Sustainable Asset Valuation Tool

WATER INFRASTRUCTURE

Andrea M. Bassi
Kieran McDougal
David Uzsoki

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Head Office

111 Lombard Avenue, Suite 325
Winnipeg, Manitoba
Canada R3B 0T4

Tel: +1 (204) 958-7700
Fax: +1 (204) 958-7710
Website: www.iisd.org
Twitter: @IISD_news

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Sustainable Asset Valuation Tool: Water Infrastructure

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This document is not meant to be an original contribution. Instead, it is a review that summarizes available knowledge in the literature for a given infrastructure type, including, for instance, the policy landscape and data availability. As a result, this document (both the light screening and in-depth review) were utilized to inform the creation of the SAVi model, a simulation tool that integrates knowledge from various disciplines and sectors for sustainable asset valuation.

TABLE OF CONTENTS

PART I: LIGHT SCREENING

Definition of sustainable infrastructure	- A sustainable water system ensures "adequate supplies of water of good quality are maintained for the entire population of the planet, while preserving the hydrological, biological and chemical functions of ecosystems, adapting human activities within the capacity limits of nature and to combat vectors of water-related diseases" (United Nations, 1992). - A sustainable water system is "one that is designed and managed to contribute fully to objectives of society, now and in the future, while maintaining ecological, environmental and hydrological integrity" (American Society of Civil Engineers & United Nations Educational, Scientific and Cultural Organization, 1998). - Sustainable urban water management reflects growing concerns over "community wellbeing (rather than just public health), ecological health and sustainable development, all of which can be collectively labelled as 'green' issues (Bartone et al., 1994)" (Marlow, Moglia, Cook, & Beale, 2013, p. 7151). The main goals of sustainable urban water management are a more natural water cycle (pollution control, ecological regeneration and enhancement of urban amenities), enhancing water security through local source diversification and resource efficiency. - "For a water utility, sustainability is practically achieved when all its activities, both internal to the business and across its supply chain, achieve net added value when assessed across each of the triple-bottom-line outcomes (financial, social and environmental) over the medium- to long-term timescales, considering all costs and benefits, including externalities" (Marlow, Beale, & Burn, 2010). - The main water-related goals in the green economy are investing in degraded river systems and watersheds, developing localized water systems, ensuring universal access to clean drinking water and sanitation services, reducing water scarcity, and balancing supply and demand (United Nations Environment Programme [UNEP], 2011). - Sustainable water infrastructure includes the "traditional human-made or built infrastructure components and the natural infrastructure, such as rivers, lakes, streams, groundwater aquifers, floodplains, floodways, wetlands and the watersheds that serve or are affected by water and wastewater systems" (The Aspen Institute, 2009). - Water management policies and technologies can be divided into three areas: water supply, water demand and wastewater management. The following technologies are generally considered: o Supply → "Green" infrastructure techniques such as restoration of wetlands, riparian buffers, reforestation, etc. o Demand → Water efficient appliances/fixtures → Smart water systems o Wastewater management → "Green" infrastructure techniques such as restoration of wetlands, riparian buffers, reforestation, etc. → Grey water recycling/separation → Localized sanitation → Decentralized rainwater collection and drainage (green roofs, permeable pavements) - This review focuses primarily on built infrastructure for water supply in the agriculture sector (irrigation) and wastewater management.
Indicators used to measure performance	- Five main categories for sustainability indicators: "(1) health and hygiene, (2) social-cultural criteria, (3) environmental criteria, (4) economic criteria, and (5) functional and technical criteria" (Hellstrom, Jeppsson, & Karrman, 2000). - Indicators commonly used in the literature to assess the sustainability of urban water systems fall into the categories of economic indicators, environment indicators, technical indicators and socio-cultural indicators (Balkema, Preisig, Otterpohl, & Lambert, 2002) - For service provision: service coverage, water quality samples, service effectiveness, cost of water, recovery of costs from charges, quality deterioration risk, environmental flow regulation, unaccounted for water, per capita water use, resource capacity (Lundin, 2003) - For water demand and supply management: withdrawal, water consumption, chemical and energy use for treatment of water supply, leakage, reused water, wastewater production per day, removal of pollutants, loads of pollutants, nutrients recycled, energy recovered (Lundin, 2003). - Water management indicators typically include water infrastructure, environmental quality, economics and finance, institutions and society, human health and technology categories (Marlow, Moglia, Cook, & Beale, 2013).

Shortcomings of business-as-usual investments	**Institutional** - The current dominant model relies on large-scale, centrally managed infrastructure systems that are designed to deliver cheap and reliable services (Marlow, et al., 2013). However, the BAU model “is incurring increasing economic, social and environmental costs, even in countries with a long tradition of successful practices. This is a consequence of aging built infrastructure, increasing urbanization, emerging contaminants, competitive water uses, and measures to mitigate the effects of climate change (e.g., water-saving measures)” (Larsen Hoffmann, Luthi, Truffer, & Maurer, 2016, p. 929). The construction of water management systems in developing countries entails substantial costs, but there is little willingness and ability to embark on large-scale infrastructure projects (Larsen et al., 2016). - “The downsides of the current [urban water management (UWM)] system are its strong dependence on large quantities of water, high investment costs and need for stable institutions, as well as long planning horizons and inefficient use of resources” (Larsen, et al., 2016, p. 928). **Ecological health (water-cycle and resource efficiency)** - Supply o Certain types of infrastructure can “lead to declines in the quality and quantity of water supply, as a result of ecosystem degradation. For example, conventional flood management infrastructure can disconnect rivers from floodplains and reduce or eliminate services such as flood control, groundwater recharge, pollution control and supply regulation (Opperman, et al., 2009; UNEP-DHI Paternership, 2014, p. 9). o “Grey infrastructure is often designed to address a specific water management problem (though some grey infrastructure may serve multiple purposes, such as reservoirs that provide water supply, flood control, hydropower, recreation, etc.). It can serve to shift amplified risks to other locations. For example, canalized rivers and urban stormwater infrastructure may cause downstream flooding” (UNEP-DHI Paternership, 2014, p. 9). - Demand o Systems are designed to supply large amounts of water, with little incentive to reuse water or reduce its use. - Wastewater management o The local built environment “has a strong influence on the natural hydrological characteristics of a catchment. A substantial part of the global urban area of 658,760 km2 comprises impermeable surfaces. This leads to a higher surface runoff and a faster response time to the rain event” (Larsen, et al., 2016, p. 928). o “In the process of urban water use, waste is produced in the form of waste water. However, waste water also contains important resources, including water, organic matter, heat and nutrients such as phosphorus and nitrogen. For example, the amount of nitrogen passing through the human metabolism on a global scale, and therefore potentially ending up in waste water, is on a par with major components of the nitrogen cycle” (Larsen, et al., 2016, p. 928).
Advantages of green investments	**Institutional** - “Decentralized systems have the advantage that they can be installed in the short term when needed, thereby reducing the requirement for large-scale investment in sewers and centralized wastewater treatment plants. Moreover, they allow the local reuse of water and therefore increase water productivity” (Larsen, et al., 2016). Localized water management systems “require less upfront investment… and are more effective at coping with the need to expand services (USEPA, 2002)” (Organisation for Economic Co-operation and Development [OECD], 2015, p. 99). - Smart water technologies contribute to “urban water management efficiency and financial stability, as municipalities and water utilities are better able to recover costs from non-revenue water (e.g. stemming from leakages and illegal connections)” (OECD, 2015, p. 97). **Ecological health (water-cycle and resource efficiency)** - Supply o Green water infrastructure has a lower impact on the functioning and health of the watershed (UNEP-DHI Paternership, 2014). - Wastewater management o Decentralized rainwater collection reduces “pollution, as rain water gets more polluted as it runs long distances on streets, pavements and parking lots.” (OECD, 2015, p. 100) o Permeable pavements also increase the quality of water returned to the environment, as it “allows rainwater to trickle through the ground and recharge aquifers” (OECD, 2015, p. 100). **Access and water security** - Demand o Increasing water productivity: Three main strategies designed to increase water productivity are reducing water waste, down-cycling or reuse of lower-quality water, and regenerating high-quality water from used water (Larsen, et al., 2016). Smart water systems can enhance water quality and reliability and decrease water losses due to leakage (OECD, 2015). o Wastewater management o Source separation of waste: Separating wastewater streams as early as possible alleviates resource recovery and/or facilitates the treatment process (Larsen, et al., 2016).

Main roadblocks for the adoption of green infrastructure	- “Part of the challenge in changing the model of service provision is that investment cycles for infrastructure often occur over timescales that are too short (e.g., five years) to allow effective adaptation to longer-term pressures. Another challenge is that the widespread adoption of a specific technological solution leads to both institutional and technological ‘lock-in’ effects (Foxon et al., 2002). Arthur (1994) identified four factors are identified that generate such effects: (1) economies of scale, (2) learning effects that improve products or reduce their cost, (3) adaptive expectations (agents become increasingly confident about quality and performance of the current technology) and (4) network economies (agents adopting the same technologies as others)” (Marlow, et al., 2013, p. 7153). - “There are a number of conceptual weaknesses associated with the arguments for SUWM and these provide alternative insights into why transformational agendas remain unfulfilled: (1) difficulties in predicting the system effects of innovative solutions, (2) practical challenges in managing innovations in technologies and service provision strategies, (3) financial considerations, and (4) the effect of bias and advocacy on the promotion of technologies and management paradigms” (Marlow, et al., 2013, p. 7153). - Innovation effects: o “The performance of an urban water system is multifaceted and difficult to predict from a system perspective. While this can be said of traditional systems, innovative solutions are, by definition, introduced into new contexts, which implies there will be a lack of institutional capacity to manage uncertainties and risk. Changes to any part the system can have both upstream and downstream impacts that affect costs, performance and future opportunities” (Marlow, et al., 2013, p. 7193). - Practical challenges: o “There are adoption issues to address, including increased management complexity, diffuse responsibilities, uncertain performance and community resistance to change. More specifically, innovative solutions often have requirements that are not necessarily clear from the outset, and institutional capacity therefore tends to develop over time” (Marlow, et al., 2013, p. 7155). o “Who is in charge of –or accountable for- a particular issue is not always clear, especially when the issue cuts across domains such as urban planning, the environment and economic development. For instance, How should permeable surfaces used for parking lots and streets be defined in the context of urban drainage—as water related or transport infrastructure?” (OECD, 2015, p. 109) - Financial considerations: o “Water supply revenues are, to some extent, often linked to the volume of potable water used by customers, so widespread implementation of alternative water sources and/or water conservation measures could lead to reduced revenues” (Marlow, et al., 2013, p. 7154). - Bias and advocacy o When businesses, authorities, universities and related organizations build up knowledge and experience with any particular solution, it is inevitable that they will develop biases, intentionally or otherwise, toward their own commercial or institutional interests (Marlow, et al., 2013). o Some communities may perceive that decentralized water systems leave them out of central infrastructure and result in lower-quality services. There is a risk that localized systems fragment cities and provide uneven levels of service (OECD, 2015).
Policy interventions	- Sustainable urban water management often benefits from policies not specifically aimed at improving green infrastructure, such as climate adaptation policies that restore watersheds or regulations on water pollution (OECD, 2015). - Economic instruments such as water tariffs “can signal resource scarcity and reflect some of the benefits of improved water security and improved water services”, while helping to cover the cost of sustainable infrastructure (OECD, 2015, p. 113).
	Grey Infrastructure - Regulatory: Environmental regulations around water use and pollution present the potential for increased costs. - Market: Centralized systems require substantial upfront financing. - Technical: Ageing infrastructure needs to be regularly repaired or replaced. Centralized systems are less able to deal with uncertainty around water supply due to climate change. - Social pressure: Concerns arise over water pollution, declining health of lakes and rivers, and total water use, especially in water scarce regions.
	Green Infrastructure - Regulatory: Regulatory systems are developed to support large-scale centralized water management infrastructure. - Market: Managing several small projects can be more of a burden for local institutions. - Technical: Uncertainty remains regarding new technologies and lack of data on green infrastructure. - Social pressure: Health concerns are related to reuse of grey water, decentralized sanitation and supply systems.
Existing sustainability standards	- Water Climate Bond Standard (http://www.climatebonds.net/standard/water)
Main organizations working on the assessment of infrastructure	- WaterNow Alliance (http://waternowalliance.org/) - US EPA Water Infrastructure and Resiliency Finance Center (https://www.epa.gov/waterfinancecenter) - POLIS project (http://poliswaterproject.org/conservation)

Table 1. Assessment of selected green economy interventions in the water management sector

		Market support			Multi-criteria analysis		
Goal	Policy	Awareness	Demand	Supply	Investment	Avoided cost	Added benefit
	Incentives for building distributed water and wastewater infrastructure			x	Public and private investment (G, P)	Lower upfront costs (G, P) Reduced water treatment costs (G)	Higher environmental water quality (G) Green industry support (P) Recharge aquifers, groundwater (G)
	Incentives for green infrastructure			x	Public investment (G)	Reduced water treatment costs (G) Reduced traditional infrastructure costs (G) Lower operation costs (G)	Flood control (G) Higher environmental water quality (G) Nutrient cycling (G)
	Smart water systems	x			Public investment (G)	Reduced water bills (H)	Maintenance issues addressed sooner (G)
	Incentives for water-efficient appliances/ fixtures		x		Private and public investment (P, G) Purchase of products (H)	Reduced water bill (H)	Recharge aquifers, groundwater (G) Green industry support (P)

Note: P – Private sector; G – Government; H - Households

PART II: IN-DEPTH REVIEW

1.0 DEFINITION OF SUSTAINABLE INFRASTRUCTURE

Sustainable water management infrastructure takes into account environmental, social, and economic outcomes of the use of infrastructure. Sustainable urban water management is concerned with community well-being alongside with traditional concerns about public health. Main goals include a more natural water cycle, enhancing water security, and resource efficiency. Sustainable urban water management tends to focus on a more decentralized approach for infrastructure, and includes natural infrastructure such as rivers, wetlands and aquifers alongside human-made components. There are three components of water management infrastructure: water supply, water demand, and wastewater management.

IISD defines sustainable infrastructure as assets that optimize value for money economy-wide, and hence for all taxpayers. Sustainable water management infrastructure must be assessed based on both its upfront and lifetime costs, including resource use, pollution control, and health outcomes. A sustainable water system requires that water consumption is lower than the natural recharge rate, and that the material and energy use of water infrastructure is sustainable over the long term.

In the case of water management, the following technologies are considered:

- Supply
    - "Green" infrastructure techniques such as restoration of wetlands, riparian buffers, reforestation etc.
    - Dual supply
    - Water recycling (Rainwater and greywater harvesting)
- Demand
    - Water efficient appliances/ fixtures
    - Smart water systems
- Wastewater management
    - 'Green' infrastructure techniques such as restoration of wetlands, riparian buffers, reforestation etc.
    - Greywater recycling/ separation
    - Localized sanitation
    - Storm water control (Green roofs, Permeable pavements)
- Irrigation
    - Water use and leakage monitoring
    - Water efficient fixtures

Table 2. **Overview of required inputs and outputs generated by buildings**

Inputs	Outputs
• Construction o Capital o Labour o Raw materials (e.g., aluminium, steel) o Water o Energy • Operation o Labour o Electricity use o Water use o Heating	• Revenues (rent, taxes) • Water quality o Human health (mortality and morbidity) o Ecological health • Water scarcity • Thermal pollution • Visual impact • Competition for land use

1.1 SHORTCOMINGS OF BAU INVESTMENTS

The current water management infrastructure model relies on large-scale centrally managed systems, which are primarily aimed at affordable and reliable service delivery (Marlow, Moglia, Cook, & Beale, 2013). These systems are facing several challenges, including aging infrastructure, increasing urbanization, emerging contaminants, competitive water uses, and the need for measures to mitigate the effects of climate change. Centralized water systems depend on large quantities of water and require high levels of investments, and stable institutions. In developing countries, there is often little willingness or ability to build large scale infrastructure projects (Larsen, Hoffmann, Luthi, Truffer, & Maurer, 2016).

Conventional water management has institutional drawbacks as well as drawbacks in water supply, water demand, and wastewater management.

- Institutional
    - Conventional water management infrastructure requires a substantial amount of investment and maintenance. Once the infrastructure is in place, it is difficult to replace or retrofit.

> ***Example:***
>
> The US spent USD 137 billion on water infrastructure in 2014. USD 109 billion of that was spent on water utilities, including water supply infrastructure (pipes, sewers) and wastewater treatment plants. The remainder was spent on water resources, including dams, levees and sources of freshwater. Thirty three per cent of the spending on water utilities was capital investment, with the remaining 67 per cent spent on operation and maintenance. The breakdown for water resource spending is 36 per cent for capital expenditure and 64 per cent for operation and maintenance (Congressional Budget Office, 2015).

-
    - Much of the existing conventional infrastructure is nearing the end of its life, increasing the cost of maintenance and water waste.

> ***Example:***
>
> The number of water main breaks in the United States is estimated to be 240,000 per year. These water main breaks are estimated to result in 1.7 trillion gallons of water waste, and USD 2.6 billion annually in repair costs. Broken water pipes also release as much as 10 billion gallons of raw sewage every year (Sabol, 2011). An estimated USD 1 trillion dollars of investment is required to upgrade and replace water infrastructure in the United States over the next 25 years (American Water Works Association, 2010).
>
> “Drinking water is lost after it leaves treatment plants because of physical leaks in urban water distribution systems and poor accounting. Worldwide, the total volume of this “nonrevenue water” is estimated to be 49 Tl per year. Pipeline losses range from over 50% in much of the developing world to less than 10% in well run utilities. The World Bank estimates that if just half of the losses in developing countries were eliminated, $1.6 billion would be saved annually in production and pumping costs, and drinking water could be extended to an additional 90 million people without the need for new treatment facilities” (Grant, et al., 2012)

- Conventional centralized water management systems require well functioning governance systems, and extensive upfront infrastructural investment. This makes it difficult for conventional water management systems to keep up with population growth in the megacities of the developing world.

> ***Example:***
>
> "As the population increased dramatically in the last 50 years, and the rate of urbanization began to accelerate, the provision of clean water and safe disposal of wastewater and stormwater in the megacities of developing countries became increasingly more complex and serious. [...] The main problem of megacities often stems from the fact that the rates of urbanization have often far exceeded the capacities of the national and local governments to plan and manage the demographic transition efficiently, equitably and sustainably" (Varis, Biswas, Tortajada, & Lundqvist, 2006, p. 194). "The megacities of the developing world witnessed explosive growth during the post-1950 period, and especially after 1960. For example, the population of Mexico City Metropolitan Area increased from 3.1 million in 1950 to 13.4 million in 1980, a 425% increase in only 30 years. This expansion continues still as the City's population has now exceeded 18 million. Such megacities were simply unable to manage such explosive growth rates. The fastest growing megacities are expected to grow more than fourfold in 25 years" (Varis, Biswas, Tortajada, & Lundqvist, 2006, p. 192).

Water supply:

- The construction and operation of large scale water supply infrastructure has multiple external environmental impacts due to the life cycle impacts of inputs such as piping or the use of electricity. The electricity use related to treating and pumping water contributes a substantial amount of water supply environmental impact.

> ***Example:***
>
> Global warming potential (GWP) values in units of equivalent carbon dioxide mass per km of pipeline were compared for six pipeline types (PVC, Ductile iron, concrete, reinforced concrete, cast iron and high density poly-ethelyene). Iron pipes have the highest GWP at 472 000 kg CO_2/km (ductile iron) and 353,000 kg CO_2/km (cast iron) for 12 inch diameter pipes. The production phase produced the largest amount of emissions (Du, Woods, Kang, Lansey, & Arnold, 2013).
>
> The southern part of California has long relied on water imported from sources located hundreds of kilometers to the east and north. "In 2001, an estimated 4 percent of the electric power consumption in California was used for water supply and treatment (largely transportation) for urban and agricultural users; this estimate increases to 7 per cent if end uses in agriculture (which are mainly related to pumping) are included (California Energy Commission, 2006). The depletion of source waters in the state has led to habitat deterioration, the decline and extinction of native fish species, the near-collapse of the Sacramento–San Joaquin River Delta ecosystem, and the desiccation of Owens Lake, whose dry lake bed is arguably the single largest source of asthma- and cancer inducing respirable suspended particles in the U.S." (Feldman, 2017, p. 73)

  - Water infrastructure can lead to declines in the quantity of water available. As cities grow, and agriculture and industry use more water, aquifers and other fresh water sources are depleted.

