# Putting the Power in Plants

## Using Green Infrastructure to Reduce Nonpoint Source Pollution in Aquatic Ecosystems in the Urban Center of Dublin

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Master Thesis Series in Environmental Studies and Sustainability Science,
No 2018:003

A thesis submitted in partial fulfillment of the requirements of Lund University International Master's Programme in Environmental Studies and Sustainability Science (30hp/credits)

**LUCSUS**
Lund University Centre for
Sustainability Studies

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Submitted May 15, 2018

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## Abstract

Coastal ecosystems are some of the most productive, and most at risk, in the world. These ecosystems are at risk due to the high levels of pollution entering the system. Most of this pollution comes from either run off or atmospheric deposition. There are a few ways in which this pollution could be tackled without a complete overhaul of societal systems, the most common solutions being grey or green infrastructure. Green infrastructure is often preferable to grey infrastructure due to its adaptability, longevity, and the multiple benefits it can bring to an area. Using Dublin as a representative urban area, this paper makes a case for reducing nonpoint source pollution through the implementation of green infrastructure methods. Complexity theory is highlighted to show how cities are complex adaptive systems that require flexible infrastructure to adapt to the evolving problems. DPSIR is used as a framework in this thesis to identify the main causes of pollution. qGIS is utilized to show the different land use in Dublin and potential areas for green infrastructure-based projects. Phytoremediation, green roofs, and living green walls are suggested to be implemented to reduce the flooding potential of the city and provide additional pollution minimizing qualities. In addition, a combination top-down and bottom-up approach for adjusting the social norms to rely more heavily on green infrastructure in the future is suggested.

**Keywords:** green infrastructure, Dublin, non-point source pollution, urban run-off, ecosystem services

**Word count: 10 562**

## Acknowledgements

In this acknowledgements section I would like to thank all of those at LUMES for accepting me into this program and allowing me to go on this wonderful two-year long journey. I have seen myself grow as a person and become this incredibly annoying critical thinker that questions everything I hear and see, and that is because of my classmates and the course itself.

I, obviously, would like to thank my parents, Andrea and Dale, for supporting me in this course of study, even though my dad doesn't think climate change is human caused (hint: it is). I'd also like to thank my brother, Jeff, for being wildly successful and putting unintentional pressure on me to be the same.

I would like to acknowledge my grandmother, Elvia Fernandez, for being the incredible, amazing woman that she was. She has influenced my life choices and academic goals more than she could ever have known, and I wish she could see this day. Gramu, I carry you with me and I always will. Thank you.

Thank you, Allie, for reading my thesis many times and suggesting feedback that brought it to the point it is today. I genuinely wouldn't have been able to do this without you. Thank you, Brynn, for calming me as I freak out, so I could calm you as you did. You two have been my rocks during this program, and I don't know what I'll do without you.

Finally, I would like to thank my thesis group, Aya and Gavin, and supervisor Stephen, for helping me through the process and giving feedback throughout the course.

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## List of Abbreviations

CAS(s) - Complex Adaptive System(s)

DPSIR - Driver Pressure State Impact Response

EPA - Environmental Protection Agency

EU - European Union

GI - Green Infrastructure

GRaLGW- Green Roofs and Living Green Walls

NPSP - Nonpoint Source Pollution

qGIS - Quantum Geographical Information Systems, a software program.

RBMP - River Basin Management Plan

RSLR - Rapid Structured Literature Review

SES(s) - Social-Ecological System(s)

UCoD - Urban Center of Dublin

UK - United Kingdom

USA - United States of America

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# 1 Introduction

## 1.1 Sustainability Problem

Sustainability science is a field defined by its intent to respond to the needs of current society, while considering and preserving the planet's life support systems for future societies (Jerneck et al., 2010). Ecosystem services are benefits that humans derive from nature, this includes provisioning, cultural, and regulating services (Cord et al., 2017). A few examples of these various services are crop yields (provisioning services), aesthetic pleasure (cultural services), and temperature regulation (regulating services) (Cord et al., 2017). Ecosystem services are included within this life support system due to their provisioning and regulating capabilities, and should be considered when researching within the field of sustainability science. While considering the preservation of these ecosystem services, one must also consider the needs of society, which fluctuate in conjunction with changes in human lifestyles, such as consumption rates and dietary habits. These changes vary temporally and geographically, adding to the complexity of problems within the field of sustainability.

Some global changes that are expected in the future are: an increase in population size, increasing pressures on societies, and more technological advances (Hoorens et al., 2013). More specifically, global trends predict a rise in the middle class, increasing inequality, and changing consumption trends (Hoorens et al., 2013). Due to the predicted increase of the middle class and global population, consumption patterns and pollution rates are expected to rise (Hoorens et al., 2013). Western societies tend to lean on technological advances to overcome problems, such as electric cars being manufactured to reduce carbon emissions, flood walls being constructed to reduce flood damage, or the idea of carbon capture and storage technology to mitigate climate change. While these technologies may be innovative and promising solutions, they are complex and inflexible, which may lead to insufficient or only temporary solutions. It is important to keep in mind that new inventions may not be necessary or the best option for solving complex problems.

One major challenge that humanity faces is providing for this growing human population, which is expected to reach roughly 9 billion people by 2050 (Cohen, 2003). Of all provisioning ecosystems available, coastal ecosystems are perhaps the most productive (Brooks et al., 2016). Coastal ecosystems provide a multitude of services, including the regulating, cultural, and provisional services mentioned above. Regulating services of coastal ecosystems include shoreline stabilization, carbon sequestration, and thermal regulation (Agardy et al., 2005). Cultural services include tourism, emotional benefits (reduced stress), and recreational use (Agardy et al., 2005). And finally, provisional services such as a food supply, energy resources, and natural products are also provided by coastal ecosystems (Agardy et al., 2005). These multifaceted attributes of coastal ecosystems are what identify them as one of the most productive ecosystems.

Unfortunately, coastal ecosystems are also among the most threatened ecosystems due to current levels of consumption and human lifestyles (Agardy et al., 2005). The increase in population size and density of coastal areas is an additional aspect which will likely affect coastal ecosystems. Nearly 40% of all people live within 100km of the coast, and these populations are increasing rapidly (Agardy et al., 2005). Some of these urban centers are having a negative impact on aquatic ecosystems, with some measurable effects being: changes in sediment flows, algal bloom increases due to decreased water quality, increase in invasive species due to changing temperatures and ecosystems, and toxic pollution from industry and the increased population (Agardy et al., 2005). The majority of this pollution (77%) originates from the land, and has been shown to come from either run off or atmospheric deposition (Agardy et al., 2005).

These threats work together to change the way the coast functions. In changing the way the coast functions the ability for the ecosystem to provide the same services is impacted. Invasive species, for example, use resources that would otherwise have gone to native species, potentially leading to the decline of the native species from the ecosystem (Agardy et al., 2005). The disappearance of one species from an ecosystem can have negative economic effects: take, for example, the disappearance of a monetarily valuable mussel species in New Zealand (Agardy et al., 2005). Therefore, it can be stated that preserving coastal ecosystems is a necessary action and reducing pollution will lead to increases in the overall health of such ecosystems.

### 1.2 Why Green Infrastructure?

Green infrastructure (GI) is comparable to grey infrastructure (seawalls, levees, and breakwaters being examples of grey infrastructure), however GI has some additional benefits. Grey infrastructure, or man-made structure, is becoming more economically and ecologically unsustainable, especially with regards to the large variations in weather events related to climate change (Morris et al., 2018). Urban areas will be impacted by climate change in particular (Gill et al., 2007). One of these measurable impacts is the urban heat island effect, which is when urban areas have a higher average temperature than their surrounding area that is caused by the higher level of energy usage comparatively (Gill et al., 2007). Additionally, urban areas have different hydrological processes, resulting in a higher volume and rate of runoff (Gill et al., 2007). Grey infrastructure generally has one use, such as seawalls, which protect inland structures from storm surges (European Climate Adaptation Platform, 2015). In contrast, GI has the potential to perform multiple services, which can span further than the primary reason for implementation (Reguero et al., 2018). GI is comparable in cost to grey infrastructure, and even has the potential to reduce cost over a long-term scenario (Reguero et al., 2018). The low cost of introduction, reduced maintenance cost, and provision of ecosystem services are the leading draws of GI (Onuma & Tsuge, 2018).

Due to the potential application of GI for multiple purposes and its efficacy in urban areas in the face of climate change, this research focuses exclusively on GI as a means to reduce pollution levels.

