Strategic Green Infrastructure Planning:
A Geodesign-based Planning Support Approach

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Abstract

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Green infrastructure is increasingly utilized to improve and restore ecosystem function and ecosystem services in urban areas; however, it is often implemented in a piecemeal, opportunistic, single-purpose fashion. This dissertation uses the Steinitz geodesign framework to demonstrate a systematic approach for analyzing synergies and trade-offs between different types of green infrastructure across multiple scales and functions, a novel application of the framework, to enable strategic green infrastructure planning at the city scale.

The focal geography and jurisdiction for this research is Seattle, WA. While regional or landscape-driven approaches (e.g. Puget Sound Regional Council, Puget Sound Partnership, WA Department of Ecology Watershed Resource Inventory Areas) to planning are important, the city scale affords the administrative, regulatory and financing mechanisms needed to implement green infrastructure programmatically across multiple infrastructure systems. By iterating through the geodesign framework, the complex picture of green infrastructure planning across multiple scales, functions, and departments with a broad range of requirements driven by many different influences is successively simplified to narrow in on a few key systems and questions.

However, the geodesign process and outcomes should be transparent, collaborative and accessible to multiple groups of stakeholders. A further contribution of this dissertation is a detailed examination of the tools and technologies needed to cyber-enable the full spectrum of the geodesign framework. Tools like GeoPlanner and Geodesign Hub have already been developed to digitally support some of the analysis and modeling aspects of the framework, and technologies like web services and geoportals already exist to increase their flexibility and extend their data management and analytic capabilities. Other aspects like conceptual modeling, and structured participation methods for analytic-deliberative decision-making also have IT system precedents, but all of the existing tools and technologies need further development on the basis of a shared ontology for geodesign to realize the potential of a comprehensive, interoperable geodesign support system.

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LIST OF ABBREVIATIONS

AGOL – ArcGIS Online
CAD – computer-aided design
CIP – capital improvement program
cf – cubic feet
CSO – combined sewer overflow
DON – Department of Neighborhoods
DPD – Department of Planning and Development[1]
ECA – environmentally critical area
GIS – geographic information system
GI – green infrastructure
GSD – Harvard University Graduate School of Design
GSI – green stormwater infrastructure
GUI – graphical user interface
HCP – habitat conservation plan
IT – information technology
KPI – key performance indicator
LID – low impact development
LTCP – Long Term Control Plan
LULCC – land use land cover change
MLA – Master of Landscape Architecture
MOESIR – Measurement-informed Ontology and Epistemology for Sustainability Information Representation
NAIP – National Agriculture Imagery Program

[1] As of 2016, DPD is two entities - the Seattle Department of Construction and Inspections, and the Office of Planning and Community Development. See http://buildingconnections.seattle.gov/2015/12/16/changes-to-the-department-of-planning-and-development/. Accessed on 9/29/17.

NDS – natural drainage system
NDVI – Normalized Difference Vegetation Index
NLCD – National Land Cover Database
NPDES – national pollutant discharge elimination system
OEM – Office of Emergency Management
OSE – Office of Sustainability and Environment
RCP – Representative Concentration Pathway
REET – real estate excise tax
ROW – right-of-way
SCL – Seattle City Light
SDOT – Seattle Department of Transportation
SEA – Street Edge Alternative
sf – square feet
SMC – Seattle Municipal Code
SPR – Seattle Parks and Recreation
SPT – Structured Participation Toolkit
SPU – Seattle Public Utilities
SYMAP - Synagraphic Mapping System
TMDL – total maximum daily load
ToP – Technology of Participation
TSS – total suspended solids
UML – Unified Modeling Language
WRIA – water resource inventory area

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Nam Myoho Renge Kyo.

Chapter 1. Introduction

1.1 Research Motivation and Scope

In the age of the Anthropocene, a time when humans are the main driver of global environmental change, boundaries for many planetary systems are being pushed beyond their proposed safe operating space (Rockström 2009). People now number 7.6 billion, a sevenfold increase since 1800, and are predominantly urban dwellers for the first time in history.[2] The number of cities with 1 million or more people increased from 17 to 388 in the last century (Millennium Ecosystem Assessment 2005), and megacities with populations over 10 million increased tenfold, from just two in 1970 to 23 in 2011. Globally, the level of urbanization is expected to rise to nearly 70 percent by 2050, with increases from 78 percent to 86 percent in more developed regions and 47 percent to 64 percent in less developed regions (United Nations Population Division 2012).

The proliferation of urban areas and their spatial character, scale, and distribution has critical implications for Earth processes. Satellite-based estimates of urban land cover range from 0.2% to 2.4% of the Earth's surface circa 2000 (Seto et al. 2011), a seemingly small fraction of the globe. However, urbanization-related land use and land cover change (LULCC) is considered a key force in human-induced global environmental change (Shepherd et al. 2010; NRC 2010; Hutyra et al. 2011; Fragkias et al. 2013). At the same

[2] United Nations. 2017. World Population Prospects: 2017 Revision. Available from https://www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html. Accessed on 10/4/2017.

time, urban areas, as dense population centers dependent on extensive manufactured infrastructure and complex supply chains, are also the most vulnerable to negative feedbacks (Rosenzweig et al. 2010). Turner et al. make an urgent appeal, "In a world fast approaching governance and de facto planning of the entire terrestrial surface, the question of deriving a sustainable land architecture constitutes a grand challenge" (2007, 20699).

Urbanization is a complex process that is propelled by distinct yet heterogeneous land use and land cover changes (LULCC), which are often described and analyzed in terms of specific patterns and materiality in the landscape. However, the biophysical impacts of urban LULCC are outcomes of the cumulative planning, implementation and management decisions of individuals, communities and institutions across geographic and jurisdictional scales with cities, as expanding population centers, leading the way both due to regulatory mandates and local funding mechanisms. Increasingly[3], cities are turning to green infrastructure (GI) to both retrofit existing development and to manage new growth in an effort to ameliorate the negative impacts of urbanization on ecosystems, resource economies and public health.

Green infrastructure has evolved from its roots in natural and wildlands conservation planning (Randolph 2004) into an umbrella solution for improving the sustainability and resilience of human-dominated metropolitan regions (Rouse and Bunster-Ossa 2013). It is

[3] See Chapter 4 of the NRDC's *Rooftops to Rivers II* report for a good overview of green infrastructure advances within the last decade, available from http://www.nrdc.org/water/pollution/rooftopsii/files/RooftopstoRivers_chapter4.pdf. Accessed on 10/13/2013.

being utilized for everything from habitat and resource provisioning and protection; growth management; and climate change mitigation and adaptation at regional scales to stormwater and flood management; landslide, erosion and sediment control; urban heat island mitigation; brownfield remediation; and mobility, recreation, education, and public health provision at city, community and site scales. The definitions of green infrastructure, like its applications, vary greatly, generally reflecting the scale of implementation and/or issue for which it is being used to address.

In 1999, The Conservation Fund, a leading green infrastructure advocate, together with the USDA Forest Service formed the Green Infrastructure Work Group to develop a program to make GI an integral part of local, regional and state plans and policies. They created the following definition, which reflects the organizational missions of the founders (emphasis added): "Green infrastructure is our nation's natural life support system, an interconnected network of waterways, wetlands, woodlands, wildlife habitats and other *natural* areas; greenways, parks and other *conservation lands*; *working farms, ranches and forests*; and *wilderness* and other open spaces that support native species, maintain natural ecological processes, sustain air and water resources and contribute to the health and quality of life for America's communities and people" (Benedict and McMahon 2007). Hubs and links, or corridors, of natural and restored ecosystems form the foundation of the group's definition of green infrastructure.

