamation center (WWTPs) in kWh/m^3 from 2008 to 2012 and bars showing maximum and minimum range

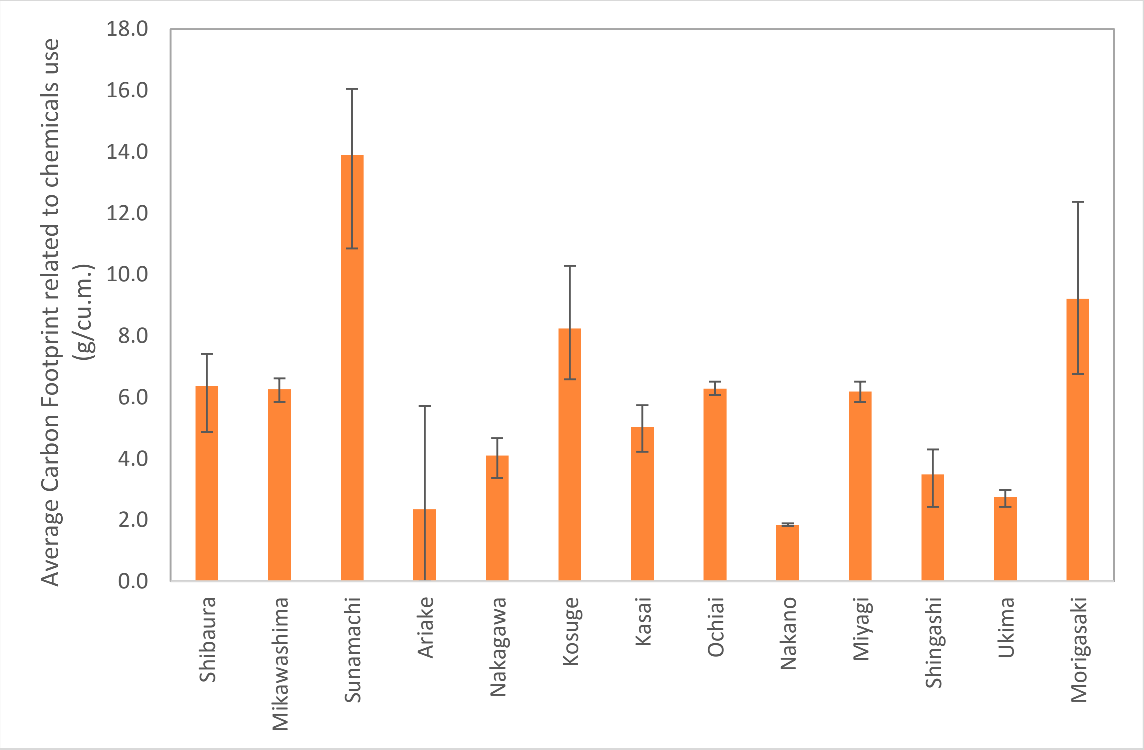


Figure 65: Average carbon footprint related to chemicals use of 13 Water Reclamation center (WWTPs) in kWh/m^3 from 2008 to 2012 and bars showing maximum and minimum range

Table 31: Average energy footprints from WWTPs

Water Reclamation Center	Total Electricity Consumption in a year (kWh/year)	Energy Intensity (kWh/m^3)
Shibaura Water Reclamation Center	62,612,007	0.270
Mikawashima Water Reclamation Center	49,801,897	0.321
Sunamachi Waste Water Reclamation	103,700,078	0.787
Ariake Waste Water Reclamation	5,764,323	1.104
Nakagawa Waste Water Reclamation	23,951,088	0.372
Kosuge Waste Water Reclamation	23,382,672	0.302
Kasai Waste Water Reclamation	67,563,650	0.575
Ochiai Waste Water Reclamation	38,179,330	0.281
Nakano Waste Water Reclamation	6,160,303	0.596
Miyagi Waste Water Reclamation	44,835,280	0.573
Shingashi Waste Water Reclamation	75,358,610	0.395
Ukima Waste Water Reclamation	19,665,270	0.573
Morigasaki Waste Water Reclamation	85,174,185	0.198

Tokyo Electric Power Company is the largest supplier of electricity in Japan which supplies to Tokyo and other prefectures. The major source of energy in the supply side are shown in figure 66. Small quantity of the renewable energy are produced within the Tokyo, which include solar, biomass and energy from waste resources.

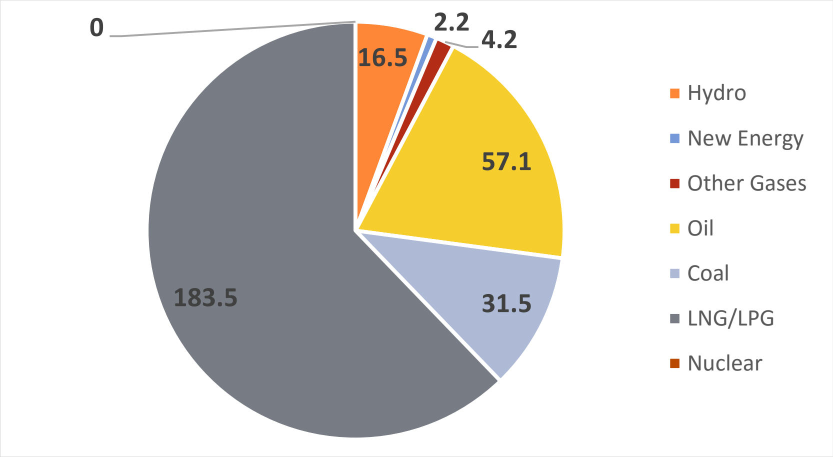


Figure 66: Power Output Composition by Energy Source including purchased power

The carbon emission factor for Tokyo Electric Power Company (TEPCO) was 0.406 kg- CO_2 /kWh.

Table 32: Carbon footprint of water and waste water treatment systems in Tokyo

Urban Water Supply Cycle	Energy Intensity per unit water (kWh/m³)	CO_2 emission (kg-CO_2/ m³)
Water Treatment System		
Abstraction & Conveyance	1.782	0.900
Water Treatment	3.211	1.675
Water Distribution	1.273	0.662
Waste Water System		
Waste Water Collection	2.882	1.194
Water Reclamation Center	6.311	2.615

Significant amount of chemicals are utilized in water and waste water treatment. These processes utilizes chemicals such as polyaluminium chloride, chloride, sodium hypochlorite, caustic soda, powered activated carbon and hydrated lime (Annexure V). The amount of these chemicals used in the water treatment adds up to overall energy and carbon footprints. Furthermore, direct GHGs are also emitted from sewer and treatment facilities.

4.4.3 Major findings

Tokyo has comparatively advanced technologies in treatment, infrastructures and management systems. The policies and practices of water/waste water management are much efficient in Tokyo, and knowledge/experience from Tokyo case study can help planners and developers in the developing countries. However, the energy footprints was found to be quite higher.

The total energy footprint for water supply sector is 6.26 kWh/m^3 and carbon footprint is 2.79 kg-CO_2/kWh/m^3. The total energy footprint for waste water sector is 9.19 kWh/m^3 and carbon footprint is 3.81 kg-CO_2/kWh/m^3.

There still need more effort to reduce overall energy footprint and GHG reduction to meet the Tokyo's target for GHG emission. Utilization of the reclaimed water for environmental protection as well as recovery of energy from waste water byproducts are the significant practices toward low carbon urban water management.

5. Conclusion

5.1 Synthesis of case studies and qualitative comparison

Table 33: Qualitative comparison of four cities

City	Water Treatment Technologies	Supply Systems	Waste Water Treatment Technologies	Water & Sludge Reuse	Energy & Carbon Implications
Bangkok	Rapid/Slow sand filtration, Advanced water treatment	Piped networks	Contact stabilization activated sludge, Two-stage activated sludge, Vertical loop reactor activated sludge, Cyclic activated sludge	No reuse	High, Carbon footprints
Delhi	Rapid/Slow sand filtration, Membrane filtration in new systems, RO & UV filters are used in end-use side	Piped networks + Tankers	Activated Sludge, New system include Membrane bio reactor	Small portion of water is reused for gardening	High energy, carbon footprints due to use of fossil fuels
Tokyo	Rapid/Slow sand filtration, Partially Advanced water treatment, Membrane filtration	Piped networks	Activated Sludge System, semi advanced, advanced wastewater process	Use of reclaimed water and recovery of energy from waste water byproducts	High energy, carbon footprints Comparatively best management practices.
Kathmandu	Rapid/Slow sand filtration, Disinfection	Piped networks + Tankers+ Individual extraction	-	-	High energy footprint due to supply tankers and excessive groundwater extraction

5.2 Synthesis of case studies and quantitative comparison

Table 34: Comparison table for case studies with quantitative comparison

	Elements of Comparison	Unit	Bangkok	Delhi	Tokyo	Kathmandu
Macro level urban water characteristics	**Residential water Consumption**	**lpcd**	211	75.9	249	55
	No. of WTPs	**Numbers**	6	9	11	16
	No. of WWTPs	**Numbers**	7	12- Institutional, 25- Municipal	13	4
	Capacity of WTPs	**M.m³/day**	6.408	3.5	6.854	0.1
	Capacity of WWTPs	**M. m³/day**	0.992 (Additional small WWTPs are there)	2.3	5.32	0.017
	Actual water treatment volume in drinking water	**M. m³/day**	6.286	2.94	4.632 (Max 2014)	0.1
	Actual wastewater treatment volume	**M. m³/day**	0.677	1.52	2.073 (2012)	-
	Capacity utilization of WTPs	**%**	30-**94**	**84**	13-**81**	-
	Capacity utilization of WWTPs	**%**	44-**91**	26 - **86**	-	-
	Water losses	**%**	23.4 (2015)	53	2.2 (2014)	38
	Water losses volume	**M. m³/year**	477	569.3	32.08	
	Energy footprint of NRW	**kWh/year**	32,730	30,542,850	3,425	
	Carbon footprint of NRW	**kg-CO₂/year**	671,376	24,800,794	64,498	
	Emission factor for national grid Electricity	**kg-CO₂/kWh**	4.8	0.812	0.5	0.003
Physical urban features	**Topography (MASL)**	**MASL**	1.5	216	37	1,200-2,300
	Climate	**Types**	Tropical Savanna	Humid Sub-tropical	Sub-Tropical	Sub-Tropical Highland
	Average Rainfall	**mm/year**	1600	790	1529	1,400
	Population	**M. Nos.**	14.5	17.7	12.95	2.7
	Population Density	**Nos./km²**	1924	12473	2168	
	Service Area	**Km²**	7,761.50	1417.56	1,235.01	49.25
	Avg. (Summer, Winter) Temp.	**°C**	33.3, 24.9	31, 19	19.8, 11.6	28, 10.1
Urban Water System Cycle	***Water Abstraction***	**M. m³/year**	2,242	Groundwater =390, Surface Water = 1073	1,141	KUKL = 28.76 Private tankers = 3.3 Registered wells= 9.43
	Total Operational Energy	**MWh/year**	Combined to conveyance	376,315	Combined to conveyance	
	Energy Footprint (Electricity)	**kWh/m³**		0.58		KUKL= 0.26-0.3 Private Tanker= 0.09 -0.119 Registered wells= 0.19-0.24 Households= 0.37 – 1.86
	Carbon Footprint (Electricity)	**g CO₂/m³**	Combined to conveyance	470	Combined to conveyance	KUKL = 0.69- 0.82 Private Tanker = 250 Registered Wells = 0.176-0.246
	Water Conveyance	**M. m³/year**	2,242	Groundwater =390, Surface Water = 1073	1,141	0.0788
	Total Operational Energy	**MWh/year**	23,473	206,407	240,999	5,800

