# Water supply resilience in coastal communities: using DPSIR to assess the next urban water paradigm

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## Abstract

Issues related to growing urban populations, protecting the environment and adapting to the changing climate cannot be ignored, especially when it comes to providing reliable water supply to urban areas. Cities worldwide must look to shift away from the traditional urban water management paradigm, characterized by a fragmented approach, and shift to form a new paradigm; one that manages the urban water cycle as a single resource, satisfying contemporary issues and adapting to future needs. Understanding the anticipated effects of future issues is key before a new paradigm can be formed.

This paper analyses the potential impacts to vulnerable urban water supply in the coastal realm by using the DPSIR (Driver-Pressure-State-Impact-Response) framework. Dunedin, a highly urbanized coastal city (on the Gulf coast of Florida, USA) is used as a case study to map out drivers, pressures, potential impacts and successful responses to water related issues. In doing so, this case study serves to showcase IUWM (Integrated Urban Water Management) as the future urban water paradigm and provides practical lessons learned for resilient cities of the future. Where most IUWM case studies in literature explore only greywater and wastewater reuse, this paper evaluates the entire urban water cycle beginning with the sustainable extraction of groundwater through discharge. As a nearly closed loop system, Dunedin's challenges and responses provide an optimistic case for IUWM. Innovative groundwater management strategies, investment in infrastructure technology and aggressive recycling and conservation have contributed toward greater sustainability and resilience.
*Keywords: adaptation, AMR, DPSIR, IUWM (Integrated Urban Water Management), reclaimed water, reverse osmosis, urban water cycle, urban wellfield, wastewater reuse.*

WIT Transactions on Ecology and The Environment, Vol 200, © 2015 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/WS150021

# 1 Introduction

Paradigms are models or approaches that serve as examples of significant design practice. They typically manifest themselves as the result of similar large scale conceptual approaches or design responses to the needs of the time. As future challenges are encountered, there must be a shift away from segregated water management by utility type and transition towards a new paradigm; one that addresses contemporary issues as well as the anticipated pressures of future climate.

Contemporary challenges to urban water are those utilities are currently faced with. The effects of urbanization and aging infrastructure are two significant challenges. Extensive development has a direct on the hydrologic cycle causing water scarcity, flooding and changes to water quality [1–4]. Urban dwellers generate large volumes of waste, which must be treated and discharged, directly impacting water bodies, threatening water quality, negatively affecting recreational waters and natural systems [5, 6]. Water infrastructure in the United States is currently in very poor condition because of poor performance due to leaking distribution pipes and water main breaks [7]. Future challenges to water supply includes the impacts that changing climate can have on infrastructure, water availability and resulting changes in water quality [8].

## 1.1 IUWM

Given these pressures on the water sector, there is a need to improve the current water management paradigm. At present, the urban water cycle is managed in a fragmented manner through three separate infrastructure systems: drinking water, wastewater and stormwater. This method has forced water away from a natural, dynamic and cyclical process into a fragmented and linear type system where water is extracted from the environment, used, polluted and disposed of. Natural systems, on the other hand, use a process where resources are constantly recycled, producing an extremely efficient cycle and minimizing consumption of precious water resources. IUWM is a paradigm that requires the individual components of the urban water cycle to be managed together rather than separately [9]. By more closely emulating a closed loop cycle, synergistic opportunities can be identified and cities can be more sustainable while contributing towards climate resilience. In the urban environment, integrated water management seeks total system solutions through these primary principles: (1) minimizing the amount of pollution generated and discharged, (2) using/reusing water as close to its point of origination as possible, and (3) closely matching the required water quality for its intended use [10, 11]. Collectively, these key principles enable IUWM to potentially establish a water management paradigm that meets the needs for contemporary and future challenges in the urban setting.

## 1.2 DPSIR

DPSIR (Driver-Pressure-State-Impact-Response) is a framework that is widely accepted and used by environmental agencies worldwide to consider the strengths and weaknesses of different decisions or policy strategies, especially those involving human decisions and how those impact the environment. It facilitates decision making by taking a holistic look at how various elements are linked and interact [12]. In this work, the DPSIR framework will focus mainly on water supply in the urban context, addressing both existing and future impacts that ultimately affect the ability to function and reliably provide critical services.

