

Rethinking urban water management through Drivers-Pressures-States-Impacts-Responses framework application in Chennai, India

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Abstract

Cities suffering water scarcity are projected to increase in the following decades. However, the application of standardized indicator frameworks for assessing urban water resource management problems is on an early stage. India is expected to have the highest urban population facing water scarcity in the world by 2050. In this study, the authors assess how the Drivers-Pressures-States-Impacts-Responses framework, a causal framework adopted by the European Environment Agency, can contribute to evaluate water management challenges in cities and apply it to Chennai, India's fourth-largest urban agglomeration.

The framework proved to be a helpful tool for the evaluation of water management challenges in cities by disentangling relationships between environmental indicators and structuring disperse data that allows a better understanding for policy makers. The main drivers identified in Chennai were population growth and economic development which generated impacts such as loss of aquatic ecosystems, low water table, low water quality and reduction of biodiversity and human health. As a response, better urban planning, projects for new water infrastructure, and water bodies restoration have been implemented. Nevertheless, Chennai keeps facing difficulties to achieve a proper water management. The severe hit of COVID-19 pandemic on the Indian economy and its future management will be key for achievements related to water management.

Keywords

Water Resources Management, Land-use change, water scarcity, Environmental causal framework, Urban resilience, South India.

1 Introduction

Cities around the globe are suffering from water scarcity. In 2009, at the end of the “Millennium Drought”, water storage volumes feeding Melbourne fell to a historic low of 25.6% of capacity (Low et al. 2015; van Leeuwen 2017). In 2013 and 2014, Sao Paulo became dependent on reservoirs with available water percentages in the single digits (Millington 2018). In 2018, Cape Town faced a Day Zero in which pipes went dry and people needed to collect drinking water from distribution points (Zetland 2021).

Urban water demand will increase by 80% by 2050, while rapid population growth and urbanization of cities put significant pressure on water resources (Newton 2016) and climate change is altering the timing and distribution of water (Flörke et al. 2018). In this context, the number of large cities facing water scarcity was projected to increase from 193 (37%) to 292 (56%) and global urban population facing water scarcity was projected to double from 933 million (33%) in 2016 to 1.693–2.373 billion (35–51%) in 2050 (He et al. 2021). Consequently, water insecurity will be one of the most severe crisis the world will face during the next several decades (UNESCO and UN-Water 2020). Cities are also facing a problem of water quality with impacts on health and ecosystems (Chaturvedi 2012). In 2020, at least 2 billion people used a drinking water source contaminated with faeces (WHO World Health Organization 2020) and 3.6 billion lacked safely managed sanitation (World Bank 2020).

India had the highest number of urban inhabitants facing water scarcity worldwide in 2016 (222 million people). This is expected to increase to 550 million in 2050, i.e. 26.7% of the world’s urban population facing water scarcity (He et al. 2021). City development and poor institutional control (Chaturvedi 2012; Hossain et al. 2013) have resulted in the pollution of the majority of surface water bodies with untreated sewage (Chaturvedi 2012) and promoted over-extraction of ground water (Wada et al. 2012). Chennai, India’s fourth-largest urban agglomeration, exhibits a complex setup around water resources management that generates social, political and environmental tensions, including water-poor areas where human development is limited (Allen et al. 2006). In 2019, the city hit Day Zero when its four major reservoirs dried up and four million people were relying solely on water tankers (Jayaraman, 2019; “Water crisis in Chennai”, 2019).

Traditionally, cities relied on large-scale infrastructure for water management, often with systems operating independently of each other (Brown et al. 2009; Marlow et al. 2013). Addressing water management in cities with complex scenarios like Chennai requires an integrated approach, such as the Integrated Urban Water Management (IUWM) process. This approach encompasses water supply, sanitation, stormwater, and wastewater management integrating them with land use planning and economic development (Bahri 2012). The concept of IUWM emerged in the 1980s, highlighting the interconnections between actors, surface water, groundwater, and issues of water quantity and quality and has evolved over the years (Benson et al. 2015; Hoekstra et al. 2018; Manny 2022). In the 1990s, Sustainable Urban Water Management (SUWM) became prominent, driven by growing concerns for ecological health and sustainable development, integrating environmental variables more

comprehensively into the discussion (Hoekstra et al. 2018; Pluchinotta et al. 2021). In the late 2000s, Adaptive Water Management emerged in response to the need for climate change adaptation (Kirono et al. 2014; Hoekstra et al. 2018). Recently, concepts such as Water Risk, Water Resilience, the Water-Food-Energy Nexus, Total Water Cycle Management (Maurya and Singh 2022), and Water Sensitive Urban Design (van der Meulen et al. 2023) have become influential (Hoekstra et al. 2018). In parallel and since around 2000, water security has also emerged as a central concept, broadly encompassing integrated, sustainable, and adaptive aspects (Hoekstra et al. 2018). The relevance of water security is underscored by its recognition and definitions from the Global Water Partnership (GWP 2000), the World Water Council (WWC 2000), and the United Nations (UN-Water 2013). Over time, the term has evolved to include various attributes, such as affordability, human well-being, water-related disasters, hazard, risk, political stability, and resilience (Romero-Lankao and Gnatz 2016; Chapagain et al. 2022).

Although IUWM is a crucial process to prevent water crises regardless of water scarcity (Di Baldassarre et al. 2018) and has the highest potential to reduce pressures on water resources (Koop and van Leeuwen 2015a), there is no internationally standardized indicator framework for it (Koop and van Leeuwen 2015a). This situation compromises the achievement of the United Nations Sustainable Development Goals (SDGs) numbers 6 Clean Water and Sanitation and 11 Sustainable Cities and Communities (United Nations 2015; He et al. 2021).

Several models and frameworks are used for analyzing water management, environmental issues and socio-ecological systems: causal-chain frameworks, such as the Pressure-State-Response (PSR), Pressure-State-Impact-Response (PSIR), and the Drivers-Pressures-States-Impacts-Responses (DPSIR), sustainability assessment frameworks, including the Social-Ecological Systems Framework (SESF) and the Ecosystem Services Framework, and integrated water management frameworks, like the City Blueprint and the Asian Water Development Outlook (AWDO) frameworks.

The PSR framework emphasizes the relationship between environmental pressures, the current state of the environment, and societal responses (Maurya and Singh 2022), while the PSIR framework incorporates an "Impact" stage (Van Ginkel et al. 2018). The DPSIR, a causal framework for describing the interactions between society and the environment, provides an organized structure to assessing the causes, consequences, and responses to changes in ecosystems (Gabrielsen and Bosch 2003; European Environment Agency 2020). The SESF is used to diagnose the sustainability of social-ecological systems (Ostrom 2009), while the Ecosystem Services Framework categorizes the benefits humans obtain from ecosystems, with an emphasis on natural resource management (Matzdorf & Meyer, 2014). The City Blueprint framework (van Leeuwen et al. 2012; Koop and van Leeuwen 2015b) uses 24 indicators across eight categories, including water security, water quality, sanitation, biodiversity, and governance. It measures integrated water resources management performance implemented by local water authorities (Hoekstra et al. 2018) and includes an additional framework for describing significant trends and pressures that may impact water management (Koop and van Leeuwen 2015b). The AWDO framework (Asian Development

Bank 2020) assesses water security through five key dimensions: households, economies, cities, the environment, and resilient communities.

The DPSIR framework is particularly suitable for urban water management due to its holistic and integrated approach. Simplified frameworks like PSR and PSIR are straightforward, easy to use, and effectively link pressures to state changes and policy responses (Hazbavi et al. 2020). This clarity makes them useful for decision-makers. However, they often lack the depth required for comprehensive urban water management by oversimplifying interactions (Niemeijer and De Groot 2008; Levrel et al. 2009). Compared to SESF and the Ecosystem Services Framework, DPSIR not only addresses sustainability and ecosystem services but also analyzes the system with a holistic approach, which is key for complex scenarios like water management in Chennai. The City Blueprint framework provides a detailed structure but is complex, requiring a dual framework that focuses on water resources management performance as well as trends and pressures. This complexity, along with the need for extensive and specific data, can impede its application, especially in developing countries (Hoekstra et al. 2018). The AWDO framework provides a holistic view of water security by addressing interconnected and interdependent dimensions. However, it is primarily designed for national assessments, includes only five urban-specific indicators, and uses averaged data for all urban areas across a country, which limits its usefulness for IUWM (Jensen and Wu 2018).

Adopted by the European Environment Agency, the DPSIR framework provides an organized structure to assess the causes, consequences, and responses regarding water management (European Environment Agency 2020), that facilitates communication with stakeholders (Tscherning et al., 2012). Additionally, it has been widely applied to assess the environmental state of cities (Kohsaka 2010), rural communities (Gari et al. 2018a) and river basins (Kong et al. 2016; Pagan et al. 2020a), and has demonstrated its utility to describe cause effect relationships in cases with limited data availability (Gari et al. 2018b), and to develop causal chains (Pagan et al. 2020b).

Hence, this study aims to address the following research questions: (i) How can the DPSIR framework contribute to evaluate water management challenges in cities with wicked water problems? (ii) What are common limitations for effective water management in cities located in developing countries and facing resource scarcity? These questions will be addressed through the application of the DPSIR framework to the city of Chennai, India.

2 Materials and methods

2.1 Study area

Chennai, known as Madras until 1996, is the capital of the Indian state of Tamil Nadu. It is located on the southeastern coast of India ($13^{\circ}05'N$ and $80^{\circ}18'E$), on the Bay of Bengal (Figure 1). Nowadays, the Chennai city limits coincide with the Chennai district (Government of Tamil Nadu 2020). According to the 2011 Indian census, the Chennai district had 7,088,000 inhabitants in an area of 426 km^2 (Directorate of Census Operations Tamil Nadu 2011). Chennai city is governed by the Greater Chennai Corporation (Chennai District 2020).

The Chennai city district together with parts of Tiruvallur, Kanchipuram and Chengalpattu districts constitute the Chennai Metropolitan Area (CMA) with an extension of 1189 km^2 (CMDA 2020a) and 8.70 million inhabitants according to the 2011 Indian census (Directorate of Census Operations Tamil Nadu 2011). The Chennai Metropolitan Development Authority is in charge of urban planning in this area.

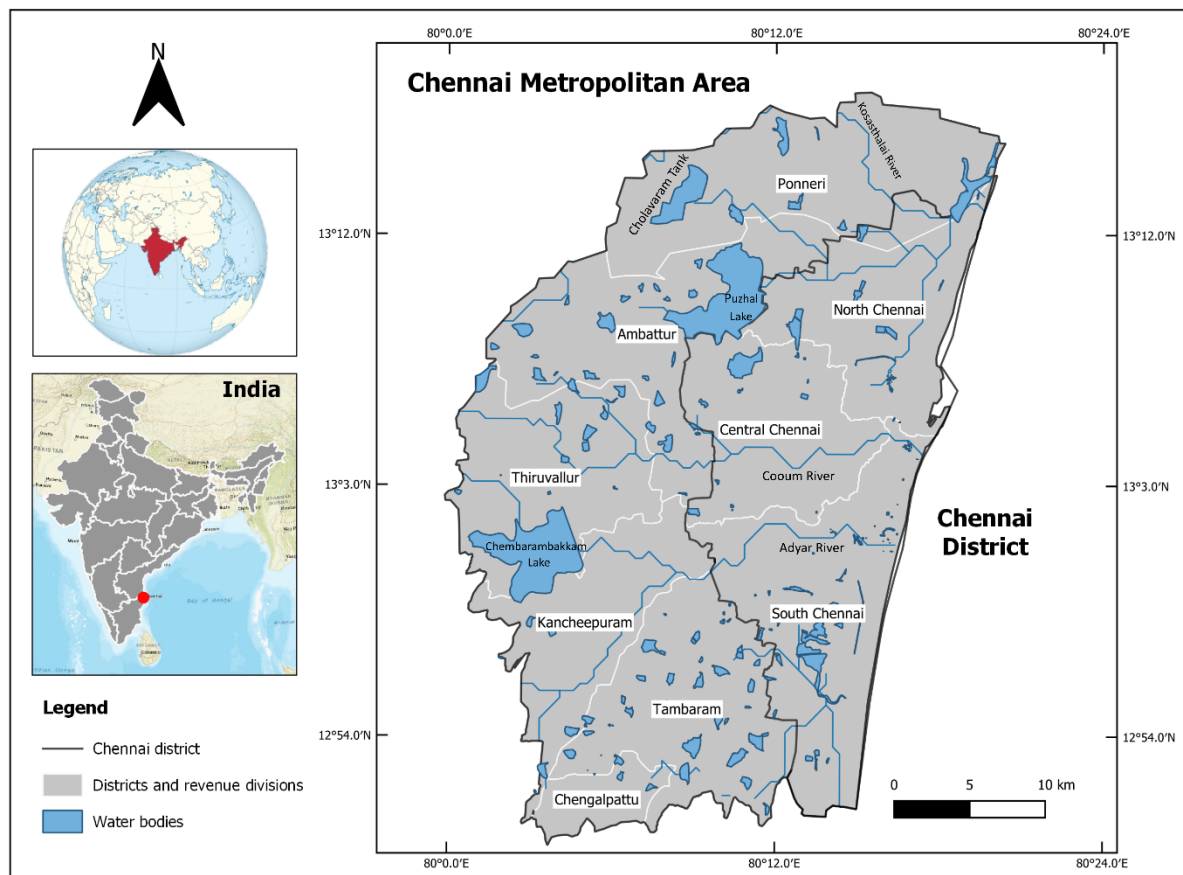


Figure 1. Chennai location and water bodies. Source: Authors. Note: India on the globe image, Wikimedia Commons, 2014 (<https://creativecommons.org/licenses/by-sa/3.0>). CC BY-SA 3.0

Chennai has a tropical wet and dry climate (Köppen: Aw) with a relative constant temperature (Rajanikanth and Rajini Kanth 2020). In the period 1971-2000, highest and lowest average monthly temperatures showed annual variations ranging from 28.9 to 37.1°C and from 21.2 to 28.0°C and the average monthly rainfall ranged from 2.2 to 407.4 mm (Selvaraj et al. 2016). The hottest part of the year is late May and early June and the coolest is January (Prakash and Punyaseshudu 2015). The average annual precipitation is around 1,400 mm (Rajanikanth and Rajini Kanth 2020). The lowest precipitations occurred in February, during the pre-monsoon season, and the highest from mid-October to mid-December in the northeast monsoon (NE) season (Selvaraj et al. 2016). Regarding climate change, mean temperatures have risen (maximum, 1.6°C; annual, 1.3°C; minimum, 1.0°C) from 1951 to 2010 (Jeganathan and Andimuthu 2013) while rainfall tendency is unclear (Ramachandran and Anushiya 2015; Rangarajan et al. 2018). Concerning floods, Oldenborgh et al. (2016) found no signal for a positive trend in extreme one-day precipitation at the southeastern coast of India over 1900-2014.