> ***Example:***
>
> Approximately one-third of the potable water provided by public water supplies in the United States is from groundwater sources. In locations with high water demand and low precipitation, groundwater oversubscription can result in seawater intrusion, land subsidence, and exhaustion of wells. (NRC, 2008c) The depletion of aquifers can be exacerbated in urbanized areas, where impervious surfaces (e.g., pavement) reduce groundwater recharge. Groundwater also is an important means of water storage, especially in areas where the construction of new surface water reservoirs is difficult due to the lack of available land or concerns about the environmental damage caused by reservoirs" (National Research Council, 2012, p. 43).

Groundwater in Dhaka is used well beyond the recharge rate. “Almost 1000 private wells abstract another 0.35 km^3 per year of groundwater, mainly for industrial purposes. Groundwater is used far beyond the sustainable rate and this groundwater mining puts a serious strain on the environment. The groundwater table has gone down 20 to 30 m in the past three decades and continues to sink 1 to 2 m per year” (Varis, Biswas, Tortajada, & Lundqvist, 2006)

  - Declines in water quantity can in turn decrease the quality of the water supply, as the watershed is less able to regulate itself, due in part to ecosystem degradation. Salt water intrusion takes place as freshwater in aquifers is replaced with salt water.

> ***Example:***
>
> Salt water intrusion has become a problem in South Florida’s Broward County. Results of a numerical modeling analysis suggest that groundwater withdrawals were the dominant cause of a multi-decade salt water intrusion event, and that historical sea-level rise (about 25 cm for the simulation period) contributed to the extent of the intrusion by about 1 km. The model projects that drinking water standards for total dissolved solids will be exceeded in 70 years with no sea-level rise, and 10 to 21 years earlier with IPCC predicted sea-level rise (Langevin & Zygnerski, 2013).

  - Conventional infrastructure is often designed to address one specific water problem. This narrow focus can shift or amplify problems in other areas.

> ***Example:***
>
> Levees do a great job of minimizing impacts from moderate size floods for small areas. Ten out of 26 years since the Winona, Minnesota levee on the Mississippi River was completed have had peak flows above flood stage. “While levees are good for individual communities in small- to moderate-size events, levees are bad for the river system’s overall capacity to deal with flood flows. By literally walling off large sections of the floodplain, levees give the river much less room to spread out horizontally… But levees basically do nothing to change the discharge, or volume, of the flood. So if the water can’t spread horizontally, it has to either speed up or get higher. At St. Louis, the 1993 Mississippi flood peaked at a stage of 49 feet. In ~1927, the same volume of water at St. Louis would have reached only 39 feet” (Jefferson, 2011).

- Water demand:
  - Water systems are designed to supply large amounts of water, and do not provide incentives to reduce or reuse water. Water demand is driven by a variety of uses, including landscaping and industrial uses.

> ***Example:***
>
> “Rapid population growth and urbanization have tripled global water withdrawals over the last 50 years and predictions forecast that almost half of humanity will face water scarcity by 2030 (OECD 2008)” (Stoker & Rothfelder, 2014). Seasonal variations are a major driver of water use. A study of urban water demand found that seasonal climate conditions were the primary drivers of water use in Salt Lake City. The mean monthly water use increased dramatically during the summer months, as residents and businesses irrigated plants, lawns and gardens. By contrast, winter water use dropped substantially because snow cover and cold temperatures made outdoor irrigation needless and almost all water use is for indoor purposes (Stoker & Rothfeder, 2014).

- Wastewater management
    - The vast majority of urban areas are impermeable. This increases the rate of runoff and produces a quicker response to rain events. Runoff also can have higher levels of pollutants, as water travels longer distances before absorption.

Example:

"Urban and exurban growth in the Spring Lake, Michigan watershed has resulted in an increase in total impervious area, particularly in the communities adjacent to Spring Lake. Between 1992–1997 and 2006, overall watershed mean percent impervious surface area increased from 8.9 to 15.1 %. In addition, watershed area with limited impervious surface areas (i.e., <10 %) decreased from 68 per cent in 1978 to only 27 per cent in 2006. […]Between 1992/1997 and 2006, total phosphorous increased 46 per cent from 3.96 to 5.76 metric tonnes/year, while total suspended solids increased an additional 36 per cent from 272.20 to 371.17 metric tonnes/year" (Steinman, Isely, & Thompson, 2015, p. 8)

Field assessments of urban streams in western North America have found that Coho salmon are dying prematurely at high rates. "Mixtures of metals and petroleum hydrocarbons – conventional toxic constitutents in urban stormwater – are not sufficient to cause the spawner mortality syndrome. By contrast, untreated highway run-off collected during nine distinct storm events was universally lethal [100% mortality] to adult coho relative to unexposed controls" (Spromberg, et al., 2015)

- Wastewater treatment requires a significant amount of energy

Example:

"Wastewater treatment accounts for about 3% of the U.S. electrical energy load, similar to that in other developed countries. The energy needs for a typical domestic wastewater treatment plant employing aerobic activated sludge treatment and anaerobic sludge digestion is 0.6 kWh/m3 of wastewater treated, about half of which is for electrical energy to supply air for the aeration basins. With conventional approaches involving aerobic treatment a quarter to half of a plants energy needs might be satisfied by using the CH4 biogas produced during anaerobic digestion, and other plant modifications might further reduce energy needs considerably. However, if more of the energy potential in wastewater were captured for use and even less were used for wastewater treatment, then wastewater treatment might become a net energy producer rather than a consumer" (McCarty, Bae, & Kim, 2011 p. 7100).

- Wastewater contains important resources, such as nitrogen and other nutrients, that are not properly captured by conventional wastewater infrastructure, which typically takes the form of aerobic wastewater treatment combined with anaerobic sludge digestion.

Example:

Wastewater contains high levels of nitrogen (N) and phosphorous (P),that is not fully utilized. "Concerning energy associated with N and P, ~7% of the world's natural gas production was used in 1990 to fix atmospheric nitrogen through the Haber-Bosch Process to satisfy the demand for N. Somewhat less is associated with P production. From a broad environmental perspective world fossil fuel consumption could be reduced through the direct use of wastewater N and P for fertilizer instead of using manufactured fertilizers" (McCarty, Bae, & Kim, 2011, p. 7100).

- Irrigation
    - Irrigation withdrawals reduce the overall level of water, whether sourced from groundwater or surface water.

Example:

"On average, 44% of total water abstraction in Europe is used for agriculture. Southern European countries use the largest percentages of abstracted water for agriculture. This generally accounts for more than two-thirds of total abstraction. In northern Member States, levels of water use in agriculture are much lower, with irrigation being less important but still accounting for more than 30% in some areas" (European Commission, 2017).

- Regular irrigation increases the incidence of water logging and raises soil salinity. Water logging occurs when the water table is high enough that the soil is nearly always saturated. Agricultural crops need air at varying depths in the soil. A related problem is soil salinity. The regular use of irrigation increases the salt in the soil. This salt most be continuously leached by continued application of water. Salts may rise to the surface in the absence of leaching, as in the case of a waterlogged field.

> ***Example:***
>
> It is estimated that 0.62 per cent of the 776,131 ha of agricultural land in South Africa is strongly saline. Within the Vaal Harts Irrigation scheme, the largest such scheme in South Africa with 35,000 ha, it is estimated that 13 to 18 per cent of the area is affected by water logging and salinization (Ojo, Ochieng, & Otieno, 2011).
>
> Nine districts in India are impacted by the problems of water logging and soil salinization. More than 50,000 ha in Haryana have a water table less than 1.5 metres deep. The salinity in these waterlogged areas is 35 to 40 deci Siemens per meter, much higher than the normal limit of 2 dS/m, and higher even than seawater at 25dS/m. In the Rohtak district, 47.2 percent of agricultural land (78 694 ha out of 166 777 ha) falls into the potentially waterlogged category with 9.9 percent already being waterlogged and saline. The issue of salinity is made worse by the use of groundwater for irrigation, as the groundwater is already highly saline (Manav, 2016).

- Irrigation causes erosion, particularly in hilly or highland areas.

> ***Example:***
>
> A study done in the Pamir region of Tajikistan found that irrigation driven erosion was not a problem for lowlands with a less than 3 degree slope (which lose an average of 2 t/ha per year). However for some agricultural plots with more than a 3 degree slope soil loss rates up to 30 t/ha per year were found (Golosov, Sosin, Belyaev, Wolfgramm, & Khodzhaev, 2015).

1.2 ADVANTAGES OF GREEN INVESTMENTS

Sustainable water management systems utilize more decentralized infrastructure in addition to natural features of the watershed such as lakes, rivers and streams. Decentralized systems can have lower cost to install, as well as being easier to maintain.

- Institutional
  - Decentralized systems can be installed where and when they are needed, which reduces the need for large upfront investments as well as making it easier to expand services as necessary.

> ***Example:***
>
> Conventional or centralized wastewater treatment systems involve advanced collection and treatment processes that collect, treat and discharge large quantities of wastewater. Constructing a centralized treatment system for small rural communities or peri-urban areas in low-income countries will result in burden of debts for the populace. “Decentralized or cluster wastewater treatment systems are designed to operate at small scale. They not only reduce the effects on the environment and public health but also increase the ultimate reuse of wastewater depending on the community type, technical options and local settings. Decentralized systems can cost 75 percent less than centralized systems” (Massoud, Tarhini, & Nasr, 2009).

- Water supply: Water productivity can be increased in three main ways, reducing water waste, reuse of lower-quality water for other purposes, and regenerating high-quality water from used water.
    - Dual and triple water supply systems reduce energy and water use by supplying water for specific purposes, rather than supplying potable water for all purposes.

Example:

"Hong Kong's dual water system, which has been in operation for over 50 years, supplies seawater for toilet flushing to 80% of its 7 million residents, cutting municipal water use in the city by 20 percent. A triple-water distribution system at Hong Kong's International Airport, consisting of freshwater, seawater, and treated graywater from sinks and aircraft washdown, cuts municipal water use by over 50 percent" (Feldman, 2017).

- Rainwater, stormwater and greywater capture and reuse reduces municipal water use. This reduces the stress on water resources as well as reducing the energy use and costs associated with delivery, as water use is more decentralized and local.

Example:

"In a case study of a model home in Melbourne (Australia) the use of rainwater tanks to supply water for laundry, dishwashing, toilets, and an outside garden reduced household municipal water use by 40 percent (muthukumaran et al, 2011). However, even in Melbourne, where rainwater-harvesting schemes are commonplace, they contribute a modest 5 GL year to the city's overall water budget, which represents 1.2 percent of the city's total water use and 1.4 percent of its municipal supply" (Feldman, 2017).

For the cities of Pachuca and Mineral de la Reforma, State of Hidalgo, Central Mexico, rainfall harvesting is capable of supplying flush toilets and washing machines with consumptions of 4.8 L/flush and 70 L/load, respectively. A maximum and a minimum consumption of eight and six flushes/day/person (flush toilets) and five and four loads/week (washing machine), are possible (Lizarraga-Mendiola, Vazquez-Rodriguez, Blanco-Pinon, Rangel-Martinez, & Gonzalez-Sandoval, 2015).

"Stormwater harvesting couples flood control and urban runoff management with urban water supply by capturing runoff and recharging it to drinking water aquifers or by reusing stormwater for nonpotable uses. This underappreciated water source is already an important part of the supply for some cities. The Los Angeles County Department of Public Works operates 27 spreading basins that recharged 149 million m^3 of surface runoff in the 2011-2012 water year" (Hering, Waite, Luthy, Drewes, & Sedlak, 2013).

- Waste water can be reused for irrigation, toilets, fire protection, laundry, ground water recharge and other urban and industrial uses.

Example:

"To avoid the need to locate reclamation facilities near users or to build dual distribution networks, some cities have turned to potable water reuse. For example, Singapore's NEWater Project [produces] around 550 ML/day of reverse osmosistreated water from the city's wastewater treatment plants. While much of the reclaimed water is used by industrial users who value the low salinity water, the reclaimed water provides around 2% of Singapore's potable water supply and will increase in the future" (Hering, Waite, Luthy, Drewes, & Sedlak, 2013).

- Using natural water features as green infrastructure reduces the impact on the functioning and health of the watershed, while also providing other ecological benefits.

Example:

Traditional horizontal flow constructed wetlands have a total nitrogen removal efficiency of 50 per cent. Hybrid systems have higher efficiencies, due to the ability to provide both nitrification and denitrification conditions. The most common hybrid systems are vertical flow – horizontal flow with efficiencies between 52 and 79 per cent (Zhi, Yuan, Ji, & He, 2015).

- Water demand:
    - Use of more water efficient appliances reduces water use and energy use

Example:

> “A modeling study of the water supply system in Florianopolis, Brazil, concluded that replacing single-flush toilets with dual-flush toilets would reduce municipal water use in the city by 14 to 28% and reduce energy use at upstream (drinking water) and downstream (wastewater) treatment plants by 4 GWh year−1 —enough energy to supply 1000 additional households” (Grant, et al., 2012).
>
> “An analysis of 96 owner-occupied single-family homes in California, Washington, and Florida concluded that the installation of high-efficiency showerheads, toilets, and clothes washers reduced household use of municipal water by 10.9, 13.3, and 14.5%, respectively. Because water is not technically required for bathroom waste disposal, the installation of composting toilets and waterless urinals can reduce municipal water use even further” (Grant, et al., 2012).

-
    - Smart water metering provides an incentive for reduced water use while also enhancing water quality and reliability. Smart water system also allow the early detection of leaks.

Example:

> “In the U.S., an average of 14% of treated water is lost to leaks. The situation is even worse in many developing countries, where losses of up to 40% are common. Modern asset management schemes are capable of achieving substantial water savings through more effective leak detection and prioritization of pipe repair and replacement. The coming shift to real-time water metering and pressure sensors will create opportunities to identify and repair water leaks in a more cost-effective manner” (Hering, Waite, Luthy, Drewes, & Sedlak, 2013).

- Wastewater management:
    - Recycling of wastewater reduces municipal water use, while also reducing the amount of wastewater that needs to be treated.

Example:

> “The Rouse Hill Development Area (RHDA) is a new residential area about 45 km northwest of Sydney. The area is located close to the Hawkesbury-Nepean River, which would have been the natural treated wastewater receiver of the RHDA. However, due to environmental concerns on the impact of the discharge of treated wastewater into the above estuary, Sydney Water (the agency which designed the sewerage and wastewater treatment system), proposed to reuse the treated water in non-potable domestic applications, such as garden irrigation, toilet flushing and car washing. As a result, a significantly smaller quantity of treated wastewater would have to be discharged into the river, with a parallel reduction in the demand for potable water. The reclaimed water is
>
> stored close to the areas of use, in three reservoirs with total capacity of 6000 m^3… The demand for potable water has been reduced by approximately 35%, since the commissioning of the reclaimed water distribution system. Approximately 2000 m^3/d of potable water are currently used to supplement the demand in reclaimed water applications, thus the reclaimed water system has been scheduled to be expanded to approximately 5200 m^3/d” (Gikas & Tchobanoglous, 2007).

-
    - Decentralized rainwater collection reduces pollution, as it prevents rain water from running long distances on streets and parking lots. Permeable pavements also increase the quality of water returned to the environment

Example:

> A study conducted in Ontario compared the effluent from 3 porous pavements against traditional asphalt roadways. “Effluent from the Kortright Porous Pavement systems contained 80% less TSS than asphalt runoff. Porous pavement effluent contained fewer heavy metal pollutants than asphalt runoff as the porous pavement systems captured 65% - 93% of Cu, Fe, Mn and Zn loadings. Simultaneously, the porous pavements appeared to introduce new dissolved materials to the stormwater. The porous pavement systems were shown to reduce concentration and loading of nitrogen and phosphorus in stormwater providing promising evidence that porous pavements may help limit the availability of nutrients in receiving surface water systems” (Drake, Bradford, & van Seters, 2014).

  - Wastewater contains energy and nutrients that can be utilized for other purposes. Separating waste water streams as early as possible makes energy recovery and treatment easier

Example:

Microorganisms are capable of converting a wide variety of biodegradable organic compounds into CO_2, water and energy. Microbial fuel cells harvest this microbially produced energy and also provide habitat to maintain their growth and metabolic activities. Power output by MFCs has increased considerably over the last decade due to several scientific and technical advances. "Applications for the microbe–electrode interactions have also been expanded to waste/wastewater treatment, bio-remediation, toxic pollutants/xenobiotics removal, recovery of commercially viable products, i.e. resource recovery, sequestration of CO_2, harvesting the energy stored in marine sediments, and desalination" (Pandey, Shinde, Deopurkar, Kale, & Patil, 2016).

- Irrigation
  - Furrow irrigation is a common practice in many areas. Switching to sprinkler irrigation has a number of benefits. Sprinkler technology can reduce erosion and runoff by reducing the rate and speed of water application. This in turn reduces nutrient loading to streams and rivers which improves the water quality. Switching to sprinklers can also reduce the total amount of water used.

Example:

A study conducted in the Upper Snake River/Rock Creek area of Idaho was conducted to compare the impacts of furrow and sprinkler irrigation on water quality and quantity. The study compares data from 1969 and 1971 (when furrow irrigation was practiced) to data from 2005 and 2006 (when sprinkler irrigation was practiced. The study found that water quality improved between 1971 and 2005. Net loss of suspended solids went from 460 kg ha to 22 kg ha from 1971 to 2005 (Bjorneberg, Westermann, Nelson, & Kendrick, 2008).

  - Drip irrigation allows for greater crop productivity while reducing total water use.

Example:

Drip irrigation has a number of beneficial environmental and economic effects. Drip irrigation reduces the need for labour-intensive activities such as weeding and ploughing, therefore reducing the cost of cultivation. The cultivation cost for drip-irrigated chillis in India is INR 78,500 compared to INR 111,200 for non-drip irrigated chillis, a saving of 29 per cent. Water use, as measured by pump horsepower output, is also greatly reduced, falling from 1,674 HP per acre to 617 HP per acre (Narayanamoorthy, Devika, & Bhattarai, 2016).

  - Sprinkler technology can improve the water use efficiency of irrigation

Example:

Flood irrigation systems are 65–75 per cent efficient. Conventional center pivot sprinklers are 80–90 perc ent efficient. Centre pivot systems with a dropped nozzle are 95-98 percent efficient (Pfeiffer & Lin, 2013).

2.0 RISKS TO PROJECT FINANCING AND O&M

Table 3. **The impact of project risks on green/ grey infrastructure**

	Grey infrastructure	Green infrastructure
Regulatory		
Environmental regulations increase costs for water use, waste water treatment	-	
Regulatory structures designed for existing centralized systems/ regulatory uncertainty	+	-
Market		
Centralized systems require substantial up front financing	-	
Technical		
Maintenance of ageing infrastructure	-	
Ability to deal with climate change	-	+
Uncertainty of performance for new technologies		-
Social Pressure		
Concerns over water pollution, health of watersheds	-	
Health concerns for reuse of water		-

2.1 GREY INFRASTRUCTURE

- Regulatory: Environmental regulations around water use and pollution present the potential for increased costs, lower revenues

> ***Example:***
>
> "The activities of water providers are financed, in whole or in part, by selling water. If less water is sold, then revenues drop. Because many of a utility's costs are fixed (e.g., the capital costs of existing infrastructure), conservation can drop revenue (income) faster than costs, leading to budgetary shortfalls that necessitate rate increases unpopular with customers, utilities, and political leaders. This link between the volume of sales and a utility's financial health is known as the "throughput incentive" and is a powerful conservation disincentive seen in several utility sectors (Erickson & Leventis, 2011)" (Kenney, 2014).

