Sherin S. Das
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A.V. Krishnan
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A Case Study of Select Thermal Power Plants in Water-Stressed Regions in India

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Executive Summary

An integrated approach to Sustainable Development Goals (SDGs) 6 and 7 is helpful to maximize the benefits of water and sanitation projects while reducing the environmental impacts of inefficient water usage, specifically in coal-fired Thermal Power Plants (TPPs) that are the largest users of water in the industrial sector. This is particularly important in most developing countries that face declining water availability due to a growing population without commensurate increases in water use efficiency. The case for an integrated approach towards realizing multiple targets under SDG 6 and SDG 7 in India is particularly strong since India is the third largest electricity generator in the World, with TPPs generating more than 78 percent of the 1715 TWh of electricity generation. This study explores the water-energy-sanitation (WES) nexus paradigm to reduce freshwater consumption in TPPs located in the proximity of urban areas by using treated sewage water from sewage treatment plants (STPs).

This report summarises the results of a field study to assess the water demand and availability in two water-stressed districts of India. This study applies an integrated approach to SDG 6 and SDG 7 to increase water efficiency, improve sanitation, and reduce the loss of power generation due to water shortages. In view of the above, suitable best fit estimates for the make-up water requirement have been derived for TPPs with installed capacities in the range of 210 – 600 MW using the recent operational data. The estimated make-up water volumes thus obtained were further used for evaluating the Specific Water Consumption (SWC) for the respective TPPs based on the different Plant Load Factors (PLF). Such an approach facilitates rapid assessment of the water consumption and would help in devising suitable strategies to optimise water use efficiency.

Chapter 1

Introduction

1.1 Background

The Sustainable Development Goal (SDG) 6, articulated by United Nations General Assembly (UN-GA) in 2015, emphasizes the need for '*Clean Water and Sanitation*' to ensure the sustainable management of water and sanitation for all [1]. Increasing water demand in urban areas calls for innovative approaches towards sustainable resource utilization, such as reclamation of municipal wastewater following multiple stages of treatment [2]. Efficient water resource management through the reuse of municipal sewage water (especially in industries) will enhance availability of drinking water for residential consumption, leading to mitigation of water supply deficit in cities (SDG target 6.4). Unfortunately, only about 56% of domestic wastewater is treated in the world (SDG Indicator 6.3.1), and this number is further lower (~27%) for India. Though 27 percent of domestic wastewater in India is safely treated, the value addition from the use of water in India is estimated to be only \$3 (approximately, Rs. 240) per m^3 which is less than one-sixth of the global average of \$19 (approximately, Rs. 1500) per m^3 [3].

In 2021, India was the third largest electricity generator in the World behind USA (4406 TWh) and China (8534 TWh) generating 1715 TWh [4]. While India generated 1338 TWh of electricity from fossil fuels (largely coal), USA and China generated 2692 TWh and 5624 TWh from fossil fuels, respectively [4]. The dependence on coal for electricity generation is likely to continue for another 30 years in India since TPPs generate more than 72% of the total electricity generated by utilities in India today, while India lacks the raw materials required for grid-scale battery-energy-storage necessary to integrate much larger amounts of Variable Renewable Electricity (VRE) generation into the power grid.

Since the dependence on TPPs to produce affordable and reliable electricity (SDG 7) will continue in India, the pressure on water sources will only increase unless alternative sources of cooling (e.g., air cooling) and/or other water sources are exploited to reduce the demand of fresh water. Therefore, one major intervention in the water starved areas involves the progressive exploration and securing of alternate and low-cost sources of water for power generation.

Treated municipal wastewater will be an alternate source for TPPs which can then release an equivalent volume of fresh water (currently drawn from shared freshwater resources) for city dwellers (SDG 6). Evidently, such an integrated intervention framework weaves multiple SDG targets together, which is also synergistic with the idea of 'indivisibility of the SDGs' [5]. In the post-COVID World impacted by several economic uncertainties at this time, the only way to realize the SDGs is to pursue them in an integrated manner, rather than in isolation [6], [7].

In order to demonstrate the practicability of such an integrated approach, the present study is focussed on the water-stressed cities of Raichur and Ballari in the State of Karnataka. Raichur and Ballari districts have a combined population of 4.3 million as per the last census conducted in 2011 [8], [9]. These districts receive an average annual rainfall of 400 mm to 700 mm whereas the annual Evapotranspiration (ET) rate varies between 180 and 1900 mm in these districts [10]. While more than 85-90 % of water in these districts is used for agriculture, large industries also consume 7-10 % of water in these districts [11]. The residents of these districts are facing a scarcity of potable water for several years [12], [13]. In rural areas, less than 64% and 47% of the households in Raichur and Ballari districts has functional tap water connections [14]. The situation is not much different in urban areas since the inhabitants of Raichur and Ballari cities receive water once in two or three days (@100 litres per capita per day (lpcd)), which is much lower than the norm of 135 lpcd mandated by the Ministry of Housing and Urban Affairs (MoHUA) for urban domestic consumption [15], [16]. Even though domestic water supply infrastructures are in place, high distribution losses (system losses), and seasonal variability of water sources tend to limit the water availability at the consumer end. Moreover, both the cities are in the vicinity of industrial clusters and thermal power plants which need water in large quantities for their daily operations.

The study area houses a total of four coal-based thermal power stations. These are Raichur Thermal Power Station (RTPS), Yeramarus Thermal Power Station (YTPS), Ballari Thermal Power Station (BTPS) and JSW Energy Limited (JSWEL, captive power plant) with nameplate capacities of 1720 MW, 1600 MW, 1700 MW and 860 MW, respectively. Except for JSWEL, the specific freshwater consumption (SWC) levels in these TPPs are substantially higher than the stipulated value of 3.5 m^3/MWh [17]–[20].

The National Tariff Policy 2016, stipulated by Ministry of Power (MoP), mandates all coal-fired Thermal Power Plants (TPPs) located within a 50 km radius of the Sewage Treatment Plants (STPs) belonging to local bodies, municipal corporations, or similar organisations to use STP-treated wastewater. The policy allows the cost incurred due to the additional arrangements to be passed on to the electricity tariff [21]. Further in 2017, India's Central Electricity Authority (CEA) had urged the TPS to enter into suitable agreements with local municipal bodies for using treated sewage water from their STPs located in the vicinity [22]. In 2018, MOEFCC issued guidelines for the grant of Environmental Clearance (EC) for new TPPs or for the expansion of existing TPP stating that, the TPPs must use the treated sewage water from STPs located within a 50 km radius of the TPP. [23].

Various government policies like National Water Policy, 2012; AMRUT Mission (2015-2023), Jal Jeevan Mission, 2019 give importance to drinking water and sanitation [24]. The Atal Mission for Rejuvenation and Urban Transformation 2.0 (AMRUT 2.0), launched on October 1 in 2021 for a period of 5 years, aims to provide universal coverage of water supply in all statutory towns through functional tap to all households and sewerage management in 500 cities. In Karnataka, 27 cities are eligible under AMRUT scheme, which includes Raichur and Ballari. A sum of $717.82 million has been allocated to Karnataka to implement the AMRUT scheme [25]. Moreover, the water policy document of GoK

(2019) particularly emphasizes the importance of integrated management of surface, ground, and wastewater [26].

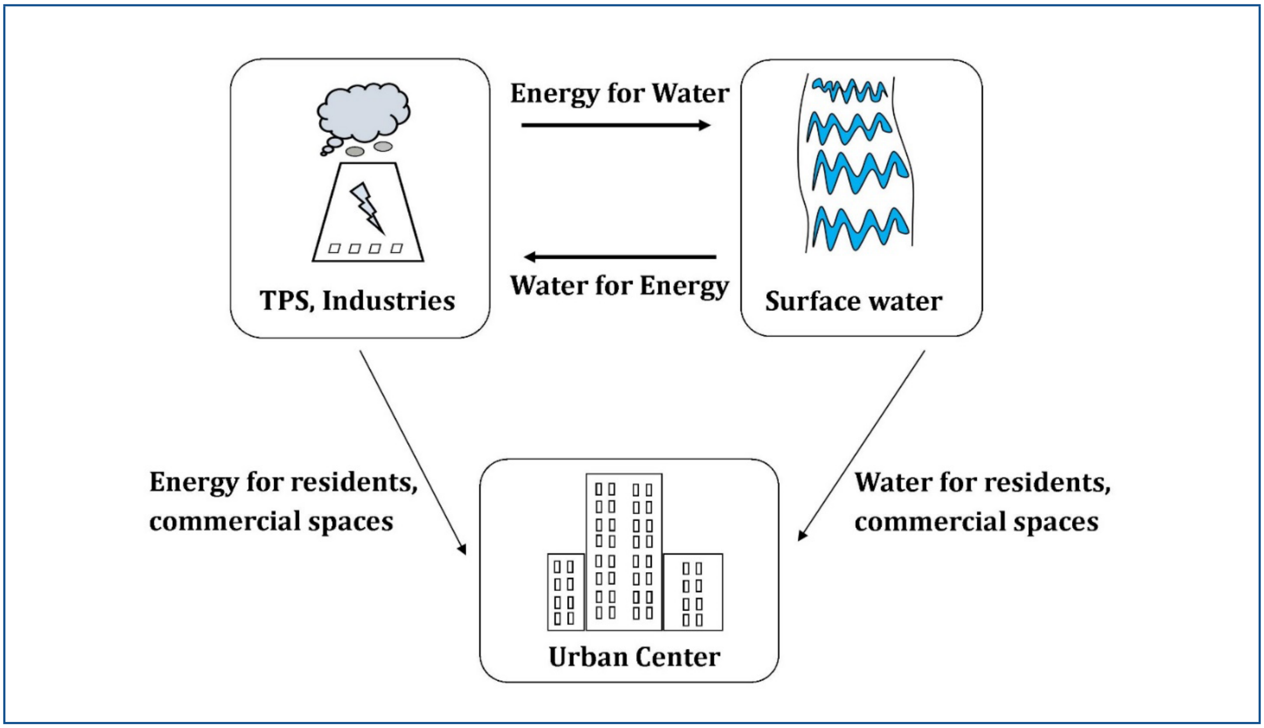
1.2 Urban Water-Energy Nexus – The Conceptual Framework

The '*urban water-energy nexus*' is an evolving conceptual framework that provides a way to look into the intricate connections between the water security, energy transition, and urbanization. The concept of Water-Energy nexus traces back to the World Economic Forum of 2008, where the challenges to economic growth were viewed from a water-energy nexus perspective [27].

A simplified schematic representation of these complex interactions is depicted in the **Figure 1**. The water-energy nexus is being used as a generic template to analyse the problems arising out of water scarcity in urban areas. Some studies are focussed on defining the 'water-energy nexus' [28], [29] whilst a few other studies consider it as a methodology to analyse and understand the coupling between the various associated elements, e.g., water, energy, and food [30], [31]. The pivotal consideration in all of these studies has been the scarcity of water from the resource point of view.

The energy sector withdraws about 30 billion cubic meters (BCM) of water annually, of which about 6 BCM (i.e., 20%) is non-reclaimable [32]. More often, these sources also cater to the irrigation and domestic needs of local communities. Increasing demand for thermal power will naturally lead to an increase in the demand for freshwater. Therefore, excessive drawal of water by TPPs will reduce the water availability for other end-users [32].

Figure 1: Schematic of Urban Water-Energy Nexus



Similarly, energy is needed at every stage of the water supply chain (from point of harnessing to the point of consumption) irrespective of the nature of end-use. Distribution of drinking water in the cities, lift irrigation, groundwater extraction, pumping for irrigation, and various processes associated with wastewater treatment requires energy, mainly in the form of electricity [33]. In India, groundwater extraction accounts about 60% of electricity consumed by the water sector, and the country is the largest consumer of groundwater, constituting around 40% of global groundwater use [32], [33]. The share of agriculture in the electricity consumption is higher than the national average of 20% in most of the arid, semi-arid regions of India like the Ballari and Raichur districts [34].

1.3 Thermal Power Plants and the Impact of Water shortage on the Electricity Generation

Globally, one-third of all conventional power plants (coal, natural gas, oil, and nuclear) are located in highly water-stressed areas where the availability of freshwater is dependent on seasonal rainfall [35]. Many power plants across the world have faced the brunt of water scarcity in the last couple of decades leading to partial or complete shutdowns. For instance, between 2003 and 2006, France reduced electricity production in its river-based nuclear power plants [36]. Similarly, in 2007, when south-eastern parts of US experienced droughts, many thermal power plants in the area as well as the Browns Ferry nuclear power plant (3.8 GW) located on Tennessee river had to curtail their power production [37]. Further, between 2006 and 2012, around 26 nuclear and coal power plants opted for partial shut downs owing to low water availability [36], [38]. The reduction in power generation increases the financial burden on the power generating companies (GENCOs), and leads to tariff hikes for electricity consumers due to increase in the cost of generation of the same TPP or due to the replacement of electricity supplies from a lower-cost TPP with a higher cost source at a higher tariff when the cheaper TPP is shut down [39], [40].

In India, coal-fired thermal power plants (TPPs) with a combined installed generation capacity of 205 GW account for 51% of total installed capacity from all the power generation sources in the country as of 31 March 2022. As per CEA reports (2015 – 2018), water shortages account for about 0.2% to 2% of the total generation losses due to the outages in various thermal power stations in India. During this period, the estimated total loss of power generation that can be directly attributed to the water shortages is estimated to be 13,089 GWh. Between 2013 and 2016, the estimated revenue loss due to TPP shutdowns caused by water shortages was about \$1.4 billion (Rs. 112 billion). In 2016 alone, 18 thermal power plants located in the water parched regions in India underwent complete or partial shutdowns for several days, leading to a cumulative generation loss of 14 TWh [41], [42].

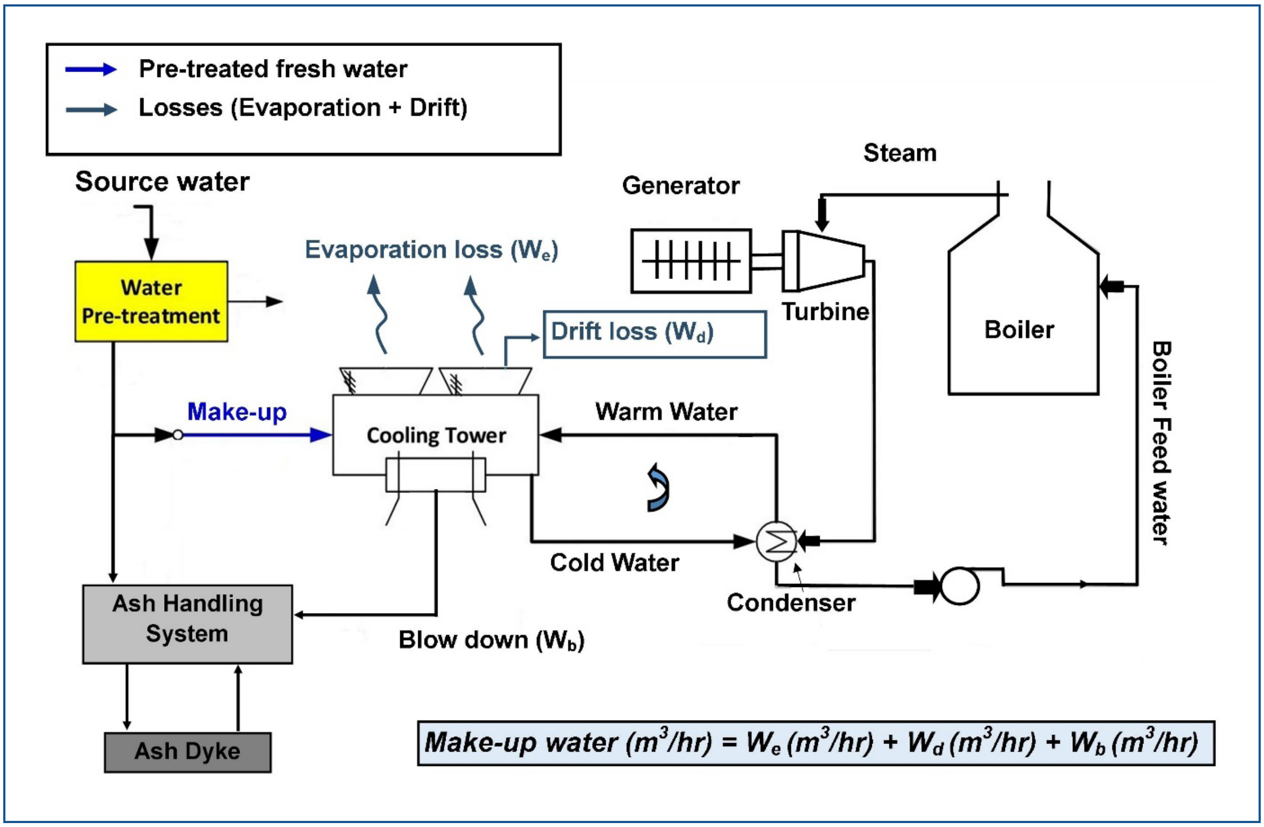
Raichur TPS and Ballari TPS located in the study areas also faced challenges in terms of water availability. Raichur TPS (1720 MW) was partially shut down for 60 days in 2016. During FY 2017-18, Ballari TPS (1700 MW) opted for partial shut downs for 98 days owing to water scarcity [42], [43].

Water scarcity and related shutdowns are expected to increase in coming decades with changing climatic patterns though this is subject to regional variability [36], [39]. While coal powers more than 35% of total electricity generation worldwide, India's dependence on coal (72%) is much higher [44]. Hence, there is an urgent necessity to ensure reliable TPP operations while ensuring the sustainability of the thermal power sector. In view of this, the reliability of water supply can be increased by diversifying the supply sources including the use of non-conventional sources of water, especially treated municipal wastewater [45].

1.4 Water Requirements and Water Characteristics in TPPs

The interdependency between water and energy is always a topic of discussion in both the sectors. All thermal power plants consume a large quantity of water for several processes like steam cycle, ash handling, flue gas desulfurization systems, cooling, fire-fighting systems, etc. But the major water requirement in the thermal power stations is attributed to the cooling activities. Since India is the second largest thermal power generator in the World (after China), the huge consumption of water for electricity generation is a major concern in terms of resource adequacy. While the consumption of fresh water for TPSs is not monitored regularly at the central level for all the TPSs, the Ministry of Power tracks the water consumption for NTPC & DVC power projects [46]. The daily consumption of water during 2017-18 in NTPC-operated TPPs is reported to be about 15.37 lakh kilolitres (1.5 Mm^3) and that of DVC-operated TPPs is around 3 lakh kilolitres (0.3 Mm^3) [46]. While NTPC owns 25% of the

Figure 2: Water flow diagram of TPS [47]



thermal power installed capacity in the country, about 4% of the country's total thermal power generation capacity is owned by DVC.

Water is made available to the TPSs by connecting to the nearest water bodies. It may be a canal stemming from a reservoir, a natural stream of water such as rivers and tributaries, a large lake, or even the sea (for the coastal TPPs). The water is drawn from the source water body and sent to the '*Raw water pond*' located within the TPS premises. Thereafter, the raw water is treated to remove the impurities, sludge, salts etc. Finally, the purified water is converted into high pressure and high temperature steam which rotates the turbine. Since the generator is coupled to the same shaft as that of turbine, the generator also rotates, and the electricity is produced. A pictorial depiction of water flow circuit inside a typical thermal power plant with induced draft cooling tower (IDCT) is shown in **Figure 2.**

1.4.1 Norms for Water Consumption in TPPs

The Ministry of Environment, Forest and Climate Change (MoEF&CC) in the Government of India (GOI) notified the norms for water consumption for thermal power plants on 7th December 2015. The norms for newer plants installed after 01 January 2017 were amended later vide notification dated 28.06.2018. The extant norms are as below [48], [49]

i. All plants with once through cooling (OTC) shall install cooling tower (CT) and achieve specific water consumption of 3.5 m^3/MWh within 2 years of notification dated 07.12.2015.

ii. All existing cooling tower -based plants shall reduce specific water consumption up to maximum of 3.5 m^3/MWh within a period of 2 years of Notification.

iii. New plants installed after 1st January 2017 shall have to meet specific water consumption of 3.0 m^3/MWh and achieve zero water discharge.