Chennai is situated on a flat area known as the Eastern Coastal Plains with an average elevation of 6.7 m.a.s.l. and a highest point of 60 m.a.s.l. (Pulikesi et al. 2006). The rivers of Chennai flow from west to east, draining into the Bay of Bengal, and divide the city into north-south sections. Two major rivers are the Cooum River, located in the center of the city, and the Adyar River to the south. A third river, the Kortalaiyar, flows through the northern fringes of the city before draining into the sea, at Ennore. The three rivers are connected by the Buckingham Canal, a fresh water artificial waterway parallel to the Coromandel Coast. Additionally, there are four reservoirs called Poondi, Cholavaram, Puzhal, and Chembarambakkam (Mariappan 2014) and many artificial lakes, locally called tanks that traditionally stored water during the monsoon season that was used for irrigation during the dry season (Devi et al. 2020).

The Chennai ecosystem has been dominated by Palmyra and Phoenix palms interspersed with thickets with a mixture of grasses and short herbs in the intervening spaces; allowing free surface water flows and preventing flooding. Trees were sparse and local (Ranjit-Daniels et al. 2020). Pallikaranai Marsh stand out with multiple species of plants, fish, birds, butterflies, and reptiles (Surya 2016) although it has been heavily urbanized within the last 30 years (Coelho 2018).

2.2 Application of the DPSIR framework

In this work, we applied the DPSIR framework (Gabrielsen and Bosch 2003; Kristensen 2004; European Environment Agency 2020) and, consequently, defined its components (drivers, pressures, states, impacts, and responses) and its causal chain in relation to water management in the city of Chennai, India. The components of the DPSIR framework and their linkages are depicted in Figure 2 while their definitions can be found in the literature (Smeets and Weterings 1999; Gabrielsen and Bosch 2003; Kristensen 2004; Semeoshenkova et al. 2017).

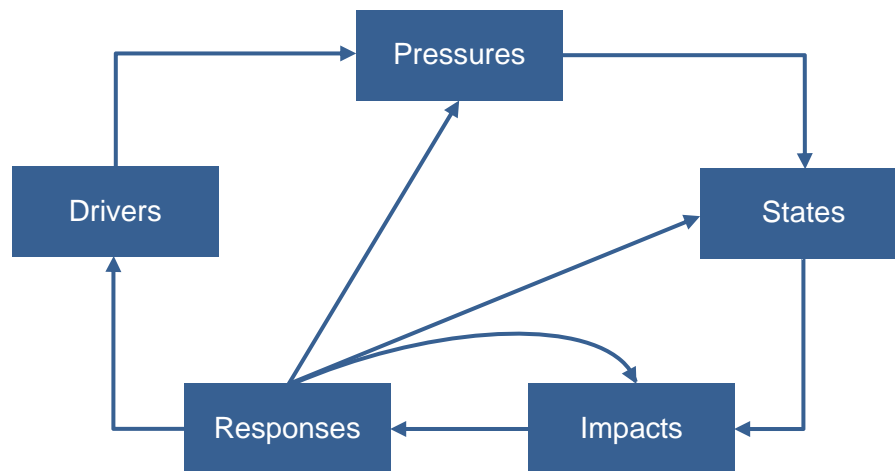


Figure 2. The components of the DPSIR framework and their connections.

The application of the DPSIR framework and the definition of its components involved an extensive literature research in Scopus, Web of Sciences core collection and Google Scholar (Patrício et al. 2016). Also, data reports and other documents provided by public administrations. Thus, the websites of the Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB, also known as Metrowater), Chennai Metropolitan Development Authority (CMDA), Tamil Nadu Water Supply and Drainage (TWAD) Board, Tamil Nadu Pollution Control Board, Central Pollution Control Board, Central Ground Water Board (CGWB) were consulted, as well as the second edition of the master plan of Chennai and renowned newspapers.

3 Results

3.1 Overview

Figure 3 presents the components and causal chain of DPSIR analysis of water management in Chennai. Also, a table shows the indicators used in this study in the supplementary material (Table S1).

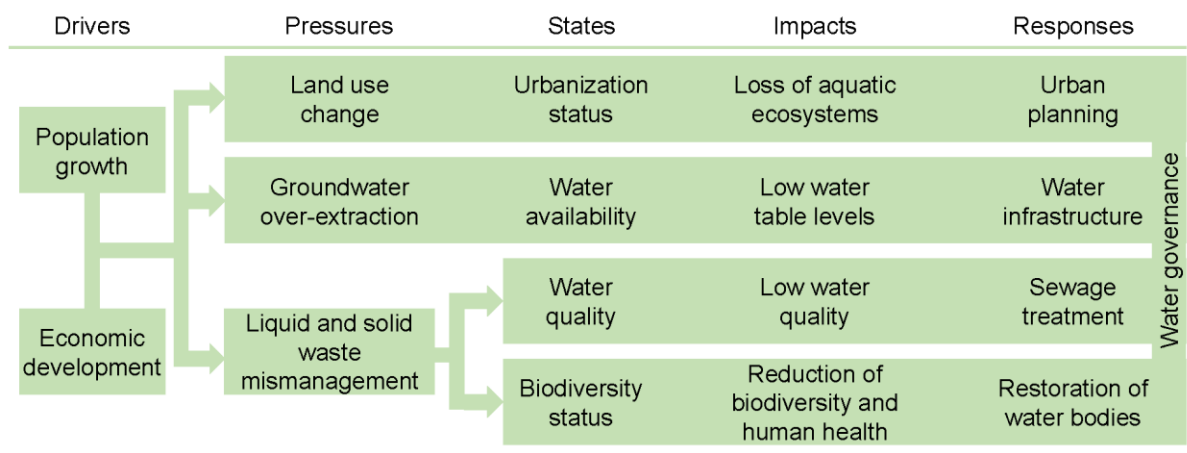


Figure 3. Components and causal chain of DPSIR analysis of the water management in Chennai, India.

3.2 Drivers

3.2.1 Population growth

Chennai is today a cosmopolitan megacity due to a transformation that started in the last century and continues in the present. The 20th century brought to Chennai an accelerated

population growth rate over a decadal 10% (Figure 4). During the period 2001-2011, the population growth rate equaled 7.8% due to the almost complete urbanization within the city limits of that time (174 km²), an average annual growth of 0.75%. Later in 2011, the area of the city was expanded to 426 km² and its population reached 7,088,000 (Directorate of Census Operations Tamil Nadu 2011). Considering the new limits, the growth rate in the period 2001-2011 was above 10%. Since then, the Chennai city limits remain untouched and coincide with the Chennai district, one of the 38 districts of the State of Tamil Nadu.

In parallel to the population, the spatial area of Chennai has expanded from 68 km² to 426 km² since 1901 (Krishnamurthy and Desouza 2015) and the population density has increased from 1,041 (1981) to 2,109 (2011) persons per km² (Aithal and Ramachandra 2016).

The Chennai Metropolitan Area is composed by the Chennai District and parts of Tiruvallur, Kanchipuram and Chengalpattu districts, the latter carved out of Kanchipuram district in November 2019 (CMDA 2020a). It has an area of 1,189 km² and 8.70 million inhabitants according to the 2011 Indian census, the fourth most populated metropolitan agglomeration in India (Directorate of Census Operations Tamil Nadu 2011). Additionally, its population has been estimated to be 10.2 million in 2016 (30th-largest in the world) and to reach 13.9 million in 2030 (United Nations 2016).

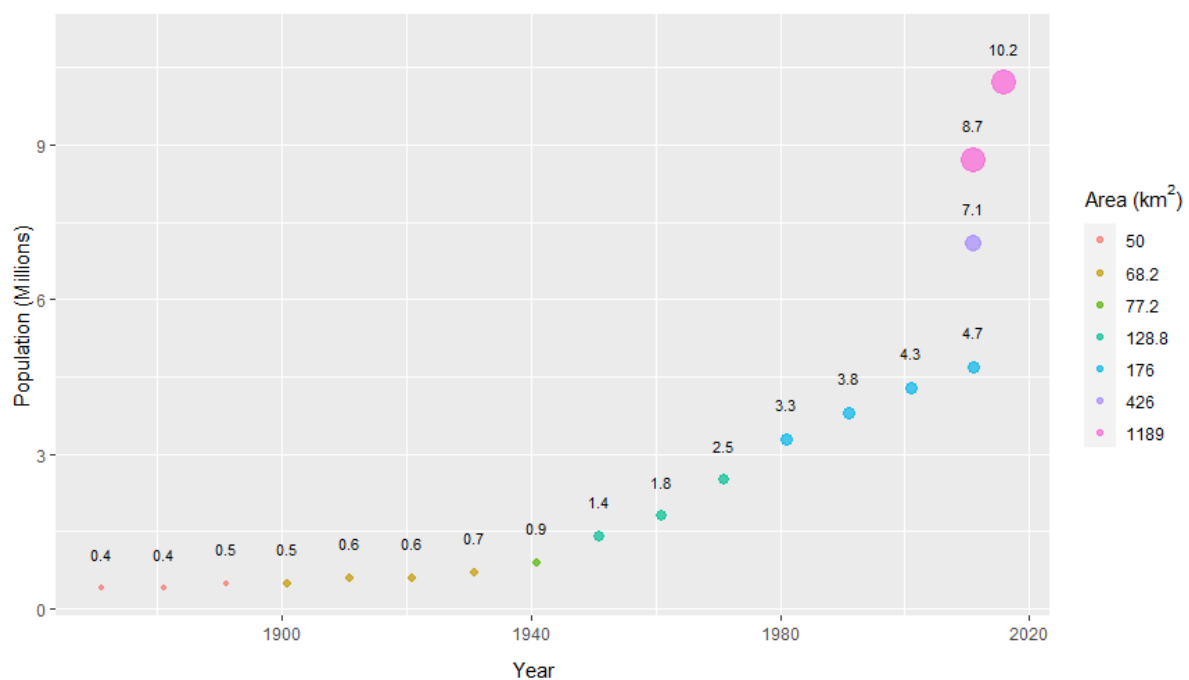


Figure 4. Population and area of Chennai City (1871-2011) and Chennai Metropolitan Area (2011-2016). Sources: 1871-1891, Secretary of State for India (1908); 1901-2001, CMDA (2008); 2011, Directorate of Census Operations Tamil Nadu (2011); 2016, United Nations (2016). Populations of 2011 from bottom to top correspond to i) the area before the expansion of the Chennai City District in 2011, ii) the area after the expansion and iii) the metropolitan area.

The constant immigration plays a key role for the population growth of Chennai, with a migrant population of 918,000 (23.9% over the total) in 1991, and 937,000 (21.57%) in 2001. In the

latter, divided into 74.5% from other parts of Tamil Nadu, 23.8% from other parts of India and 1.7% from foreign countries (CMDA 2008). Since 2000, the population from foreign countries has increased from 35,000 in 2009 to 82,790 in 2011 (Krishnamurthy and Desouza 2015). Traditionally, the high fertility rate also explained the population growth. However, today in Tamil Nadu it is among the lowest of the country and it is similar to developed countries decreasing from 2.5 in 1993 to 1.7 in 2016 (International Institute for Population Sciences 2017; NITI Aayog 2020). This rapid population growth increases the demand for water and the scarcity and shortages likelihood.

3.2.2 Economic development

During the British rule of India, Chennai was the capital of Madras Presidency and therefore the economic center of South India (Haufe 2017). Today, Chennai is one of the most economically developed and industrialized cities in India, and the largest industrial center in South India (Bloodgood 2007; Krishnamurthy and Desouza 2015).