- Market: Centralized systems require substantial up front financing, difficult to get private financing

> ***Example:***
>
> "According to the World Bank's Private Participation in Infrastructure (PPI) database, the water sector received only 5 percent of total private investment in infrastructure between 1990 and 2002. It has thus been a particularly difficult sector for attracting sorely needed private capital, operational skills, and management expertise. The main reason is that the water sector is subject to a number of specific risks, which do not affect the other infrastructure sectors—or affect them to a lesser degree. These risks include high capital intensity, political pressure on tariffs, a frequently held conviction of water as a "free" good, deficient regulation, subsovereign risk and lack of subsovereigns' access to financing, poor condition and insufficient knowledge of networks and customer bases, and currency mismatch between revenues and financing sources" (Baietti & Raymond, 2005).

- Technical: Ageing infrastructure needs to be regularly repaired or replaced. Centralized systems less able to deal with uncertainty around water supply due to climate change.

> ***Example:***
>
> The American Society of Civil Engineers estimates that there are 240,000 water main breaks every year. The majority of the water supply pipes in America were laid 75 to 100 years ago, and the rate of replacement is only 0.5%. It will take an estimated 200 years to replace all pipes at that rate, taking them well beyond their useful lifetime (ASCE, 2017).
>
> “Where precipitation levels decline, sewerage systems may become more difficult to operate and maintain. This will be a particular problem for conventional sewerage with its relatively high water requirements. Further problems may also arise from the reduced capacity of water resources to absorb and dilute pollution, which will increase the performance requirements, and hence the cost and potentially the carbon footprint, of wastewater treatment. Sewers are also at risk from flooding damage. Where sewers also carry stormwater, increased flooding will result in widespread contamination, overwhelm treatment facilities and increase public health risks” (WHO & DFID, 2009).

- Social Pressure: Concerns over water pollution, declining health of lakes and rivers. Concerns over total water use, especially in water scarce regions.

> ***Example:***
>
> “Between 1985 and 2000, the Centers for Disease Control (CDC) documented 251 separate disease outbreaks and nearly half a million cases of waterborne illness from polluted drinking water in the United States. Another study by the CDC and the National Academy of Sciences concluded that most illnesses caused by eating tainted seafood have human sewage as the root cause” (American Rivers, 2016). Many of the sewage plants in the United States are outdated and unable to handle wastewater flows. Older sewage systems combine stormwater with household sewage, but even in systems where they are separated some stormwater ends up in the sewer, where it contributes to raw sewage overflows (American Rivers, 2016).

2.2 GREEN INFRASTRUCTURE

- Regulatory: Regulatory systems are developed to support large scale centralized water management infrastructure.

> ***Example:***
>
> “If use of decentralized systems were to expand, private companies could become more involved in the invention and manufacture of equipment. The current market is mixed. Large corporations are involved in water-efficiency appliances, such as washing machines. However, most of the decentralized wastewater system manufacturers are still relatively small due to great fragmentation in local regulations and systems that are permitted across the country. The larger companies look at the field and back away. Companies do not want to have to redesign a new system for each different set of local regulations, nor go through the expense of getting their systems permitted in one locale after another” (Nelson, 2008).

- Social Pressure: Health concerns related to reuse of greywater, decentralized sanitation and supply systems.

> ***Example:***
>
> “As a new non-potable water source, reclaimed water has been widely used for many purposes, including landscape replenishment, sprinkler irrigation and toilet flushing. However, although pathogenic microorganisms can be effectively removed by water treatment process, especially after chemical disinfection, such as chlorination adopted in this study, microbial regrowth of bacteria or viral pathogens such as *Escherichia coli, Salmonella* and rotavirus, due to the decreasing doses of disinfectant residuals during water reuse processes, or the enrichment of nutritional supplement such as biodegradable dissolved organic carbon (BDOC), nitrogen and phosphorus which supporting the regrowth of pathogens in reclaimed water, may bring about potential health risks, and thus may restrict the utilization of reclaimed water to a large extent” (Gao, et al., 2016).

3.0 CHALLENGES AND OPPORTUNITIES

3.1 MAIN ROADBLOCKS FOR THE ADOPTION OF SUSTAINABLE INFRASTRUCTURE

Conventional water management systems can be difficult to change once they have been implemented. The widespread adoption of a specific water management solution leads to both institutional and technological 'lock-in' effects. This is due to both the difficulty of retrofitting existing water systems, and the long expected life times of conventional water systems. Four factors contribute to these effects (Marlow, Moglia, Cook, & Beale, 2013):

- (1) economies of scale: wastewater treatment costs decrease as the size of plants increases. This may put new, smaller treatment options at a disadvantage.

> ***Example:***
>
> A survey of 176 water industry actors found that treatment costs declined as facility size increased. For facilities with flows less than 100,000 gallons per day, the treatment cost per 1000 gallons was nearly 15 times greater than that incurred by the largest facilities (Industrial WaterWorld).

- (2) learning effects that improve products or reduce their cost,
- (3) adaptive expectations (people become increasingly confident about quality and performance of the current technology. This can make it difficult to switch to new systems that have different quality expectations)

> ***Example:***
>
> "For drinking water supply, decentralized solutions (e.g., point of entry systems, roof water collection) have usually been considered viable only for small service areas. A major impediment to expansion of such decentralization to urban systems is the need to frequently monitor water quality within the household. Further development of reliable real-time monitoring systems and successful demonstration projects are needed before decentralization will have a major impact on potable water supply" (Hering, Waite, Luthy, Drewes, & Sedlak, 2013).

- (4) network economies (agents adopting the same technologies as others)

In addition to the lock in effects that encourage the continued use and expansion of conventional water management, there are also shortcomings with sustainable water systems that hinder their use and expansion: (Marlow, Moglia, Cook, & Beale, 2013).

- (1) Innovation effects: a lack of capacity to manage the risks and uncertainties associated with novel water management systems.
- (2) Practical challenges: Issues such as day to day management complexity, community resistance to change
- (3) Financial considerations: Water utilities often face financial challenges for maintaining current infrastructure, making it difficult to allocate funds to new infrastructure. Water service provider revenues are often linked to volume of water use, which provides incentives to increase water supply and demand. In some cases, building new green infrastructure is more expensive than using or expanding current infrastructure.

Example:

"A survey of water utilities in California found that financial or economic challenges were the main hindrance to increasing water recycling. 87% of respondents cited financial or economic challenges as one of the three most important hindrances to water reuse implementation. One respondent commenting on the single most important hindrance to implementation simply stated, 'These projects are big ticket items outside the range of a rate base.' Despite various sources of policy and financial support for water reuse in California, lack of sufficient funding may be the main factor preventing recycling goals from being achieved" (Bischel, Simon, Frisby, & Luthy, 2011)

"For 16 projects seeking regional federal funding as part of the San Francisco Bay Area Recycled Water Coalition, the total costs ranged from $220/Acre Feet (AF) to $3400/AF, with a $1200/AF median value, assuming a 20-year period for recycled water generated at the initial project yield. 31 Recycled water deliveries expected for these projects range from 115 AFY (0.0045 m^3 /s) initially to up to 28,000 AFY (1.1 m3 /s) in the future. A City of Palo Alto analysis indicated an annualized cost of $2700/AF (over 30 years, in March 2008 dollars) expected for expansion of distribution facilities. This compared with a projected cost of $1,600/AF by 2015 for wholesale purchase of potable water from the San Francisco Public Utilities Commission" (Bischel, Simon, Frisby, & Luthy, 2011).

- (4) Bias and advocacy: businesses, governments, and communities have built up familiarity with existing water systems, biasing them toward these systems. Decentralized systems may also be perceived to reduce water quality or service.

Example:

"Use of recycled water may face opposition from water users. While utilities and consultants have developed more appropriate modes of communicating with the public, some remain skeptical about the safety of the practice, especially as projects are proposed in their community and the likelihood of human contact increases. Nearly two-thirds of respondents (61%) to a 2010 Survey of water utilities in California cited perceptions or social attitudes as hindrances to program implementation, though these factors were less frequently considered among the most important challenges to overcome. 'Perceived human or environmental health risks due to constituents of emerging concern' was cited as a hindrance to implementation by almost half of respondents" (Bischel, Simon, Frisby, & Luthy, 2011).

3.2 POLICY INTERVENTIONS

Sustainable urban water management often benefits from policies not specifically aimed at improving green infrastructure, such as climate adaptation policies that restore watersheds, or regulations on water pollution (OECD, 2015).

Water consumption standards can be set for a variety of products.

Example:

"The Energy Policy Act (EPAct) of 1992 generated dramatic water savings after taking effect in January 1994 by establishing maximum water use for toilets, urinals, showerheads, and faucets. Manufacturers complained that there wasn't enough time to modify products to function well with less water, and customers complained about misting showerheads and toilets that needed double-flushing to do the job, but those problems were eventually solved, and today's plumbing products generally perform well. In 2007, California adopted legislation to lower the allowable flush volume for toilets and urinals to the high-efficiency toilet (HET) and high-efficiency urinal (HEU) standards that many water utilities have been promoting. These new standards reduce the flush-volume limit from the EPA mandated 1.6 gallons (6.1 l) to 1.28 gallons (4.8 l) for toilets and from 1.0 gallons (3.8 l) to 0.5 gallons (1.9 l) for urinals" (Wilson, 2008).

Subsidies for homeowners to install water management systems and efficient appliances can encourage uptake, as well as helping reduce costs. Installation of efficient appliances can also be mandated. Subsidies and incentive programs can also be used to encourage the adoption of water efficient irrigation technologies.

> ***Example:***
>
> "In the mid-1990s, New York City provided cash rebates for 1.3 million toilets, reducing water consumption in the city by 80–90 million gallons (300–340 million l) per day, or about 20%. The Metropolitan Water District of Southern California, a consortium of 26 cities and water districts that provide water to 18 million people, currently offers residential rebates on high efficiency toilets, clothes washers with a water factor of 5.0 or lower, timers and water-efficient nozzles for irrigation systems, and artificial turf. For commercial customers, 15 different products qualify for rebates" (Wilson, 2008).
>
> "Some jurisdictions encourage customers to save water by giving away replacement fixtures, or providing rebates on replacement fixtures that reduce water use. The Southern Nevada Water Authority (SNWA), which serves Las Vegas and the surrounding region, has probably gone the furthest with direct payments. SNWA's Water Smart Landscapes program pays customers to replace turf with xeriscaping. The current payment is $1.50 per ft2 ($16.15/m^2), with no cap on the area—meaning that some homeowners can earn tens of thousands of dollars through such conversions.
>
> Each square foot of lawn conversion saves 56 gallons per year (2,300 l/m^2/year). Since the program began in 1999, SNWA has spent over $110 million on more than 30,000 conversion projects, paying for the removal of nearly four square miles (1,000 ha) of irrigated turf. The water authority can afford to spend so much money on water conservation because the cost of ensuring supply to support the growth that the Las Vegas region is experiencing is even greater" (Wilson, 2008).
>
> "Between 1998 and 2005, the state of Kansas spent nearly $6 million on incentive programs, such as the Irrigation Water Conservation Fund and the Environmental Quality Incentives Program, to fund the adoption of more efficient irrigation systems. Such programs paid up to 75% of the cost of purchasing and installing new or upgraded irrigation technology, and much of the money was used for conversions to dropped nozzle systems" (Pfeiffer & Lin, 2013)

Economic instruments such as water tariffs can signal resource scarcity and reflect some of the benefits of improved water security and improved water services, while helping to cover the cost of sustainable infrastructure (OECD, 2015).

> ***Example:***
>
> "Over the past several decades, conservation has played an increasingly important role in satisfying demand, through the adoption of water-saving devices in the residential, commercial and industrial sectors. Singapore, for example, employed consumption-based tariffs and a water conservation tax to achieve an 11% reduction in average monthly water consumption between 1995 and 2004" (Hering, Waite, Luthy, Drewes, & Sedlak, 2013).

Installation and use of water meters ensures that water use is measured, and allows for pricing and feedback on actual water use.

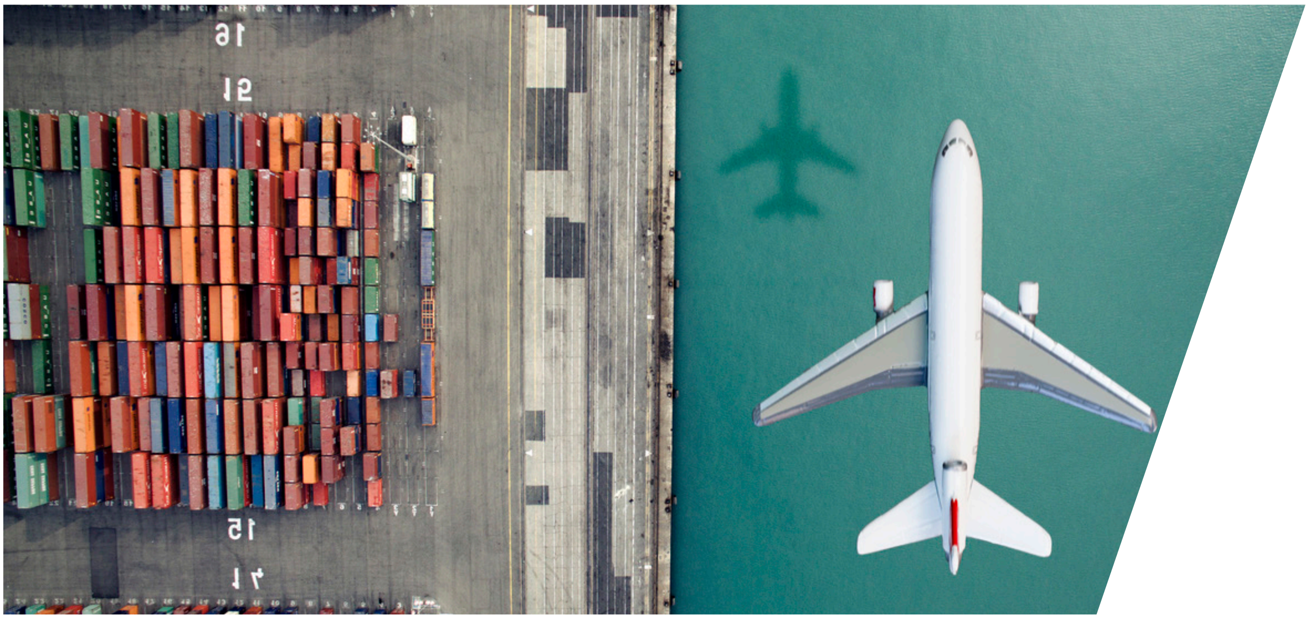
> ***Example:***
>
> "In the early 1980s, New York City was one of the few large municipalities that did not meter the water use of most residential buildings. Water fees were levied based on the street frontage of buildings, so there was no incentive to conserve. Metering began in earnest in 1985 and, although data about the effect on water use is scarce, a 15%–17% drop in consumption was observed in some parts of the city. In 2008, the city embarked on a $68-million program to install wireless transmitters on the city's 875,000 water meters, which serve 8 million residents" (Wilson, 2008).

Restrictions or water supply and sewerage standards may be placed on new buildings and developments in order to encourage the use of high efficiency technologies, water re-use technologies, or wastewater control.

> ***Example:***
>
> The US Green Building Council's LEED program for green buildings includes a water efficiency section for scoring. The section includes indicators such as outdoor water use, indoor water use, water metering, and water use reduction actions (USBGC, 2017).

Table 4. Policies to encourage deployment of renewable energy generation

Policy	Definition
Fiscal Incentives	
Subsidies and rebates	Cash transfers to help cover individuals costs for the installation of water efficient appliances and products
Water tariffs	Water pricing structure that charges more for large water users. Attempts to charge full cost to encourage conservation
Regulations	
Route design	Routes can be designed to avoid sensitive ecosystems, reducing the potential impact from construction
Infrastructure and urban planning	Ensure that the transport system is designed in a holistic manner, and allows for multiple transport modes.
Regulations	
Construction/ development Standards	Water supply and wastewater control standards for new buildings and developments
Metering	Installation of water meters to monitor use
Product standards	Water efficiency standards for new products



4.0 ACTORS INVOLVED

Governments: to set standards for drinking water, water use, and water management systems. Governments also build and maintain water management systems and construction policy.

> ***Example:***
>
> The Guidelines for Canadian Drinking Water Quality have been developed and published by the federal/provincial/territorial Committee on Drinking water since 1968. The guidelines deal with microbiological, chemical and radiological contaminants, as well as concerns with physical characteristics such as colour, taste, and odour (Health Canada, 2016).
>
> The City of Melbourne implemented permanent water use rules in December of 2012. These rules apply only to drinking water, and include restrictions on watering lawns and gardens, cleaning driveways and vehicles, and use in fountains. Further voluntary water efficiency was implemented in 2016 with the goal of limiting water consumption to 155 litres per person per day (Melbourne Water, 2017).
>
> "The Southwest Virginia Regional Wastewater Study (SVRWS) was developed in 2005 as part of an attempt to manage wastewater in Southwest Virginia. The project focused largely on extending centralized sewer lines to areas with antiquated septic systems and considered some decentralized managed wastewater systems due to remote location, topographic situations, small size, or soil conditions. In all, over 136 sites were examined under the following criteria: degree of health hazard, severity of environmental problems, number of customers served, construction cost per connection, construction feasibility, as well as residential, commercial, and industrial growth potential. The top 44 centralized projects, 12 decentralized projects, and three hybrid projects were then recommended for implementation. Of the 44 centralized projects, 40 were sewer extensions to existing wastewater treatment plants" (Kautz, 2015).

Private sector: The private sector builds and maintains some water utilities, especially decentralized systems. The private sector also develops new technologies such as microbial sewage digestion.

> ***Example:***
>
> In 1996, the EPA published a paper for congress that concluded that decentralized sewage systems can protect public health and water quality. Since then the EPA has partnered with public and private partners to improve the performance and management of decentralized systems. Members include the International Association of Plumbing and Mechanical Officials, the National Association of Homebuilders, and the National Onsite Wastewater Recycling Association (EPA, 2014).
>
> "Boston-based Cambrian Innovation began field tests of what's known as a microbial fuel cell at the Naval Surface Warfare Center in Maryland. Called BioVolt, in one day it can convert 2250 litres of sewage into enough clean water for at least 15 people. Not only that, it generates the electricity to power itself – plus a bit left over.
>
> This is a big deal, as conventional treatment plants guzzle energy – typically consuming 1.5 kilowatt-hours for every kilogram of pollutants removed. In the US, this amounts to a whopping 3 per cent of the total energy demand. If the plants could be self-powered, recycling our own waste water could become as commonplace as putting a solar panel on a roof" (Adee, 2016).

Individual Households: Households can participate in water management through personal reductions in water use, installation of water efficient appliances, and household wastewater management.

> ***Example:***
>
> The government of Australia provides guidelines for the reuse of grey and black water for homeowners. Each wastewater type must be treated differently and can be used in various ways. "Greywater is ideal for garden watering, with the appropriate precautions, such as using low or no sodium and phosphorus products and applying the water below the surface. Appropriately treated greywater can also be reused indoors for toilet flushing and clothes washing, both significant water consumers. Blackwater requires biological or chemical treatment and disinfection before reuse. For single dwellings, treated and disinfected blackwater can be used only outdoors, and often only for subsurface irrigation" (Australian Government, 2017). Reusing wastewater reduces water bills, uses less water, allows for watering the garden during water restrictions, cuts down on pollution entering waterways, and reduces societal costs for infrastructure (Australian Government, 2017).

5.0 MEASUREMENT STANDARDS AND DATA

5.1 EXISTING SUSTAINABILITY STANDARDS

Water Climate Bond Standard (http://www.climatebonds.net/standard/water)

The water Climate Bond Standard criteria are being developed by the Climate Bonds Initiative, AGWA, Ceres, CDP and the World Resources Institute. An initial phase to develop criteria for the assessment grey infrastructure has been completed. A second phase to develop criteria for the assessment of green infrastructure is underway.