The aforesaid limit for water consumption shall not be applicable for thermal power plants using sea water.

The water usage or consumption in different systems of a typical 2 x 500 MW Thermal Power Station is shown below in **Table 1**.

Table 1: Total water distribution in TPS [50]

Sl. No.	Water usage area	Quantity (m^3/h)
1	Cooling towers (make-up water)	3450
2	Ash disposal	1300
3	DM water make up	120
4	Potable & service water	250
5	Clarifier sludge etc.	110
6	Coal dust suppression	70
	Total	**4000**

1.4.2 Water Characteristics

Demineralized (DM) water is used as make-up water in the boiler and its desirable characteristics include specific values or ranges for key physico-chemical parameters such as pH (7.5 – 9.6), conductivity (1 µS/cm), dissolved oxygen (0.04 mg/l), alkalinity (carbonate free), hardness (0.3 mg/l), silica (0.5 mg/l). Further, it should be free of oil and grease to be used as boiler feed water [51].

The cooling water used in the water circulation system must not have a conductivity exceeding 80 µS/cm, while the maximum limits of chloride and sulphate concentration, and methyl orange alkalinity are 200 mg/l and 100 mg/l, respectively. The total hardness, dissolved Fe content, dissolved Cu content, ammonia concentration, and residual chlorine must not exceed, 200 mg/l, 1 mg/l, 0.3 mg/l, 0.1 mg/l, and 0.3 mg/l, respectively to minimize corrosion and deterioration in the heat exchanger performance. The pH should be in the range 6.2-8.2 and cooling water should be free of sulphide [52].

Chapter 2

Objectives and Research Methodology

The main objective of the present study is to analyse the Water-Energy nexus in the study area to develop a model for similar studies in TPPs and adjacent towns located in other areas in India. This will serve as a guideline to develop and implement an integrated approach to SDG 6 and SDG 7 in the cities and TPPs located in various water-deficit regions of the country.

2.1 Population Projections

Population projections provide trends regarding the future population based on a particular set of assumptions. Apart from predicting the population, projection methods are widely used for planning and decision-making purposes [53]–[55]. For instance, the state of Texas in the USA uses population projections to develop rolling, long-term water plans from 1961 for a 50-year period [53].

In this study, the decadal population data (1981 to 2011) of the cities are retrieved from Raichur District census handbooks [8], [56]–[59] and Ballari District census handbooks [9], [60]–[62], respectively. We have used the Incremental Increase Method (IIM), a modified version of *linear extrapolation method*, or otherwise called *Arithmetic Increase method* [63], to obtain realistic population projections. The IIM considers both average decadal numeric change and the increase in decadal numeric change across the decades of interest, which gives a self-balancing effect to the population growth. If the increment in decadal change is positive, a steeper growth is witnessed. On the other hand, a negative increment in decadal change leads to a less steep profile in the projected growth trajectory [56], [63]. The mathematical formulation pertinent to the *IIM is* provided in **Equation 1**.

$$P_n = P_b + n.ADNC + \left\{\frac{n(n+1)}{2}\right\} I.D.C. \qquad (1)$$

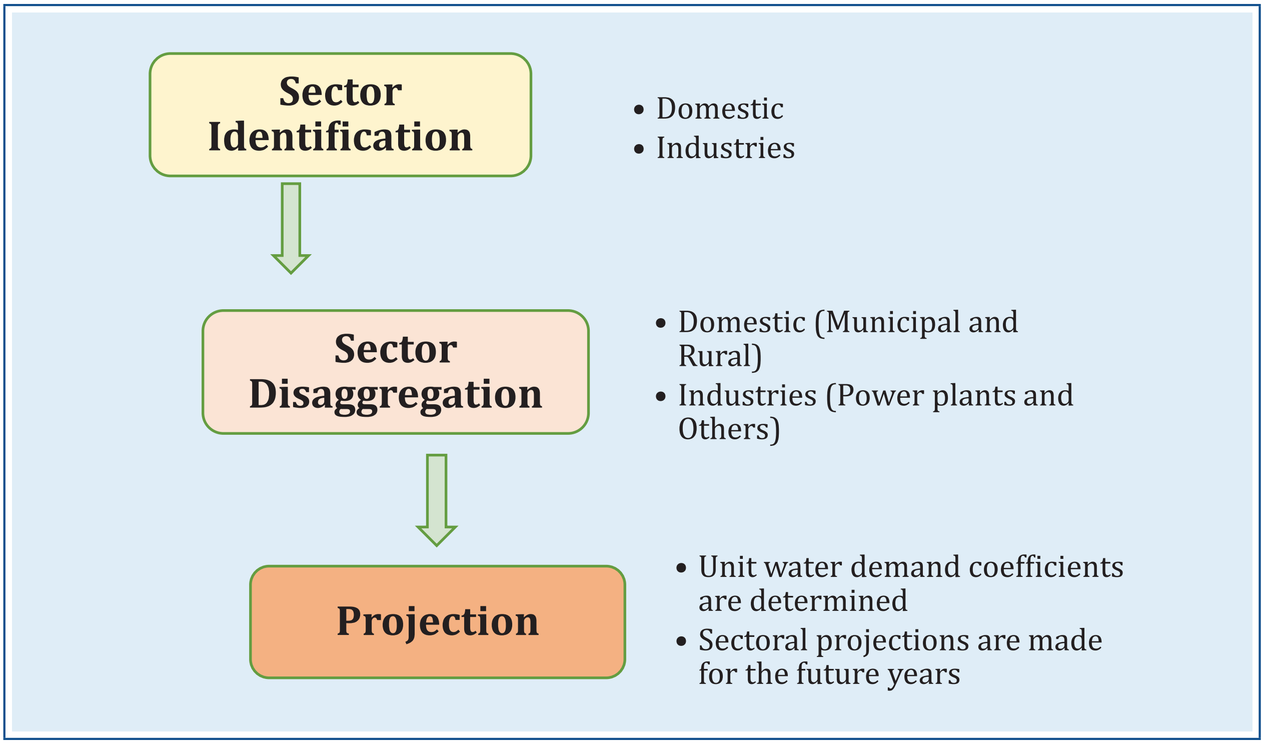
Where, *ADNC* denotes average decadal numeric change, denotes increment in decadal change, and 'n' symbolizes the number of decades counted from the base year. P_b corresponds to the base year population.

2.2 Water demand Analysis

The water demand is projected for the two identified major segments, domestic (municipal), and industrial (thermal power stations and industrial growth centre). For projections of domestic water demand, the general convention is to choose low or medium variant population projections. This is because an 'Upper bound demand estimate' would lead to significant overestimation of the capital costs, which will finally be passed on to the customers through increases in tariff if the costs are not completely borne by the Government [64].

The method used for water demand analysis is known as **'per unit demand analysis'** [54],

Figure 3: Methodological framework for water demand analysis



[55], [64]. The water requirement at a particular time in future is obtained by multiplying the mandated minimum water requirement (in lpcd) with the projected population associated with that timeline. Per unit demand analysis is used for demand projection in the different segments using '***unit water demand coefficients***' determined in terms quantity of water required per person / per unit of sectorial output (industrial or agricultural) [55], [64]. **Figure 3** depicts a schematic representation of the adopted methodological framework. The unit water demand analysis involves customer disaggregation into categories such as domestic, commercial, industrial, and public-sector uses to facilitate sectoral forecasting [54], [64]. The key limitation of this methodology lies in the fact that it does not account for possible future changes in unit water consumption due to socio-economic attributes such as evolving water tariffs, household income, etc. [54], or due to technological developments.

Chapter 3

Estimation of Make-up Water Requirement for Subcritical TPPs

3.1 Background

From the foregoing discussions, it is evident that the water consumption is a pivotal performance metric for the TPPs. The subcritical boiler technology consumes substantially higher amount of water as against the supercritical (SC) and ultra-supercritical (SC) technologies for the generation of same amount of electrical power [65]. Since a large fleet of subcritical TPPs are still operational in India, and TPPs with nameplate capacities in the range of 250- 600 MW will continue to operate in the near-to-medium term future [66], there is an urgent need to evaluate the make-up water requirement for the TPPs equipped with subcritical technology (unit -level generation capacities ranging between 210 and 600 MW).

The water used in the cooling towers for extracting the heat are subjected to the evaporative as well as drift losses. Since the evaporation of pure water leaves behind the dissolved solids in the system water, Total Dissolved Solids (TDS) increase over time as the tower operates. The ratio of the concentration of total dissolved solids (TDS) in cooling tower water at a particular instant to that in the fresh makeup water is defined as Cycles of Concentration (CoC) [67], [68]. The CoC value indicates how often freshwater needs to be added into the loop, since a higher CoC value ensures that the circulating water can be used or pumped around for a larger number of cycles before it is blown down or bled off from the cooling tower.

The manufacturers of cooling towers typically provide limiting and recommended values for the critical water parameters, such as conductivity, TDS, pH, which are often intricately linked. Therefore, water treatment is always necessary for the uptaken freshwater before it can be used as the make-up water for the TPP cooling towers.

While make-up water requirement in a TPP can be reduced by increasing the Cycles of Concentration (CoC) value, there is a limit to increase the CoC value based on the limiting values of the physico-chemical parameters of the circulating water, which in turn is dictated by the performance of the water treatment facility.

For the subcritical TPPs with improved technology (250-600 MW units) the water facilities are better, therefore realizing higher CoC values may not be very difficult. However, for 210 MW units that may continue to run with extension-of-life interventions and necessary R&M activities, the water treatment facilities need to be upgraded to ensure effective and optimal utilization of freshwater in the cooling towers.

3.2 Mathematical Formulation for Make-up Water Estimation

Traditionally, the make-up water requirement for a TPP cooling tower is estimated as the sum of evaporative loss, drift loss and the blowdown quantity. Mathematically, the relationship can be expressed as below [67], [68]:

$$W_m = W_e + W_d + W_b \qquad (2),$$

Where, W_m denotes the make-up water, W_e indicates the evaporative loss, W_d denotes the drift loss, and W_b denotes the blowdown quantity. All the terms in **Eq. 2** assume consistent unit of m^3/h. The evaporative loss can be estimated using the following mathematical formulation [67], [68]

$$W_e = 0.00085\, W_c(T_1 - T_2) \qquad (3),$$

Where, W_c is the circulating water flow (in m^3/h). The symbols T_1 and T_2 denote the water temperatures at the inlet and the outlet of the cooling tower, respectively.

The drift loss can be estimated as below [67], [68]:

$$W_d = 0.0002 W_c \qquad (4).$$

The Cycles of Concentration (CoC) can be evaluated using the following expression [67],

$$CoC = \frac{W_e + W_d + W_b}{W_d + W_b} \qquad (5).$$

Therefore, the blowdown quantity can be expressed using the formula provided below [67],

$$W_b = \frac{W_e - (CoC - 1)W_d}{(CoC - 1)} \qquad (6).$$

Since the blowdown quantity is a strong function of CoC, and it is also the dominant component of the make-up water requirement, the following can be written,

$$W_m = f(CoC) \qquad (7),$$

Where, f(.) denotes any realistic function specific to the context.

Now, since blowdown quantity decreases with increasing CoC value, make-up requirement should also follow the same trend. Therefore, it would be reasonable to assume that the *f*(CoC) should be such that its value decreases with increasing CoC values.

Using **Eq. 7**, the reflection of the make-up water (calculated as m^3/h) on the specific water consumption (in m^3/MWh) of a TPP can be calculated once the hourly electricity generation (MWh/h) is known.

The hourly electricity generation (MWh/h) for a TPP unit with nameplate capacity of K MW_e can be written as below,

$$P_{u,hour} = K * PLF \qquad (8).$$

In a particular TPS, the TPPs are constructed and commissioned over different timelines, and therefore, it is likely that often there will be many TPP Stages where multiple units having identical generation capacities will be commissioned over a short duration.

In that case, **Eq. 8** gets modified to account for the stage-level hourly generation as below,

$$P_{s,hour} = n * K * PLF \qquad (9).$$

Where, **n** denotes the number of identical units with installed capacity of **K** MW_e. Therefore, the specific water consumption (in m^3/MWh) for a particular TPS Stage comprising multiple units can be written as below,

$$SWC = \frac{f(CoC)}{n*K*PLF} \qquad (10).$$

Evidently, the SWC value will be lower with higher CoC values since f(CoC) reduces with increasing CoC. Further, for a fixed CoC value the SWC will also get reduced as the PLF increases. Therefore, from **Eq. 10** it can be concluded theoretically that to ensure the optimal water consumption in a TPP, one must identify the highest possible CoC, and the plant must be run at higher PLF values. It is noteworthy that make-up water requirements account for about 80% of the total freshwater requirements in a thermal power plant. Therefore, the SWC derived from the make-up water requirement will provide a reasonable estimate for the overall SWC in a typical TPP. The values can be scaled up/ down for comparison, based on the specific context.

Often the PLF values of the TPPs are limited by the availability of coal and water as well as electricity demand. India's electricity generation has increased by 9.6% approximately between April and December 2022 due to the rapid recovery from the COVID-19 pandemic-induced slowdown, and this was possible only due to the 9.1% increase in thermal power generation (73% share in total electricity generation by utilities) during this period. Therefore, these resource-level bottlenecks need to be addressed first to achieve a better overall performance in the thermal power plants in order to meet the country's growing energy needs.

3.3 Choice of Thermal Power Plants for the Estimation of Make-up Water Requirements and SWC

The choice of TPP locations for this exercise are based on their geographical location as well as the water resource sustainability in the vicinity of the thermal power plants, keeping in mind that the diversion of freshwater for the domestic use of the city / village-dwellers is of utmost priority, especially during the periods of acute water stress.

A. Rayalaseema Thermal Power Project (5x210 MW + 1x600 MW) in Andhra Pradesh

YSR (previously known as Cuddapah and Kadapa) district in the State of Andhra Pradesh is one of the 255 water-stressed districts in India with an average annual rainfall of 700 mm against the long period average rainfall of 1160 mm for the country. Owing to the water stress witnessed by this place in the previous years, in 2019 the district adopted several progressive means for water conservation under the Jal Shakti Abhiyaan (JSA) [69]. Pathways such as water conservation and rainwater harvesting, renovation of traditional and other water bodies/ tanks, watershed development, and intensive afforestation have been found to yield positive results. However, the rural areas in Kadapa district have been seriously affected by lack of access to clean water. Reportedly, almost 625 villages belonging to this district suffered from a severe crisis of drinking water in 2019 [70].

Since the TPPs have huge water demand, the freshwater withdrawal by the Rayalaseema Thermal Power Project (RayTPS), located at

Yerraguntla has been evaluated to understand the most dominant industrial freshwater demand.

The RayTPS has four stages, and the stage-wise installed capacities are listed in **Table 2**. As evident from **Table 2**, 210 MW capacity units are distributed over three stages and one unit of 600 MW capacity was put up in Stage-IV. The two 210 MW units in the Stage -I were commissioned during 1994-95, whereas the latest 600 MW unit was commissioned in 2018. Stages I-III in the RTPP receives water from the Mylavaram reservoir [71], which is located 22 km away; whereas the 600 MW unit in the Stage -IV is supplied with the water from the Sri Potuluri Veerabrahmam Reservoir (SPVBR) (located 70 km away) by the means of pumping [71]. Since the SPVBR is being also evaluated for establishment of small hydropower projects [72], the freshwater withdrawal from this reservoir for meeting the requirements of RTPP Stage-IV needs to be evaluated. In our study, these units serve as the representative 210 MW and 600 MW units, respectively, for the make-up water estimation.

Table 2: Stage-wise Installed Capacities in the Rayalaseema TPS

Stage No.	Installed Capacity with Break-up
I	2 x 210 MW = 420 MW
II	2 x 210 MW = 420 MW
III	1 x 210 MW = 210 MW
IV	1 x 600 MW = 600 MW

B. Satpura Thermal Power Station (Units 10 and 11) (2 x 250 MW) in Madhya Pradesh

Betul district in the State of Madhya Pradesh also suffers from severe water stress for prolonged periods over the past few decades [73]. In 2016, the Betul district administration imposed a ban on all the construction work in the area owing to severe water crisis [74]. This made a good case for investigating the freshwater consumption by the TPP units in the Satpura Thermal Power Station. Units 10 and 11 in the Satpura TPS, both having a nameplate capacity of 250 MW, were chosen as the candidate 250 MW plants for study. These units were commissioned between 2013 and 2014 to replace the older subcritical units (5 x 62.5 MW and 4 x 210 MW) of this TPS which have already been decommissioned.

C. Atal Bihari Vajpayee Thermal Power Station (2 x 500 MW) in Chhattisgarh

Atal Bihari Vajpayee Thermal Power Station (ABVTPS) is located in the district of Jangjir-Champa, Chhattisgarh. The TPS comprises two units, each having an installed generation capacity of 500 MW_e. Both the units were commissioned in 2016. The freshwater required for the plant operations is sourced from the Kudri barrage located on the Hasdeo River [75]. The two 500 MW TPP units of ABVTPS are chosen to represent 500 MW TPP units for assessing their water consumption levels against the stipulated norms.

Hasdeo River is one of the major tributaries of the Mahanadi River. The original character of the Mahanadi River has been lost due to the construction of dams and barrages. Barrages are perfectly conducive for industries, but a hindrance to irrigation. Moreover, the water dispute over the Mahanadi River is a persistent issue between the states of Chhattisgarh and Odisha [76].

The Kudri barrage is a multipurpose hydro project envisaged to fulfil the needs of industries (mainly TPS), recharge groundwater, and drinking water and lift irrigation purposes. The barrage is designed to store 15.60 Mm^3 (MCM) of water, to enable reliable supply for the industrial and domestic consumption during the summer months, and to facilitate lift irrigation for the *Kharif* crops in the neighbouring villages. The Janjgir-Champa district is generally water-scarce and solely dependent on rainwater [77].

Therefore, the three thermal power stations selected for this study are, the Rayalaseema Thermal Power Station (RayTPS) located in Kadapa district in the State of Andhra Pradesh, Satpura Thermal Power Station located in Betul district in the State of Madhya Pradesh, and the Atal Bihari Vajpayee Thermal Power Station located in Janjgir-Champa district in the State of Chhattisgarh.

3.4 Evaluation of Make-up Water Requirements

From Equations 3, 4 and 6, it is evident that to estimate the make-up water requirement from the different losses and the blowdown quantity, the volumetric flow rate of the circulating water (W_c in m^3/h) is needed. The circulating water flow rate for TPPs with different installed generation capacities of interest (210 -600 MW) are shown in **Table 3**.

Table 3: Circulation flow rate (m^3/h) for TPP units with different installed capacities

Installed Generation Capacity of TPP unit (MW$_e$)	Circulation flow rate (m^3/h)
210	30,000
250	35,000
500	60,000
600	75,000

The evaporative and drift losses were calculated using **Equations 3** and **4**, respectively. **Table 4** presents evaporation and drift losses for TPP units different installed generation capacities. The temperature difference between the inlet and the outlet of the cooling tower is taken as 10°C based on the values obtained through the Right to Information (RTI) Act of 2005 [18], [78], [79].

Figure 4 depicts the circulating water forebay in the 2x 800 MW YTPS. The figure also shows the side view of one of the induced draft cooling towers (i.e., IDCT-1) located in the YTPS premises.