Several factors have contributed to its explosive economic development. At a national scale, after the 1947-1991 protectionist period, the economy of India was liberalized and received massive foreign investments. Since the start of the 21st century, annual average gross domestic product (GDP) growth has been around 6% to 7% (Kanungo et al. 2018), and from 2014 to 2018, India was the world's fastest growing major economy with an average of 7.4%, surpassing China (International Monetary Fund 2019). At a state level, Tamil Nadu is the second largest state in India by GDP and the per capita net state domestic product in percentage at constant prices of Tamil Nadu (Figure 5) has increased at an average 6.59% between financial years 98-99 and 18-19 (Reserve Bank of India 2020a).

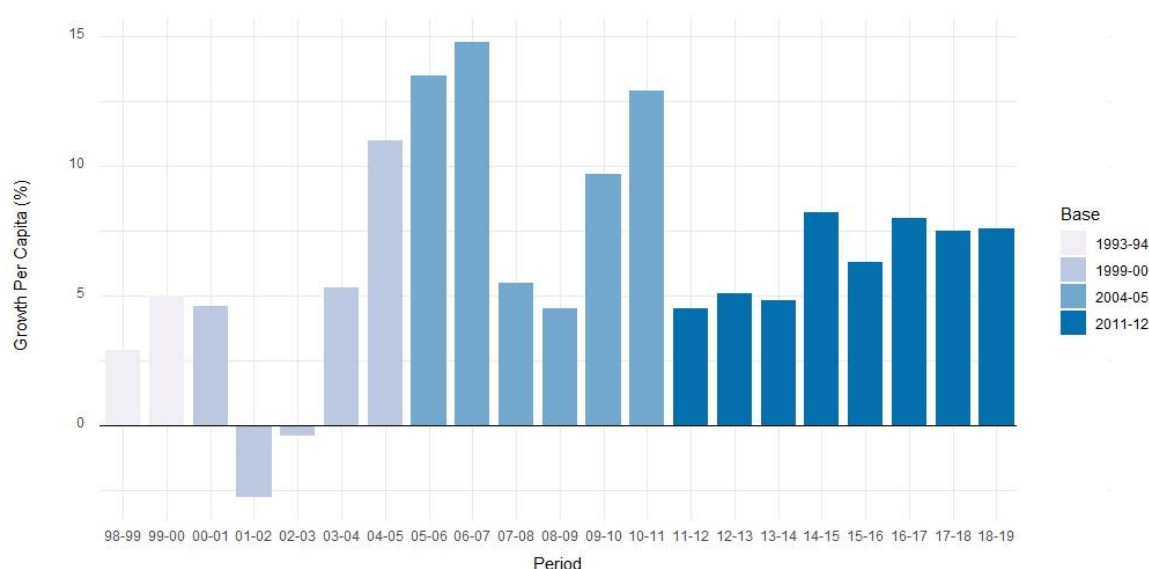


Figure 5. Per capita net state domestic product (NSDP) growth in percentage (rupees) at constant prices in Tamil Nadu (1998-1999 to 2019-2020). Source: Reserve Bank of India (2020). Average exchange rate (2021) is 73.9339 INR for 1 USD.

At a city level, Chennai received large-scale investments from multinational companies and a

tremendous industrialization took place, especially in the automobile, health, IT and banking sectors (Krishnamurthy and Desouza 2015). With an estimated GDP (PPP) of \$78.6 billion in 2018, Chennai metropolitan area is the fifth largest city by GDP in India (Haritas 2017). Other important industries include petrochemicals, textiles, apparels and the ports of Chennai and Ennore. The main industrial developments of Chennai took place along three main corridors: the Old Mahabalipuram Road alongside the coast, as IT corridor; the Grand Southern Trunk (GST) Road, towards southwest, as the logistics and industries corridor; and the Chennai–Bengaluru Highway as an automotive and electronic hardware corridor (Haufe 2017). This economic development increases the per capita consumption of water due to new industries and the higher purchasing power of the population (Bao and Chen 2015).

3.3 Pressures

3.3.1 Land use change

Chennai experienced significant changes in land use because of intense urbanization due to rural to urban migration, the natural increase of population, reclassification of rural settlements into urban, and changes in boundaries of existing urban settlements (Adelina 2015). Urban areas expanded by 173.8% (211.2 km² to 578.4 km²) in the period 1988-2017, i.e. an average annual growth of 1.92%, while rural areas and water bodies shrank as depicted in Figure 6 (Mathan and Krishnaveni 2020).

Figure 6. Land use change in Chennai Metropolitan Area from 1988 to 2017. Derived from LANDSAT data (Mathan and Krishnaveni 2020).

3.3.2 Groundwater over-extraction

The growing water demand by the increasing industries and population has led to an uncontrolled extraction of groundwater within the city and its peri-urban areas estimated on average in 200 million liters per day (Venkatachalam 2015) despite the Chennai Metropolitan Area Groundwater Act from 1987 prohibition to extract groundwater in 302 villages. This regulation is frequently violated (Butterworth et al. 2007). Many peri-urban farmers have shifted from agriculture to water production (Roumeau et al. 2015) and sell groundwater directly to Metrowater (Ruet et al. 2007) and private tankers (Butterworth et al. 2007). In the city, around 6530 deep bore-wells have been dug (Venkatachalam 2015). The general status of aquifers is monitored by the public authorities (Roumeau et al. 2015).

3.3.3 Liquid and solid waste mismanagement

According to Metrowater (CMWSSB 2020a), Chennai generates 550 million liters per day (MLD) that are treated in 12 sewage treatment plants with a total capacity of 727 MLD. Arappor lyakkam (2017) agrees 550 MLD are treated, but also that around 1500 to 2000 MLD of sewage are generated in the city. Hence, nearly 1073 MLD of sewage would be directly discharged into water bodies and only 33.90% would be treated. Several areas lack access to an efficient sewage system, therefore wastewater is disposed in septic tanks (Thirumurthy

2017).

Chennai currently exhibits the highest per capita solid waste generation rate in India: 0.65 kg/person/day. Municipal Solid Waste generation has increased from 600 to 5400 metric tons per day (MTD) within 20 years with residential (68%) as main origin (Greater Chennai Corporation 2020). Collected waste is disposed with limited processing at two non-technically managed open dumpsites (Greater Chennai Corporation 2020): Kodungaiyur (1.089 km²) and Perungudi (0.809 km²). An important amount of waste remains unattended at collection centers, roadsides, drains and riverbanks (Esakku et al. 2007; Mahajan 2016).

3.4 States

3.4.1 Urbanization status

Urban areas expanded by 173.8% (211.2 km² to 578.4 km²) in the period 1988-2017 (Mathan and Krishnaveni 2020) and reached 48.7% of the Chennai Metropolitan Area surface (1189 km²). Chennai's urban core is intensely developed and is surrounded by rural or peri-urban areas that lack basic amenities. Slums that lack access to water, sanitation and electricity are home to 1.3 million people (CMDA 2006; Saharan et al. 2018) which was estimated to be 18.9% of the urban population in 2001 (CMDA 2008) and 28% in 2011 (Directorate of Census Operations Tamil Nadu 2011).

3.4.2 Water availability

Chennai has been historically in water deficit because of the lack of perennial rivers due to the monsoon climate. The city has the lowest per capita water availability of all the metropolitan cities in India (CMDA 2006; Packialakshmi et al. 2011). The water supply is around 90 liters per capita a day and is reduced during the dry period (Feb-Mar). Water demand for Chennai urban area in 2014 was 1173 MLD, while the supply was only 831 MLD (Government of Tamil Nadu 2014).

The core of the Chennai Metropolitan Area benefits of a better water supply (Government of Tamil Nadu 2014). In other areas, it is only 30 to 40 liters per capita a day, is only available on alternate days or for only 2 to 6 hours per day (CMDA 2006). Around 20% of population in slums lack of piped water and rely on public fountains and mini tanks (CMDA 2006).

Drought events are common in Chennai. Between 2003-2004, the entire piped water system was inoperative. The packaged water market boomed, resulting in a downward spiral of over-extraction of groundwater and unequal water distribution (Roumeau et al. 2015). During the summer of 2019, all the four main reservoirs run dry after two years of scarce rainfall and 200 days without rain (Dhillon 2019; Upadhyay 2019). Tap water stopped running and costly private water tankers emerged as alternative water sources (Karthikeyan 2019) making the poor vulnerable (Masih 2019).

3.4.3 Water quality

The numerous sources of pollution, such as sewage discharge, have reduced quality of the

348 water bodies (**Error! Reference source not found.**). All water bodies fail to comply in one or
349 more parameters with the guidelines for propagation of wildlife in surface water provided by
350 Water Quality Standards in India (BIS 1992): pH (6.5-8.5), electrical conductivity (<1000
351 $\mu\text{S}/\text{cm}$), dissolved oxygen (≥ 4 mg/L) and BOD (≤ 2 mg/L). Precisely, pH is not meet in the
352 tanks, electrical conductivity and dissolved oxygen in Cooum river and Buckingham Canal,
353 BOD in Adyar river and the three water bodies mentioned previously.

354 Table 1.Values of environmental quality parameters in water bodies of Chennai, India. Results are in surface water (SW), ground water (GW),
355 sediment (SD) and mussel *Perna viridis* (PV^a: gills; PV^b: hepatopancreas). In the major and trace elements section of the table, results in surface
356 water and ground water are in mg/L and results in sediments and in *Perna viridis* are in mg/kg. Other abbreviations: Pr: Pre-monsoon. Mo:
357 Monsoon. Po: Post-monsoon. Dr: dry season. Wt. wet season. BDL: below detection limit.

In situ parameters															
Water body		pH	EC (μS/cm)		TDS (mg/L)		DO (mg/L)		Turbidity (NTU)		Reference				
Cooum river	SW - Pr	7.3-7.9	1,696-14,160		1,103-9,820		0-3.8				Dhamodharan et al. (2016)				
	SW - Mo	7.0-7.4	1,510-7,140		920-4,385		0.2-0.4								
	SW - Po	7.3-8.1	2,260-42,400		1,308-25,520		0								
	SW				1,119-20,553		BDL-4.75				Nethaji Mariappan et al. (2017)				
	GW	7.5-8.6	1,760-2,540		859-1,611										
Buckingham Canal	SW	7.24- 8.36	1,546- 2,215		1,422- 4,250		3.5- 5.9		150- 258		Kumar et al. (2018)				
Lakes (tanks): Porur, Perungudi, Velachery, Nandhivaram and Karapakkam	SW	6-8.7											Raji and Abraham (2018)		
Ground water City area	GW	6.0-8.2	580-7,250		374-4,669								Krishna Kumar et al. (2015)		
Ennore creek	SW	6.2-8.1						4.5-6.1						Vasanthi et al. (2017)	
Coast of Chennai	SW - Dr	7.17-8.60						0.00-12.37						Mishra et al. (2015)	
	SW - Wt	7.30-8.70						0-9.98							
Chemical and biological parameters															
Water body		COD (mg/L)	BOD (mg/L)	NH ₃ (mg/L)	NO ₂ ⁻ (mg/L)	NO ₃ ⁻ (mg/L)	TN (mg/L)	PO ₄ ³⁻ (mg/L)	TP (mg/L)	SO ₄ ²⁻ (mg/L)	Tot Alk (mg/L)	Chlorides (mg/L)	Reference		
Adyar river	SW		20-78											Kumar et al. (2019)	
Cooum river	SW - Pr	113-376	35-128	11-18.5	0-0.1	0-2.2		0.8-3.8		280-4,360	194-440	308-4,829	Dhamodharan et al. (2016)		
	SW - Mo	102-236	35-85	9-19	BDL	BDL		0.2-2.5		140-815	176-340	140-1,529			
	SW - Po	124-396	36-128	11-20	0-0.29	0-2.9		3.1-8 0-0.29		780-6,660	288-549	410-10,147			
	SW	195-1,204	16-375									349-990	Nethaji Mariappan et al. (2017)		
	GW			0-4						117-672	165-354	284-347			
Buckingham Canal	SW	640-1,572	146- 511									150-1396	Kumar et al. (2018)		
Lakes (tanks): Porur, Perungudi, Velachery, Nandhivaram and Karapakkam	SW	13-102	9-34					0.4- 2.4	0.02-0.162					Raji and Abraham (2018)	
Ground water City area	GW						0.1-3.9				22.2-98.6	18.3-360	115-2,012	Krishna Kumar et al. (2015)	
Coast of Chennai	SW - Dr		0.32-148	0-3.15	0-2.37	0-7.62	0-14.02							Mishra et al. (2015)	
	SW - Wt		0.01-168	0.002-2.88	0-0.749	0-4.19	0-20.02								
Major and trace elements															
Water body		Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Zn (mg/L)	Cu (mg/L)	Pb (mg/L)	Cd (mg/L)	Hg (mg/kg)	Fe (mg/L)	Cr (mg/L)	Ni (mg/L)	Reference	
Cooum river	SW - Pr	40-244	24-255	296-4,803	21.3-136										Dhamodharan et al. (2016)
	SW - Mo	36-144	20-140	208-1,402	10-75										
	SW - Po	208-593	15-43	405-9,250	27-227										
	SW					0.34-2.41	0.11-0.86	BDL-0.09							Nethaji Mariappan et al.