### 1.3 Research Question and Aims

With human behaviors causing high levels of pollution in aquatic ecosystems, discovering potential solutions is imperative to preserve these ecosystems. In order to narrow the scope of research for this study, the city of Dublin, Ireland was selected as the urban center to be studied, the reasoning for which is described in Section 3. To further improve the clarity and specificity of the study, it was essential to stipulate what source of pollution would be studied. Nonpoint source pollution (NPSP) was identified as an understudied source of pollution, as agricultural and industrial pollution were the focus of prior studies in the study area (Coveney, 2017). NPSP is defined as pollution that comes from a number of diffuse sources, such as urban runoff, unlike pollution from a particular source, such as from treatment plants (EPA, 2017). Some examples of NPSP are oil and grease from vehicles, pesticides and nutrients from gardens, waste from septic systems, road salts, and heavy metals from roofs, vehicles, and other sources (United States, Environmental Protection Agency, Nonpoint Source Control Branch, 2003).

The primary aim of this study is to identify the potential for sustainable (green) infrastructure to reduce aquatic pollution in the coastal city of Dublin. To identify the potential, the following questions were addressed throughout the research process:

1. What types of green infrastructure would be most effective environmentally, economically, and with regards to the ease of implementation in an urban area to reduce the impacts of nonpoint source pollution on aquatic ecosystems?
2. From a spatial planning perspective, where can green infrastructure be implemented to reduce the impacts of nonpoint source pollution on local aquatic ecosystems?
3. What methodology is available to integrate this green infrastructure within city planning?

This report was limited to a theoretical application of infrastructure, discovered through literature review and the use of a geographical information systems program, qGIS, to identify potential areas of application for the proposed infrastructure.

# 2. Theoretical Setting

## 2.1 Theory

The theory that is applied to this thesis is complexity theory. Complexity theory, particularly aggregate complexity, is concerned with how individual elements work together in order to form complex systems (Manson, 2001). This theory considers the relationships between elements, how they are nonlinear and constantly evolving, and how complex behaviors may emerge from simple, local interactions (Manson, 2001). Norberg and Cumming (2008), define complex adaptive systems (CASs) as systems that "...are made up of interacting components (the system) whose interactions may be complex (in the sense of nonlinear) and whose components are diverse and/or have a capacity for learning that generates reactive or proactive adaptive behavior" (p. 2). A city can be considered a CAS as it is made up of multiple different components that work together to form certain outcomes. For instance, a city has interactions between people, infrastructure (roads, buildings), transportation (cars, buses, bikes), and the environment (water, plants, air) that all work together to form a CAS.

Within this case the CAS focuses on how social norms reinforce the human actions that result in NPSP. Social norms are expectations about appropriate behaviors within a group context that are formed within group situations and characterize regularities in attitudes and behaviors, which are often distinct between social groups (McDonald & Crandall, 2015). The social norms within cities have helped to dictate how urban centers are laid out. In this case, the reliance on automotive transportation is particularly important. One way of understanding how these urban centers are laid out, or the spatial planning of a city, is through spatial software, such as qGIS. Depending on the context of the urban center, construction materials may differ and can be impacted by various social norms which outline what is appropriate material for building use. The choice of building material affects what pollutants are released into the environment, for example most roof material results in heavy metal runoff (United States, Environmental Protection Agency, Nonpoint Source Control Branch, 2003).

Connected to the social norms of a city, the aforementioned reliance on automotive transportation influences human actions and reinforces the daily use of vehicles. This daily use of vehicles affects the amount of pollutants being released, such as oil and gasoline from the cars. An increase in population size could result in an increase of vehicles on the road, further affecting the pollution levels. These human actions and use of fossil fuel reliant vehicles have an effect on climate change, increasing the frequency and severity of flooding and extreme weather events (NASA, 2017).

Weather events, such as increased precipitation, then move water across the impermeable roads in urban areas, picking up particulates, like oil, as they move towards water bodies (rivers, lakes, estuaries, bays, and/or oceans). Once this runoff is introduced into the aquatic ecosystems, it begins to alter the habitat and negatively affect the health of the system as described in Section 1.1.

As explained, pollution levels are increasing, and future trends in population growth will only exacerbate the problem. There is a need to reduce these pollution levels in order to protect the ecosystems around society. Some ways to mitigate this are changes in social norms and behaviors, future advances in technology, and addition of new infrastructure. Changes in social norms and human behavior may be the most effective, however people have a tendency to resist change (Halvorson, 2012), therefore this may be the most complex and difficult change to implement. In addition, the longer a system has been in place, the more people believe, consciously or subconsciously, it is the best way to do things (Halvorson, 2012). Technological advances may be effective; however, they take time to test for efficacy before implementation, and time is of the essence. It is for this reason that addition or modification of infrastructure is the most reasonable step forward.

Social norms, human behavior, pollutant levels, weather events, and ecosystem health are all interconnected parts of this system. This makes the study area within this thesis a CAS, as these components affect and react to each other. Although addressing and changing the social norms would be beneficial, the implementation of behavioral change it is too difficult to address in a short time frame, and therefore is not the focus of this thesis.

The methods of analysis in this project are a literature review and the use of qGIS. The literature review identifies how GI is useful, why it can be an improvement upon standard infrastructure, and names specific types of GI for the case. qGIS is necessary to understand the spatial aspect of city planning, the relative permanence of a city's layout, and to identify best areas for GI implementation with the least amount of disruption to current human actions.

### 2.2 Framework

The framework chosen for this study is the driver-pressure-state-impact-response (DPSIR) framework introduced by Burkhard and Müller (2008). This framework aims to "identify and describe processes and interactions in human-environmental systems" (Burkhard & Müller, 2008) (p. 967). Within this framework, drivers are the factors that cause change in the behavior of a system (Burkhard & Müller, 2008). Pressures are the initial consequences of the mainly human caused actions that result from the driver (Burkhard & Müller, 2008). The state is often the environmental indicator that has reacted to the pressures or driver (Burkhard & Müller, 2008). Impact is the response to changes in the state, generally some circumstance of human life (Burkhard & Müller, 2008). Finally, the response refers to the human action that occurs in an attempt to address some portion of the system (Burkhard & Müller, 2008). In order to be most effective, the response should address the driver and/or pressure to improve the environmental state (Burkhard & Müller, 2008). Through the identification of cause and effect relationships, DPSIR helps identify proper solutions. To view how DPSIR is applied to this study in depth, see section 6.1.

# 3. Situational Context

## 3.1 Identifying a Study Area

Several criteria were considered to determine the area of study. In order to ensure an availability of readable literature, preference was given to urban areas with the dominant language of English. In addition, the search area was limited to the European Union to allow for travel to the study area if this was deemed necessary. This narrowed the potential study area down to the Republic of Ireland, and from this Dublin was chosen due to its size and anticipated future development (Brennan, Hochstrasser, & Shahumya, 2012).

## 3.2 Background on Dublin

Dublin, located on the Eastern coast of Ireland, is the country's capital and holds a population of an estimated 1.2 million people (World Population Review, 2017). The city has experienced a rapid urban expansion in the past 20 years, much of which has been economically driven and led by developers (Brennan, Hochstrasser, & Shahumya, 2012). Some observed consequences of this expansion have been urban sprawl, congestion, and a reduction in environmental quality (Brennan, Hochstrasser, & Shahumya, 2012). Brennan, Hochstrasser, and Shahumya (2012) simulated potential developmental trends for Dublin, and these showed that if these trends continue in this area, there will be negative impacts on the environment surrounding the area, reducing the ability for the ecosystem to provide ecosystem services. Within the coastal area of Dublin, the simulated development and urbanization increased the volume of runoff, and also showed an increase in flooding events for this area (Brennan, Hochstrasser, & Shahumya, 2012). Because of this, construction of buffers along rivers, construction of artificial wetlands, and utilization of porous pavement have been called for to reduce run-off (Brennan, Hochstrasser, & Shahumya, 2012).

Urbanization resulting in an increase in population density and an intensification of recreational pressures are putting additional stressors on Dublin Bay, which is one of the five most important wetlands in the country (Brooks et al., 2016). The rivers Liffey, Dodder, and Tolka, as well as the Royal and Grand canals, all drain into this bay, with Liffey being modified to supply electricity and water to the city, and with Dodder and Tolka being well known for flooding (Brooks et al., 2016). There is an input of excess contaminants from sewage, industrial waste, agricultural runoff, and, most important to this paper, urban runoff, which remains a concern for the maintenance of Dublin Bay (Brooks et al., 2016). In particular, this contamination comes from the rivers Liffey and Tolka (Brooks et al., 2016). The fluctuating levels of nutrients is a cause for concern because it modifies the way ecosystems function (Brooks et al., 2016), and with Dublin Bay being one of the most important wetlands in the country, it is paramount that it maintains a healthy balance of nutrients. Algal blooms and invasive species have been recorded as increasing in Dublin Bay and expect to continue increasing with climate change, causing concern over its maintenance (Brooks et al., 2016).