Table 4: Evaporative and Drift Losses for TPP units with different installed capacities

Installed Generation Capacity of TPP unit (MW$_e$)	Evaporative Losses (m^3/h)	Drift Losses (m^3/h)
210	255	6
250	297.5	7
500	510	12
600	637.5	15

Although theoretically the CoC values in a subcritical plant can range between 1 and 6 [67], the realistic values usually remain within a limited range for an operational TPP. For the three thermal power stations identified before, the stage-wise (for Rayalaseema TPP and ABVTPS) or the unit-wise (Satpura TPS) monthly average CoC values have been procured from the respective power stations through the Right to Information (RTI) Act [71], [75], [80].

The RTI data from the *three chosen thermal power stations* were available for the recent period *April 2019 to March 2022*. However, since the complete datasets were not available for the whole period of consideration, the duration with continuous data availability was chosen suitably for each candidate power plant.

Both synthetic CoC value full-range (1.1-6.0) and the actual CoC values obtained from the thermal power stations were used in **Eq. 6** to calculate

Figure 4: Circulating Water Forebay and Induced Draft Cooling Towers in Yeramarus TPS

the blowdown quantities for the respective TPP units. Thereafter, the make-up water requirement for the different installed generation capacities were calculated by adding the respective values presented in **Table 4** to the calculated blowdown quantities (**see Eq. 2**).

After calculating the make-up water requirements, best fits were obtained for both the synthetic CoC values ($1.1 \leq CoC \leq 6$), as well as the realistic CoC values obtained from plant data. These best fits for different candidate plants provide us with the function *f(CoC)* indicated in **Eq. 10**. The best fit equations for make-up water estimation are summarized in **Table 5**.

The stage-level or unit-level monthly average Plant Load Factors (PLFs) for the chosen thermal power stations were obtained from RTI data [71], [75], [80], as well as other openly available sources.

Finally, the specific water consumptions (SWCs) were calculated by dividing the make-up water flow rate with the hourly generation (see **Eqs. 9** and **10**). The detailed month-wise calculations for different TPPs (for the period over which continuous data was available) is provided in the **Tables A1** to **A16** in the Annexure.

Evaluating the RMSE values associated with the make-up water quantity required (m^3/h), it can be concluded that the results from the best-fit relations obtained for the make-up water quantity based on the operational CoC values (see **Table 5**) are closer to the actual values calculated using Equation (2) (with values emerging from **Eqs. 3**, **4**, and **6**) as compared to that from the best-fit relations based on synthetic CoC values (see **Table 5**).

However, since the RMSE values are within acceptable limits even for the best-fit relations based on synthetic CoC values, those equations (see **Table 5**) can be used in a generalized manner for the respective nameplate capacities. Consequently, the corresponding SWC values (evaluated using **Eq. 10**) can also be used as a baseline information.

For the optimisation of water consumption, it is essential to forecast the approximate SWC, so that necessary interventions can be adopted by the TPP. **Table 5** provides the best fit equations for the make-up water requirement for different categories of sub-critical TPPs (210, 250, 500,

Table 5: Best fit equations for make-up water estimation based on synthetic and operational values of CoC

Unit Rating (MW_e)	Best fit equation for make-up water requirement (m^3/hr) from synthetic range of CoC values		Best fit equation for make-up water requirement (m^3/hr) from CoC values obtained from Power Plant Operational Data	
	CoC Range	Equation	CoC Range	Equation
210	**1.1 to 1.5**	$y = 17000x^2 - 49300x + 36465$ $R^2 = 1$	**1.41 to 1.6**	$y = 2130.8x^2 - 7445.2x + 7138.3$ $R^2 = 0.9999$
	1.6 to 3	$y = 171.68x^2 - 993.92x + 1825.1$ $R^2 = 0.9934$		
	3 to 6	$y = 7.132x^2 - 88.066x + 579.08$ $R^2 = 0.9964$	**2.27 to 4.48**	$y = 22.72x^2 - 207.58x + 805.15$ $R^2 = 0.9963$
250	**1.1 to 1.5**	$y = 19833x^2 - 57517x + 42543$ $R^2 = 1$	**1.6 to 1.97**	$y = 657.89x^2 - 2853.9x + 3674.7$ $R^2 = 0.9998$
	1.6 to 3	$y = 200.29x^2 - 1159.6x + 2129.3$ $R^2 = 0.9934$	**2.02 to 3.49**	$y = 70.846x^2 - 499.71x + 1302.7$ $R^2 = 0.997$
	3 to 6	$y = 8.3207x^2 - 102.74x + 675.59$ $R^2 = 0.9964$		
500	**1.1 to 1.5**	$y = 34000x^2 - 98600x + 72930$ $R^2 = 1$	**4.7 to 5.1**	$y = 8.7113x^2 - 118.95x + 1014.5$ $R^2 = 1$
	1.6 to 3	$y = 343.35x^2 - 1987.8x + 3650.3$ $R^2 = 0.9934$		
	3 to 6	$y = 14.264x^2 - 176.13x + 1158.2$ $R^2 = 0.9964$		
600	**1.1 to 1.5**	$y = 42500x^2 - 123250x + 91163$ $R^2 = 1$	**1.5 to 1.99**	$y = 3347.7x^{-1.411}$ $R^2 = 0.9904$
	1.6 to 3	$y = 429.19x^2 - 2484.8x + 4562.9$ $R^2 = 0.9934$		
	3 to 6	$y = 17.83x^2 - 220.17x + 1447.7$ $R^2 = 0.9964$	**2.02 to 3.78**	$y = 121.3x^2 - 912.71x + 2592.7$ $R^2 = 0.9943$

600 MW_e) as a function CoC. These relations can be used in **Equation 10** to further calculate the SWC**,** with the help of PLF values from the operational data. The PLF in a TPP is maintained as per the prior intimation from Load dispatch centres regarding the expected demand. Since the PLF of a particular unit/ plant is known beforehand, the SWC can be reduced suitably by increasing the CoC within the permissible limits. From the operational point of view, the quantities of the chemicals used in the water treatment can also be estimated with a view to maintaining the desired quality parameters for the recirculating cooling water for the efficient operation of the TPPs. The best-fit models will help the power plant operators in estimating the water treatment requirements with the changing plant operating parameters.

Chapter 4

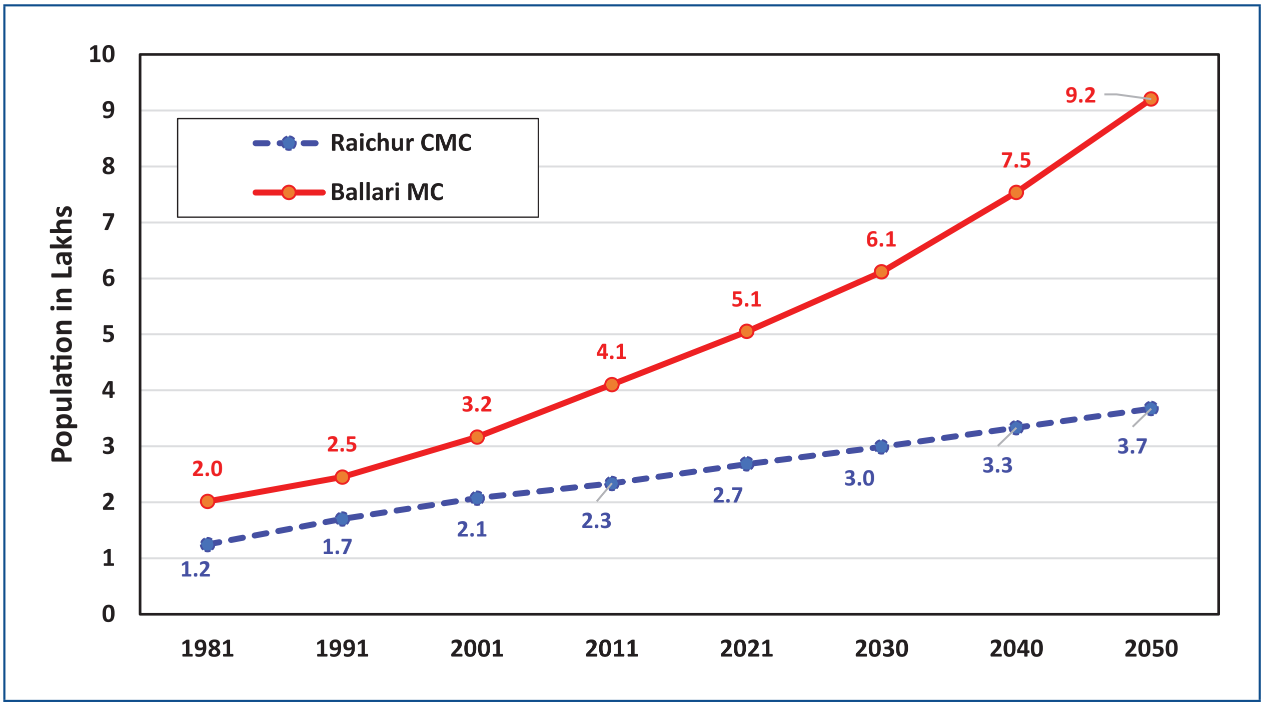
Study Area

As highlighted earlier in the Introduction section, field surveys were conducted in the Raichur city municipal council area and Ballari municipal corporation area with a view to identifying the freshwater requirements in the TPPs located in these two areas, water quality parameters, and to evaluate water availability aspects for the city dwellers. Subsequently, it is important to have realistic population projections for these two areas in order to estimate freshwater requirements for domestic consumption considering the future timelines (2030 and 2050).

4.1 Population projections for the Raichur CMC and Ballari Municipal Corporation

Figure 5 shows the projected evolution of population in the Raichur City Municipal Council (CMC) and Ballari Municipal Corporation (MC) areas till 2050 using the IIM. These projections are used to estimate the future domestic water needs and assess the potential supply shortage due to population growth, especially during the periods of low rainfall or drought.

Figure 5: Population Projections for Raichur CMC and Ballari MC



4.2 Domestic Water Supply in Raichur CMC and Ballari MC

A. Raichur CMC

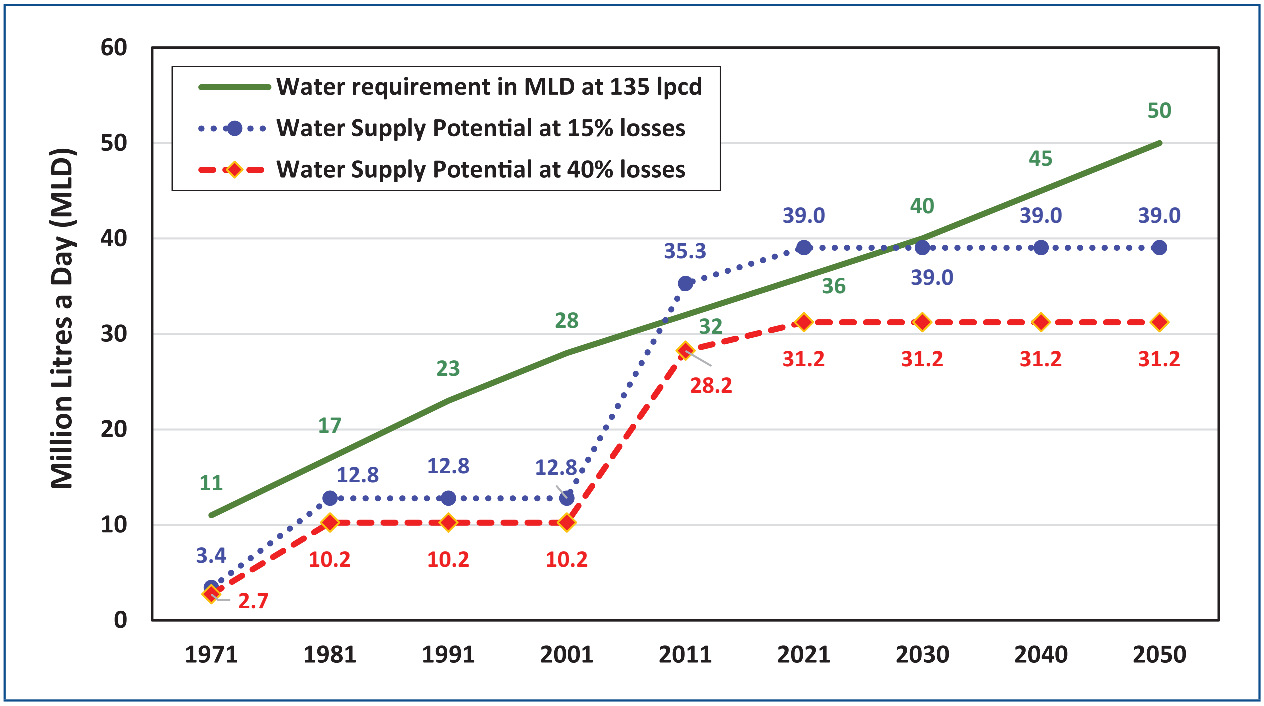
The Krishna River is the main freshwater source for the Raichur city (Raichur CMC). It flows 18 km away from the city centre [81]. The details of the water treatment plants (WTPs) in Raichur city are given in **Table 6**.

Figure 6 shows the temporal evolution of freshwater requirements at 135 lpcd for the period 1971-2050, calculated for the changing population levels during the same period as projected in **Figure 5**. The water requirements are compared with the water supply potential, based on the previous as well as the currently existing water supply infrastructures available from the published reports [81]. In 2003, a major source augmentation was done by establishing a 40 MLD WTP with water sourced from the Krishna River. Out of this quantum, 30 MLD was allocated for the domestic water supply and the rest 10 MLD was allocated towards Industrial Growth Centre [81]. System losses of 15% and 40%, respectively, are considered to simulate different scenarios. It is evident from **Figure 6**

Table 6: Domestic Water Supply Infrastructure in Raichur CMC (2021) [15], [81]

Sl. No.	Name	Capacity (in MLD)	Source	Type
1	Chicksugur	30	Krishna River	Rapid Sand Filtration
2.	Devasugur	10	Krishna River	Rapid Sand Filtration
3.	Rampur	12.5	Tungabhadra (TB) Canal	Rapid Sand Filtration

Figure 6: Domestic Water Requirement vs. Supply Potential (Raichur CMC)



that there would be a significant gap between the supply potential and water demand after 2025 in case of 40% supply losses. The estimated gap between the supply and demand is 19 MLD in 2050. If the system losses are reduced to 15% (the level allowed by water transmission norms), the supply-demand gap can be reduced by about 8 MLD, resulting in a gap of 11 MLD in 2050.

B. Ballari City –Drinking water supply

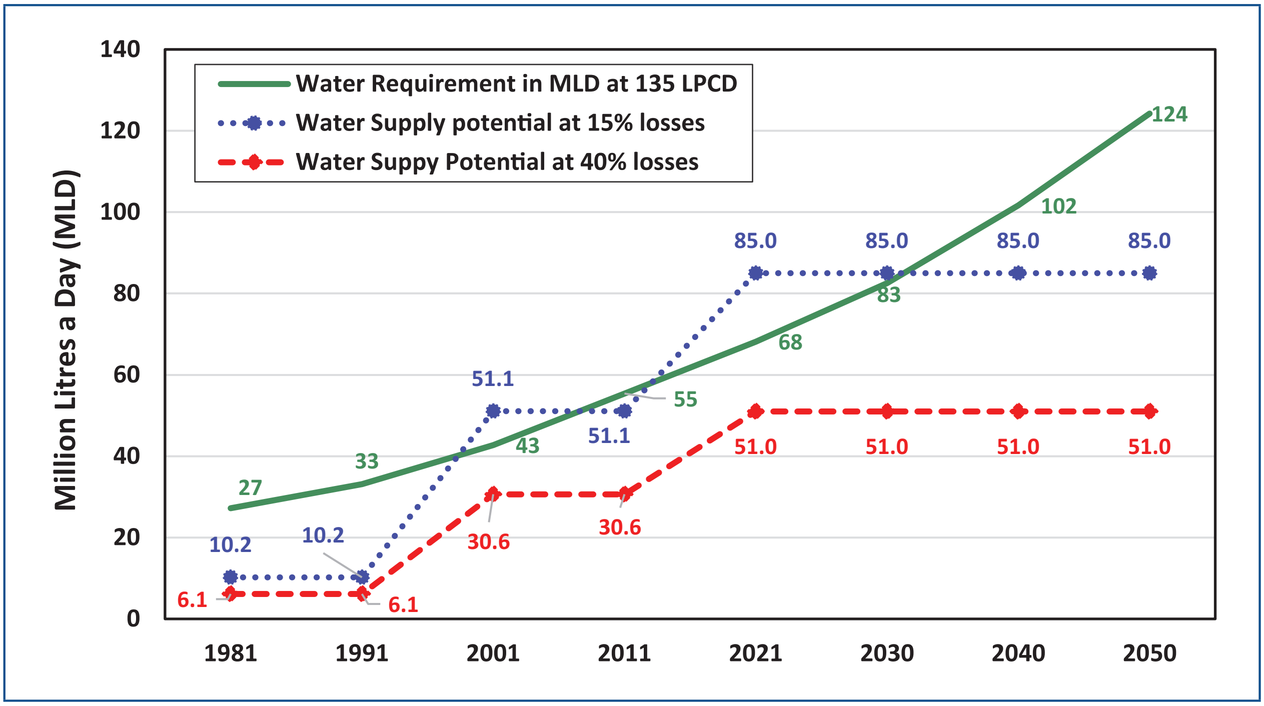
The drinking water supply to the Ballari city is met from two impounding reservoirs, Allipur and Moka. The water is drawn from high-level and low-level canals of Tungabhadra passing through the outskirts of the city. Water flows into the high-level canal (TB-HLC) for about six months, whilst it is available for about 10 months in the low-level canal [82]. Allipur reservoir meets about 65% of the drinking water requirement in the city and about 35% is met the supplies from Moka reservoir. The details of the water treatment plant (WTPs) in Ballari city are provided in **Table 7.**

While the initial water supply scheme with a capacity of 10.22 MLD started in Ballari along

Table 7: Domestic water Infrastructure in Ballari MC [83]

Sl. No.	Name	Capacity (in MLD)	Source	Type
1	Allipur	40	TB-HLC	Rapid Sand filtration
2.	Moka	10	TB-LLC	Rapid Sand filtration
3.	Sanganakal (near Moka Village)	20	TB-LLC	Tube Settler filtration
4.	Allipur premise	15	TB-HLC	Tube Settler filtration

Figure 7: Domestic Water Requirement vs. Supply Potential (Ballari MC)



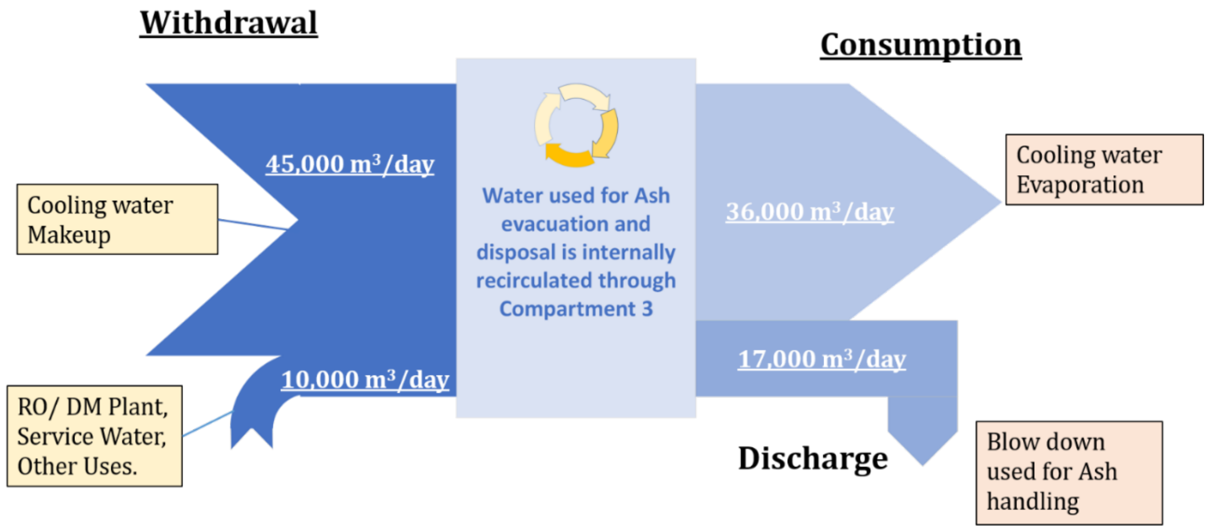
with the Tungabhadra Low Level Canal (TB-LLC), subsequent water supply infrastructures were not able to satisfy the needs of the population. The water supply potential was enhanced subsequently with the commissioning of Allipur WTP of 40 MLD capacity [82]. The water requirement for the population at 135 lpcd is compared with the potential water supply capacity at 15% and 40% system losses, respectively, in the **Figure 7.** Ballari city reports system losses exceeding 40% in the domestic water supply system [82], [84]. The city is estimated to require an additional water requirement of 73 MLD in 2050 if the current system losses (40%) are not reduced.