Sustainable Urban Water Management Program Sweden (http://www.urbanwater.se/en)

The Sustainable Urban Water Management Program was initiated by the Swedish Foundation for Strategic Environmental Research (MISTRA) in 1999. The goal of the project was to make urban water systems both widely accessible as well as environmentally sustainable. Five areas of focus were chosen: moving towards nontoxic environment, improving health and hygiene, saving human resources, conserving natural resources, and saving financial resources (Hellstrom, Jeppsson, & Karrman, 2000).

BREEAM for Communities (http://www.breeam.com/communities)

BREEAM for Communities expands the sustainability assessment standard from individual buildings to larger developments. Although the system is not focused on water management, it is included. The overall goal is to create communities that are good for the environment, the people, and are economically vibrant.

LEED Neighbourhood Design (http://www.usgbc.org/leed)

The U.S. Green Building Council developed LEED Neighbourhood Design to provide a holistic assessment of the sustainability of a city or community. The assessment standard is not focused on water, but includes many water related indicators.

Table 5. **Water system assessment categories and indicators (Hellstrom, Jeppsson, & Karrman, 2000) (BREEAM, 2012) (USGBC, 2016)**

Sustainable Urban Water Management Sweden		**BREEAM for Communities**		**LEED Neighborhood Design**	
Criteria	**Indicator**	**Criteria**	**Indicator**	**Criteria**	**Indicator**
Health and hygiene	Acceptable drinking water quality	Social and economic well-being	Green infrastructure	Smart Location and Linkage	Wetland and waterbody conservation
	Non access to drinking water		Flood risk assessment		Floodplain avoidance
	Number of waterbourne outbreaks		Flood risk management		Site design for habitat or wetland an water body conservation
	Number of affected persons	Resources and energy	Water strategy		Restoration of habitat or wetlands and waterbodies
	Number of accidents	Land use and ecology	Land use		Long-term conservation management of habitat or wetlands and waterbodies
Social and cultural criteria	Easy to understand system		Water pollution	Green infrastructure and buildings	Indoor water use reduction
	Work demand		Rainwater harvesting		Outdoor water use reduction
	Social acceptance				Rainwater management
	Availability				Wastewater management
Environmental criteria	Groundwater level				
	Eutrophication				
	Contribution to acidification				
	Contribution to global warming				
	Spreading of toxic compounds to water				
	Spreading of toxic compounds to arable land				
	Use of natural resources				
Economic criteria	Total cost				
	Capital cost				
	Operation and maintenance				
Functional and technical criteria	Robustness (overflow, sewer stoppage, basement flooding)				
	Performance				
	Flexibility				

5.2 DATA

In the case of water management, the data is required for the following technologies, as well as for existing business as usual technology.

- Supply: includes the use of water along with the external impacts associated with supply, such as the materials and energy used in infrastructure. Infrastructure costs are also included.
    - ‘Green’ infrastructure techniques such as restoration of wetlands, riparian buffers, reforestation etc.
    - Dual supply
    - Water recycling (Rainwater and greywater harvesting)
- Demand: includes data on measures to reduce water demand, such as costs and water efficiency.
    - Water efficient appliances/ fixtures
    - Smart water systems
- Wastewater management: includes data on managing wastewater, such as pollutant loadings to the watershed, and cost data.
    - ‘Green’ infrastructure techniques such as restoration of wetlands, riparian buffers, reforestation etc
    - Greywater recycling/ separation
    - Localized sanitation
    - Storm water control (Green roofs, Permeable pavements)

Table 6. Overview of required inputs and outputs generated by water management

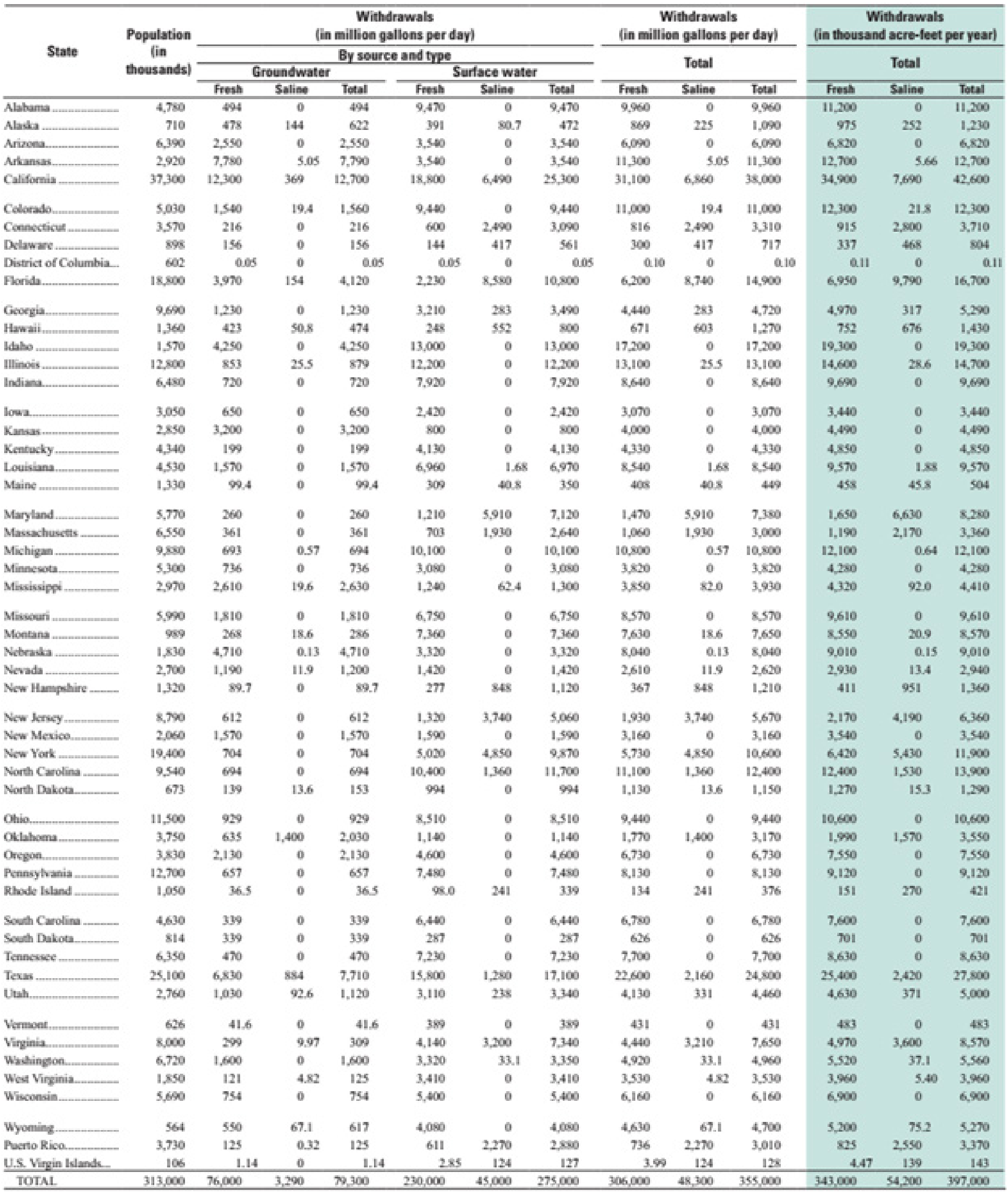
Inputs	Outputs
• Construction o Capital o Labour o Raw materials (e.g., aluminium, steel) o Water o Energy • Operation o Labour o Electricity use o Water use o Heating	• Revenues (rent, taxes) • Water quality o Human health (mortality and morbidity) o Ecological health • Water scarcity • Thermal pollution • Visual impact • Competition for land use

5.2.1 General Data

- **Water infrastructure spending** in the US, 2014: The US spent $137 billion on water infrastructure in 2014. $109 billion of that was spent on water utilities, including water supply infrastructure (pipes, sewers) and wastewater treatment plants. The remainder was spent on water resources, including dams, levees and sources of freshwater. Thirty three percent of the spending on water utilities was capital investment, with the remaining 67 percent spent on operation and maintenance. The breakdown for water resource spending is 36 percent for capital expenditure and 64 percent for operation and maintenance (Congressional Budget Office, 2015).

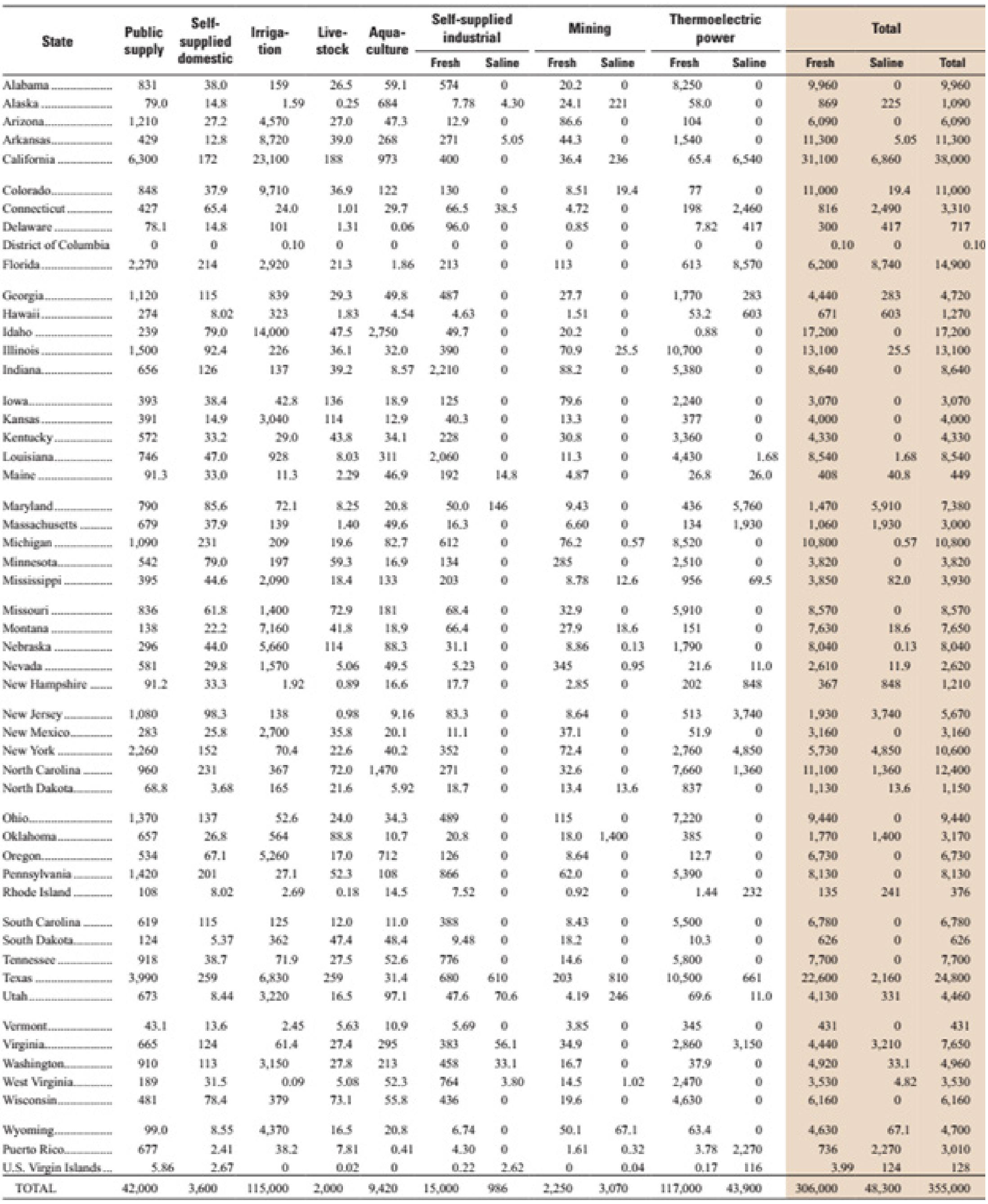
- **Desalination costs** in California: brackish groundwater costs range between $110 and $1000 per 1000 m^3 of water. Ocean desalination costs $650 to $1200 per 1000m3 (Horvath & Stokes, 2011).

Table 7. **Water withdrawals by source and state (USGS, 2014)**



State	Population (in thousands)	Withdrawals (in million gallons per day)						Withdrawals (in million gallons per day)			Withdrawals (in thousand acre-feet per year)		
		By source and type						Total			Total		
		Groundwater			Surface water								
		Fresh	Saline	Total	Fresh	Saline	Total	Fresh	Saline	Total	Fresh	Saline	Total
Alabama	4,780	494	0	494	9,470	0	9,470	9,960	0	9,960	11,200	0	11,200
Alaska	710	478	144	622	391	80.7	472	869	225	1,090	975	252	1,230
Arizona	6,390	2,550	0	2,550	3,540	0	3,540	6,090	0	6,090	6,820	0	6,820
Arkansas	2,920	7,780	5.05	7,790	3,540	0	3,540	11,300	5.05	11,300	12,700	5.66	12,700
California	37,300	12,300	369	12,700	18,800	6,490	25,300	31,100	6,860	38,000	34,900	7,690	42,600
Colorado	5,030	1,540	19.4	1,560	9,440	0	9,440	11,000	19.4	11,000	12,300	21.8	12,300
Connecticut	3,570	216	0	216	600	2,490	3,090	816	2,490	3,310	915	2,800	3,710
Delaware	898	156	0	156	144	417	561	300	417	717	337	468	804
District of Columbia	602	0.05	0	0.05	0.05	0	0.05	0.10	0	0.10	0.11	0	0.11
Florida	18,800	3,970	154	4,120	2,230	8,580	10,800	6,200	8,740	14,900	6,950	9,790	16,700
Georgia	9,690	1,230	0	1,230	3,210	283	3,490	4,440	283	4,720	4,970	317	5,290
Hawaii	1,360	423	50.8	474	248	552	800	671	603	1,270	752	676	1,430
Idaho	1,570	4,250	0	4,250	13,000	0	13,000	17,200	0	17,200	19,300	0	19,300
Illinois	12,800	853	25.5	879	12,200	0	12,200	13,100	25.5	13,100	14,600	28.6	14,700
Indiana	6,480	720	0	720	7,920	0	7,920	8,640	0	8,640	9,690	0	9,690
Iowa	3,050	650	0	650	2,420	0	2,420	3,070	0	3,070	3,440	0	3,440
Kansas	2,850	3,200	0	3,200	800	0	800	4,000	0	4,000	4,490	0	4,490
Kentucky	4,340	199	0	199	4,130	0	4,130	4,330	0	4,330	4,850	0	4,850
Louisiana	4,530	1,570	0	1,570	6,960	1.68	6,970	8,540	1.68	8,540	9,570	1.88	9,570
Maine	1,330	99.4	0	99.4	309	40.8	350	408	40.8	449	458	45.8	504
Maryland	5,770	260	0	260	1,210	5,910	7,120	1,470	5,910	7,380	1,650	6,630	8,280
Massachusetts	6,550	361	0	361	703	1,930	2,640	1,060	1,930	3,000	1,190	2,170	3,360
Michigan	9,880	693	0.57	694	10,100	0	10,100	10,800	0.57	10,800	12,100	0.64	12,100
Minnesota	5,300	736	0	736	3,080	0	3,080	3,820	0	3,820	4,280	0	4,280
Mississippi	2,970	2,610	19.6	2,630	1,240	62.4	1,300	3,850	82.0	3,930	4,320	92.0	4,410
Missouri	5,990	1,810	0	1,810	6,750	0	6,750	8,570	0	8,570	9,610	0	9,610
Montana	989	268	18.6	286	7,360	0	7,360	7,630	18.6	7,650	8,550	20.9	8,570
Nebraska	1,830	4,710	0.13	4,710	3,320	0	3,320	8,040	0.13	8,040	9,010	0.15	9,010
Nevada	2,700	1,190	11.9	1,200	1,420	0	1,420	2,610	11.9	2,620	2,930	13.4	2,940
New Hampshire	1,320	89.7	0	89.7	277	848	1,120	367	848	1,210	411	951	1,360
New Jersey	8,790	612	0	612	1,320	3,740	5,060	1,930	3,740	5,670	2,170	4,190	6,360
New Mexico	2,060	1,570	0	1,570	1,590	0	1,590	3,160	0	3,160	3,540	0	3,540
New York	19,400	704	0	704	5,020	4,850	9,870	5,730	4,850	10,600	6,420	5,430	11,900
North Carolina	9,540	694	0	694	10,400	1,360	11,700	11,100	1,360	12,400	12,400	1,530	13,900
North Dakota	673	139	13.6	153	994	0	994	1,130	13.6	1,150	1,270	15.3	1,290
Ohio	11,500	929	0	929	8,510	0	8,510	9,440	0	9,440	10,600	0	10,600
Oklahoma	3,750	635	1,400	2,030	1,140	0	1,140	1,770	1,400	3,170	1,990	1,570	3,550
Oregon	3,830	2,130	0	2,130	4,600	0	4,600	6,730	0	6,730	7,550	0	7,550
Pennsylvania	12,700	657	0	657	7,480	0	7,480	8,130	0	8,130	9,120	0	9,120
Rhode Island	1,050	36.5	0	36.5	98.0	241	339	134	241	376	151	270	421
South Carolina	4,630	339	0	339	6,440	0	6,440	6,780	0	6,780	7,600	0	7,600
South Dakota	814	339	0	339	287	0	287	626	0	626	701	0	701
Tennessee	6,350	470	0	470	7,230	0	7,230	7,700	0	7,700	8,630	0	8,630
Texas	25,100	6,830	884	7,710	15,800	1,280	17,100	22,600	2,160	24,800	25,400	2,420	27,800
Utah	2,760	1,030	92.6	1,120	3,110	238	3,340	4,130	331	4,460	4,630	371	5,000
Vermont	626	41.6	0	41.6	389	0	389	431	0	431	483	0	483
Virginia	8,000	299	9.97	309	4,140	3,200	7,340	4,440	3,210	7,650	4,970	3,600	8,570
Washington	6,720	1,600	0	1,600	3,320	33.1	3,350	4,920	33.1	4,960	5,520	37.1	5,560
West Virginia	1,850	121	4.82	125	3,410	0	3,410	3,530	4.82	3,530	3,960	5.40	3,960
Wisconsin	5,690	754	0	754	5,400	0	5,400	6,160	0	6,160	6,900	0	6,900
Wyoming	564	550	67.1	617	4,080	0	4,080	4,630	67.1	4,700	5,200	75.2	5,270
Puerto Rico	3,730	125	0.32	125	611	2,270	2,880	736	2,270	3,010	825	2,550	3,370
U.S. Virgin Islands	106	1.14	0	1.14	2.85	124	127	3.99	124	128	4.47	139	143
TOTAL	313,000	76,000	3,290	79,300	230,000	45,000	275,000	306,000	48,300	355,000	343,000	54,200	397,000

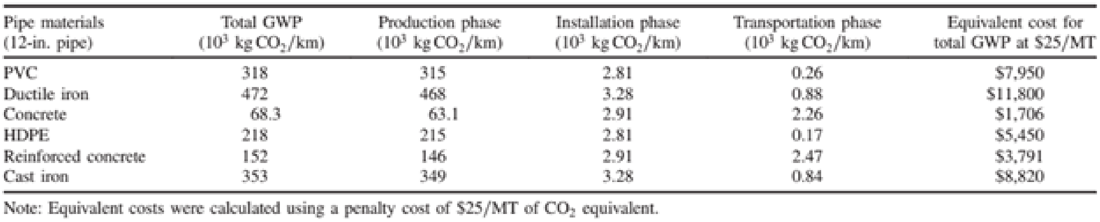
Table 8. **Total water withdrawals by water-use category, millions of gallons per day (USGS, 2014)**



