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Review

Investigating the impacts of urban densification on buried water infrastructure through DPSIR framework

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ABSTRACT

Urban densification is seen as a possible solution in response to the intense urbanization and sustainable development. Urban densification counteracts the negative effects of urban sprawl, which include increased mobility challenges, demand of natural resources, greenhouse gas emissions, and encroachment on green spaces. In spite of its benefits, urban densification creates pressure on the existing buried water infrastructure (BWI) (i.e., drinking water, wastewater, and stormwater) and the environment. The impacts of urban densification on the level of service of BWI are overlooked in the published literature. This study aims to identify and discuss the key drivers, induced pressures, their effects on the level of service, corresponding impacts, and finally the possible responses using the Driver-Pressure-State-Impact-Response (DPSIR) linkage-based sustainability assessment framework. The DPSIR framework was selected due to its simplicity and most powerful communication tool between environment and society. The outcome of this study provide a conceptual model, which interlinks the steps (i) identification of system indicators, (ii) data processing, (iii) decision making, and (iv) impact analysis with factors influencing the integrated level of service of BWI at three different levels. Together these steps create a basis for evaluating the level of service of multifaceted BWI. The uncertainties associated with scenarios, datasets, and model development could be a challenge during the application of proposed conceptual framework. The proposed conceptual model may serve as reference for multi-stakeholders in understanding the dynamic balance between urban densification, BWI, and sustainable use of water services.

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1. Introduction

Contemporary urban development is a complex process challenged by several dynamic factors such as rapid population growth, economic growth, limited resources, urbanization, globalization, and climate change (Amer et al., 2017; Battha, 2010; Wilby, 2007). Within the next few decades, the majority of the world's population will reside in cities and ultimately increase the pressure on urban areas (United Nations, 2011). Globally, around 3.6 billion people reside in urban areas and an additional 2.5 billion urban dwellers are expected to move into cities by 2050, 90% of this increase will be in Asia and Africa (United Nations, 2018a). At the beginning of the 21st century, many developed countries have faced waves of urbanization and land development in most of the municipal districts, which has increased pressure on the existing infrastructure (Mikovits et al., 2018) and this phenomenon is anticipated to continue in coming years.

In recent years, land for built-up areas has increased significantly to accommodate the social and economic development of cities. Globally, it has been estimated that the total area covered by cities will increase threefold by the middle of the century at a 2.4% rate of expansion (Artmann et al., 2019). This rate covers an area of over 300 miles annually (Artmann et al., 2019; Inostroza et al., 2013; Seto et al., 2012b, 2011; Shlomo et al., 2005), and is expected to increase further by 2050. The biggest change in urban land has been reported in Africa and Asia; however, a notable change has occurred in North America with a 3.31%/yr rate of urban land expansion from 1970 to 2000 (McPhearson et al., 2013) and expected to exceed 6%/yr by 2030 (Seto et al., 2012a). This urban expansion will cover both farm and countryside land. Currently, 82% of the total population is residing in urban areas in North America. Such a rapid urban expansion has led to several challenges related to sustainable municipal services such as water supply, wastewater management, roads, street lighting, and recreation programs (McPhearson et al., 2013; Shu et al., 2018).

In general, urban development includes both horizontal and vertical forms of expansion (Shi et al., 2009), which are referred as urban sprawl and urban densification respectively. More specifically, urban densification is high-density vertical expansion with a mixed-use strategy. In contrast, urban sprawl refers to low-density horizontal development (low-floor area ratio) and single/distinct uses such as residential, commercial, and industrial. In the field of urban planning, urban sprawl is not a suitable approach for urban expansion due to several reasons, such as increases in land use to build new neighbourhoods, infrastructure costs to provide services to newly build neighbourhoods (Fatone et al., 2012), high car-dependent cities due to larger distances among several facilities and functions of cities, energy use for transportation, amount of carbon dioxide (CO_2) (Norman et al., 2006), and related ecological footprints (Australia State of the Environment, 2016). In 1990, the European Commission advocated "urban densification" as the most sustainable way of urban development (Commission of the European Communities, 1990); it also refers to the compactness of the built environment (Zhang et al., 2017).

Urban densification is preferable to sprawl for urban growth because of growing sustainability concerns, land constraints, compact city policies, economic factors, and targets to reduce the greenhouse gas (GHG) emissions (Pichler et al., 2017; Ruparathna et al., 2017a; Zhuang and Zhao, 2014). In literature (e.g., (Attia, 2015; Broitman and Koomen, 2015; Pedraza et al., 2000; Ruparathna et al., 2017a; Silva et al., 2018)), various urban density approaches, such as roof extension and infill development, have been discussed. These approaches have been used to accomplish urban densification and simultaneously accommodate a growing population in urban areas. Furthermore, urban densification approaches have been approved to pursue sustainability goals including reduction in land use, energy consumption, and associated GHG emissions (Fatone et al., 2012).

Compact cities intend to mitigate several effects of low-density and sprawling cities by limiting mobility challenges (Simoni et al., 2018). For example, the amount of travel; car-dependency; energy use for commuting; GHG emissions from transport; energy consumption in buildings for heating, cooling, and other purposes (Fatone et al., 2012); demand on urban land and natural resources; cost of services; goods delivery; and encroachment on green spaces; and agriculture areas (Næss, 2014). In addition, urban densification makes the best use of existing infrastructure and meets the affordable housing demand (Bunker et al., 2002).

However, moving towards urban densification may inherit several ecological and health impacts initiated by compactness such as air pollution and congestion, effect on urban heritage, wind discomfort, environmental noise (King, 2008), urban heat island effects, heat wave vulnerability (Lemonsu et al., 2015), reduction in urban public spaces (Reiter, 2010), solar access and daylight (Marique and Reiter, 2014a), and tree canopy (Kaspar et al., 2017). Therefore, while achieving the sustainability goal of effective and possible use of territorial urban resources, the built environment discourages physical activities, which are considered favourable for both the environment and public health. Cities are unable to facilitate for a healthy environment inner-city residents due to high exposure to noise, air pollution, and traffic accidents. In addition, urban densification exerts pressure (Australia State of the Environment, 2016) on the existing infrastructure and its services, such as roads, bridges, water supply, sewage, and some of them are buried infrastructure (Felio and Lounis, 2009).

Buried infrastructure comprises at least seven main underground utilities: (i) potable water production and distribution lines, (ii) sewers (wastewater and stormwater), (iii) oil and gas pipes, (iv) electricity transmission lines, (v) fibre optic lines, (vi) traffic, and (vii) street lighting (Professional Surveyors Canada, 2016; Rogers et al., 2012). These infrastructures work together to accommodate and meet the needs of a growing population in cities (Australia State of the Environment, 2016). The above mentioned buried infrastructures are facing various challenges such as main breaks, leakages, and internal pipe corrosion because of less visibility than other infrastructures (American Water Works Service Company Inc, 2002). Increases in the total length of buried infrastructure (e.g., length of pipes) makes it more complex.

This study is particularly focused on buried water infrastructure (BWI) including drinking water, wastewater, and stormwater in the residential sector. Municipalities are struggling with the multifaceted challenges of water and its infrastructure to provide reliable services (Mukheibir et al., 2014; US Water Alliance, 2016) alleviating hydrological impacts (Peña-Guzmán et al., 2017). Many cities are facing environment, economic, and social issues from improper urban water supply and drainage services. Among the services the city provides repair and maintenance of infrastructure holds a key importance. The aging and deteriorating infrastructure demand timely maintenance practices (i.e., repair, rehabilitation, replacement, and upgradation) to avoid serious accidents and achieve an acceptable level of service (LOS) in the future (Tscheikner-Gratl et al., 2014). LOS is the assessment of the quality of service, which is provided to the users throughout the life cycle of the infrastructure (Felio and Lounis, 2009). The adequate LOS of BWI is a fundamental part of any municipality to achieve high quality of life, health protection, and economic prosperity. In this study, LOS of BWI is defined based on three different levels including tactical, technical, and customer. Further, the aggregation of the LOS of drinking water, wastewater, and stormwater at three different levels will provide an integrated level of service (ILOS) of BWI.

The estimated increase in BWI investment in the timeframe of three decades, considering the future development and growth perspective, is around 6.8 billion (USD) in North America (American Water Works Association, 2012; Global Infrastructure Hub, 2018). The whole water cycle is an integrated system, which includes reliable drinking water supply, wastewater treatment and reuse, stormwater management, green infrastructure, climate resilience, and climate change adaptation (The Water Research Foundation, 2017). In order to move towards an integrated water system, municipalities need to identify and evaluate an increasing urban densification impacts on the ILOS of BWI. Providing a linkage between all the dynamic factors that drive pressure on BWI and their affect on state will help municipalities to adopt some strategies to formulate responses and to maintain an acceptable ILOS of BWI. In the literature, several linkage based sustainability assessment frameworks have been proposed and developed including Pressure-State-Response (PSR), Driver-State-Response (DSR), and Driver-Pressure-State-Impact-Response (DPSIR).

In recent years, the DPSIR framework has been widely used and is popular among the decision-makers and scientists to assess and manage various environmental problems. It develops the cause-effect linkage between all the components of sustainability (Song and Frostell, 2012). The DPSIR linkage-based framework has thus been adopted in the current study to evaluate the impacts of urban densification on the state of BWI. Further, based on the above mentioned challenges this review generates a systematic approach in the context of a conceptual model, to assess the ILOS of BWI. This conceptual model will help in the process to understand and develop relationships between multiple dynamic factors to address the impacts of urban densification on BWI.