	Energy Footprint (Electricity)	**kWh/m^3**	0.1014	-	1.7817	0.14
	Carbon Footprint (Electricity)	**kg CO_2/m^3**	0.4867	-	0.9001	0.0004
	Water Treatment	**M. m^3/year**	2,096	1,073	1,502	41.43
	Embodied Energy		-	-	-	-
	Total Operational Energy	**MWh/year**	330,526	748,081	263,198	5,800
	Energy Footprint (Electricity)	**kWh/m^3**	1.1014	0.16	3.2112	0.14
	Energy Footprint (Chemical)	**kWh/m^3**	-	0.4187	-	-
	Carbon Footprint (Electricity)	**kg CO_2/m^3**	5.2866	0.13	1.6748	0.0004
	Carbon Footprint (Chemical)	**g CO_2/m^3**	14 (7 - **31**)	**149**	69 (6 -**253**)	-
	Water Distribution	**M. m^3/year**	1,995	Network =1,536	1,458	Network = 0.0788
	Embodied Energy	**kWh/day**	-	470.22	-	
	Total Operational Energy	**MWh/year**	126,274	5,583	155,667	
	Energy Footprint (Electricity)	**kWh/m^3**	0.3879	Network = 0.1	1.2725	Network= 0.16 – 0.42 Tankers = 9.97
	Carbon Footprint (Electricity)	**kg CO_2/m^3**	1.8621	Network = 0.05	0.6624	Network = 0 Tankers = 2.5
	Waste water collection	**M. m^3**	-	-	804.69	-
	Embodied Energy	**MWh/day**	-	116.55	-	-
	Total Operational Energy	**MWh/year**	Combined to Treatment	31,755	116,658	-
	Energy Footprint (Electricity)	**kWh/m^3**	Combined to Treatment	0.019	2.8816	-
	Carbon Footprint (Electricity)	**Kg CO_2/m^3**	Combined to Treatment	0.02	1.1940	-
	Waste Water Treatment	**M. m^3/year**	264.25	834	1,669	-
	Embodied Energy	**MWh/day**	-	21.12	-	-
	Total Operational Energy	**MWh/year**	124,739	82,081	605,215	-
	Energy Footprint (Electricity)	**kWh/m^3**	2.16	0.40 - 4.87	6.3111	-
	Carbon Footprint (Electricity)	**kg CO_2/m^3**	10.35	2.6 – 3.1	2.6149	-
	Carbon Footprint (Chemical)	**g CO_2/m^3**	1.38 (Min to Max= 0.18 to 4.76)	35 - 180	6 (2-16)	-
	Carbon emission (Material)	**g CO_2/m^3**	-		-	-
	Carbon emission (On site: Fugitive +Biogas)	**g CO_2/m^3**	-	252 - 1600	-	-

Higher carbon footprint related to energy use by water/waste water utilities

The emission factors of the national energy mix for all cities are calculated and Bangkok has highest emission factor of 4.8 kg- CO_2/kWh due to higher share of combined cycle power plant, thermal power plant and lesser share of renewable energy. Tokyo has electricity related emission factor of 0.5 kg-CO_2/kWh. Kathmandu on the other hand has lowest emission factor of 0.017 kg- CO_2/kWh, being primary electricity source from hydropower plants. Although the comparative energy use is all stages of urban water system is higher in Tokyo, it has significant lower carbon footprint due to its energy source.

Water loss has significant effect on water-energy-carbon nexus

Non-Revenue Water losses, which account for all the physical losses of the urban water system has significant effects due to loss of energy used and additional carbon footprints associated to energy and chemical use of lost water. Bangkok were able to significantly reduce water loss to 23.4% in 2015 (in MWA system). Still the figure is very high compared to Tokyo 2.2 % (in 2014). Delhi has highest NRW loss of 53%. NRW loss only account for 32.7 MWh/year of energy use in Bangkok, 30,542 MWh/year of energy use in Delhi and 3.4 MWh/year in Tokyo. Their respective carbon emissions are 671,376 kg- CO_2/year, 24,800,794 kg- CO_2/year and 64,498 kg- CO_2/year in Bangkok, Delhi and Tokyo.

Energy-Carbon footprint in Water Abstraction in higher when groundwater is involved

Water abstraction and conveyance data were not available separately for Bangkok and Tokyo, hence is combined together. Source of water has different implications in the nexus. In Bangkok, groundwater extraction is prohibited and surface water from rivers are only source, in Delhi and Kathmandu, both surface water and ground water (being major share) are sources of water. Additionally in Kathmandu, conveyance has no significant energy use as the systems are designed for gravity flow. However, in Tokyo, majority of share for water source are from surface water, still few percentage is extracted from ground water. Groundwater extraction has other environmental implications for e.g. land subsidence (e.g. in Bangkok), apart from direct implication in excessive energy use (e.g. in Delhi). Study in Delhi has compared ground water depth in West, East, South and Southwest Delhi and just in one year (2008-2009) there is notably increased depth of groundwater table in West, East and Southwest Delhi. Delhi Jal Board (DJB) owns 4043 functional tube Wells and 14 Ranney Wells in Delhi, with total groundwater production from these wells is 389 MLD. Water abstraction and conveyance in four cities (Bangkok, New Delhi, Tokyo, Kathmandu) consumes 23,473 MWh, 582,722 MWh, 240,999 MWh and 5,800 MWh respectively. Energy footprint is higher for Tokyo with 1.8 kWh/m^3, whereas Bangkok has lowest of 0.1 kWh/m^3, which is also comparable to Kathmandu. Despite of lowest energy footprint, Bangkok has carbon footprint of 0.5 kg/ m^3 and Tokyo's carbon footprint is 0.9 kg/ m^3.

Energy-Carbon footprint in Water Treatment depends on water quality standard

Bangkok has higher energy footprint (direct energy use only) in water treatment, also Bangkok has comparatively highest water extraction. Total operational energy use for (Bangkok, New Delhi, Tokyo, Kathmandu) are 330,526 MWh, 748,081 MWh, 263,198 MWh and 5,800 MWh respectively. Tokyo has highest energy footprint (3.21 kWh/m^3) in water treatment plants due to higher standard of water quality. Bangkok's energy footprint is 1.1 kWh/m^3. New Delhi and Kathmandu comparative energy footprint of 0.16 and 0.14 kWh/m^3 respectively. Energy use related carbon footprint is highest in Bangkok (5.3 kg CO_2/m^3) and lowest in Kathmandu (0.0004 kg CO_2/m^3). Chemical use related carbon footprint is highest in Tokyo (69 g CO_2/m^3) and lower in Bangkok (14 g CO_2/m^3). Highest range of chemical related carbon footprint is higher in Tokyo 253 g CO_2/m^3, 149 g CO_2/m^3 in New Delhi and 31 g CO_2/m^3 in Bangkok.

Energy-Carbon footprint in Water Distribution depends on condition of the system and design

Water distribution related energy-carbon footprint is higher in New Delhi and Kathmandu. Tanker water supply is still major practice in unconnected regions of water network and unreliable supply in New Delhi and Kathmandu. Total operational energy use for piped network, which is of booster pumps to maintain pressure in the network for Bangkok, Delhi and Tokyo is 126,274 MWh, 5,583 MWh and 155,667 MWh respectively. Energy footprint again is higher in Tokyo (1.3 kWh/m^3) with lowest carbon footprint (0.66 kg/m^3), for Bangkok, energy footprint is 0.38 kWh/m^3 but carbon footprint is higher at 1.86 kg/m^3.

Energy-Carbon footprint in Wastewater collection depends on system design

Energy use in wastewater collection accounts for pumping energy used to transport waste water to treatment centers. Data for Bangkok is not available separately, as total pumping energy is combined with treatment in the analysis. Total operational energy for wastewater collection in Tokyo is 116,658 MWh/year with energy footprint of 2.88 kWh/m^3 and carbon footprint of 1.19 kg/m^3.

Energy-Carbon footprint in Wastewater treatment depends on treatment standards

Total operational energy for major wastewater treatment plants in Bangkok is 124,739 MWh/ year, for Tokyo is 605,215 MWh/year and New Delhi is 82,081 MWh/year. Energy footprint for Tokyo is higher at 6.311 kWh/m^3 with lower energy related carbon footprint of 2.61 kg CO_2/m^3. Energy footprint of Bangkok is lower (3.29 kWh/m^3) but energy related carbon footprint is higher (15.84 kg CO_2/m^3). Energy footprint in Delhi range from 0.4 to 4.87 kWh/m^3 with energy related carbon footprint of 2.6 to 3.1 kg CO_2/m^3. Due to waste water standard to meet the safe environmental discharge in natural ponds, Tokyo has higher chemical related carbon footprints of 6 g CO_2/m^3, compared to Bangkok, which is 1.38 g CO_2/m^3.

Capacity utilization of water and waste water treatment plants affects the nexus

In Bangkok Bangkhen WTP utilize 94% of its treatment capacity compared to other Samsen WTP (51%), Thonburi WTP (30%) and Mahasawat (64%). Energy footprint in Bangkhen WTP is lower than Samsen WTP and similar to Thonburi and Mahasawat WTP. Also to be noted that Bangkhen WTP has highest treatment capacity. This might suggest that larger WTP is more energy efficient in long run. Similarly, capacity utilization of Thrung Khru WWTP and Chatuchak WWTP is highest among 7 WWTPs in Bangkok, at 91% and 81% respectively. The energy intensity of these two WWTP is comparatively lower. Sipraya WWTP has the lowest treatment capacity with lowest capacity utilization, with higher implication in energy footprints. Therefore, size and capacity utilization is important aspect in water-energy-carbon nexus.

In Tokyo, WTPs of larger capacities have lower energy footprint than WTPs of lower capacities. WTPs with lower capacity utilization (Kinuta, Sakai, Kinuta-Shimo and Suginami WTPs) has comparatively higher energy footprints on average and maximum scale. However, two larger capacity WTPs Misato and Asaka (capacity utilization of 73% and 59%), still has higher energy footprint.

Policies related to water-energy-carbon nexus in cities

Summary of policies and issues in each cities are presented in the Table below.

Table 35: Summary of policies and major issues in four cities

Cities	Summary of Policies and Practices	Major Issues
Bangkok	• Regulatory policies for GW • Reduce pollution of canals • Reduce NRW and optimize energy use	• Pollution of canals within city due to inadequate wastewater treatment.

		• Increased GW table affecting underground infrastructures.
Delhi	• Reduce water losses, rehabilitate and upgrade existing infrastructure. • Increase coverage and optimize capacity utilization.	• GW abstraction increased by 2.4 times and energy consumption by 3 times in last 10 years. • Change in treatment technology choices e.g. simple filters to Reverse Osmosis.
Tokyo	• TMG aims to reduce GHG emitted by the sewerage industry by 25% or more by 2020 and 18% or more by 2014, based on 2000 levels. • Advanced leakage prevention • Recover chemical energy for treatment byproducts	• Comparative best practice, aims towards reducing energy-carbon footprints through use to alternative energy source.
Kathmandu	• Melamchi Water Supply project (MWSP) is in progress which will reduce stress on groundwater use.	• Water security and individual extraction of groundwater is the major problem. • Diesel based water transport system has high energy/ carbon implications.