### 3.3 River Basin Management Plan, Dublin

Dublin's River Basin Management Plan (RBMP) features sustainable development as a goal, and focuses on a catchment-based framework, a collaborative approach that includes all stakeholders, and the sustainable use of water (Coveney, 2017). It highlights the use of 1.7 billion Euros to improve the infrastructure and protect high status waters through a variety of programs (Coveney, 2017). As current wastewater infrastructure in Dublin is lacking, it is reasonable to say that the application of money to address this is appropriate. Examples of inadequate wastewater infrastructure are: the high levels of pipe leakages, and the use of outdated pipe technology such as cast-iron pipes, asbestos pipes, and mild steel with PVC pipes (McGee, 2018). The issue is so severe that the Environmental Protection Agency (EPA) has criticized the Irish system, which doesn't comply with standards, given fines to Ireland due to this non-compliance, and is taking Ireland to court over these problems (O'Sullivan, 2017). This situation further shows the necessity for this 1.7 billion Euro investment into Dublin infrastructure.

In addition to this investment in infrastructure, there is a focus on licensing urban wastewater discharges, investing in wastewater treatment, and implementing the Nitrates Action Programme in order to reduce the excess runoff of agricultural nutrients (Coveney, 2017). Within this plan, 1,515 water bodies are labeled as at risk, 1,945 water bodies are not at risk, and the remaining 4,832 water bodies within the Republic of Ireland require further investigation to determine their status (Coveney, 2017). Of the water bodies at risk, pressures include agriculture, urban wastewater, domestic wastewater, peat extraction, and urban runoff (Coveney, 2017). There is a long-term trend of decline in the status of rivers, with fewer being labeled as high status, or in good condition (Coveney, 2017).

Within the RBMP, there is a directive that requires the maintenance of buffer zones near watercourses where fertilizer is not allowed (Coveney, 2017), however this directive is restricted to agricultural areas and does not extend to urban areas or urban runoff. This is problematic due to the fact that while urban runoff accounts for 10% of the pressure being put on these waters and is identified as a significant pressure for water quality in areas downstream of urban centers (Coveney, 2017), strategies to reduce this number are not addressed in this action plan. Additionally, there is no mention of GI in the report, suggesting that grey infrastructure and hard methods are currently the only options that Dublin's city council is considering to help remedy these problems. It is within this research and planning gap that this thesis attempts to find its niche, identifying a potential plan to increase the water quality in Dublin Bay through sustainable methods.

## 4. Green Infrastructure

### 4.1 Defining GI

GI has a variety of definitions that differ slightly from publication to publication. According to Lennon and Scott (2014), GI aims to "understand, leverage, and value the different ecological, social, and economic functions provided by natural systems in order to guide more efficient and sustainable land use and development patterns as well as protect ecosystems" (p. 564). In another article, Lennon (2015) refers to GI as "a belief in the ability and necessity of planning, designing, constructing and managing nature to deliver desired benefits from particular 'environmental resources', be they watercourses, green open spaces or tree-lined streets" (p. 958). This definition refers to GI as an ecological network, often used when discussing habitat conservation and restoration (Lennon, 2015). An additional definition is put forth by Lennon, Scott, and O'Neill (2014), where GI is seen as "an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions and provides a wide array of benefits for people and wildlife" (p. 750). For the purposes of this thesis, the latter definition is how GI will be interpreted. As this definition is quite broad, it encompasses a multitude of options available when implementing GI and allows for the specialization of implementation on a case by case scenario.

### 4.2 Global History of the Phrase

GI is a term commonly used in Ireland, the United Kingdom (UK), and The United States of America (USA), however it has different implications in each of these countries. The history of GI in Ireland has historically referred to habitats, but the discussion has been moving away from this niche and towards the use of green areas that have been neglected by planners for multiple functions (Lennon, 2015). The discussion is also beginning to emphasize that green space isn't doing nothing, but it is actually beneficial and providing services to the surrounding area (Lennon, 2015). With these considerations, society in Ireland is beginning to understand that GI enables development while still protecting the provisioning functions of ecosystem services (Lennon, 2015). In the UK, the concept of GI is rather ambiguous, however this is seen as positive because it allows the concept to adapt to a variety of different scenarios (Lennon, 2015). The definition of GI in the USA differs slightly from Ireland and the UK, in that GI is generally a term used when discussing sustainable development (Lennon, 2015). A common theme between all of these definitions of GI is that it is a framework through which ecological conservation, economic development, and social equity can be reconciled (Lennon, 2015).

## 5. Methodology

### 5.1 Literature Review

This thesis began with a literature review in order to identify potential methods for the reduction of NPSP caused by urban runoff in an urban center. Once GI was established as more beneficial than grey infrastructure, a methodology for finding literature was necessary. Due to the amount of time and resources necessary for a systematic literature review, a rapid structured literature review (RSLR) was performed. A RSLR, as identified by Armitage and Keeble-Ramsay (2009), is better suited for master's level research projects than a standard systematic literature review. RSLRs take methods from a systematic literature review, however they omit certain portions in order to streamline the process and provide information in a shorter time frame (Khangura et al., 2012). For this study, the aim was to find 15-25 articles within the area of study, as this was identified as an appropriate number of articles for a project of this size (Armitage & Keeble-Ramsay, 2009). It is noted that this process may result in a biased literature review, however all articles resulting from the RSLR were considered in an attempt to reduce the possibility of researcher bias.

Due to the higher availability of older articles compared to databases such as Scopus, Web of Science was used as the primary search engine (Chadegani et al., 2013). After establishing Web of Science as the main search engine and deciding upon using only academic, peer reviewed articles, a search string, or list of search terms, was made. The process of narrowing down this search string can be seen in Table 1. The resulting 14 articles (see Appendix A for an overview) were read to generate a background of information on GI and the potentials it holds. In order to deepen the knowledge on GI, supplemental articles were located when deemed necessary.

Table 1. Search string terms and number of resulting articles.

| Search Terms | Number of Results |
|---|---|
| (green OR sustainab*) AND (develop* OR infrastructure) | > 550,000 |
| (green OR sustainab*) AND (develop* OR infrastructure) AND (urban OR city) | > 23,000 |
| (green OR sustainab*) AND (develop* OR infrastructure) AND (urban OR city) AND (water AND purification) | 57 |
| (green OR sustainab*) AND (develop* OR infrastructure) AND (urban OR city) AND (water) AND (ecosystem service*) | 320 |
| (green OR sustainab*) AND (develop* OR infrastructure) AND (urban OR city) AND (water purification) AND (ecosystem service*) | 14 |

### 5.2 qGIS

In addition to a literature review, qGIS was determined to be a beneficial methodology for this project. qGIS enables researchers to spatially orient real-world scenarios through latitude and longitude. From this geographically accurate base map, layers can be built with additional information, which makes spatial analysis more easily accessible. Examples of information that can be placed into qGIS are road networks, land use, water bodies, and distance buffers. As this project deals with infrastructure, qGIS is valuable specifically in that it will enable the analysis of land use and the identification of potential sites for GI implementation in the urban area of Dublin. Land use is an important factor within this thesis due to the need to identify potential areas for GI implementation, which can only be done through an understanding of the current landscape. Therefore, spatial analysis is an integral part of successful GI implementation due to its ability to optimize benefits and minimize disruptions to the current system.

For the qGIS portion of this project, downloading relevant information was the first step. A vector, a representation of information in visual form, of the world coastline was downloaded from Natural Earth (Natural Earth, n.d.). Detailed information for Ireland was downloaded through Robert Hijmans' online data resource (Hijmans, n.d.). In order to locate the necessary information, Ireland was selected and administrative areas (for county boundaries), roads, and inland water (rivers and lakes) were downloaded. The roads located within this database were not detailed enough for the purposes of this study, therefore Geofabrik (2016) was used to provide a detailed map of roads. Land cover was located from the EPA, and the Corine Landcover 2012 files were downloaded (EPA, 2012).

This included a PDF with definitions of the coding to understand the different types of land within the GIS download. Each of these layers can be seen in Appendix B. Once all of the information was located, it was uploaded into a qGIS project as vector files, each in an individual layer. This enabled the identification and spatial analysis of land use within Dublin, as can be seen in depth in section 6.3.

# 6. Analysis

## 6.1 DPSIR

For this study, analysis began with the identification of the components within the DPSIR model, which can be seen in Table 2. As previously mentioned, DPSIR was chosen as the framework in order to help address the main aim of identifying sustainable infrastructure to reduce aquatic pollution. In order to reduce aquatic pollution, identifying the source of said pollution is essential, as if this is not done thoroughly, solutions put forward may not address the proper cause of the pollution, but the suspected or expected source. DPSIR enables a researcher to identify the specific drivers of a problem and formulate an appropriate response.

The drivers identified were the use of automobiles (cars, buses, motorcycles), urban infrastructure, the choice of material within the built environment, economic growth, and impervious surfaces. Pressures included urbanization, population growth, land use, pollution, and climate change driven events such as flooding and increased precipitation. The state of concern in this study is the high pollution levels within the aquatic ecosystems in Dublin. Reduced ecosystem productivity, changes in the function of the ecosystem, biodiversity loss, and invasive species are all identified as impacts. Finally, the suggested response is GI. These variables are expanded upon further in the following paragraphs.