The American Society of Landscape Architects (ASLA) builds upon this definition to include a finer spatial scale and broader functional scope: "[at] the urban level, parks and

urban forestry are central to reducing energy usage costs and creating clean, temperate air. Lastly, green roofs, walls, and other techniques within or on buildings bring a range of benefits, including reduced energy consumption and dramatically decreased stormwater runoff. At all scales, green infrastructure provides real ecological, economic, and social benefits."[4]

Both of these perspectives draw upon the concept of ecosystem services – the benefits that people derive from ecosystems. In its second State of the Nation's Ecosystems report, the Heinz Center defines both ecosystems and services: "Ecosystems [are] dynamic, interacting, complexes of living organisms and their non-living environment within a defined area. Ecosystems produce important goods and services, provided fundamental life-support services for people and other organisms, and have intrinsic value to many people as well. Because they are shaped by many forces, ecosystems reflect the ultimate outcome of all human and natural influences combined" (2008, 3). Ecosystem services are generally conceptualized as provisioning, regulating, supporting, and cultural services (Rouse and Bunster-Ossa 2013). For example, forested watersheds provide clean drinking water; undeveloped floodplains and wetlands attenuate riverine flooding; pollinators enable crop production; and undammed rivers support whitewater sports (among many other cultural, supporting, regulating and provisioning services).

The Millennium Ecosystem Assessment (MEA), a cooperative effort from 2001 to 2005 of over 1,300 researchers from 95 countries, 44 governments, and nine scientific

[4] ASLA. 2011. Green Infrastructure. Available from http://www.asla.org/greeninfrastructure.aspx.

organizations under the auspice of the United Nations Environmental Programme, found that 15 of the 24 global ecosystem services necessary to sustain life are already degraded. Their main findings were summed up as follows "human actions are depleting the Earth's natural capital, putting such strain on the environment that the ability of the planet's ecosystems to sustain future generations can no longer be taken for granted. At the same time, the assessment shows that with appropriate actions it is possible to reverse the degradation of many ecosystem services over the next 50 years, but changes in policy and practice required are substantial and currently not underway" (MEA 2005).

The term green infrastructure, like the reference to natural capital in the MEA, translates ecosystems and their services into utilitarian concepts with identifiable corollaries in the people's daily lives- a common evolution in environmental discourse (Dryzek 2005). As a capital-oriented concept, many aspects of green infrastructure have become operationalized to address the changes in policy and practice recommended by the MEA to restore ecosystem function in urban areas. For example, the Center for Neighborhood Technology (2010) has developed a guide for valuing GI from an ecosystem service perspective. The ASLA and partner organizations have developed site-level metrics as a part of the Sustainable Sites Initiative to assess green infrastructure implementation, and the Center for Green Infrastructure Design has also developed an open space analysis approach for identifying and mapping green infrastructure assets (cultural, educational, developmental, agricultural and recreational – referred to as CEDAR).[5]

[5] CGID. 2011. CEDAR Explained. Available from http://www.greeninfrastructuredesign.org/media/document/cedar-explained.pdf.

But how do we plan to achieve these multiple ecosystem services, fulfill these metrics and preserve these assets? How do we reconcile green infrastructure as conservation (e.g. connected habitat hubs and corridors) versus retrofit and restoration (e.g. green roofs, bio-swales, riparian buffers) versus cultural artifact (e.g. yards, cemeteries, golf courses, vegetable gardens) versus accident (e.g. vacant lots, remnant landscapes)? A multi-scalar, multi-functional perspective has the potential to create stronger interrelationships and investment opportunities, but requires strategic planning to realize synergies and manage trade-offs. According to The Conservation Fund's Green Infrastructure Network, "most land and water conservation initiatives in the United States are reactive not proactive; haphazard not systematic; piecemeal not holistic; single-scale not multi-scale, single-purpose not multi-functional. Current conservation efforts often focus on individual pieces of land, limiting their conservation benefits to the environment and human health."[6] Their assessment captures the essence of and need for a multi-scalar and functional strategic planning approach.

Cities like New York, Philadelphia, and Portland have developed and are investing heavily in green infrastructure plans and programs, and while citing multiple benefits, focus on water resource management and water quality improvements as their primary concern.[7] In the Pacific Northwest, King County's Sustainable Cities program recognizes that with "deliberate, strategic planning, Sustainable Cities can realize the benefits of green

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[6] Urban Green Spaces. *Ecosystem Services and Green Infrastructure.* Available from http://www.urbangreenspaces.org/ecosystem.

[7] See NYC's Green Infrastructure Plan ($787M 2017-2022), Philadelphia's Green City, Clean Waters plan ($1.68B 2011-2036), Portland's Grey to Green program ($68M 2010-2013).

infrastructure systems, including increased property tax revenue, reduced burden on public infrastructure, local economic development resulting from in-migration of residents and businesses, increased access to funding sources, and improved public health."[8] While the county insists that green infrastructure requires coordinated planning, they only provide a handful of resources related to biodiversity and stormwater, and do not have a comprehensive green infrastructure plan in place. In Seattle, the University of Washington's Green Futures Lab spearheaded the Open Space Seattle 2100 Project in 2006, and developed, together with a broad and diverse group of community stakeholders, a Green Future vision for green infrastructure that was multi-scalar and multi-functional in scope, which was endorsed by the Seattle City Council. Organizers recognized that the vision would only come to fruition with the continued support of city officials and staff, professional planners and citizen activists, and requires interdepartmental collaboration and funding to achieve implementation (Open Space Seattle 2100 2006).

While the vision was widely supported and well developed, with a solid set of principles, strategies and a spatial template for implementation, it is unclear if and how it has influenced and permeated the day-to-day activities of the many city departments that are planning and managing green infrastructure. **The first phase of this dissertation research analyzes the green infrastructure planning process and plan content from key City of Seattle departments to understand how green infrastructure is defined, and related projects are prioritized, implemented and evaluated.** Synergies and tradeoffs related to

[8] King County. 2010. GreenTools for Green Infrastructure. Available from http://your.kingcounty.gov/solidwaste/greenbuilding/green-infrastructure.asp.

these efforts are identified, as well as the recognition and accounting of such by the individual departments. The scope of this work is to report on the current state of green infrastructure planning in Seattle, not an evaluation of the adoption of Open Space Seattle 2100.

Green infrastructure, as the word infrastructure implies, involves a physical intervention in the world. While it is certainly related to and often a manifestation of one of the many proactive -isms of the day (e.g. sustainable urbanism, landscape urbanism, bioregionalism), and benefits from their conceptualization of how to harmonize humanity with our environment and each other, green infrastructure requires a place-based, geographically informed planning support system for understanding the social, economic and environmental factors and dynamics that influence and are impacted by spatial-temporal process changes resulting from implementation. Geodesign, changing geography by design (Steinitz 2012), has emerged as a framework for enabling place-based assessment and evaluating landscape interventions.