In order to examine water issues in a context where water supply conditions are most critical, Dunedin, a small coastal city, is presented as a case study. The analysis begins by identifying the urban waters, discussing the application of the DPSIR elements to the study site, the contemporary and future impacts affecting water supply in the City, and the specific responses and successful strategies employed in navigating these risks.

## 2 IUWM case study

The approach for this study consisted mostly of qualitative collecting data in order to characterize the City's water infrastructure and management practices. A literature review of the City's documents and reports relevant to water management background data and challenges was conducted. Additional data and anecdotal information was gleaned through surveying water infrastructure, interviews and meetings with water utility managers and operators, as well as sustainability coordinators and City urban planners.

The City of Dunedin is located in west central Florida on the Gulf of Mexico. It is approximately ten square miles in size and highly urbanized. Although the City's water cycle consists of the traditionally segregated water infrastructure, it can be described as a nearly closed loop cycle, operated with great efficiency (Figure 1). It has a fit-for-purpose dual distribution system for its water supply, potable and reclaimed water.

### 2.1 Urban waters

The urban water bodies vital to the Dunedin's community are St. Joseph Sound and the urban wellfield. St. Joseph Sound is the body of water immediately to the west of Dunedin, and lies between its barrier islands and the mainland, making up four miles of its coastline. It is the City's recreational waters and part of Pinellas County's Aquatic Preserve. The wellfield, uniquely situated beneath the city, is directly linked to the health of its surrounding urban waters. It is the City's only source of drinking water and is vulnerable to the urban pollution within the watershed (above it) as well as the condition of the coastal waters (adjacent to it). The City extracts groundwater from the Upper Floridan Aquifer through 28 production wells; 1.7 billion gallons of groundwater was extracted in 2008.

### 2.2 Water infrastructure

The water treatment plant is a reverse osmosis (RO) membrane water treatment facility. It provides high quality softening (removal of calcium and magnesium) of raw groundwater from its urban wellfield. The facility is the largest in the

United States to use greensand filtration for pretreatment to remove iron, manganese and hydrogen sulfide. The combination of greensand filtration and RO provides high quality water to its customers, allowing for flexibility in the treatment of a range of water quality types, now and in the future. The treatment process creates two byproduct streams: RO concentrate and greensand filter backwash. Both of these streams are sent to the WWTP.

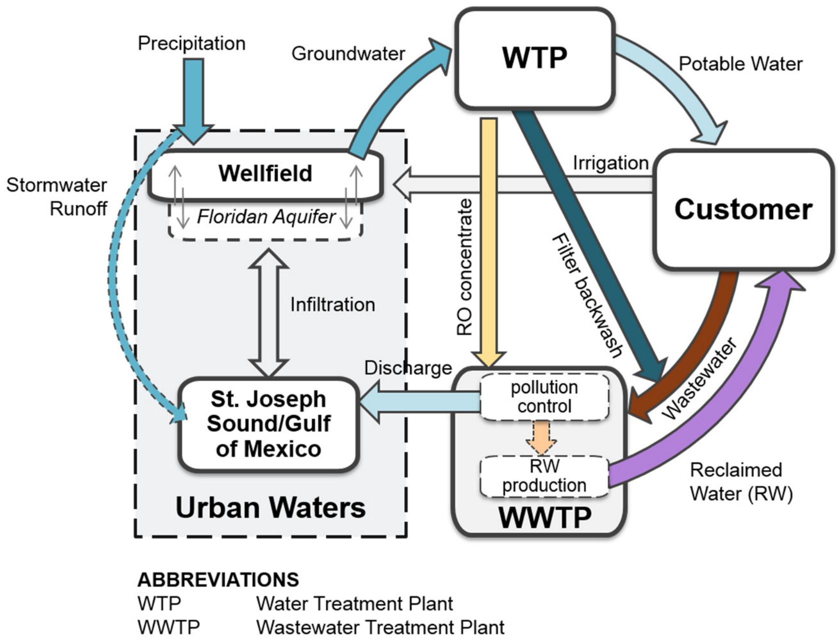


Figure 1: Dunedin's urban water cycle.