5.3 Policy Implications

Water-energy-carbon nexus in cities is a key area, both from direct and indirect perspectives, and is an essential part of reducing overall GHG emissions from cities. The energy and carbon footprints of the urban water cycle depend on multiple characteristics, which include the nature of water sources, transportation distances, nature/extent of infrastructure, choices of technologies, water losses and management practices. A better understanding of the drivers of the water-energy-carbon nexus would assist policy makers because energy security, climate change mitigation and water security are three key contemporary items on the policy agenda and must be integrated and optimized locally. This study tried to characterize and quantify the water-energy-carbon nexus in urban water and waste water sectors in four cities. This assists city planners to think towards low carbon urban water systems as well as direct future research direction for researchers. City governments and water utilities should plan urban water infrastructure development in a coherent manner addressing the optimization of overall energy use. Resource recovery and reuse of resources from waste water treatment helps to reduce overall energy-carbon footprints. GHG emission from operational stage of water/wastewater sectors directly links with the source of energy used. Top down approach of overall shift toward clean energy systems will not be practical in the short term, however, water/waste water utilities should consider “self-sufficiency” by going for renewable energy resources and resources recovery from treatment byproducts. The design of new systems should be compatible to operate on its optimum capacities; this requires optimization of the overall system design. Proper evaluation of centralized vs decentralized systems is necessary. The objectives for better water-energy-carbon nexus in cities should be an improved water quality, equitable and sufficient supply and access, efficient systems and low GHGs emissions.

6. Future Directions

Urban water infrastructure offers significant opportunities to reduce cities' GHG emission as well as ensure water and energy security. As cities continue to grow, water demand will increase significantly, therefore for sustainable utilization of resources and efficient design of future infrastructure necessary guidelines towards optimized water-energy nexus is crucial. Water utilities and cities government hold the key role to intervene relevant policies. Resource recovery and utilization, and use of renewable energy resources will become the integral part of low carbon pathways. On the other hand if we look beyond the city boundaries, energy systems utilizes significant amount of water, in most of the cities where decentralized energy systems are located it utilizes drinking water. Future research shall look into water footprinting in energy systems. There are also complex systems at the end use side of the urban water system, which is difficult to quantify and perhaps will be dynamic than the centralized water utilities systems. End use side of water systems, relevant policies to optimize water-energy-carbon is essential area to be explored. Furthermore specific decision support tools for policy makers and planners would help to put this knowledge into practice.

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8. Annexure

Appendix I – WEC Nexus of Water Supply System, New Delhi

1. WE nexus for water sourcing

About 47 % of the total water in Delhi is supplied from a distance of 240 kms and the remaining from an average distance of about 50 kms. The energy consumption of surface water conveyance system varies considerably and depends on the length of the system and the elevation changes involved. Several authors have looked into the water conveyance energy use for long distances. Broadly, the energy consumption in a canal system is influenced by length of the channel, hydraulic perimeter, material of construction, permeability of the soil or the terrain bed, and evapotranspiration rate. Similarly, the amount of energy consumed during ground water pumping depend on the efficiency of the pump, the pipeline length and diameter, pipe material roughness or friction factor, and the volumetric demand for water and the time over which the water is pumped. Therefore, the energy consumption is site specific. Based on the meta-analysis of the data25 a conservative estimate of energy consumption is 0.002 kWh/m^3/km for surface water conveyance and 0.004 kWh/m^3/m for ground water pumping. On the basis of these considerations, it is estimated that about 956 MWh/day of energy is consumed for surface water sourcing and about 75 MWh/day for ground water sourcing. For groundwater sourcing, the amount of water withdrawn is considered as 390 MCM/annum. GW values in do not include the information about south district. There are large numbers of unregulated private ground water abstraction. The Central Ground Water Board (CGWB) could not effectively enforce the regulations related to access to ground water and registration of tube well. There is no precise estimation of the exact number of such private groundwater abstraction and the values of groundwater abstraction are broad estimates by CGWB officials.

2. Water treatment and distribution infrastructure

DJB is responsible for complete supply services in Municipal Corporation of Delhi (MCD) area whereas it supplies in bulk to the New Delhi Municipal Corporation (NDMC) and Delhi Cantonment Board (DCB). DJB has divided Delhi into 22 Operating Zones (OZ)[26] with 10 WTPs to supply water to Delhi (Table A). Bawana and Dwarka are newest and commissioned in April, 2015[1]. The major WTPs i.e. Chandrawal, Haiderpur and Wazirabad are concentrated at northern part of Central Delhi and mostly along the outer ring road in the Cis-Yamuna area. However, two WTPs at Bhagirathi and Sonia Vihar are located in the north of the trans-Yamuna area.

Table A. Description of Water treatment plants, command area, population served and length of the pipeline (both for conveyance to- and distribution from-)[27]

S. No.	WTP	Capacity (MGD)	Actual capacity (MGD)	Area (Sq. km)	Population (according	Pipeline length (km)*

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[25] Plappally, A.K and Leinhard J.H.V. 2012. Energy Requirement for Water Production, Treatment End Use, Reclamation and Disposal, Renewable and Sustainable Energy Reviews, 16: 4818-4848

[26] Delhi Jal Board, 2005. DWSSP – Project Preparation Study – Final Report -Part B-Water Supply- Executive Summary. Prepared by Price Water House Coopers, DHV Consultants, The Netherlands
And TCE Consulting Engineers Ltd. Delhi
www.delhijalboard.nic.in/djbdocs/reform_project/docs/docs/doc_project_prep_docs/docs/pdf/final_report/Water%20supply/Exec%20Summary/FR-Water%20Supply-Exec%20Summ.pdf

[27] Primary data collection by interviewing DJB official, Delhi Jal Board, Delhi, 9 October 2015

					to 2001 census)	
1	Not served by any WTP			22.75436	NA	7.88
2	Bawana	20	18.00	144.2533	526407	306.6
3	Bhagirathi	100	106.21	54.65379	2153354	1343.16
4	Chanderawal I & II	90	90.85	126.8856	2117090	1271.04
5	Dwarka	50	30.00	292.2185	540516	1118.62
6	Haiderpur I & II	200	216.82	173.0634	4516063	2511.66
7	Nangloi	40	40.29	32.4502	118000	62.02
8	Ohkla	20	2.68	62.81979	1250599	362.02
9	Sonia vihar	140	141.29	19.16989	403566	81.98
10	Wazirabad I, II & III	120	131.30	105.7752	1101633	300.3
11	Palla R/W T/W**	100	18.00	268.8344	3019408	2180.63
12	Recycling Filter***	45	106.21	114.6782	2461092	1484.03
	Total	**925**	**777.44**	**1417.557**		**11029.94**

* Updated pipeline length ** Ranney wells and Tubewells *** Recycling of Water at Bhagirathi, Haiderpur & Wazirabad

The raw water from the sources flows to the plant under gravity through conduits and is collected in sumps. The length of wired conduit from Muradnagar covers a distance of 26 km to reach Bhagirathi WTP with diameter of 2850 mm and second conduit covers a distance of 30 km to reach Sonia Vihar WTP with diameter of 3200 mm. The water is then pumped to WTPs.

Table B. Details of pipeline materials of various diameter[13]

Diameter* (mm)	Total Length (km)	Material wise length*		
		CI (km)	MS (km)	PSC (km)
3	26.21	26.21	0	0
4	3.65	3.65	0	0
6	14.40	14.40	0	0
30	94.72	0.15	94.57	0
50	48.36	23.12	25.24	0
60	61.11	9.52	51.59	0
75	238.04	157.02	81.02	0
80	90.01	9.99	80.02	0
100	6078.83	6005.44	73.39	0
125	58.40	43.32	15.08	0
150	935.87	930.78	5.09	0
175	14.24	14.24	0	0
200	428.32	428.32	0	0
225	34.60	34.60	0	0
250	315.29	315.29	0	0
300	320.42	170.10	0	150.32
350	82.73	43.92	0	38.81
375	18.65	9.90	0	8.75
400	88.95	47.22	0	41.73
450	116.12	61.64	0	54.48
500	103.80	55.10	0	48.70
600	246.18	130.69	0	115.49
700	99.23	52.68	0	46.55
750	46.35	24.61	0	21.75

800	75.77	7.98	0	67.80
900	143.18	15.07	0	128.11
1000	77.48	8.16	0	69.33
1100	66.44	6.99	0	59.45
1200	88.46	9.31	0	79.15
1300	10.18	1.07	0	9.11
1400	0.99	0.10	0	0.89
1500	36.57	3.85	0	32.72
1600	8.06	0.85	0	7.21
1800	0.66	0.07	0	0.59
1900	7.40	0.78	0	6.62
2850	26	0	0	26
3200	30	0	0	30
Total	**10135.68**	**8666.14**	**426**	**1038.61**

CI-Cast Iron, MS-Mild Steel, PSC- Pre stressed concrete
* Details with respect to updated pipeline diameter, material used is not available

Table C. Chemicals used in WTPs[13]

WTP	Actual flow (m^3/d)	Chemicals used during treatment process (kg/day)			Dewatering-polymer (kg/d)
		Alum	PAC	Chlorine	
Bawana	91000	430.00	1467.00	256.00	1897.00
Bhagirathi	455000	1960.00	10268.00	0.00	12228.00
Chanderawal I & II	409000	695.18	9422.90	2620.00	10118.08
Dwarka	227000	579.00	5467.00	0.00	6046.00
Haiderpur I & II	910000	1660.00	13970.00	3210.00	15630.00
Nangloi	182000	1115.05	3425.22	527.97	4540.27
Ohkla	91000	5479.45	38136.99	0.00	43616.44
Sonia Vihar	636000	5479.45	9589.04	3287.67	15068.49
Wazirabad I, II & III	546000	2102.14	12374.19	0.00	14476.32
Total	**3547000**	**19500.27**	**104120.34**	**9901.64**	**123620.6**

PAC-Poly aluminium chloride

DJB has established its Bottling Plant in August 2002. Initially, the board packed 20L of water jars to be distributed with market name 'JAL' which in 2007 added 250 ml packaged drinking water glasses. These products are available in 11 *Jal Suvidha Kendras* (local water accessibility centres) in Delhi[28]. The water quality is maintained as prescribed by BIS norms (IS: 14543-2004)[29]. Source of water for these bottled water is Sonia Vihar WTP. Disinfection method followed are chlorination, activated charcoal filters, micron filter, ozonation[15]. Reverse Osmosis (RO) facility is used in case the water tapped from borewells where treated water from treatment plants are not available. Daily production is about 1,500 jars of 20 L (production goes upto 2,000 jars/day in the month of July) whereas, almost 100 cartons (24 glasses in each carton) of 250 ml disposable glasses.

Table D. Details of bottling plant operated in Delhi[30]

Container types	Production of water per day-litre	No. of units manufactured per day	Capacity of each unit-litre
Bottles	30000	1500	20

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[28] Delhi Jal Board's Packaged Drinking water Bottling plant, Available at: www.delhi.gov.in/wps/wcm/connect/2262fc0041744eaba1f8e1a613ea00d1/packed_drinking+water_25.04.2014.pdf?MOD=AJPERES

[29] Delhi Jal Board's 2015, Summer Action Plan, Available at: www.delhi.gov.in/wps/wcm/connect/32c8720043b6dd7c9705bf7dfcfecf7e/SAP2015.pdf?MOD=AJPERES&lmod=-311071680

[30] Primary data collection from interviewing official at DJB, 7 Oct 2015

Glass	600	2400	0.25

DJB also supplies potable water in water deficit areas through tankers. Different types of tankers are as follows[31]

1. Departmental (DJB owned) tanker
2. Hired Tanker
3. GPS enabled SS (Stainless Steel) Tanker

Table E. Tankers used in Delhi to combat water supply deficiency[32]

Tankers	Category	Numbers	Capacity (L)
High Capacity	GPS Enabled stainless steel	111	9000
	DJB owned	21	9000
	Hired from private partners	485	9000
Low capacity	GPS Enabled stainless steel	296	3000
Total		**913**	**31000**

3. WE nexus for water treatment and distribution

The distribution facilities include Underground Reservoirs (UGRs), Booster pumping stations (BPSs), and Overhead Service Reservoirs (OHSRs). Water is pumped from WTPs to UGRs (in some cases OHSRs) and then to BPSs for water distribution. Water supply system in Delhi has more than 100 UGRs and 550 BPSs.