State	Public supply	Self-supplied domestic	Irrigation	Livestock	Aquaculture	Self-supplied industrial		Mining		Thermoelectric power		Total		
						Fresh	Saline	Fresh	Saline	Fresh	Saline	Fresh	Saline	Total
Alabama	831	38.0	159	26.5	59.1	574	0	20.2	0	8,250	0	9,960	0	9,960
Alaska	79.0	14.8	1.59	0.25	684	7.78	4.30	24.1	221	58.0	0	869	225	1,090
Arizona	1,210	27.2	4,570	27.0	47.3	12.9	0	86.6	0	104	0	6,090	0	6,090
Arkansas	429	12.8	8,720	39.0	268	271	5.05	44.3	0	1,540	0	11,300	5.05	11,300
California	6,300	172	23,100	188	973	400	0	36.4	236	65.4	6,540	31,100	6,860	38,000
Colorado	848	37.9	9,710	36.9	122	130	0	8.51	19.4	77	0	11,000	19.4	11,000
Connecticut	427	65.4	24.0	1.01	29.7	66.5	38.5	4.72	0	198	2,460	816	2,490	3,310
Delaware	78.1	14.8	101	1.31	0.06	96.0	0	0.85	0	7.82	417	300	417	717
District of Columbia	0	0	0.10	0	0	0	0	0	0	0	0	0.10	0	0.10
Florida	2,270	214	2,920	21.3	1.86	213	0	113	0	613	8,570	6,200	8,740	14,900
Georgia	1,120	115	839	29.3	49.8	487	0	27.7	0	1,770	283	4,440	283	4,720
Hawaii	274	8.02	323	1.83	4.54	4.63	0	1.51	0	53.2	603	671	603	1,270
Idaho	239	79.0	14,000	47.5	2,750	49.7	0	20.2	0	0.88	0	17,200	0	17,200
Illinois	1,500	92.4	226	36.1	32.0	390	0	70.9	25.5	10,700	0	13,100	25.5	13,100
Indiana	656	126	137	39.2	8.57	2,210	0	88.2	0	5,380	0	8,640	0	8,640
Iowa	393	38.4	42.8	136	18.9	125	0	79.6	0	2,240	0	3,070	0	3,070
Kansas	391	14.9	3,040	114	12.9	40.3	0	13.3	0	377	0	4,000	0	4,000
Kentucky	572	33.2	29.0	43.8	34.1	228	0	30.8	0	3,360	0	4,330	0	4,330
Louisiana	746	47.0	928	8.03	311	2,060	0	11.3	0	4,430	1.68	8,540	1.68	8,540
Maine	91.3	33.0	11.3	2.29	46.9	192	14.8	4.87	0	26.8	26.0	408	40.8	449
Maryland	790	85.6	72.1	8.25	20.8	50.0	146	9.43	0	436	5,760	1,470	5,910	7,380
Massachusetts	679	37.9	139	1.40	49.6	16.3	0	6.60	0	134	1,930	1,060	1,930	3,000
Michigan	1,090	231	209	19.6	82.7	612	0	76.2	0.57	8,520	0	10,800	0.57	10,800
Minnesota	542	79.0	197	59.3	16.9	134	0	285	0	2,510	0	3,820	0	3,820
Mississippi	395	44.6	2,090	18.4	133	203	0	8.78	12.6	956	69.5	3,850	82.0	3,930
Missouri	836	61.8	1,400	72.9	181	68.4	0	32.9	0	5,910	0	8,570	0	8,570
Montana	138	22.2	7,160	41.8	18.9	66.4	0	27.9	18.6	151	0	7,630	18.6	7,650
Nebraska	296	44.0	5,660	114	88.3	31.1	0	8.86	0.13	1,790	0	8,040	0.13	8,040
Nevada	581	29.8	1,570	5.06	49.5	5.23	0	345	0.95	21.6	11.0	2,610	11.9	2,620
New Hampshire	91.2	33.3	1.92	0.89	16.6	17.7	0	2.85	0	202	848	367	848	1,210
New Jersey	1,080	98.3	138	0.98	9.16	83.3	0	8.64	0	513	3,740	1,930	3,740	5,670
New Mexico	283	25.8	2,700	35.8	20.1	11.1	0	37.1	0	51.9	0	3,160	0	3,160
New York	2,260	152	70.4	22.6	40.2	352	0	72.4	0	2,760	4,850	5,730	4,850	10,600
North Carolina	960	231	367	72.0	1,470	271	0	32.6	0	7,660	1,360	11,100	1,360	12,400
North Dakota	68.8	3.68	165	21.6	5.92	18.7	0	13.4	13.6	837	0	1,130	13.6	1,150
Ohio	1,370	137	52.6	24.0	34.3	489	0	115	0	7,220	0	9,440	0	9,440
Oklahoma	657	26.8	564	88.8	10.7	20.8	0	18.0	1,400	385	0	1,770	1,400	3,170
Oregon	534	67.1	5,260	17.0	712	126	0	8.64	0	12.7	0	6,730	0	6,730
Pennsylvania	1,420	201	27.1	52.3	108	866	0	62.0	0	5,390	0	8,130	0	8,130
Rhode Island	108	8.02	2.69	0.18	14.5	7.52	0	0.92	0	1.44	232	135	241	376
South Carolina	619	115	125	12.0	11.0	388	0	8.43	0	5,500	0	6,780	0	6,780
South Dakota	124	5.37	362	47.4	48.4	9.48	0	18.2	0	10.3	0	626	0	626
Tennessee	918	38.7	71.9	27.5	52.6	776	0	14.6	0	5,800	0	7,700	0	7,700
Texas	3,990	259	6,830	259	31.4	680	610	203	810	10,500	661	22,600	2,160	24,800
Utah	673	8.44	3,220	16.5	97.1	47.6	70.6	4.19	246	69.6	11.0	4,130	331	4,460
Vermont	43.1	13.6	2.45	5.63	10.9	5.69	0	3.85	0	345	0	431	0	431
Virginia	665	124	61.4	27.4	295	383	56.1	34.9	0	2,860	3,150	4,440	3,210	7,650
Washington	910	113	3,150	27.8	213	458	33.1	16.7	0	37.9	0	4,920	33.1	4,960
West Virginia	189	31.5	0.09	5.08	52.3	764	3.80	14.5	1.02	2,470	0	3,530	4.82	3,530
Wisconsin	481	78.4	379	73.1	55.8	436	0	19.6	0	4,630	0	6,160	0	6,160
Wyoming	99.0	8.55	4,370	16.5	20.8	6.74	0	50.1	67.1	63.4	0	4,630	67.1	4,700
Puerto Rico	677	2.41	38.2	7.81	0.41	4.30	0	1.61	0.32	3.78	2,270	736	2,270	3,010
U.S. Virgin Islands	5.86	2.67	0	0.02	0	0.22	2.62	0	0.04	0.17	116	3.99	124	128
TOTAL	42,000	3,600	115,000	2,000	9,420	15,000	986	2,250	3,070	117,000	43,900	306,000	48,300	355,000

- **Construction of water systems** uses energy and produces GHGs. The Global warming potential of different pipes is below.

Table 9. **Performance grade and costs of roads for different asphalt binders (European Commission, 2012)**



Pipe materials (12-in. pipe)	Total GWP (10^3 kg CO_2/km)	Production phase (10^3 kg CO_2/km)	Installation phase (10^3 kg CO_2/km)	Transportation phase (10^3 kg CO_2/km)	Equivalent cost for total GWP at $25/MT
PVC	318	315	2.81	0.26	$7,950
Ductile iron	472	468	3.28	0.88	$11,800
Concrete	68.3	63.1	2.91	2.26	$1,706
HDPE	218	215	2.81	0.17	$5,450
Reinforced concrete	152	146	2.91	2.47	$3,791
Cast iron	353	349	3.28	0.84	$8,820

Note: Equivalent costs were calculated using a penalty cost of $25/MT of CO_2 equivalent.

5.2.2 Supply Data

Rainwater harvesting

- **Harvesting rainwater** reduces municipal water use as well as reducing the amount of storm water runoff. Recycling greywater further amplifies this effect. A study of Woden township (32,611 people in 13,890 houses), Australia found significant reductions in municipal water use, wastewater and stormwater runoff (Sharma, Gray, Diaper, Liston, & Howe, 2008).

Table 10. **Monthly volume of harvestable rainwater (in m3) as a function of household roof area in central Mexico (Lizarraga-Mendiola, Vazquez-Rodriguez, Blanco-Pinon, Rangel-Martinez, & Gonzalez-Sandoval, 2015)**

	45 m^2	50 m^2	100 m^2	200 m^2
January	1.010	1.122	2.244	4.489
February	2.349	2.610	5.219	10.439
March	1.908	2.120	4.239	8.479
April	2.150	2.389	4.778	9.557
May	4.050	4.500	8.999	17.999
June	4.009	4.454	8.908	17.817
July	7.540	8.378	16.755	33.511
August	4.626	5.140	10.280	20.561
September	6.664	7.405	14.809	29.619
October	5.401	6.001	12.002	24.005
November	2.238	2.487	4.974	9.949
December	0.720	0.800	1.600	3.201

Table 11. **Effect of water saving measures in Woden township, Australia (Sharma, Gray, Diaper, Liston, & Howe, 2008)**

	Base case/ no rain tanks or greywater recycling	Rain tanks in use		Greywater for garden irrigation		Rain tanks and greywater in use	
	ML/yr	ML/yr	% reduction	ML/yr	% reduction	ML/yr	% reduction
Water	4765	3649	24	4166	13	3160	34
Wastewater	2836	2836	0	2256	20	2258	20
Stormwater	4875	3758	23	4858	0	3850	21

Water recycling

- The **reuse of graywater** for toilet flushing and yard irrigation can cut household municipal water use by 50% or more (Grant, et al., 2012).
- The **reuse of potable water** consumes less than one-half the energy [~1000 to 1500 kilowatt-hours per megaliter (kWh Ml−1)] beyond conventional treatment) required for the desalination of seawater (~3400 to 4000 kWh Ml−1)
- Energy and emissions by water source (Table 12).

Table 12. Water source comparison California (Energy: GJ/100Acre Foot, others: Mg/100Acre Foot) (Horvath & Stokes, 2011)

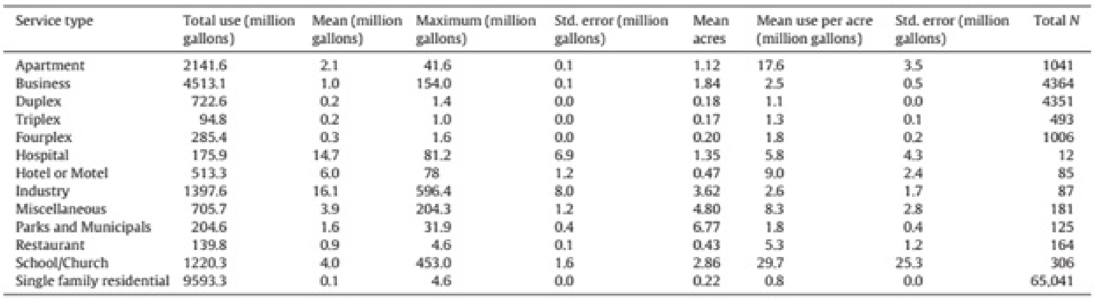
	Imported	Desalinated	Recycled	Local reservoirs
Energy	1900	4600	1300	2200
GHG	140	350	120	150
NOx	0.37	0.73	0.17	0.46
PM	0.067	0.11	0.026	0.11
Sox	0.36	0.71	0.090	0.54
VOC	0.084	0.26	0.027	0.15
CO	0.52	0.74	0.10	0.69

5.2.3 Demand Data

Water demand by building type

- A study of water demand in Salt Lake City found the average water demand by acre of different building types.

Table 13. Annual water use by building type, Salt Lake City (Stoker & Rothfeder, 2014)



Service type	Total use (million gallons)	Mean (million gallons)	Maximum (million gallons)	Std. error (million gallons)	Mean acres	Mean use per acre (million gallons)	Std. error (million gallons)	Total *N*
Apartment	2141.6	2.1	41.6	0.1	1.12	17.6	3.5	1041
Business	4513.1	1.0	154.0	0.1	1.84	2.5	0.5	4364
Duplex	722.6	0.2	1.4	0.0	0.18	1.1	0.0	4351
Triplex	94.8	0.2	1.0	0.0	0.17	1.3	0.1	493
Fourplex	285.4	0.3	1.6	0.0	0.20	1.8	0.2	1006
Hospital	175.9	14.7	81.2	6.9	1.35	5.8	4.3	12
Hotel or Motel	513.3	6.0	78	1.2	0.47	9.0	2.4	85
Industry	1397.6	16.1	596.4	8.0	3.62	2.6	1.7	87
Miscellaneous	705.7	3.9	204.3	1.2	4.80	8.3	2.8	181
Parks and Municipals	204.6	1.6	31.9	0.4	6.77	1.8	0.4	125
Restaurant	139.8	0.9	4.6	0.1	0.43	5.3	1.2	164
School/Church	1220.3	4.0	453.0	1.6	2.86	29.7	25.3	306
Single family residential	9593.3	0.1	4.6	0.0	0.22	0.8	0.0	65,041

Water efficient appliances

- Water efficient appliances and fixtures can reduce the amount of water used per person. Water use in three neighborhoods in Canberra is compared in Table 14. The low rate of demand management assumed 57 per cent of households with dual flush toilets, 32 per cent low flow shower heads, 15 per cent front loading washing machines, 47 per cent dishwashers, 10 per cent reduced lawn area and 10 per cent irrigation system. For the Woden high demand management area uptake is increased to 82 per cent dual flush toilets, 77 per cent low flow showerheads, 65 per cent water efficient washing machines, and 90 per cent water efficient dishwashers. The Gungaderra area increased uptake of all appliances to 100 per cent (Sharma, Gray, Diaper, Liston, & Howe, 2008).

Table 14. **Typical water use per person, Canberra (Sharma, Gray, Diaper, Liston, & Howe, 2008)**

Water demand	Low rate of demand management (L/p/day)	High rate of demand management – Woden (L/p/day)	High rate of demand management – Gungaderra
Kitchen	23	22	23
Bathroom	77	54	47
Laundry	50	43	38
Toilet	70	53	49

Smart water systems

- **Non-revenue water** (NRW) (due to leaks or mismanagement) "levels of 47 water utilities across Indonesia, Malaysia, Thailand, the Philippines, and Vietnam, average 30 percent of the water produced, with wide variations among individual utilities ranging from 4 percent to 65 percent … It is likely that the 35 percent figure is less than the global NRW level in the developing world because large developing countries with known high levels of NRW are still not covered by IBNET and the utilities that report operating data tend to be the ones with the better performance levels, while the worst-performing utilities rarely report data or, if they do, the information is not reliable. The actual figure for overall NRW levels in the developing world is probably more in the range of 40–50 percent of the water produced" (Kingdom, Liemberger, & Marin, 2006, pp. 1–2).

Table 15. **Non-revenue water losses by region (Kingdom, Liemberger, & Marin, 2006)**

	Supplied population (millions, 2002)	System input (l/capita/day)	Level of NRW (% of system input)	Ratio		Volume (billions of m^3/year)		
				Physical losses (%)	Commercial losses (%)	Physical losses	Commercial losses	Total NRW
Developed countries	744.8	300	15	80	20	9.8	2.4	12.2
Eurasia	178.0	500	30	70	30	6.8	2.9	9.7
Developing countries	837.5	250	35	60	40	16.1	10.6	26.7
					Total	**32.7**	**15.9**	**48.6**

Table 16. **Estimated value of NRW (Kingdom, Liemberger, & Marin, 2006)**

	Marginal cost of water (USD/m^3)	Average tariff (USD/m^3)	Estimated value (billions USD/year)		
			Cost of Physical losses	Lost revenue resulting from Commercial losses	Total cost of NRW
Developed countries	0.3	1.00	2.90	2.40	5.30
Eurasia	0.30	0.50	2.00	1.50	3.50
Developing countries	0.20	0.25	3.20	2.60	5.80
		Total	**8.10**	**6.50**	**14.60**

5.2.4 Wastewater Data

Wastewater Generation

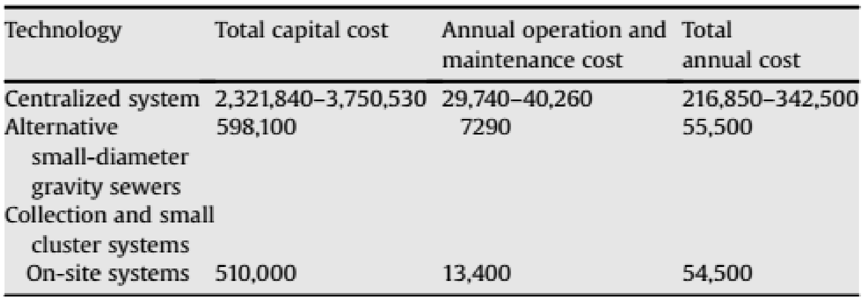
Table 17. Wastewater generation in average Australian home with Water Efficiency Labelling and Standards scheme 3 star rated fixtures (Australian Government, 2017)

Wastewater type	Wastewater source	Litres/person/day
Blackwater	Toilet	20
Greywater	Shower	63
	Handbasin	6
	Washing machine	13
	Laundry	2
Other	Kitchen tap	12
	Dishwasher	5
Total greywater		**84**
Total wastewater		**121**

Centralized vs decentralized wastewater management costs

- Wastewater treatment technology costs in a rural US town

Table 18. Summary of EPA technology costs (Massoud, Tarhini, & Nasr, 2009)



Technology	Total capital cost	Annual operation and maintenance cost	Total annual cost
Centralized system	2,321,840–3,750,530	29,740–40,260	216,850–342,500
Alternative small-diameter gravity sewers	598,100	7290	55,500
Collection and small cluster systems			
On-site systems	510,000	13,400	54,500

Energy and resource use, Centralized vs decentralized

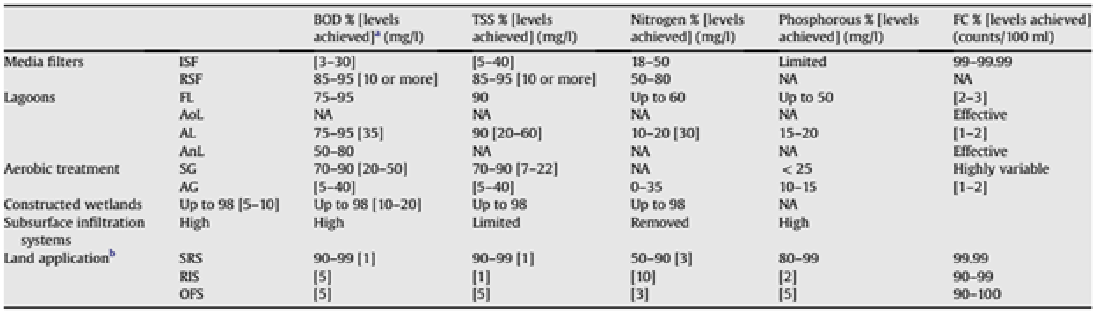
- The Southwest Virginia Regional Wastewater Study estimated the costs, energy, and carbon use for centralized and decentralized sewer connection. Costs for each project are based on material and construction costs. The materials were used to determine the embodied energy and carbon for each project. The decentralized option in this case is a three-bedroom septic system designed using the State of Virginia's regulations (Kautz, 2015).

Table 19. Average per connection resource consumption, centralized and decentralized sewerage (Kautz, 2015)

	Centralized per connection	Decentralized per connection	Difference	Percent difference
Embodied energy (MJ)	157 563	40 025	117 538	75
Embodied carbon (kg CO_2)	7 006	1 908	5 099	73
Cost (USD)	18 590	5 954	12 636	68

Removal rates of decentralized wastewater treatment technologies

Table 20. Pollutant removal rates of decentralized wastewater technologies (Massoud, Tarhini, & Nasr, 2009)



		BOD % [levels achieved][a] (mg/l)	TSS % [levels achieved] (mg/l)	Nitrogen % [levels achieved] (mg/l)	Phosphorous % [levels achieved] (mg/l)	FC % [levels achieved] (counts/100 ml)
Media filters	ISF	[3–30]	[5–40]	18–50	Limited	99–99.99
	RSF	85–95 [10 or more]	85–95 [10 or more]	50–80	NA	NA
Lagoons	FL	75–95	90	Up to 60	Up to 50	[2–3]
	AoL	NA	NA	NA	NA	Effective
	AL	75–95 [35]	90 [20–60]	10–20 [30]	15–20	[1–2]
	AnL	50–80	NA	NA	NA	Effective
Aerobic treatment	SG	70–90 [20–50]	70–90 [7–22]	NA	< 25	Highly variable
	AG	[5–40]	[5–40]	0–35	10–15	[1–2]
Constructed wetlands	Up to 98 [5–10]	Up to 98 [10–20]	Up to 98	Up to 98	NA	
Subsurface infiltration systems	High	High	Limited	Removed	High	
Land application[b]	SRS	90–99 [1]	90–99 [1]	50–90 [3]	80–99	99.99
	RIS	[5]	[1]	[10]	[2]	90–99
	OFS	[5]	[5]	[3]	[5]	90–100

‘Green’ infrastructure (bio retention ponds, swales, buffers etc)

- A study of stormwater retention and treatment options in Canberra Australia found significant reduction of total suspended solids (TSS), total nitrogen (TN), and total phosphorous (TP) with the use of ponds, gross pollutant traps (GPT) and bioretention.