The wastewater treatment plant performs a very important role in the urban water cycle at Dunedin: it reduces pollution and it produces an alternative water source for irrigation. Figure 1 depicts these two distinct functions. The wastewater treatment plant is an advanced biological nutrient removal ($A^2O$) facility. This efficient process allows for low energy wastewater treatment while providing high quality effluent to be used for irrigation of residential landscapes and golf courses, or discharged into St. Joseph's Sound during the wet season.

The City's stormwater collection system consists mostly of traditional drainage methods. Roadside gutters or swales are used, using gravity to route stormwater through underground piping systems with outfalls to stormwater ponds or water bodies within its respective drainage basin. Since St. Joseph's Sound is immediately adjacent to Dunedin's watershed basins, it receives all the stormwater runoff, bringing with it common urban water quality issues, caused by the transport of sediments and nutrients.

# 3 DPSIR analysis

## 3.1 Identification of existing DRIVERS

In order to anticipate the pressures on water supply in this coastal city, the driving forces were identified. The main driving forces are urbanization and climate change.

## 3.2 Identification of existing PRESSURES

### 3.2.1 Development

Dunedin lies within Pinellas County, the most densely populated county in Florida, with more than 3,000 people per square mile [13]. Dunedin has a permanent population of approximately 35,000, which translates into a fairly high population density compared to many coastal cities. Dunedin's white sandy beaches and subtropical climate also attracts temporary visitors; tourists during the warmer months and *snow birds* during the cooler months.

The City is nearly built-out with watersheds are 98% to 100% developed. Dense urban areas such as these leave little room for changing the issues they cause. For instance, conventional development often has expansive impervious areas, which generate a significant amount of stormwater runoff. With minimal pervious areas, urban flooding can be a problem. In addition, groundwater recharge is obstructed and wellfield expansion is severely restricted due to the lack of land available for development.

### 3.2.2 Coastal location

Coastal areas pressures are a result of location, particularly due to issues regarding water supply. For instance, the majority of the US population lives in coastal counties. Urbanized coasts bring demands for fresh water, most of which depend on groundwater for at least part of their drinking water supply. These populations have increased 45% in the 40 year period between 1970 and 2010, and are expected to grow at a faster rate than those in noncoastal areas. Coastal cities are exposed to the threats of sea level rise (SLR) and changes in the frequency and intensity of storms, and are thus more susceptible to the effects of climate change than inland settlements. The topography along Dunedin's coast also affects effective functioning of water infrastructure and coastal water quality. The steep slopes along the Gulf's shoreline is such that stormwater drains by sheet flow directly into St. Joseph Sound and prevents its interception and treatment prior to outfall.

## 3.3 Existing STATE of water supply

### 3.3.1 Limited and sensitive water source

The precipitation in west central Florida is approximately 54 inches annually (1372 mm), most of which comes during the summer months in the form of thunderstorms. However, up to two-thirds of the water received returns to the atmosphere by evaporation or transpiration. Coastal locations like Dunedin tend to receive less rainfall than inland areas because of a lack of convectional heating [14].

Few communities in Pinellas County supply their own drinking water; Dunedin is one of them. Except for a tie-in to the Pinellas County water system as an emergency backup measure, it is water independent, relying on groundwater as its source for drinking water. Groundwater provides the benefit of a fairly consistent, relatively high-quality drinking water source for Dunedin. However, if mismanaged, there is a potential for undesirable impacts. Over-pumping has also been known to cause land subsidence and, in extreme cases, sinkholes. Karst, a type of geological formation, has a tendency for a high incidence of sinkholes common in this geographical location.

#### 3.3.2 Water quality

The existing quality of the groundwater is not ideal. It contains high levels of iron, sulfide and hardness, all of which must be removed. Furthermore, chloride levels in the freshwater wells have been increasing, indicating a graduate shift in diminishing water quality.

Surface waters are also susceptible to diminishing water quality, due to the pollutants and nutrients carried forth from pavement and landscaped areas to receiving waters, degrading the quality of the receiving waters [15]. Effluent from wastewater treatment plants also contribute to the diminished water quality. WWTP discharges its effluent into St. Joseph Sound.

### 3.4 Identification of existing and future IMPACTS

#### 3.4.1 High demands

High population densities create large demands on limited resources including water. Meeting demands can lead to over pumping of groundwater and can lead to the draw-down of groundwater levels, causing salt water intrusion (SWI) by lowering the hydraulic head.