	GW	40-68	63-107	110-357	3-9	(2017)								
Pallikaranai marshland	SW					0.002–0.14	0-0.02	0.03–1.13	0-0.019		0-1.52	0.10–1.52	0-0.60	Karpagavalli et al. (2012)
	SD					149.4	102	36.6	1.6	0.58	30,201	382	85	Jayaprakash et al. (2010)
Ground water City area	GW	26-130	1.2-141.6	71-1,200	3-36									Krishna Kumar et al. (2015)
Ennore creek	PV ^a					4.658	3.289	0.761	0.416		8.957			Vasanthi et al. (2017)
	PV ^b					3.378	3.098	0.892	0.315		7.987			

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3.4.4 Biodiversity status

Encroachment and pollution of natural and artificial water bodies has affected Chennai's aquatic biodiversity. Amali et al. (2019) found that the wetlands located within the coastal districts of Tiruvallur, Chennai and Kancheepuram were only 15.8% of the total area in 2016. In the Pallikaranai marshland species diversity has been reduced due to wetland occupation and wastewater and solid waste pollution. According to Azeez et al. (2007) and Vencatesan (2007), 114 plant and 223 animal species can be found in the wetland, including endangered species. Plants include two endemics to Peninsular India (*Cynodon barberi* and *Iseilema enthephroides*), and exotic plants like water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*). 115 bird, 46 fish, 21 reptile, 10 amphibian, 10 mammal, 9 mollusk, 5 crustacean and 7 butterfly species have been reported. Raj et al. (2010) reported 101 species of resident and migratory birds. Knight and Devi (2010) found 75 fish species on the freshwater habitats around Chennai.

3.5 Impacts

3.5.1 Loss of aquatic ecosystems

Urbanization involved occupation, mismanagement and drainage of wetlands and the abandonment of water tanks (Amirtham et al. 2009; Meenatchi Sundaram 2011; Murawski 2015). Therefore, water bodies shrank by 30.6%, i.e. an average annual reduction of 1.25% (Mathan and Krishnaveni 2020).

The Pallikaranai marshland drained about 250 km² and occupied an area of 56 km² over today's residential localities such as Velachery, Thoraipakkam, Perungudi and Pallikaranai until 1980 (Vencatesan 2007; Sree Sharmila and Swathika 2016). Construction in this area reduced its extension to only 6 km² (Steinbruch and Hörmann 2015; Sree Sharmila and Swathika 2016). In 2005, 0.57 km² were used as a dumpsite and 1.37 km² were impacted by garbage and sewage (Vencatesan 2007). In 2007, 3.17 km² were declared as a Reserve Forest (Vencatesan 2007). Nowadays, there are two garbage-dumping yards in its outskirts. Into the bargain, untreated or partially treated sewage enters the wetland due to direct discharge or the Perungudi sewage treatment plant (The Hindu 2019).

Shifting drinking water supply from surface water to ground water sources in the past resulted in the degradation and abandonment of water tanks (Ariza et al. 2007; Palanisami et al. 2008; Adelina 2015). The Tamil Nadu administration tried to change this situation with the Protection of Tanks and an Eviction of Encroachment Act, in October 2007. However, this law has not been fully implemented (Lavanya 2013). Approximately 15% of the water storage capacity of the tanks in Adyar basin was lost due to heavy siltation (Massuel et al. 2014).

3.5.2 Low water table

Groundwater over-extraction and reduced groundwater recharge due to dense urbanization and increase of paved areas have caused declining groundwater levels (Srinivasan et al.

2013). Subsequently, aquifers are salinized due to seawater intrusion (Butterworth et al. 2007; Brunner et al. 2014; John 2015).

According to the Central Groundwater Board, 80% of Chennai's groundwater has been depleted (Balan et al. 2012) and all of the 20 groundwater assessment units in Chennai are over-exploited. In May 2019 (pre-monsoon), 64% of 11 monitored wells presented a water level of 5 to 10 m and 36% of 2 to 5 m (Central Ground Water Board 2020). Any further exploitation could lead to severe salt water intrusion (Balan et al. 2012). In peri-urban areas, groundwater over-extraction has caused a decline of the groundwater table: the pre-monsoon and post-monsoon groundwater level fluctuation varied from 2–6 m to 0–5 m, respectively, during 1971–2007 (Packialakshmi et al. 2011). An evaluation of the total change in groundwater storage across the state of Tamil Nadu from 2002 to 2012 concluded that groundwater depletion rate is 8% higher than the annual recharge rate (Chinnasamy and Agoramoorthy 2015).

3.5.3 Low water quality

The estimated 1073 MLD of sewage directly discharged into water bodies, together with industrial waste water produced a poor quality status of the aquatic ecosystems of Chennai (Amirthalingam 2003).

The Adyar river suffers from agricultural pollution upstream Nandambakkam, where it starts to receive untreated sewage (Venugopal et al. 2009; Lakshmi and Deepa 2011). This river is not perennial and only carries enough water during the rainy season. The rest of the year is almost stagnant due to the lack of water and the formation of sand bars near the mouth (Lakshmi 2011), transporting undiluted effluents from sewage treatment plants (CMDA 2008). The situation is similar in the Cooum river (Dhamodharan et al. 2019). Beyond Vanagaram up to its mouth, the river is highly polluted due to its perennial state, siltation, sand bar formation and almost stagnant state (Mukhopadhyay et al. 2020), and the discharges of untreated sewage and industrial waste water (Nethaji Mariappan et al. 2017). Also in the Buckingham Canal, that receives sewage and industrial effluents during its course through the city and the silting up of the canal has left the water stagnant (Jayaprakash et al. 2012). Encroachment in some sections of the central area has shrunk its width from 100 m to 10 m (2019b).

The lakes and the Pallikaranai marshland have suffered from encroachments, dumping, burning of wastes and sewage and industrial waste water discharge (Shahina et al. 2020). The Pallikaranai marshland is additionally polluted by the non-isolated Perungudi dumpsite (Padmavathi 2007). High concentrations of Cd, Hg, Cr, Cu, Ni, Pb, and Zn were found in its sediments (Jayaprakash et al. 2010). Sea water has intruded up to 16.5 km inland in Minjur - Panjetty area due to over exploitation of groundwater (Government of India 2017).

Seawater is polluted nearby the river mouths of the Adyar and the Cooum rivers by high concentrations of nutrients, low dissolved oxygen, high biochemical oxygen demand (BOD) and chemical oxygen demand (COD), high total suspended matter, high trace elements (Shanmugam et al. 2007; Mishra et al. 2015), high level of coliforms, *Vibrio* and *Pseudomonas*, (Santhiya et al. 2011), and presence of antibiotic resistant pathogens (Vignesh et al. 2012)

and microplastics (Kumar et al. 2016).

3.5.4 Reduction of biodiversity and human health

Amali et al. (2019) found that the wetlands located within the coastal districts of Tiruvallur, Chennai and Kancheepuram have decreased to 31.6%, from 23.1% in 1988 to 15.8% in 2016, i.e. an average annual reduction of 1.35%.

The degradation of aquatic ecosystems in Chennai has impacted its biodiversity. Invasive species, like the ornamental fish suckermouth, have been introduced and affected local species population (Oppili 2017). Water hyacinth colonized and significantly affected the biodiversity in Pallikaranai Marshland (Surya 2016). The construction of roads fragmented the marshland and limited the movement of animals (Azeez et al. 2007), with a reduction of resident birds in general (Vencatesan 2007) and the Black-winged Stilt in particular from 836 individuals in 2000 (Subramanian 2000) to 150 in 2010 (Raj et al. 2010).

For Buckingham Canal, the changes in the water quality reduced the primary productivity, affecting the entire aquatic ecosystem (Kumar et al. 2018). In Ennore estuary, 15 species were found dead in large numbers in August 2014 (Sachithanandam et al. 2017). High concentrations of Fe, Mn, Zn, Cu, Pb and Cd in *Mugil cephalus* fish and ultrastructural alterations on the green mussel *Perna viridis* have been found (Arockia Vasanthi et al. 2013; Vasanthi et al. 2017). At the discharge site of the power plant located in Ennore, the population density of phytoplankton and zooplankton is reduced by 64% and 93%, respectively (Prince Prakash Jebakumar et al. 2018).

The pollution of water resources has also adversely affected Chennai's inhabitants health. The stagnant water in Buckingham canal creates an attractive habitat for malaria-spreading mosquitoes (Jayaprakash et al. 2012). Water-borne diseases like Diarrhea and Typhoid are common (Sethuram 2014). Drinking water in some areas was highly contaminated with coliforms, *Cryptosporidium* and *Isospora* (Anbazhagi et al. 2007; Lavanya 2013; Chopra and Dworkin 2013), including sachet water but not bottled water (Venkatesan et al. 2014).

3.6 Responses

3.6.1 Urban planning

Chennai has had two master plans for urban planning. The First Master Plan for Chennai Metropolitan Area was approved in 1976 and the Second is in force since September 2008 (CMDA 2020b). Nevertheless, the urban form of the Chennai Metropolitan Area has been dictated by developments along the major roads and rail links radiating from the center of Chennai into the peri-urban regions (CMDA 2008). The second Plan included chapters for infrastructure for water supply and sanitation, with a recommendation to allocate water to areas within the city and outside, and for environment, with a recommendation to reduce pollution levels to acceptable standards in the waterways of Chennai. Recently, the elaboration of a third master plan with long-term vision document produced through a participatory approach has been announced, being planned to be implemented from 2026 and

474 to last for two decades (Shivakumar 2020).

475 **3.6.2 Water infrastructure**

476 Chennai has developed a big water infrastructure consisting on dams and interbasin transfers,
477 groundwater pumping, rainwater harvesting, desalination plants and water tankers.

478 Over 90% of the water supply of Chennai is covered by water stemming from reservoirs
479 (Brunner et al. 2014; Sakthivel et al. 2015). Surface water is provided mostly through two
480 systems of interconnected reservoirs. The oldest system has three reservoirs at Poondi (91.5
481 hm³) and Cholavaram (25 hm³), that discharge into Puzhal (93.5 hm³), also called Red Hills.
482 This water is treated at Puzhal (300 million liters per day, MLD), Kilpauk (270 MLD) and
483 Surapet (14 MLD) (CMDA 2006; CMWSSB 2020b). The newest system has
484 Chembarambakkam reservoir (103,2 hm³) and Chembarambakkam Water Treatment Plant
485 (530 MLD) (CMDA 2006; CMWSSB 2020b).

486 When water is scarce, around 500 MLD water from the Srisailem reservoir in the Krishna
487 River, can be diverted towards Poondi Lake through a series of 400 km-long inter-linked
488 canals called the Telugu Ganga project (CMDA 2006). Also, Veeranam lake and Vadakuthu
489 Water Treatment Plant (180 MLD) are added to the system. In total, the capacity of the cited
490 water treatment plants is 1,294 MLD (CMWSSB 2020c).

491 Groundwater's contribution has significantly diminished due to overexploitation
492 (Packialakshimibb et al. 2011; Sakthivel et al. 2015) from a maximum of 25% to around 6%
493 during the 2000's (Brunner et al. 2014). Because of low water level in the inner-city,
494 Metrowater started to hire private peri-urban agricultural wells in 2000 that yielded 77 MLD in
495 2005 compared to only 5.99 MLD of previous wells (CMDA 2006). Currently, Metrowater
496 continues extracting in peri-urban areas: Minjur, Panjetty, Tamaraipakkam Poondi and
497 Kannigaiper (CMWSSB 2020d). In fact, most of the agricultural wells in the villages in the
498 Chennai Metropolitan Area feed the inner city water market through water tankers
499 (Packialakshimibb et al. 2011) depriving peri-urban farmers of irrigation water (Butterworth et
500 al. 2007). In the southern peri-urban interface, 17.1 MLD are extracted by private water tankers
501 and 19.2 MLD by packaged water industries (Packialakshimibb et al. 2011). Also many
502 households in Chennai have in-house wells (Ruet et al. 2007).

503 To improve this situation, installation of Rain Water Harvesting (RWH) structures became
504 mandatory for new buildings in 2002 (CMWSSB 2020d). Since then, 38,218 structures have
505 been constructed (CMWSSB 2020d) with high acceptance by the public (Vivek 2016) but
506 maintenance issues were reported (Ministry of Water Resources and Government of India
507 2011).

508 Since 2010, a 100 MLD seawater desalination plant is operating at Minjur, north of the city,
509 and a similar 100 MLD plant at Nemmeli, south of the city, since 2013 (CMWSSB 2020e). A
510 third 150 MLD plant is expected to be completed by April 2023 (Lakshmi 2022) and a fourth
511 400 MLD at Perur by 2024 (Lakshmi 2019).

512 Tanker-based water supply is estimated to be 21% of the total water supplied in Chennai

(Maheshwari et al. 2020) i.e. around 125 MLD (Venkatachalam 2015), that would be delivered by up to 20,000 daily tanker loads of water (The Hindu 2018). About 80% of households in the Chennai Metropolitan Area consume packaged drinking water instead of piped water (The Hindu 2018). About 15-20 MLD of packaged drinking water are sold in the city daily (Srinivasan 2008).

3.6.3 Sewage treatment

The total installed wastewater treatment capacity in Chennai reaches 727 MLD in 12 sewage treatment plants, however, it is estimated that nearly 1073 MLD of sewage are directly discharged into water bodies (Arappor lyakkam 2017). The 12 treatment plants are divided in zones from I to V and their treatment capacity ranges from 12 to 120 MLD. In Nesapakkam, Koyambedu and Kodungaiyur, plants use activated sludge process and in Villivakkam an aerated lagoon (CMDA 2020b). In 2005 and 2006, the Chennai City River Conservation Project (CCRCP) invested Rs. 7201.5 million to increase the sewage treatment capacity, prevent overflow of sewage into the city waterways and renovate part of the system (CMDA 2006).