4.3 Thermal Power plants and water withdrawal in Raichur CMC and Ballari MC

The quantity of water required in a TPP primarily depends on the cooling system, ash handling, and boiler type. The drawal of water is also influenced by the availability of water from natural sources, and local climatic parameters [45]. The major constraint for water conservation in TPPs is that, more than 70% of water drawn is utilized in various processes, which includes evaporative loss of total circulating water from the cooling towers. Since the consumed water cannot be reclaimed back, the focus here is to reduce the water withdrawal, which is the only controllable parameter from the resource end.

As per the notification issued by MoEFCC in 2015 and its subsequent amendment in 2018, all existing Cooling Tower (CT) based plants must reduce the specific water consumption to a maximum of 3.5 m^3/ MWh. Moreover, new plants installed after 1st January, 2017 must limit their water consumption up to a maximum of 3.0 m^3/ MWh [48], [49]. **Figure 8** shows a typical day water balance diagram for an operating 800 MW supercritical TPP unit (Unit 2) in the

Figure 8: Water Balance of one unit of YTPS (1x800 MW) [19], [85]



✓ Withdrawal - water diverted from a surface or groundwater source.
✓ Consumed - withdrawn water that is not returned to its source (e.g. majorly evaporation)

Table 8: Salient details of Thermal Power Stations in Raichur and Ballari districts

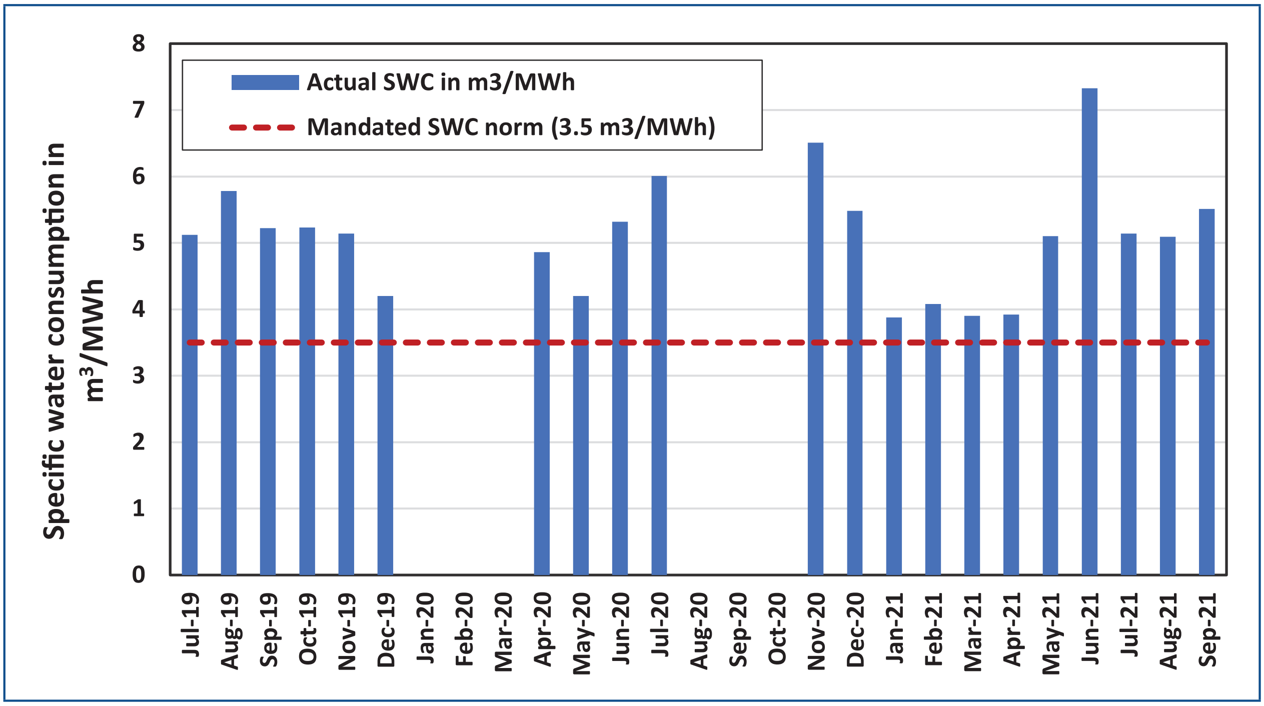
Name	No. of Units	Installed capacity and configuration	Type of Boiler	Commercial Operation Date
RTPS	8	7 x 210 + 1 x 250 = 1720 MW	Sub critical	1985-2009
BTPS	3	2 x 500 + 1 x 700 =1700 MW	Sub Critical; Super critical	2008 – 2017
YTPS	2	2 x 800 = 1600 MW	Super Critical	2017
JSW Energy Ltd.	4	2 x 130 + 2 x 300 =860 MW	Sub Critical	2000-2009

Yeramarus Thermal Power Station (YTPS) premises, Raichur.

As shown in **Table 8**, there are four coal-fired thermal power plants in the study area. The average monthly specific water consumption (SWC) (m^3/ MWh) of RTPS, for the period July 2019 to September 2021, comes around 5.08 m^3/ MWh [17]. This is well above the mandated norm of 3.5 m^3/ MWh. Even though GoK increased the freshwater price from Rs. 0.1 (10 paisa) per m^3 to Rs. 10.60 per m^3 of water in 2019 [18], [79] , there was no substantial reduction in water intake, as evident from **Figure 9**.

The RTPS authorities cited reserve shutdowns and partial load operation of TPP units due to 'No Load Demand' as the key reasons behind increased water consumption. For instance, for the third quarter of 2019-20 (October-December) only 2-4 units were operation till first week of December and other units were kept under reserve shut down. It is observed that during December, when more than 6 units

Figure 9: Specific Water Consumption (m^3/MWh) of RTPS (from July 2019 to Sept. 2021)



were working, SWC reduced to a level of about 4 m^3/ MWh as against 5.14 m^3/ MWh during November, when half of the units were kept under reserve shutdown (ref. **Figure 9**) [17].

The second thermal power plant in Raichur is YTPS, which comprises two supercritical units with nameplate capacity of 800 MW each (commissioned in 2017). The units are not fully operational due to reserve shutdown and 'No-Load Demand' from the State Load Dispatch Centre (SLDC).

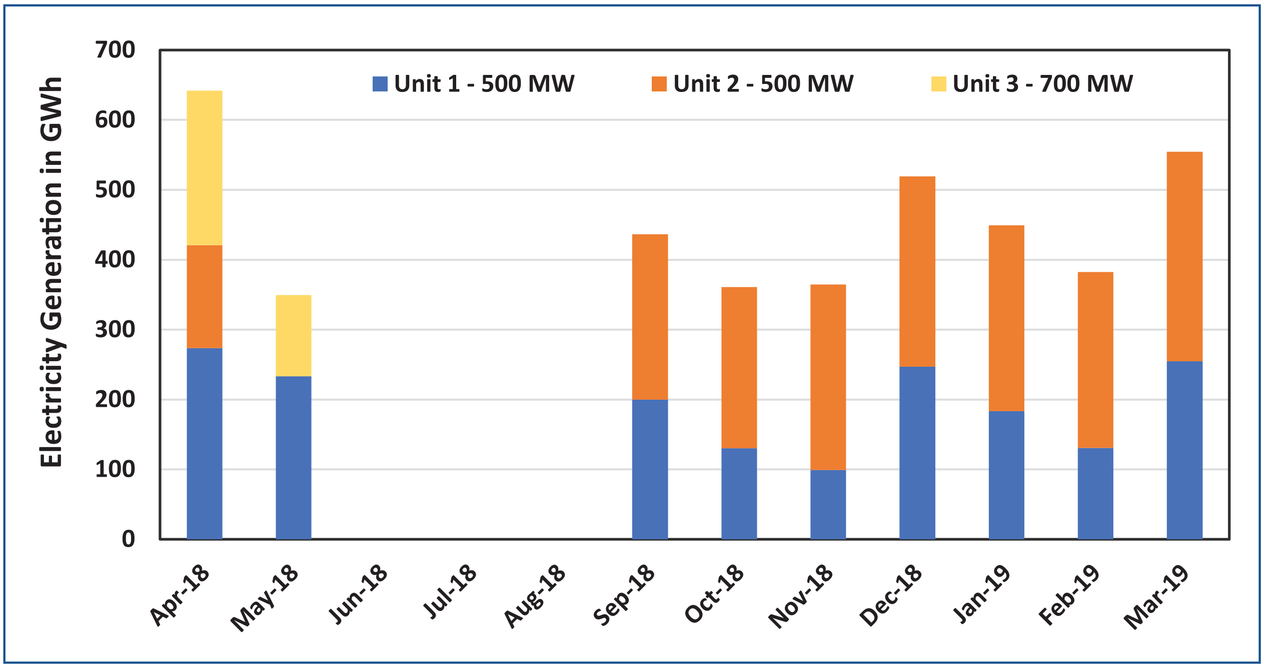
The allowable SWC for YTPS is 3.0 m^3/MWh as per the latest specific water consumption norms of 2018 for the plants installed after 01 January 2017. During the financial year 2019-20, the average specific water consumption of YTPS (4.78 m^3/ MWh) was considerably higher than the allowable limit. As shown in **Table 9,** although the average SWC of YTPS (3.27 m^3/ MWh) during July-September 2020 declined from the extraordinary high levels recorded in FY 2019-20, it continued to exceed the norm of 3.0 m^3/MWh [20], [86].

There are two thermal power stations in Ballari region, Ballari Thermal Power Station (BTPS) with a total generation capacity of 1700 MW, and JSW Energy limited (JSWEL) captive power

Table 9: Quarterly account of water consumption of YTPS (July-September 2020)

Month	Power Generation (MU)	Water consumption (m^3)	SWC (m^3/MWh)
July 2020	189.81	615589	3.3
August 2020	86.51	309382	3.6
September 2020	142.89	445786	3.1

Figure 10: Electricity generation by BTPS in Gigawatt Hours (GWh) (April 2018- March 2019)



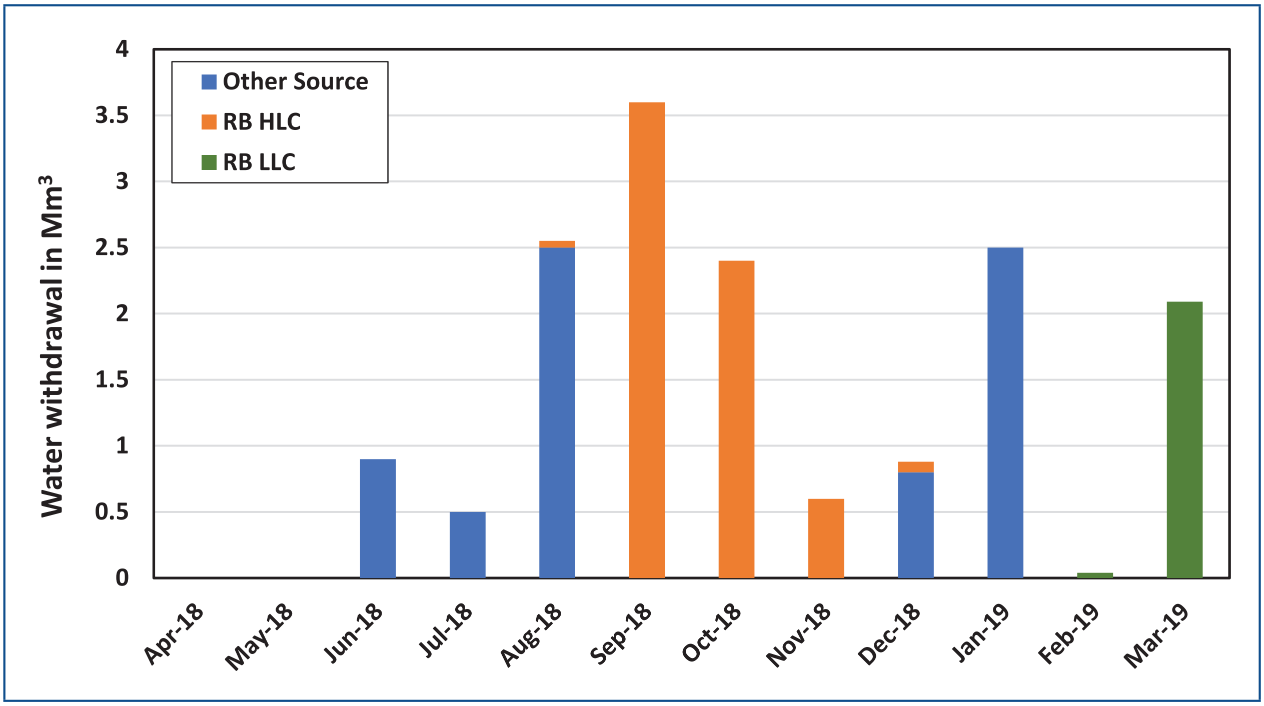
plant at Toranagallu with a capacity of 860 MW. In addition to this, Ballari is also a hub of steel and apparel industries.

The average specific water consumption (m^3/MWh) of JSW captive power plant during 2017-18 is 2.24 m^3/MWh [87], which is well below the allowable limit of 3.5 m^3/MWh, as per the latest norms. Since JSWEL's SWC is well below the mandated norms, the focus is on Ballari Thermal Power Station (BTPS) to assess the potential for saving a portion of the freshwater for possible diversion to the city, through successful reclamation of treated wastewater from STPs under the Ballari MC and its reuse in the BTPS.

BTPS is allocated with an annual drawal limit of 57.76 Mm^3 of recycled agriculture water from Maralihalla in Koppal district. However, the availability of water has been intermittent. For instance, in 2017-18, BTPS could not generate electricity for approximately 1000 hours due to raw water shortage [43]. Month-wise electricity generation at BTPS for the year 2018-2019 is shown in **Figure 10.** It is likely that the non-availability of water was one of the key reasons responsible for the forced shutdowns in addition to reserve shutdown and 'No-Load Demand' from the SLDC. Therefore, BTPS only produced 4055 GWh at an annual PLF of 27% during FY 2018-19.

To mitigate the scarcity of water, GoK has allowed BTPS to draw water from the Tungabhadra High Level Canal (TB - HLC) and the Tungabhadra Low Level Canal (TB-LLC). The TB – HLC and TB-LLC are the only two sources of water catering to the domestic requirements of the people living in the Ballari Municipal Corporation (Ballari MC) area. BTPS received 6.3 Mm^3 of water from the TB-HLC during August to December of 2018, and 2.1 Mm^3 of water from the TB-LLC during February and March 2019 [18], as shown in the **Figure 11**.

Figure 11: Source wise water withdrawal – BTPS (April 2018- March 2019)



4.4 Water Chemistry in Thermal Power Plants with insights from YTPS field visit

Raw water chemistry is an important aspect in power plant operation. Water chemistry varies with water source, its flow, seasonality of rain etc. [45]. For instance, during summer, the flow of water in river will be less (i.e., low turbulence condition), leading to the growth of microorganism which can be attributed to the increased COD level (~ 400 mg/L). The increased microorganism load is detrimental for the filtration units which use sieves made of protein membranes. Progressive degradation occurs in the membranes that eventually disrupts the filtration process. Another important factor is turbidity that indicates the murkiness of water and is measured in Nephelometric Turbidity Units (NTU). The higher NTU values indicate larger extent of suspended solids, algae, organic material, and other particles in the river water. The extent of pre-treatment and the settling time increases with increasing turbidity levels. In order to mitigate this issue, catalysing agents like alum is added to reduce the load of suspended solids in the raw water. Further, the impurities (e.g., Iron, Copper, Aluminium, Silica, Calcium, Magnesium etc.) present in the feed water are carried to different parts of the system and gets deposited in large amounts causing scaling and corrosion of the tubes and pipes [45], [52]. Thus, proper water treatment is essential to prevent the incursion of contaminants, corrosive elements into power plant processes. **Table 10** summarises the key physico-chemical challenges faced by YTPS in terms of water availability as captured during the fieldwork done in March 2022.

The recommended parameters for the recirculating water to be used in TPP cooling towers are provided in **Table 11**.

Table 10: Challenges faced by YTPS in terms of water quality and quantity

Summer (Mid-March – May)	Monsoon (August – September)
• No flow in the river. Hence, TPPs are dependent on the opening of Gugal and Girjapur Barrages which also supply water for irrigation. • Chemical Oxygen Demand (COD) rises to 400 mg/L during these months. This is because of low turbulence and stacking up of water in the barrage. • Since the membranes are made of proteins, micro-filtration tubes get choked due to increased level of microorganisms. The flux of micro-filtration units drops considerably. • Evaporation losses are high owing to low humidity (Relative Humidity - 27%) and dry conditions. About 2,200 m^3/ hr. of cooling water is lost per day during the summer season, as compared to the specified value of 1,750 m^3/hr. This implies a larger quantum of freshwater withdrawal.	• Turbidity is the main concern. Crosses 2000 NTU as against the specified limit of 500 NTU of raw water. • Requires more pre-treatment. Chemical dosing of alum is done frequently. Retention time of raw water in pre-treatment tanks is more.

Table 11: Water quality requirements for cooling tower recirculating water in TPS [88]

Parameter	Acceptable limits for Cooling Towers
pH	6.8 -7.8
BOD (mg/L)	5.0
Total Suspended Solids (TSS) (mg/L)	5.0
Turbidity (NTU)	< 5.0
Total Nitrogen (N) (mg/L)	< 10
Total Phosphorous (mg/L)	< 0.5
Total Coliform (MPN/100 ml)	< 1000
Dissolved Oxygen (mg/L)	> 2.0
Residual Chlorine (mg/L)	0.2-0.5

For a qualitative comparison, the water quality parameters needed for the boiler feed operation are presented in **Table 12**. Boiler feed water quality parameters are dictated by the need for highest purity water/ steam in the TPP Boilers for effective operation. The boiler feed water ideally should be devoid of all kinds of impurities, including dissolved ionic species. The presence of ionic species (cations and anions) is responsible for the specific conductivity [52]. For example, the cations (Na^+, Li^+, Cu^{2+}, Ca^{2+}, Mg^{2+}, NH_4^+, $N_2H_4^+$, $C_4H_9ON^+$, etc.) and the anions (Cl^-, F^-, NO_3^-, SO_4^{2-}, PO_4^{3-} etc.). A high specific conductivity indicates larger extent of ionic impurities in the feed water, which leads to scaling, and acid corrosion (when pH levels go below 8.5) in the boiler tubes [52]. Evidently, the water quality parameter requirements are more stringent in case of boiler feed water, as compared to those for recirculating cooling water (CW).