#### 3.4.2 Water quality

Since St. Joseph Sound is immediately adjacent to Dunedin's watershed basins, the Sound receives all of its stormwater runoff, bringing with it common urban water quality issues, caused by the transport of sediments and nutrients. In 2008, Dunedin saw about 45 inches of rain, which translates into approximately 4.5 billion gallons of runoff for that year alone. The pollutant loading due to this volume was undoubtedly significant. St. Joseph Sound also receives pollutants from another source: the wastewater treatment plant; receiving about 1.5 billion gallons of discharge annually.

#### 3.4.3 Infrastructure

On the surface, a fully-developed community, without the worries of expansion or development, would imply an ideal situation. However, aging infrastructure requires maintenance and replacement, such as corroded or leaking water lines. Drinking water transmission lines transport water under pressure generally lose between 6% and 25% of their finished water through leaks and breaks [16, 17].

Sewer lines suffer a similar ailment; wet weather flows leak through inflow and infiltration (I&I). The City estimates that 24.5% of the wastewater flows are attributed to I&I. This additional volume of water translates into added chemicals, energy, labor and cost that must be invested to treat the diluted wastewater and be in compliance with State regulations.

#### 3.4.4 Storm surge

High pressure storm systems push Gulf water inland, creating storm surge, which brings saltwater into coastal communities. Flooding is worsened through the stormwater conveyance systems because they back up with both rainwater and saltwater. Also, a phenomenon known as stormwater backflow can occur through the conveyance system, where storm surge causes saltwater to travel backwards through the outfall pipes, inadvertently introducing saltwater to inland areas. This increases the potential for impacting groundwater quality, allowing saltwater to infiltrate vertically through the soil.

#### 3.4.5 Future effects of climate change

The City's challenges for the future are even greater. According to the United States Global Change Research Program, water scarcity, SLR and severe weather events are anticipated for the Southeastern United States and coastal areas due to changing climate [18]. Long periods of drought can affect recharge of the aquifer and cause a cascading effect of low groundwater levels, land subsidence and SWI. SLR can also have a detrimental effect on Dunedin. Even a seemingly minimal rises in sea level can cause permanent contamination of their only drinking water source through SWI. SLR can also reduce the effectiveness of stormwater systems. Some areas of Florida, such as Miami-Dade and Broward Counties are already seeing higher levels of coastal waters [19].

## 4 Responses

#### 4.1.1 Protect: prevent impairment

Protection of the drinking water source is of primary importance. A two-step strategy has been implemented to carefully manage the urban wellfield which allows the City to rely exclusively on its own water source. Step one is to increase the number of wells although there is no anticipated significant population growth. This strategy allows for better distribution of well locations more evenly throughout the area while extracting water at a lower rate (restricting withdrawals). The second step involves reducing the depth of the wells. A significant improvement in water quality has been detected in extracting water from shallower wells, at a 200 foot depth (61 m), than from deeper wells. A program for backfilling the deeper wells is currently underway. This two-step approach, carefully crafted to sustainably maintain their water supply, has been affectionately dubbed by its water managers as the *Sippy Straw Approach*. A sippy cup is an infant's drinking cup, specifically designed to restrict flow through the built-in straw and to prevent spilling if the cup is tipped because of its tightly sealed lid. Similarly, the Sippy Straw Approach mimics these two qualities, with the ultimate goal of judiciously restricting withdrawals and preventing waste. This approach also minimizes drawdown, making groundwater supply more resilient against SWI. A secondary benefit is that the number of sinkhole formations has been significantly reduced, from thirty to just over ten in one year.

#### 4.1.2 Reduce (conserve)

Water use reduction through conservation helps communities make the best use of existing water supplies and reduce pressures on the environment. Dunedin has implemented both traditional and innovative conservation methods in order to minimize wasteful practices and achieve maximum efficiency. An obvious indicator is the declining per capita use in spite of population increases. When the national average for per capita water use was at 183 gallons per day (gpd) (693 L/day), Dunedin's average in 2010 was 82 gallons per capita-day (gpcd) (310 L/inhabitant/day); considerably less than other Florida cities.