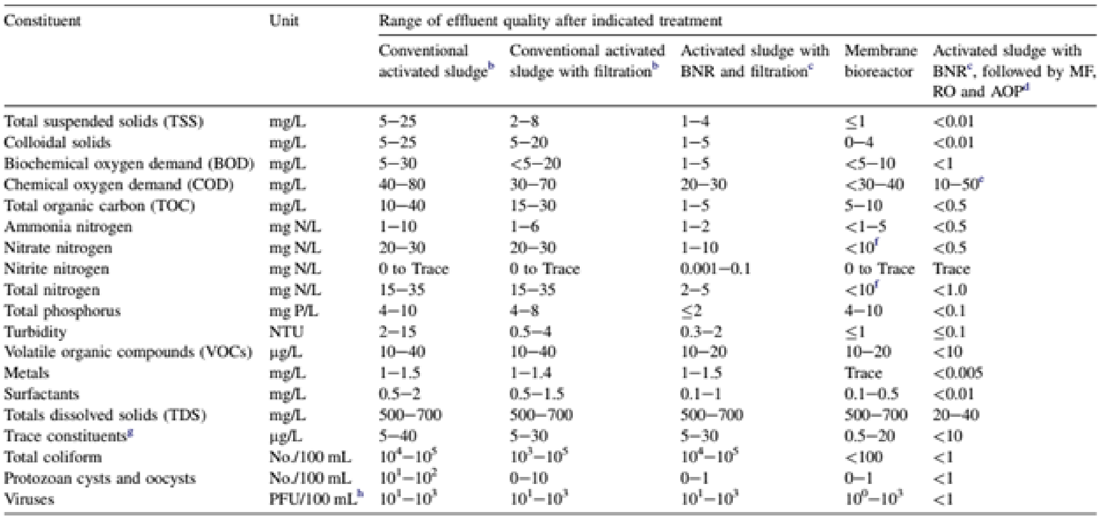
Table 21, Reduction of stormwater contaminant loads and concentration, Woden area Australia (Sharma, Gray, Diaper, Liston, & Howe, 2008)

	Mean flow (m3/s)	TSS (kg/day)	TN (kg/day)	TP (kg/day)	TSS (mg/L)	TN (mg/L)	TP (mg/L)
Total area as greenfield	0.086	962	18.7	2.34	24.6	2.13	0.168
Developed area with no Treatment measures	0.186	2390	41.6	5.48	42.2	2.2	0.193
	Flow reduction (%)	**TSS reduction (%)**	**TN reduction (%)**	**TP reduction (%)**	**TSS reduction (%)**	**TN reduction (%)**	**TP reduction (%)**
GPT and ponds (4ha, 3ha, and 3ha)	0	68	26	38	59	26	25
GPT, ponds (4ha, 3ha, and 3ha), and bioretention systems	0	71	32	42	61	33	26
Buffers	0	37	18	25	28	16	24
Buffers and swales	0	41	18	27	26	21	20
Buffers and bioretention systems	0	45	29	34	57	70	67

Wastewater treatment

- **Conventional wastewater treatment** “employing aerobic activated sludge treatment and anaerobic sludge digestion uses 0.6 kWh/m^3 of wastewater treated. Conventional approaches supply about a quarter to half of this energy using the methane produced during anaerobic digestion” (McCarty, Bae, & Kim, 2011).
- **Comparison of wastewater treatment technologies**, including conventional sludge, biological nutrient removal (BNR), microfiltration (MF), reverse osmosis (RO) and advance oxidation process (AOP) (Gikas & Tchobanoglous, 2007).

Table 22. Range of effluent quality of removal of residual particulate matter (Gikas & Tchobanoglous, 2007)



Constituent	Unit	Range of effluent quality after indicated treatment				
		Conventional activated sludge[b]	Conventional activated sludge with filtration[b]	Activated sludge with BNR and filtration[c]	Membrane bioreactor	Activated sludge with BNR[c], followed by MF, RO and AOP[d]
Total suspended solids (TSS)	mg/L	5–25	2–8	1–4	≤1	<0.01
Colloidal solids	mg/L	5–25	5–20	1–5	0–4	<0.01
Biochemical oxygen demand (BOD)	mg/L	5–30	<5–20	1–5	<5–10	<1
Chemical oxygen demand (COD)	mg/L	40–80	30–70	20–30	<30–40	10–50[e]
Total organic carbon (TOC)	mg/L	10–40	15–30	1–5	5–10	<0.5
Ammonia nitrogen	mg N/L	1–10	1–6	1–2	<1–5	<0.5
Nitrate nitrogen	mg N/L	20–30	20–30	1–10	<10[f]	<0.5
Nitrite nitrogen	mg N/L	0 to Trace	0 to Trace	0.001–0.1	0 to Trace	Trace
Total nitrogen	mg N/L	15–35	15–35	2–5	<10[f]	<1.0
Total phosphorus	mg P/L	4–10	4–8	≤2	4–10	<0.1
Turbidity	NTU	2–15	0.5–4	0.3–2	≤1	≤0.1
Volatile organic compounds (VOCs)	µg/L	10–40	10–40	10–20	10–20	<10
Metals	mg/L	1–1.5	1–1.4	1–1.5	Trace	<0.005
Surfactants	mg/L	0.5–2	0.5–1.5	0.1–1	0.1–0.5	<0.01
Totals dissolved solids (TDS)	mg/L	500–700	500–700	500–700	500–700	20–40
Trace constituents[g]	µg/L	5–40	5–30	5–30	0.5–20	<10
Total coliform	No./100 mL	10^4–10^5	10^3–10^5	10^4–10^5	<100	<1
Protozoan cysts and oocysts	No./100 mL	10^1–10^2	0–10	0–1	0–1	<1
Viruses	PFU/100 mL[h]	10^1–10^3	10^1–10^3	10^1–10^3	10^0–10^3	<1

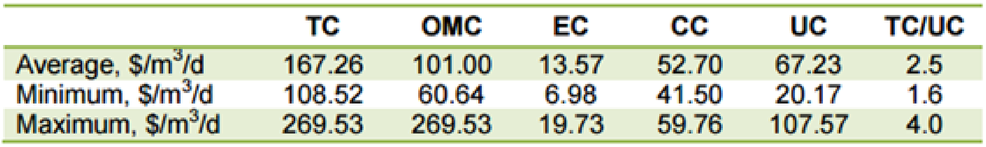
- Wastewater contains **energy and nutrients** that can be reclaimed if properly used and processed.

Table 23. Energy characteristics of typical domestic wastewater (McCarty, Bae, & Kim, 2011)

		Energy (kWh/m^3)		
Constituent	**Typical concentration (mg/L)**	**Maximum potential from organic oxidation**	**Required to produce fertilizing elements**	**Thermal heat available for heat-pump extraction**
Organics				
Total	500			
Refractory	180			
Suspended	80	0.31		
Dissolved	100	0.39		
Biodegradable	320			
Suspended	175	0.67		
Dissolved	145	0.56		
Nitrogen				
Organic	15		0.29	
Ammonia	25		0.48	
Phosphorous	8		0.02	
Water				7.0
Total		**1.93**	**0.79**	**7.0**

- “The total cost (TC), which includes maintenance and operational costs (OMC), pumping energy costs (EC) and chemicals cost (CC) per volume of wastewater treated per day revealed that about $167 Colombian pesos was spent for the treatment of each cubic meter of wastewater pumped into the WWTP per day which corresponds to about 0.1 US dollars (see Table 32). This value is considered to be on the low side given that conventional treatment processes may cost US$ 0.25-0.50 per cubic meter and that nonconventional options may cut costs by at least one-half” (Kingsley, 2011).

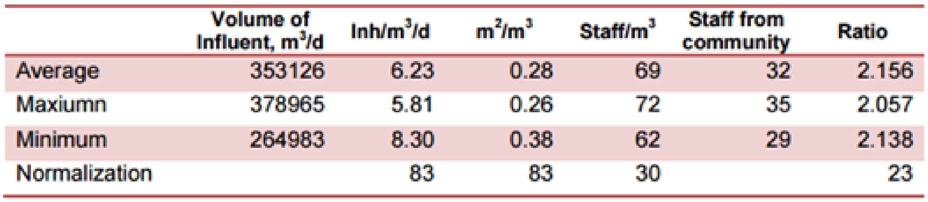
Table 24. Average costs per m^3 of wastewater treated in Colombian peso (Kingsley, 2011)



	TC	OMC	EC	CC	UC	TC/UC
Average, \$/m^3/d	167.26	101.00	13.57	52.70	67.23	2.5
Minimum, \$/m^3/d	108.52	60.64	6.98	41.50	20.17	1.6
Maximum, \$/m^3/d	269.53	269.53	19.73	59.76	107.57	4.0

- Operational data on employment

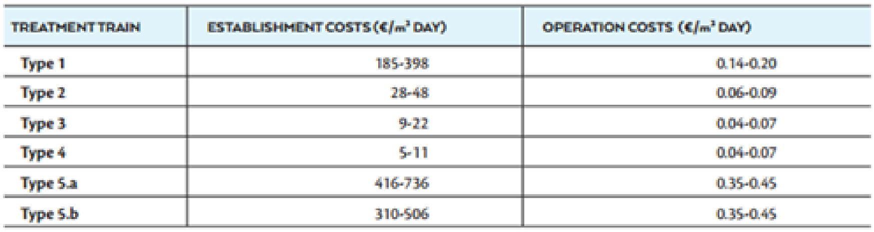
Table 25. Operational data on coverage and employment of the El Salitre WWTF (Kingsley, 2011)



	Volume of Influent, m^3/d	Inh/m^3/d	m^2/m^3	Staff/m^3	Staff from community	Ratio
Average	353126	6.23	0.28	69	32	2.156
Maxiumn	378965	5.81	0.26	72	35	2.057
Minimum	264983	8.30	0.38	62	29	2.138
Normalization		83	83	30		23

- Establishment and operation costs for several wastewater treatments trains (Table 28):
  - **Type 1:** Physical-chemical treatment with a lamella settling system, depth filtration, ultrafiltration and disinfection
  - **Type 2:** Physical-chemical treatment with a lamella settling system, depth filtration and disinfection
  - **Type 3:** filtration and disinfection
  - **Type 4:** depth filtration
  - **Type 5a:** physical-chemical treatment with a lamella settling system, depth filtration, ultrafiltration, reverse osmosis and residual chlorine removal
  - **Type 5b:** Physical-chemical treatment with a lamella settling system, double depth filtration, electrodialysis and disinfection.

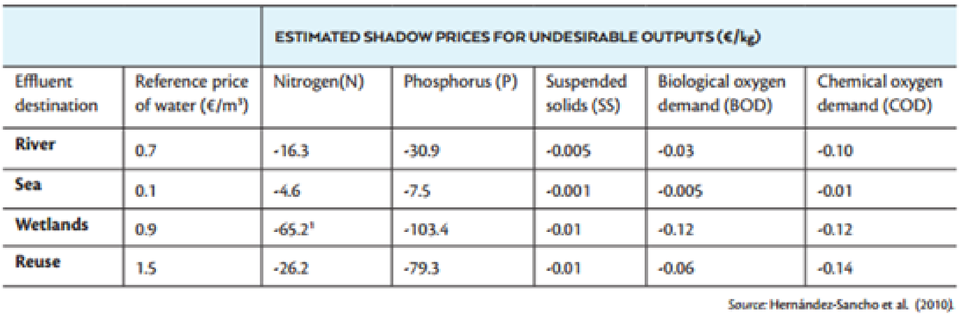
Table 26. Establishment and operation costs for several wastewater treatment trains (Iglesias, Ortega, Batanero, & Quintas, 2010)



TREATMENT TRAIN	ESTABLISHMENT COSTS (€/m^3 DAY)	OPERATION COSTS (€/m^3 DAY)
Type 1	185-398	0.14-0.20
Type 2	28-48	0.06-0.09
Type 3	9-22	0.04-0.07
Type 4	5-11	0.04-0.07
Type 5.a	416-736	0.35-0.45
Type 5.b	310-506	0.35-0.45

- Reference price for water treated and shadow prices for undesirable outputs from untreated wastewater (UNEP, 2015)

Table 27. **Reference price for water treated and shadow prices for undesirable outputs from untreated wastewater (Hernández-Sancho, Molinos-Senante, & Sala-Garrido, 2010)**

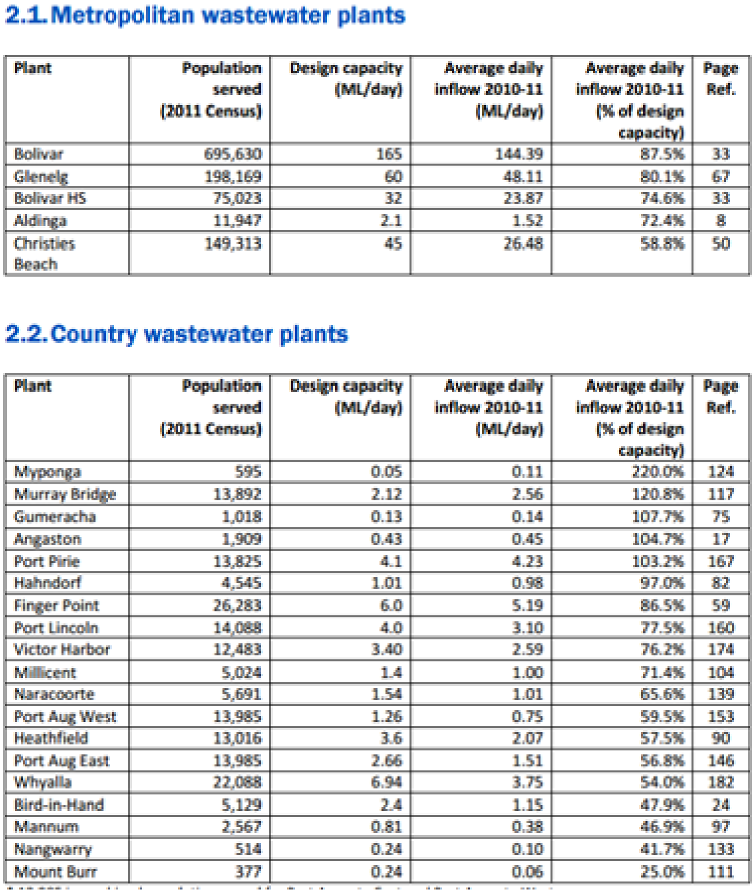


		ESTIMATED SHADOW PRICES FOR UNDESIRABLE OUTPUTS (€/kg)				
Effluent destination	Reference price of water (€/m³)	Nitrogen(N)	Phosphorus (P)	Suspended solids (SS)	Biological oxygen demand (BOD)	Chemical oxygen demand (COD)
River	0.7	-16.3	-30.9	-0.005	-0.03	-0.10
Sea	0.1	-4.6	-7.5	-0.001	-0.005	-0.01
Wetlands	0.9	-65.2[1]	-103.4	-0.01	-0.12	-0.12
Reuse	1.5	-26.2	-79.3	-0.01	-0.06	-0.14

Source: Hernández-Sancho et al. (2010).

- Impacts of untreated wastewater on health and agriculture productivity
  - “Regarding health costs, Grangier et al. (2012) demonstrated important differences between wastewater and freshwater-irrigated areas. On the average, the annual health cost per child in the wastewater-irrigated environment was US$67.1 (€49.4); this was 73 per cent higher than the annual health cost per child in the freshwater-irrigated area (US$38.7, or €28.5, on average)” (Grangier, Qadir, & Singh, 2012).
  - “Rice productivity loss from water pollution was estimated as the difference in rice yield between the two regions coupled with production costs and profit. The results showed the yield of rice in the polluted area was about 0.67 tons per ha per year less than in the non-polluted area. The production cost increase due to additional compensatory inputs was US$46.6 per ha per year, giving a total profit loss of US$150.4 per ha per year as compared to the non-polluted area. For the 148 polluted ha, the total cost increase due to water pollution could be estimated at US$6,750 and approximately US$22,260 per year for the total economic loss – slightly over US$100 per household” (Khai & Yabe, 2013).
- Overview of metropolitan and country wastewater plants, population served , capacity and average daily flows

Table 28. Metropolitan and country wastewater plants and operational information (SA-Water, 2013)



2.1. Metropolitan wastewater plants

Plant	Population served (2011 Census)	Design capacity (ML/day)	Average daily inflow 2010-11 (ML/day)	Average daily inflow 2010-11 (% of design capacity)	Page Ref.
Bolivar	695,630	165	144.39	87.5%	33
Glenelg	198,169	60	48.11	80.1%	67
Bolivar HS	75,023	32	23.87	74.6%	33
Aldinga	11,947	2.1	1.52	72.4%	8
Christies Beach	149,313	45	26.48	58.8%	50

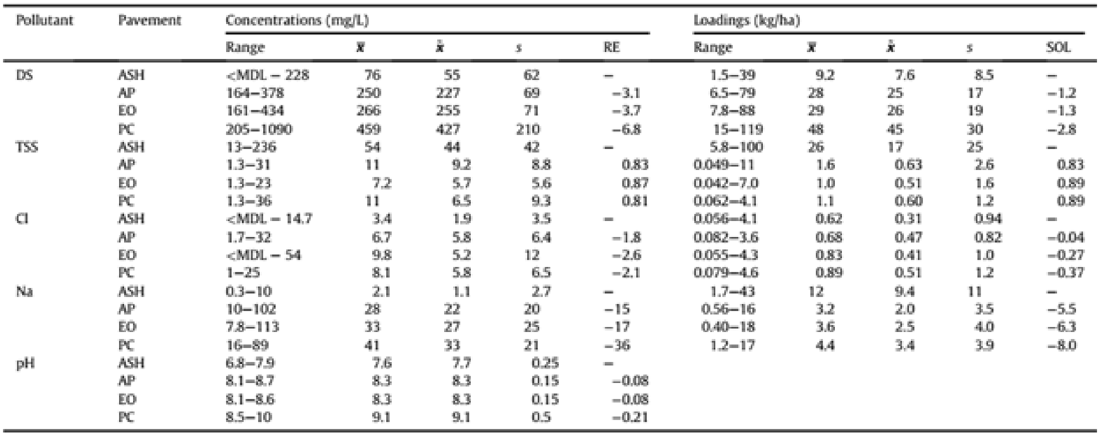
2.2. Country wastewater plants

Plant	Population served (2011 Census)	Design capacity (ML/day)	Average daily inflow 2010-11 (ML/day)	Average daily inflow 2010-11 (% of design capacity)	Page Ref.
Myponga	595	0.05	0.11	220.0%	124
Murray Bridge	13,892	2.12	2.56	120.8%	117
Gumeracha	1,018	0.13	0.14	107.7%	75
Angaston	1,909	0.43	0.45	104.7%	17
Port Pirie	13,825	4.1	4.23	103.2%	167
Hahndorf	4,545	1.01	0.98	97.0%	82
Finger Point	26,283	6.0	5.19	86.5%	59
Port Lincoln	14,088	4.0	3.10	77.5%	160
Victor Harbor	12,483	3.40	2.59	76.2%	174
Millicent	5,024	1.4	1.00	71.4%	104
Naracoorte	5,691	1.54	1.01	65.6%	139
Port Aug West	13,985	1.26	0.75	59.5%	153
Heathfield	13,016	3.6	2.07	57.5%	90
Port Aug East	13,985	2.66	1.51	56.8%	146
Whyalla	22,088	6.94	3.75	54.0%	182
Bird-in-Hand	5,129	2.4	1.15	47.9%	24
Mannum	2,567	0.81	0.38	46.9%	97
Nangwarry	514	0.24	0.10	41.7%	133
Mount Burr	377	0.24	0.06	25.0%	111

Water runoff and impervious surfaces

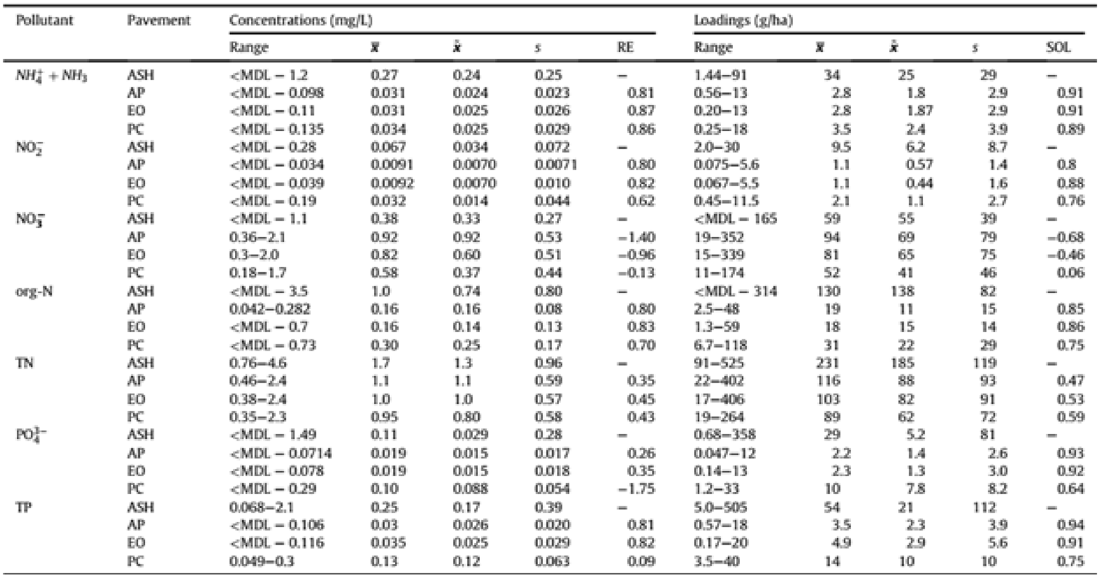
- Porous pavement reduces pollution in runoff as compared to traditional pavements such as asphalt. The following tables give data on pollutant loading and concentrations in effluent from three different porous pavements (Aquapave (AP), Eco-Optiloc (EO) and Hydromedia Pervious Concrete (PC)) and traditional asphalt (ASH). (MDL = minimum detection limit). (Table 24, Table 25, Table 26).