2. Review scope

In this study, 114 peer-reviewed articles and book chapters were selected from a reference pool primarily published after 2010. The keywords used for the literature search includes water, wastewater, and stormwater infrastructure, level of service, performance, linkage-based frameworks, urban growth, densification, sprawl, population growth, urbanization, climate change, housing demand and supply, land use, user satisfaction, economic and environmental sustainability. The journals that were used to collect information includes Utilities Policy, Sustainable Cities and Society, Science of the Total Environment, Ecological Indicators, European Journal of Operational Research, Computers, Environment and Urban Systems, Cities, Urban Policy and Research, Journal of Cleaner Production, Journal of Building Engineering, Transactions on Ecology and the Environment, Environmental Impact Assessment Review, Environmental Research Letters, Water Resources Management, Urban Climate, Environmental Science & Policy, Energy and Buildings, European Planning Studies, Journal of Industrial Ecology, Journal of Hydrology, PLOS One, Sustainability, Environmental Pollution, Water, Built Environment, Water Science & Technology, and Water Resources Management. This study also viewed Official Community Plan (OCP) reports, infrastructure report cards, and technical reports from international and national organizations. As shown in Fig. 1, this literature was conducted through Web of Science, Engineering Village, and Science Direct research engines. Among the selected research articles 52% of articles are published in Elsevier's, 10% in Taylor & Francis, 12% in Springer and MDPI and remaining articles are published in AGU, Wiley, PLOS, The International Water Association (IWA), WIT,

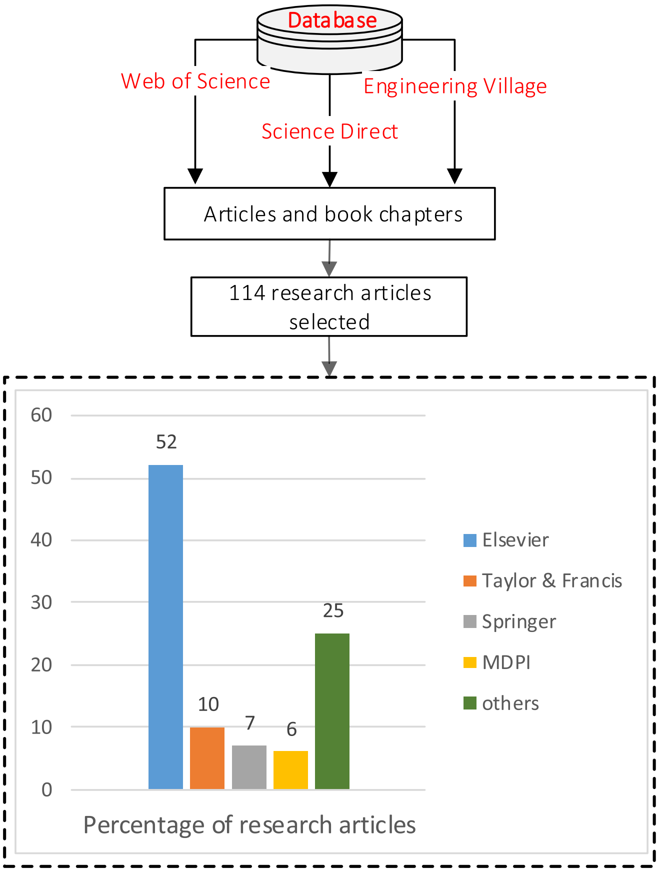


Fig. 1. Scope of the literature review.

Proceedings of the National Academy of Science (PNAS), JSTOR, American Water Works Association (AWWA), American Chemical Society (ACS), American Society of Civil Engineers (ASCE), IOP, American Association for the Advancement of Science (AAAS), AMS, and Nature.

3. Linkage-based frameworks

In general, the densification phenomenon contributes to several environmental, economic, and social impacts associated with BWI. Densification policy decisions cause several impacts on the natural environment. These impacts consist of pollutants released to the natural water bodies such as; untreated wastewater and stormwater runoffs; chemicals (e.g., methane, carbon dioxide, and hydrogen sulfide) released to the air; solid waste to the land from the wastewater (Government of Canada, 2014); soil permeability of sewage and stormwater; increasing energy consumption; aging BWI, and combined sewer overflows. Moreover, the abovementioned factors cause deterioration in the service level of BWI and therefore present a significant risk to the public health and safety, which relates to the society. However, resources required for maintenance practices because of aging and deteriorating infrastructure may have impacts on the economy. All these factors directly affect sustainability, which is an inter-linkage among three environmental, economic, and social components; and achieves a balance, while mitigating, reducing, and eliminating the impacts throughout the life cycle of BWI. However, achieving sustainability over temporal and spatial horizons has proven to be a challenging task for all the stakeholders involved in the decision-making process. It is necessary to enhance knowledge and understanding of the linkages among the complex factors of BWI and related densification process, which are affecting all the components of sustainability in different ways.

Several approaches and frameworks have been proposed and developed to quantitatively assess sustainability. In the literature, the sustainability assessment frameworks are classified into different categories based on their use in various disciplines. Waheed et al. (2009) classified these frameworks into six categories based on the objective, impact, influence, stakeholder/process, life cycle assessment, and linkage. Among these framework categories, the linkage-based frameworks are widely used due to their effectiveness and efficiency, they follow the concept of cause-effect relationship. The use of linkage-based frameworks provides the inter-linkage between all the components of sustainability while defining the indicators for each component and corresponding required actions to reduce or control the effects.

3.1. Pressure-State-Response (PSR) framework

The PSR framework is one of the most widely used linkage-based frameworks. It has been developed by the Organization for Economic Co-operation and Development (OECD, 1993) in the early 1990s, and was the extension of the stress-response model. Later, it was used to assess the interactions between environmental pressures (P), state (S), and responses (R). The PSR framework can be used to understand the pressures induced by the actions, activities, and processes, which have direct effects on the state of the system and corresponding responses to reduce or mitigate the pressures (Hambling et al., 2011). The state of the environment measured using indicators and then response indicators help to measure and maintain the state, while mitigating the pressures and improving the state. However, evaluating the environmental problems via PSR in the context of anthropocentric pressures and responses to improve the environmental state makes it deviate from natural variability on driving forces. To address this problem, the United Nations Commission on Sustainable Development (UNCSD) (Hambling et al., 2011) modified the PSR framework with the DSR framework.

3.2. Driver-State-Response (DSR) framework

In DSR, “driver forces”, which describe human actions, activities and patterns that affect sustainable development, replace the “pressure”. Driver force is a pressure that has been introduced to incorporate not only the additional economic, institutional, political, and social indicators more precisely, but also the pressures generated from the natural system (Carr et al., 2007). Although the DSR framework has succeeded in addressing the limitation of PSR’s focus on the anthropocentric, but has not addressed two critical issues. First, both the PSR and DSR frameworks use the terms “pressures” or “drivers”, but does not highlight the underlying reasons for these pressures (Bowen and Riley, 2003). Second, both frameworks lack an element to measure a response change in the state of the environment. The PSR and DSR frameworks represent all the changes in state and pressures, which lead to change in state; however, Bowen and Riley (2003) identified that to make changes in the environmental state the required social resources are not infinite, so it is essential to prioritize the responses to a range of factors. Specifically, this prioritization should consider the impacts on the significant social costs required to achieve the benefits. Therefore, a framework comprised of the indicators to measure the human and ecosystem related impacts make the framework more meaningful.

3.3. Driver-Pressure-State-Impact-Response (DPSIR) framework

In late 1990s, European Union proposed the DPSIR framework (Fig. 2) (Hambling et al., 2011). Since then, several authors have adopted DPSIR framework in various environmental problems to analyze their overall mechanism. For instance, it has been applied in assessing the impacts of urban sprawl on the freshwater environment to balance the urban water (Haase and Nuissl, 2007); in developing the sustainability indicators of coastal areas (Bell, 2012); and examining the various environmental issues in river basin aiming to design a management plan (Kagalou et al., 2012). DPSIR has been used as a basis for problem structuring and scientific modeling (Lewison et al., 2016). In the nutshell, DPSIR framework is a powerful tool to address the effects and consequences of human activities and corresponding planning and policies for responses (Lewison et al., 2016).

In the present research context, drivers include anthropogenic activities and processes, while the social and economic development in urban residential areas having direct effects on the environment, economy, and society are known as pressures. At a given point of time, the state reflects condition of the environment, natural resources, assets, or particular aspects of them. The impact is the measurement of environmental effects mainly due to the development in urban residential areas. Responses are the specific actions to reduce the pressures and impacts, while maximizing the corresponding state as shown in Fig. 2.

In this study, the DPSIR framework has been used to study the dynamic relationship between urban densification and its impacts on the BWI (Fig. 3).

4. Indicators for buried water infrastructure (BWI)

The details of all the identified indicators of BWI have been discussed in the following sub-sections.

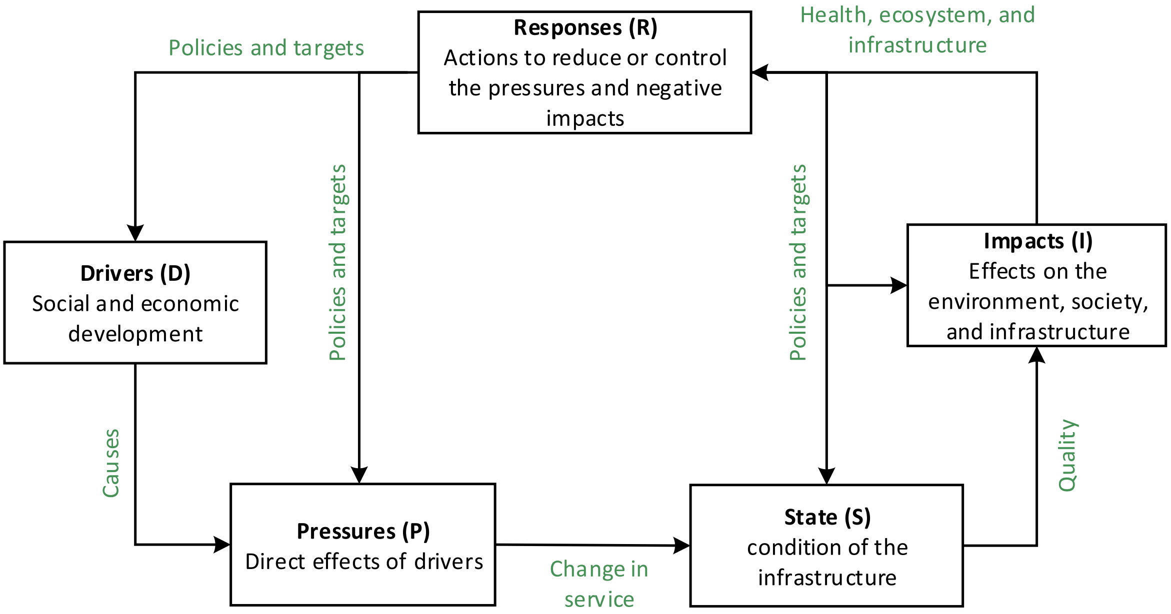


Fig. 2. DPSIR framework (Bell, 2012; Bowen and Riley, 2003; Lewison et al., 2016; Sun et al., 2016; Waheed et al., 2009).

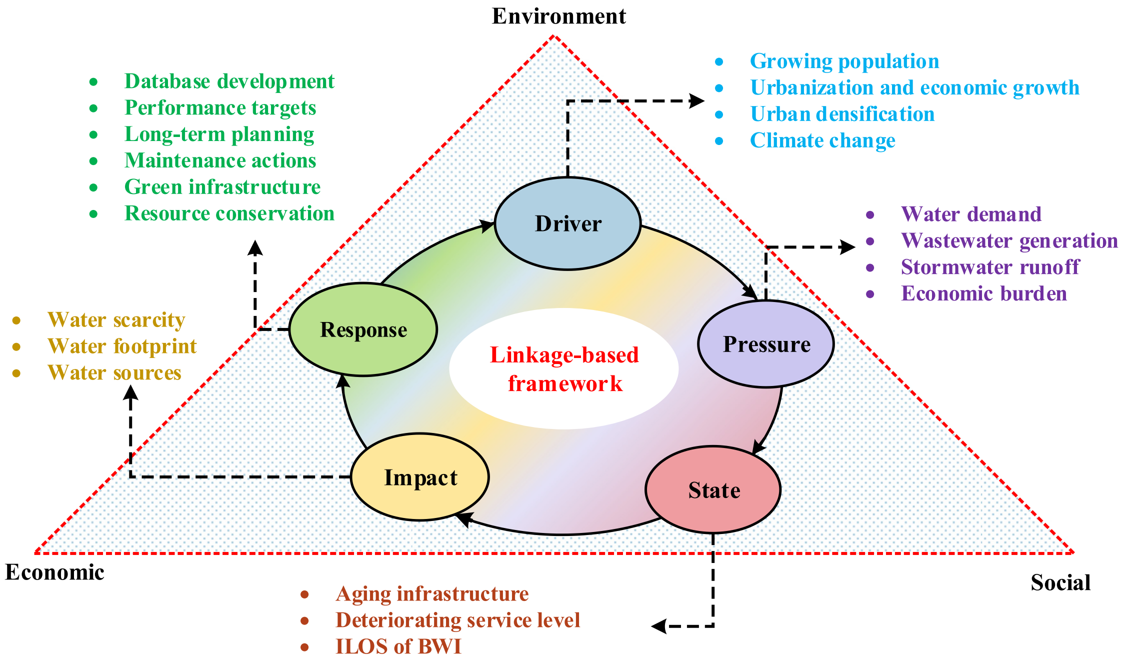


Fig. 3. Impacts of urban densification on buried water infrastructure (BWI) using DPSIR.