Figure 2 shows potable and reclaimed demand since 1990. Potable water consumption dropped from 131 gpcd (496 L/inhabitant/day) to its current rate of 62 gpcd (235 L/inhabitant/day, which does not include fire use or flushing); a reduction of approximately 50% since 1993. Reclaimed water consumption also dropped considerably. In 1997, only one thousand or so reclaimed water customers were receiving reclaimed water service. As the planned phases of the system were installed, the customer base grew. Service was provided to many residential communities as well as high volume users, such as golf courses.

Various approaches to help improve conservation were taken. For instance, in 1993, Dunedin worked together with the South West Water Management District to distribute indoor water reducing fixtures; the overall average water savings for the residential customers was 15.6%. An inverted rate structure was also implemented and has proven effective in the conservation of potable water. To reduce water consumption used towards irrigation, a landscape ordinance was adopted and low volume irrigation systems are mandatory in new developments. Finally, watering restrictions have been implemented to allow for residents to water their gardens and landscapes only one predetermined day per week, which is actively enforced. Reclaimed water conservation measures were also successful shown by the steadily decreasing gpd/customer trend and a 64% reduction (Figure 2). Scheduled watering days allow reclaimed water customers to watering their lawns and gardens to a three day per week allowance during predetermined times of the day.

#### 4.1.3 Reuse

Opportunities for reuse increase through integrated urban water management. The waste streams from the RO water production process totals approximately 1.0 MGD (3,785 $m^3$/day). Instead of discharging this waste to the nearby urban waters, it is reused to augmenting the volume of reclaimed water. In doing so, it closes the loop by minimizing the amount of point source discharges into coastal recreational waters, reuses water close to its point of origin (within the City limits), and closely matches the quality of water required for irrigation (its intended use) [20]. Another example of reuse is what occurs at the development at Honeymoon Island. This barrier island was slated for high density development. The water infrastructure was designed and in place prior to the completion of the final phase which never came to fruition. As a result, utility managers were faced with the issue of an oversized water main without the designed demands and a lift station with a fraction of the designed flows. Utility managers realized that the excess potable water could augment the much needed flow at the nearby lift station. A valve and discharge pipe were piped directly into the lift station, synergistically solving both issues and closing the loop on water loss.

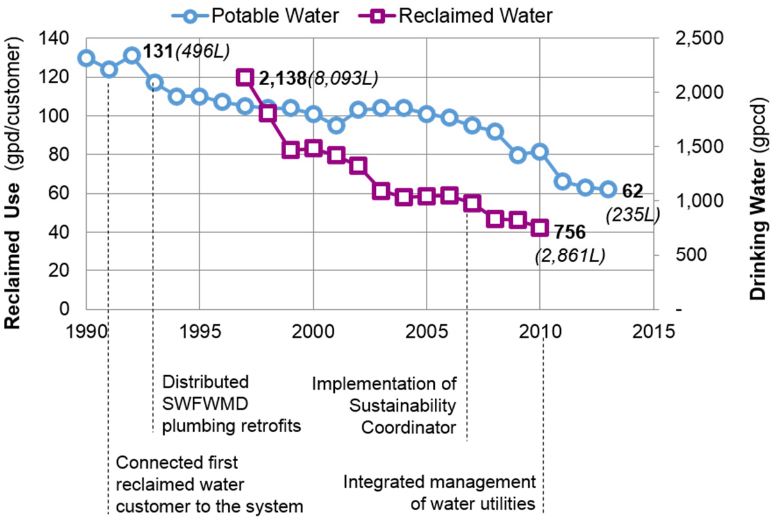


Figure 2: Historical potable and reclaimed water demand.

### 4.1.4 Recycle

Wastewater is consistently available in the urban setting. It can be recycled and is a drought-proof alternative water source that can be used for non-potable applications in an urban setting [21]. Yet, in 2008, only 2.5% of the treated wastewater from an estimated 21,594 publicly owned wastewater treatment facilities in the US was being recycled [22]. In Dunedin, wastewater flows quite consistently at an average 4.6 MGD (17,413 $m^3$/day). Since approximately 50% of residential water use is non-potable in nature, reclaimed water is ideal as potable water offset.