3.6.4 Restoration of water bodies

There are several projects to restore Chennai's water bodies. The Chennai Rivers Restoration Trust, founded in 2006 by Government of Tamil Nadu as Adyar Poonga Trust, have three projects: the Eco-Restoration of Adyar Creek (58 acres), the Eco-Restoration of the Adyar Creek and Estuary (300 acres) and the Integrated Cooum River Eco-Restoration Plan (Chennai Rivers Restoration Trust 2020).

The non-governmental organizations (NGOs) Care Earth Trust and The Nature Conservancy, among others, have developed wetland restoration projects introducing a sustainability and community participation focus. Care Earth Trust has successfully completed the restoration of the Narayanapuram Lake, the Perungalathur Periya Eri, the Puduthangal Lake, Thazhambur Eri, the Sembakkam Lake, the Puducheri Keni kulam and the Odai keni kulam (Care Earth Trust 2020).

In the Pallikaranai marshland, 317 ha of its southernmost portion were declared as a bird sanctuary on April 2007 (Vencatesan 2007; Steinbruch and Hörmann 2015) and its declaration as Ramsar site is in progress (Shekhar 2020).

3.6.5 Water governance

The Chennai Metropolitan Water Supply and Sewerage Act, 1978, amended in 1997, also known as Tamil Nadu Act 28 of 1978 founded Metrowater and gave it the mission to provide the Chennai Metropolitan Area an adequate supply of good quality water and a safe disposal of waste water at a reasonable price (CMWSSB 2020f). Metrowater subsidizes its residential customers by overpricing its industries (Gopakumar 2009). According to their data, 830 million liters per day (MLD) of drinking water are produced in Chennai, whereas the treatment capacity reaches 1,494 MLD. The expansion to cover the whole Chennai Metropolitan Area is

in progress (CMWSSB 2020c). A few years later, the Chennai Metropolitan Area Ground Water (Regulation) Act, 1987 came into force to preserve ground water and gave Metrowater the power to authorize permits to sink wells and licenses for extraction and the obligation of keeping well registers and the use of groundwater for agricultural purposes (The Chennai metropolitan area groundwater (regulation) act 1987 1987). Furthermore, The Tamil Nadu Pollution Control Board is responsible for setting, monitoring and enforcement of environmental regulations and standards (Roumeau et al. 2015).

Current approaches to water governance struggle to meet Chennai's demands for water. Legislation exists but for political, institutional and social reasons it is not always enforced (Janakarajan and Lakshmi 2005).

The insufficient supply of water by public entities has made private owned tankers and the packaged water vendors critical actors in water governance (Roumeau et al. 2015). Many farmers have left their agricultural activities to sell groundwater directly to private tankers following a greater revenue (Packialakshmi et al. 2011; Roumeau et al. 2015). Other stakeholders are water suppliers in the private sector, farmers, and the civil society (Roumeau et al. 2015) as well as multiple NGOs dealing with water and environmental issues, like Environmentalist Foundation of India or the Care Earth Trust.

4 Discussion

Different studies have assessed the DPSIR framework in terms of its application for sustainable development studies (Carr et al. 2009), determination of causal relationships (Niemeijer and De Groot 2008) and its feasibility for supporting decision making (Tscherning et al. 2012). These authors enunciate that the DPSIR presents drawbacks regarding to its hierarchical structure, the establishment of unidirectional relationships and, in some studies, the lack of integration of decision makers into the participative process. Nevertheless, they also stress the DPSIR's potential to emphasize causality between environmental indicators and to structure disperse data to provide meaningful explanations of complex environmental issues to policy makers (Niemeijer and De Groot 2008; Tscherning et al. 2012) that facilitates communication and comparison (Patrício et al. 2016). Since the development of the DPSIR, 25 derivatives in more than 152 studies have been proposed in the literature (Taft and Evers 2016; Patrício et al. 2016). However, none has been adopted by the scientific community as a replacement for the DPSIR nor by international institutions as the original DPSIR framework was by the European Union and European Environment Agency (European Commission 1999).

Through the application of the DPSIR in Chennai, the authors agree on its advantages and its potential to be connected with the SDGs 6 and 11. The application of the DPSIR involves indicators regarding water resources and pollution, waste, land use change, and loss of biodiversity among others (Smeets and Weterings 1999; Kristensen 2003; European Environment Agency 2005, 2014) that are also included in the SDGs 6 and 11, like the indicators 6.3.1 Proportion of domestic and industrial wastewater flows safely treated, 6.3.2 Proportion of bodies of water with good ambient water quality or 6.6.1 Change in the extent of water-related ecosystems over time and 11.3.1 Ratio of land consumption rate to population

growth rate (United Nations 2022a, b).

The application of the DPSIR framework also found limitations on water management. First, water management requires to be faced from several perspectives and considering a large number of variables. Today, decision-makers and stakeholder work in many cases independently with contradictory interests. Therefore, a deeper integration of the public administration bodies involved in water management and a better cooperation of different stakeholders is necessary. Secondly, poor law enforcement hinders efficient water management. For example, groundwater over-extraction in periurban areas. Thirdly, data scarcity or difficult access impedes to develop new efficient policies adapted to the city needs.

In the Indian context, the implementation of effective policies to manage water challenges in cities is limited by inaccessible and unreliable data, limited coordination between stakeholders, non-implementation of policies and projects, environmental legislation violations, unclear or overlapped responsibilities, inadequate maintenance of water infrastructure (Aartsen et al. 2018). The Organisation for Economic Cooperation and Development (OECD 2015) provides a framework to understand water governance systems' performance. In addition, the implementation of adaptive management approaches has been stated as a comprehensive solution for improving decision making and managing water resources (Pahl-Wostl 2008; Kattel 2019a). For instance, Kattel, 2019, has proposed six key elements for enhancing water security in river basins i.e. the implementation of early warning systems, water footprints management, groundwater aquifers management, increased water stewardship and governance, enhanced resilience of social and ecological systems of freshwaters and the promotion of the water-energy-food nexus.

Chennai and its metropolitan area are expected to keep facing water stress and difficulties to implement the SDGs 6 and 11. The current water supply system has proven to be insufficient even with average weather conditions, with a gap of 342 MLD between estimated demand (1173 MLD) and supply (831 MLD) in 2014 (Government of Tamil Nadu 2014) and with a supply of only around 90 liters per capita a day (CMDA 2006). Chennai needs to urgently find new water sources to meet the always increasing demand.

Conventional surface water sources, like new reservoirs, are fed by Northeast Monsoon and would face a similar trend of drought (Chennai Metropolitan Development Authority, 2006). Catchments depending on the Southwest Monsoon are far from Chennai and would require high costs to build and operate long channels and tensions between communities would emerge, like in the Telugu Ganga project. Groundwater is unable to supply sufficient water in a sustainable manner. Recharging the aquifers by water harvesting would contribute to a more stable and reliable water supply. The two new seawater desalination plants (2x500 MLD) planned for 2024 can cater more than 2 million people, although a final affordable water price has to be granted for poorer areas. Otherwise, water bills could remain unpaid as it happens in the rest of the state of Tamil Nadu (Gopakumar 2009). Furthermore, management of brine produced by desalination plants requires to be considered.

Chennai's water bodies are being polluted because of the lack of waste water treatment plants.

The likely 1073 million liters per day (MLD) gap between treated (550 MLD) and non-treated (1500-2000 MLD) sewage is directly discharged into water bodies (Arappor Iyakkam 2017; CMWSSB 2020a). However, it is insufficient to cover the present and future sewage generation. The authorities need to find funds to build new sewage treatment plants and an efficient waste management system, including the closure of the current two main open dumpsites. The ability of the institutions to implement urban plans that consider sewage treatment and waste management systems will be key for pollution prevention of water bodies at a lower cost. The third master plan of Chennai brings a new and promising focus with a long-term vision document produced through a participatory approach.

Biodiversity in the Pallikaranai marshland and other water bodies has been reduced due to increased water pollution and invasive species like the water hyacinth (Oppili 2017). NGOs like Care Earth Trust, The Nature Conservancy and Environmentalist Foundation of India play a major role in the restoration of aquatic ecosystems. Restoration success relies significantly on the interest of the institutions to implement this kind of projects on their own or with the help of NGOs and also in the ability of these NGOs to achieve external funds.

Environmental regulations need to meet international standards and to be enforced to ensure the protection of the aquatic ecosystems (Janakarajan and Lakshmi 2005). In May 2020, a new draft of the Environment Impact Assessment Notification 2020, under the Environment (Protection) Act, 1986 came into force. It set aside several essential provisions such as public consultation and introduced ex-post facto clearance for many projects, including some irrigation and hydroelectric projects, all inland waterway projects, and others (Ananthakrishnan 2020). This sets a worrying precedent that could affect other environmental regulations.

The severe hit of COVID pandemic on Indian economy dropped investment growth in the year 2020 to 10% (United Nations 2021) and this will probably delay many of the mentioned projects.

5 Conclusions

This study applied the DPSIR Framework to water management in Chennai, South India. The study provides answers to the research questions raised in the introduction section. First, the DPSIR proved to be a valuable tool to evaluate water challenges in cities by disentangling relationships between environmental indicators and structuring disperse data that allows policy makers for a better understanding. The indicators used for the DPSIR framework can be also easily aligned with the indicators of the Sustainable Development Goals 6 and 11. Second, limited integration of decision-makers and stakeholders, poor law enforcement and scarcity of data limit effective water management in Chennai, which can be applied to other cities with similar scenarios.

As a result of the DPSIR analysis, the unplanned population growth fueled by the rapid economic development were identified as the two main drivers. They brought pressures such as rapid land use change, groundwater over-extraction to partially cover the higher water demand, and bigger volumes of solid wastes and untreated sewage that are discharged into water bodies. This situation headed to low values of indicators related to the status of

671 urbanization, water availability, water quality and biodiversity and visible environmental
672 impacts within the city: loss of aquatic ecosystems and encroachment, low water table levels,
673 low water quality, that reduces aquatic biodiversity and human health. Urban planning and the
674 third Chennai master plan was identified as a key response. Stakeholders executed numerous
675 water infrastructure projects that increased drinking water availability with conventional (dams
676 and interbasin transfers, groundwater pumping) and non-conventional (desalination plants,
677 water tankers, rainwater harvesting) techniques. They also built sewage treatment plants,
678 restored ecosystems and improved water governance.

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680 References

- 681 Aartsen M, Koop S, Hegger D, et al (2018) Connecting water science and policy in India:
682 lessons from a systematic water governance assessment in the city of Ahmedabad. *Reg*
683 *Environ Chang* 18:2445–2457. <https://doi.org/10.1007/S10113-018-1363-1/TABLES/2>
- 684 Adelina C (2015) Internship Report IGCS. Chennai
- 685 Aithal BH, Ramachandra T V. (2016) Visualization of Urban Growth Pattern in Chennai Using
686 Geoinformatics and Spatial Metrics. *J Indian Soc Remote Sens* 44:617–633.
687 <https://doi.org/10.1007/s12524-015-0482-0>
- 688 Allen A, Dávila JD, Hofmann P (2006) The peri-urban water poor: Citizens or consumers?
689 *Environ Urban* 18:333–351. <https://doi.org/10.1177/0956247806069608>
- 690 Amali G, Rajasree R, Kumar D, Sriganesh J (2019) Assessment of wetland change dynamics
691 of Chennai coast, Tamil Nadu, India, using satellite remote sensing. *Indian J Geo Mar*
692 *Sci* 48:1258–1266
- 693 Amirthalingam M (2003) Ecological Heritage Sites of Chennai. *Eco News*
- 694 Amirtham LR, Devadas MD, Perumal M (2009) Mapping of Micro-Urban Heat Islands and
695 Land Cover Changes: A case in Chennai City, India. *Int J Clim Chang Impacts*
696 *Responses* 1:71–84. <https://doi.org/10.18848/1835-7156/cgp/v01i02/37258>
- 697 Ananthakrishnan G (2020) The Hindu Explains | What are the key changes in the Environment
698 Impact Assessment Notification 2020? *The Hindu*
- 699 Anbazhagi M, Loganathan D, Tamilselvan S, et al (2007) *Cryptosporidium* Oocysts in Drinking
700 Water Supply of Chennai City, Southern India. *Clean – Soil, Air, Water* 35:167–171.
701 <https://doi.org/10.1002/clen.200600034>
- 702 Arappor Iyakkam (2017) Why Chennai Stinks? Chennai
- 703 Ariza P, Galán E, Serrano T, Reyes-García V (2007) Water tanks as ecosystems. Local
704 ecosystemic perception for integral management of water tanks in Tamil Nadu, South
705 India. *Perifèria Rev d'investigació i Form en Antropol* 7:1–27.
706 <https://doi.org/10.5565/rev/periferia.178>
- 707 Arockia Vasanthi L, Revathi P, Mini J, Munuswamy N (2013) Integrated use of histological and
708 ultrastructural biomarkers in *Mugil cephalus* for assessing heavy metal pollution in
709 Ennore estuary, Chennai. *Chemosphere* 91:1156–1164.
710 <https://doi.org/10.1016/j.chemosphere.2013.01.021>
- 711 Asian Development Bank (2020) Asian Water Development Outlook 2020: Description of
712 Methodology and Data
- 713 Azeez P, Bhupathy S, Ranjini J, et al (2007) Management Plan for the Eco-restoration of
714 Pallikaranai Reserve Forest. Chennai
- 715 Bahri A (2012) Integrated Urban Water Management - TEC Background paper no.16.
716 Stockholm
- 717 Balan IN, Shivakumar M, Kumar PDM (2012) An assessment of groundwater quality using
718 water quality index in Chennai, Tamil Nadu, India. *Chronicles Young Sci* 3:146–150
- 719 Bao C, Chen X (2015) The driving effects of urbanization on economic growth and water use
720 change in China: A provincial-level analysis in 1997–2011. *J Geogr Sci*.
721 <https://doi.org/10.1007/s11442-015-1185-8>
- 722 Benson D, Gain AK, Rouillard JJ (2015) Water governance in a comparative perspective:
723 From IWRM to a “nexus” approach? *Water Altern* 8:756–773
- 724 BIS (1992) Indian standard Water Quality Standards in India IS 2296:1992