4.1. Driver

Environmental, societal, and economic interlinked processes, including growing population, urbanization, economic growth, limited resources, urban densification, and climate change directly drives the effect on the state of BWI (Easterling et al., 2000; OECD, 2012; Olsson et al., 2009; Pathak et al., 2017; Sagarika et al., 2016, 2015; 2014; Tamaddun et al., 2016; Thakali et al., 2016). Detail discussion on the present statistics and projections of each driver by 2050 has been discussed as follows:

4.1.1. Population growth

A rapid population growth has occurred in the past few years all over the world. According to the recent survey of the United

Nations world population is 7.6 billion as of 2018, which is expected to reach 9.7 billion by 2050 with the annual rate of 1.09% (United Nations, 2018b). The variation in the population density (i.e., people per square kilometer) from 1961 to 2017 has been shown in Table 1, which shows a clear image of densification. Undoubtedly, the densification will upturn by the estimated projections of the population growth.

There is a huge difference in the demographic developments based on both regions and countries. Moreover, a significant increase in the population levels of North America has been observed mainly due to immigration (OECD, 2012). For instance, Canada's current population is 37 million with an average annual rate of 1.2%, which will reach 43 million by 2056 (Government of Canada, 2018). Considering some of the developed countries, the top five ranked countries are China, India, United States, Indonesia, and Brazil; whereas, Russia, South Africa, and Canada are on 9, 25, and 38 position respectively, in the list of the global population (Central Intelligence Agency, 2016). Additionally, the Australian Bureau of Statistics stated that the current population of Australia is 25 million and likely to reach 35.9 million by 2050 (Australian Bureau of Statistics, 2018). In 2017, according to the data of World Bank, the population growth rate of Australia (1.6%) was much higher than countries with immigration programs like Canada (1.2%), US (0.7%), and UK (0.6%) (The World Bank, 2019). However, in the "BRIICS" countries (Brazil, Russia, India, Indonesia, China, and South Africa) the average annual rate of population growth is 0.4%. The growth rate of India is higher than the other countries, whereas slightly negative trends have been seen in Russia. Additionally, the population growth rates are assumed to be low in Japan, Korea and some of the other European countries with 0.2%/yr on average from 2010 to 2050 (OECD, 2012). The annual average growth rate in developing countries is projected to grow at 1.3% in coming decades. Overall, Africa and South Asia's growth rate projected to be higher than in Latin America (OECD, 2012).

4.1.2. Urbanization and economic growth

A major part of the growing population is moving towards the cities for many social and economic benefits and its immediate result is urbanization. The tendency of urbanization is mainly due to family, employment, housing, education, climate change, healthcare, natural disaster, change in lifestyle, immigration, increasing tourism, and others (Angel and Blei, 2016; United States Census, 2011). Approximately, 55% of the current world's population is living in urban areas (United Nations, 2018a) and is anticipated to increase nearly 68% by 2050. In the context of North America, more than 80% population is living in urban areas (United Nations, 2018c). However, in Asian and African countries around 40–50% population lives in urban areas and is expected to urbanize in coming few decades (United Nations, 2018c). According to the Canadian statistics, percentage change in population of major cities in last one decade is ranged between 16 and 29 (Canada statistics, 2017). The percentage change in urban population in the world's largest cities over time is shown in Fig. 4.

Table 1
Population density in the developed and developing countries (The World Bank, 2014).

Country	Population density (person per sq. km)	
	1961	2017
Canada	2	4
Russia	7	9
Brazil	9	25
United States	20	36
South Africa	15	47
Indonesia	50	146
China	70	148
India	154	450

Urbanization and economic growth have a close relation with each other (Chen et al., 2014). In most of the developed countries, urbanization is an impetus to the economic growth. Economic growth or development of a country is "*increase in the total outcome or gross domestic product (GDP) over a time*". Economic growth is driven by the extensive use of natural (e.g., water, land, minerals, fossil fuels) and physical (e.g., machines, roads, buildings, infrastructure) capitals (OECD, 2012). An input of labor is considered as an employment and is correlated to the urbanization. To increase the economic growth, most of the Asian countries are making polices to promote the urbanization. However, the municipalities, managers, and policymakers have to facilitate people with the development in urban areas to support economic growth rather than making faster urbanization. In addition, it has been estimated that over the 80% of GDP is developed in urban areas (Nguyen and Nguyen, 2018).

Urbanization (planned or unplanned) can have both negative and positive factors. On the positive side, cities permit higher economic growth up to a certain limit. The high concentration of people makes easy to provide access to efficient infrastructure for the water supply and lower down the per-capita costs for water infrastructure connections. However, magnified use of limited resources may put pressure on the environment. These pressures may demand to upgrade or new infrastructure and natural resources influenced by the economic growth and changing lifestyle, which results in the economic shocks. For example, the recession during 2008–2009 was due to the economical crisis (OECD, 2012). In addition, an extensive concentration of economic activities causes a high level of air pollution. Which are generally because of the traffic congestion and increasing demand for energy (OECD, 2012). The GHG emissions are directly or indirectly related to the GDP. For instance, In the OCED environmental outlook to 2030, it has been estimated that 16% growth in GDP results 10% increase in GHG emissions (OECD, 2012) and would be expected to increase further by 2050. In general unplanned urbanization is of more concern for municipalities as it might be a cause for various adversities, which includes environmental degradation, water quality deterioration, increased demand of water, sanitation problems, wastewater treatments, inadequate infrastructure, housing demand, unemployment, and poverty (Mikovits et al., 2018; National Geographic, 2015).

4.1.3. Urban densification

Any city is classified into built-up (industrial, commercial, residential, institutional, transport) and non-built up land area (open spaces e.g., playgrounds, parks, agricultural, vacant area, and water bodies) (Sun et al., 2007). The relationship between planning and different land use patterns with appropriate classification of land is a remedy to municipalities for smart urban development (City of Coquitlam, 2013). On average the highest component of land (i.e., >70%) is used for residential and transportation area. Moreover, institutional area (i.e., public buildings, commercial) represents 12% of total land followed by other land use including open/green and industrial areas in the typical cities (Clark et al., 2006), (Fig. 5).

As a result of urbanization and concomitant expansion, the residential areas will be further densified to accommodate the growing population in urban areas by 2050 (Güneralp et al., 2017). With high energy consumption in residential areas, the associated GHG emissions are also expected to rise with increasing urban growth. GHG emissions are mainly due to the high dependency on private automobiles for commuting in low-density areas

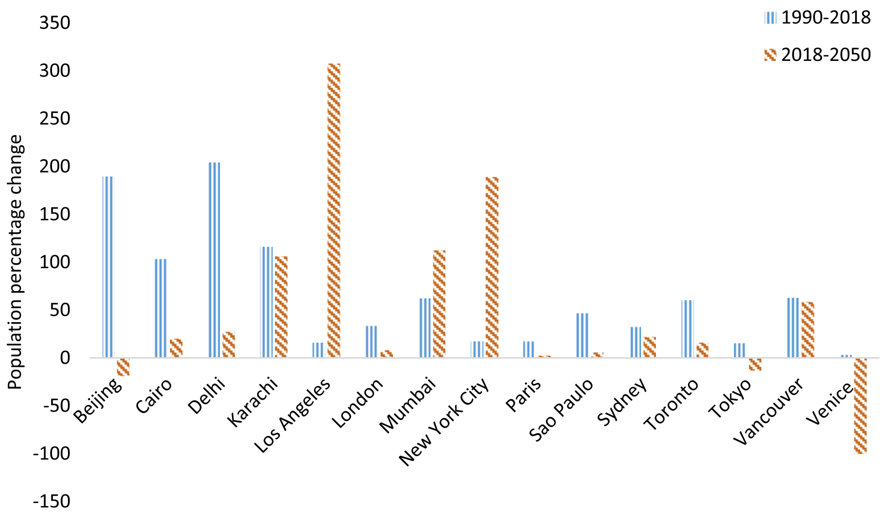


Fig. 4. Population change in percentage for world's big cities (The World Bank, 2019; University of Ontario, 2018).

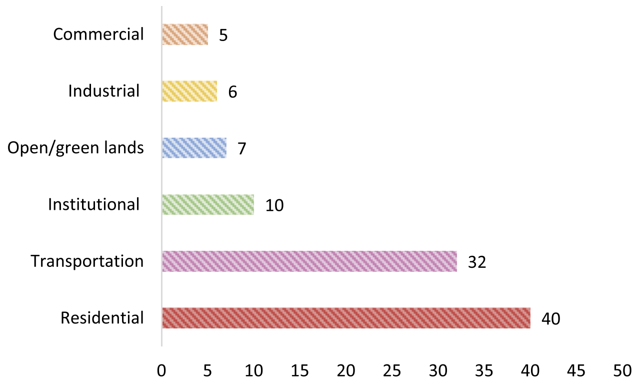


Fig. 5. Classification of land use in cities.

(Vandeweghe and Kennedy, 2007). According to a case study analysis in Toronto metropolitan area, it has been noted that emissions from transportation are 18% higher in the low-density areas than high-density areas (Norman et al., 2006). Moreover, the ideal way to promote sustainable development (to accommodate growing population and to provide other facilities) is through urban densification in comparison to the urban sprawl (NORDREGIO, 2012).

Multiple urban densification approaches have been discussed in different urban structures, which weigh in the favour of sustainable urban development. Urban structures are categorized under high-density (mostly built areas), compact density (share of green spaces such as parks nearby the highly built areas), low-density (few built areas with the high share of open space) and mixed (combinations) structures (Federal Institution for Research on Building Urban Affairs and Spatial Development, 2014). Further, several researchers have discussed these structures through different approaches of urban densification focused on the optimal use of existing infrastructure and mitigating GHG emissions (Amer and Attia, 2017; Dieleman and Wegener, 2004; Ewing et al., 2007; Marique and Reiter, 2014b; Nabielek, 2011; Riera Pérez and Rey, 2013; Skovbro, 2002; Steemers, 2003; Swedish National Board of Housing, 2017). Some of the commonly used approaches for urban densification are illustrated in Table 2 and Fig. 6 (Amer et al., 2017; Amer and Attia, 2017).