Extensive recycling of wastewater into reclaimed water for irrigation significantly reduces nitrogen loading to St. Joseph Sound. It is part of Pinellas County's Aquatic Preserve and is the main area of recreational waters. During the dry season when irrigation demand is high, 100% of the wastewater is recycled and used as reclaimed water, resulting in zero discharge at the WWTP; an amazing feat. Because the demand for reclaimed water can sometimes exceed the available supply, the City has implemented an irrigation schedule that takes reclaimed water availability offline for one day during the week (Wednesdays) to allow time to replenish supplies in the water storage tanks. If necessary, raw groundwater is blended with reclaimed water to meet peak demand. This allows for an expanded reclaimed water customer base and achieves an overall net decrease in groundwater withdrawal.

#### 4.1.5 Infrastructure investment

With less than ideal groundwater quality, Dunedin researched appropriate treatment methods that would provide superior finished water quality. The treatment process begins with a pretreatment step using greensand filtration. This application uses potassium permanganate to oxidize the iron in the water. The iron is filtered and cleaned in the backwash cycle. As an added bonus, greensand also is effective in treating low levels of hydrogen sulfide, also found in the local groundwater [23]. The reverse osmosis membranes then remove remaining salts, bacteria, viruses and other compounds present in groundwater. This combined treatment method provides high quality water for its residents. Dunedin's coastal location makes it susceptible to changes in water quality due to SWI. Even in the case that brackish water were to partially offset groundwater withdrawals, the water treatment facility can treat water up to 2,000 mg/L of total dissolved solids [24].

Investing in smart grid technology for both potable and reclaimed water customers has contributed to Dunedin's success in water conservation. AMR (Automated Meter Reading) technology does more than save money by eliminating the labor required to read meters manually. Since AMR tracks water usage in real time, it can help pinpoint elusive water leaks in a relatively short timeframe, serve as a deterrent to those violating watering restrictions and helps water managers anticipate water demands tied to seasonal trends, to name a few.

## 5 Discussion and conclusion

The Dunedin case study shows how water can successfully be managed as a single resource under the IUWM paradigm, even with the limitations of traditional infrastructure. IUWM principles encourage sustainable extraction and use of water through the entire water cycle. It also provides multiple opportunities to synergistically address contemporary and future issues, such as that of changing water quality (i.e. increased salinity). However, though possessing the ideal water treatment method for groundwater that is viable in anticipation of uncertain and alternative climate futures, it does present unique challenges. For instance, the interconnection between the WTP and the WWTP limits the City's ability to produce water; the waste stream from the RO process must be properly diluted. Otherwise, the high level of dissolved solids in these waste streams can negatively affect the survival of the microorganisms in the activated sludge used at the WWTP.

The DPSIR analysis of the impacts resulting from the effects from climate and urbanization was useful in identifying policy and management of water in this coastal city, especially when considering the impacts of water demand on the environment and preventing the impairment of natural resources. The luxury of responding to an impact to the wellfield/aquifer, for instance, cannot be afforded;

the City's drinking water source could be irreparably damaged. This exercise also served to highlight that some impacts, regardless of which driver/pressure it was (i.e. drought or high demands), led to similar responses (conservation, preservation, etc.), all of which served to preserve natural resources.

However, there are challenges within the City that DPSIR does not capture. For instance, DPSIR does not pinpoint operational thresholds, such as increased salinity, within (a) the entire system or (b) between subsystems. Critical thresholds are thresholds that, if crossed, can have sudden and significant impacts [25–27]. Impacts from slow moving climate threats may not immediately manifest themselves in water operations until the utility is compromised. Water systems can continue to operate and achieve production and performance targets although system indicators fluctuate within a desirable regime. However, if these exceed system (or subsystem) thresholds, the entire system could fail within what seems a small margin [28]. Future research can involve providing a closer look at impacts and responses within water infrastructure systems and subsystems instead of only using human needs and the environment as endpoints. It is important to consider causal loops in a more dynamic setting and the interrelationships between subsystems and components in water systems.

## Acknowledgements

The authors would like to acknowledge Paul Stanek and the City of Dunedin for their kind contribution in sharing their time, knowledge and experience. This work was supported by the University of South Florida's Signature Research Doctoral Fellowship and the Alfred P. Sloan Foundation Graduate Scholarship.

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