The other processes involving water are the ash handling and auxiliary processes. The ash handling involves movement of ash from boiler bottom (bottom ash) to ash pond and fly ash (left-over from flue gas), which is collected in hoppers for secondary uses mainly in cement and brick industry. The fly ash is removed in the dry form through vacuum and suction pumps and collected in hoppers. The bottom ash is moved to ash pond through wet mode, that is, water is used to carry the bottom ash to the ash pond. The water required for ash handling is often sourced from the CT blow down water, back wash water from filtration unit, effluent treatment plants etc. Hence, no additional fresh water is needed for ash handling. Moreover, the auxiliary cooling system that provides cooling water to the turbine equipment, generator auxiliaries, and compressors, requires slightly purer water as compared to that used in the cooling towers. The auxiliary cooling water is often sourced from the DM and RO plants [51].

Table 12: Water quality requirements for Boiler Operations in TPS

Parameter	Acceptable limits for Boiler Operation
Silica (mg/L)	<.020
Total Iron (mg/L)	<.020
Specific conductivity (	2.5 to 7
Sodium (mg/L)	<0.005
pH	9.0 to 9.6

Chapter 5

Reclaimed Wastewater as an Alternative to Freshwater in Power Plant: Cost and Quality Challenges

Wastewater treatment involves physical, chemical, and biological processes that remove pollutants, and organic matters from wastewater. Usually, there are three main stages of wastewater treatment, primary, secondary, and tertiary [89]. Primary treatment includes physical operations like sedimentation and removes floating and suspended particles. Chemicals like Alum and chlorine are added to facilitate the process. Secondary treatment involves removal of biodegradable organic matter and removes nutrients such as nitrogen and phosphorous. The final stage (tertiary treatment) consists of filtration using Ultra filtration (UF) and Reverse osmosis (RO) membranes. UF removes suspended/colloidal particles and micro-organisms to avoid particulate and biological fouling. UF filters up to 0.01-micron size particles. The RO unit, on the other hand, removes dissolved solids to reduce load on the DM water unit. The tertiary treatment is akin to the processes in RO-DM plant deployed in thermal power plants.

In the case of MAHAGENCO model, the wastewater does not undergo tertiary treatment involving more expensive UF and RO processes before being pumped to Koradi and Khaperkheda Thermal Power Plants. This secondary-treated water costs around Rs. 3.70 per m^3. The MAHAGENCO case and the learnings from the field visit to YTPS indicate that the secondary-treated municipal sewage water can be reliably used in the cooling tower and ash handling applications without a major capital investment in tertiary treatment facilities that will increase water treatment costs and therefore, the electricity tariffs.

5.1 A review of a reference case on the use of treated municipal wastewater in a TPP

The use of STP-treated water in the Koradi Thermal Power Station (KTPS) located in Nagpur shows a successful business model for industrial reuse of treated municipal sewage water. About a decade earlier, MAHAGENCO decided to expand KTPS with an additional capacity of 1980 MW (3 x 660 MW). Since additional water allocation was not possible from Kamptee Khairee Pench Project, and the Vidharbha region suffers from an acute shortage of drinking water, MAHAGENCO started exploring options for using treated wastewater as an alternative source [90]. Back then, 425 MLD of sewage was generated in the city with Nagpur Municipal Corporation (NMC) having only one STP with a treatment capacity of 100 MLD. Therefore, bulk of the municipal sewage was being discharged into the Nag and Pili rivers [90].

In 2008, MAHAGENCO and NMC signed a Memorandum of Understanding (MoU) for supplying 110 MLD of treated wastewater from Bhandewadi STP to be used at KTPS for cooling tower operations [24], [90]. The partnership was based on the Build-Operate-Transfer (BOT) basis with an end user contract of 30-year concession [90]. The total capital cost of the project was Rs.1950 million, excluding the land. The land area for putting up the subsequent treatment facilities was provided by NMC. To meet the capital expenditure, Rs.900 million was sourced from the Jawaharlal Nehru National Urban Renewal Mission (JNNURM), and the rest was financed by MAHAGENCO [90], [91]. MAHAGENCO committed to build, operate, and maintain wastewater treatment plants and to pay a fixed amount of Rs.150 million per year towards NMC for the 110 MLD treated wastewater (~ Rs. 3.73 per m^3), and Rs. 2.3 per m^3 for the flows exceeding the contract amount of 110 MLD [90].

Subsequently in 2017, NMC, MAHAGENCO, and Nagpur Wastewater Management Pvt. Ltd (NWWMPL) entered into a tripartite agreement for the supply of Tertiary Treated Water (TTW) to MAHAGENCO on a daily basis. NWWWPL started to supply TTW to MAHAGENCO effective from June 2020 onwards [88]. The cost of tertiary treated water for MAHAGENCO is around Rs. 3.73 per m^3 which is significantly lower than the cost of freshwater costing Rs. 9.60 per m^3[90]. This amounts to capital savings to the tune of Rs. 230 million and freshwater savings of 40 Mm^3 per year. NMC receives royalties from the sale of TTW to MAHAGENCO with the potential to generate revenue of Rs. 4000 million over the contract period. This additional income stream allows the NMC to cover the operation and maintenance expenses of sewage treatment plants in the city [24], [90].

The success of this initiative encouraged MAHAGENCO to purchase additional 200 MLD of treated sewage water from a second STP near Bhandewadi to augment water requirements in Koradi and Khaperkheda Thermal Power Stations. Currently, 330 MLD of municipal sewage in Nagpur city is treated out of the total 550 MLD of sewage produced in the city, which would otherwise be discharged into the Nag and Pili rivers [24]. Treated municipal wastewater thus serves the twin objective of providing constant and reliable source of water during the periods of scarcity, while substantially reducing freshwater drawal that could be reallocated for the domestic needs of city dwellers. Besides contributing to SDG target 6.1, this arrangement also incentivizes NMC to enhance water use efficiency (SDG target 6.4) and provide proper sanitation services to the people living in Nagpur (SDG target 6.2). **Figure 12** shows an aerial view of the Bhandewadi STP, where the key components are visible.

5.2 Proposed use of STP-treated Water in TPS and Industries of Raichur CMC

There are two STPs operational in Raichur, namely Eklaspur and Hosur, with design capacities to treat 20 and 8 million litres of raw sewage daily, respectively. Both are Facultative Aerated Lagoon (FAL) type STPs. Another STP of 5.5 MLD capacity is under construction at Yeramarus with Sequential Batch Reactor (SBR) technology. A proposed schematic for the integration of STPs with the TPS for the Raichur CMC area is shown in **Figure 13.**

Figure 12: Aerial view of the Bhandewadi STP in Nagpur

On an average, the Eklaspur and Hosur STPs collectively treat only 12 MLD of sewage water [92]. Therefore, the overall STP utilization is currently about 43%. This is primarily attributed to the poor connectivity of underground drainage networks (UGD), leading to subpar collection of sewage water. Of the 500 km of drainage network envisaged, only 300 km have been completed, and the remaining part is under various stages of construction [93].

During 2018-19, Raichur CMC spent around Rupees 13 million in the operation and maintenance of STPs [15]. Currently, there is no revenue generation from the STPs. Raichur CMC is trying to generate income by selling primary treated sewage water to YTPS on a demand basis.

Table 13 shows that the water quality parameters at the outlet of the Hosur and Eklaspur STPs are compatible with the raw water quality requirements in the Thermal Power Plant (YTPS**)**. Therefore, the use of STP-treated water for the purpose of ash handing is a likely option in this case. The possibility is also favoured by the plant's proximity to the STPs.

Water requirements for Thermal Power Plants and Industries are likely to reduce with the progressive decommissioning of the existing units of RTPS by 2030. The demand for freshwater for industrial purposes in this area can be further reduced by using the treated wastewater from STPs in YTPS. The current and projected freshwater requirements (BAU scenario) in the Raichur CMC area, for domestic and industrial purposes are shown in **Figure 14**. With the reclamation of treated wastewater, freshwater drawal can be reduced by 28% by 2030 and by 32% in 2050. A comparison of two scenarios, business-as-usual (BAU) and the scenario where the STP-treated water is used in the industry (mainly, TPPs) can be drawn looking at the **Figures 14** and **15** respectively. The YTPS can save around Rs. 60 million and Rs. 80 million respectively in the years 2030 and 2050 with the use of treated wastewater in their facility (assuming a price of Rs. 3.70 /m^3 for treated municipal wastewater- ref. Ballari case).

Table 13: Outlet Parameters of STPs [92]

Water Parameters at the STP outlet	Hosur (8 MLD)	Eklaspur (20 MLD)
pH	7.8	8.2
COD (mg/L)	109.7	115.9
BOD (mg/L)	14.2	15.2
Dissolved Oxygen (mg/L)	5.3	5.1
Turbidity (NTU)	30.1	41.1
TSS (mg/L)	12.8	15.5
Total Coliform (mg/L)	416.3	402.2
Residual Chlorine (PPM)	0.64	0.91
Flow in MLD	3.12	8.9

Figure 13: Schematic of the proposed STP integration in Raichur City with TPS

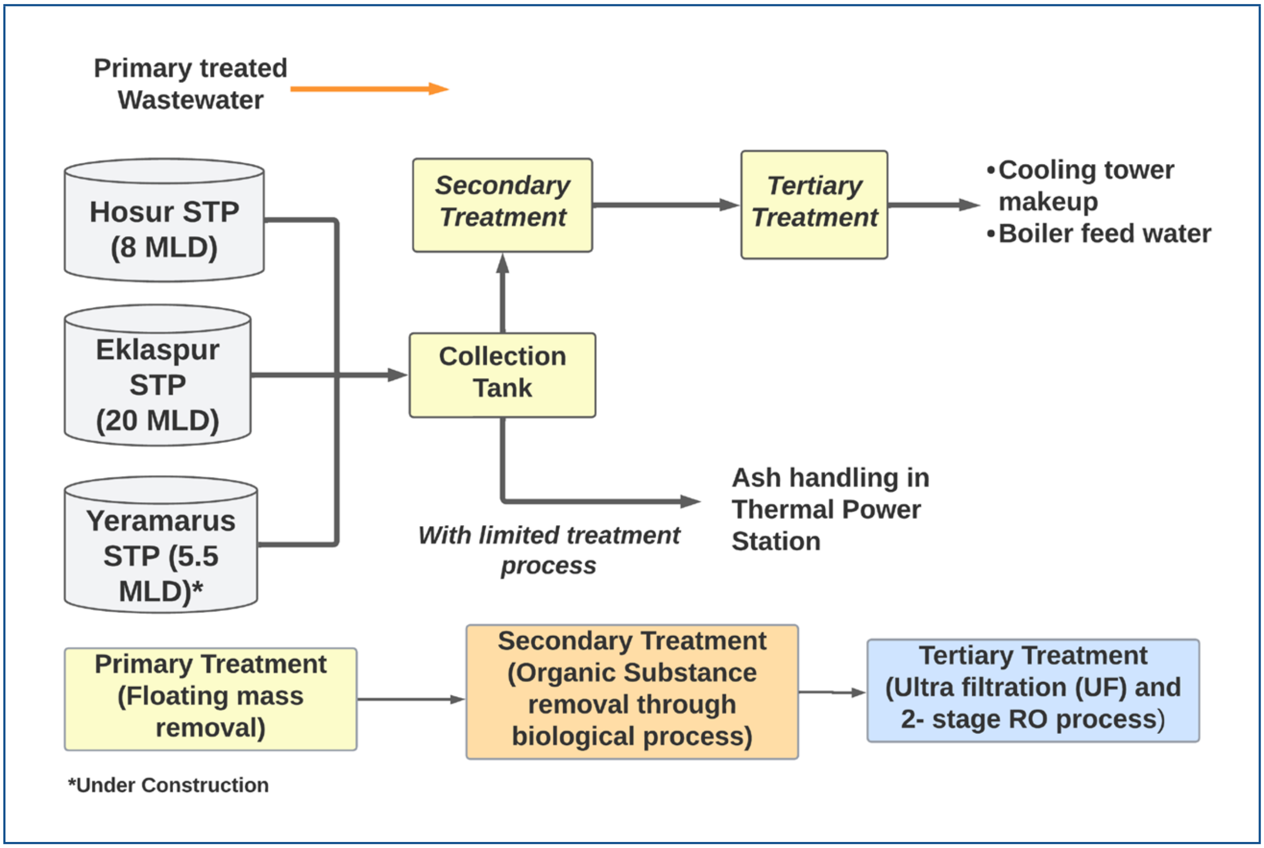


Figure 14: Annual Fresh water withdrawal for Domestic and Industrial consumption (Mm^3) in 2019, 2030 and 2050 under Business as Usual (BAU) scenario till 2050

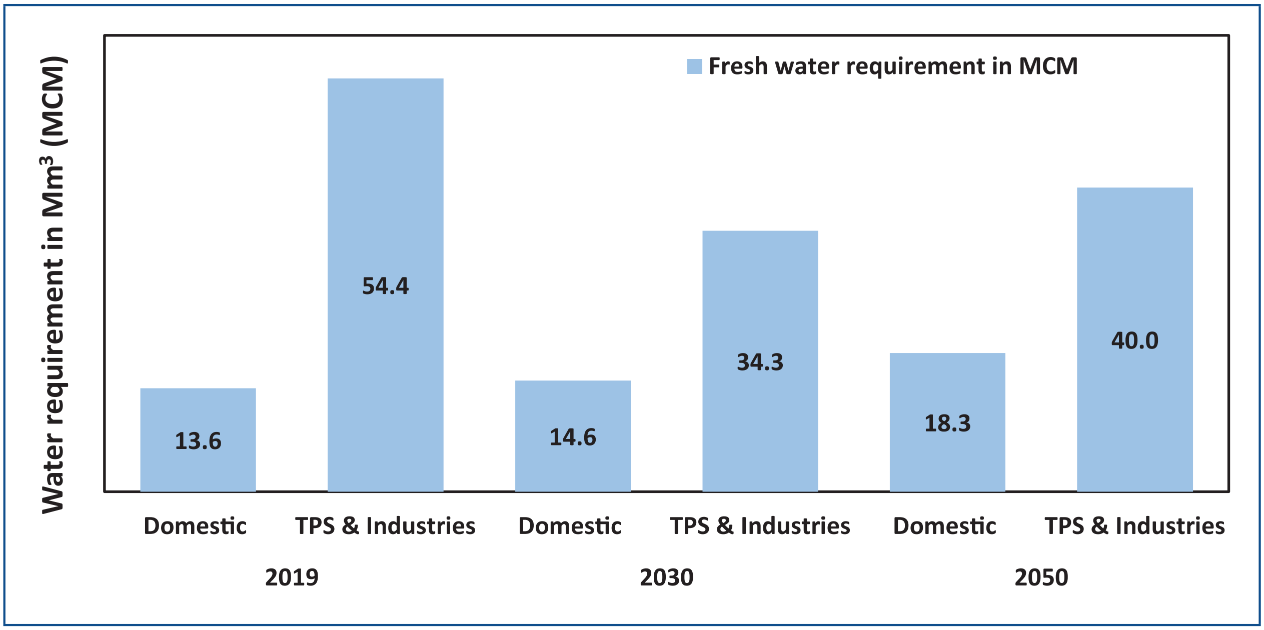
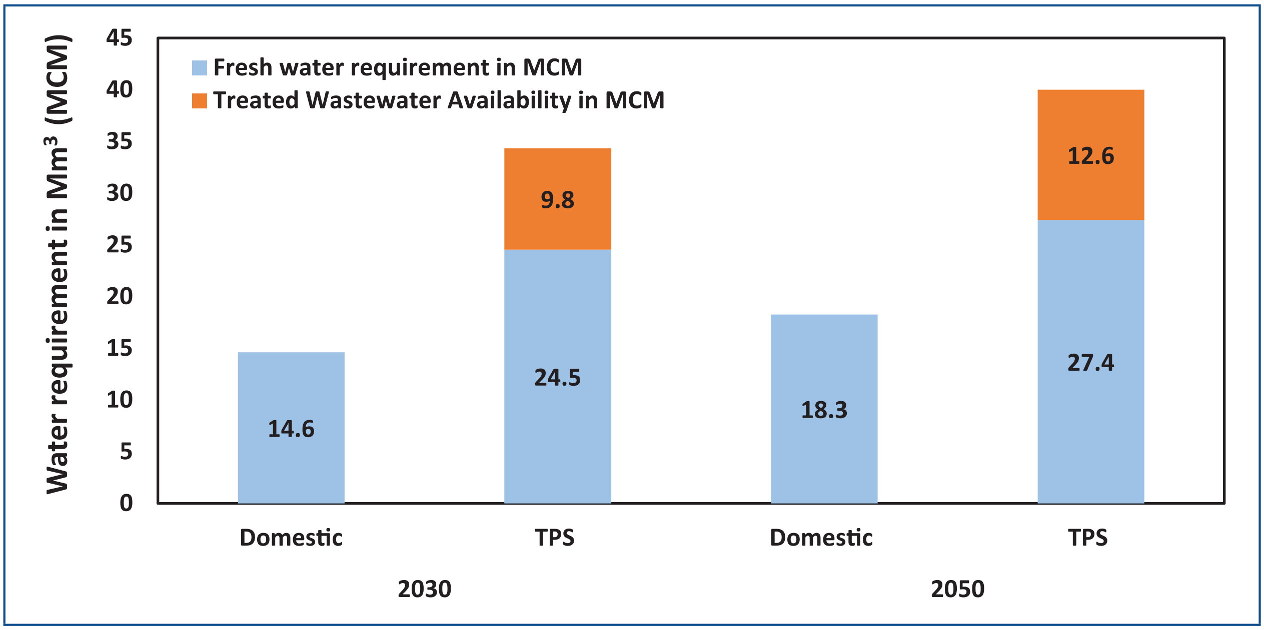


Figure 15: Annual Fresh water withdrawal for Domestic and Industrial consumption (Mm^3) in 2030 and 2050, considering reuse of STP-treated water in industries



5.3 Potential for using STP-treated water in the TPS and industries around Ballari MC

As of today, a total 27.5 MLD of treated sewage water is available from the STPs located in the Ballari MC area. There are two sewage treatment facilities, a 30 MLD STP near Anantapur Road and a 15 MLD near Cowl Bazar. The municipal corporation is selling treated wastewater to sponge iron factories near the Ballari MC area at a price of Rs. **3.70/m^3**. Details of STPs in the Ballari MC Area are provided in **Table 14**.

Janaki Steel was first to draw treated sewage water (3 MLD) in Ballari for industrial purposes. Further, S.S.C Steels Pvt. Ltd secured permission to draw 10 MLD of treated wastewater from Anantapur STP in 2015 [94]. In 2019 NITI Aayog conducted a study to estimate treated wastewater demand in the industrial clusters around Ballari city. They estimated that about 8.825 MLD of treated wastewater may be used in existing sponge iron factories and 15 MLD of treated wastewater may be required in the upcoming projects such as Kudathini Industrial Area and Uttam Galva Steel Plant.

Figure 16 shows the current and projected freshwater requirement for domestic and industrial purposes. The water requirement for the thermal power plants is calculated assuming an average PLF of 75% and average SWC of 3.5 m^3/MWh.

Figure 17 highlights the freshwater requirements for industrial purposes for the years 2030 and 2050, considering the use of treated wastewater in TPS and industries present in and around Ballari MC. Assuming the aforesaid power generation levels, as well as the current price of the treated wastewater the estimated annual savings for BTPS works out to be Rs. 88 million in 2030 and 126 million in 2050, with the reuse of treated wastewater in its facilities.