Table F. Electrical energy used by TWs, BPSs and UGRs

Zones	Electrical energy used-kW/day[33]
Central-North	31680.59
East	65990.00
West	81764.83
South	31244.05
Total	**210679.47**

Table G. Embodied energy use by pipelines in WTPs[13]

Diameter (mm)	Total Length (km)	Embodied energy use kWh/d				Total EE kWh/day
		CI	MS	PSC		
3	26.21	0.03	0.00	0.00		0.03
4	3.65	0.01	0.00	0.00		0.01
6	14.40	0.05	0.00	0.00		0.05
30	94.72	0.00	0.19	0.00		0.19
50	48.36	0.12	0.08	0.00		0.20
60	61.11	0.06	0.22	0.00		0.27
75	238.04	1.88	0.43	0.00		2.31
80	90.01	0.14	0.56	0.00		0.70
100	6078.83	111.91	0.59	0.00		112.50
125	58.40	1.10	0.19	0.00		1.30
150	935.87	30.58	0.08	0.00		30.65
175	14.24	0.56	0.00	0.00		0.56

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[31] www.delhi.gov.in/wps/wcm/connect/DOIT_DJB/djb/our+services1/schedule+of+water+tankers

[32] Primary data collected by interviewing DJB official, Delhi Jal Board, Delhi. 6 and 10 October, 2015

[33] Primary data collection by interviewing DJB officials, Delhi Jal Board, Delhi. 9 and 12 October, 2015

200	428.32	20.47	0.00	0.00		20.47
225	34.60	1.98	0.00	0.00		1.98
250	315.29	20.90	0.00	0.00		20.90
300	320.42	11.28	0.00	0.56		11.84
350	82.73	5.51	0.00	0.19		5.70
375	18.65	1.30	0.00	0.05		1.35
400	88.95	7.56	0.00	0.26		7.81
450	116.12	11.05	0.00	0.37		11.42
500	103.80	10.93	0.00	0.46		11.39
600	246.18	45.27	0.00	1.36		46.63
700	99.23	25.36	0.00	0.62		25.98
750	46.35	13.23	0.00	0.32		13.55
800	75.77	5.18	0.00	1.08		6.26
900	143.18	12.96	0.00	2.41		15.37
1000	77.48	9.11	0.00	1.53		10.64
1100	66.44	9.76	0.00	1.52		11.27
1200	88.46	16.06	0.00	2.32		18.38
1300	10.18	2.11	0.00	0.30		2.42
1400	0.99	0.24	0.00	0.03		0.27
1500	36.57	10.25	0.00	1.38		11.63
1600	8.06	2.58	0.00	0.34		2.91
1800	0.66	0.27	0.00	0.03		0.30
1900	7.40	3.75	0.00	0.38		4.13
2850	26	0	0			25.14
3200	30	0	0			33.70
Total	**10135.68**	393.54	2.34	15.50		**470.22**

Table H. Electrical and chemical energy used at WTPs[19]

S No.	WTP	Treatment capacity (m^3/day)	Electrical energy used (kWh/day)	Chemical energy (kWh/day)	Total energy use for operation (kWh/day)
1	Bawana	91000	9260.00	24200.45	33830
2	Bhagirathi	455000	48982.84	133652.04	180932.84
3	Chanderawal I & II	409000	61259.45	146065.44	208499.45
4	Dwarka	227000	34561.88	66082.78	100391.88
5	Haiderpur I & II	910000	153653.55	214299.30	372053.55
6	Nangloi	182000	14683.75	56773.94	71103.75
7	Ohkla	91000	12240.47	476727.67	489080.47
8	Sonia vihar	636000	118025.10	209213.70	327905.1
9	Wazirabad I, II & III	546000	111630.42	158226.21	269970.42
	Total	**4207000**	**564297.45**	**1485242**	**2049539**

Table I. Electricity consumption from packaging of water[18]

Container types	Production of water per day-litre	Electrical energy used-kW/day
Bottles	30000	1200
Glass	600	

Table J. Energy use by water tankers[18]

Type of Tanker	Capacity (L)	No. of tankers	Av. distance travelled (tanker/day)	Diesel consumed (lit/day/tanker)	Total Diesel consumed (lit/day)	Energy use (kWh/day)*

Low Capacity	3000	296	105	30	8880	138528
High capacity	9000	617	75	12.5	7712.5	120315

*Energy consumption has been calculated on the basis of average distance covered by a truck/day and corresponding diesel consumption. Diesel consumption has been used to calculate embodied energy of the vehicle used.

Annexure II: WEC Nexus of Wastewater System, New Delhi

Estimation of energy use

The net energy (E_n) of a STP is calculated by using Equation 1.

$$E_n = E_l + E_D + E_{mt} + E_{ch} - E_B \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

where En is the total net energy consumption (kWh/m^3)
E_l is the electrical energy consumption (kWh/m^3)
E_d is the total diesel energy consumption (kWh/m^3)
E_{mt} is the material energy consumption (kWh/m^3)
E_{ch} is the chemical energy consumption (kWh/m^3)
E_B is the energy utilised from biogas (kWh/m^3)

Electricity and diesel

Electrical energy (E_l) consumption in various units of a STP was estimated by the method used by Singh et al. (2012), and the cumulative electrical energy consumption of the STP thus obtained was cross-checked with the energy consumption shown in electricity bills of the STP. The final values were arrived at in consultation with engineers operating the STP. Energy used in pumping stations to transfer sewage from one treatment unit to the other was considered under the energy use of the process to which the sewage thus transferred was subjected. Diesel energy was calculated from the diesel consumed during operation and maintenance of the STP (Singh et al. 2012). Diesel energy (E_d) used in vehicles for disposing the sludge was estimated using equation 2.

$$E_d = \frac{\sum_{i=0}^{n}\left(\frac{D_i}{E_i}\right)\times CF}{Q} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 2$$

where E_d is the total diesel energy consumption (kWh/m^3)
i is the type of vehicle (empty and full-payload-capacity vehicles were considered separately)
D_i is the total distance travelled by i^{th} vehicle (km/day)
E_i is fuel efficiency of the i^{th} vehicle (km/L)
Q is annual average daily inflow in the STP (m^3/day)
CF is the energy unit conversion factor for diesel (from litres of diesel to kilowatt-hours, taken as 15.64 kWh/L (Devi et al. 2007a).

Values for Biogas (E_B) – the energy produced in the form of biogas in an STP and the amount of useful energy derived from biogas used in an STP – were obtained from the STP operators. The biogas energy was subtracted from the total energy consumption of the STP to arrive at the net energy consumption.

2.2.2. Embodied energy

Embodied energy (Chen et al. 2001) of the material was calculated using equation 3.

$$E_{mt} = \frac{\left(\sum_{i=0}^{n}\left(V_i \times \rho_i\right) \times E_{mi}\right)/N_i}{F} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 3$$

where E_{mt} is the total embodied energy of construction material (kWh/m^3)
i is the type of construction material
V_i is the volume of the i^{th} construction material (m^3)
ρ_i is the density of i^{th} material (kg/m^3)
E_{mi} is unit energy consumed during manufacturing of i^{th} construction material (kWh/kg)

N_i is the life of the i^{th} construction material (years)
F is the treatment capacity of the STP (m^3/year).

Values for the density of a material and its unit energy were obtained from the literature (Table K). The quantity of material used in the construction of an STP was estimated from its structural drawings and other records related to its construction maintained by STP officials. The life of the construction material was taken as 50 years for concrete, reinforced cement concrete (RCC) , and other cement-based construction and 10 years for iron and steel (other than that used in RCC), pumps, and other mechanical and electrical devices (CPHEEO, 2012).

Table K: Embodied energy and carbon footprint of materials

Material	ρ (kg/m^3)[8]	Unit energy (kWh/kg)	Carbon emissions (EFi) (kg CO_2/kg)
Construction			
Reinforced cement concrete	2500	0.66[1]	0.258[1]
Cast iron	6800	10.94[1]	0.446[1]
Mild steel	7850	11.6[2]	4.116[3]
Stainless steel	8030	14.3[5]	5.047[5]
Copper-based wire	8940	31.1[4]	10.976[4]
Cement	1440	2.08[5]	0.735[5]
Sand	1840	0.02[5]	0.005[5]
Burnt brick	1920	1.8[5]	0.5[5]
Gravel	1600	0.3[5]	0.08[5]
Mortar	2000	0.4[5]	0.141[5]
Chemical			
Polymer	-	10.93[7]	13.54[6]
Disinfectant	-	13.54[7]	1.124[6]
Alum	-	0.17[9]	0.539[9]

(Sources: 1- Bansal, 2002; 2- Venkatarama Reddy & Jagadish 2003; 3- Singh et al. 2011; 4- Lim et al. 2008; 5- Auroville Earth Institue 2008; 6- Q. H. Zhang et al. 2010; 7- Haas, 2009; 8- IS : 875 (Part 1) - 1987; 9- Robert 1978)

Chemicals are used in some large-scale STPs for sludge dewatering and for disinfecting treated sewage. In the surveyed STPs, chlorine was used as a disinfectant and polymers were used in CF. Embodied energy of chemicals used in the various treatment processes was calculated using equation 4. Unit energy values of chemicals taken from the literature are given in Table 2.

$$E_{ch} = \frac{(\sum_{i=0}^{n} W_i \ \times E_{ci})}{Q}$$

where E_{ch} is the total embodied energy of a chemical (kWh/m^3)
i is type of chemical
W_i is the quantity of the i^{th} chemical used (kg/day)
E_{ci} is the unit energy consumed during manufacturing of i^{th} chemical (kWh/kg)
Q is the annual average of daily inflow in the STP (m^3/day).

Carbon emissions

Off-site carbon emissions from the use of electricity (G_e) and diesel (G_d) in the operation for STPs were estimated using the country emission factor of 0.81 $kgCO_2$/kWh (CEC, 2011) and 2.9 $kgCO_2$/L (Haas et al. 2009) respectively. Off-site carbon emissions from the use of electricity (G_e) are estimated after considering the carbon credit for the electricity production from biogas. On-site carbon emissions in the form of fugitive emissions ($G_{fugitive}$) from the biochemical processes and emissions due to flaring of biogas (G_{biogas}) were estimated using the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and greenhouse gas emissions estimation methodologies for biogenic emissions for selected source categories (USEPA, 2010). In applying this method, country-specific values were taken from the Ministry of Environment and Forests, Govt of India (MoEF, 2010). Indirect carbon emissions embodied in construction materials (G_{mt}) and chemicals (G_{ch}) were taken from literature (Table 2) and calculated using equation 4 and equation 5 respectively.

$$G_{mt} = \frac{\left(\sum_{\mathrm{i=0}}^{\mathrm{n}}\left(V_i \times \rho_i\right) \times \mathrm{EF_i}\right)/\mathrm{N_i}}{\mathrm{F}}$$

Where,
G_{mt} is the total carbon emissions of construction materials ($kgCO_2eq/m^3$)
i is the type of construction material
V_i is the volume of i^{th} construction material (m^3)
ρ_i is the density of i^{th} material (kg/m^3)
EF_i is emission factor of i^{th} material ($kgCO_2eq/kg$)
N_i is the life of i^{th} construction material (years)
F is the treatment capacity of the STP (m^3/year).

$$G_{ch} = \frac{\left(\sum_{i=0}^{n} W_i \times EF_i\right)}{Q}$$

Where,
G_{ch} is the total carbon from chemicals consumed during operation ($kgCO_2eq//m^3$)
i is the type of chemical
W_i is the quantity of i^{th} chemical used (kg/day)
EF_i is emission factor of the i^{th} chemical ($kgCO_2/kg$)
Q is the annual average daily inflow of the STP (m^3/day).