Urban densification has spatial-temporal and functional effects on the environment in terms of the BWI (Haase, 2009). Urban densification helps to reduce per capita land use (Chhipi-Shrestha et al., 2017) though, a significant amount of wastewater is produced due to the increase rate of per-capita water use. It also augments the sealed surfaces, resulting in less infiltration of rainwater consequently, magnified volume of runoffs and demand for the appropriate infrastructure services for the proper drainage of these runoffs.

4.1.4. Climate change

Over recent years, it has been reported that climate variability is increasing (Hambling et al., 2011) and putting many social, environmental, economic challenges. For instance, increase in average global temperature, glacier and snow/ice melting, soil moisture, change in the distribution of rainfall, sea level rise, river, and groundwater flows, severity of floods and some other extreme events (UNESCO, 2012). These events cause significant economic damage and casualties in the form of destroying infrastructure, crops, and animals, displacement of millions of people, loss of human life, degrading water quality, ozone depletion, waterborne diseases, wildfire, pollution, heat-waves, energy demand, and droughts.

Several effects of all the above-mentioned challenges have been recorded on a global scale. For instance, the number of wildfires has been doubled since 1970 due to the high temperature considering the North American context (Montgomery, 2018). As a result, thousands of tonnes of carbon have been emitted into the atmosphere, which further increases the GHG emissions, and heat absorption. In 2010, CO_2 emissions (related to the energy) have reached up to 30.6 Gt, which was the all-time highest value (OECD, 2012). In the business-as-usual scenario, the GHG emissions are anticipated to increase nearly 50% by 2050, which is mainly driven by the 70% increase in CO_2 emissions from energy use. In an ongoing temperature analysis at NASA's institute, the scientists

Table 2
Different urban densification approaches.

Approaches	Description
Infill	Construct a new building in a vacant plot nearby build-up areas or between the existing buildings. This is one of the most effective way to use the existing infrastructure (Brunner and Cozens, 2013; Marique and Reiter, 2014b).
Filling backyard	Implement by constructing a new building in the backyard of existing building and refers to horizontal extension (Attia, 2015; Marique and Reiter, 2014b).
Demolish and rebuild	Demolish the existing building and reconstructing the high-rise building in low-density area. It has a higher potential to increase density and new design strategies can also be applied (Attia, 2015; Marique and Reiter, 2014b).
Roof stacking	Easily applicable to the existing building by adding one or two stories over the rooftop. It increases the usage of existing infrastructure and helps to keep the green spaces (Floerke et al., 2014; Nilsson et al., 2016; Peronato et al., 2014).
Roof transformation	Very easy and quick approach to transform the saddle roof to another storey with the use of existing and minimal space (Attia, 2015).
Adaptive reuse	Use of existing building such as old factory, commercial building for the development of residential building (Shipley et al., 2006).

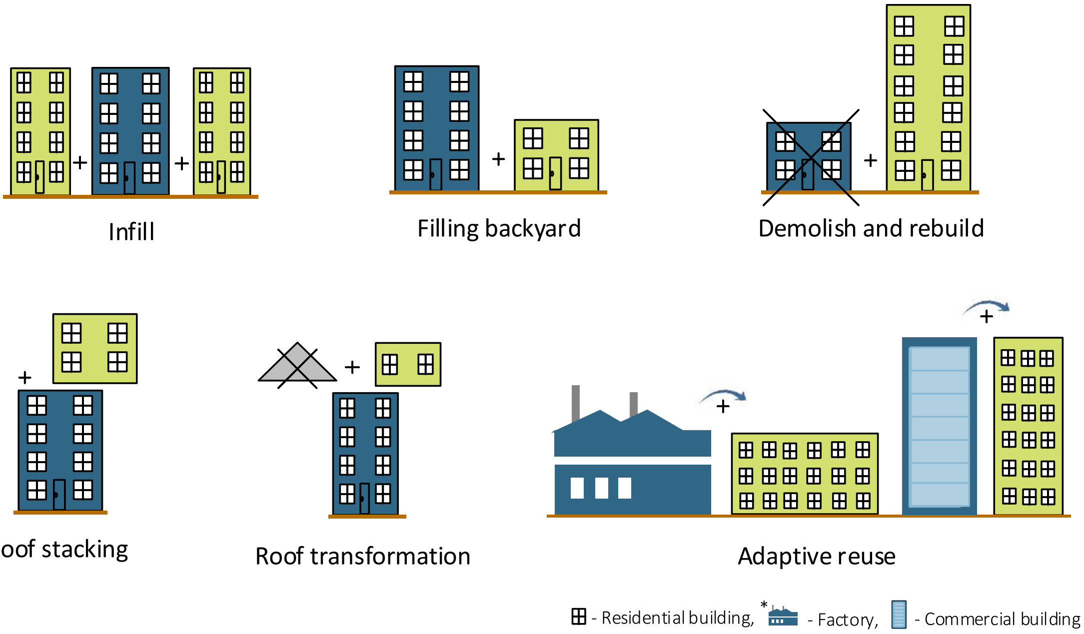


Fig. 6. Different urban densification approaches.

have estimated that the average global temperature has increased by 0.8° Celsius since 1880 mainly due to the GHG emissions (NASA earth observatory, 2010).

In recent decades, sea levels are rising on average at a rate of 3 mm/yr and approximately 12 mm/yr considering the western pacific (Cazenave and Remy, 2011). Eventually, this rise in sea level is putting many islands at danger, which may affect the population growth pattern (Sustainability for all, 2018). Fig. 4, shows the percentage change in population growth of major cities and it was observed that population of Venice (Italy) is expected to decline at a high rate by 2050 as the city has repeatedly been flooded and damaged. In last century, the average water level in the city has increased by five inches and expected to reach 140 cm. These statistics anticipates that the city will be underwater before the next century if this acceleration of climate change is not curbed.

4.2. Pressure

4.2.1. Water demand

In any urban area drinking water is an essential element of an urban water system (Walsh et al., 2012). The direct effect of the urban densification and the other drivers (e.g., growing population, urbanization, and climate change) outlined above drive ever-increasing demands for freshwater (Connor and Milleto, 2015) and adequate wastewater and stormwater services, thereafter putting pressure on the existing BWI (Amer et al., 2017). Global water demand is projected to increase 55% in 2050 due to growing water use for various purposes including domestic, manufacturing, and electricity mainly due to urbanization (OECD, 2012).

The average rate of domestic water consumption varies largely in the urban areas of developed countries. Water demand is highly dependent on the development and geography of the countries. Water consumption typically varies from 150 to 600 L/capita/day on average for domestic use (McGhee and Steel, 1991). Fig. 7 shows the water consumption in different regions of the world which varies from 125 L/capita/day in India to 382 L/capita/day in United States (Government of Canada, 2010; Njehia, 2015). However, in various parts of the world it is reported beyond the mentioned range. For instance, the average domestic water usage in British Columbia is 490 L/capita/day and 675 L/capita/day in Okanagan Valley of British Columbia, which is the double of the Canadian average water usage (OBWB, 2011). It even reaches up to 1000 L/capita/day in the summers (OBWB, 2011). The rate of water consumption in Canada is very high, which refers to overconsumption (Renzetti, 1999). As a result, during years 1994–1999, around 26% of Canadian municipalities experienced water supply shortages

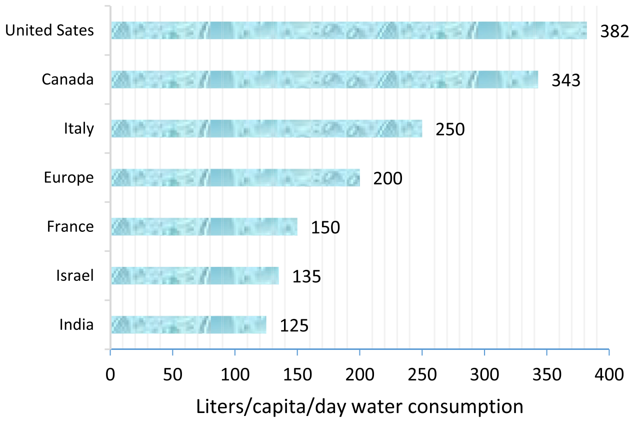


Fig. 7. Liters/capita/day domestic water usage (Government of Canada, 2010; Njehia, 2015).

mainly due to a high consumption and infrastructure problems (Environment Canada, 2004).

4.2.2. *Wastewater generation and stormwater runoff*

A significant amount of wastewater is produced due to an increase in per capita water use. According to the Canada statistics (Government of Canada, 2015), approximately two-third of the total wastewater flows into the municipal sewers from the residential sector. On average nearly 80% of water is transformed into wastewater (Philippines Environment Monitor, 2003). Rapid growth in population, urbanization, and economic development is increasing the per capita water use and eventually the generation of wastewater volume, which is putting pressure on the existing infrastructure. According to a study, the maximum average value of wastewater connection rate is in Europe (80%) and South Asia is with the lowest average (28%). The Middle East and North Africa (65%) has the second highest value following Europe, whereas the North America has the third highest (58%) value (Malik et al., 2015).

Additionally, municipalities are facing a huge problem not only with the drainage of wastewater but also with the drainage of stormwater runoff associated with urban densification and climate change. The magnified impervious surface is contributing to a high volume of stormwater runoff in the cities (O'Neill and Cairns, 2016; Walsh et al., 2012). A change in weather patterns, heavy rainfall, and melting snow also turn into the storm runoffs, which pollutes the nearby water bodies and causes urban flooding (O'Neill and Cairns, 2016; OSWCA, 2018). For instance, the most catastrophic natural disasters were experienced in the different parts of Ontario. It caused more than 1 billion USD dollars of damage to the assets (OSWCA, 2018). Many similar events happened in the different regions of Germany, Ireland, France, and United Kingdom, which caused damage to infrastructure and inconvenience to humanity (Sperotto et al., 2015).

Another major problem is the combined sewer overflows (CSOs) because of the single waterbody (i.e., combined sewer infrastructure) for receiving and transporting the municipal storm runoff and wastewater (Government of Canada, 2013; OSWCA, 2018). In the industrialized countries, there is a strong trend of separate sewer systems; however, the combined sewer systems still form the majority. These systems are designed due to economical and technological factors and mostly the older or under-developed urban areas are drained by combined sewer systems (Shi et al., 2018). The capacity of combined sewers and wastewater treatment plants may be exceeded during the wet and thaw weather, which leads to the release of both stormwater and wastewater into receiving streams without treatment. This phenomenon is commonly known as CSOs and poses serious concerns for their hydraulic weights on combined sewer infrastructure.

It has been documented in the EPA's 2004 report (USEPA, 2004) that annually CSOs results in an estimated 3.2 million m^3 (850 billion gallons) of untreated sewage releases to the waterways in the United States. Various government have set target towards virtually eliminating combined sewers in most of the urban areas. For instance, in 2006 for the Kingston city of Ontario, complete elimination of combined sewers has been set as a target by 2036 (OSWCA, 2018). Furthermore, the stormwater discharges and CSOs are not monitored regularly and its quantity varies with the sewer design, location, and local climate. However, an estimation of discharge and loads of stormwater can be measured over a large drainage area. Thus for the great lakes basin, the average annual discharge rate of stormwater was estimated about 760 L/capita/day. However, in the wet-weather days, this discharge rate would be 2000–3000 L/capita/day.