While the Nagpur Municipal Corporation (NMC) received Rs.900 million as a grant from the JNNURM to construct their first large STP at Bhandewadi in 2008, the GoK can also utilise a part of the funds set aside for socio-economic development of mining-affected districts (including, Ballari) in the report submitted by GoK to the Hon'ble Supreme Court of India on 9 October 2018 [95]. In their report, GoK had earmarked Rs. 14 billion for a drinking water project and Rs. 1.74 billion for an underground-drainage-cum sanitation project in mining affected Ballari town and adjoining urban areas. Once this proposal is approved by the Hon'ble

Table 14: Sewage Treatment Plants in the Ballari MC area

Sl. No.	Name	Capacity (in MLD)	Actual Utilisation (in MLD)	Type	Date of Commissioning
1	Anantapur Road	30	20	Facultative Aerated Lagoon (FAL)	2004
2.	Cowl Bazaar	15	7.5	Facultative Aerated Lagoon (FAL)	2004
3.	Enturi Nagar (Under construction)	10	-	Sequencing Batch Reactor (SBR)	-
4.	Talur Road (Under construction)	2	-	SBR	-
Total		**57**	**27.5**		

Supreme Court of India, GoK can commence work on these two schemes in Ballari town so that the STP-treated water can be supplied to BTPS at an agreed price, thereby reducing BTPS's freshwater withdrawal from the Tungabhadra reservoir and/or its canal system to this extent. This will be a great boon to the people living in the Ballari MC area.

Figure 16: Annual Freshwater withdrawal for Domestic and TPS & Industries (Mm^3) in 2019, 2030 and 2050 under Business As Usual (BAU) scenario

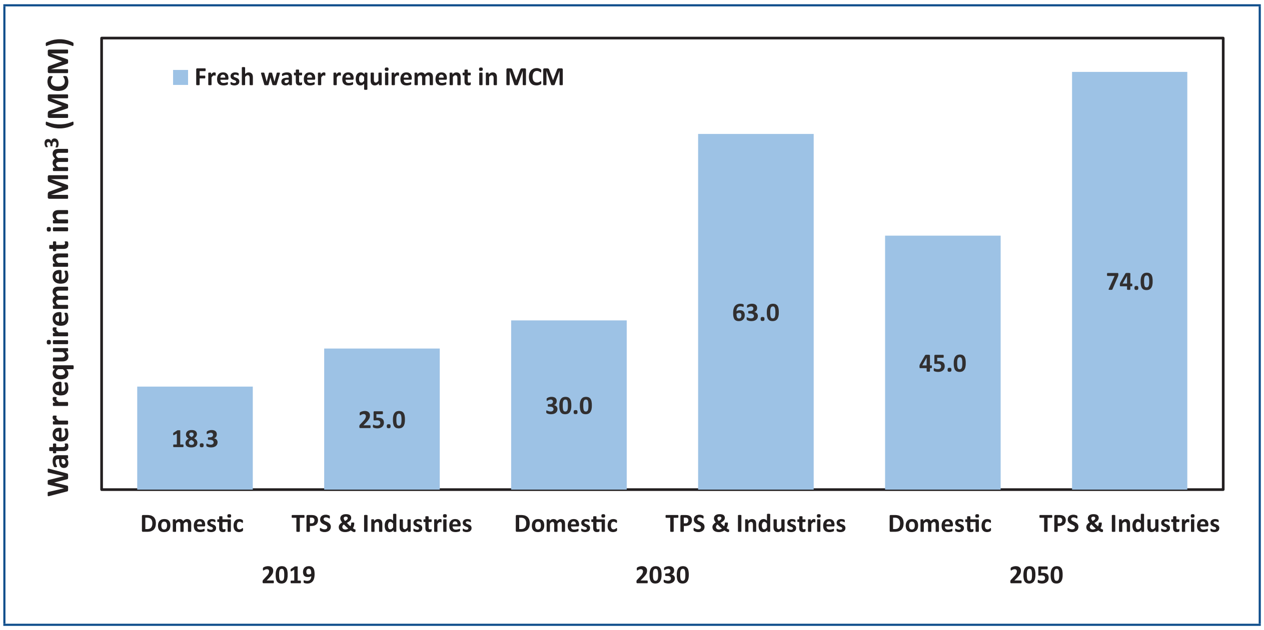
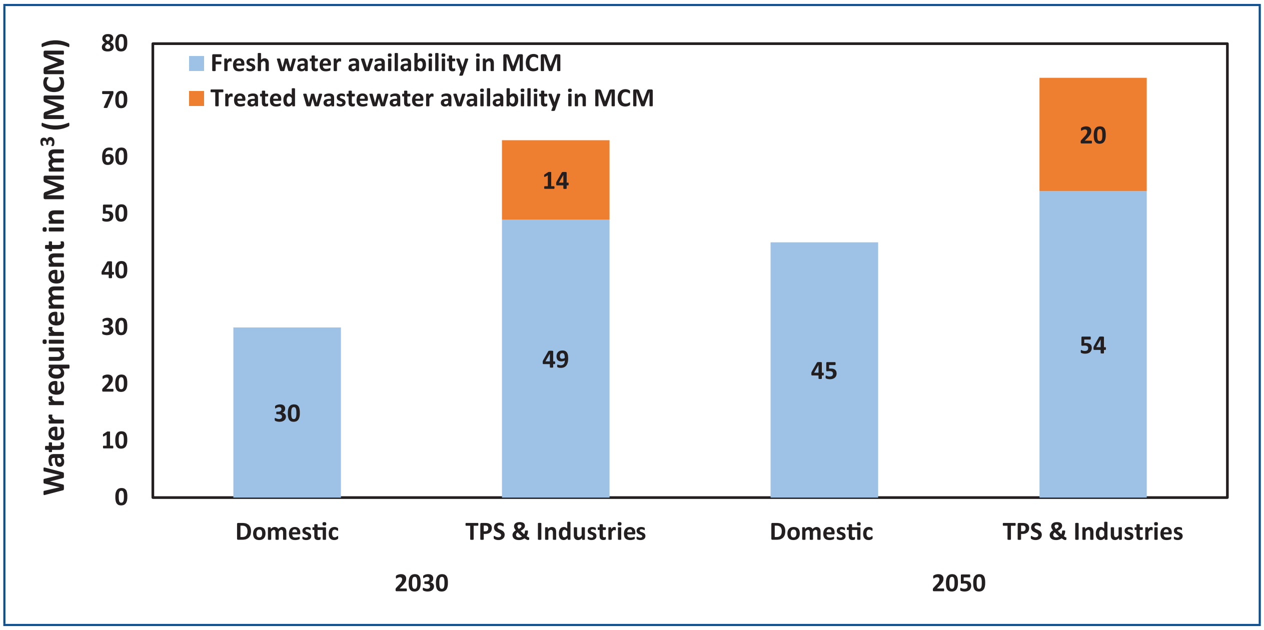


Figure 17: Annual Freshwater withdrawal for Domestic and Industrial consumption (Mm^3) in 2030 and 2050, considering the reuse of STP treated water in industries



Chapter 6

A Possible Business Model for Implementation of the use of STP-Treated Water

As discussed in **Chapter 5**, the GoK has already set aside ample funds for a drinking water project and for an underground-drainage-cum sanitation project in the mining affected Ballari district from the funds collected in the form of royalty from the mining companies for aiding the socio-economic development of mining-affected communities. Now, this is a special case where there was a ready availability of funds for public welfare. However, the situation in different urban centres across India may be quite different. Therefore, there is an urgent need to conceptualize and adopt a suitable business arrangement that might be applicable to a large number of towns across the country, especially those which are located in water-stressed regions.

Figure 18 encapsulates a novel proposal that might be considered by the thermal power plants and the urban local bodies responsible for managing the municipal town areas located in the vicinity of the TPPs (within a radius of 50 km).

As mentioned earlier, the National Tariff Policy (2016) mandated all coal-fired Thermal Power Plants (TPPs) located within 50 km radius of the STPs) belonging to urban local bodies (municipal corporations, or similar organisations) to use STP-treated wastewater. Further to this notification, India's Central Electricity Authority (CEA) had urged the thermal power plants in 2017 to enter into suitable agreements with respective local municipal bodies for using treated sewage water from the STPs located in the plant vicinity. Thereafter, MOEFCC issued guidelines for granting the Environmental Clearance (EC) to the TPPs in 2018, stating that the TPPs must use the treated sewage water from STPs located within a 50 km radius of the TPP.

Upon reviewing the arrangement of treated water supply between STPs and power plants, MoP issued a circular on 05 March 2020 to promote the use of treated sewage water. As per the current policy, collection of municipal sewage water within the town limits, transporting the same to a STP, and the construction, operation, and maintenance of the STP facility is the responsibility of ULB (Urban Local Body). After the secondary treatment in the STP, the treated sewage water transportation system is to be constructed by TPP, and the cost of transportation of treated sewage water up to the plant shall be borne by the TPP. The urban local bodies (ULB) shall facilitate the power plants in obtaining the right of way for laying the water transportation pipeline up to the TPP. The tertiary treatment plant is to be constructed by the power plants, and consequently, the cost of tertiary treatment plant will be borne by the TPP [96]. This essentially means that ***point C onwards*** in **Figure 18** is to be taken care of by the TPP.

As discussed earlier in detail (see **section 4.4)**, the water quality parameters required by the TPPs are standardized. Since several STPs installed by ULBs are equipped with old and inefficient technologies, they are unable to meet the water quality parameters in the treated sewage water, as required by the thermal power plants.

Also, most ULBs in India (other than those in the Megacities or 'Smart' Cities) lack the capacity and the financial strength to design and construct a large STP. Therefore, no progress is evident in the use of STP-treated water in TPPs located within 50 km of a town, despite the mandates of MoEFCC (2018 onwards) and the National Tariff Policy (2016).

To overcome this impasse and expedite the use of STP-treated water in TPPs, we propose that the responsibility for construction, operation, and maintenance of the STP itself (primary and secondary treatment) be assigned to the TPP under a bipartite agreement with the ULB, who is obliged to construct the town sanitation systems and deliver adequate amount of sewage to the STP constructed, operated, and maintained by the TPP. Since the construction and O &M of the STP will be a part of its business expenses, the TPP will be able to recover the cost through a suitable hike in the tariff as per the National Tariff Policy (2016). This essentially means that ***point B onwards*** in **Figure 18** should be a part of the business expenses of the TPP.

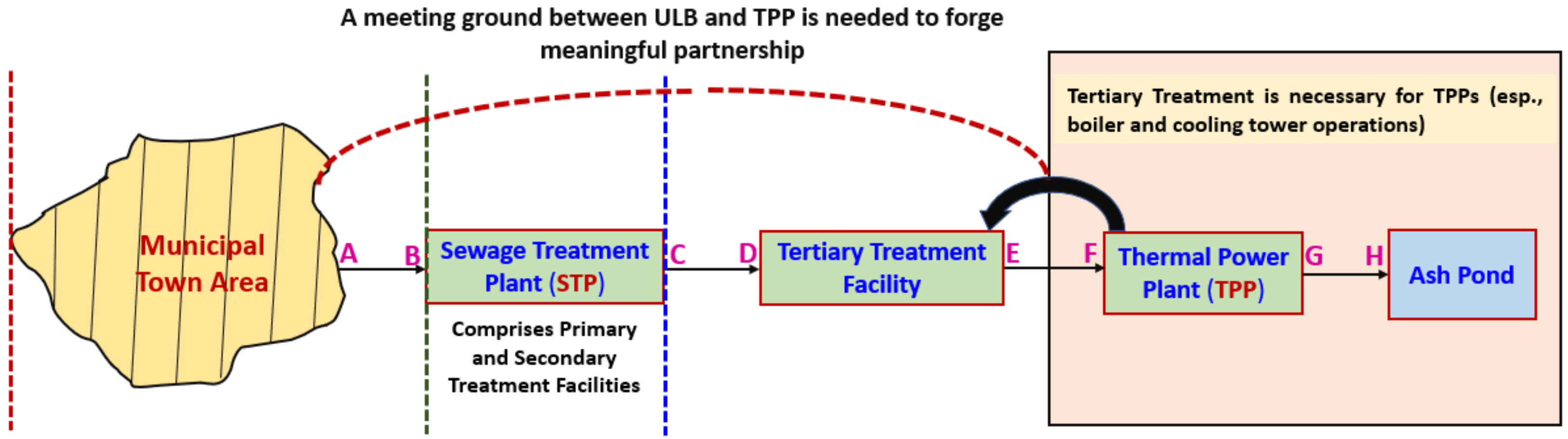
In case the ULB lacks the finances to undertake the construction of the Town Sanitation System (including UGDs), they can approach the Govt' (or even large companies in the vicinity of the town, as per the CSR Policy announced by the Government under the Companies Act 2013) for the required funds.

The opportunity for attracting CSR funds from the large companies is there since **Schedule VII** in **section 135** of the **Companies Act, 2013 (18 of 2013)** highlights *'sanitation'* as one of the key activities that can be undertaken by the companies as part of the *Company Social Responsibility (CSR) Policies* [97]. Schedule VII was brought into force with effect from 1st April 2014 and was amended (effective from 1st April 2014) vide notification number GSR 130(E) dated 27th February 2014 [98]. The full scope of the term '*sanitation*' mentioned in the Schedule VII has been further clarified in a notification dated October 24th, 2014, by saying that sanitation includes '*contribution to the Swach Bharat Kosh set-up by the Central Government for the promotion of sanitation*' [98].

By attracting the funds from various sources (including the sewerage tax collected by the urban municipal bodies) the ULBs can construct state-of-the-art STP facilities that will be able to provide the treated water with the quality parameters as desired by the tertiary treatment facilities managed by the TPPs. In order to ensure reliable availability of STP-treated water for the TPPs, the O & M of the UGD network and town sanitation systems must be regularly carried out by the ULB. The required operational expenses can be recovered from the TPP who will be using the treated wastewater.

For the above arrangement to materialize, a thorough stakeholder consultation is needed involving the GENCOs, urban local bodies, State-level administration, and the policymakers at the highest level in the Government of India, in order to understand the issues and challenges in the different water starved areas in the country. Further, a thorough field survey of underground drainage systems should take place in the urban town areas, to assess the status of sanitation system and the quantum of upgradation that might be required to ensure efficient collection of municipal sewage.

Figure 18: The conceptual template for the business model for expediting the use of STP-treated water in TPPs



1. As per the current policy, collection of municipal sewage water within the town limits, transporting the same to a STP, and the construction, operation and maintenance of the STP facility is the responsibility of ULB (Urban Local Body). However, most ULBs in India (other than those in the Megacities or 'Smart' Cities) lack the capacity and the financial strength to design and construct large STP. Therefore, no progress is evident in the use of STP-treated water in TPPs located within 50 km of a town, despite the mandates of MoEFCC (2018 onwards) and the National Tariff Policy (2016)

2. To overcome this impasse and expedite the use of STP-treated water in TPPs, we propose that the responsibility for construction, operation and maintenance of the STP itself (primary and secondary treatment) be assigned to the TPP under a bipartite agreement with the ULB, who is obliged to construct the town sanitation systems and deliver adequate amount of sewage to the STP constructed, operated, and maintained by the TPP. Since the construction and O &M of the STP will be a part of its business expenses, the TPP will be able to recover the cost through a suitable hike in the tariff as per the National Tariff Policy (2016).

3. In case the ULB lacks the finances to undertake the construction of the Town Sanitation System (including UGDs), they can approach the Govt' (or even large companies in the vicinity of the town, as per the CSR Policy announced by the Government under the Companies Act 2013) for the required funds.

4. The O& M of the UGD network and town sanitation systems need to be regularly carried out by the ULB. The required operational expenses can be recovered from the TPP who will be using the treated wastewater.

Chapter 7

Conclusions and Policy Recommendations

Rapid urbanisation, increased need of energy and water, combined with susceptibility to severe drought render water supply a crucial issue in water stressed districts like Raichur and Ballari. In the absence of improved water infrastructure and efficient water management strategies, both districts will face serious socio-economic and environmental consequences, not only in cities but also in surrounding rural areas. This study proposes an integrated approach towards realizing multiple targets under SDGs 6 and 7.

If the thermal power plants in these areas use treated wastewater, then an additional freshwater can be made available for Raichur (9.8 Mm^3 per year) and Ballari cities (14 Mm^3 per year) by 2030 to meet the domestic requirement. This will translate to an additional 30-40 litres per capita a day (lpcd) of drinking water availability for the city dwellers. Usage of the treated wastewater instead of fresh water will substantially reduce the power plant's expenses associated with water, and selling of the wastewater would ensure additional income for the city administration that can be utilized to upgrade their sewage infrastructures.

By ensuring enhanced availability of drinking water for the city dwellers SDG target 6.1 can be achieved, which emphasizes universal and equitable access to safe and affordable drinking water for all. The upgradation and modernization of underground drainage (UGD) network and sewage handling infrastructure will pave way for achieving target 6.2, which aims for access to adequate and equitable sanitation and hygiene. The use of treated wastewater by the TPPs would help in realizing target 6.3, which largely focuses on reducing the quantum of untreated wastewater through recycling and ensuring safe reuse of treated wastewater. This would however require a suitable business model involving the thermal power plant and the urban local body. The prudent reuse of treated wastewater would increase the availability of potable water for the water-parched areas, which inherently serves the purpose delineated in target 6.4, to increase water-use efficiency across all sectors and to ensure sustainable withdrawals and supply of freshwater to address water scarcity.

Fresh water savings can be achieved by increasing the CoC in the TPPs which would need improvements in the water treatment facilities. Such improvements can be planned in an integrated manner considering other infrastructural upgradation that might be needed to ensure minimal losses and optimal water consumption in the TPPs located in the water stressed regions across India. Since our study comprises TPPs belonging to the water stressed areas of four different states in India (Karnataka, Madhya Pradesh, Chhattisgarh, and Andhra Pradesh), this approach is not location specific and can be extended for different places by incorporating suitable customisation in the methodology.

The use of treated wastewater in TPS would reduce the loss of generation due to shortage of water, and the power plants can be consistently run at higher PLFs leading to further efficiencies in the usage of water. This would ensure the realization of target 7.1 aimed at ensuring universal access to affordable, reliable, sustainable, and modern energy.

Also, the additional amount freshwater (surface water) that can be saved through reuse of treated wastewater in TPS would alleviate the need for groundwater pumping. This leads to enhancement in energy efficiency (target 7.3) since additional electricity can be provided to the consumers, which would have otherwise been spent in pumping groundwater. Overall, the different measures suggested in the current approach would lead to the realization of integrated water resource management (target 6.5) forming a key strategy for the long-term sustainable future.