Table 2. DPSIR Model

| | | |
|---|---|---|
| Drivers | -use of automobiles<br>-urban infrastructure<br>-building material choice | -economic growth<br>-impervious surfaces |
| Pressures | -urbanization<br>-population growth<br>-land use | -pollution<br>-flooding<br>-increased precipitation |
| State | -high pollution levels in aquatic ecosystems | |
| Impacts | -reduced ecosystem productivity<br>-changes in the ecosystem function<br>-biodiversity loss | -invasive species |
| Response | -green infrastructure | |

To reiterate, drivers are factors that cause change in the behavior of a system (Burkhard & Müller, 2008). The use of automobiles is identified as a driver because of the potential for the distribution of oil, grease, and heavy metals (United States, Environmental Protection Agency, Nonpoint Source Control Branch, 2003). Urban infrastructure in this scenario is referring to the way cities are laid out and the way they influence human actions, one example being the difficulty of functioning without using automobiles for transportation. The choice of building material affects the pollutants that enter the surrounding environment, often being heavy metals, which come from roofs (United States, Environmental Protection Agency, Nonpoint Source Control Branch, 2003). Economic growth tends to increase consumption levels and population size (Hoorens et al., 2013), which could lead to an increase in the number of automobiles on the road, intensifying the distribution of pollutants simultaneously. Impervious surfaces contribute to storm-water runoff and the quantity of surface pollutants (Zhou et al., 2017).

Drivers then cause pressures, which are the initial consequences of the mainly human caused actions in this case (Burkhard & Müller, 2008). These include urbanization and population growth, in general caused by the economic growth of the area (Hoorens et al., 2003). Land use change and increased pollution often occurs with an increase in urbanization (Hoorens et al., 2003). And finally, climate change due to industrialization is increasing the risk and rate of flooding and high precipitation events (Dunne et al., 2008).

The state, defined as the environmental indicator affected by the pressures and/or drivers (Burkard & Müller, 2008), is the high pollution levels within the aquatic ecosystems in Dublin. As mentioned previously, 1,515 water bodies in the Irish river basin are labeled at risk partially due to urban runoff (Coveney, 2017). In addition, the overall trend is a decline in the status of rivers within Ireland (Coveney, 2017). To reiterate, NPSP accounts for 10% of aquatic pollution in Ireland and is a significant pressure for water quality in areas downstream of urban centers (Coveney, 2017).

Impact has been defined as the response to the measured changes in the state (Burkhard & Müller, 2008). Reduced ecosystem productivity, changes in the way the ecosystem functions, biodiversity loss, and the introduction of invasive species are interconnected impacts in this case. The introduction of invasive species often results in competition between species, resulting in a loss of certain species and potentially a loss of biodiversity (Brooks et al., 2016). Alterations in the species that make up an ecosystem will change the way the ecosystem functions, and with a change in ecosystem function, there might also be a change in productivity and other related aspects

The last portion of the DPSIR is the response, or the human action that addresses the system (Burkhard & Müller, 2008). This report suggests GI as the proper response because of how it can impact certain drivers and pressures, specifically how it can affect impervious surfaces, building material choice, pollution, and flooding. GI can influence impervious surfaces by reducing the rate of storm water runoff, which would also slow the negative impacts from building material choice (Zhou et al., 2017). Phytoremediation, a form of GI detailed in the next section, would help reduce the amount of heavy metal pollution (in general from roofs and cars) (Fischerová et al., 2006). Finally, GI often helps reduce the chance of flooding through slowing the movement of water in a city (Young et al., 2014).

### 6.2 Phytoremediation

A valuable method to reduce NPSP is that of phytoremediation. Phytoremediation uses specific species of plants to pull toxic elements from the earth (Fischerová et al., 2006). As different plants are able to pull different toxins from the environment, establishing what plants would be valuable in Dublin relies upon understanding what pollutants are present in the waters. In Dublin, the waters are polluted with the metals Nickel (Ni), Cadmium (Cd), Mercury (Hg), and Lead (Pb) (Coveney, 2017). In particular, this contamination comes from the rivers Liffey and Tolka (Brooks et al., 2016). Certain plants are able to pull more than one of these contaminants from the ground, therefore they will be further examined in the following section.

One plant species that has been shown to be effective in pulling Ni from the environment is *Brassica juncea* (Panwar, Ahmed, & Mittal, 2002), commonly referred to as Chinese mustard (EOL, 2018a). *B. juncea* is able to survive within many climates, including that of Ireland (EOL, 2018a). In fact, it's already found on the Western coast of Ireland in County Clare (EOL, n.d.). For these reasons, the application of *B. juncea* in Dublin would be plausible for the removal of Ni

In order to pull Cd from the environment, several plants are listed as possibilities. *Noccaea caerulescens* (alpine penny-cress), *Arabidopsis halleri* (rockcress), and *Salix viminalis* (basket willow) are all able to extract Cd (Fischerová et al., 2006). Alpine penny-cress and rockcress are known as hyperaccumulators, which means they take up the most amount of toxin per dry mass (Raskin, Smith, & Salt, 1997). *N. caerulescens* is commonly found in the UK, therefore it could be adapted to the climate of Ireland easily if implemented in this scenario, however introducing a new plant is not ideal (EOL, 2018b). *A. halleri* is not commonly found in Ireland or the UK, therefore it is not suggested to introduce into the area (EOL, 2018c). For *S. viminalis*, willows are commonly found in the northern hemisphere in cold and temperate regions, such as Ireland and lower altitudes in the UK (EOL, 2018d). Because *S. viminalis* is already found in Ireland, it is the best candidate for utilization in this scenario.

For the removal of Hg, *Jatropha curcas*, commonly referred to as physic nut, has been shown to be effective (Marrugo-Negrete et al., 2015). Carica papaya wood and *Ricinus communis* (castor bean) are also effective at removing Hg (Kumar, Smita, & Flores, 2017). *J. curcas* unfortunately is only commonly found around the equator (EOL, 2018e), and therefore would not be suitable for application in this landscape. Carica papaya wood is similarly not found in areas such as Ireland (EOL, 2018f), deeming it unsuitable to use. While these two species are not appropriate for Ireland, *R. communis* is already found in Ireland and would be an effective Hg remediator (EOL, 2018g).

Finally, Pb has a multitude of plants that can be used for phytoremediation. *Thlaspi rotundifolium, Noccaea caerulescens* (alpine penny-cress), *Brassica juncea* (mustard plant), *Lolium perenne* (perennial ryegrass)*, Zea mays* (corn)*,* and *Helianthus annuus* (sunflower) have all been shown to be effective (Raskin, Smith, & Salt, 1997). Due to the fact that *N. caerulescens* and *B. juncea* have already been identified as remediators for other toxins, and *B. juncea* is already found in Ireland, it will make the most sense to apply it for both the remediation of Pb and Ni.

The former section has established that *B. juncea*, *R. communis*, and *S. viminalis* are all already found in or around Ireland and in combination would effectively help to remove Ni, Cd, Hg, and Pb from the environment. Therefore, these plants are suggested to be placed within Dublin in order to reduce NPSP's impacts on aquatic ecosystems.

### 6.3 qGIS

When beginning the process of analysis within qGIS, the area residing within the M50 motorway surrounding Dublin was established as the area of focus. This is due to the fact that the Urban Center of Dublin (UCoD) is generally accepted to be within these boundaries (Dublin City Council, n.d.). The study area can be seen in Figure 1. Within this area of study are a variety of types of land use, three rivers, and two canals, which will be expanded upon in the following paragraphs. It is worth noting that the topography within the study area exists within the same elevation (Hijmans, n.d.).