Carl Steinitz formalized the geodesign framework following decades of research and application with the Harvard University Graduate School of Design and the now extinct, but highly influential, Laboratory for Computer Graphics (Steinitz 2014). Steinitz describes geodesign as the "development and application of design-related processes intended to change the geographic study areas in which they are applied and realized" (2012, 1). He emphasizes the collaborative nature of geodesign across design professions, geographical sciences, information technologies and the people of the place "to solve large,

complicated, and significant design problems, often at geographic scales ranging from a neighborhood to a city, landscape region or river basin." (2012, 2). His geodesign framework, first introduced as a scaffold for theory-driven inquiry and modeling (1990), was developed to support these collaborations and provide a structured approach to complex problem solving that spans these different geographic scales and discipline specific modes of analysis.

The geodesign framework organizes questions and models about the landscape into six levels, which build upon another: representation, process, evaluation, impact, change and decision (Steinitz 2012). While each level of the framework could be purely conceptual, it is intended to be an operational tool (i.e. supported by data and simulations) for a contextually defined landscape, which can be enabled by diverse information technologies including geographic information systems (McElvaney 2012). It has been used to develop alternative land use scenarios and project their impacts on a set of indicators, as well as to design and evaluate landscape interventions for a specific problem (Steinitz 2012, McElvaney 2012).

Green infrastructure is both about alternative land uses and multi-scalar landscape interventions and is, thus, an ideal application area for geodesign. The original intended audience and executors of this framework were design and environmental professionals (Steinitz 1990); however, Nyerges and Jankowski (2010) have adapted it to participatory modeling and decision processes, and Steinitz (2003) has also used to framework to engage a broad group of stakeholders to provide feedback on the modeling outputs and to make

decisions regarding proposed landscape interventions. Because green infrastructure is a tool used by many city departments to address a range of issues of interest to a broad group of stakeholders, the participatory dimension is a key requirement of a geodesign planning support system. As demonstrated by Nyerges and Jankowski (2010), in both transportation and climate adaptation planning, participation can be successfully facilitated by a cyber-enabled (i.e. online) analytic-deliberative environment. **Phase two of the research uses insights gained in phase one about green infrastructure planning to explore the requirements for a strategic green infrastructure planning approach that is participatory, cyber-enabled and geodesign-based.** Currently available information technologies are also evaluated that can be used to implement the planning support system, which will drive future research activities to move the planning support system from concept to reality.

1.2 Research Question and Hypotheses

The overarching research questions are:

1. How can disparate green infrastructure planning efforts in a metropolitan region be synthesized to inform strategic green infrastructure planning and improve the sustainability and resilience of metropolitan regions?

2. How can a participatory, cyber-enabled, geodesign-based planning support approach facilitate strategic green infrastructure planning?

Key hypotheses are:

- An integrated view of green infrastructure can reveal opportunities to connect scales and functions of GI, and identify synergies and trade-offs among these to support strategic GI planning.

- Integration across scales and functions supports both the sustainability and resilience paradigms.
- The geodesign framework can support the synthesis of disparate green infrastructure planning efforts, the inclusion of sustainability and resilience factors and dynamics, and the development of an integrated view of green infrastructure.
- A suite of available and emerging information technologies can provide a platform for iterating through the geodesign framework to enable multi-scalar and multi-functional GI planning.
- A broadly accessible (participatory, cyber-enabled) geodesign-based planning support approach to green infrastructure planning fosters an integrated view, and also improves sustainability and resilience of metropolitan regions through the inclusion of a diversity of perspectives and the wide-dissemination of information.

1.3 Research Setting

The focal geography and jurisdiction for this research is Seattle, WA at the city scale of planning. While regional or landscape-driven approaches (e.g. Puget Sound Regional Council, Puget Sound Partnership, WA Department of Ecology Watershed Resource Inventory Areas) to planning are important, the city scale affords the administrative, regulatory and financing mechanisms needed to implement green infrastructure programmatically across multiple infrastructure systems, a phenomenon demonstrated in city leadership[9] on climate change action (Rosenzweig et al. 2010). However, planning and

[9] Marxist urban political ecology studies provide a more critical lens through which to view the role of the city in shaping the local and global landscape, but reinforce the idea of cities as sources and centers of action. See Swyngedouw and Heynen's essay *Urban Political Ecology, Justice and the Politics of Scale* in the homonymous special issue of Antipode (2003).

implementation at different scales certainly influence and interact with city initiatives, thus key intersections are also included in the analysis. Examples include county (King County wastewater and flood management), state (WA Shoreline Management Act and Growth Management Act), and federal (USACE flood and navigation management, EPA Endangered Species Act, CERCLA superfund cleanup) government regulations, plans and programs.

Seattle, Washington, branded Metronatural™ (from 2006-2013) by the Seattle Convention and Visitors Bureau to express "having the characteristics of a world-class metropolis within wild, beautiful natural surroundings" and "one who respects the environment and lives a balanced lifestyle of urban and natural experiences"[10], provides fertile ground for examining the opportunities for synergistic green infrastructure planning at multiple scales and for multiple benefits. Nestled between the Cascade and Olympic Mountains, draped in evergreens and surrounded by water, it is also known as the Emerald City, a metaphor that pervades the city's planning ethos. A systematic approach[11] to improving environmental quality and a longstanding commitment to green infrastructure reinforces the metaphor.

The city of Seattle, population 713,700[12], has nearly 10,000 employees working for 58 departments and commissions, many of whom are tasked with green infrastructure

[10] Visit Seattle. How is Metronatural Defined? Available from http://visitseattle.org/Articles/Features-and-Latest-News/How-is-metronatural-defined-.aspx. Accessed on 12/10/13.
[11] See the Environmental Management Plan, which was adopted in 1999. Available from http://www.seattle.gov/environment/documents/EMPFinal1-02%5B1%5D.pdf. Accessed on 10/26/13.
[12] State of Washington. 2017. Population growth in Washington remains strong. Available from http://www.ofm.wa.gov/pop/april1/ofm_april1_press_release.pdf. Accessed on 10/4/17.

planning and implementation as demonstrated by the city budget and capital improvement program. The 2017 operating budget is $5.4 billion dollars, 54% of which ($2.926 billion) is allocated for annual utilities and transportation expenditures[13] through which much of the city's green infrastructure is realized. The 2017-2022 Capital Improvement Program (CIP), which guides investments in the city's physical assets, includes 474 individual projects and totals $6.6 billion, with $1.108 billion allocated for 2017.[14] Figure 1 shows the CIP breakdown by department. Four out of six policy drivers for the CIP are related to green infrastructure:

- 2011 Sustainable Building and Sites Policy
- 2035 Comprehensive Plan (which includes open space, environmentally critical area and low impact development requirements)
- NPDES stormwater discharge permits and 2013 Combined Sewer Overflow (CSO) Consent Decree
- Endangered Species Act (driven primarily by the listing of Chinook salmon) and resulting 50-year Cedar River Watershed Habitat Conservation Plan (2000-2050).

[13] City of Seattle. 2017. Adopted Budget. Available from http://www.seattle.gov/financedepartment/14adoptedbudget/default.htm.
[14] City of Seattle. 2017. Adopted Capital Improvement Program. Available from http://www.seattle.gov/financedepartment/1722adoptedcip/documents/2017-2022AdoptedCIP.pdf. Accessed on 10/2/2017.