725 Bloodgood L (2007) Competitive Conditions for Foreign Direct Investment in India

726 Brown R, Farrelly M, Keath N (2009) Practitioner perceptions of social and institutional barriers
727 to advancing a diverse water source approach in Australia. *Int J Water Resour Dev*
728 25:15–28. <https://doi.org/doi.org/10.1080/07900620802586090>

729 Brunner N, Starkl M, Sakthivel P, et al (2014) Policy preferences about managed aquifer
730 recharge for securing sustainable water supply to Chennai City, India. *Water* 6:3739–
731 3757. <https://doi.org/10.3390/w6123739>

732 Butterworth J, Ducrot R, Faysse N, Janakarajan S (2007) Peri-Urban Water Conflicts:
733 Supporting dialogue and negotiation. IRC International Water and Sanitation Centre,
734 Delft, the Netherlands

735 Care Earth Trust (2020) Wetland Restoration. In: Care Earth Trust.
736 <https://careearthtrust.org/wetland-restoration/>. Accessed 11 Sep 2020

737 Carr ER, Wingard PM, Yorty SC, et al (2009) Applying DPSIR to sustainable development. *Int*
738 *J Sustain Dev World Ecol* 14:543–555. <https://doi.org/10.1080/13504500709469753>

739 Central Ground Water Board (2020) Groundwater data access. [http://cgwb.gov.in/GW-data-](http://cgwb.gov.in/GW-data-access.html)
740 [access.html](http://cgwb.gov.in/GW-data-access.html). Accessed 28 Jul 2020

741 Chapagain K, Aboelnga HT, Babel MS, et al (2022) Urban water security: A comparative
742 assessment and policy analysis of five cities in diverse developing countries of Asia.
743 *Environ Dev* 43:100713

744 Chaturvedi MC (2012) India's waters: Environment, economy, and development. CRC Press,
745 Boca Raton

746 Chennai District (2020) Local Bodies of the Greater Chennai Corporation.
747 <https://chennai.nic.in/about-district/administrative-setup/local-bodies/>. Accessed 28 Mar
748 2020

749 Chennai Rivers Restoration Trust (2020) Projects description.
750 <http://www.chennairivers.gov.in/index.html>. Accessed 10 Sep 2020

751 Chinnasamy P, Agoramoorthy G (2015) Groundwater Storage and Depletion Trends in Tamil
752 Nadu State, India. *Water Resour Manag* 29:2139–2152. [https://doi.org/10.1007/s11269-](https://doi.org/10.1007/s11269-015-0932-z)
753 015-0932-z

754 Chopra RD, Dworkin MS (2013) Descriptive epidemiology of enteric disease in Chennai, India.
755 *Epidemiol Infect* 141:953–957. <https://doi.org/10.1017/S0950268812001409>

756 CMDA (2020a) Website of the Chennai Metropolitan Development Authority.
757 <http://www.cmdachennai.gov.in/>. Accessed 28 Mar 2020

758 CMDA (2008) Second Master Plan For Chennai Metropolitan Area, 2026. Chennai

759 CMDA (2006) Development Plan for Chennai Metropolitan Area. Chennai

760 CMDA (2020b) Website of the Chennai Metropolitan Development Authority

761 CMWSSB (2020a) Chennai Sewerage System. In: CMWSSB.
762 <https://chennaietrowater.tn.gov.in/seweragesystem.html>. Accessed 20 Jul 2020

763 CMWSSB (2020b) Metrowater Operational Area.
764 <https://chennaietrowater.tn.gov.in/metrowateroperationalarea.html>. Accessed 29 Mar
765 2020

766 CMWSSB (2020c) Water Supply System.
767 <https://chennaietrowater.tn.gov.in/watersupplysystem.html>. Accessed 29 Mar 2020

768 CMWSSB (2020d) Rain Water Harvesting. <https://chennaietrowater.tn.gov.in/rwh.html>.
769 Accessed 12 Sep 2020

770 CMWSSB (2020e) Desalination Plants at Nemmeli and Minjur.
771 <https://chennaietrowater.tn.gov.in/desalination-Nemmeli.html>. Accessed 29 Mar 2020

772 CMWSSB (2020f) CMWSS Act. <https://chennaietrowater.tn.gov.in/administration.html>.
773 Accessed 16 Aug 2020

774 Coelho K (2018) Reading History and Power in Urban Landscapes: The Lens of Urban
775 Political Ecology. *Ecol Econ Soc INSEE J* 1:19–30

776 Devi NN, Sridharan B, Bindhu VM, et al (2020) Investigation of role of retention storage in
777 tanks (Small water bodies) on future urban flooding: A case study of chennai city, india.
778 *Water (Switzerland)*. <https://doi.org/10.3390/w12102875>

779 Dhamodharan A, Abinandan S, Aravind U, et al (2019) Distribution of Metal Contamination
780 and Risk Indices Assessment of Surface Sediments from Cooum River, Chennai, India.
781 *Int J Environ Res* 13:853–860. <https://doi.org/10.1007/s41742-019-00222-8>

782 Dhamodharan A, Shanthakumar S, Ganapathy GP (2016) Assessment of seasonal variations
783 in surface water quality of cooum river in Chennai, India-a statistical approach. *Artic Glob*
784 *Int J* 18:

785 Dhillon A (2019) Chennai in crisis as authorities blamed for dire water shortage. *Guard*.

786 Di Baldassarre G, Wanders N, AghaKouchak A, et al (2018) Water shortages worsened by
787 reservoir effects. *Nat Sustain* 1:617–622. <https://doi.org/10.1038/S41893-018-0159-0>

788 Directorate of Census Operations Tamil Nadu (2011) Census of India 2011 - District Census
789 Handbook Chennai, Part XII-B

790 Esakku S, Swaminathan A, Parthiba Karthikeyan O, et al (2007) Municipal solid waste
791 management in Chennai city, India. In: *Proceedings Sardinia*. pp 1–5

792 European Comission (1999) Towards environmental pressure indicators for the EU.
793 Luxembourg

794 European Environment Agency (2020) European Environment Agency glossary.
795 <https://www.eea.europa.eu/help/glossary/eea-glossary/dpsir>. Accessed 20 Sep 2020

796 European Environment Agency (2005) EEA core set of indicators. Guide. Luxembourg

797 European Environment Agency (2014) Digest of EEA indicators 2014

798 Flörke M, Schneider C, McDonald RI (2018) Water competition between cities and agriculture
799 driven by climate change and urban growth. *Nat Sustain* 2017 11 1:51–58.
800 <https://doi.org/10.1038/s41893-017-0006-8>

801 Gabrielsen P, Bosch P (2003) Environmental Indicators: Typology and Use in Reporting

802 Gari SR, Ortiz Guerrero CE, A-Urbe B, et al (2018a) A DPSIR-analysis of water uses and
803 related water quality issues in the Colombian Alto and Medio Dagua Community Council.
804 *Water Sci* 32:318–337. <https://doi.org/10.1016/J.WSJ.2018.06.001>

805 Gari SR, Ortiz Guerrero CE, A-Urbe B, et al (2018b) A DPSIR-analysis of water uses and
806 related water quality issues in the Colombian Alto and Medio Dagua Community Council.
807 *Water Sci* 32:318–337. <https://doi.org/10.1016/J.WSJ.2018.06.001>

808 Gopakumar G (2009) Investigating Degenerated Peripheralization in Urban India: The Case
809 of Water Supply Infrastructure and Urban Governance in Chennai. *Public Work Manag*
810 *Policy* 14:109–129. <https://doi.org/10.1177/1087724X09350629>

811 Government of India (2017) Aquifer mapping and ground water management for Chennai
812 Aquifer System, Tamil Nadu. Chennai

813 Government of Tamil Nadu (2020) Website of the Government of Tamil Nadu.
814 https://www.tn.gov.in/district_view. Accessed 28 Mar 2020

815 Government of Tamil Nadu (2014) Vision Tamil Nadu 2023. Strategic Plan for Infrastructure
816 development in Tamil Nadu

817 Greater Chennai Corporation (2020) Solid waste management.
818 [https://www.chennaicorporation.gov.in/departments/solid-waste-](https://www.chennaicorporation.gov.in/departments/solid-waste-management/index.htm)
819 [management/index.htm](https://www.chennaicorporation.gov.in/departments/solid-waste-management/index.htm). Accessed 28 Jul 2020

820 GWP (2000) Towards water security: Framework for Action. Glob Water Partnersh

821 Haritas B (2017) Richest cities of India. BW Businessworld

822 Haufe L (2017) Water Management and Urbanisation in Sriperumpudur Town a case study in
823 the peri-urban of Chennai, South India. Technische Universitat Berlin

824 Hazbavi Z, Sadeghi SH, Gholamalifard M, Davudirad AA (2020) Watershed health
825 assessment using the pressure–state–response (PSR) framework. L Degrad Dev 31:3–
826 19. <https://doi.org/10.1002/ldr.3420>

827 He C, Liu Z, Wu J, et al (2021) Future global urban water scarcity and potential solutions. Nat
828 Commun 2021 12:1–11. <https://doi.org/10.1038/s41467-021-25026-3>

829 Hoekstra AY, Buurman J, Van Ginkel KCH (2018) Urban water security: A review. Environ
830 Res Lett 13:53002

831 Hossain F, Degu AM, Woldemichael AT, et al (2013) Water Resources Vulnerability in the
832 Context of Rapid Urbanization of Dhaka City (a South Asian Megacity). In: Climate
833 Vulnerability: Understanding and Addressing Threats to Essential Resources. Elsevier
834 Inc., pp 393–404

835 International Institute for Population Sciences (2017) National Family Health Survey (NFHS-
836 4), India, 2015-16: Tamil Nadu. Mumbai

837 International Monetary Fund (2019) World Economic Outlook: Global Manufacturing
838 Downturn, Rising Trade Barriers. Washington, DC

839 Janakarajan S, Lakshmi G (2005) Intricacies of Chennai Metropolitan Water Laws

840 Jayaprakash M, Nagarajan R, Velmurugan PM, et al (2012) Assessment of trace metal
841 contamination in a historical freshwater canal (Buckingham Canal), Chennai, India.
842 Environ Monit Assess 184:7407–7424. <https://doi.org/10.1007/s10661-011-2509-5>

843 Jayaprakash M, Urban B, Velmurugan PM, Srinivasalu S (2010) Accumulation of total trace
844 metals due to rapid urbanization in microtidal zone of Pallikaranai marsh, South of
845 Chennai, India. Environ Monit Assess 170:609–629. [https://doi.org/10.1007/s10661-009-](https://doi.org/10.1007/s10661-009-1261-6)
846 1261-6

847 Jayaraman N (2019) Viewpoint: Why India's Chennai has run out of water. BBC News

848 Jeganathan A, Andimuthu R (2013) Temperature trends of Chennai City, India. Theor Appl
849 Climatol 111:417–425. <https://doi.org/10.1007/s00704-012-0646-6>

850 Jensen O, Wu H (2018) Urban water security indicators: Development and pilot. Environ Sci
851 Policy 83:33–45

852 John R (2015) Governance of peri-urban water resources: A case study of the discursive
853 practises around sustainable water management in greater Chennai region, India

854 Kanungo RP, Banerjee AN, Rowley C (2018) Changing the indian economy: Renewal, reform
855 and revival. Elsevier

856 Karpagavalli MS, Malini P, Ramachandran A (2012) Analysis of heavy metals in dying wetland
857 Pallikaranai, Tamil Nadu, India. J Environ Biol 33:757–761

858 Karthikeyan D (2019) “Our whole life is disrupted”: hope dries up as Chennai battles historic
859 drought | World news | The Guardian. Guard.