Table L: Energy analysis of surveyed STPs

Type of STP	Energy use (Wh/m³)				E_n (Net energy) (kWh/m³)
	E_I	E_D	E_{mt}+E_{ch}	E_B	
Municipal STP					
M1	34–157	3–60	6.1–14.9	10–100	0.11-0.05
M2	184.9	1.7	31.7	0	0.22
M3	203.4	17	276.5	92	0.4
M4	419.2	46	852	0	1.32
M5	110.2	0.8	38.81	55	0.09
M6	232.5	3	61.36	0	0.3
Institutional STP					
I1	1290	120	120	0	1.53
I2	5910	64.6	2410	0	8.33
I3	4235	80	1325	0	7.72
I4	750	46.9	940	0	1.67
I5	1480	40	3850	0	6.99
I6	5530	100	280	0	5.91
I7	2020	130	550	0	2.71
I8	2380	90	1520	0	4.15

Table M: Carbon emissions from STPs in India.

Type of STP	Carbon emissions (kg CO_2eq/m^3)			
	Off-site ($G_e + G_d$)	On-site ($G_{fugitive} + G_{biogas}$)	Indirect ($G_{mt} + G_{ch}$)	Total
Municipal				
M1	0.07	2.09-0.68	0.0083	2.16
M2	0.15	2.86-3.37	0.0214	3.03
M3	0.17	1.79-0.38	0.0311	1.99
M4	0.35	2.03-0.22	0.1224	2.50
M5	0.09	3.69-0.63	0.0099	3.79
M6	0.19	1.84-0.35	0.0170	2.05
Institutional				
I1	1.50-1.83	0.33	0.04	1.87
I2	4.98-5.17	0.19	0.20	5.37
I3	3.65-3.88	0.23	0.29	4.17
I4	0.80-0.99	0.19	0.08	1.07
I5	1.33-1.46	0.13	0.48	1.94
I6	4.78-5.08	0.30	0.09	5.17
I7	2.01-2.39	0.38	0.07	2.46
I8	2.24-2.51	0.27	0.19	2.72

Table N: Average electrical energy use in STPs at different stages of sewage treatment.

Type of STP		Electrical energy consumption (Wh/m^3)					
	PT	ST	Sld.H	TT	NT	TSD	TOTAL
Municipal							
M1	6.0	75.0	2.0	0	4.9	NA	87.3
M2	2.0	178.0	0.1	0	5.1	NA	185.5
M3	4.0	138.6	18.3	30.2	12.2	NA	203.3
M4	133.3	220.3	10.9	0	65.0	NA	429.3
M5	3.0	101.0	3.0	0.6	2.8	NA	110.2
M6	5.0	180.0	38.0	2.9	7.6	NA	232.5
Institutional							
I1	273.3	929.3	0	0	NA	89.6	1290
I2	288.3	4684.6	0	928.50	NA	455.3	6360
I3	210.0	3429.0	0.04	390.00	NA	210.0	4230
I4	54.6	607.5	0	59.50	NA	119.0	840
I5	239.7	871.1	0.16	0	NA	369.9	1480
I6	297.3	5084.0	0	0	NA	149.1	5530
I7	250.0	1490.0	0	0	NA	280.0	2020
I8	263.5	1412.3	0	175.20	NA	526.3	2380

Table O: Energy and carbon footprints of treatment technologies for sewage treatment.

Treatment technology	No. of units surveyed	Avg. electrical energy (Wh/m^3) (SD)		Avg. carbon footprint ($kgCO_2eq/m^3$) (SD)	
		E_e	E_{ch}	$C_{fugitive}$	C_{biogas}
Primary treatment					
SC	36	10.61 (43.96)	NA	NA	NA
GC	26	11.46 (28.29)	NA	NA	NA
PST	22	17.89 (78.65)	NA	NA	NA
FM+CL	3	180.94 (109.22)	836.3 (0.0713)	0.09 (0.007)	NA
Secondary treatment					
ASP	18	126.41 (246.35)	NA	2.05-0.68 (0.38)	NA
EA	5	310.65 (384.12)	NA	2.86 – 3.37(0.80)	0

TF	1	138.6	NA	1.79-0	0
SBR	7	2458.8 (2511.1)	NA	2.03-0.22 (0.57)	0
UASB	1	101.14	NA	NA	0.11
FBR	3	1982.5 (2606.6)	NA	1.84-0	0
CAACO	1	656	NA	0.22-0	NA
RBC	1	250	NA	0.2-0	NA
Sludge handling					
AD	20	4.7 (9.37)	NA	NA	0.045 (0.029)
SDB	30	1.2 (5.5)	NA	NA	NA
BFP	5	5.3 (4.67)	NA	NA	NA
Cf	1	162	1049.3	NA	NA
Tertiary treatment					
Cl	11	421.96 (571.42)	1511.8 (1887)	0.170 (0.16)	NA
2nd stage BT	1	30.2	NA	NA	NA
SF+AC	6	225.9 (77.43)	NA	NA	NA
MGF	7	173.19 (104.38)	NA	NA	NA
NT	25	6.4 (6.55)	NA	NA	NA

(NA-Not Applicable)

Annexure III: Zoom in study for end use, New Delhi

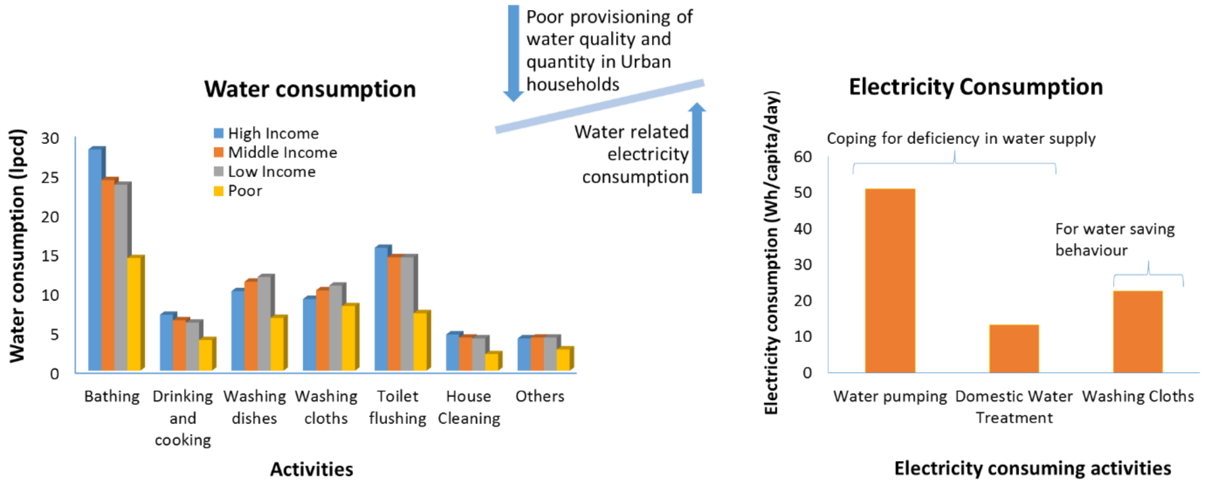

Figure: Graphical abstract for iimplications of end-user behavior in response to deficiencies in water supply for electricity

Methodology for Zoom in study on end use

A variety of approaches were used for collecting and analysing different types of data required for various objectives of the study. These approaches were drawn from the methods and techniques used in quantitative and qualitative research (Clark and Creswell, 2007). Questionnaires and interviews were used for obtaining data on the following aspects: socio-economic and demographic attributes of respondents, sources of water, risk-averting behaviour of households, behaviour related to water use, stock of water-related household appliances, and the monetary cost of obtaining safe water. The data were supplemented with simulated experiments on select groups of volunteers to measure water consumption for various end uses. Data on electricity consumption and water requirements of different appliances were assessed using information from the manufacturers' catalogues.

4.1 Questionnaire survey and design

All households in Delhi were considered for the sampling frame. Semi-purposive sampling was used since the study required respondents from a broad spectrum of households (Crona et al., 2009; Sovacool et al., 2012). The survey was conducted from May to July 2014 and from March to April 2015 through personal interviews in the homes of the respondents by graduates in environmental studies, who were given special training for conducting the survey. The sampling frame comprised the computerized records of household electricity connections given by the Delhi Vidyut Board (Kansal et al., 2011) and a list of slum households maintained by the Delhi Urban Shelter Improvement Board. A total of 2800 households were selected for the survey, 700 each from the four housing categories mentioned in Section 3 (Slums, LIG, MIG, and HIG). Adult members of the household were chosen as respondents for the survey. Of the selected households, only 496 cooperated fully (394 in May–July 2014 and 102 in March–April 2015), and their responses were considered for data analysis.

The cardinal qualitative information was recorded in the form of numerical codes. The first section of the survey included general information such as name, address, and telephone number of the respondent (these details were used only for identification purposes). The second section included questions on socio-economic and demographic characteristics of the respondents, such as age, education, general awareness of challenges related to water faced by family members, family size, income and occupation of family members, and sources of water. The third section included an inventory of water-consuming activities recorded in the form of code numbers. For each coded activity, further information required to estimate the water consumption was sought. Depending on the nature of the activity, such information included frequency and duration of the activity, whether individual or collective, etc. If the frequency was once a week, the estimated water consumption was divided by 7 to arrive at the daily consumption. Water used in minor activities was estimated by the enumerators through a set of pertinent questions. The fourth section included information on household behaviour related to water consumption and on relevant household appliances (capacity, make and model, and nature of use). Information about risk-averting behaviour was captured in the fifth section and included information on perceptions of the adequacy of quantity and quality of water and information required for estimating water and electricity consumption for each risk-averting activity. The information sought under this section was cross checked with that sought under the earlier sections. The sixth and final section sought information on total monthly expenditure on water, namely the amount paid for water (whether in the form of charges paid to the DJB or to private parties, suppliers of water tankers, and so on) plus the expenses related to the risk-averting behaviour.

4.2 Simulated experiments and estimation of water consumption for each end use

Experiments were performed during May–June 2015 with the help of five graduate students to estimate the quantity of water used by an individual for each activity that requires water but is not related to any appliance. The activities were timed with a stopwatch and the consumption of water, in litres, measured with graduated vessels. The data in each case were the average of ten observations (each experiment was repeated ten times). Standard water fixtures were used during the experiments. For collective household activities, as distinct from individual activities, similar experiments were performed to measure the water used for washing clothes manually and for washing the dishes (including pots and pans) and the results were estimated in terms of litres per minute. This figure was arrived at by dividing the total amount of water used for a full cycle of washing by the time taken. Water and energy consumed in appliance-based activities were estimated by taking the average of values given in the manufacturers' catalogues. Water and energy used in storing the water to meet the daily needs for drinking and cooking were based on the responses to the questionnaire and from manufacturers' catalogues for domestic water treatment systems.

4.3 Data analysis for water consumption and electricity use

Total water use was estimated using Equation 1.

$$Q = \frac{\sum_{i=o}^{n} q_i}{FS} \qquad (1)$$

where Q is total water used (lpcd), n is number of water-related activities of a household, FS is family size (number of individuals), and q_i is water used by the household for ith activity in litres per day (lpd) estimated using Equation 2.

$$q_i = \frac{f_i \times c_i}{7} \qquad (2)$$

where f_i is the frequency of ith activity in the household in a week, c_i is the water consumed in litres (L) during ith activity , and 7 is the number of days in a week.

Data for c_i were the measured values for non-appliance-based activities and from manufactures' catalogues for appliance-based activities.

Electricity consumption (E_l, in watt-hours per capita per day) from water-related appliances was estimated using Equation 3.

$$E_l \frac{\sum_{i=0}^{n} E_{pi}}{FS} \qquad (3)$$

where E_{pi} is the electrical energy used in ith activity (in watt-hours per day) estimated using Equation 4.

$$E_{pi} = P_i \times T_i \qquad (4)$$

where P_i is the rated power of ith electrical appliance in watts (W), T_i is the number of hours ith appliance is used daily (h/d), averaged over a week.