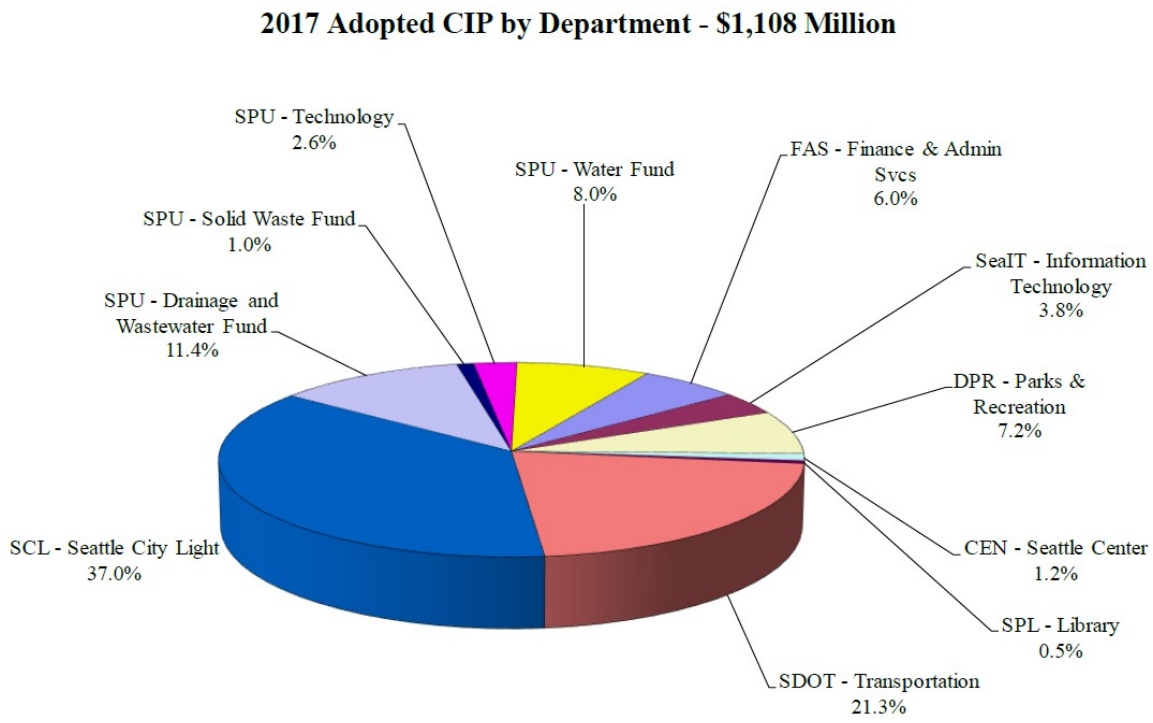

Figure 1. Seattle's CIP by department.

1.4 Research Outline

The research questions and key hypotheses are explored in six chapters. Chapter 2 lays the foundation for the research and presents the current state of green infrastructure planning in the City of Seattle based on a review of key departmental plans and interviews with planning personnel. It details current, operational city GI planning initiatives, including existing synergies and known trade-offs, as well as constraints such as regulations and funding mechanisms since these can be a barrier to integrated planning. It also includes a GI characterization for each department: GI definition, spatial-temporal representation and scales bounding the system. Chapters 3 and 4 apply the geodesign framework to develop an integrated view of green infrastructure. Chapter 5 explores current and emerging information technologies and tools, particularly those that are participatory and cyber-enabled, that can support the geodesign framework and strategic green infrastructure

planning. Chapter 6 synthesizes the findings and implications for green infrastructure planning in Seattle, as well as the potential for adaptation to other planning jurisdictions and directions for future research.

Chapter 2. Taking Stock: Green Infrastructure Planning in Seattle

2.1 Introduction

Drawing from the CIP policy drivers and funding distribution, these departments are responsible for GI policy and implementation: Seattle Public Utilities (SPU), Office of Sustainability and Environment (OSE), Seattle Department of Transportation (SDOT), Seattle Parks and Recreation (SPR), Department of Neighborhoods (DON) and the Department of Planning and Development (DPD). The Office of Emergency Management (OEM) was also considered because both mitigation and recovery activities can involve green infrastructure; however, the OEM partners with the aforementioned departments to implement mitigation measures.[15] The following sections highlight key GI planning activities by department, with an emphasis on affinities and gaps among plans, as well as functional GI synergies and trade-offs, to demonstrate the need for strategic planning and decision-support. Figure 2 provides an overview of the agencies and types of green infrastructure that will be discussed. The Relation Browser, an open source visualization tool, was used to develop a multi-department, multi-level green infrastructure concept map similar to the EPA's EnviroAtlas Eco-Health Relationship Browser.[16] The information for the Relation Browser was derived from planning documents referenced throughout the following sections.

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[15] Roles of OEM and other departments in hazard mitigation described in City of Seattle 2015-2021 All-Hazards Mitigation Plan. Available from http://www.seattle.gov/Documents/Departments/Emergency/PlansOEM/HazardMitigation/Seattle%202015%20-%202021%20HMP%20Final.pdf. Accessed on 10/3/2017.

[16] See the EPA's Eco-Health Relationship Browser in action here: http://www2.epa.gov/enviroatlas/enviroatlas-eco-health-relationship-browser

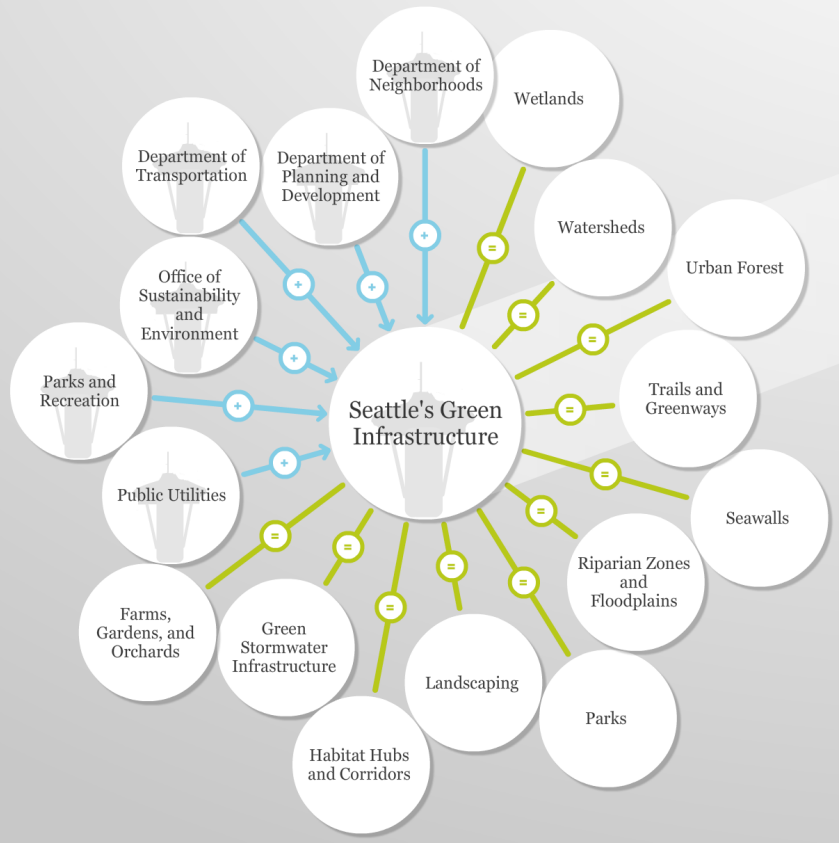

Figure 2. Primary departments and types of green infrastructure treated in the case studies.