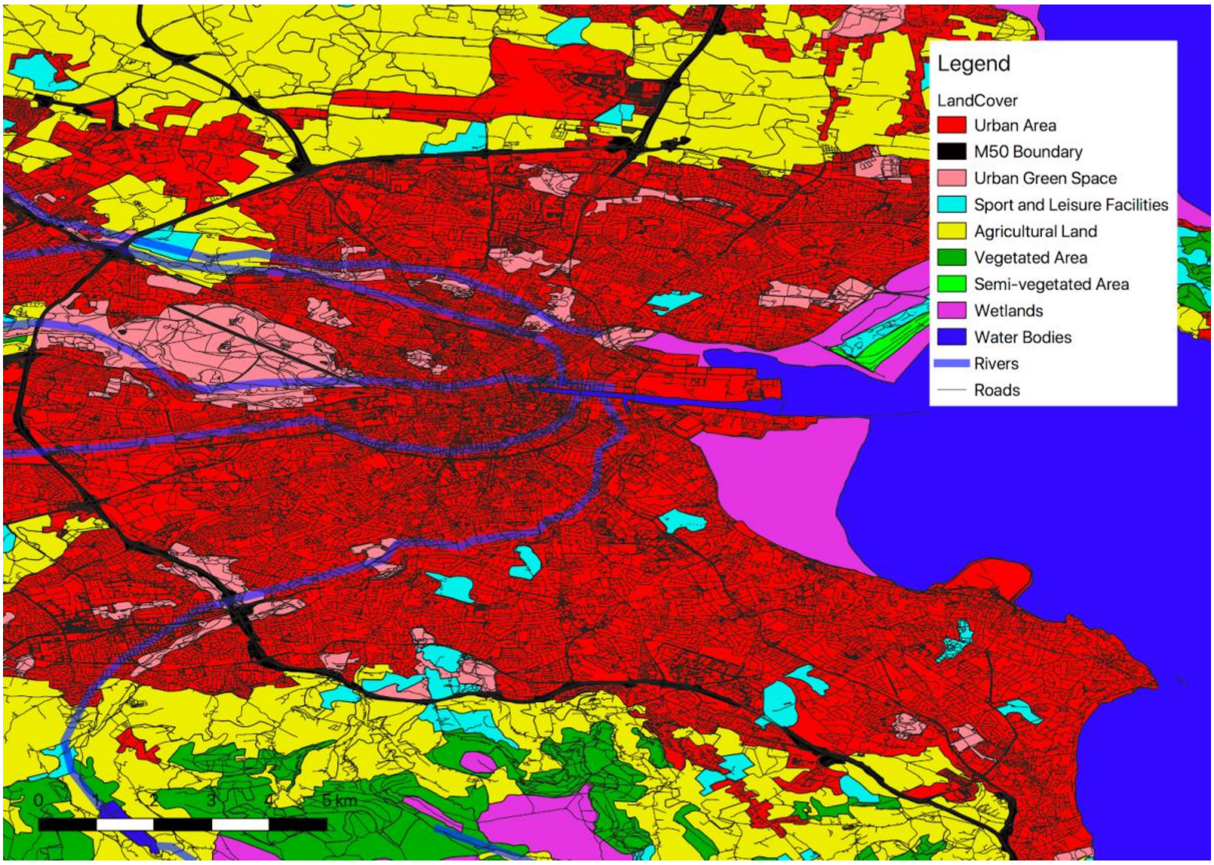


Figure 1. Black line represents the M50, or the outer boundary of the UCoD. In addition, the various land use within the UCoD is visible.

The first step taken in this analysis was to identify the variety of land use within the study area. The variety of land use can also be seen in Figure 1. The majority of land use within the area of study is either continuous or discontinuous urban fabric. Continuous urban fabric is defined as land that is mostly covered by buildings, roads, and other artificial surfaces (European Environment Agency, 1995). Similarly, discontinuous urban fabric is also mostly covered by buildings, roads, and artificial surfaces, but also has discontinuous areas covered with vegetated areas and bare soil (European Environment Agency, 1995). In order to simplify the identification of land use types, any urban area was identified as red, agricultural land coded yellow, vegetated areas as green, wetlands purple, and water bodies as blue. Two additional types of land use were identified, those of urban vegetated areas (pink) and sport and leisure facilities (blue). Urban vegetated areas include parks and cemeteries, and sport and leisure facilities are defined as campgrounds, sports grounds, golf courses, and racecourses (European Environment Agency, 1995).

It is important to note the placement of the different types of land use within the study area. The wetland areas between the urban center and the bay are classified specifically as intertidal flats at the southwestern and northern portions of the bay, and as a mixture of beaches, dunes, sands, and salt marshes at the northwestern portion of the bay. As intertidal flats are characterized by frequent flooding and exposure (Daidu, 2013), therefore they are not an ideal location for the implementation of GI. The inconsistent environment would not enable a long-term placement for GI, however it is important to note that constructed wetlands (engineered wastewater treatment systems that have similar processes to natural wetlands) are valuable in reducing environmental pollution (Babatunde et al., 2008).

The vegetated areas within the urban center are classified as either green urban areas or sport and leisure facilities as can be seen in Figure 1. In the eastern portion of the study area Phoenix Park can be found, which is an important green space within Dublin and will be expanded upon in the next paragraph. In the northern portion of the study area there are urban green spaces near the River Tolka, the Royal Canal, and the River Liffey. Due to this, the existing green space could be developed to produce more ecosystem services. Contrastingly, in the southern portion of the study area there is a lack of urban green space, which would necessitate the construction of additional areas.

Phoenix park is the largest enclosed park within a European capital city, and it is a hotspot of biodiversity for Ireland (Office of Public Works, 2017). Within this park, 50% of mammal species and 40% of bird species found in Ireland are supported (Office of Public Works, 2017). In addition, it has 351 different plant species within its boundaries (Office of Public Works, 2017). Phoenix park is an environmentally important area within Dublin, however it is not ideal to be used for any GI within the scope of this study due to it being situated upstream of the urban center. This means it would not be able to absorb pollutants coming from the urban center before they enter the aquatic ecosystem.

Within the study area, the River Tolka, Royal Canal, River Liffey, Grand Canal, and River Dodder are present (named as seen from North to South on the western portion of study area) and lead into Dublin Bay, as can be seen in Figure 2. The analysis of what space is available for the implementation of GI becomes more difficult when road networks are considered, as can also be seen in Figure 2.

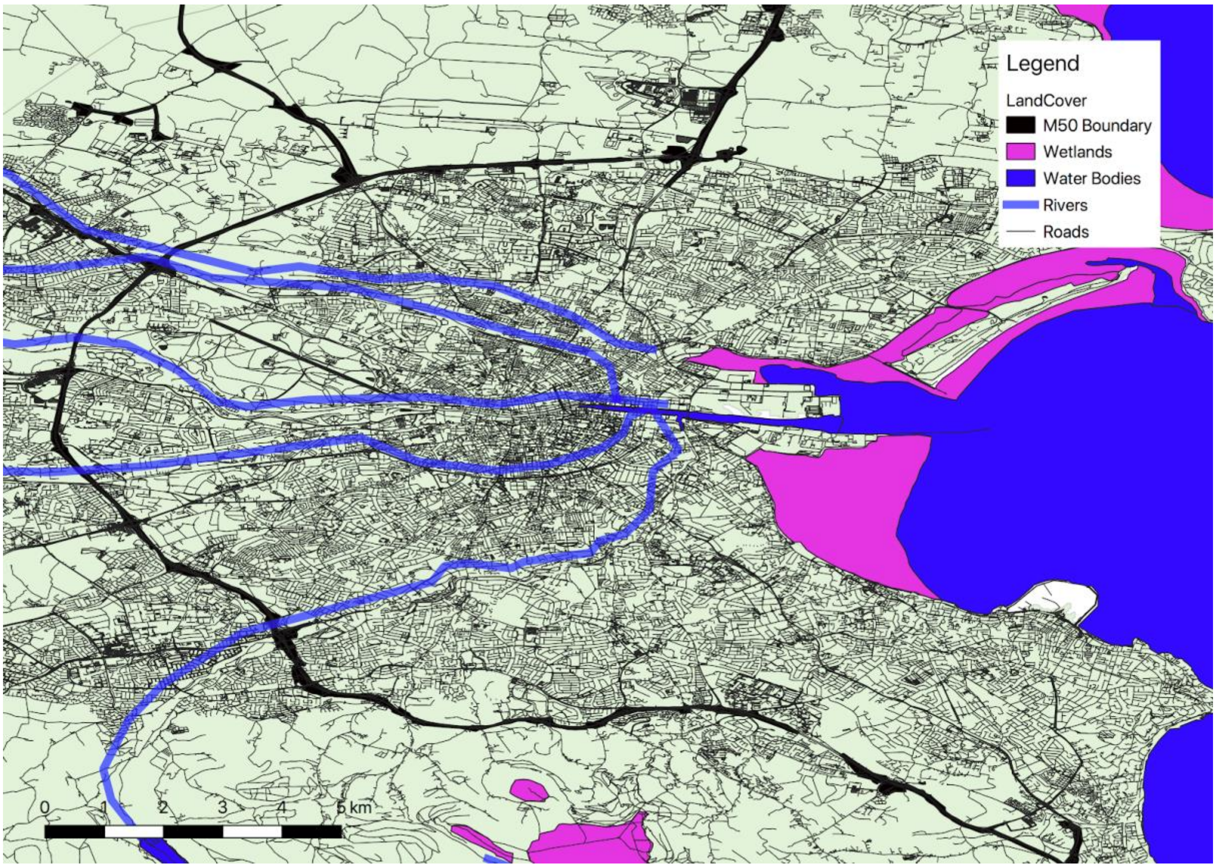


Figure 2. Rivers and roads within the study area. From North to South, the River Tolka, Royal Canal, River Liffey, Grand Canal, and River Dodder.