4.2.3. *Economic burden*

The additional constraint that poses significant pressure on the municipalities is the cost to accommodate the rapidly growing needs of BWI. In most of the countries, the BWI has been in operation from more than a century. The aging infrastructure needs regular maintenance practices for their physical parameters such as pipes and pumps throughout their lifespan. However, the ineffectuality in regular inspections and maintenance practices are gradually deteriorating the LOS of BWI both temporally and spatially. To maintain the adequate LOS and physical state of BWI municipalities are in need to take several actions and require a significant amount of investment over time.

In developing countries, there is significant underinvestment in maintenance practices. Fig. 8 shows that currently United States, China, Russia, India, Brazil, and Germany retain less per capita investments in the BWI compared to Australia, Canada, France, Japan, UK, and Italy; however, approximately 40–52% of increase in per capita investment has been estimated in Russia, China, and India by 2050. Australia is investing about double as compared to Canada and three to four times more than France, Japan, UK, and Italy and approximately ten times more than the countries like China, United

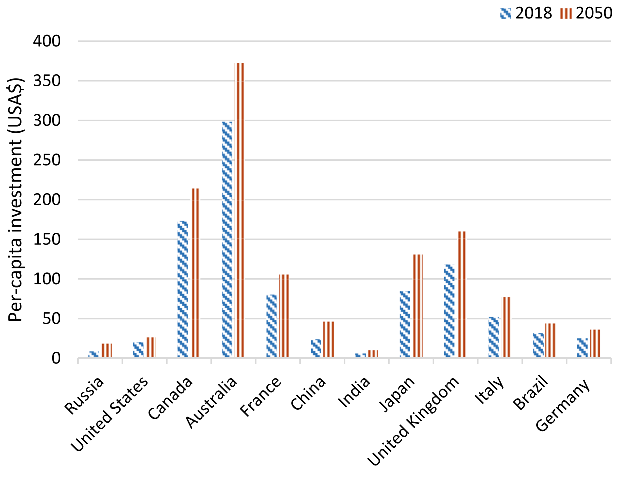


Fig. 8. Per-capita investment in buried water infrastructure (Global Infrastructure Hub, 2018).

States, Brazil, and Germany. Australia and Canada are predicted to increase 20% of investments by 2050. Additionally, UK, Japan, France, and Italy are investing less but expected to increase (25–35%) investments by 2050 than Australia and Canada (Global Infrastructure Hub, 2018).

Important statistics can be found in the history of different countries' which emphasise the immense need of investments. In the report card of America's infrastructure (American Water Works Service Company Inc, 2002), it has been indicated that the grade of potable water, wastewater, and dams was very low in comparison of other infrastructures. Along with American Society of Civil Engineers (ASCE) many other professional organizations such as the Water Infrastructure Network (WIN), and American Water Works Association (AWWA), have addressed the concerns of BWI and developed cost estimates. For instance, according to WIN in the next 20 years, 460 billion dollars are needed to invest in the water and wastewater services (American Water Works Service Company Inc, 2002).

Canadian infrastructure report card provides a summary survey of 120 municipalities' across Canada. The report accounts that per Canadian household replacement cost for the water, wastewater, and stormwater infrastructure will be ranging from $9000 to $16,000 (Canadian Society of Civil Engineers, 2016). The drinking water infrastructure accounts for the 50 to 80 percent expenses for overall operations and up to 80% overall cost for the collection of wastewater and stormwater. Therefore, unsustainable funding for BWI has become a global issue and most of the municipalities are struggling (Connor and Milleto, 2015).

4.3. State

The state of an infrastructure typically speaks about the condition of an asset and service refers to LOS with respect to its physical condition, functionality, and ability to meet the demand of given population. Originally, LOS was introduced for the road infrastructure and then extended to other assets (Ruparathna et al., 2017b). In the literature, several authors have used different terminologies and definition for LOS of civil infrastructure as a whole and also for a specific (e.g., transportation, buildings, and water utilities) infrastructure type. Table 3 shows the mentioned diversity among the authors and infrastructure types. According to Felio and Lounis (2009), LOS is the assessment of quality of service provided to the users during the life cycle of infrastructure. The LOS assessment will assist municipalities in decision making such as prioritization of expansion, maintenance, renewal, and replacement to keep the certain LOS of infrastructure throughout its life (Felio and Lounis, 2009; Ireland et al., 2008).

The above-mentioned several actions of all the components of BWI are required to maintain certain LOS over time. The components of drinking water, wastewater, and stormwater need to be discussed in detail to manage and measure the performance of BWI. There is an extensive cluster of components that have been organized under the BWI. A water system comprises of source of supply, transmission mains, reservoirs and pumping systems for the distribution, and collection of the water (Grigg, 2012). Additional components such as treatment facilities, generators, valves, collector sewers, regulators, and hydrants are also involved in drinking water and wastewater infrastructure (City of Ottawa, 2009; Grigg, 2012). Further, a stormwater system consists the collection systems for treatment and disposal facilities connected to open green spaces and water streams (Government of Canada, 2011; Grigg, 2012).

In the large context of availability, supply, and management of BWI is inseparable. The concept of integrated water systems has been accepted in various national and international organizations. This concept can be a driving force to achieve sustainable and resilient BWI. The integrated study is the best management of limited water resources and its services to meet the ever-increasing worldwide demand with minimum cost (UNDESA, 2014).

Furthermore, most of the urban areas are adopting different urban densification approaches for sustainable urban development. Eventually, this urban densification is putting pressure on the ILOS of BWI, which gradually deteriorates the ILOS beyond its minimum ILOS over time (Fig. 9). This deterioration and damage mechanism and the assessment of ILOS with respect to urban densification is not considered in the literature. In this study, the LOS of BWI is defined at three different levels including (Fig. 10(a)):

(i) Tactical level: relates with the higher level regulatory requirements to provide the high-quality and reliable service in a cost-effective manner;
(ii) Technical level: covers the technical/operational and physical aspects, which ensure the required function of the service delivery; and
(iii) Customer level: defines the user satisfaction with the service being deliver and ensure the effectiveness (performance and presentation) of the delivered service.

Further, the integration of LOS of drinking water, wastewater and stormwater at above-mentioned three different levels will provide the ILOS of BWI. Different alternatives can be adopted to assess the ILOS of BWI. For instance, (i) aggregate the service at tactical, technical and customer level to get the LOS of drinking water. The LOS of wastewater and stormwater can be calculated in a similar manner. Further, the combined LOS of these three infrastructure types will give the ILOS of BWI (Fig. 10(b)) and (ii) first aggregate the service of drinking water, wastewater, and stormwater at tactical level followed by technical and customer level. Finally, combine all the service levels of BWI to get the ILOS of BWI (Fig. 10(c)).

Additionally, there is a need of a conceptual model to support the adoption of ILOS of BWI to assess the state and performance of physical and operational components as mentioned earlier. The model will assist uniformly to assess the ILOS at three different levels (Fig. 11). This model will help to identify the challenges to its implementation such as data availability and related activities that would advance the ILOS of BWI at different levels.

This conceptual model has been developed through the lens of DPSIR framework. However, the main focus of this model is to assess the ILOS of BWI while identifying the performance objectives, criteria, and indicators. This information will be further used by the managers of BWI for detained technical information of assets, policy developers for the broad overview of service performance and then development of different plans and policies, elected decision makers to take the decisions and prioritization between different decisions and public to achieve the required ILOS. Subsequently, the high-level decision making for attaining the ILOS would promote the sustainable development while combining data and information on the individual systems of BWI.

4.4. Impact

In developing countries', most urban areas are facing problem of increasing demand of safe, fresh, and sufficient accessibility of water for their daily use (Vairavamoorthy et al., 2008). Globally, 80% of wastewater is released to the environment without adequate treatment (UN Water, 2017), with harmful impacts to the public health, freshwater resources, and ecosystems. The impacts generally focus on both direct and indirect effects (American Water Works Service Company Inc, 2002) of several factors on the

Table 3
Recent literature review on level of service (LOS) in civil infrastructure.

S #	Asset type	FIN	OM	ENV	PHY	SOC	TM	ENG	Level of service	Ref.
1.	Transportation		✓						Quality of an asset service.	O'Connor and Caulfield (2018)
2.	Transportation		✓						Reflection of the operational condition of the asset which lead to several actions for improving the service quality.	Navandar et al. (2019)
3.	Transportation	✓				✓			Ensures the social acceptability at minimum cost	Bråthen and Eriksen (2018)
4.	Transportation						✓		The total time expenditure on transfer including transportation transfer and waiting time	Kopylova et al. (2018)
5.	Transportation		✓		✓		✓		Delay, available space, reliability, and accessibility while getting the service	Teodorović and Janić (2017)
6.	Buildings		✓		✓				Operational performance provided to the society, environment and citizens.	Ruparathna et al. (2017b)
7.	Civil Infrastructure		✓		✓				Combination of capacity (availability) and maintenance (operation).	Chasey et al. (2002)
8	Transportation		✓						Performance of an asset	Ireland et al. (2008)
9	Civil infrastructure		✓						Quality of the service provided to the society.	Felio and Lounis (2009)
10	Transportation		✓			✓	✓		Quality measure defining the operational condition with respect to travel time, speed, comfort, convenience, and interruptions of metro mass transit	Birago et al. (2017)
11.	Transportation		✓			✓			Operational quality which facilitate the pedestrian with comfort	Cepolina et al. (2018)
12	Transportation						✓		Measurement of the control delay at traffic circle.	Nedevska et al. (2017)
13.	Transportation		✓						Measurement of absolute free flow traffic and congestion conditions	Axer et al. (2012)
14	Transportation				✓				Percentage of an area covered by the transit supportive area	Din et al. (2016)
15.	Transportation						✓		Estimation of delay in vehicle state overtaking actions	Martín et al. (2016)
16.	Buildings		✓						The pre-defined level of maintenance in order to improve or restore the initial conservation state of the building	Rodrigues et al. (2018)
17.	Buildings	✓	✓		✓				Level of building performance is studied from financial, functional, and physical aspects	Marzouk and Seleem (2018)
18.	Buildings	✓	✓						Minimizing the financial costs over the life cycle while maintaining the asset value for all the stakeholders	Dejaco et al. (2017)
19.	Buildings					✓		✓	Comfort and energy consumed by the building	Ioannidis et al. (2016)
20.	Buildings	✓	✓		✓				Based on the three aspects including physical, Functional, and financial	Marzouk and Seleem (2018)
21.	Water utilities		✓	✓	✓				Physical, operational, and environmental factors	Kilinç et al. (2018)
22.	Water utilities		✓	✓	✓				Influenced by the design, technology, operational, and environmental conditions.	Hadwan and Alkholidi (2018)
23.	Water utilities	✓							Financial/life cycle costs	Sousa et al. (2019)
24.	Water utilities	✓		✓				✓	Function of energy, operational cost, and environmental impacts	Behzadian and Kapelan (2015)
25.	Water utilities	✓	✓						Coverage equity, quality of supplied water, and O&M costs	Jaladhi et al. (2016)
26.	Water utilities		✓						Operational performance	Gomes et al. (2014)
27.	Water utilities	✓	✓						Financial and technical/operational assessment	Abubakar (2016)
28.	Water utilities	✓	✓			✓			the quality of the service provided to the society and associated costs	Pinto et al. (2017)
29.	Water utilities	✓	✓						Quality of service and maintenance costs	Romano et al. (2017)
30.	Water utilities	✓	✓			✓			Quality, quantity, pressure, continuity, billing, complaints, collection supply	Molinos-Senante et al. (2017)

*FIN: financial; OM: operational and maintenance; ENV: environment; PHY: physical; SOC: social; TM: time; ENG: energy.

society, environment, and economy. The ILOS of BWI is deteriorating not over time and material type but also with the emerging effects of several dynamic factors. Due to these dynamic factors, some water system have experienced intensive break rates and severe corrosion, which cause a loss in the system pressure and hence results in poor water quality (American Water Works Service Company Inc, 2002).