While each department's GI plans will be treated in turn, one approach to unifying different scales and concepts of green infrastructure is that of *landscape,* which Rouse and Bunster-Ossa define as "the visible expression of natural and human ecosystem processes that work across scales and contexts to provide multiple benefits for people and their environments" (2013, 1). The landscape approach to green infrastructure advocated by Rouse and Buster-Ossa entreats planners to think in terms of an integrated whole, rather than through the piecemeal lens of 'green' site improvements to address specific issues. In practice, however, city departments are responsible for networks of infrastructure (e.g. utilities, transportation, buildings) that shape and interact with the landscape through co-constitutive dynamics (Mugerauer 2012). The challenge is to harmonize these networks with the four-

dimensional landscape structure and function (i.e. the horizontal, lateral and vertical axis of space combined with the continuum of time) in which they are embedded. It requires us "to redefine the conventional meaning of modern infrastructure by amplifying the biophysical landscape that it has historically suppressed, and to reformulate landscape as a sophisticated, instrumental system of essential resources, services, and agents" (Bélanger 2009).

The opportunity for rethinking and retooling infrastructure is enormous. In 2017, the American Society of Engineers (ASCE) issued its quadrennial *Report Card for America's Infrastructure* and gave the country an overall rating of D+, requiring an estimated $2 trillion investment by 2025, or $206 billion annually (which is substantial but just over 1/3 of the US defense budget for 2017[17]), based on the condition and performance of our infrastructure in four major categories: water and the environment, transportation, public facilities and energy.[18] While the ASCE report focuses primarily on the replacement and expansion of grey infrastructure in most categories (e.g. airports, dams, locks, levees, railroads, bridges, roads, buildings, water and sewer mains, treatment plants, electric grid, pipelines), a landscape perspective that connects these infrastructure nodes and networks to broader ecosystem processes, augmented by green infrastructure interventions to reduce environmental impacts, restore ecosystem function and increase resource efficiencies, is a must to avoid the continued erosion of our natural capital (MEA 2005, Kareiva et al. 2011).

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[17] DoD. 2016. 2017 Budget Proposal. Available from https://www.defense.gov/News/News-Releases/News-Release-View/Article/652687/department-of-defense-dod-releases-fiscal-year-2017-presidents-budget-proposal/. Accessed on 10/3/2017.
[18] ACSE. 2017 Report Card for America's Infrastructure. Available from http://www.infrastructurereportcard.org. Accessed on 10/3/2017.

In each case study, the landscape dimension will be highlighted to support synthesis across different GI implementations in section 2.4.

2.2 Research Methodology

Archival research of key departmental plans, as well as related GI programs and regulations, and eleven semi-structured interviews with lead planning personnel involved in plan development were conducted to develop the Seattle GI case studies and to better understand the heterogeneity of the phenomenal realm of green infrastructure planning in the city (Mugerauer 2010) (see Appendix A for a list of interviewees). The case studies detail current, operational city-level GI planning initiatives as well as constraints such as regulations and funding mechanisms since these often pose a barrier to integrated planning. They also include a GI characterization for each department including their individual GI definition, spatial-temporal representation, and scales bounding their particular infrastructural system. Integrating both the archival research and interviews as well as the representational definitions and data contributes to the more fully elaborated empirical documentation espoused by Actor-Network Theory (ANT).[19] However, while informed by planning process, this study emphasizes planning outcomes more so than the enactment typical of true ANT-based studies (Mugerauer 2010).

The following questions guided the research and are divided into process and content-oriented information:

[19] Actor-Network Theory (ANT) focuses on tracing the actors and their associations (networks) involved in creating 'things' (products, meaning, outcomes) to better understand how these 'things' came to be what they are. Bruno Latour, together with Michel Callon and John Law, initially developed ANT to provide a social explanation of scientific practice, but have since applied it to many other realms (Latour 2005).

Planning Process

1) Why was the plan or plan component developed (i.e. which regulations, mandates, consent decrees, issues, etc… motivated the plan)? Does it have a legacy, i.e. roots in community-based activities/action?
2) Who was involved in plan development (policy-makers, staff, consultants, stakeholders; single or multiple agencies/institutions)? Are the actors who will implement the plan involved in plan development?
3) Was the planning activity coordinated with other planning efforts or existing programs, such as disaster mitigation? How have trade-offs with other types of land uses been addressed?
4) How long was the planning process, and was it terminal or is it part of an ongoing activity? Is there an update mechanism in place?
5) What types of communication and analytical tools and technologies were used in plan development?
6) What type of stakeholder engagement and outreach was conducted?

Plan Content

7) How is green infrastructure defined in the plan?
8) What is the spatial-temporal scope of the plan?
9) What were the decision factors and processes (social, ecological/environmental, economic, political, etc…) that were included in the plan?
10) What are the plan goals, measurable targets and/or desired outcomes? Who is to be served by plan (see City Nature at Stanford, http://citynature.stanford.edu)?
11) How is the plan to be implemented? What are the funding mechanisms?
12) Have projects and/or policies been prioritized, and if yes, how?
13) Have projects and/or policies been implemented as a result of the plan?
14) Is there an implementation monitoring and evaluation strategy? Do the results feedback into the plan?

The following case studies highlight important departmental green infrastructure planning aspects, discovered through these questions. A synthesis of synergies and trade-offs within and across cases closes the chapter.

2.3 Green Infrastructure Planning Case Studies

2.3.1 Seattle Public Utilities

SPU oversees the most common and usual suspects of green infrastructure from the regional to site scale: watersheds and water supply; floodplains and riparian zones; and

stormwater drainage. At the regional scale, two municipal watersheds, the Cedar River and South Fork Tolt River, provide water to 1.3 million people in the Seattle area (including 21 other jurisdictions). Both watersheds are protected and restricted access. The upper 90,638 acres of the Cedar River Watershed are owned by the city. Seattle also owns 70% of the South Fork Tolt River Watershed, approximately 8,400 acres, and the other 30% lies in the Mt. Baker-Snoqualmie National Forest. Seattle was an early adopter of municipally owned utilities and watershed acquisition after the Great Fire in 1889, when the private supplier failed to deliver. The city began to acquire the Cedar River Watershed in 1890 and the water rights to the South Fork Tolt River Watershed in 1936.[20] Current CIP funding for watershed stewardship, estimated at just over $15,500,000 from 2014-2019, comes from a combination of water ratepayer revenue and the issuance of bonds, which are serviced by ratepayers.

A 50-year Habitat Conservation Plan (HCP)[21] guides management and restoration activities in the Cedar River Watershed, which was heavily logged from the mid-1890s into the 1940s. The HCP was developed under the auspices of the Endangered Species Act between 1993-1997 and effective beginning in 2000 to address incidental takes of fish species due to the water supply infrastructure, as well as to comply with the Muckleshoot Indian Tribe's fishing rights. Congruent with a perspective, the HCP covers five

[20] City of Seattle. Our Watersheds. Available from http://www.seattle.gov/util/EnvironmentConservation/OurWatersheds/index.htm. Accessed on 10/29/13.
[21] City of Seattle. 2000. Cedar River Watershed Habitat Conservation Plan. Available from http://www.seattle.gov/util/EnvironmentConservation/OurWatersheds/Habitat_Conservation_Plan/AboutheHCP/Documents/index.htm. Accessed on 10/29/13.

geographic areas, referred to as the "Five Links": the headwaters, lowlands, Lake Washington, Ballard Locks and the route to ocean (Figure 2), and provides protection for 83 species of fish, birds, mammals and amphibians – 14 of which are listed as endangered or threatened. While watershed protection is often touted for its multiple benefits, water supply was at odds with habitat provision and species protection for more than a century due to a diversion dam and water supply aqueduct built in 1901. Through the integrated approach of the HCP, partial fish passage to upstream spawning grounds was restored in 2003, just three years after plan implementation began.