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Annexure

Table A1: Calculation of Root Mean Square Error (RMSE) values for the Makeup water requirement (m^3/hr) of Rayalaseema TPS - Stage 1 (2 x 210 MW)

Month / Year	CoC (Rayalaseema TPS Stage 1 - 2 x 210 MW)	Make-up water per TPP Unit (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water per TPP Unit (m^3/hr) using best-fit on operational CoC values	Make-up water per TPP Unit (m^3/hr) fusing best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-2019	1.49	775.41	775.54	749.70	0.0	660.9
May-2019	1.47	797.55	798.30	729.30	0.6	4658.5
Jun-2019	1.49	775.41	775.54	749.70	0.0	660.9
Jul-2019	1.36	680.00	680.83	674.33	0.7	32.2
Aug-2019	1.41	876.95	876.81	764.99	0.0	12535.4
Sep-2019	1.57	702.37	701.54	687.82	0.7	211.7
Oct-2019	1.59	687.20	687.31	678.79	0.0	70.8
				Sum of Squares	1.99	18830.3
				RMSE (m^3/hr)	**0.53**	**51.87**

Table A2: Calculation of Root Mean Square Error (RMSE) values for the Specific Water Consumption (m^3/MWh) of Rayalaseema TPS - Stage 1 (2 x 210 MW)

Month / Year	CoC (Rayalaseema TPS Stage 1 - 2 x 210 MW)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on operational CoC values	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-2019	1.490	4.946	4.947	4.782	0.000	0.027
May-2019	1.470	5.045	5.049	4.613	0.000	0.186
Jun-2019	1.490	5.200	5.201	5.028	0.000	0.030
Jul-2019	1.600	5.097	5.103	5.055	0.000	0.002
Aug-2019	1.410	7.828	7.827	6.829	0.000	0.999
Sep-2019	1.570	7.165	7.157	7.017	0.000	0.022
Oct-2019	1.590	7.487	7.488	7.395	0.000	0.008
				Sum of Squares	0.00	1.27
				RMSE (m^3/MWh)	**0.00**	**0.43**

Table A3: Calculation of Root Mean Square Error (RMSE) values for the Makeup water requirement (m^3/hr) of Rayalaseema TPS - Stage 2 (2 x 210 MW)

Month / Year	CoC (Rayalaseema TPS Stage 2 - 2 x 210 MW)	Make-up water per TPP Unit (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water per TPP Unit (m^3/hr) using best-fit on operational CoC values	Make-up water per TPP Unit (m^3/hr) fusing best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-2019	2.44	432.08	433.92	422.05	3.4	140.9
May-2019	2.48	328.28	331.19	327.69	8.5	12.3
Jun-2019	2.56	418.46	422.64	405.79	17.5	284.1
Jul-2019	2.39	438.45	438.81	430.28	0.1	72.7
Aug-2019	2.68	406.79	412.02	394.47	27.4	308.0
Sep-2019	2.30	451.15	447.90	447.27	10.6	0.4
Oct-2019	2.27	455.79	451.02	453.55	22.8	6.4
				Sum of Squares	90.19	824.93
				RMSE (m^3/hr)	**3.59**	**10.86**

Table A4: Calculation of Root Mean Square Error (RMSE) values for the Specific Water Consumption (m^3/MWh) of Rayalaseema TPS - Stage 2 (2 x 210 MW)

Month / Year	CoC (Rayalaseema TPS Stage 2 - 2 x 210 MW)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on operational CoC values	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-2019	2.44	2.96	2.97	2.89	0.0002	0.0066
May-2019	2.48	1.98	2.00	1.98	0.0003	0.0004
Jun-2019	2.56	2.73	2.75	2.64	0.0007	0.0121
Jul-2019	2.39	3.23	3.23	3.17	0.0000	0.0039
Aug-2019	2.68	3.02	3.06	2.93	0.0015	0.0170
Sep-2019	2.3	5.33	5.30	5.29	0.0015	0.0001
Oct-2019	2.27	4.47	4.42	4.45	0.0022	0.0006
				Sum of Squares	0.01	0.04
				RMSE (m^3/MWh)	**0.03**	**0.08**

Table A5: Calculation of Root Mean Square Error (RMSE) values for the Makeup water requirement (m^3/hr) of Rayalaseema TPS - Stage 3 (1 x 210 MW)

Month / Year	CoC (Rayalaseema TPS Stage 3 - 1 x 210 MW)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-2019	3.81	345.75	344.08	347.08	2.8	9.0
May-2019	3.92	342.33	340.56	343.45	3.1	8.4
Jun-2019	3.71	349.10	347.75	350.52	1.8	7.7
Jul-2019	3.5	357.00	356.94	358.22	0.0	1.6
Aug-2019	3.62	352.33	351.44	353.74	0.8	5.3
Sep-2019	3.74	348.07	346.60	349.47	2.2	8.3
Oct-2019	3.41	360.81	361.49	361.71	0.5	0.0
				Sum of Squares	11.14	40.28
				RMSE (m^3/hr)	**1.26**	**2.40**

Table A6: Calculation of Root Mean Square Error (RMSE) values for the Specific Water Consumption (m^3/MWh) of Rayalaseema TPS - Stage 3 (1 x 210 MW)

Month / Year	**CoC (Rayalaseema TPS Stage 3 - 1 x 210 MW)**	**Reflection of Actual Make-up water requirement on SWC (m^3/MWh)**	**Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on operational CoC values**	**Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on synthetic CoC values**	**Square Error (Actual vs. best fit on operational CoC data)**	**Square Error (Actual vs. best fit on synthetic CoC data)**
Apr-2019	3.81	3.09	3.08	3.10	0.0002	0.0007
May-2019	3.92	2.10	2.09	2.11	0.0001	0.0003
Jun-2019	3.71	2.31	2.30	2.32	0.0001	0.0003
Jul-2019	3.5	3.17	3.17	3.18	0.0000	0.0001
Aug-2019	3.62	2.51	2.50	2.52	0.0000	0.0003
Sep-2019	3.74	37.40	37.25	37.56	0.0248	0.0954
Oct-2019	3.41	5.27	5.28	5.28	0.0001	0.0000
				Sum of Squares	0.03	0.10
				RMSE (m^3/MWh)	**0.06**	**0.12**

Table A7: Calculation of Root Mean Square Error (RMSE) values for the Makeup water requirement (m^3/hr) of Satpura TPS – Unit 10 (1 x 250 MW)

Month / Year	CoC Values for Unit 10 (Operational data)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	2.23	539.37	540.66	539.41	1.66	0.00
May-19	2.44	504.10	505.20	492.32	1.21	138.64
Jun-19	2.04	583.56	578.12	597.24	29.52	187.28
Jul-19	1.94	613.99	614.17	633.49	0.03	380.18
Aug-19	2.36	516.25	517.97	508.18	2.95	65.14
Sep-19	2.38	513.08	514.69	503.97	2.59	82.90
Oct-19	2.02	589.17	582.37	604.17	46.25	225.14
Nov-19	1.9	628.06	627.27	649.11	0.61	443.16
Dec-19	2.04	583.56	578.12	597.24	29.52	187.28
Jan-20	2.09	570.44	567.77	580.62	7.11	103.77
Feb-20	2.21	543.37	544.36	544.82	0.98	2.11
Mar-20	2.21	543.37	544.36	544.82	0.98	2.11
Apr-20	2.31	524.60	526.41	519.39	3.28	27.12
May-20	2.36	516.25	517.97	508.18	2.95	65.14
Jun-20	2.4	510.00	511.47	499.93	2.16	101.40
Jul-20	2.54	490.68	490.51	476.11	0.03	212.43
Aug-20	2.28	529.92	531.65	526.60	2.98	11.04
Sep-20	2.06	578.16	573.94	590.47	17.82	151.64
Oct-20	2.22	541.35	542.50	542.10	1.32	0.55
Nov-20	2.17	551.77	551.94	556.11	0.03	18.84

Month / Year	CoC Values for Unit 10 (Operational data)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Dec-20	2.17	551.77	551.94	556.11	0.03	18.84
Jan-21	2.22	541.35	542.50	542.10	1.32	0.55
Feb-21	2.29	528.12	529.89	524.16	3.12	15.71
Mar-21	2.55	489.44	489.12	474.71	0.10	216.97
Apr-21	2.5	495.83	496.21	482.11	0.14	188.26
May-21	2.33	521.18	522.99	514.79	3.27	40.93
Jun-21	2.06	578.16	573.94	590.47	17.82	151.64
Jul-21	2.32	522.88	524.69	517.07	3.30	33.75
Aug-21	1.85	647.50	646.61	669.53	0.79	485.43
Sep-21	1.91	624.42	623.80	645.14	0.39	429.27
Oct-21	2.39	511.53	513.07	501.93	2.38	92.09
Nov-21	2.22	541.35	542.50	542.10	1.32	0.55
Dec-21	2.74	468.48	465.38	455.69	9.60	163.43
Jan-22	3.44	419.43	422.06	420.63	6.94	1.44
Feb-22	3.25	429.72	426.95	429.57	7.67	0.02
Mar-22	2.88	455.74	451.16	450.94	21.02	23.11
				Sum of Squares	233.20	4267.88
				RMSE (m^3/hr)	**2.55**	**10.89**

Table A8: Calculation of Root Mean Square Error (RMSE) values for the Specific Water Consumption (m^3/MWh) of Satpura TPS – Unit 10 (1 x 250 MW)

Month / Year	CoC Values for Unit 10 (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on operational CoC values	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	2.23	2.45	2.45	2.45	0.0000	0.000
May-19	2.44	4.08	4.09	3.98	0.0001	0.009
Jun-19	2.04	5.13	5.09	5.25	0.0023	0.014
Jul-19	1.94	5.73	5.73	5.91	0.0000	0.033
Aug-19	2.36	3.55	3.56	3.49	0.0001	0.003
Sep-19	2.38	4.15	4.16	4.07	0.0002	0.005
Oct-19	2.02	30.19	29.85	30.96	0.1215	0.591
Nov-19	1.9	3.21	3.21	3.32	0.0000	0.012
Dec-19	2.04	2.59	2.56	2.65	0.0006	0.004
Jan-20	2.09	2.64	2.63	2.69	0.0002	0.002
Feb-20	2.21	2.20	2.20	2.21	0.0000	0.000
Mar-20	2.21	2.63	2.63	2.63	0.0000	0.000
Apr-20	2.31	2.56	2.57	2.54	0.0001	0.001
May-20	2.36	2.43	2.44	2.39	0.0001	0.001
Jun-20	2.4	2.62	2.63	2.57	0.0001	0.003
Jul-20	2.54	1.99	1.99	1.93	0.0000	0.004
Aug-20	2.28	3.71	3.72	3.68	0.0001	0.001
Sep-20	2.06	3.67	3.64	3.75	0.0007	0.006
Oct-20	2.22	2.26	2.27	2.26	0.0000	0.000

Month / Year	CoC Values for Unit 10 (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on operational CoC values	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Nov-20	2.17	2.48	2.48	2.49	0.0000	0.000
Dec-20	2.17	2.38	2.38	2.40	0.0000	0.000
Jan-21	2.22	2.40	2.41	2.41	0.0000	0.000
Feb-21	2.29	2.18	2.19	2.16	0.0001	0.000
Mar-21	2.55	2.12	2.11	2.05	0.0000	0.004
Apr-21	2.5	2.06	2.06	2.00	0.0000	0.003
May-21	2.33	2.84	2.85	2.81	0.0001	0.001
Jun-21	2.06	4.01	3.98	4.09	0.0009	0.007
Jul-21	2.32	2.51	2.52	2.48	0.0001	0.001
Aug-21	1.85	5.30	5.29	5.48	0.0001	0.032
Sep-21	1.91	3.34	3.34	3.45	0.0000	0.012
Oct-21	2.39	2.60	2.61	2.55	0.0001	0.002
Nov-21	2.22	3.11	3.11	3.11	0.0000	0.000
Dec-21	2.74	2.05	2.03	1.99	0.0002	0.003
Jan-22	3.44	2.14	2.15	2.15	0.0002	0.000
Feb-22	3.25	1.77	1.76	1.77	0.0001	0.000
Mar-22	2.88	1.88	1.86	1.86	0.0004	0.000
				Sum of Squares	0.13	0.76
				RMSE (m^3/MWh)	**0.06**	**0.15**

Table A9: Calculation of Root Mean Square Error (RMSE) values for the Makeup water requirement (m^3/hr) of Satpura TPS – Unit 11 (1 x 250 MW)

Month / Year	CoC Values for Unit 11 (Operational data)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	2.4	510.00	511.47	499.93	2.16	133.14
May-19	2.28	529.92	531.65	526.60	2.98	25.48
Jun-19	2.25	535.50	537.01	534.17	2.28	8.08
Jul-19	1.6	793.33	792.66	786.68	0.46	35.71
Aug-19	2.42	507.01	508.30	496.05	1.68	150.26
Sep-19	2.27	531.75	533.42	529.08	2.78	18.82
Oct-19	1.92	620.87	620.46	641.22	0.17	430.95
Nov-19	1.93	617.39	617.25	637.33	0.02	403.40
Dec-19	2.04	583.56	578.12	597.24	29.52	365.52
Jan-20	2.1	567.95	565.74	577.42	4.90	136.40
Feb-20	2.23	539.37	540.66	539.41	1.66	1.54
Mar-20	2.22	541.35	542.50	542.10	1.32	0.16
Apr-20	2.33	521.18	522.99	514.79	3.27	67.32
May-20	2.34	519.51	521.30	512.54	3.20	76.72
Jun-20	2.41	508.49	509.88	497.97	1.92	141.88
Jul-20	2.59	484.61	483.69	469.50	0.83	201.41
Aug-20	2.2	545.42	546.23	547.58	0.67	1.83
Sep-20	2.04	583.56	578.12	597.24	29.52	365.52
Oct-20	2.23	539.37	540.66	539.41	1.66	1.54
Nov-20	2.18	549.62	550.02	553.23	0.16	10.30

Month / Year	CoC Values for Unit 11 (Operational data)	Make-up water (m³/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m³/hr) using best- fit on operational CoC values	Make-up water (m³/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Dec-20	2.17	551.77	551.94	556.11	0.03	17.45
Jan-21	2.21	543.37	544.36	544.82	0.98	0.21
Feb-21	2.3	526.35	528.14	521.75	3.23	40.81
Mar-21	2.53	491.94	491.91	477.55	0.00	206.31
Apr-21	2.52	493.22	493.33	479.03	0.01	204.54
May-21	2.35	517.87	519.63	510.34	3.09	86.25
Jun-21	2.12	563.13	561.73	571.13	1.96	88.48
Jul-21	2.32	522.88	524.69	517.07	3.30	58.15
Aug-21	1.73	705.03	706.45	722.64	2.01	262.05
Sep-21	1.94	613.99	614.17	633.49	0.03	373.21
Oct-21	2.41	508.49	509.88	497.97	1.92	141.88
Nov-21	2.24	537.42	538.83	536.77	1.98	4.22
Dec-21	2.77	465.58	462.10	454.01	12.12	65.36
Jan-22	3.49	416.98	421.62	418.37	21.58	10.56
Feb-22	3.28	427.98	425.84	428.12	4.59	5.20
Mar-22	2.91	453.26	448.47	450.94	22.89	6.08
				Sum of Squares	170.88	4146.72
				RMSE (m³/hr)	**2.18**	**10.73**

Table A10: Calculation of Root Mean Square Error (RMSE) values for the Specific Water Consumption (m^3/MWh) of Satpura TPS – Unit 11 (2 x 250 MW)

Month / Year	CoC Values for Unit 11 (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on operational CoC values	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	2.4	2.31	2.32	2.27	0.0000	0.0027
May-19	2.28	4.29	4.30	4.26	0.0002	0.0017
Jun-19	2.25	4.71	4.72	4.70	0.0002	0.0006
Jul-19	1.6	7.40	7.40	7.34	0.0000	0.0031
Aug-19	2.42	3.48	3.49	3.41	0.0001	0.0071
Sep-19	2.27	4.30	4.31	4.28	0.0002	0.0012
Oct-19	1.92	31.82	31.80	32.86	0.0004	1.1319
Nov-19	1.93	3.16	3.16	3.26	0.0000	0.0106
Dec-19	2.04	2.59	2.56	2.65	0.0006	0.0072
Jan-20	2.1	2.63	2.62	2.67	0.0001	0.0029
Feb-20	2.23	2.18	2.19	2.18	0.0000	0.0000
Mar-20	2.22	2.62	2.62	2.62	0.0000	0.0000
Apr-20	2.33	2.54	2.55	2.51	0.0001	0.0016
May-20	2.34	2.44	2.45	2.41	0.0001	0.0017
Jun-20	2.41	2.62	2.62	2.56	0.0001	0.0038
Jul-20	2.59	1.97	1.96	1.91	0.0000	0.0033
Aug-20	2.2	3.81	3.82	3.83	0.0000	0.0001
Sep-20	2.04	3.70	3.67	3.79	0.0012	0.0147
Oct-20	2.23	2.25	2.26	2.25	0.0000	0.0000

Month / Year	CoC Values for Unit 11 (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on operational CoC values	Reflection of Make-up water requirement on SWC (m^3/MWh) for best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Nov-20	2.18	2.47	2.47	2.48	0.0000	0.0002
Dec-20	2.17	2.38	2.38	2.40	0.0000	0.0003
Jan-21	2.21	2.41	2.42	2.42	0.0000	0.0000
Feb-21	2.3	2.17	2.18	2.15	0.0001	0.0007
Mar-21	2.53	2.13	2.13	2.06	0.0000	0.0039
Apr-21	2.52	2.05	2.05	1.99	0.0000	0.0035
May-21	2.35	2.82	2.83	2.78	0.0001	0.0026
Jun-21	2.12	3.90	3.89	3.96	0.0001	0.0042
Jul-21	2.32	2.51	2.52	2.48	0.0001	0.0013
Aug-21	1.73	5.77	5.78	5.91	0.0001	0.0175
Sep-21	1.94	3.29	3.29	3.39	0.0000	0.0107
Oct-21	2.41	2.59	2.59	2.53	0.0000	0.0037
Nov-21	2.24	3.08	3.09	3.08	0.0001	0.0001
Dec-21	2.77	2.03	2.02	1.98	0.0002	0.0012
Jan-22	3.49	2.13	2.15	2.14	0.0006	0.0003
Feb-22	3.28	1.77	1.76	1.77	0.0001	0.0001
Mar-22	2.91	1.87	1.85	1.86	0.0004	0.0001
				Sum of Squares	0.005	1.245
				RMSE (m^3/MWh)	**0.012**	**0.186**

Table A11: Calculation of Root Mean Square Error (RMSE) values for the Makeup water requirement (m^3/hr) in a 250 MW unit in Satpura TPS using the average CoC values

Month / Year	Average of CoC Values from Units 10 & 11 (Operational data)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	2.32	523.74	525.55	518.23	3.30	53.67
May-19	2.36	516.25	517.97	508.18	2.95	95.83
Jun-19	2.15	557.33	556.79	563.50	0.29	45.04
Jul-19	1.77	683.86	684.40	704.30	0.29	395.85
Aug-19	2.39	511.53	513.07	501.93	2.38	124.10
Sep-19	2.33	522.03	523.84	515.92	3.29	62.70
Oct-19	1.97	604.20	605.72	622.19	2.31	271.30
Nov-19	1.92	622.64	622.11	643.17	0.28	443.62
Dec-19	2.04	583.56	578.12	597.24	29.52	365.52
Jan-20	2.10	569.19	566.75	579.02	5.94	150.39
Feb-20	2.22	541.35	542.50	542.10	1.32	0.16
Mar-20	2.22	542.36	543.43	543.45	1.15	0.00
Apr-20	2.32	522.88	524.69	517.07	3.30	58.15
May-20	2.35	517.87	519.63	510.34	3.09	86.25
Jun-20	2.41	509.24	510.67	498.94	2.04	137.55
Jul-20	2.57	487.60	487.06	472.68	0.29	206.69
Aug-20	2.24	537.42	538.83	536.77	1.98	4.22
Sep-20	2.05	580.83	576.02	593.84	23.12	317.34
Oct-20	2.23	540.36	541.58	540.75	1.49	0.68

Month / Year	Average of CoC Values from Units 10 & 11 (Operational data)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Nov-20	2.18	550.69	550.98	554.67	0.08	13.62
Dec-20	2.17	551.77	551.94	556.11	0.03	17.45
Jan-21	2.22	542.36	543.43	543.45	1.15	0.00
Feb-21	2.30	527.23	529.01	522.95	3.18	36.76
Mar-21	2.54	490.68	490.51	476.11	0.03	207.35
Apr-21	2.51	494.52	494.76	480.55	0.06	202.03
May-21	2.34	519.51	521.30	512.54	3.20	76.72
Jun-21	2.09	570.44	567.77	580.62	7.11	165.23
Jul-21	2.32	522.88	524.69	517.07	3.30	58.15
Aug-21	1.79	674.08	674.16	695.37	0.01	449.48
Sep-21	1.93	619.12	618.84	639.27	0.08	417.53
Oct-21	2.40	510.00	511.47	499.93	2.16	133.14
Nov-21	2.23	539.37	540.66	539.41	1.66	1.54
Dec-21	2.76	467.02	463.72	454.81	10.85	79.46
Jan-22	3.47	418.19	421.80	419.50	13.02	5.30
Feb-22	3.27	428.85	426.38	428.84	6.08	6.07
Mar-22	2.90	454.49	449.80	450.89	22.00	1.19
				Sum of Squares	162.31	4690.06
				RMSE (m^3/hr)	**2.12**	**11.41**