Some assumptions and system boundaries: water-related activities performed occasionally (fewer than once a week) and those performed outside the house (having a car washed in a garage, for example) were ignored; energy used for heating water for cooking or bathing was not considered; and water loss due to leakages was not accounted for.

Findings from Zoom in study on end use

Table P shows the descriptive statistics of the surveyed population for each housing category. For further analysis, the data were pooled to understand the effect of socio-economic and demographic attributes on household water consumption. Low-, medium-, and high-income group housing falls under the category of *organized housing* the residents of which are the consumers of urban services, and urban local bodies are the service providers. Slums are *unorganized urban settlements* the residents of which enjoy urban services as beneficiaries of social schemes. The enumerators cautioned us that the data on household income are probably unreliable; therefore, we assumed that the sound correlation between housing category and income-class reported by Shaban and Sharma (2007) holds good even today. Family size was more variable in HIG and Slums and the average for all the groups was 4.25, a value close to the value of 4.39 reported by GNCTD (2012). More than half the family members in the surveyed households were adults, and about 85% of them contributed to the household income, although that proportion was lower in HIG and higher in Slum residents. Majority of people in organized housing worked in the service sector and showed no significant difference in occupation pattern (p = 0.0841) except that the higher the income category, the greater the proportion of self-employed skilled workers. Slum dwellers were mostly labourers or self-employed unskilled workers. No variation in educational status was observed in the organized housing category whereas in Slum residents had on average up to 8 years of schooling. A significant number of HIG and Slum residents obtain water from multiple sources: the HIG group typically used groundwater from tube-wells to augment the piped supply from DJB whereas for Slum dwellers, the major sources were tankers, private groundwater from privately owned tube-wells, and community taps. The organized housing category used alternative sources only when the supply from DJB was disrupted. Some households also used bottled water for drinking and cooking.

Table P: Socio-economic and demographic profile of sampled population.

Variable	Housing category			
	HIG	MIG	LIG	Slum dwellers
Sample size	122	146	112	116
Household profile				
Mean family size (σ)	4.12 (1.56)	4.06 (1.24)	4.25 (1.16)	4.64 (1.48)
Adult members in family (%) (rounded median value)	54	61	58	49
Family members contributing to household income (%) (rounded median value)	42	53	48	47
Age of family members (%) (rounded median value)				
< 18 years	46	39	42	51
> 50 years	26	31	29	16
Occupation of main earning member of the family (%) (rounded median value)				
Salaried employment	66	71	74	49
Executive, senior level	22	23	23	Nil
Executive, middle level	19	17	18	Nil
Executive, junior level	18	19	21	2
Clerical	7	12	12	18
Labour	nil	nil	nil	29
Business	*34*	*29*	*26*	*51*
Self-employed skilled worker	18	17	13	6
Self-employed unskilled worker	Nil	1	5	42
Trader or shop owner	12	8	5	3
Industry	4	3	3	nil
Source of water (%)				
Multiple sources	82	51	23	85
Piped water	100	100	100	9
Groundwater from tube-wells	21	12	4	29
Tankers	nil	nil	8	36
Bottled water	11	14	12	12
Community tap	nil	nil	3	24

Table Q shows the frequency of, and time spent on, various water-consuming activities, namely bathing, storing water for drinking and for cooking, washing the dishes, washing clothes, toilet flushing, cleaning the house, and minor activities (grouped together under the heading ‘others’) such as watering plants and filling flower vases, brushing, shaving, hand washing, and vehicle cleaning. None of the household surveyed had a private garden. Those living in organized housing were similar in terms of the frequency and duration of the activities whereas in the case of Slum dwellers, the frequency was less and the duration was shorter. Activities under the *Others* category were all individual activities.

Table Q: Frequency (per week) and duration (min) of water-consuming activities.

	Water-consuming activity						
	Bathing	Storing for drinking and cooking	Washing dishes and pots and pans	Washing clothes (manually)	Toilet flushing	Cleaning the house	Others
HIG							
Frequency*	9	10	16	6	112	8	NA
Duration** (σ)	8 (2)	NA	36 (8)	82 (61)	NA	NA	NA
MIG							
Frequency*	7	10	14	9	106	7	NA
Duration** (σ)	7 (2)	NA	34 (19)	80 (60)	NA	NA	NA
LIG							
Frequency*	8	11	12	9	104	8	NA
Duration** (σ)	7 (2)	NA	33 (27)	84 (46)	NA	NA	NA
Slum dwellers							
Frequency*	7	7	10	7	72	5	NA
Duration** (σ)	6 (2)	NA	19 (7)	40 (26)	NA	NA	NA

*Median value, **Values rounded off, NA = not applicable

Table 3 shows the similarities and differences in different socio-economic segments in terms of devices and processes used in water-consuming activities. In most households, people fill a bucket with water for bathing and wash themselves down, using a mug to draw water from the bucket: showers and bath tubs are limited to some households in the HIG category, and even in these households, not all members of the household prefer to use them. Similarly, washing the dishes and pots and pans under a running tap is the preferred method; where piped supply is not available, mostly in Slums, utensils are cleaned by keeping them in standing water, in a bucket, and rinsing them a couple of times by filling the bucket with fresh water each time. This method is neither particularly hygienic nor safe.

Residents of organized housing use flush toilets whereas nearly 60% of the surveyed houses for Slum dwellers do not have a toilet at home: the residents either use shared or public toilets (mostly women) or defecate in the open (mostly men). Similarly, the use of washing machines is growing among the residents of organized housing: several models are used, semi-automatic machines, in which clothes have to be rinsed manually, being more common than fully automatic machines.

Table R: Devices and processes using in water-consuming activities (all numbers are percentages of the surveyed households)

Activity	HIG	MIG	LIG	Slum dwellers
Bathing				
Bucket and mug	84	88	93	100
Shower	13	11	7	Nil
Bath tub	3	1	Nil	Nil
Storing water for drinking and cooking				
Without domestic treatment	16	19	23	74
With domestic treatment				
Filtration only	4	3	12	Nil
Filtration + UV (ultraviolet light for disinfection)	3	34	38	9
Filtration + RO (reverse osmosis)	14	21	11	16
Filtration + RO + UV	63	23	16	1
Washing dishes and pots and pans				
Washing and rinsing in standing water, using buckets	Nil	Nil	Nil	27
Running water	97	100	100	73
Dish washer	3	Nil	Nil	Nil
Washing clothes				
Manual	4	23	24	100
Semi-automatic machine	38	46	45	Nil
Fully automatic machine	58	31	31	Nil
Toilet flushing*				
Bucket	Nil	Nil	Nil	87
Flush toilets	100	100	100	13

*percentage of houses with attached toilets

Respondents from organized housing complained about intermittent water supply and low pressure in the mains and did not consider the water to be of good quality or safe for drinking without treatment. To cope with intermittent water supply, water is stored in rooftop water tanks of capacities ranging from 250 L to 2000 L per household. To make up for the low pressure in the water distribution network, many households use booster pumps to draw water from the supply lines and lift it to fill the rooftop tanks. Approximately 83% of the households in organized housing and 8% households in Slums uses booster pumps of 0.5–1 hp capacity (short for horse power, 1 hp being approximately 0.75 kW) and run them for about 50 minutes a day (σ = 14 minutes). Households that use bore-wells as an additional source of water use 1 hp motors and run them for 10 minutes a day (averaged over a week). Nearly 80% of the respondents from organized housing and approximately 57% from Slums do not find the quality of DJB-supplied water to be reliable. To avoid risks to health due to poor-quality water, people use domestic water purifiers or use bottled water. Amongst the households that use domestic water-treatment systems, those based on reverse osmosis (RO) are more common in HIG and among Slum residents whereas filtration and disinfection using ultraviolet (UV) radiation is more common in MIG and LIG. Households that use RO are mostly those that use groundwater as an additional source of water.

Households in organized housing spent on average INR 355 (σ = INR 86) a month on water and EWS spent INR 213 (σ = INR 98). Approximately 93% respondents reported payments to DJB as the principal expense on water. In general, respondents did not perceive the money spent on measures to compensate for poor quality (domestic purifiers) and for inadequate supply (booster pumps, rooftop tanks, and bore-wells) as part of the cost of water.

Table S gives the water consumption – based on actual measurements – for various activities. Table 5 gives a breakdown of the same data by the category of housing. The average consumption was 75.9 lpcd in organized housing but only 45.2 lpcd in Slum dwellers. The average consumption in Delhi is 63.9 lcpd. These estimates do not account for water lost in leakages because this study aims to estimate the water required to meet basic needs. The largest share (approximately 32%) was claimed by bathing, followed, in that order by toilet flushing, washing dishes and pots and pans, and washing clothes.

Table S: Water consumption of different activities as actually measured. (Value in brackets is the standard deviation.)

Activity	Average water consumption (L)	Rated power of the appliance (W)	Duration of use of appliance (h)
Bathing			
Bucket and mug	24.6 (4.3)		
Shower	29.3 (7.4)		
Bath tub	38.7 (5.3)		
Storing water for drinking and cooking			
Without treatment	28.3 (5.9)		
With domestic treatment			
Filtration + UV	34.6 (4.9)	40	0.34 (0.06)
Filtration + RO	57.9 (8.4)	60 (80 with UV)	0.61 (0.13)
Washing dishes and pots and pans			
Washing and rinsing in standing water, using buckets	43.1 (5.4)		
Running water (per minute)	3.3 (0.24)		
Dish washer (one cycle)	45	320	1.1 (0.32)
Washing clothes			
Manually (per minute)	2.6 (0.13)		
Semi-automatic machine (one load of clothes)	54.6 (11.2)	230	1.13 (0.29)
Fully automatic machine (one load of clothes)	48.3 (5.8)	320	1.82 (0.38)
Toilet flushing (per flush)			
Bucket	7.4 (1.2)		
Flush toilets	5.5		

Table T: Average water consumption (litres per capita per day) for various activities, by category of housing. (Value in brackets is the standard deviation.)

Activity	Organized housing				Slum dwellers	Overall average
	HIG	MIG	LIG	Pooled data		
Bathing	28.1 (12.7)	24.2 (11.4)	23.6 (12.2)	24.9 (12.8)	14.3 (12.8)	19.6 (10.3)
Storing water for drinking and cooking	7.1 (3.6)	6.4 (3.4)	6.1 (3.4)	6.5 (3.3)	3.9 (2.9)	5.1 (3.8)
Washing dishes and pots and pans	10.1 (8.8)	11.3 (7.8)	11.9 (6.1)	11.4 (6.7)	6.7 (6.4)	10.1 (6.9)
Washing clothes	9.1 (6.9)	10.2 (5.9)	10.8 (6.8)	10.2 (6.4)	8.2 (7.6)	9.4 (6.7)
Toilet flushing	15.6 (9.4)	14.4 (8.3)	14.4 (8.4)	14.4 (8.6)	7.3 (6.7)	12.1 (7.4)
House cleaning	4.6 (3.2)	4.2 (3.1)	4.1 (3.2)	4.3 (3.9)	2.1 (1.9)	3.7 (1.9)
Others	4.1 (2.7)	4.2 (2.6)	4.2 (2.7)	4.2 (2.7)	2.7 (0.5)	3.9 (2.6)
Total	78.7 (21.7)	74.9 (18.2)	75.1 (19.9)	75.9 (14.7)	45.2 (26.1)	63.9 (14.1)

Within organized housing, water consumption among the three categories did not differ significantly (*p* value between HIG and MIG Mean = 0.063 and HIG and LIG Mean = 0.0927), an observation contrary to the conclusions of earlier studies, which found water consumption to be positively correlated to household income (Beal et al., 2013). Increasing use of appliances in all income categories is one likely explanation for this outcome. Water and energy consumption of various water-consuming activities and appliances as measured experimentally is shown in Fig. 1. Bathing by the bucket-and-mug method and using dishwashers and fully automatic washing machines can reduce water consumption; however, the machines consume more electricity. Domestic water purifiers, on the other hand, increase the consumption of both water and electricity, because people tend to discard the unused stored water of the previous day. However, the impact of domestic water purifiers on domestic household water consumption is not significant because such stored water for drinking and cooking accounts for less than 10% of the total household water consumption. The method of bathing could affect water consumption substantially, although not many respondents preferred the more water-intensive method.