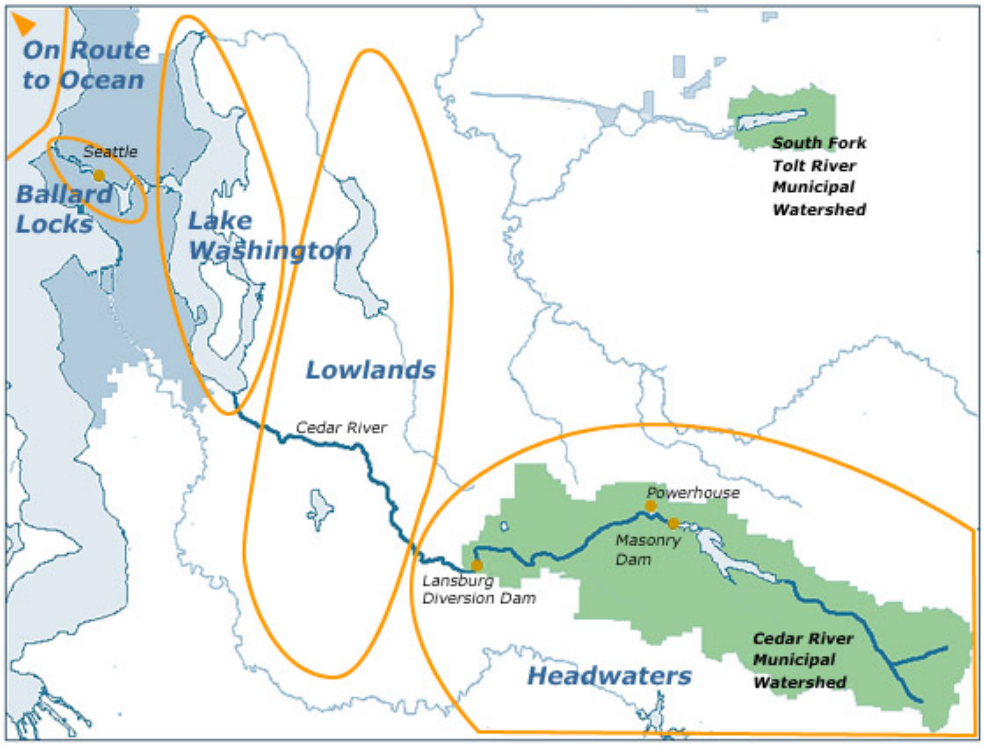

Figure 3. The "Five Links" of the ecosystem-based Cedar River Watershed HCP. Source: SPU.

The South Fork Tolt Municipal Watershed Plan[22], completed in 2011 with a 25-year planning horizon, also focuses on reforestation, ecological forest management and aquatic resource rehabilitation to remediate issues related to the commercial timber harvest that occurred until the mid-1990s as well as impacts from on-going reservoir operation. Much of it is based on the experience gained with the Cedar River Watershed HCP. Both municipal watersheds, important nodes in Seattle's infrastructure network, green and grey, demonstrate that the range of benefits provided have to be carefully balanced (e.g. water supply, in-stream flows, and migration pathways), and that some, like water source protection and commercial timber harvest are at odds with each other.

In addition to on-going restoration beyond the municipal watershed boundaries in the lower reaches of the Cedar and Tolt Rivers, the city's Restore Our Waters strategy, administered by SPU, focuses on habitat restoration and green stormwater management in urban creek watersheds within the city's boundary including projects along Lake Washington and the Puget Sound, which may complement the efforts along the "Five Links", but are not actively coordinated in part because several projects were executed by the Department of Parks and Recreation (SPR) and others fall within SPU's Natural Drainage System (NDS) stormwater management program.[23]

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[22] City of Seattle. 2011. South Fork Tolt Watershed Management Plan. Available from http://www.seattle.gov/utIl/groups/public/@spu/@conservation/documents/webcontent/01_012728.pdf. Accessed on 10/29/13.

[23] Interactive map of Seattle Watershed Projects with links to project descriptions available here: http://www.seattle.gov/util/groups/public/@spu/@conservation/documents/webcontent/01_015334.pdf. Accessed on 10/29/13.

Restore Our Waters, re-launched as Protect Our Waters within the context of SPU's 'Protecting Seattle's Waterways' Plan, [24] integrates urban creek watersheds and manufactured drainage basins, which better expresses the synthetic nature of the urban landscape and is a reminder that there is more to landscape than meets the eye. The 'Protecting Seattle's Waterways' Plan, finalized in May 2015, presented two alternatives to meet the requirements of Seattle's 2013 combined sewer overflow (CSO) consent decree - first consent decree to allow stormwater projects to be prioritized ahead of CSO control projects. The Long-term Control Plan (LCTP) alternative focuses solely on controlling CSO by 2025 at a total project cost of $503M (August 2014 dollar value). The Integrated Plan alternative includes the LCTP recommended projects, but defers six of them for five years in order to implement stormwater management in non-CSO basins at an additional cost of $127.8M (which includes capital, operating and maintenance costs).

Both plan alternatives include natural drainage as a part of the solution to reduce and improve the quality of stormwater runoff. Seattle pioneered the use of natural drainage in the right-of-way (ROW) to address stormwater runoff with the SEA (Street Edge Alternative) Street project in 2001, and has since completed five NDS projects that have been scaled up from a few blocks to entire neighborhoods (the largest is Seattle Housing Authority's High Point neighborhood redevelopment with 34 blocks and 129 acres) to

[24] City of Seattle. 2015. Protecting Seattle's Waterways. Available from http://www.seattle.gov/util/EnvironmentConservation/Projects/SewageOverflowPrevention/IntegratedPlan/index.htm. Accessed on 9/30/17.

reduce stormwater runoff to creeks by 74 - 99%. Four more neighborhood-scale projects are currently underway.[25]

In 2009, SPU moved the NDS from projects to policy through the adoption of green stormwater infrastructure (GSI) requirements (now referred to as on-site stormwater management as of January 2016) in the Seattle Stormwater Code for sites with greater than 1,500sf of new or replaced hard[26] surfaces (750sf if the parcel plat was created or amended after January 1, 2016) or 7,000sf of land disturbing activity. GSI is defined specifically as "a drainage control facility that uses infiltration, evapotranspiration, or stormwater reuse. Examples of green stormwater infrastructure include permeable pavement, bioretention facilities and green roofs." [27] In June 2015, the Stormwater Code was also updated to include regulations for using low impact development (LID) techniques in new development, redevelopment, and construction sites to mimic pre-disturbance hydrologic processes and minimize impervious surface, native vegetation loss and stormwater runoff. Each department covered by the NPDES Phase 1[28] permit – SPU, SPR, SDOT, DPD, Seattle City Light (SCL), and the Department of Finance and Administration (FAS), will be responsible for a development-related document that incorporates LID practices and

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[25] City of Seattle. 2013. Current Projects. Available from http://www.seattle.gov/util/EnvironmentConservation/Projects/DrainageSystem/GreenStormwaterInfrastructure/CurrentGSIProjects/index.htm. Accessed on 10/29/13.

[26] The term *hard* has replaced *impervious* in the 2016 Stormwater Code update to be congruent with WA ECY's terminology. Hard surfaces are defined as impervious surface, permeable pavement or vegetated roof.