Table A12: Calculation of Root Mean Square Error (RMSE) values for the Specific Water Consumption (m^3/MWh) in a 250 MW unit in Satpura TPS using the average CoC values

Month / Year	Average of CoC Values from Units 10 & 11 (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on operational CoC	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on synthetic CoC	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	2.32	2.38	2.38	2.35	0.000068	0.0006
May-19	2.36	4.18	4.19	4.11	0.000193	0.0043
Jun-19	2.15	4.90	4.90	4.96	0.000022	0.0029
Jul-19	1.77	6.38	6.39	6.57	0.000025	0.0364
Aug-19	2.39	3.51	3.53	3.45	0.000112	0.0043
Sep-19	2.33	4.22	4.23	4.17	0.000215	0.0024
Oct-19	1.97	30.97	31.04	31.89	0.006079	0.8503
Nov-19	1.92	3.18	3.18	3.29	0.000007	0.0110
Dec-19	2.04	2.59	2.56	2.65	0.000580	0.0037
Jan-20	2.10	2.64	2.63	2.68	0.000127	0.0021
Feb-20	2.22	2.19	2.20	2.19	0.000022	0.0000
Mar-20	2.22	2.62	2.63	2.63	0.000027	0.0000
Apr-20	2.32	2.55	2.56	2.52	0.000079	0.0008
May-20	2.35	2.44	2.44	2.40	0.000068	0.0013
Jun-20	2.41	2.62	2.63	2.57	0.000054	0.0028
Jul-20	2.57	1.98	1.98	1.92	0.000005	0.0037
Aug-20	2.24	3.76	3.77	3.75	0.000097	0.0000
Sep-20	2.05	3.69	3.66	3.77	0.000932	0.0068
Oct-20	2.23	2.26	2.26	2.26	0.000026	0.0000

Month / Year	Average of CoC Values from Units 10 & 11 (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on operational CoC	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on synthetic CoC	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Nov-20	2.18	2.47	2.47	2.49	0.000002	0.0003
Dec-20	2.17	2.38	2.38	2.40	0.000000	0.0004
Jan-21	2.22	2.41	2.41	2.41	0.000023	0.0000
Feb-21	2.30	2.18	2.18	2.16	0.000054	0.0003
Mar-21	2.54	2.12	2.12	2.06	0.000001	0.0040
Apr-21	2.51	2.06	2.06	2.00	0.000001	0.0034
May-21	2.34	2.83	2.84	2.79	0.000095	0.0014
Jun-21	2.09	3.95	3.93	4.02	0.000342	0.0050
Jul-21	2.32	2.51	2.52	2.48	0.000076	0.0008
Aug-21	1.79	5.51	5.51	5.69	0.000000	0.0303
Sep-21	1.93	3.31	3.31	3.42	0.000002	0.0116
Oct-21	2.40	2.59	2.60	2.54	0.000056	0.0026
Nov-21	2.23	3.09	3.10	3.09	0.000055	0.0000
Dec-21	2.76	2.04	2.03	1.99	0.000207	0.0028
Jan-22	3.47	2.13	2.15	2.14	0.000339	0.0000
Feb-22	3.27	1.77	1.76	1.77	0.000104	0.0000
Mar-22	2.90	1.88	1.86	1.86	0.000376	0.0002
				Sum of Squares	0.01	1.00
				RMSE (m^3/MWh)	**0.02**	**0.17**

Table A13: Calculation of Root Mean Square Error (RMSE) values for the Makeup water requirement (m^3/hr) in a 500 MW Unit of ABVTPS

Month / Year	CoC Values (Operational data)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	5	637.50	637.53	634.15	0.0011	11.22
May-19	4.7	647.84	647.87	645.48	0.0009	5.56
Jun-19	5.1	634.39	634.44	630.94	0.0021	11.88
Jul-19	5	637.50	637.53	634.15	0.0011	11.22
Aug-19	4.9	640.77	640.80	637.64	0.0012	9.78
Sep-19	4.8	644.21	644.25	641.42	0.0014	7.80
Oct-19	5	637.50	637.53	634.15	0.0011	11.22
Nov-19	4.8	644.21	644.25	641.42	0.0014	7.80
Dec-19	5	637.50	637.53	634.15	0.0011	11.22
Jan-20	5	637.50	637.53	634.15	0.0011	11.22
Feb-20	4.7	647.84	647.87	645.48	0.0009	5.56
Mar-20	5	637.50	637.53	634.15	0.0011	11.22
Apr-20	5	637.50	637.53	634.15	0.0011	11.22
May-20	5	637.50	637.53	634.15	0.0011	11.22
Jun-20	4.8	644.21	644.25	641.42	0.0014	7.80
Jul-20	5	637.50	637.53	634.15	0.0011	11.22
Aug-20	5	637.50	637.53	634.15	0.0011	11.22
Sep-20	4.7	647.84	647.87	645.48	0.0009	5.56
Oct-20	4.9	640.77	640.80	637.64	0.0012	9.78
Nov-20	4.9	640.77	640.80	637.64	0.0012	9.78

Month / Year	CoC Values (Operational data)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Dec-20	4.8	644.21	644.25	641.42	0.0014	7.80
Jan-21	4.9	640.77	640.80	637.64	0.0012	9.78
Feb-21	4.9	640.77	640.80	637.64	0.0012	9.78
Mar-21	4.9	640.77	640.80	637.64	0.0012	9.78
Apr-21	5	637.50	637.53	634.15	0.0011	11.22
May-21	5	637.50	637.53	634.15	0.0011	11.22
Jun-21	5	637.50	637.53	634.15	0.0011	11.22
Jul-21	4.9	640.77	640.80	637.64	0.0012	9.78
Aug-21	4.9	640.77	640.80	637.64	0.0012	9.78
Sep-21	4.9	640.77	640.80	637.64	0.0012	9.78
Oct-21	4.9	640.77	640.80	637.64	0.0012	9.78
Nov-21	4.9	640.77	640.80	637.64	0.0012	9.78
Dec-21	4.9	640.77	640.80	637.64	0.0012	9.78
Jan-22	5	637.50	637.53	634.15	0.0011	11.22
Feb-22	5	637.50	637.53	634.15	0.0011	11.22
Mar-22	5	637.50	637.53	634.15	0.0011	11.22
				Sum of Squares	0.04	356.67
				RMSE (m^3/hr)	**0.03**	**3.15**

Table A14: Calculation of Root Mean Square Error (RMSE) values for the Specific Water Consumption (m^3/MWh) in a 500 MW Unit of ABVTPS

Month / Year	CoC Values (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on operational CoC	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on synthetic CoC	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	5	1.94	1.94	1.93	0.00000001	0.0001
May-19	4.7	3.77	3.77	3.76	0.00000003	0.0002
Jun-19	5.1	2.07	2.07	2.06	0.00000002	0.0001
Jul-19	5	1.78	1.78	1.77	0.00000001	0.0001
Aug-19	4.9	2.67	2.67	2.66	0.00000002	0.0002
Sep-19	4.8	2.77	2.77	2.76	0.00000003	0.0001
Oct-19	5	2.98	2.98	2.97	0.00000002	0.0002
Nov-19	4.8	3.52	3.52	3.50	0.00000004	0.0002
Dec-19	5	2.01	2.01	2.00	0.00000001	0.0001
Jan-20	5	3.20	3.20	3.18	0.00000003	0.0003
Feb-20	4.7	2.81	2.81	2.80	0.00000002	0.0001
Mar-20	5	3.16	3.16	3.14	0.00000003	0.0003
Apr-20	5	3.16	3.16	3.15	0.00000003	0.0003
May-20	5	3.26	3.26	3.24	0.00000003	0.0003
Jun-20	4.8	3.14	3.14	3.12	0.00000003	0.0002
Jul-20	5	2.19	2.19	2.18	0.00000001	0.0001
Aug-20	5	1.88	1.88	1.87	0.00000001	0.0001
Sep-20	4.7	2.76	2.76	2.75	0.00000002	0.0001
Oct-20	4.9	3.13	3.13	3.12	0.00000003	0.0002
Nov-20	4.9	2.03	2.03	2.02	0.00000001	0.0001

Month / Year	CoC Values (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on operational CoC	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on synthetic CoC	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Dec-20	4.8	1.93	1.93	1.92	0.00000001	0.0001
Jan-21	4.9	2.05	2.05	2.04	0.00000001	0.0001
Feb-21	4.9	2.58	2.58	2.57	0.00000002	0.0002
Mar-21	4.9	1.90	1.90	1.89	0.00000001	0.0001
Apr-21	5	1.76	1.76	1.75	0.00000001	0.0001
May-21	5	2.04	2.04	2.02	0.00000001	0.0001
Jun-21	5	2.18	2.18	2.17	0.00000001	0.0001
Jul-21	4.9	3.33	3.33	3.32	0.00000003	0.0003
Aug-21	4.9	2.27	2.27	2.25	0.00000001	0.0001
Sep-21	4.9	2.79	2.79	2.78	0.00000002	0.0002
Oct-21	4.9	2.48	2.48	2.47	0.00000002	0.0001
Nov-21	4.9	4.57	4.57	4.54	0.00000006	0.0005
Dec-21	4.9	3.39	3.39	3.38	0.00000003	0.0003
Jan-22	5	2.13	2.13	2.11	0.00000001	0.0001
Feb-22	5	1.81	1.81	1.80	0.00000001	0.0001
Mar-22	5	1.60	1.60	1.59	0.00000001	0.0001
				Sum of Squares	0.000000716	0.00601
				RMSE (m^3/MWh)	**0.0001**	**0.0129**

Table A15: Calculation of Root Mean Square Error (RMSE) values for the Makeup water requirement (m^3/hr) of Rayalaseema TPS - Stage IV (1 x 600 MW)

Month / Year	CoC Values (Operational data)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	2.56	1046.15	1051.11	1014.55	24.60	998.70
May-19	2.85	982.09	976.74	967.32	28.72	218.41
Jun-19	2.45	1077.16	1084.66	1051.35	56.38	665.75
Jul-19	2.73	1006.00	1005.04	978.11	0.92	777.91
Aug-19	2.16	1187.07	1187.18	1198.16	0.01	123.03
Sep-19	3.78	866.82	875.84	870.22	81.41	11.58
Nov-19	1.5	1177.75	1179.46	1185.72	2.90	63.43
Dec-19	2.18	969.53	961.84	966.73	59.17	7.85
Jan-20	2.92	945.47	933.92	979.64	133.41	1167.30
Feb-20	3.07	945.47	933.92	979.64	133.41	1167.30
Mar-20	3.07	1031.02	1034.05	998.86	9.20	1034.44
Jan-21	2.62	1109.72	1117.71	1093.82	63.82	252.82
Feb-21	2.35	1010.31	1010.10	981.11	0.04	852.68
Mar-21	2.71	991.67	988.10	970.31	12.69	456.12
Apr-21	2.8	1238.92	1227.27	1265.52	135.70	707.96
Jun-21	2.06	1262.50	1243.98	1294.87	343.05	1047.87
Jul-21	2.54	1008.14	1007.55	979.56	0.34	816.60
Aug-21	2.02	1038.44	1042.47	1006.32	16.24	1032.08
Sep-21	2.72	1109.72	1117.71	1093.82	63.82	252.82
Oct-21	2.59	1535.39	1545.25	1568.89	97.30	1122.19

Month / Year	CoC Values (Operational data)	Make-up water (m^3/hr) (based on Eq. (6)) using operational CoC data	Make-up water (m^3/hr) using best- fit on operational CoC values	Make-up water (m^3/hr) using best fit on synthetic CoC values	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Nov-21	2.35	1281.44	1241.94	1317.78	1560.51	1320.88
Dec-21	1.71	1160.04	1164.30	1161.86	18.13	3.32
Jan-22	1.99	1080.21	1087.86	1055.21	58.54	624.74
Feb-22	2.22	1173.21	1175.63	1179.63	5.85	41.11
Mar-22	2.44	1151.61	1156.86	1150.45	27.58	1.35
				Sum of Squares	2933.74	14768.28
				RMSE (m^3/hr)	**10.83**	**24.30**

Table A16: Calculation of Root Mean Square Error (RMSE) values for the Specific Water Consumption (m^3/MWh) of Rayalaseema TPS - Stage IV (1 x 600 MW)

Month / Year	CoC Values (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on operational CoC	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on synthetic CoC	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Apr-19	2.56	4.13	4.15	4.01	0.000384	0.02
May-19	2.85	2.52	2.51	2.48	0.000189	0.00
Jun-19	2.45	4.45	4.48	4.35	0.000963	0.01
Jul-19	2.73	2.86	2.86	2.78	0.000007	0.01
Aug-19	2.16	5.63	5.63	5.68	0.000000	0.00
Sep-19	3.78	2.95	2.98	2.96	0.000945	0.00
Nov-19	1.5	4.46	4.47	4.49	0.000042	0.00
Dec-19	2.18	2.67	2.64	2.66	0.000447	0.00
Jan-20	2.92	2.52	2.49	2.61	0.000946	0.01
Feb-20	3.07	3.41	3.36	3.53	0.001732	0.02
Mar-20	3.07	5.70	5.72	5.53	0.000281	0.03
Jan-21	2.62	2.72	2.74	2.68	0.000382	0.00
Feb-21	2.35	2.61	2.61	2.53	0.000000	0.01
Mar-21	2.71	2.48	2.47	2.42	0.000079	0.00
Apr-21	2.8	3.75	3.72	3.83	0.001244	0.01
Jun-21	2.06	6.71	6.61	6.88	0.009695	0.03
Jul-21	2.54	2.75	2.74	2.67	0.000003	0.01
Aug-21	2.02	2.70	2.71	2.61	0.000110	0.01
Sep-21	2.72	4.52	4.56	4.46	0.001060	0.00
Oct-21	2.59	15.61	15.72	15.96	0.010064	0.12

Month / Year	CoC Values (Operational data)	Reflection of Actual Make-up water requirement on SWC (m^3/MWh)	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on operational CoC	Reflection of Make-up requirement on SWC (m^3/MWh) for best fit on synthetic CoC	Square Error (Actual vs. best fit on operational CoC data)	Square Error (Actual vs. best fit on synthetic CoC data)
Nov-21	2.35	4.15	4.02	4.26	0.016337	0.01
Dec-21	1.71	3.07	3.08	3.07	0.000127	0.00
Jan-22	1.99	2.94	2.96	2.87	0.000434	0.00
Feb-22	2.22	2.99	3.00	3.01	0.000038	0.00
Mar-22	2.44	2.83	2.85	2.83	0.000167	0.00
				Sum of Squares	**0.05**	0.29
				RMSE (m^3/MWh)	**0.04**	**0.11**

List of Abbreviations

ABVTPS	Atal Bihari Vajpayee Thermal Power Station
ADNC	Average Decadal Numeric Change
AMRUT	Atal Mission for Rejuvenation and Urban Transformation
BAU	Business-As-Usual
BCM	Billion Cubic Meters
BOD	Biological Oxygen Demand
BOT	Built-Operate-Transfer
BTPS	Ballari Thermal Power Station
CEA	Central Electricity Authority
CMC	City Municipal Council
CoC	Cycles of Concentration
CoD	Date of commercial operation
COD	Chemical Oxygen Demand
CT	Cooling Tower
CW	Cooling Water
DM	Demineralization
DO	Dissolved Oxygen
EC	Environmental Clearance
ET	Evapotranspiration
FAL	Facultative Aerated Lagoon
FGD	Flue Gas Desulfurization
FY	Financial year
GENCO	Generating Companies
GoK	Government of Karnataka
GW	Gigawatt
GWh	Gigawatt-hour
IDC	Increment in Decadal Change
IIM	Incremental Increase Method
INR	Indian Rupees (Rs.)
JJM	Jal Jeevan Mission

JNNURM	Jawaharlal Nehru National Urban Renewal Mission
JSA	Jal Shakti Abhiyaan
JSWEL	JSW Energy Limited
KTPS	Koradi Thermal Power Station
LDC	Load Dispatch center
LPCD	Litres per capita per day
MAHAGENCO	Maharashtra State Power Generation Company Limited
MC	Municipal Corporation
MCM	Million Cubic Meters
MLD	Million Liters per Day
MoEFCC	Ministry of Environment, Forest and Climate Change
MoHUA	Ministry of Housing and Urban Affairs
MoP	Ministry of Power
MoU	Memorandum of Understanding
MPN	Most Probable Number
MU	Million Units
MW	Megawatt
MWh	Megawatt-hour
NMC	Nagpur Municipal Corporation
NTU	Nephelometric Turbidity Unit
NWP	National Water Policy
NWWMPL	Nagpur Waste Water Management Pvt. Ltd
pH	Potential of Hydrogen
PLF	Plant Load Factor
PPM	Parts Per Million
R&M	Renovation and Modernisation
RB-LLC	Right Bank-Low Level Canal
RH	Relative Humidity
RMSE	Root-Mean-Square-Error
RO	Reverse-Osmosis
RPCL	Raichur Power Corporation Limited
RTI	Right to Information Act 2005
RTPP	Rayalaseema Thermal Power Project

RTPS	Raichur Thermal Power Station
SBR	Sequencing Batch Reactor
SDG	Sustainable Development Goals
SPVBR	Sri Potuluri Veerabrahmam Reservoir
STP	Sewage Treatment Plant
SWC	Specific water consumption (in m3/MWh)
TB-HLC	Tungabhadra High-Level Canal
TB-LLC	Tungabhadra Low-Level Canal
TDS	Total Dissolved Solids
TPP	Thermal Power Plant
TPS	Thermal Power Station
TSS	Total Suspended Solids
TTW	Tertiary Treated Water
TWh	Terawatt-hour
UF	Ultra-Filtration
ULB	Urban Local Body
UGD	Under-Ground Drainage
UN-GA	United National General Assembly
WB	Water Bodies
WEN	Water-Energy-Nexus
WTP	Water Treatment Plant
YTPS	Yeramarus Thermal Power Station

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11 **Abstract:**

An integrated approach to Sustainable Development Goals (SDGs) 6 and 7 will be helpful to maximize the benefits of water and sanitation projects while reducing the environmental impacts of inefficient water usage, specifically in Thermal Power Stations (TPSs) that are the largest users of water in the industrial sector. This is particularly important in most developing countries that face declining water availability due to a growing population without commensurate increases in water use efficiency. The case for an integrated approach towards realizing multiple targets under SDG 6 and SDG 7 in India is particularly strong since India is the third largest electricity generator in the World with TPS generating more than 78 percent of the 1715 TWh of electricity generation. This study explores the water-energy nexus paradigm to reduce freshwater consumption in TPSs located in the proximity of cities by using treated sewage water from sewage treatment plants (STPs). This report summarizes the results of a field study to assess the water demand and availability in two water-stressed districts of India. This study applies an integrated approach to SDG 6 and SDG 7 to increase water efficiency, improve sanitation, and reduce the loss of power generation due to water shortages. In view of the above, suitable best-fit estimates for the make-up water requirement have been derived for TPPs with installed capacities in the range of 210 – 600 MW using the recent operational data. The estimated make-up water volumes thus obtained were further used for evaluating the Specific Water Consumption (SWC) for the respective TPPs based on the different Plant Load Factors (PLF). Such an approach facilitates rapid assessment of water consumption and would help in devising suitable strategies to attain optimal water use efficiency.

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