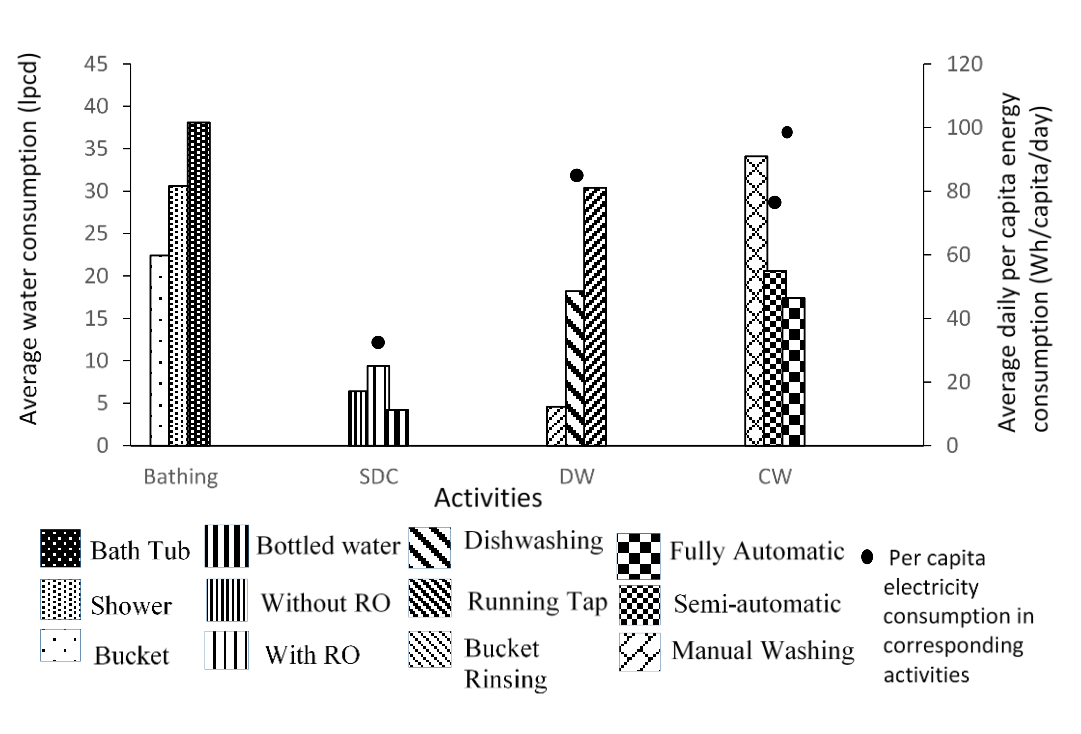

Fig 1. Impact of water-use behaviour on water and energy consumption.

Family size also influenced per-capita daily water consumption (Fig. 2): it was the lowest in single-occupancy houses; increased gradually with family size up to a family of four, and then decreased in larger families. The findings are again contrary to the earlier findings, which reported a steady and consistent decrease in per-capita consumption as family size increased, perhaps due to the economies of scale (Arbués et al., 2010). We found that low-occupancy homes mainly have working adults, who are away for many hours at a stretch during the day and also prefer to outsource many of the water-consuming activities such as laundry and cooking. Large families are more likely to use water-saving appliances, which accounts for the slight decrease in per-capita water consumption.

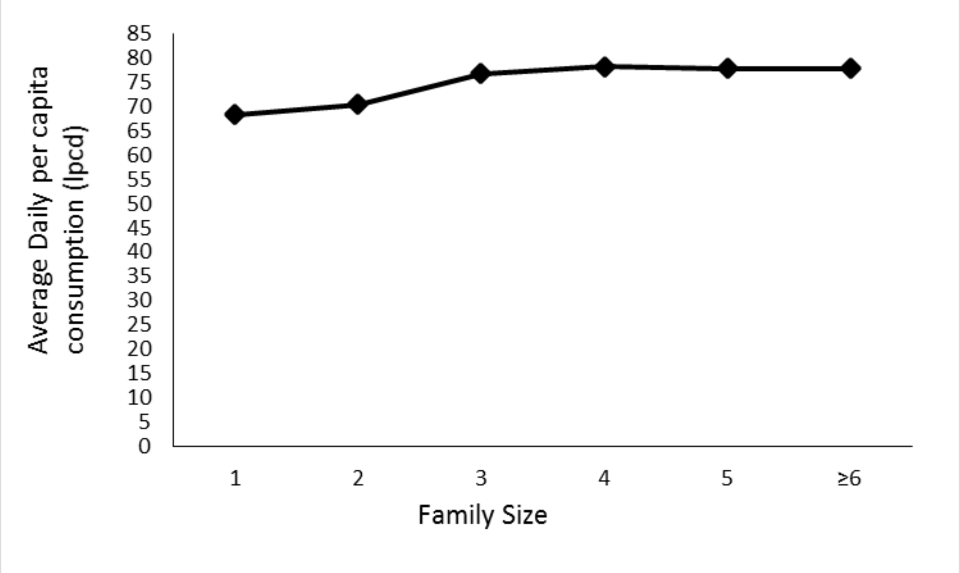

Fig 2. Relationship between family size and per-capita water consumption.

Water consumption of Slum dwellers was only 60% that of organized housing residents although many families in slums had children who were home most of the day. Yet, that lower per-capita water use is at the cost of sanitation and hygiene: washing up using stored water may consume less water but dishes washed under a running tap are cleaner; skipping a bath, washing clothes less often, and using non-flushing toilets, again, may save on water but are not hygienic practices. Slum households also showed wider variation in overall water consumption than those in organized housing because some Slum dwellers' households did have access to piped water and bore-wells.

Table 6 shows the electricity consumption of various water-consuming household activities. The average monthly electricity consumption per capita was 2.6 kWh and that of residents of organized housing alone was 3.25 kWh. A family of four living in organized housing consumed 10–16 kWh/month. More than 50% of this electricity was used in coping with low pressure in the water distribution network and in augmenting the inadequate supply by pumping groundwater from bore-wells. Using water purifiers to make up for the unreliable quality of water consumed about 15% of the total electricity spent on water-related activities, and remaining electricity consumption was for activities that have the potential to save water. The cost of coping with inadequate water supply and unreliable water quality was approximately INR 172 a month in organized housing: INR 60 on electricity and INR 112 on maintenance of domestic water purifiers and rooftop water tanks.

Table U: Daily per-capita water-related energy consumption (Wh) of households. (Value in brackets is standard deviation.)

Activity or device	Housing category				Overall average
	HIG	MIG	LIG	Slum dwellers	
Booster pumps and bore-wells	81 (49)	64 (45)	57 (52)	13 (11)	51 (39)
Washing clothes	31 (22)	25 (33)	14 (13)	Nil	23 (25)
Washing dishes and pots and pans	0.9 (0.5)	Nil	Nil	Nil	Negligible
Domestic water purifiers	19 (9)	16 (10)	16 (8)	6 (7)	13 (9)
Total	132 (37)	105 (37)	87 (37)	19 (10)	87 (31)

If one considers the behaviour of residents of organized housing as appropriate from the view of health, sanitation, and hygiene, the expected requirement would be 76 lpcd ($p = 0.042$); this value would be 78.3 lpcd ($p = 0.037$) if neither dishwashers nor washing machines are used and 77.9 lpcd ($p = 0.028$) if domestic water purifiers are done away with. Similarly, in the best-case scenario – all residents use dishwashers and washing machines, take baths using a bucket and a mug, and give up using domestic water purifiers – the basic water needs can be met with 70.6 lpcd ($p = 0.034$), although it also means that monthly per-capita electricity consumption increases by 4.28 kWh. Therefore, a family of four can save as much as 1 kL of water a month, although at the cost of increasing its electricity consumption by 1.75 kWh a month—which can be avoided if water supply is adequate, reliable, and safe, making it possible to do away with booster pumps, overhead tanks, bore-wells, and water purifiers.

Annexure IV: Thermal power plants of Delhi

Thermal power plants in Delhi are both coal and gas based. The managing authorities are Indraprastha Power Generation Company Limited (IPGCL), Pragati Power Corporation Limited (PPCL) and National Thermal Power Corporation (NTPC) Ltd. IPGCL and PPCL are managing four power plants in Delhi having a total installed generation capacity of 2106.2 MW (Derated)[HH]. NTPC manages Badarpur coal based plant.

Table V. Thermal power generated in Delhi

S. No	Name of power station	Fuel[1]	Units	Capacity (MW)[1]	Load factor (LF)* in % (**)[1]	Source of water[II]	Present status
1	Rajghat Power House	Coal	2	**135**	57.41 (65.82)	Yamuna	Working
2	Badarpur thermal power plant[JJ]	Coal	3+2	**705**	53.13[KK]	Agra Canal	Working
3	Gas Turbine Power Station (GTPS)	Gas+steam	6+3	**270**	44.93 (61.21)	Yamuna	Working
4	Pragati-I Power Station	Gas+steam	2+1	**330**	66.93 (69.93)	Treated water From Sen Nursing Home & Delhi Gate STPs	Working
5	Pragati-III Power Station, Bawana	Gas+steam	4+2	**1371.2**	14.61 (95.86)	Treated water From Rithala STP	Working
	Total	**840 (coal) + 1971.2 (Gas) = 2811.2 MW**					

*In the electricity industry, load factor is a measure of the output of a power plant compared to the maximum output it could produce. The availability factor of a power plant is the amount of time that it is able to produce electricity over a certain period, divided by the amount of the time in the period. **Figures in parenthesis relates to availability factor. NA=Not available

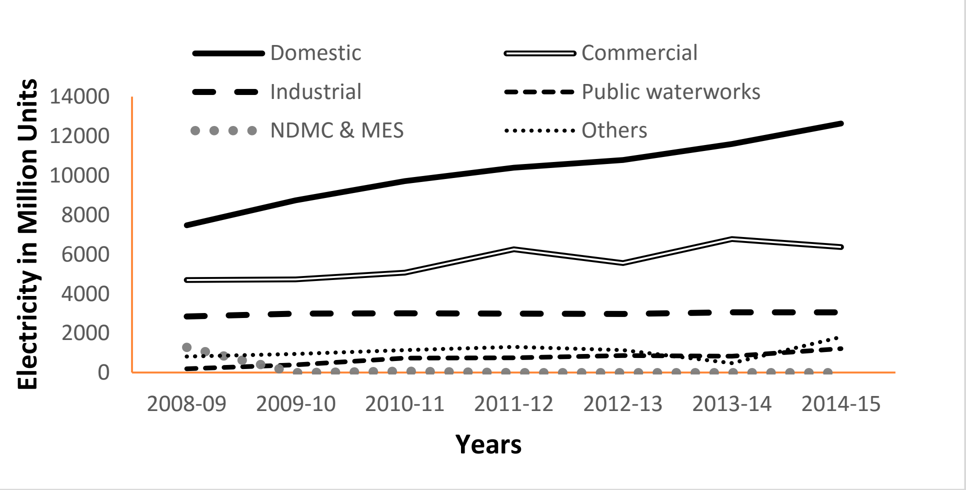

FIGURE 1. DISTRIBUTION OF ELECTRICITY IN DIFFERENT SECTORS IN DELHI[LL]