[27] City of Seattle. 2014. NPDES Phase 1 Municipal Stormwater Permit Stormwater Management Plan. Available from http://www.seattle.gov/util/cs/groups/public/@spu/@drainsew/documents/webcontent/01_030117.pdf. Accessed on 02/15/2015.

[28] The NPDES (National Pollutant Discharge Elimination System) Phase 1 permit is mandated by the federal Clean Water Act and managed by WA Department of Ecology. It applies to municipally owned separated and partially separated sewer system (MS4).

performance standards defined in the WA Department of Ecology's Stormwater Management Manual for Western Washington.

2.3.2 Office of Sustainability and Environment

Though both regulations serve to integrate GSI into daily operations across departments, in 2013 the city also adopted a Green Stormwater Infrastructure Goal (aka Green Goal) of managing 700 million gallons (MG) of stormwater through GSI by 2025 (up from approximately 100MG annually in 2012, and 192MG in 2016) to accelerate GSI implementation (Figure 4).[29] OSE led the development of the GSI Implementation Strategy, released in November 2015. As part of the plan, SPU, SDOT, and DPD are developing a coordinated approach to the integration of GSI in the ROW. SPU, SPR, SDOT, DPD, SCL, and FAS are also tasked with ensuring that their development-related codes, rules, and standards remove barriers to GSI and prioritize its use in capital projects, as well as with conducting an economic valuation study of GSI that considers benefits beyond water quality.

[29] City of Seattle. 2013. Executive Order. Available from http://www.seattle.gov/mayor/opengov/executiveorders/ExecOrder201301.pdf. Accessed on 10/15/13.

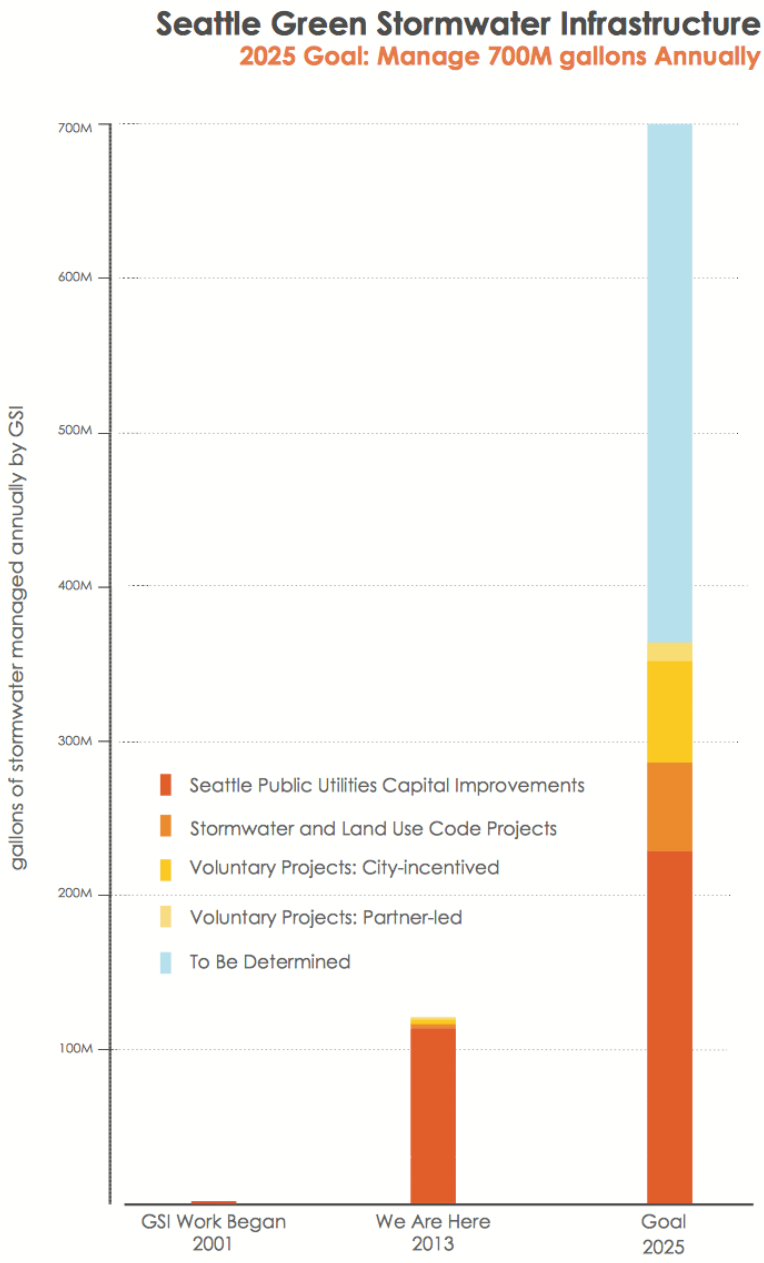

Figure 4. Seattle's GSI Goal, current and future projections (Source: SPU). In addition to removing barriers to GSI across departments, new opportunities and partners for GSI need to be identified. Source: OSE.

To put the Green Goal in perspective, 115.6 million gallons of combined sewage and stormwater overflowed into water bodies on 406 separate overflow events in 2014, and another estimated 13 billion gallons of stornwater runoff enters Seattle-area water bodies annually. The 700MG goal addresses runoff from approximately 1125 acres of impervious surface, which is 3.6% of all impervious surface in Seattle or 10% of all impervious in the

public ROW. To drive near-term innovation, an interim goal of managing 400M gallons annually by 2020 has been established. This goal is expected to be meet largely through public realm retrofits led by SPU and the King County Wastewater Treatment Division as well as retrofits on private property triggered by Stormwater Code. To further diversify Seattle's GSI portfolio and meet the interim target, additional strategies are needed for roadways, parks, and parcel-level projects that emphasize retrofits of existing impervious surface at the point of redevelopment, optimizing multiple community benefits through integrated design and development of infrastructure improvements, and removing barriers to implementation across all project types. A range of barriers has been identified, summarized in Table 1.[30]

Table 1. Summary of major GSI barriers and challenges by project type. Source: OSE. Issues in italics can be addressed through a strategic planning approach.

Stormwater Code-Required Projects
Lack of clarity about minimum requirements and site-viable design alternatives
Legal constraints limiting options for alternative compliance approaches
Tension between regional density goals and community-level greenspace needs
GSI tracking currently aggregates all facility types
Utility-Led and Funded Retrofit Projects
Tension between cost increases to achieve multiple community benefits and stormwater cost/gallon efficiency
Rate increase limitations that restrict investment potential (SPU cannot increase drainage rates above the level set in the 2015-2020 Strategic Business Plan)
Legacy pollution unmitigated from pre-existing development
Lag time between GSI policy and design guidance and uptake by City and private sector
Utility Incentives
Consistent outreach required to ensure on-going participation
Limited to uncontrolled CSO basins and specific GSI facility types (raingardens and cisterns)
Non-Utility Led Projects
No capital budget for GSI integration

[30] City of Seattle, 2015, Green Stormwater Infrastructure Implementation Strategy 2015-2025. Available from http://www.seattle.gov/Documents/Departments/OSE/GSI_DRAFT_July_2015_WEB.pdf. Accessed on 9/25/15. Final available from https://www.seattle.gov/Documents/Departments/OSE/GSI_Strategy_Nov_2015.pdf.