Table 29. General quality concentration and mass loading results (Drake, Bradford, & van Seters, 2014)



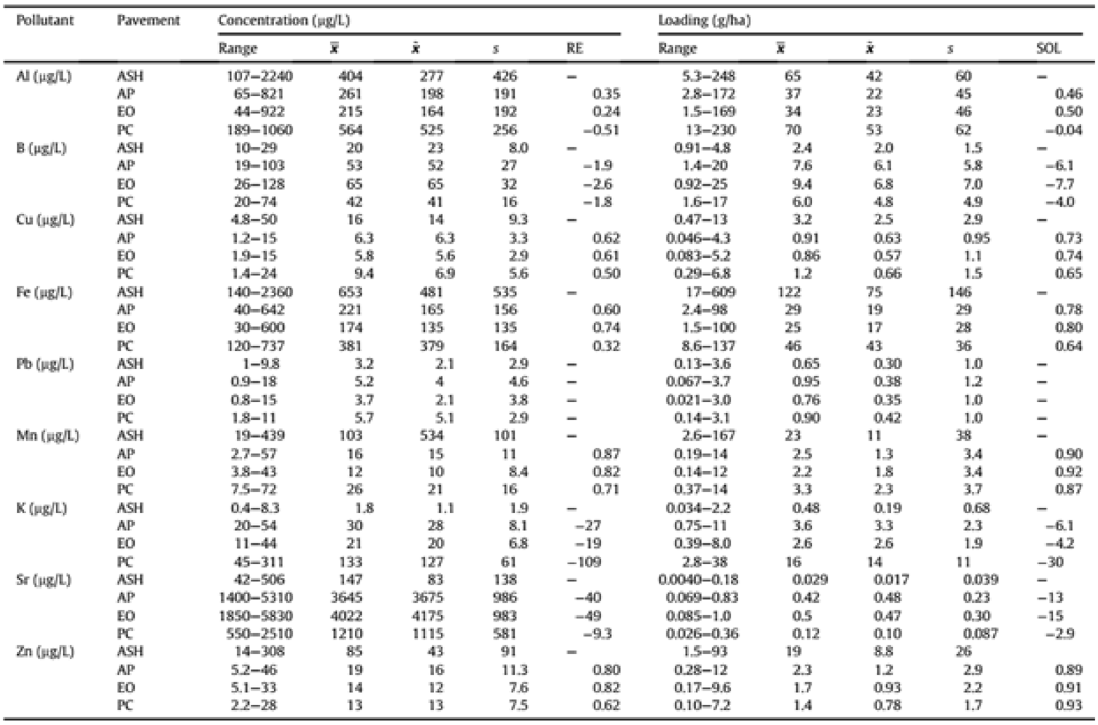
Pollutant	Pavement	Concentrations (mg/L)					Loadings (kg/ha)				
		Range	$\bar{x}$	$\tilde{x}$	s	RE	Range	$\bar{x}$	$\tilde{x}$	s	SOL
DS	ASH	<MDL – 228	76	55	62	–	1.5–39	9.2	7.6	8.5	–
	AP	164–378	250	227	69	−3.1	6.5–79	28	25	17	−1.2
	EO	161–434	266	255	71	−3.7	7.8–88	29	26	19	−1.3
	PC	205–1090	459	427	210	−6.8	15–119	48	45	30	−2.8
TSS	ASH	13–236	54	44	42	–	5.8–100	26	17	25	–
	AP	1.3–31	11	9.2	8.8	0.83	0.049–11	1.6	0.63	2.6	0.83
	EO	1.3–23	7.2	5.7	5.6	0.87	0.042–7.0	1.0	0.51	1.6	0.89
	PC	1.3–36	11	6.5	9.3	0.81	0.062–4.1	1.1	0.60	1.2	0.89
Cl	ASH	<MDL – 14.7	3.4	1.9	3.5	–	0.056–4.1	0.62	0.31	0.94	–
	AP	1.7–32	6.7	5.8	6.4	−1.8	0.082–3.6	0.68	0.47	0.82	−0.04
	EO	<MDL – 54	9.8	5.2	12	−2.6	0.055–4.3	0.83	0.41	1.0	−0.27
	PC	1–25	8.1	5.8	6.5	−2.1	0.079–4.6	0.89	0.51	1.2	−0.37
Na	ASH	0.3–10	2.1	1.1	2.7	–	1.7–43	12	9.4	11	–
	AP	10–102	28	22	20	−15	0.56–16	3.2	2.0	3.5	−5.5
	EO	7.8–113	33	27	25	−17	0.40–18	3.6	2.5	4.0	−6.3
	PC	16–89	41	33	21	−36	1.2–17	4.4	3.4	3.9	−8.0
pH	ASH	6.8–7.9	7.6	7.7	0.25	–					
	AP	8.1–8.7	8.3	8.3	0.15	−0.08					
	EO	8.1–8.6	8.3	8.3	0.15	−0.08					
	PC	8.5–10	9.1	9.1	0.5	−0.21					

Table 30. Nutrient Concentration and mass loading results (Drake, Bradford, & van Seters, 2014)



Pollutant	Pavement	Concentrations (mg/L)					Loadings (g/ha)				
		Range	$\bar{x}$	$\hat{x}$	s	RE	Range	$\bar{x}$	$\hat{x}$	s	SOL
$NH_4^+ + NH_3$	ASH	<MDL – 1.2	0.27	0.24	0.25	–	1.44–91	34	25	29	–
	AP	<MDL – 0.098	0.031	0.024	0.023	0.81	0.56–13	2.8	1.8	2.9	0.91
	EO	<MDL – 0.11	0.031	0.025	0.026	0.87	0.20–13	2.8	1.87	2.9	0.91
	PC	<MDL – 0.135	0.034	0.025	0.029	0.86	0.25–18	3.5	2.4	3.9	0.89
NO_2^-	ASH	<MDL – 0.28	0.067	0.034	0.072	–	2.0–30	9.5	6.2	8.7	–
	AP	<MDL – 0.034	0.0091	0.0070	0.0071	0.80	0.075–5.6	1.1	0.57	1.4	0.8
	EO	<MDL – 0.039	0.0092	0.0070	0.010	0.82	0.067–5.5	1.1	0.44	1.6	0.88
	PC	<MDL – 0.19	0.032	0.014	0.044	0.62	0.45–11.5	2.1	1.1	2.7	0.76
NO_3^-	ASH	<MDL – 1.1	0.38	0.33	0.27	–	<MDL – 165	59	55	39	–
	AP	0.36–2.1	0.92	0.92	0.53	−1.40	19–352	94	69	79	−0.68
	EO	0.3–2.0	0.82	0.60	0.51	−0.96	15–339	81	65	75	−0.46
	PC	0.18–1.7	0.58	0.37	0.44	−0.13	11–174	52	41	46	0.06
org-N	ASH	<MDL – 3.5	1.0	0.74	0.80	–	<MDL – 314	130	138	82	–
	AP	0.042–0.282	0.16	0.16	0.08	0.80	2.5–48	19	11	15	0.85
	EO	<MDL – 0.7	0.16	0.14	0.13	0.83	1.3–59	18	15	14	0.86
	PC	<MDL – 0.73	0.30	0.25	0.17	0.70	6.7–118	31	22	29	0.75
TN	ASH	0.76–4.6	1.7	1.3	0.96	–	91–525	231	185	119	–
	AP	0.46–2.4	1.1	1.1	0.59	0.35	22–402	116	88	93	0.47
	EO	0.38–2.4	1.0	1.0	0.57	0.45	17–406	103	82	91	0.53
	PC	0.35–2.3	0.95	0.80	0.58	0.43	19–264	89	62	72	0.59
PO_4^{3-}	ASH	<MDL – 1.49	0.11	0.029	0.28	–	0.68–358	29	5.2	81	–
	AP	<MDL – 0.0714	0.019	0.015	0.017	0.26	0.047–12	2.2	1.4	2.6	0.93
	EO	<MDL – 0.078	0.019	0.015	0.018	0.35	0.14–13	2.3	1.3	3.0	0.92
	PC	<MDL – 0.29	0.10	0.088	0.054	−1.75	1.2–33	10	7.8	8.2	0.64
TP	ASH	0.068–2.1	0.25	0.17	0.39	–	5.0–505	54	21	112	–
	AP	<MDL – 0.106	0.03	0.026	0.020	0.81	0.57–18	3.5	2.3	3.9	0.94
	EO	<MDL – 0.116	0.035	0.025	0.029	0.82	0.17–20	4.9	2.9	5.6	0.91
	PC	0.049–0.3	0.13	0.12	0.063	0.09	3.5–40	14	10	10	0.75

Table 31. Heavy metal concentration and mass loading results



Pollutant	Pavement	Concentration (μg/L)					Loading (g/ha)				
		Range	$\bar{x}$	$\hat{x}$	s	RE	Range	$\bar{x}$	$\hat{x}$	s	SOL
Al (μg/L)	ASH	107–2240	404	277	426	–	5.3–248	65	42	60	–
	AP	65–821	261	198	191	0.35	2.8–172	37	22	45	0.46
	EO	44–922	215	164	192	0.24	1.5–169	34	23	46	0.50
	PC	189–1060	564	525	256	−0.51	13–230	70	53	62	−0.04
B (μg/L)	ASH	10–29	20	23	8.0	–	0.91–4.8	2.4	2.0	1.5	–
	AP	19–103	53	52	27	−1.9	1.4–20	7.6	6.1	5.8	−6.1
	EO	26–128	65	65	32	−2.6	0.92–25	9.4	6.8	7.0	−7.7
	PC	20–74	42	41	16	−1.8	1.6–17	6.0	4.8	4.9	−4.0
Cu (μg/L)	ASH	4.8–50	16	14	9.3	–	0.47–13	3.2	2.5	2.9	–
	AP	1.2–15	6.3	6.3	3.3	0.62	0.046–4.3	0.91	0.63	0.95	0.73
	EO	1.9–15	5.8	5.6	2.9	0.61	0.083–5.2	0.86	0.57	1.1	0.74
	PC	1.4–24	9.4	6.9	5.6	0.50	0.29–6.8	1.2	0.66	1.5	0.65
Fe (μg/L)	ASH	140–2360	653	481	535	–	17–609	122	75	146	–
	AP	40–642	221	165	156	0.60	2.4–98	29	19	29	0.78
	EO	30–600	174	135	135	0.74	1.5–100	25	17	28	0.80
	PC	120–737	381	379	164	0.32	8.6–137	46	43	36	0.64
Pb (μg/L)	ASH	1–9.8	3.2	2.1	2.9	–	0.13–3.6	0.65	0.30	1.0	–
	AP	0.9–18	5.2	4	4.6	–	0.067–3.7	0.95	0.38	1.2	–
	EO	0.8–15	3.7	2.1	3.8	–	0.021–3.0	0.76	0.35	1.0	–
	PC	1.8–11	5.7	5.1	2.9	–	0.14–3.1	0.90	0.42	1.0	–
Mn (μg/L)	ASH	19–439	103	534	101	–	2.6–167	23	11	38	–
	AP	2.7–57	16	15	11	0.87	0.19–14	2.5	1.3	3.4	0.90
	EO	3.8–43	12	10	8.4	0.82	0.14–12	2.2	1.8	3.4	0.92
	PC	7.5–72	26	21	16	0.71	0.37–14	3.3	2.3	3.7	0.87
K (μg/L)	ASH	0.4–8.3	1.8	1.1	1.9	–	0.034–2.2	0.48	0.19	0.68	–
	AP	20–54	30	28	8.1	−27	0.75–11	3.6	3.3	2.3	−6.1
	EO	11–44	21	20	6.8	−19	0.39–8.0	2.6	2.6	1.9	−4.2
	PC	45–311	133	127	61	−109	2.8–38	16	14	11	−30
Sr (μg/L)	ASH	42–506	147	83	138	–	0.0040–0.18	0.029	0.017	0.039	–
	AP	1400–5310	3645	3675	986	−40	0.069–0.83	0.42	0.48	0.23	−13
	EO	1850–5830	4022	4175	983	−49	0.085–1.0	0.5	0.47	0.30	−15
	PC	550–2510	1210	1115	581	−9.3	0.026–0.36	0.12	0.10	0.087	−2.9
Zn (μg/L)	ASH	14–308	85	43	91	–	1.5–93	19	8.8	26	
	AP	5.2–46	19	16	11.3	0.80	0.28–12	2.3	1.2	2.9	0.89
	EO	5.1–33	14	12	7.6	0.82	0.17–9.6	1.7	0.93	2.2	0.91
	PC	2.2–28	13	13	7.5	0.62	0.10–7.2	1.4	0.78	1.7	0.93

- “Permeable pavement systems constructed with underdrains that had valves for restricting outflow reduced peak flows by over 90% and reduced runoff volumes by 43% even though they were constructed over clayey soils.[…] PICP (Permeable interlocking concrete pavement) has the highest infiltration rates (1,800 cm/hr), pervious concrete the second highest (~1,100 cm/hr), and porous asphalt the lowest (360 39 cm/hr). Results should be expected to vary because infiltration rates depend on materials, mix designs, construction techniques, maintenance received, etc.” (Gulliver, 2015).

5.2.5 Irrigation Data

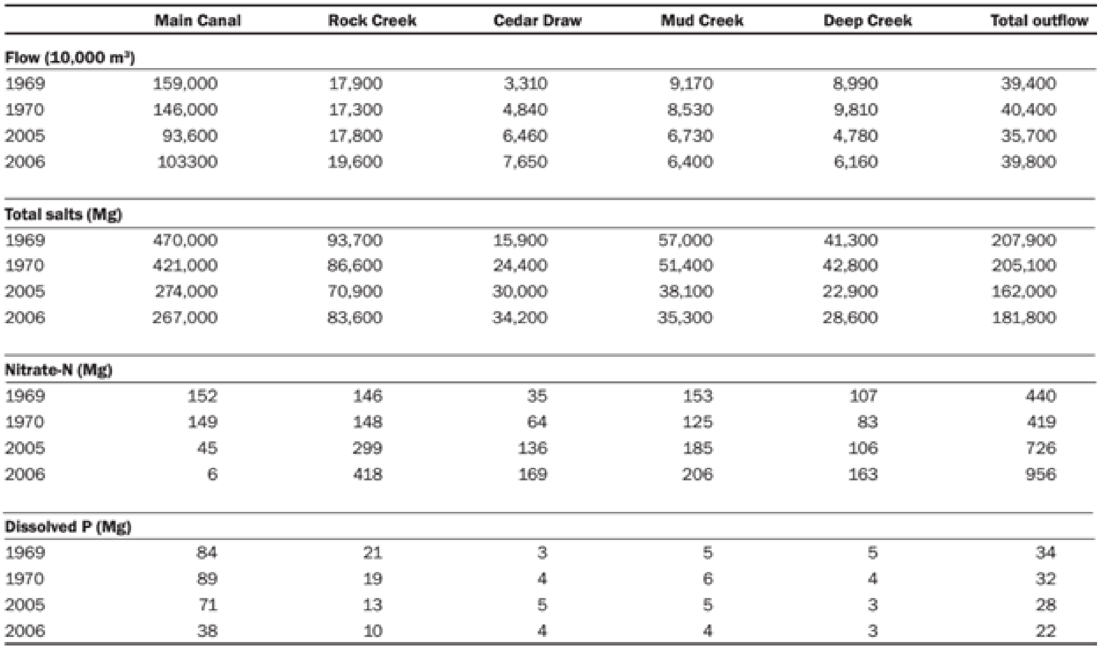
- Irrigation data is available for all OECD countries from the OECD Environmental database available at stats.oecd.org.

Table 32. Australia irrigation data (OECD, 2017)

Country	Environmental indicator					
Australia	Water use,	..	..	..	..	..
	Total agricultural water withdrawals, million m^3	11689	8521	6989	7286	7359
	Total freshwater withdrawals, million m^3	..	..	..	..	14101
	Share of agriculture in total freshwater withdrawals, %	..	..	..	..	52.2
	Irrigation	..	..	..	..	..
	Irrigated area, Hectares	2546318	1922982	1850937	1760758	1840610
	Share of irrigated area in total agricultural area, %	0.6	0.5	0.4	0.4	0.5
	Irrigation freshwater withdrawals, million m^3	10737	7636	6285	6501	6596
	Share of irrigation freshwater withdrawals in total agricultural water withdrawals, %	91.9	89.6	89.9	89.2	89.6
	Irrigation water application rates, Megalitres per hectare of irrigated land	4.2	4	3.4	3.7	3.6

- Soil salinity and waterlogging are a result of irrigation and often a problem in arid and semiarid regions. In India, Rohtak district has 75,651 ha of potentially waterlogged and saline land and 16,516 ha of existing waterlogged and saline land (out of 166,777 ha total). Jhajjar has 75,651 ha of potentially waterlogged and saline land and 12,980 ha of existing waterlogged and saline (out of 186 670 ha total) (Manav, 2016)
- Irrigation causes erosion, particularly on sloped soils. In the Pamir region of Tajikistan it was found that slopes less than 3 degrees had a soil loss rate of 2 t/ha/year while slopes greater than 3 degree had soil loss rates up to 30 t/ha/year (Golosov, Sosin, Belyaev, Wolfgramm, & Khodzhaev, 2015)
- Changes to suspended solids, salinity and nitrogen in the Twin Falls irrigation tract in Ohio, 1969, 1971, 2005, and 2006. Illustrates differences between furrow and sprinkler irrigation.