[HH] GNCTD, 2015a. Economic Survey of Delhi. Chapter 11 Energy. Directorate of Statistics and Planning. Govt. of Delhi. Delhi. http://www.delhi.gov.in/wps/wcm/connect/1c8dbf8048d8eb34a8dbf97a2b587979/ESD+2014-15+-+Ch-11.pdf?MOD=AJPERES&lmod=519247184&CACHEID=1c8dbf8048d8eb34a8dbf97a2b587979

[II] http://ipgcl-ppcl.gov.in/manuals/m-1.pdf

[JJ] http://www.ntpc.co.in/power-generation/coal-based-power-stations/badarpur

[KK] http://www.ntpc.co.in/en/power-generation/turnaround-capability

[LL] GNCTD, 2015b, Delhi Statistical Handbook, 2014-15. Directorate of Statistics and Planning. Govt. of Delhi. Delhi

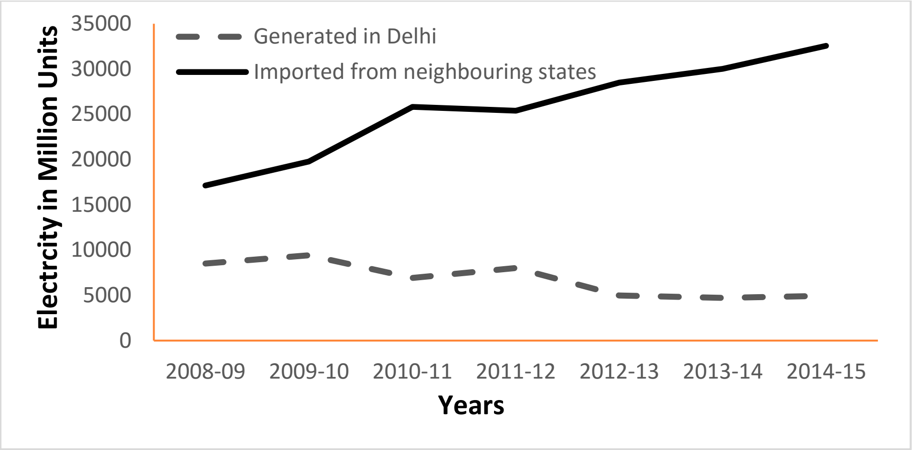

FIGURE 2. ELECTRICITY SUPPLY IN DELHI[5]

Water consumption by thermal power plants (TPPs)

Specific water consumption of TPPs varies in the range of 1.7 to 8.0 m^3/MW (Supplementary sheets I). More than 80% of input water is required for make up in cooling tower[MM]. Variation in water consumption is due to

- Difference in size, age and the type of the plant (either coal based or gas based)
- Type of water circulation (once through system or recycling of water)
- Ash handling (dry or wet)
- Provision for ash water recycling

Estimation of water consumption

Table W. Water requirement in TPPs of Delhi

Name of power station	Ash handling; cooling system	Estimated Energy production*	Estimated Water Requirement		Estimated Wastewater released	
		MWh/day	m^3/MW^	m^3/day	m^3/MW^^	m^3/day
Rajghat Power House	Wet ash disposal; wet cooling tower	1860.084	3	5580.252	0.363***	669.63024
Badarpur TPP	Wet ash disposal; wet cooling tower	8989.596	3	26968.788	0.363***	3236.25456
Gas Turbine Power Station (GTPS)	Wet cooling tower	2911.464	2	5822.928	NA, nearly 20%	-
Pragati-I Power Station	Wet cooling tower	5300.856	2	10601.712	NA, nearly 20%	-
Pragati-III Power Station, Bawana	Wet cooling tower	4807.975	2	9615.95	NA, nearly 20%	-
Total water consumption (m^3/day) = 58589.63 (32549=coal) + (26041=gas)						

[MM] CEA, 2012. Report on Minimisation of Water Requirement In Coal Based Thermal Power Stations. CEA, Delhi. http://cea.nic.in/reports/others/thermal/tetd/min_of%20water_coal_power.pdf

Total wastewater released (m^3/day)= 3905.9 (coal)

* Energy estimated (MWh/d)= (MW×LF)×24

* *Water requirement (m^3/day)= [(m^3/MW) × 24× (MW× LF)]

Wastewater released (m^3/day)= [(m^3/MW)×24× (MW× LF)]

^ As per Table Z of Supplementary sheets I

^^ As per Table AB of supplementary sheet I

NA- Not available

Table X. Weighted average specific emissions for fossil fuel-fired stations in FY 2011-12, in ton CO_2-e/MWh

	Coal	**Diesel**	**Gas**	**Lignite**	**Naptha**	**Oil**
NEWNE	1.06	1.07	0.45	1.42	0.38	0.65
South	1.00	0.58	0.43	1.43	0.72	0.62
All India	1.05	0.59	0.45	1.42	0.38	0.64

Source-CEC (CO_2 Baseline Database for Indian power sector, User Guide version 8.0, Jan 2013)

Table Y. CO_2 emission from thermal power plants in ton CO_2-e per day

Name of power station	**Estimated Carbon emission**
	ton CO_2-e/day
Rajghat Power House	1953.0882
Badarpur TPP	9439.0758
Gas Turbine Power Station (GTPS)	1310.1588
Pragati-I Power Station	2385.3852
Pragati-III Power Station, Bawana	2163.58875
Total emission (ton CO_2/day)= 17251.3 [11392.2 (coal) + 3137.7 (gas)]	

Emission factor coal based TPP=1.05 and Gas based TPP=0.45

Supplementary sheets I

Table Z. Water requirement in TPPs[6], [NN]:

Power plant type	**Range m^3/MW**
Gas based power plants	1.7-2.0
Total dry ash handling power plants	3.0-3.5
200 MW coal based thermal power plants with once trough system	3.0-3.5
200 MW coal based thermal power plants	4.5-5.0
500 MW coal based super thermal power plants	4.0-4.5
200 MW coal based power plants with ash water recycling	3.5-4.0
500 MW coal based super thermal power plants with ash water recycling	3.0-4.0
110 MW coal based old power plants	7.0-8.0

Water requirement and wastewater released from a typical thermal power plants

Table AA. Plant water requirement and wastewater released (m^3/h) for a typical 2x500 MW coal based thermal power plant[6].

SI No.	**Description**	**In-Land plants using Indigenous coal with**	
		Wet Cooling Tower	**Dry Cooling System**
A	**Plant Input Water**		
1	Cooling water make up		
	a) Evaporation	2040	138

[NN] FICCI, 2010. Water Use and Efficiency in Thermal Power Plants. FICCI and HSBC Knowledge Initiative, Federation House, New Delhi http://www.ficci.com/spdocument/20147/ficci-Water-use.pdf

	b) Drift	60	6
	c) Blow down	450	30
	Sub- total	2550	174
2	Bottom Ash handling system make-up	90*	90**
3	De-Mineralised (DM) plant input	85	85
4	Service Water	200	200
5	Potable water system input	52	52
6	#Reservoir Evaporation	30	5
7	Side Stream filter back wash (considered as a part of Cooling Tower (CT) blow down)	30	2
8	Clarifier sludge	90	15
9	Sludge water recovery	(-)83	(-)14
10	Filter backwash water recycled	(-)5	(-)5
11	Boiler blow down used as CT make up	(-)20	-
12	Plant water Input (1+3+4+5+6+8-9-10-11)	2899	512
	Say	***3000***	***550***
B	**Plant Waste water**		
1	Unused CT blow down	350	-
2	DM & Condensate Polishing (CP) plant regeneration	10	10
3	Treated Effluents of Plant drains etc.	53	26
4	Treated Effluent from fuel oil area	5	5
5	Waste water utilized for coal dust suppression/ ash disposal	(-)50 (coal dust suppression)	(-)22 (ash disposal)
6	Waste water utilized for gardening	(-)5	(-)5
7	***Waste water to be disposed from Central monitoring basin (CMB) (1+2+3+4-5-6)***	***363***	***14***

* 70 m3 /h to be met from Cooling Tower (CT) blow down and 20 m3 /h available as seal water for Ash handling pump (AHP) pumps.

** to be met as 28m3 /h from CT blow down, 20 m3 /h as seal water for AHP pumps, 20m3 /h as boiler blow down and 22 m3 /h from CMB.

for reservoir surface area corresponding to 10 days plant requirement with water depth as 8 m.

Table AB. The water and wastewater requirement in m^3/h for typical 2x500 MW plant[6]

Description	**In land plant using indigenous coal m^3/h per MW**	
	Plant with wet cooling tower	Plant with dry cooling tower
Water requirement for first year of plant operation	3600 (3.6)	750 (0.75)
Water required for subsequent period	3000 (3.0)	550 (0.55)
Wastewater released	*363 (0.3)*	*14 (0.014)*

Specific water consumption from some case studies (Thermal power plants (TPPs) in India[7, oo]

1. **Coal based**

TATA Power Company Limited- Coal based	
Location	Jojobera, Jamshedpur
Capacity	547.5 MW (1×67.5 MW+4×120 MW)
Specific Water consumption	2.78 m^3/MW
Water conservation	Reuse in ash handling and blow down

(The amount of water used is 1,520 tonnes/hr, which is equal to 1520 m^3/hr. For calculating specific water consumption 1520 is divided by 547.5 MW)

[oo] http://indianpowersector.com/home/power-station/thermal-power-plant/

NTPC Limited- Coal based	
Location	Vindhyachal Super Thermal Power Station (VSTPS) is situated in Singrauli district of Madhya Pradesh
Capacity	3260 MW (6×210, 4×500)
Specific Water consumption (Ash handling+cooling tower + DM water + Drinking water +Fire fighting+ Others)	4.80 m^3/MW
Water conservation	Ash water recycling

(Specific water consumption has directly been mentioned in this case study)

2. Gas based

Essar Power Limited- Multi fuel based (natural gas and naptha)	
Location	Hazira in Surat district of Gujarat
Capacity	515 MW
Specific Water consumption	0.86 m^3/MW
Water conservation	85 per cent of total wastewater is being recycled and reused

(Total raw water intake to the power plant is given as 38.6 lacs m^3/annum. For calculating specific water consumption it was divided by 365x24 hrs, and then by 515 MW.)

NTPC Ltd. - Gas based	
Location	Bharuch district of Gujarat
Capacity	657 MW
Specific Water consumption (Cooling tower+ make up water +DM water)	62.66 m^3/MW
Water conservation	ETP+STP+DM water regeneration plant

(As per the report the volume of water used in the cooling tower is 40,000 m^3/hr, the makeup rate is 1,000 m^3/hr (the plant has a COC value of 4). DM water requirement for water injection amounts to 165 m^3/hr. Thus total water requirement comes out to be 41165 m^3/hr. For calculating specific water consumption 41165 is divided by 657.)

Annexure V: Chemicals data in water and waste water sectors

Table AC: Chemicals used in drinking water and waste water treatment processes

	Chlorine	Alum	Polyaluminum chloride	Quick lime	Hydrated lime	Hydrogen Peroxide	Activated Carbon	Concentrated sulfuric acid	Sodium hypochlorite (12.0%)	Caustic soda (NaOH)	Polymer (For WWT)
Bangkok	✓	✓	✓	✓	✓	✓	✓				✓
New Delhi	✓	✓	✓								
Tokyo	✓	✓			✓		✓	✓	✓	✓	
Kathmandu											

Table AD: Emission factors of different chemicals

	Chlorine	Alum	Polyaluminum chloride	Quick lime	Hydrated lime	Hydrogen Peroxide	Activated Carbon	Concentrated sulfuric acid	Sodium hypochlorite (12.0%)	Caustic soda (NaOH)	Polymer (For WWT)
Emission Factor (kg CO2/ kg)	0.885	0.248	1.182	1.64	1.64	2.33	8.5	0.078	0.885	0.838	13.54
Reference	ASTE (2013), Q. H. Zhang et al. 2010										

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