4.4.1. *Water scarcity*

Water scarcity is related to the quality and quantity of per capita available water. The temporal and spatial variations play a vital role to define the water scarcity. An area in which a large number of people do not have access to safe (quality) and sufficient (quantity) water for their domestic use for a significant period of time is considered underwater scarce (Rijsberman, 2006). The temporal and spatial variations in the water are mainly due to the dynamic factors as mentioned earlier. Globally, the reflection of severe impacts of the dynamic factors including climate change, population growth, and urban densification can be seen in history. For instance, various recent reports has documented the water supply shortage problem in 12 cities of United States (Dorfman et al., 2011; Ginley and Ralston, 2010; Means et al., 2005). In the sustainable development goals report, it was revealed that in the future there is a strong probability of water scarcity due to the high stress levels (i.e., >70%) in 22 countries worldwide.

All the above-mentioned dynamic factors cause the evaporation, variation in rains, and runoffs, which impair water quality and quantity and directs its value to the ecosystem and people (Rijsberman, 2006). Additionally, water will be scarce in all those areas where rainfall is low and population density is relatively high (Rijsberman, 2006). The risk of monthly water shortage has been recorded as the most severe in Northern China and South Asia and

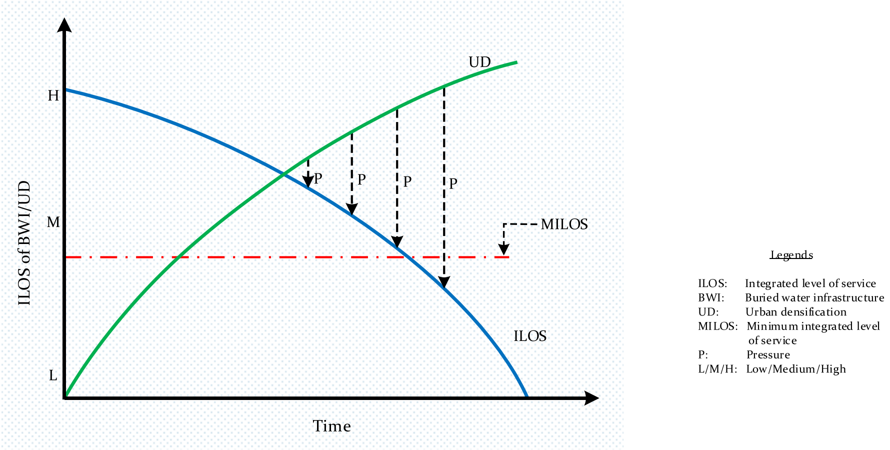
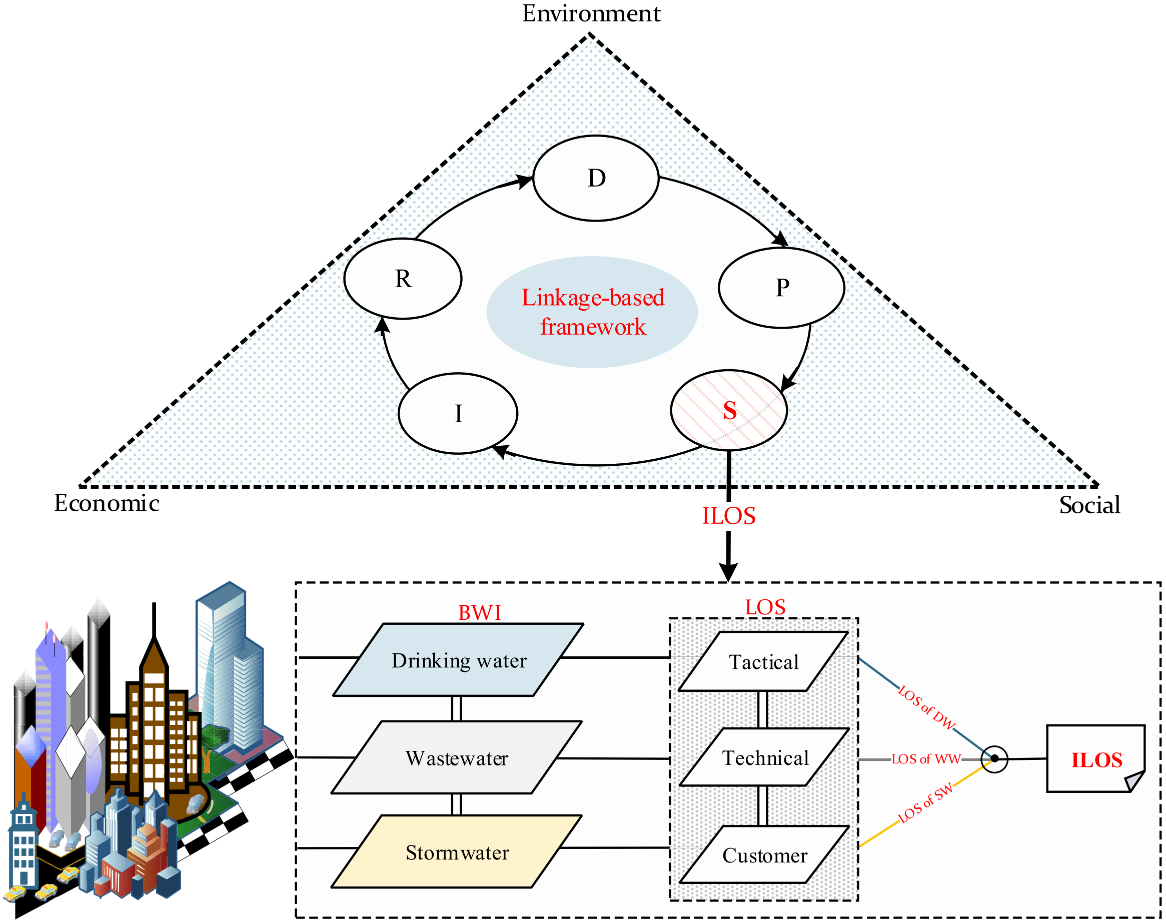


Fig. 9. Integrated level of service of buried water infrastructure under urban densification.



(a)

Fig. 10. Integrated level of service (ILOS) of buried water infrastructure (BWI) under urban densification environment using DPSIR and different alternative to aggregate the ILOS.

significant seasonal water shortage appears all over the world.

Globally, 70% of the total freshwater withdrawals are for agriculture use and it has been expected to increase 20% by 2050 (UN Water, 2016). Further, water use in manufacturing, electricity, and for domestic use is adding stress on the water resources.

4.4.2. Water footprint

Another impact of urban densification having on the water resources is water footprint. It is a measure of the total volume of freshwater consumed to produce the product and services in its life cycle by an individual, region, or nation and the related impacts such as the amount of water, which has been evaporated and polluted. It is very relevant at the locations where there is a serious problem of water scarcity and water-intensive processes (Paterson et al., 2015). In terms of water flows, there are commonly two types of water balance: engineered (piped) and hydrologic (natural) in urban areas. The engineered water balance is measured by the amount of the water, which has been demanded and supplied and subsequently generated wastewater in the urban areas, whereas the hydrologic water balance comprises all the natural inflows, outflows, and the total change of water in the storage of urban basins. There is a significant relationship between both the water balances such as leakage due to the aging infrastructure and sewer (separate/combined) overflows (Bhaskar and Welty, 2012; Padowski and Jawitz, 2012; Paterson et al., 2015).

Water quality includes the surface and groundwater, freshwater, sanitation, runoffs, and infrastructure related impacts on the human health and ecosystem. In urban areas growth of population, urbanization, and urban densification increases pumping the groundwater than its recharge due to the sealing of ground with concrete. Eventually, enormous amount of water is circulating and transported in the pipe network through BWI under a high pressure, which cause leakages (Wakode et al., 2018). Worldwide 30% water abstraction is lost due to the leakage. In the developing and developed countries this loss can be higher than 30%; for instance, urban areas of Norway reaching up to 32% (UN Water, 2016). Moreover, the pressure in the drinking water mains is more than sewer mains and any leakage causes a large amount of discharge, which can be a major source of contamination (Wakode et al., 2018) and has negative impacts on both the human-health and physical condition of infrastructure.

4.4.3. Water sources

Groundwater is the source of freshwater in various urban areas, especially where the surface water is inaccessible or scarce. It has been anticipated that population growth, urbanization, and urban densification results in the greater demand of freshwater, which causes the depletion of the groundwater levels (Lashkaripour and Ghafoori, 2011). The amount of water evaporates, runoffs into rivers, lakes, canals and eventually emptying into oceans is increasing sea levels. In a study, it has been estimated that pumping of groundwater will cause rise in sea level up to 0.8 mm annually by 2050 (Wada et al., 2012).