Table 33. **Total annual flow and total sale, nitrate-nitrogen, and dissolved phosphorous loads for the Main Canal and four return streams**



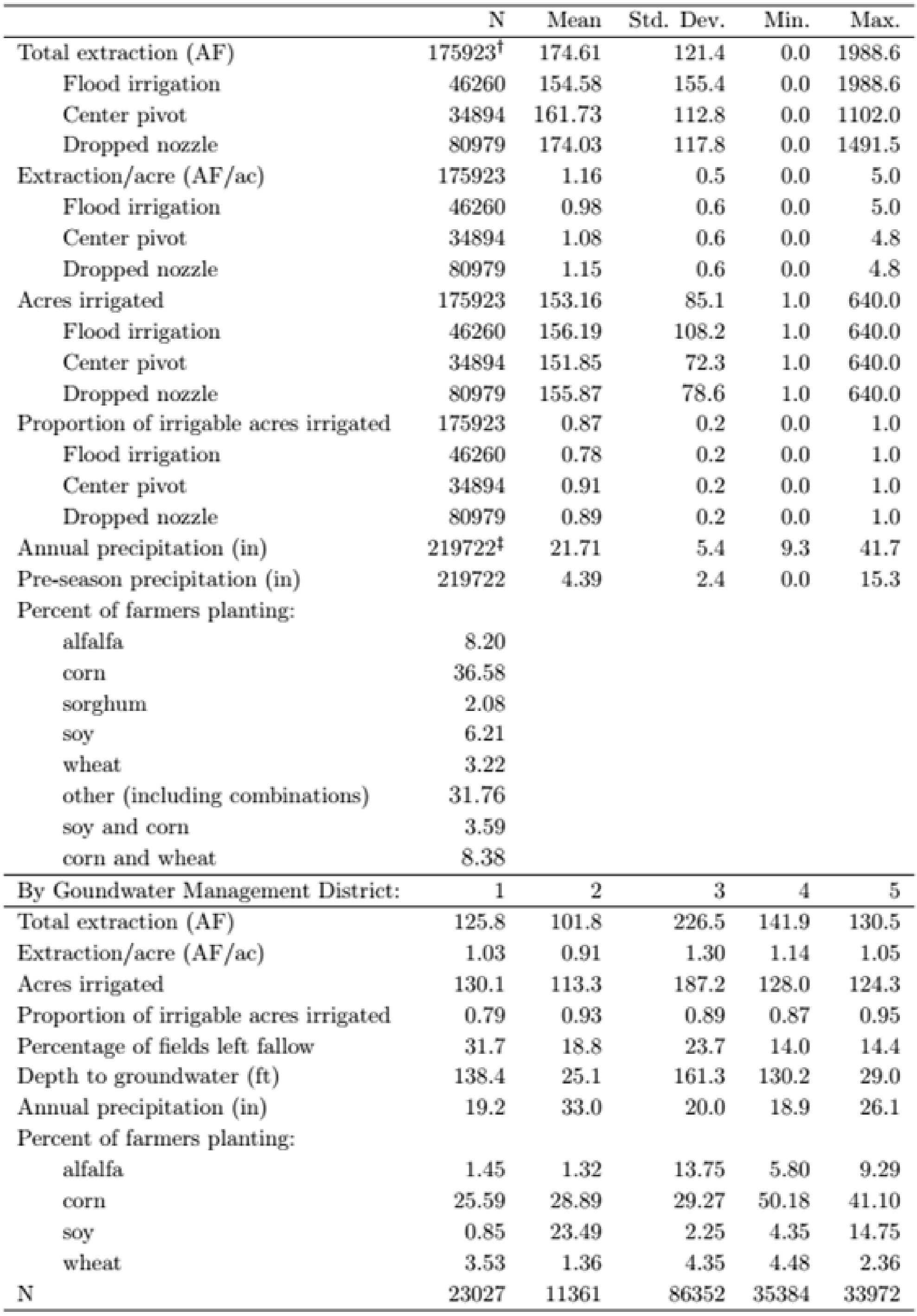
	Main Canal	Rock Creek	Cedar Draw	Mud Creek	Deep Creek	Total outflow
Flow (10,000 m³)						
1969	159,000	17,900	3,310	9,170	8,990	39,400
1970	146,000	17,300	4,840	8,530	9,810	40,400
2005	93,600	17,800	6,460	6,730	4,780	35,700
2006	103300	19,600	7,650	6,400	6,160	39,800
Total salts (Mg)						
1969	470,000	93,700	15,900	57,000	41,300	207,900
1970	421,000	86,600	24,400	51,400	42,800	205,100
2005	274,000	70,900	30,000	38,100	22,900	162,000
2006	267,000	83,600	34,200	35,300	28,600	181,800
Nitrate-N (Mg)						
1969	152	146	35	153	107	440
1970	149	148	64	125	83	419
2005	45	299	136	185	106	726
2006	6	418	169	206	163	956
Dissolved P (Mg)						
1969	84	21	3	5	5	34
1970	89	19	4	6	4	32
2005	71	13	5	5	3	28
2006	38	10	4	4	3	22

Table 34. **Water efficiency of irrigation technology (Pfeiffer & Lin, 2013)**

Flood irrigation	65-75 percent
Centre pivot	80-90 percent
Dropped nozzle	95-98 percent

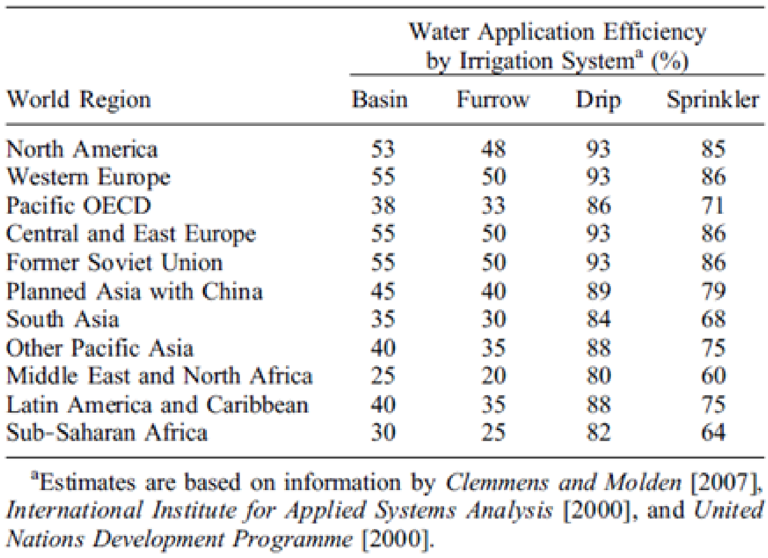
- A comparison of center pivot and dropped sprinkler heads in Kansas found that although dropped sprinklers are a more efficient technology, farmers respond by irrigating more land and irrigating land in production more often.

Table 35. **Comparison of irrigation technologies (Pfeiffer & Lin, 2013)**



	N	Mean	Std. Dev.	Min.	Max.
Total extraction (AF)	175923[†]	174.61	121.4	0.0	1988.6
Flood irrigation	46260	154.58	155.4	0.0	1988.6
Center pivot	34894	161.73	112.8	0.0	1102.0
Dropped nozzle	80979	174.03	117.8	0.0	1491.5
Extraction/acre (AF/ac)	175923	1.16	0.5	0.0	5.0
Flood irrigation	46260	0.98	0.6	0.0	5.0
Center pivot	34894	1.08	0.6	0.0	4.8
Dropped nozzle	80979	1.15	0.6	0.0	4.8
Acres irrigated	175923	153.16	85.1	1.0	640.0
Flood irrigation	46260	156.19	108.2	1.0	640.0
Center pivot	34894	151.85	72.3	1.0	640.0
Dropped nozzle	80979	155.87	78.6	1.0	640.0
Proportion of irrigable acres irrigated	175923	0.87	0.2	0.0	1.0
Flood irrigation	46260	0.78	0.2	0.0	1.0
Center pivot	34894	0.91	0.2	0.0	1.0
Dropped nozzle	80979	0.89	0.2	0.0	1.0
Annual precipitation (in)	219722[‡]	21.71	5.4	9.3	41.7
Pre-season precipitation (in)	219722	4.39	2.4	0.0	15.3
Percent of farmers planting:					
alfalfa	8.20				
corn	36.58				
sorghum	2.08				
soy	6.21				
wheat	3.22				
other (including combinations)	31.76				
soy and corn	3.59				
corn and wheat	8.38				
By Goundwater Management District:	1	2	3	4	5
Total extraction (AF)	125.8	101.8	226.5	141.9	130.5
Extraction/acre (AF/ac)	1.03	0.91	1.30	1.14	1.05
Acres irrigated	130.1	113.3	187.2	128.0	124.3
Proportion of irrigable acres irrigated	0.79	0.93	0.89	0.87	0.95
Percentage of fields left fallow	31.7	18.8	23.7	14.0	14.4
Depth to groundwater (ft)	138.4	25.1	161.3	130.2	29.0
Annual precipitation (in)	19.2	33.0	20.0	18.9	26.1
Percent of farmers planting:					
alfalfa	1.45	1.32	13.75	5.80	9.29
corn	25.59	28.89	29.27	50.18	41.10
soy	0.85	23.49	2.25	4.35	14.75
wheat	3.53	1.36	4.35	4.48	2.36
N	23027	11361	86352	35384	33972

Table 36. Efficiency of irrigation systems (Sauer, et al., 2010)

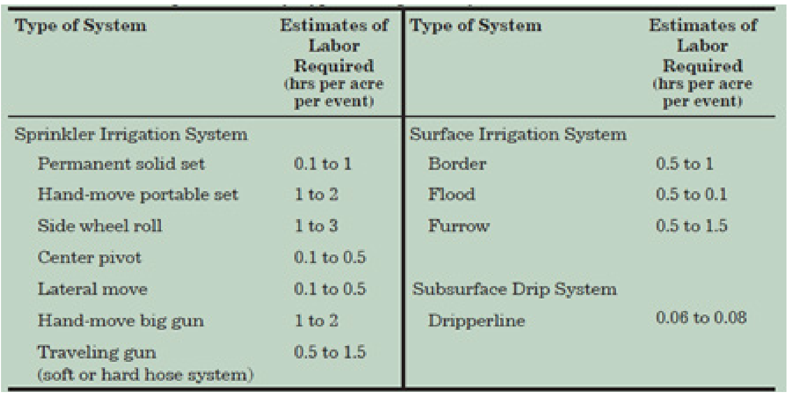


	Water Application Efficiency by Irrigation System[a] (%)			
World Region	Basin	Furrow	Drip	Sprinkler
North America	53	48	93	85
Western Europe	55	50	93	86
Pacific OECD	38	33	86	71
Central and East Europe	55	50	93	86
Former Soviet Union	55	50	93	86
Planned Asia with China	45	40	89	79
South Asia	35	30	84	68
Other Pacific Asia	40	35	88	75
Middle East and North Africa	25	20	80	60
Latin America and Caribbean	40	35	88	75
Sub-Saharan Africa	30	25	82	64

[a]Estimates are based on information by *Clemmens and Molden* [2007], *International Institute for Applied Systems Analysis* [2000], and *United Nations Development Programme* [2000].

- Labor requirements for irrigation are depending on the irrigation technology used and the number of irrigation events. Table 37 provides an overview of the estimated labor requirements for an irrigation event[1] for each irrigation technology, based on Buchanan and Cross (2002).

Table 37. Labour requirements per irrigation event by irrigation technology (Buchanan & Cross, 2002)



Type of System	Estimates of Labor Required (hrs per acre per event)	Type of System	Estimates of Labor Required (hrs per acre per event)
Sprinkler Irrigation System		Surface Irrigation System	
Permanent solid set	0.1 to 1	Border	0.5 to 1
Hand-move portable set	1 to 2	Flood	0.5 to 0.1
Side wheel roll	1 to 3	Furrow	0.5 to 1.5
Center pivot	0.1 to 0.5		
Lateral move	0.1 to 0.5	Subsurface Drip System	
Hand-move big gun	1 to 2	Dripperline	0.06 to 0.08
Traveling gun (soft or hard hose system)	0.5 to 1.5		

- Energy and fuel requirements for the irrigation process depend on the distance and height that the water needs to be transported to the irrigation system, the length and materials of pipes and the efficiency and fuel use of the pumps used to move the water for irrigation. Buchanan and Cross (2002) provide an overview of the efficiency of different pump efficiencies and an indicated brake horse-power (bhp) output per unit of fuel by pump type (Table 38). Further, they provide a methodology for calculating the required bhp for the irrigation system in use, which can be found in their *Irrigation Cost Handbook* (Buchanan & Cross, 2002).

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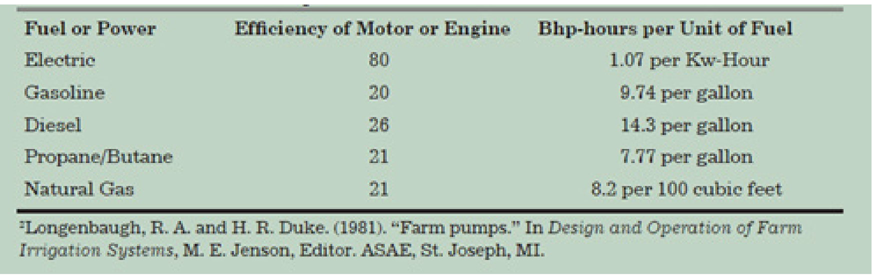
[1] As a reference, cotton and corn have 6 irrigation events, soybean has 5

Table 38. **Pump efficiencies and brake-horse-power output per fuel unit (Buchanan & Cross, 2002)**

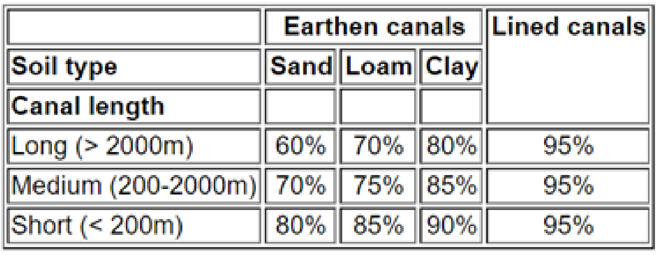


Fuel or Power	Efficiency of Motor or Engine	Bhp-hours per Unit of Fuel
Electric	80	1.07 per Kw-Hour
Gasoline	20	9.74 per gallon
Diesel	26	14.3 per gallon
Propane/Butane	21	7.77 per gallon
Natural Gas	21	8.2 per 100 cubic feet

[1] Longenbaugh, R. A. and H. R. Duke. (1981). "Farm pumps." In *Design and Operation of Farm Irrigation Systems*, M. E. Jenson, Editor. ASAE, St. Joseph, MI.

- Next to the efficiency of the irrigation technology itself, the water demand for irrigation systems also depends on the conveyance efficiency of the channels that are used to transport the water onto the fields. Table 39 provides an overview of the average conveyance efficiency for water channels depending on soil type and channel length (Brouwer, Prins, & Heilbloem, 1989).

Table 39. **Conveyance efficiency for adequately maintained channels according to the FAO (Brouwer, Prins, & Heilbloem, 1989)**



	Earthen canals			Lined canals
Soil type	**Sand**	**Loam**	**Clay**	
Canal length				
Long (> 2000m)	60%	70%	80%	95%
Medium (200-2000m)	70%	75%	85%	95%
Short (< 200m)	80%	85%	90%	95%

Table 40. **Benefits of drip irrigation vs flooding for green chillis in India (Narayanamoorthy, Devika, & Bhattarai, 2016)**

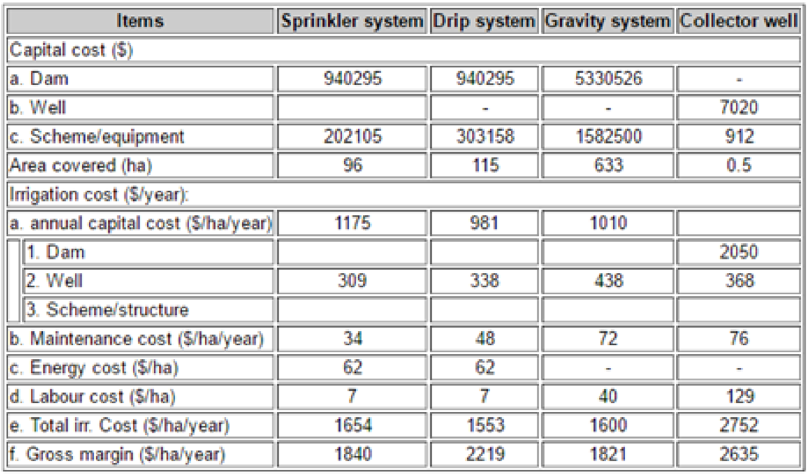
	Non-drip irrigation	Drip irrigation	Percent reduction
Cost of cultivation	111 200 rupees	78 500 rupees	29
Water pumping horse power	1 674 HP per acre	617 HP per acre	63
Electricity savings	1 256	462	
Crop productivity	77.4 quintal per acre	118 Quintal per acre	53

- Cost for a 128 acre centre pivot is about $1 100 per acre (NDSU, 2013)
- Drip irrigation costs USD 500 to USD 1,200 per acre (EDIS, 2015)

Table 41. **Cost per acre of irrigation technologies (Dumler, O'Brien, & Rogers, 2007)**

Irrigation technology	Cost per acre (USD)
Center pivot	476
Flood irrigation	33
Subsurface Drip	1228

Table 42. O&M costs for irrigation systems in Zimbabwe (FAO, 1997)



Items	Sprinkler system	Drip system	Gravity system	Collector well
Capital cost ($)				
a. Dam	940295	940295	5330526	-
b. Well		-	-	7020
c. Scheme/equipment	202105	303158	1582500	912
Area covered (ha)	96	115	633	0.5
Irrigation cost ($/year):				
a. annual capital cost ($/ha/year)	1175	981	1010	
1. Dam				2050
2. Well	309	338	438	368
3. Scheme/structure				
b. Maintenance cost ($/ha/year)	34	48	72	76
c. Energy cost ($/ha)	62	62	-	-
d. Labour cost ($/ha)	7	7	40	129
e. Total irr. Cost ($/ha/year)	1654	1553	1600	2752
f. Gross margin ($/ha/year)	1840	2219	1821	2635

6.0 MAIN ORGANIZATIONS WORKING ON THE ASSESSMENT OF INFRASTRUCTURE FOR SUSTAINABLE WATER MANAGEMENT

- **WaterNow Alliance** (http://waternowalliance.org/)

  Founded in 2014, the WaterNow Alliance is a network of water utilities working toward sustainable water management in their communities. The purpose is to facilitate the adoption of reuse and efficiency technologies, green infrastructure, watershed health, stormwater recapture and groundwater management.

- **US EPA Water Infrastructure and Resiliency Finance Center** (https://www.sustainablehighways.org/)

  The goal of the Water Infrastructure and Resiliency Finance Center is to accelerate the quality of water infrastructure in the United States. The Center helps communities find financial solutions to meet their infrastructure needs. The ultimate goal is to rehabilitate America's declining water infrastructure.

- **POLIS project** (http://poliswaterproject.org/conservation)

  The POLIS Water Project began in 2003 at the University of Victoria. The focus was originally on demand management but expanded to include governance issues such as watershed planning, and legal reforms. The four core research themes are water conservation, the water-energy nexus, watershed governance, and water law and policy.

Table 33. **Reports and indicators by organization**

Organization	Resource description	Link
WaterNow Alliance	Policy work	http://waternowalliance.org/our-work/our-work-policy/
	Project work	http://waternowalliance.org/our-work/our-work-projects/
Water Infrastructure and Resiliency Finance Center	Financial technical assistance tools	https://www.epa.gov/waterfinancecenter/financial-technical-assistance-and-tools-water-infrastructure
POLIS project	Research reports	http://poliswaterproject.org/publications
	Policy papers	http://poliswaterproject.org/publications/notes

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