There are few possibilities for GI implementation, one being the use of current green space, one being the development of new green space, and finally the development of green roofs and/or living green walls (GRaLGW). The use of current green space and the development of GRaLGW are the most likely methods for implementation due to the lack of disruption in current city infrastructure. The next section discusses the implementation of these potential GI methods.

# 7. Findings and Discussion

## 7.1 Main Aims

Throughout this paper it has been established that GI is a promising sustainable methodology to reduce aquatic pollution in a coastal city. Phytoremediation can be used specifically to reduce the heavy metals within aquatic ecosystems. Three plant species have been identified to combat the specific heavy metal pollution in Dublin Bay, *B. juncea*, *R. communis*, and *S. viminalis*. In addition to this phytoremediation, green roofs and living green walls are suggested to minimize the causes of NPSP. At this point, the research questions posed in the beginning of this thesis are brought to focus again. The main aim for this study was to identify potential sustainable infrastructure to reduce aquatic pollution in a coastal city. Within this aim, the questions of finding an appropriate type of infrastructure, how to implement this infrastructure, and how to integrate this into city planning were specified at the outset of this study. In the following sections of this paper, each research question will be directly addressed.

## 7.2 Types of GI

The first research question posed in this study was 'what types of green infrastructure would be most effective environmentally, economically, and with regards to the ease of implementation in an urban area to reduce the impacts of nonpoint source pollution on aquatic ecosystems?' Since this project is mainly concerned with NPSP, due to the research and implementation gap within Ireland's RBMP, pollutants identified as NPSP were the focus. As previously mentioned, NPSP often consists of oil and grease from vehicles, pesticides and nutrients from gardens, waste from septic systems, road salts, and heavy metals from roofs, vehicles, and other sources (United States, Environmental Protection Agency, Nonpoint Source Control Branch, 2003). From the available data, heavy metals were decided to be the focus to reduce within this study as this area is known to be an issue within Dublin. The heavy metals that have been identified within Dublin Bay are Cd, Ni, Hg, and Pb. Through a literature review, it was established in section 6.2 that phytoremediation is an effective way to pull pollutants from an environment.

In addition to phytoremediation, GRaLGW may reduce the amount of NPSP while providing other valuable services and would be ideal for Dublin due to the high density of the urban center. Green roofs are roofs with a covering of vegetation that performs a variety of functions (Berndtsson, 2010). Studies on green roofs have shown that they are effective in reducing storm water runoff and reducing air pollution, in addition to benefits such as providing habitats, reducing noise levels, and thermal benefits that reduce the cost of heating and cooling (Berndtsson, 2010). Furthermore, green roofs are able to be placed in urban areas where ground level green space is sparse or unavailable (Berndtsson, 2010). In regards to effects on storm water runoff, green roofs retain a certain level of water before draining, enabling its use by plants or its evaporation before reaching aquatic systems (Berndtsson, 2010). While green roofs may not pull the pollutants from the surrounding landscape, as rainwater is generally considered to be unpolluted (Berndtsson, 2010), it will reduce the amount of water reaching the streets and slow the flow of pollutants. An important side note is that green roofs have been shown to reduce the air pollution (Francis & Jensen, 2017), which reduces the overall pollution in the system, and is beneficial in itself.

Living green walls provide similar benefits to those of green roofs, including increasing biodiversity, storm water management, an increase in air quality, and temperature regulation (Manso & Castro-Gomes, 2015). Additionally, green walls have the potential to provide more benefits than green roofs as their surface area tends to be larger (Manso & Castro-Gomes, 2015). While there are a few different varieties of green walls, living walls are the type suggested in this report due to their ability to combine multiple types of plants (Manso & Castro-Gomes, 2015). A living wall is characterized as a wall that has a lightweight screen placed over the building, onto which plants can be attached (Manso & Castro-Gomes, 2015). An example of a living green wall in Europe is the Caixa Forum in Madrid, which can be seen in Figure 3.

Figure 3. Caixa Forum, Madrid, 2018. Own photo.

In summation, to address the first research question, phytoremediation and GRaLGW would be the most applicable types of GI in Dublin due to the infrastructure, density, and the NPSP found in the city.

## 7.3 Where?

The second research question in this study is 'how and where can green infrastructure be implemented to reduce the impacts of NPSP on local aquatic ecosystems.' In section 6.2, the species of plants were identified that would be the most beneficial for use for phytoremediation. The qGIS portion of this paper in section 6.3 showed that there are limited areas within the study area to provide this GI, therefore additional green areas would be beneficial for phytoremediation. With GRaLGW, the space necessary is not ground space, therefore there are more available options with regards to them.

The addition of *B. juncea*, *R. communis*, and/or *S. viminalis* to the green areas identified in section 6.3 would help reduce the amount of NPSP reaching the aquatic ecosystems, but their positioning within the city is not ideal for implementation. Therefore, a more effective implementation would be the formation of green strips between roads and water bodies (henceforth referred to as green barriers) where *B. juncea*, *R. communis*, and *S. viminalis* could be planted. This would not disrupt the city infrastructure by removing current urban space, but would create green space in an underutilized area. Portions of the five waterways in Dublin could be given additional banks which would house the aforementioned plants. The creation of these green barriers in the Rivers Liffey and Tolka in particular would be most beneficial as the majority of contamination comes from these rivers (Brooks et al., 2016). Due to the fact that the pollutants gather as they move through the city towards the bay, green barriers which are closer to the bay have the potential to trap the highest amount of pollution. Following this logic, these green barriers should be placed as close to the estuaries and Dublin bay as possible as it would maximize the potential to trap pollutants.

One aspect to consider in this approach is that there is a potentiality that additional land mass may raise the water levels, increasing the risk of flooding. However, GI has been shown to reduce the frequency of flood events due to the slowing of the movement of water (Lennon, Scott, & O'Neill, 2014). Therefore, the implementation of green barriers and GRaLGW, in particular near the River Dodder and River Tolka which are known for flooding (Brooks et al., 2016), would have a positive effect on flood patterns.

With regards to GRaLGW, city buildings would be an initial target for implementation due to the city's jurisdiction over them. Once the GRaLGW are established, it can be determined to what level they are beneficial on whatever buildings available, and it would then be possible to advertise the benefits (environmental and economic) to other building owners who may show interest in the implementation. Some of these economic benefits include the improvement of the integrity of the building through a reduction of the weathering, energy savings through thermoregulation, and increasing the value of the property (Sheweka, & Magdy, 2011). For infrastructure owned by the city, which is aware of the economic benefits of GRaLGW, the implementation of GRaLGW would be easier to push for. Unfortunately, information on which buildings are publicly owned or privately owned within Dublin was not freely available, therefore it is unclear how many possibilities there are for the initial implementation of GRaLGW.

This research question asked how and where GI could be implemented, the answer to which is that GI could be implemented around the rivers with phytoremediation through the construction of some additional river banks, and initially on city buildings for GRaLGW with an expansion to privately owned buildings once the success of GRaLGW is proven.

### 7.4 Integration of GI

The final research question in this study asks, 'what methodology is available to integrate this green infrastructure within city planning?' In order to answer this question certain social norms must be identified, and potential methods to overcome these norms should be suggested. As previously defined, social norms are expectations in group contexts that characterize regularities in attitudes and behaviors and are often distinct between social groups (McDonald & Crandall, 2015).

Changing social norms is a complex process, but before diving into that, the social norms that need to be changed must be identified. In this case, one major norm that is being dealt with is the use of grey infrastructure over GI. When addressing problems in a publicly controlled institution, the tendency is to approach with grey infrastructure, as can be seen in the lack of the term GI within Ireland's RBMP (Coveney, 2017). As can be seen from the RBMP in Dublin, the central focus is to provide money to improve upon the waste management system, and GI is not an option mentioned in the report. Therefore the norm in Dublin is a tendency to rely on grey infrastructure to address issues of development as well as find potential solutions. As mentioned before, social norms are developed through expectations within society, therefore to effectively change this social norm, the structure of the society must be considered

In this paper, the two methods to instigate a change in social norms that will be addressed are a bottom up approach and a top down approach. A top down approach comes from the governmental body or the body that is in power, where a bottom up approach comes from individuals or groups at lower levels of power (Fromhold-Eisebith & Eisebith, 2005). Both of these approaches have been shown to be effective in different scenarios. A bottom up approach will rely on individuals or small groups to commit to a greener city until a tipping point is reached where the rest of society follows suit (Kinzig et al., 2013). This approach is further justified through studies that have shown that the pressure to conform, whether intentional or individually manifested, can be effective at shifting social norms (McDonald & Crandall, 2015). This tipping point can be as low as 10% of the community in order to affect systemic change (Kinzig et al., 2013).

A top down approach in this case would include the implementation of policies, regulations, penalties for noncompliance, and/or incentives. These policies must be focused on influencing a short-term change in individual behavior, but a long-term change in social norms (Kinzig et al., 2013). An example of such policy was the normalization of recycling in the United States. When policies requiring recycling or charging more for trash pick-ups were put in place, many people were unhappy with this required change in behavior (Kinzig et al., 2013). However, as time went on, recycling became a common occurrence, and not recycling became the social abnormality in many societies (Kinzig et al., 2013). This shows that top down policies regarding environmental impact can be effective when properly carried out.