Surface water is another main source of freshwater in various urban areas of North America (Howard and Gerber, 2018). The rapid growth of urban areas has many other effects on the ecosystem and human health such as more floods, impervious surfaces, mitigation in freshwater and level of groundwater, polluted natural streams (surface water) due to the discharge of untreated wastewater and stormwater. Urban areas are facing serious problems of stormwater runoff due to the increased impervious surfaces and climate change, which increases the volume of stormwater causing combined sewer overflows, flooding, and water pollution (NACTO, 2017). In 2013, the damage from floods has been estimated over

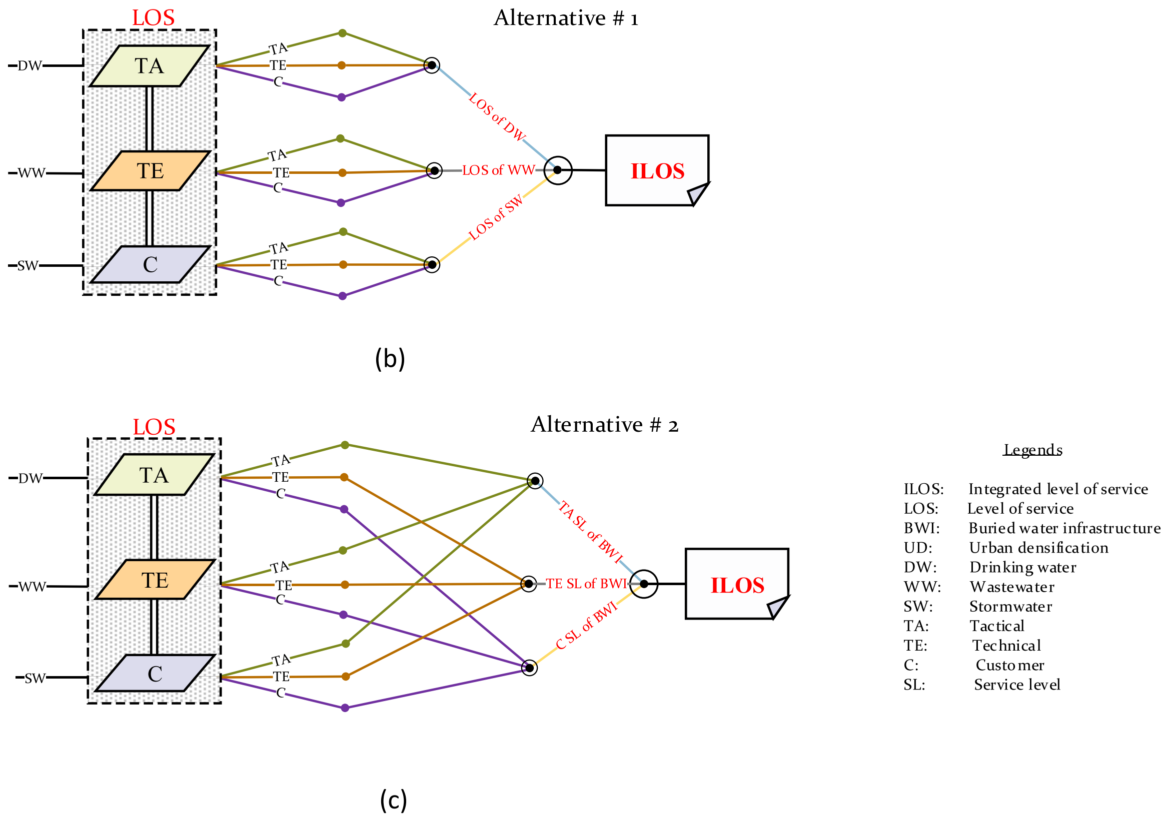
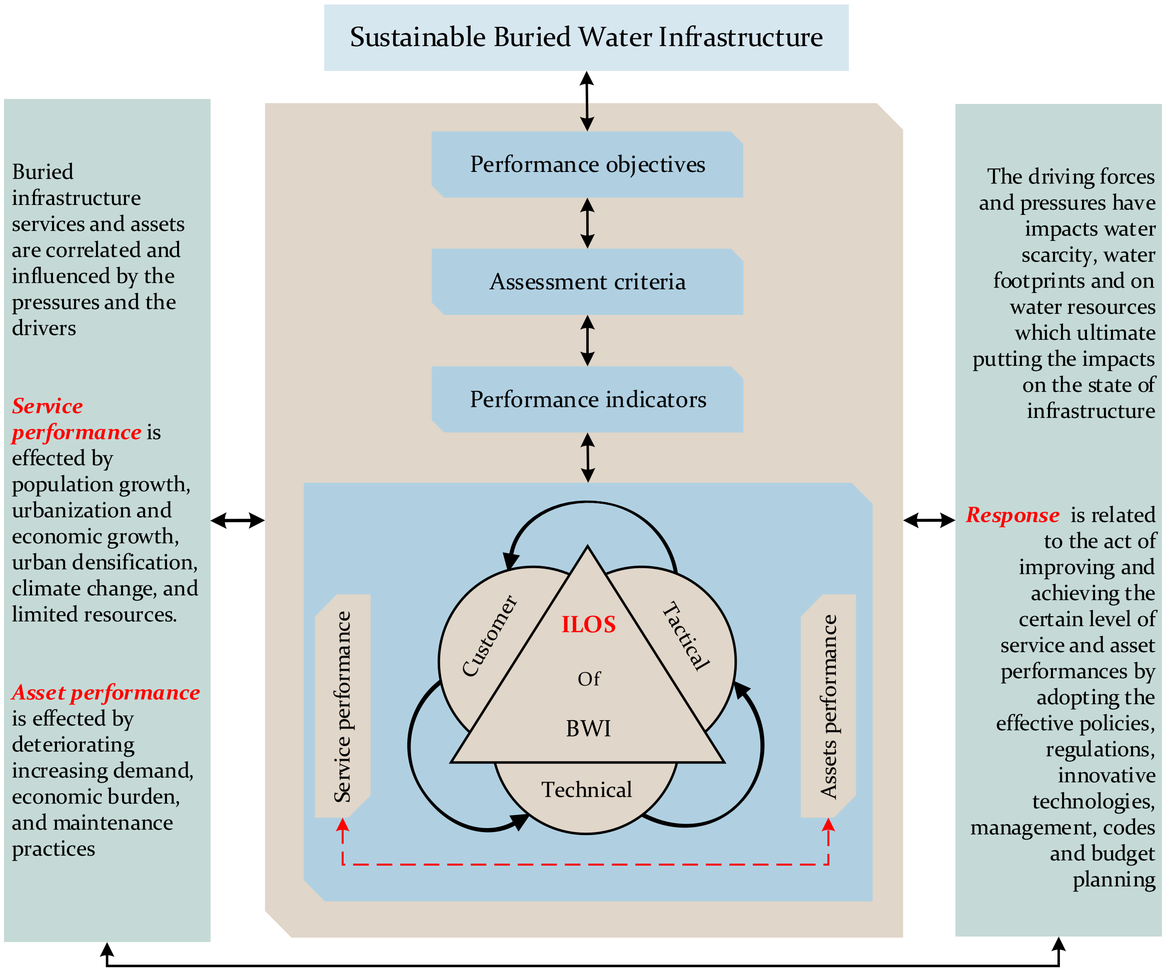


Fig. 10. (*continued*).



Buried infrastructure services and assets are correlated and influenced by the pressures and the drivers

Service performance is effected by population growth, urbanization and economic growth, urban densification, climate change, and limited resources.

Asset performance is effected by deteriorating increasing demand, economic burden, and maintenance practices

The driving forces and pressures have impacts water scarcity, water footprints and on water resources which ultimate putting the impacts on the state of infrastructure

Response is related to the act of improving and achieving the certain level of service and asset performances by adopting the effective policies, regulations, innovative technologies, management, codes and budget planning

Fig. 11. A conceptual model for integrated level of service (ILOS).

US $50 billion and expected to increase in the future (UN Water, 2016).

4.5. Response

In urban areas, municipalities are struggling to provide adequate water services. In practice, cities are challenged by providing these services mainly due to drivers and related pressures on BWI, which effects the LOS. To practice this government and municipalities are required to set the performance targets such as cost-effective investments, accommodating higher number of population, financial and asset management planning, long-term integrated planning for BWI, compliance with regulatory requirements, and considering a range of infrastructure alternatives. These performance targets can be achieved through best management practices (i.e., responses). Some responses may face uncertainty and ambiguity, while making future policies; for instance, making policies to the stormwater infrastructure are highly dependent on climate change. Eventually, a large body of literature is available to incorporate the uncertainty, which can facilitate in decision-making under uncertainty (Hoekstra et al., 2018). Sometimes, the undesirable drivers, pressures, change in states, and related impacts are resultant of immature policies and improper implementation, lack of expert teams, governance failure at multiple levels, and social unacceptability needs institutional and organizational improvements (Pahl-Wostl, 2017).

Municipalities need to maintain records related to the growth rate of population in the city and related demand and supply of the drinking water, produced wastewater, runoffs, capacity, and availability of infrastructure. Detailed information on the current state of BWI, its lifespan and related costs to maintenance and repair must be recorded in a detailed manner (US EPA, 2012). In addition, municipalities must have up-to-date information on available technologies with the educated and trained personnel for better understanding of the technical concerns associated with BWI. This information will assist them to maximize the life of assets at a minimum life-cycle cost (American Water Works Service Company Inc, 2002; Boudreau, 2005).

Further, the state of municipal BWI can be assessed on the basis of survey responses and ranked on the scale of “very good - (10)”, “good - (8)”, “fair - (6)”, “poor - (4)”, and “very poor - (2)” (Canadian Society of Civil Engineers, 2016). Infrastructure from “fair” to “very poor” rating required the project planning actions such as maintenance, repair, replacement, and up-gradation to achieve its adequate ILOS. Multiple interventions of regular inspections and maintenance practices will help to preserve, improve, and increase the ILOS of BWI through its life cycle (Fig. 12). The BWI will gradually deteriorate if not controlled by the maintenance/repair