860 Kattel GR (2019a) State of future water regimes in the world's river basins: balancing the water
861 between society and nature. *Crit Rev Environ Sci Technol* 49:1107–1133.
862 <https://doi.org/10.1080/10643389.2019.1579621>

863 Kattel GR (2019b) State of future water regimes in the world's river basins: balancing the water
864 between society and nature. *Crit Rev Environ Sci Technol* 49:1107–1133.
865 <https://doi.org/10.1080/10643389.2019.1579621>

866 Kirono DGC, Larson S, Tjandraatmadja G, et al (2014) Adapting to climate change through
867 urban water management: a participatory case study in Indonesia. *Reg Environ Chang*
868 14:355–367

869 Knight JD., Devi K. (2010) Species persistence: a re-look at the freshwater fish fauna of
870 Chennai, India. *J Threat Taxa* 2:1334–1337. <https://doi.org/10.11609/jott.o2519.1334-7>

871 Kohsaka R (2010) Developing biodiversity indicators for cities: Applying the DPSIR model to
872 Nagoya and integrating social and ecological aspects. *Ecol Res* 25:925–936.
873 <https://doi.org/10.1007/s11284-010-0746-7>

874 Kong B, He B, Nan X, et al (2016) The evaluation of water resources sustainable utilization in
875 Kosi Basin based on DPSIR Model. *Commun Comput Inf Sci* 569:537–548.
876 <https://doi.org/10.1007/978-3-662-49155-3>

877 Koop SHA, van Leeuwen CJ (2015a) Assessment of the Sustainability of Water Resources
878 Management: A Critical Review of the City Blueprint Approach. *Water Resour Manag*
879 29:5649–5670. <https://doi.org/10.1007/S11269-015-1139-Z/FIGURES/4>

880 Koop SHA, van Leeuwen CJ (2015b) Assessment of the sustainability of water resources
881 management: a critical review of the city blueprint approach. *Water Resour Manag*
882 29:5649–5670

883 Krishna Kumar S, Logeshkumaran A, Magesh NS, et al (2015) Hydro-geochemistry and
884 application of water quality index (WQI) for groundwater quality assessment, Anna
885 Nagar, part of Chennai City, Tamil Nadu, India. *Appl Water Sci* 5:335–343.
886 <https://doi.org/10.1007/s13201-014-0196-4>

887 Krishnamurthy R, Desouza KC (2015) Chennai, India. *Cities* 42:118–129.
888 <https://doi.org/10.1016/j.cities.2014.09.004>

889 Kristensen P (2004) The DPSIR Framework. Nairobi

890 Kristensen P (2003) EEA core set of indicators. Revised version

891 Kumar AA, Sivakumar R, Reddy YSR, et al (2016) Preliminary study on marine debris pollution
892 along Marina beach, Chennai, India. *Reg Stud Mar Sci* 5:35–40.
893 <https://doi.org/10.1016/j.rsma.2016.01.002>

894 Kumar P, Dasgupta R, Ramaiah M, et al (2019) Hydrological simulation for predicting the
895 future water quality of Adyar River, Chennai, India. *Int J Environ Res Public Health* 16:.
896 <https://doi.org/10.3390/ijerph16234597>

897 Kumar SV, Mazher S, Pascal LF, et al (2018) Analysis of physicochemical water quality
898 parameters of Buckingham Canal, Chennai, Tamil Nadu, India. *Int J Zool Stud* 3:226–
899 231

900 Lakshmi K (2011) WRD plans groynes. *The Hindu*

901 Lakshmi K (2022) Nemmeli third desalination plant to be ready by April 2023. *The Hindu*

902 Lakshmi K (2019) Work on a third desalination plant in Nemmeli to begin by October-end. *The*
903 *Hindu*

904 Lakshmi K, Deepa HR (2011) Untreated sewage pollutes waterways. *The Hindu*

905 Lavanya KA (2013) Urban Flood Management – A Case Study of Chennai City. *Archit Res.*

906 <https://doi.org/10.5923/j.arch.20120206.01>

907 Levrel H, Kerbirou C, Couvet D, Weber J (2009) OECD pressure-state-response indicators
 908 for managing biodiversity: A realistic perspective for a French biosphere reserve.
 909 *Biodivers Conserv* 18:1719–1732. <https://doi.org/10.1007/s10531-008-9507-0>

910 Low KG, Grant SB, Hamilton AJ, et al (2015) Fighting drought with innovation: Melbourne's
 911 response to the Millennium Drought in Southeast Australia. *Wiley Interdiscip Rev Water*
 912 2:315–328. <https://doi.org/10.1002/WAT2.1087>

913 Mahajan N (2016) Solid waste management in Chennai: Lessons from Exnora. *Innov J* 21:1–
 914 26

915 Maheshwari A, Misra S, Gudi RD, Subbiah S (2020) A Short-Term Planning Framework for
 916 the Operation of Tanker-Based Water Distribution Systems in Urban Areas. *Ind Eng*
 917 *Chem Res* 59:9575–9592. <https://doi.org/10.1021/ACS.IECR.0C00303>

918 Manny L (2022) Socio-technical challenges towards data-driven and integrated urban water
 919 management: a socio-technical network approach. *Sustain. Cities. Soc* 90, 104360

920 Mariappan J (2014) Public consultation for Adyar river restoration to be held in Chennai on
 921 Wednesday. *The Times of India*

922 Marlow DR, Moglia M, Cook S, Beale DJ (2013) Towards sustainable urban water
 923 management: A critical reassessment. *Water Res* 47:7150–7161

924 Masih N (2019) India drought: As Chennai runs out of water, 9 million people pray for rain.
 925 *Washington Post*

926 Massuel S, Perrin J, Mascre C, et al (2014) Managed aquifer recharge in South India: What
 927 to expect from small percolation tanks in hard rock? *J Hydrol* 512:157–167.
 928 <https://doi.org/10.1016/j.jhydrol.2014.02.062>

929 Mathan M, Krishnaveni M (2020) Monitoring spatio-temporal dynamics of urban and peri-
 930 urban land transitions using ensemble of remote sensing spectral indices-a case study
 931 of Chennai Metropolitan Area, India. *Environ Monit Assess* 192:15.
 932 <https://doi.org/10.1007/S10661-019-7986-Y/TABLES/7>

933 Maurya SP, Singh R (2022) Multiobjective optimization techniques for integrated urban water
 934 management: A case study of Varanasi city. In: *Current Directions in Water Scarcity*
 935 *Research*. Elsevier, pp 433–445

936 Meenatchi Sundaram A (2011) Urban green-cover and the environmental performance of
 937 Chennai city. *Environ Dev Sustain* 13:107–119. [https://doi.org/10.1007/s10668-010-](https://doi.org/10.1007/s10668-010-9251-y)
 938 9251-y

939 Millington N (2018) Producing water scarcity in São Paulo, Brazil: The 2014-2015 water crisis
 940 and the binding politics of infrastructure. *Polit Geogr* 65:26–34.
 941 <https://doi.org/10.1016/J.POLGEO.2018.04.007>

942 Ministry of Water Resources, Government of India (2011) Groundwater Scenario in Major
 943 Cities of India. Faridabad

944 Mishra P, Panda US, Pradhan U, et al (2015) Coastal water quality monitoring and modelling
 945 off Chennai city. In: *Procedia Engineering*. Elsevier Ltd, pp 955–962

946 Mukhopadhyay M, Sampath S, Muñoz-Arnanz J, et al (2020) Plasticizers and bisphenol A in
 947 Adyar and Cooum riverine sediments, India: occurrences, sources and risk assessment.
 948 *Environ Geochem Health* 1–14. <https://doi.org/10.1007/s10653-020-00516-3>

949 Murawski M (2015) Sustainable development in the peri-urban regions of Chennai (Madras)
 950 Spatial analysis using optical remote sensing data. *Kiel*

951 Nethaji Mariappan VE, German Amali Jacintha T, Dass Batvari P (2017) *Water Quality Studies*

952 of Cooum Sub Basin, Chennai. *Nat Environ Pollut Technol* 16:969–974

953 Newton D (2016) *The Global Water Crisis: a reference Handbook*. ABC-CLIO, Santa Barbara

954 Niemeijer D, De Groot RS (2008) Framing environmental indicators: Moving from causal
 955 chains to causal networks. *Environ Dev Sustain* 10:89–106.
 956 <https://doi.org/10.1007/s10668-006-9040-9>

957 NITI Aayog (2020) Total Fertility Rate Statistics. [https://niti.gov.in/content/total-fertility-rate-tfr-](https://niti.gov.in/content/total-fertility-rate-tfr-birth-woman)
 958 [birth-woman](https://niti.gov.in/content/total-fertility-rate-tfr-birth-woman). Accessed 14 Jul 2020

959 OECD (2015) *The OECD Principles on Water Governance*

960 Oldenborgh GJ van, Otto FEL, Karsten H, Achutarao K (2016) The heavy precipitation event
 961 of December 2015 in Chennai, India. In: *Explaining Extremes of 2015 from a Climate*
 962 *Perspective*. *Bull. Amer. Meteor. Soc.* 97 (12), S14–S18

963 Oppili P (2017) Killer exotic fish loose in city water bodies. *Times of India*

964 Packialakshmi S, K Ambujam N, Nelliya P (2011) Groundwater market and its implications
 965 on water resources and agriculture in the southern peri-urban interface, Chennai, India.
 966 *Environ Dev Sustain* 13:423–438. <https://doi.org/10.1007/s10668-010-9269-1>

967 Padmavathi M (2007) Assessment of Ground Contamination at Perungudi Municipal Dumping
 968 Yard in Chennai

969 Pagan J, Pryor M, Deepa R, et al (2020a) Sustainable Development Tool Using Meta-Analysis
 970 and DPSIR Framework — Application to Savannah River Basin, U.S. *JAWRA J Am*
 971 *Water Resour Assoc* 56:1059–1082. <https://doi.org/10.1111/1752-1688.12872>

972 Pagan J, Pryor M, Deepa R, et al (2020b) Sustainable Development Tool Using Meta-Analysis
 973 and DPSIR Framework — Application to Savannah River Basin, U.S. *JAWRA J Am*
 974 *Water Resour Assoc* 56:1059–1082. <https://doi.org/10.1111/1752-1688.12872>

975 Pahl-Wostl C (2008) Requirements for Adaptive Water Management. *Adapt Integr Water*
 976 *Manag* 1–22. https://doi.org/10.1007/978-3-540-75941-6_1

977 Palanisami K, Jegadeesan M, Fujita K, Kono Y (2008) Impacts of the Tank Modernization
 978 Programme on Tank Performance in Tamil Nadu State, India. *Kyoto*

979 Patrício J, Elliott M, Mazik K, et al (2016) DPSIR—Two decades of trying to develop a unifying
 980 framework for marine environmental management? *Front Mar Sci* 3:1–14.
 981 <https://doi.org/10.3389/fmars.2016.00177>

982 Pluchinotta I, Pagano A, Vilcan T, et al (2021) A participatory system dynamics model to
 983 investigate sustainable urban water management in Ebbsfleet Garden City. *Sustain*
 984 *Cities Soc* 67:102709. <https://doi.org/10.1016/j.scs.2021.102709>

985 Prakash TJ, Punyaseshudu D (2015) Analysis of Tropical Cyclone and its Impact on Coastal
 986 Areas. *Int J Innov Eng Sci* 5:

987 Prince Prakash Jebakumar J, Nandhagopal G, Rajan Babu B, et al (2018) Impact of coastal
 988 power plant cooling system on planktonic diversity of a polluted creek system. *Mar Pollut*
 989 *Bull* 133:378–391. <https://doi.org/10.1016/j.marpolbul.2018.05.053>

990 Pulikesi M, Baskaralingam P, Elango D, et al (2006) Air quality monitoring in Chennai, India,
 991 in the summer of 2005. *J Hazard Mater* 136:589–596.
 992 <https://doi.org/10.1016/j.jhazmat.2005.12.039>

993 Raj N, Ranjini J, Dhanya R, et al (2010) Consolidated checklist of birds in the Pallikaranai
 994 Wetlands, Chennai, India. *J Threat Taxa* 2:1114–1118.
 995 <https://doi.org/10.2139/ssrn.591861>

996 Rajanikanth J, Rajini Kanth T V. (2020) Chennai Weather Data Analysis Using Hybrid Data
 997 Mining Techniques. Springer, Cham, pp 357–367