Taking these things into account, a combination of top down and bottom up approaches may be the most effective. A study done by Christine Wamsler (2015) showed the efficacy of different mainstreaming activities for Ecosystem-Based Adaptations (EbAs) in eight municipalities in Southern Germany. EbAs can be defined as an adaptation strategy that uses biodiversity and ecosystem services to help sustain humanity (Wamsler, 2015). Six types of mainstreaming activities, broken down into two categories, were identified as successful. The first category, horizontal mainstreaming, or actions implemented by low power entities, includes add-on mainstreaming, programmatic mainstreaming, and inter- and intra-organizational mainstreaming (Wamsler, 2015). The second category Wamsler (2015) identifies is that of vertical mainstreaming. Both categories will be elaborated upon below. Vertical mainstreaming, or implementation by powerful government bodies, includes managerial mainstreaming, regulatory mainstreaming, and directed mainstreaming (Wamsler, 2015). Horizontal mainstreaming has many of the same principles of a bottom-up approach, and vertical mainstreaming shares principles with a top-down approach.

Starting with the different methods of horizontal mainstreaming, add-on mainstreaming refers to the implementation of projects or programs that are not part of a department's core, but that are directly targeting adaptation (Wamsler, 2015), and in this case directly targeting the implementation of GI. Programmatic mainstreaming modifies a group's core values by adding new values to projects and programs (Wamsler, 2015). Inter- and intra-organizational mainstreaming includes the collaboration between stakeholders in order to take joint action to push forward a new paradigm (Wamsler, 2015). Within the category of vertical mainstreaming, managerial mainstreaming refers to changing norms within an office and working on structures to institutionalize the new values

(Wamsler, 2015). Regulatory mainstreaming modifies policies, regulations, and legislation to help integrate the new values (Wamsler, 2015). Finally, directed mainstreaming redirects the focus to integrating the values, including funding, new projects, and education (Wamsler, 2015).

The research done by Wamsler (2015) suggests that a combined top-down and bottom-up approach is the most successful methodology for mainstreaming EbAs, and other research suggests the same for a shift in social norms (Kinzig et al., 2013; McDonald & Crandall, 2015). Therefore, a combination of top-down and bottom-up approaches to help mainstream the idea of GI into a social norm answers the final research question of what methodology is available for the integration of GI with city planning.

## 8. Conclusion

This study has aimed to show how GI can be beneficial within an urban center to reduce NPSP, using Dublin as a case study. Complexity theory was used to show how cities are complex systems and how changes in one sector of a city affects all other sectors of the city. DPSIR was used to represent these complex relationships and focus in on the causes of problems relating to NPSP in Dublin's aquatic ecosystems. This allowed the identification of GI as the most beneficial response. Phytoremediation utilizing specific plants, green roofs, and living green walls are the suggested types of GI to be implemented for Dublin due to the density of the city and the area of study. Forming additional barriers along rivers and using city buildings for the initial implementation of GRaLGW would be the first steps taken towards implementation. This process would require a shift in societal norms, specifically with regards to city planning and the present reliance on grey infrastructure. By using the economic benefit of GI as an emphasis, city planners may be more inclined to accept this approach and integrate it with current city planning.

### 8.1 Future Research

As within any thesis, there are gaps in the research. Further studies are suggested, specifically looking into the land ownership within Dublin to better identify possible placement of GRaLGW. In addition, the precise amount of heavy metals in Dublin Bay should be identified so a recommendation towards the quantity of plants for the phytoremediation could be identified. Finally, an action plan to mainstream GI within Dublin should be researched, similar to the research done on mainstreaming EbAs by Wamsler (2015).

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# Appendices

## Appendix A – RSLR Results

| Lead Author | Article Title | Publication Year | Key Words | Summary |
|---|---|---|---|---|
| Baron, Jill | Meeting Ecological and Societal Needs for Freshwater | 2002 | ecological education, ecological integrity, ecosystem protection, ecosystem services, freshwater, freshwater ecosystems, lakes, restoration, rivers, waterflow, quantity, quality, timing, seasonality, water management policy, watersheds, wetlands | Dynamic environmental drivers affect what an ecosystem needs to function properly. We must protect these and restore ecosystems in order to have optimal functioning. |
| Gao, Jie | Application of BMP to urban runoff control using SUSTAIN model: Case study in an industrial area | 2015 | stormwater management, best management practices, SUSTAIN model, optimization, ecosystem services | BMP includes green infrastructure in order to reduce the amount of npsp in urban areas due to urban runoff. |
| Kattel, Giri | Developing a Complementary Framework for Urban Ecology | 2013 | Complementary framework, Ecological resilience, landscape design and architecture, urban ecology | Aims to develop a framework to help with the ecological resilience of urban ecosystems (E-LAUD - ecosystem, land use, architecture, and urban design). |
| La Rosa, Daniele | Characterization of non-urbanized areas for land-use planning of agricultural and green infrastructure in urban contexts | 2013 | Non-urbanized areas, land cover, fragmentation, proximity, suitability matrix, land-use planning | Non-urban areas, or green space in metropolitan areas, are exceedingly important in the face of climate change due to their ability to perform ecosystem services. These areas are currently threatened by urban sprawl, therefore scenarios for land-use should be planned with environmental, social, economic, and cultural benefits in mind. |

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|---|---|---|---|---|
| Liquete, Camino | Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits | 2016 | Sustainable urban drainage systems, constructed wetland, ecosystem services, integrated valuation, multi-criteria analysis, water management | Green infrastructure, comparable to grey infrastructure in cost, is the most effective methodology for water pollution control in the area of study for this project. Green infrastructure has been shown to be more efficient, adaptable, have many purposes, and last longer than grey infrastructure for similar projects. |
| Liu, Huan | "Sponge city" concept helps solve China's urban water problems | 2017 | N/A | A "Sponge city" refers to an urban environment that aims to find ecologically suitable alternatives to grey infrastructure, transforming infrastructure into GI so water is able to be captured, controlled, and reused in a useful way. The utilization of this in China would reduce the country's water problems in a manageable and sustainable way. |
| Mexia, Teresa | Ecosystem services: Urban parks under a magnifying glass | 2018 | Ecosystem services, urban parks, spatially detailed, land management, vegetation type | Urban parks are areas that provide several valuable ecosystem services, but the services rendered depend on the types of vegetation in the park. Knowing what types of vegetation make up the park can aid in developing the best management practices for the area. |
| Shen, Chengcheng | Study on the cumulative impact of reclamation activities on ecosystem health in coastal waters | 2016 | Reclamation, ecosystem health, coastal ecosystem, marine management, assessment model, Bohai sea | Developed a model and indicator system to assess the impact of reclamation activities on ecosystem health in coastal waters. Cumulative impacts on ecosystem health varies between reclamation phase, environmental interface, and reclamation function. |

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|---|---|---|---|---|
| Sun, Xiang | Integrative assessment and management implications on ecosystem services loss of coastal wetlands due to reclamation | 2017 | Coastal wetlands, agriculture-related ecosystem service, reclamation, ecological infrastructure, China | Presented a modified ecosystem services valuation method to integrate the valuation of ecosystem services into the assessment, management, planning, and restoration of coastal infrastructures. |
| Sun, Xiao | Spatiotemporal assessment and trade-offs of multiple ecosystem services based on land use changes in Zengcheng, China | 2017 | Ecosystem services (ESs), land use change, alternative scenario, trade-offs | Rapid urbanization resulting in land use change negatively affects ecosystem services, therefore assessing the spatiotemporal changes associated with ecosystem services is vital. Urbanization impacts a variety of ecosystem services differently, with water supply, water purification, and vegetable and fruit production increasing and soil conservation, biodiversity, climate regulation, and grain production decreasing between 2003 and 2013 in Zengcheng. |
| De Troyer, Niels | Water quality assessment of streams and wetlands in a fast growing East African city | 2016 | Impact of urbanization, water quality, decision support in water management, invertebrates, chemical assessment, biological assessment | Urbanization, industrialization, population growth, and low environmental awareness are threatening the freshwater resources and ecosystem services these provide worldwide. A rapidly growing city in Southwest Ethiopia was studied, and possible remediation options were evaluated. Waste stabilization ponds and constructed wetlands are proposed as techniques that could purify the wastewater in a sustainable, cheap, effective, and reliable way. |