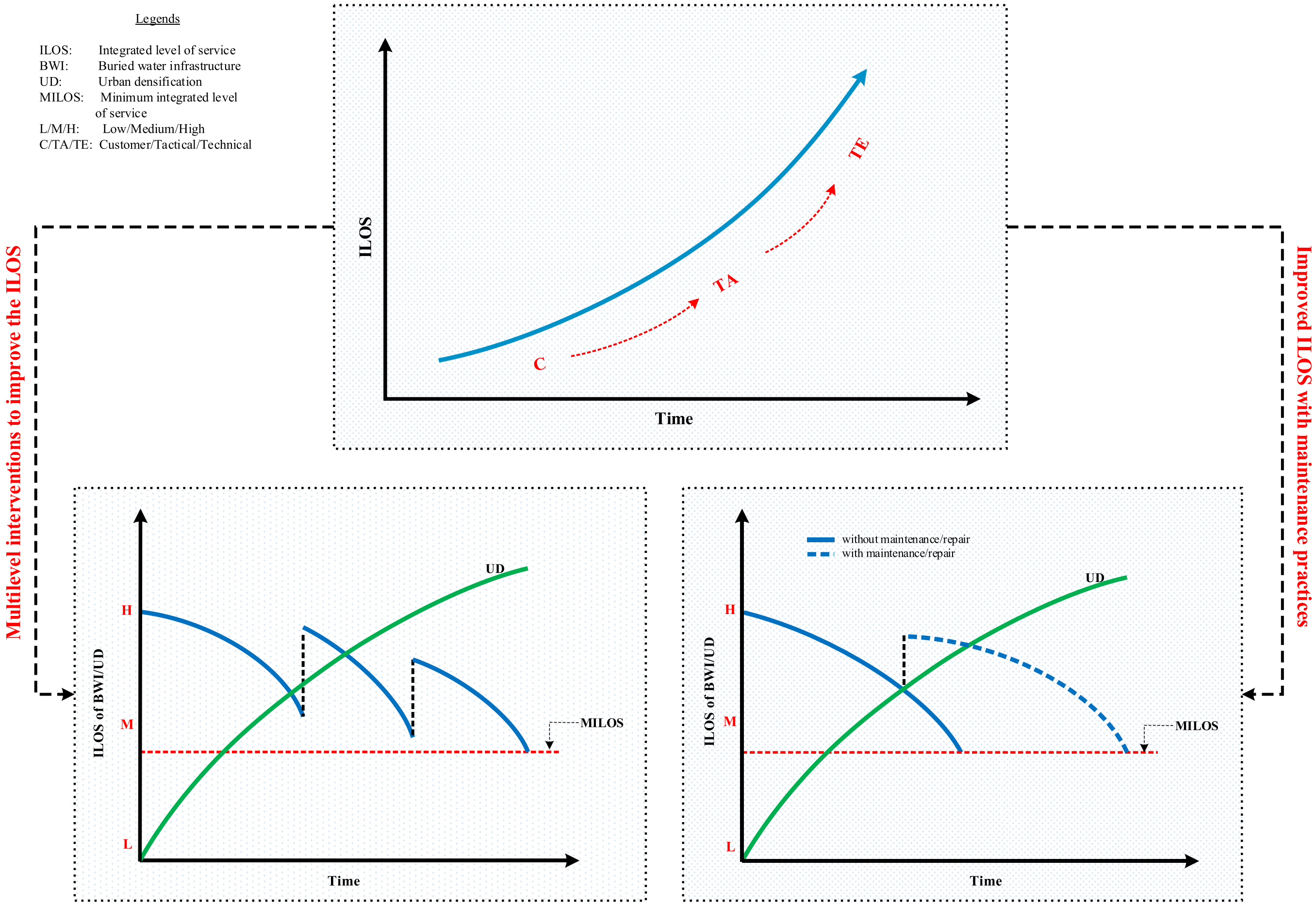


Fig. 12. Improved integrated level of service over the time with the multilevel interventions for maintenance practices.

programs, which can lead to the loss of serviceability and structural failure. However, applying the strict regulatory constraints on the maintenance/repair programs will increase the service level of BWI and reduce associated costs. Deterioration and damage are a significant problem of aging infrastructure and many unreliable decisions have made in the absence of prior information and data availability. Further, compiling the records will help to develop a database, which will assist the municipalities to assess the current condition of the infrastructure.

To date, many countries are fronting the problems of having a huge number of deteriorated BWI. According to the Canadian infrastructure report of 2016 (Canadian Society of Civil Engineers, 2016), it has been estimated that on average about 30% of the physical condition of BWI was under "fair" to "very poor" rating with the total replacement cost between $61 billion to $112 billion. Another observation made during this report was lower reinvestment rate than the recommended targets for asset management. To avoid the costly and premature reinvestments, it is essential to invest the money in preventive repairs and maintenances to minimize the reinvestment and to make sure the implementation of the set targets.

The municipalities must have a long-term plan, which allows them to plan for the future to satisfy demand of projected population and under the extreme events. The indicator-based approach can be adopted to collect information on the current condition of BWI. These indicators can be developed and further shortlisted with the help of expert advice or literature. Municipalities must used the advance technology to assess the condition and corresponding required actions on BWI (Canadian Society of Civil Engineers, 2016).

Efficient and advance treatment facilities must be provided to treat, maintain, and recycle wastewater and stormwater in the cities. In some regions such as Aqaba, Chennai, and Durban the reuse of wastewater is between 40 and 70% of the total extracted water (IWA, 2018), and irrigation is the most common strategy to reuse the municipal wastewater. A few cities (e.g., Singapore and Windhoek) have used the recycled wastewater for drinking use (Lee and Tan, 2016; Van Rensburg, 2016). Recycled drinking water signifies a cost-effective source of water for urban areas but still faces the emotional and psychological barriers (Ching, 2016). Further, the use of rainwater harvesting and green infrastructure having the direct impact on reducing the water consumption. Regulators and water managers should mitigate the use of potentially harmful chemicals during the supply of drinking water to reduce the water pollution in wastewater and challenges of its treatment (Larsen et al., 2016).

Green stormwater infrastructure must be intensively used by the municipalities for the management of water, which helps to control the floods by reducing runoff to the gray infrastructure (e.g., sewer mains, tanks, and treatment plants) as well as improve the water quality by filtering pollutants in the runoff before releasing into the downstream local water bodies (NACTO, 2017). Municipalities should design the green infrastructure, which can accommodate the peak runoff flows during the heavy rainstorm event. Additionally, stormwater collection system should be separate from the wastewater collection system, because in most of the cases stormwater is discharged into the receiving bodies without or with limited treatment (NACTO, 2017).

In a report, under the business-as-usual scenario, it has been estimated that with the continuous increase in population the world could face the 40% deficit in the water by 2030 and even more by 2050 (UN Water, 2016). To address 40% gap between the water demand and supply, and for the sustainable water use, municipalities should put restrictions on water use. For instance, an emergency mandatory restrictions have been declared by the California government to achieve 25% reduction in the use of drinking water and imports of water supply has been reduced from 90% to 50%, while increasing the use of local water sources in Los Angeles (Hogue and Pincetl, 2015). Globally, the policies to conserve water varies widely; although increase in the price, fines, watering restrictions, and reduction in volume and outdoor water use (during drought) are the common practices for the sustainable use of water.

Additionally, wastewater can also be treated as a resource of water rather than waste, for instance in Australia, the wastewater is reused after treatment for the irrigation of recreational grounds (e.g., golf grounds), landscaping, and non-potable applications for industry (e.g., cooling towers) (Nick et al., 2011). Reusing the wastewater has many environmental (e.g., increase the groundwater recharge, lower down the amount of sewerage discharge in water bodies and pressure on freshwater sources), financial (e.g., reducing the water bills), and social (e.g., enable use in the absence of potable water, green garden all over the year) benefits, which ensures the sustainable use of water (EMRC, 2011).

5. Discussion

The implications of this research have been discussed as follows:

- The DPSIR framework has been reviewed and revised over the years to support and structure the conceptual understanding of the system under the study. The drawing of system boundaries depends on the particular issue of interest and conceptualization, which are strongly influenced by those who are using it. The DPSIR framework has been criticized due to its definitional limitations and to be known as a device of experts. However, these criticisms do not indicate its weakness as a tool. The DPSIR can never be a layman's device but a tool to be familiarized with, who have learnt how to use, adapt, and handle it with clear sight of definitional knowledge as well as system boundaries and research objectives. The linkage-based DPSIR framework, with several challenges and appreciations, is still considered as a simple and most powerful communication tool. It is widely used to assess and analyses the relationship between several anthropogenic activities and environmental related issues. DPSIR framework has the ability to relate all the environmental changes, which are driven from the urban densification and eventually its pressures on the BWI in the context of natural and economic capital and their measurement to mitigate the negative impacts.
- This study will call the top-level management (e.g., government, municipalities, regulators, policy makers, and decision makers), operators, managers, and users to put more attention to understand the impacts from urban densification on the state of BWI. It is very important for all the above-mentioned people to improve their understanding of induced pressures from human activities on the BWI and policy responses. Thereafter, the better and proactive strategies can be developed to meet the targets of providing the acceptable services of BWI at minimum cost. It can also be used for the decision making towards the management and policy responses for sustainable use of BWI, evaluation under different alternatives, and to achieve the sustainable development.
- In general, the cost is highly associated with urban densification in the context of providing adequate BWI services within the city (Fig. 13). As per the figure, the costs are high with a low urban density, which gradually decrease with an overall increase in urban densification. However, after a certain point (when maximum sustainable urban capacity also known as a breakeven point of densification is achieved) the cost will again redeem a direct relation with urban densification. In nutshell after the breakeven point of densification, any additional densification will lead to low ILOS, which ultimately mark the city as an expensive urban area.
- DPSIR framework is an effective way to manage the natural system in the presence of their use and transformation related conflicts. It helps to provide drinking water, wastewater, and stormwater services while minimizing the environment impacts and life-cycle cost. DPSIR framework can be coupled with new methods to understand and analyze the impacts of urban densification on the other infrastructures (e.g., transportation, oil, and pipelines, building) in different sectors other than residential. Additionally, the findings of this DPSIR can be applied globally on regional or national scales.

6. Conclusions and recommendations

Due to many dynamic factors, globally more than half of the population is living in the urban areas and anticipated to increase by 2050. Municipalities are facing many challenges providing the basic services and housing facilities to the growing population. One solution is urban densification due to limited land and targets to reduce the greenhouse gas emissions. Urban densification has a direct impact on buried water infrastructure (BWI) in terms of an increase in water consumption, generating a significant amount of wastewater, and increase in stormwater runoffs. There is a need to put attention on the integrated study of the impacts of urban densification on the state of BWI and its sustainable management. The study makes a pioneering attempt to assess integrated level of service (ILOS) of BWI against the urban densification context. This is where it scholarly contributes to the field of knowledge.

In this study, a comprehensive review of all the dynamic factors of urban densification, induced pressures, their effects on the state of BWI, corresponding impacts and responses has been conducted using the Drivers, Pressures, States, Impacts, and Responses (DPSIR)

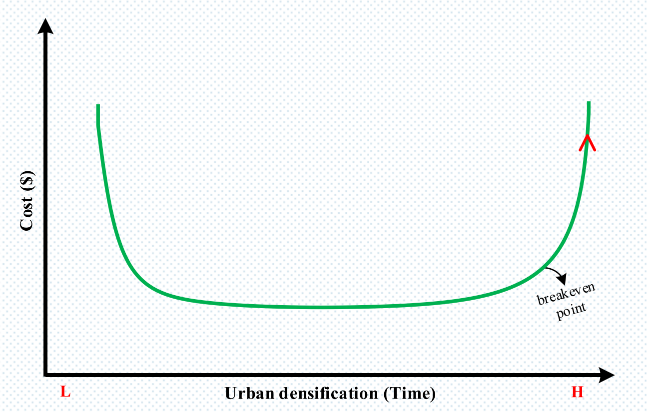


Fig. 13. Relationship between cost and urban densification.

linkage-based framework. In addition, a conceptual model to assess the ILOS was developed to address the above-mentioned gap in the published literature. The ILOS of BWI was defined at three levels including tactical, technical, and customer. Further, it will lead to better-targeted policy responses in the decision-making process to monitor and manage the physical and operational performance at different levels of the hierarchy of BWI.

This review explores mechanisms underlying the complex system of multilayered BWI with ongoing urban growth. However, a deeper aggregation of all the dimensions of BWI along with the changing patterns of urban growth is still needed for future research. Further research needs to define key components and associated data variables to quantify and analyze the impacts of urban densification on the performance of BWI using the proposed conceptual model. The findings of this study will provide an integrated toolkit to the responsible authorities to deal with their challenges associated with sustainable expansion of a region and ensure the adequate performance of BWI. The proposed conceptual model is widely applicable and can be applied on any type of infrastructure.

This research can serve as a baseline to identify pathways and establish link between them to asses the overall performance of infrastructure. The further work needs to be done in refining the uncertainties associated with scenarios, datasets and model development for the performance assessment of BWI. These developments will provide municipalities with comprehensive and inclusive tool to take the rational and optimized approach to define urban density plans. In the longer run various municipalities can engage under a common platform to learn and optimize several urban growth scenarios.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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