- 998 Raji PK, Abraham M (2018) Comparative study of water quality of different lakes in Chennai.
999 *Rasayan J Chem* 11:828–833. <https://doi.org/10.31788/RJC.2018.1122005>
- 1000 Ramachandran A, Anushiya J (2015) Long-term rainfall trends of Indian urban station and its
1001 variation in different phases and seasons. *Int J Glob Warm* 7:307–321.
1002 <https://doi.org/10.1504/IJGW.2015.069364>
- 1003 Rangarajan S, Thattai D, Yellasiri SRR, et al (2018) Detecting Changes in Annual and
1004 Seasonal Rainfall Patterns for Chennai, India. *J Hydrol Eng* 23:05018001.
1005 [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001630](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001630)
- 1006 Ranjit-Daniels RJ, Muthu-Karthick N, Vencatesan A, Vencatesan J (2020) Of ants and
1007 antelopes – the ecological history of Chennai was not what one would imagine.
1008 *Mongabay*
- 1009 Reserve Bank of India (2020a) Handbook of Statistics on Indian Economy
- 1010 Reserve Bank of India (2020b) Handbook of Statistics on Indian Economy
- 1011 Romero-Lankao P, Gnatz DM (2016) Conceptualizing urban water security in an urbanizing
1012 world. *Curr Opin Environ Sustain* 21:45–51
- 1013 Roumeau S, Seifelislam A, Jameson S, Kennedy L (2015) Water Governance and Climate
1014 Change Issues in Chennai. HAL, Chennai
- 1015 Ruet J, Gambiez M, Lacour E (2007) Private appropriation of resource: Impact of peri-urban
1016 farmers selling water to Chennai Metropolitan Water Board. *Cities* 24:110–121.
1017 <https://doi.org/10.1016/j.cities.2006.10.001>
- 1018 Sachithanandam V, Mageswaran T, Sridhar R, et al (2017) Rapid assessment on mass
1019 mortality of fishes in Ennore estuary of Tamil Nadu, India. *Indian J Geo Mar Sci* 46:1647–
1020 1650
- 1021 Saharan T, Pfeffer K, Baud I (2018) Shifting approaches to slums in Chennai: Political
1022 coalitions, policy discourses and practices. *Singap J Trop Geogr* 39:454–471.
1023 <https://doi.org/10.1111/sjtg.12244>
- 1024 Sakthivel P, Elango L, Amirthalingam S, et al (2015) Managed aquifer recharge: The widening
1025 gap between law and policy in India. *Water Sci Technol Water Supply* 15:1159–1165.
1026 <https://doi.org/10.2166/ws.2015.074>
- 1027 Santhiya G, Lakshumanan C, Selvin J, Asha D (2011) Microbiological analysis of seawater
1028 and sediments in urban shorelines: Occurrence of heavy metals resistance bacteria on
1029 Chennai beaches, Bay of Bengal. *Microchem J* 99:197–202.
1030 <https://doi.org/10.1016/j.microc.2011.05.004>
- 1031 Secretary of State for India (1908) *Imperial Gazetteer of India*. Oxford
- 1032 Selvaraj K, Pandiyan J, Yoganandan V, Agoramoorthy G (2016) India contemplates climate
1033 change concerns after floods ravaged the coastal city of Chennai. *Ocean Coast Manag*
1034 129:10–14. <https://doi.org/10.1016/j.ocecoaman.2016.04.017>
- 1035 Semeoshenkova V, Newton A, Rojas M, et al (2017) A combined DPSIR and SAF approach
1036 for the adaptive management of beach erosion in Monte Hermoso and Pehuen Co
1037 (Argentina). *Ocean Coast Manag* 143:63–73.
1038 <https://doi.org/10.1016/j.ocecoaman.2016.04.015>
- 1039 Sethuram S (2014) Case Study: Water Management Issues in Chennai, India. *Univers J*
1040 *Environ Res Technol* 4:299–306
- 1041 Shahina SJ, Sandhiya D, Rafiq S (2020) Bacteriological Quality Assessment of Groundwater
1042 and Surface Water in Chennai. *Nat Environ Pollut Technol* 19:349–353
- 1043 Shanmugam P, Neelamani S, Ahn YH, et al (2007) Assessment of the levels of coastal marine

1044 pollution of Chennai city, Southern India. *Water Resour Manag* 21:1187–1206.
1045 <https://doi.org/10.1007/s11269-006-9075-6>

1046 Shekhar L (2020) How an international tag can help save the Pallikaranai marshland. In: *Citiz.*
1047 *Matters.* [https://chennai.citizenmatters.in/how-international-tag-can-help-save-](https://chennai.citizenmatters.in/how-international-tag-can-help-save-pallikarnai-marshland-14057)
1048 [pallikarnai-marshland-14057](https://chennai.citizenmatters.in/how-international-tag-can-help-save-pallikarnai-marshland-14057). Accessed 28 Jul 2020

1049 Shivakumar C (2020) Chennai's new masterplan, with a vision plan, to come into being from
1050 2026. *New Indian Express*

1051 Smeets E, Weterings R (1999) Environmental indicators: Typology and overview. Technical
1052 report No 25. Copenhagen

1053 Sree Sharmila T, Swathika R (2016) Prediction of environmental changes in dumpyard sites:
1054 A case study of pallikaranai dumpyard, Chennai, Tamil Nadu. In: *Communications in*
1055 *Computer and Information Science*. Springer Verlag, pp 674–682

1056 Srinivasan V (2008) An integrated framework for analysis of water supply strategies in a
1057 developing city: Chennai, India. Stanford University

1058 Srinivasan V, Seto KC, Emerson R, Gorelick SM (2013) The impact of urbanization on water
1059 vulnerability: A coupled human-environment system approach for Chennai, India. *Glob*
1060 *Environ Chang* 23:229–239. <https://doi.org/10.1016/j.gloenvcha.2012.10.002>

1061 Steinbruch F, Hörmann G (2015) Towards Integrated Water Management of Pallikaranai
1062 Wetland in Chennai City, India. Kiel

1063 Subramanian J (2000) A preliminary study of Pallikaranai marshes. Chennai

1064 Surya S (2016) Landscape Ecological Urbanism for Restoration of Pallikaranai Marsh Land,
1065 Chennai, Tamil Nadu. *Procedia Technol* 24:1819–1826.
1066 <https://doi.org/10.1016/j.protcy.2016.05.227>

1067 Taft L, Evers M (2016) A review of current and possible future human-water dynamics in
1068 Myanmar's river basins. *Hydrol Earth Syst Sci* 20:4913–4928.
1069 <https://doi.org/10.5194/hess-20-4913-2016>

1070 The Chennai metropolitan area groundwater (regulation) act 1987 (1987) Tamil Nadu Act 27
1071 of 1987. <https://chennaietrowater.tn.gov.in/pdf/GroundwaterAct1987-2020.pdf>.
1072 Accessed 16 Aug 2020

1073 The Hindu (2019) Pallikaranai marsh has shrunk to a tenth of its size since 1965: Amicus
1074 Curiae. *The Hindu*

1075 The Hindu (2018) To tackle water crisis, Metrowater pitches in. *The Hindu*

1076 Thirumurthy P (2017) Where does Chennai's poop go? The stinking truth. *News Minute*

1077 Tscherning K, Helming K, Krippner B, et al (2012) Does research applying the DPSIR
1078 framework support decision making? *Land use policy* 29:102–110.
1079 <https://doi.org/10.1016/j.landusepol.2011.05.009>

1080 UN-Water (2013) Water security and the global water agenda: A UN-Water analytical brief

1081 UNESCO, UN-Water (2020) United Nations World Water Development Report 2020: Water
1082 and Climate Change. UNESCO, Paris

1083 United Nations (2015) Transforming our world: the 2030 Agenda for Sustainable Development

1084 United Nations (2016) The World's Cities in 2016

1085 United Nations (2022a) Goal 6.Ensure availability and sustainable management of water and
1086 sanitation for all. <https://sdgs.un.org/goals/goal6>. Accessed 4 Apr 2022

1087 United Nations (2022b) Goal 11.Make cities and human settlements inclusive, safe, resilient
1088 and sustainable. <https://sdgs.un.org/goals/goal11>. Accessed 4 Apr 2022

- 1089 United Nations (2021) World Economic Situation and Prospects as of mid-2021. New York
- 1090 Upadhyay P (2019) India's Water Crisis: A Permanent Problem Which Needs Permanent
- 1091 Solutions. SSRN Electron J. <https://doi.org/10.2139/ssrn.3451715>
- 1092 van der Meulen GJM, Bacchin TK, van Dorst MJ (2023) The hydro-cultural dimension in
- 1093 Water-Sensitive Urban Design for Kozhikode, India. *J Landsc Archit* 18:22–33
- 1094 Van Ginkel KCH, Hoekstra AY, Buurman J, Hogeboom RJ (2018) Urban water security
- 1095 dashboard: systems approach to characterizing the water security of cities. *J water*
- 1096 *Resour Plan Manag* 144:4018075
- 1097 van Leeuwen CJ (2017) Water governance and the quality of water services in the city of
- 1098 Melbourne. *Urban Water J* 14:247–254.
- 1099 <https://doi.org/10.1080/1573062X.2015.1086008>
- 1100 van Leeuwen CJ, Frijns J, van Wezel A, van de Ven FHM (2012) City blueprints: 24 indicators
- 1101 to assess the sustainability of the urban water cycle. *Water Resour Manag* 26:2177–
- 1102 2197. <https://doi.org/10.1007/s11269-012-0009-1>
- 1103 Vasanthi LA, Revathi P, Babu Rajendran R, Munuswamy N (2017) Detection of metal induced
- 1104 cytopathological alterations and DNA damage in the gills and hepatopancreas of green
- 1105 mussel *Perna viridis* from Ennore Estuary, Chennai, India. *Mar Pollut Bull* 117:41–49.
- 1106 <https://doi.org/10.1016/j.marpolbul.2017.01.040>
- 1107 Vencatesan J (2007) Protecting wetlands. *Curr Sci* 93:288–290
- 1108 Venkatachalam L (2015) Informal water markets and willingness to pay for water: a case study
- 1109 of the urban poor in Chennai City, India. *Int J Water Resour Dev* 31:134–145.
- 1110 <https://doi.org/10.1080/07900627.2014.920680>
- 1111 Venkatesan KD, Balaji M, Victor K (2014) Microbiological Analysis of Packaged Drinking
- 1112 Water Sold in Chennai. *Int J Med Sci Public Heal* 3:.
- 1113 <https://doi.org/10.5455/ijmsph.2014.150220143>
- 1114 Venugopal T, Giridharan L, Jayaprakash M, Periakali P (2009) Environmental impact
- 1115 assessment and seasonal variation study of the groundwater in the vicinity of River
- 1116 Adyar, Chennai, India. *Environ Monit Assess* 149:81–97. <https://doi.org/10.1007/s10661-008-0185-x>
- 1117
- 1118 Vignesh S, Muthukumar K, Arthur James R (2012) Antibiotic resistant pathogens versus
- 1119 human impacts: A study from three eco-regions of the Chennai coast, southern India.
- 1120 *Mar Pollut Bull* 64:790–800. <https://doi.org/10.1016/j.marpolbul.2012.01.015>
- 1121 Vivek V (2016) Rainwater Harvesting In Chennai: What Made It Work? *IIM Kozhikode Soc*
- 1122 *Manag Rev* 5:91–106. <https://doi.org/10.1177/2277975215617272>
- 1123 Wada Y, Van Beek LPH, Bierkens MFP (2012) Nonsustainable groundwater sustaining
- 1124 irrigation: A global assessment. *Water Resour Res* 48:.
- 1125 <https://doi.org/10.1029/2011WR010562>
- 1126 WHO World Health Organization (2020) Drinking water. [https://www.who.int/news-room/fact-](https://www.who.int/news-room/fact-sheets/detail/drinking-water)
- 1127 [sheets/detail/drinking-water](https://www.who.int/news-room/fact-sheets/detail/drinking-water). Accessed 1 Apr 2022
- 1128 World Bank (2020) Sanitation. <https://data.unicef.org/topic/water-and-sanitation/sanitation/>
- 1129 WWC WWC (2000) A Water Secure World – Vision for Water, Life and the Environment.
- 1130 Commission Report. Marseille, FRWorld Wate
- 1131 Zetland D (2021) The role of prices in managing water scarcity. *Water Secur* 12:100081.
- 1132 <https://doi.org/10.1016/J.WASEC.2020.100081>
- 1133 (2019a) Water crisis in Chennai: Why Chennai's water crisis should worry you. Times of India
- 1134 (2019b) Buckingham Canal clean-up to be focus. The Hindu

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1136 **Supplementary material**

1137 Table S1. Main indicators considered for every component of the Drivers-Pressures-States-
 1138 Impacts-Responses analysis of water management in Chennai in this study.

		Indicator	Value	Years	Source
Drivers	Population growth	Average annual population growth (%)	0.75	2001-2011	Directorate of Census Operations Tamil Nadu (2011)
	Economic development	Average annual growth of per capita net state domestic product in rupees at constant prices in Tamil Nadu (%)	6.59	1998-1999 to 2018-2019	Reserve Bank of India (2020)
Pressures	Land use change	Average annual increase of urban area (%)	1.92	1988-2017	Mathan and Krishnaveni (2020)
	Groundwater over-extraction	Average groundwater extracted (million liters per day)	200	2015	Venkatachalam (2015)
	Liquid and solid waste mismanagement	Waste water treated (%)	33.90	2017	Arappor lyakkam (2017)
States	Urbanization status	Urban area over the total of the Chennai Metropolitan Area (%)	48.7	2017	Mathan and Krishnaveni (2020)
	Water availability	Water supply (liter/inhabitant/day)	90	2014	Government of Tamil Nadu (2014)
	Water quality	Biochemical oxygen demand (mg oxygen/l)	9-375	2015-2019	Kumar et al. (2019); Dhamodharan et al. (2016); Nethaji Mariappan et al. (2017); Kumar et al. (2018); Raji and Abraham (2018); Krishna Kumar et al. (2015)
	Biodiversity status	Wetland area over the total of the Chennai Metropolitan Area (%)	15.80	2016	Amali et al. (2019)
Impacts	Loss of aquatic ecosystems	Average annual reduction in water surface (%)	1.25	1988-2016	Mathan and Krishnaveni (2020)
	Low water table	Water extracted of the aquifer (%)	80	2012	Balan et al. (2012)
	Low water quality	Untreated waste water discharged (million liters per day)	1073	2017	Arappor lyakkam (2017)
	Reduction of biodiversity and human health	Average annual reduction in wetlands (%)	1.35	1988-2016	Amali et al. (2019)

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