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|---|---|---|---|---|
| Verma, Madhu | Valuing ecosystem services of wetlands- a tool for effective policy formulation and poverty alleviation | 2011 | Urban wetland, economic value, ecosystem services, ecological modelling, incentive based mechanisms, poverty alleviation | Wetlands perform services such as flood control, groundwater replenishment, sediment retention, water purification, recreation, and climate change mitigation and adaptation. However, this is not well known by policymakers, therefore wetlands are often overused, misused, or abused. This paper shows the need for adopting an integrated approach to understand the needs of a wetland ecosystem and the role of stakeholders in alleviation of poverty. |
| Yang, Liyun | Water-related ecosystem services provided by urban green space: A case study in Yixing City (China) | 2015 | Ecosystem services, water regulation, water purification, urban green space, Yixing City | Green space in urban areas is often seen as a symbol of urban ecosystem health due to its positive role in water regulation and purification, however this is often ignored by the municipality. This study shows the differences between ecosystem services of urban green space inside and outside built-up areas within Yixing city. |
| Zhang, Da | Impacts of urban expansion on ecosystem services in the Beijing-Tianjin-Hebei urban agglomeration, China: A scenario analysis based on the Shared Socioeconomic Pathways | 2017 | Ecosystem service, urban expansion, scenario analysis, SSPs, LUSD-urban model | It's necessary to understand the impact of urban expansion on ecosystem services in order for sustainable development to be achieved, however the future impacts are difficult to predict due to the uncertainty of expansion. Scenarios in the BTH area of China suggest food production, carbon storage, water retention, and air purification will all decrease due to the conversion of cropland to urban land. Therefore, effective policies |

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|---|---|---|---|---|
| | | | | and regulations should be implemented in order to protect these areas from land use change. |
| Zhou, Long | Ecological and economic impacts of green roofs and permeable pavements at the city level: the case of Corvallis, Oregon | 2017 | Green roofs, permeable pavements, ecosystem services, ecological and economic impacts | Impervious roofs and surfaces contribute to storm-water runoff, surface pollutants, less carbon sequestration, and worse ecosystem services. Low impact development such as intensive green roofs on buildings and permeable pavements for parking lots would play a significant role for long-term urban sustainability, regardless of the higher initial implementation cost. |

## Appendix B – Additional qGIS Figures

**Appendix B - Additional qGIS Figures**

Figure 4. World Coastline in qGIS

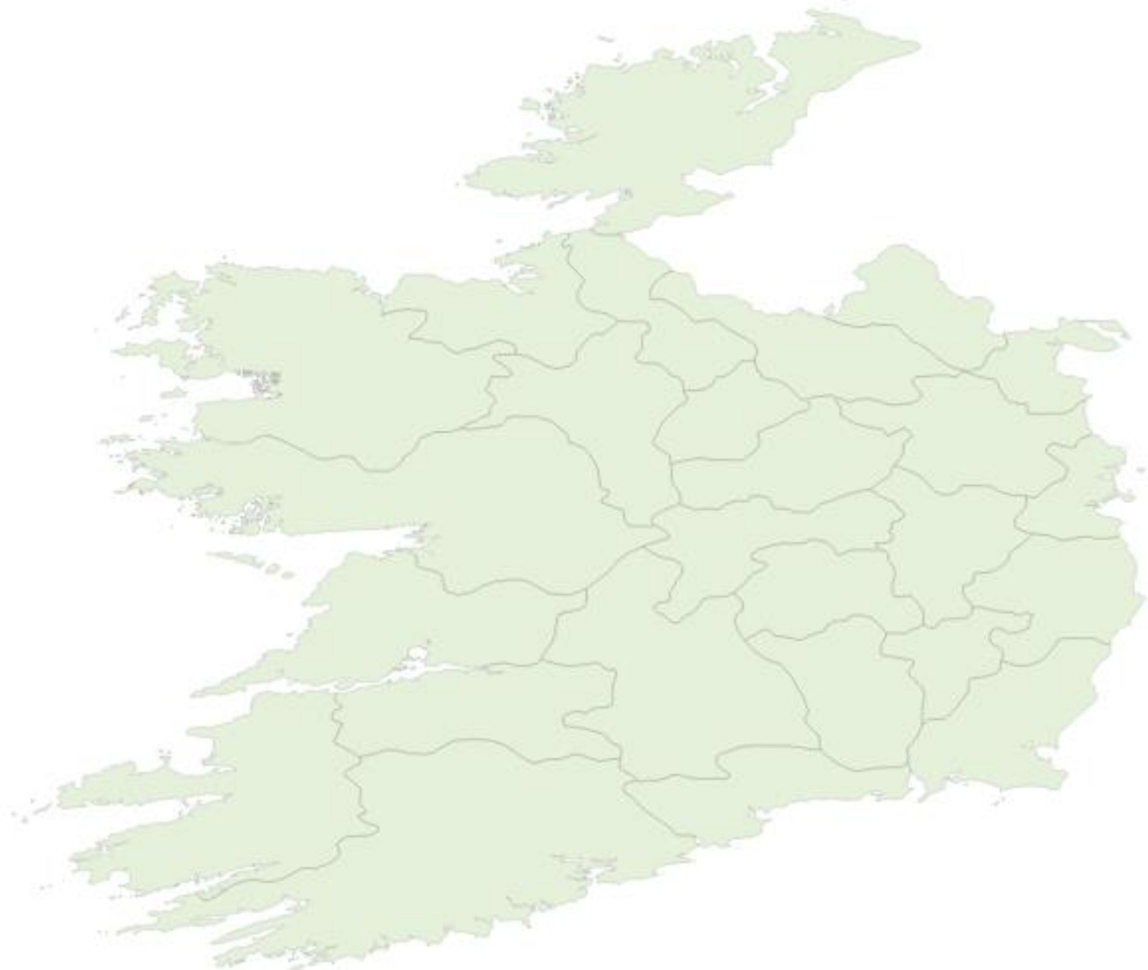

Figure 5. Country and county lines within Ireland.

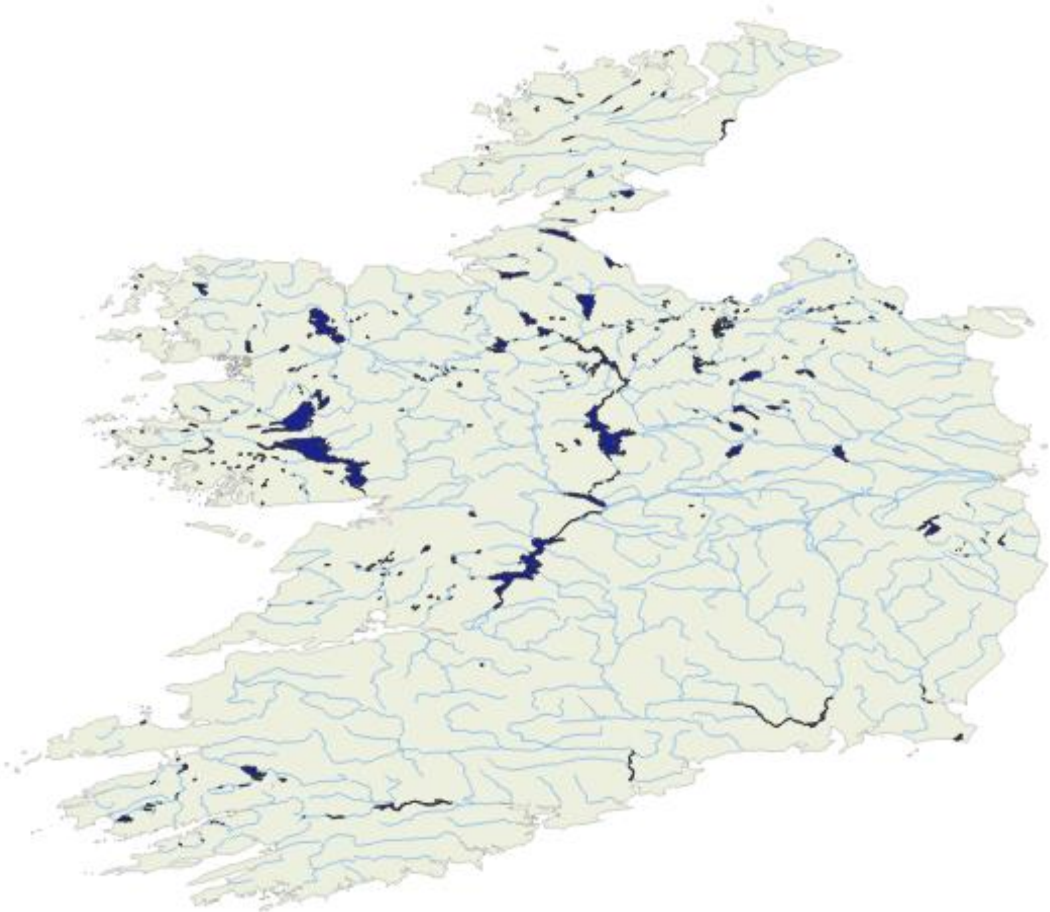

Figure 6. Water bodies and Rivers within Ireland.

Figure 7. Corine Land Cover Map 2012 in Ireland.


Figure 8. Roads in the Dublin area.