Insufficient maintenance budget for street trees
Few external funding sources at city-wide scale
GSI tracking systems not developed or inconsistent
Lack of guidance for partnering opportunities
Voluntary bioretention in the ROW is technically complex, which can translate into cost barriers

Some of the barriers listed in Table 1, such as minimum GSI requirements, alternative compliance approaches, limits on location and types of GSI and maintenance budgets, can be addressed through policy changes. Those in italics can be addressed by strategic planning for multiple functions and scales of green infrastructure and planning support tools. While the city's GSI Goal and Implementation Plan are a very important step in formalizing and synergizing GSI efforts across city departments (Figure 5), when designed in isolation the plant palette, soil amendments, structural design and pollutant loads may be at odds with achieving other benefits from green infrastructure. By prioritizing multiple benefits from the beginning (e.g. flood management, habitat provision, carbon sequestration in addition to water quality improvement), optimal parcels and designs can be selected for green infrastructure and compatible development; partners can be identified for cost sharing so that stormwater ratepayers are not footing the entire bill; other agencies do not have to sacrifice their mission and budget just for GSI; and know-how can be more readily disseminated through both the public and private realm.

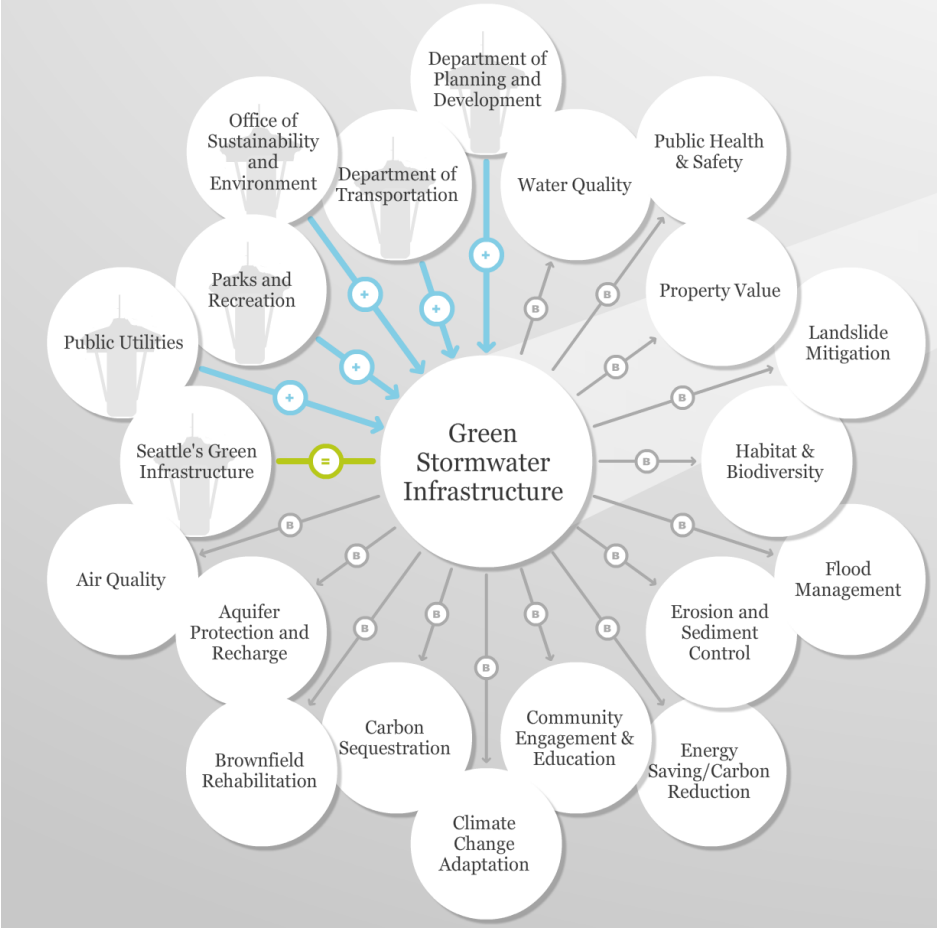

Figure 5. Primary departments providing GSI (FAS is not shown because GSI is triggered by code requirements for municipal capital projects, managed by FAS, rather than being implemented as part of a formal plan). GSI benefits are derived from the draft GSI Implementation Plan.

A review of the Seattle's 2013 Urban Forest Stewardship Plan[31], also prepared by the OSE, indicates that the proposed ecological approach to tree management is congruent with GSI since it seeks to improve forest function (which includes understory and soils) and not just expand canopy cover – though there is a 30% canopy goal by 2037 (canopy was estimated at 28% in 2016).[32] Typical of green infrastructure literature, the forest plan highlights a

[31] City of Seattle. 2013. Urban Forest Stewardship Plan. Available from http://www.seattle.gov/trees/docs/2013%20Urban%20Fores%20Stewardship%20Plan%20091113.pdf. Accessed on 10/30/13.
[32] City of Seattle. 2016. Seattle Tree Canopy Assessment. Available from http://www.seattle.gov/trees/canopycover.htm. Accessed on 8/3/17.

wide range of functions provided by trees, including but not limited to stormwater management: air pollutant removal, carbon storage and sequestration, terrestrial and aquatic habitat, steep slope stabilization, building energy reduction, increased property values, food production and urban foraging, neighborhood cohesion, and public health benefits (e.g. reduced cardiovascular and respiratory illnesses, reduced stress levels). However, the plan does not address trade-offs among tree species/planting schemes and this range of benefits. Some are likely to provide multiple functions, but those, for example, that are optimal for air and stormwater pollutant removal are generally not fit for food production. The 30-year plan's Action Agenda of 105 short-term (1-5 years), mid-term (5-10 years), and long-term (10+ years) actions, all in partnership with other agencies (SPU, SPR, SDOT, DPD, SCL, FAS), does focus on coordinating urban forest stewardship with specific issues like stormwater (SPU), habitat (SPR), sensitive areas (DPD), and food production (OSE), which should reduce conflicts among different functional goals, but may also reduce potential synergies. Long-term action C8 "Conduct urban forestry activities as a city-wide program with a de-emphasis on the roles of specific departments"[33] anticipates the need for a holistic approach, but the 10+ year delay in implementation also speaks to the difficulty of the task.

Even though the OSE is the lead department for the GSI Implementation Plan, the Urban Forest Stewardship Plan, and the Food Action Plan, different people developed these plans for different purposes. The 2012 Seattle Food Action Plan[34] seeks to increase food

[33] Ibid.
[34] City of Seattle. 2012. Seattle Food Action Plan. Available from http://www.seattle.gov/environment/food_plan.htm. Accessed on 10/30/13.

production in the city ROW and on city-owned property, which is incompatible with stormwater management and may conflict with forestry goals due to shading (with the exception of orchards). With 14,682 acres of ROW in the city (27% of the land area), conflict can likely be avoided; however, a mechanism needs to be developed to identify parcel suitability for different green infrastructure options. Urban agriculture is experiencing a revival through the local food movement, and needs to be included in the green infrastructure portfolio, rather than treated as a limited benefit of certain types of GSI (i.e. green roofs and trees) as it is in the Center for Neighborhood Technology's *The Value of Green Infrastructure* guide.[35] More than 6,000 Seattleites already garden nearly 15 acres of land in 88 P-Patches (community gardens) and steward another 18.8 acres of gardens and orchards throughout the city, thus food production is an important and popular dimension of green infrastructure in the city landscape. However, GSI and forest will need to make room for gardens, and the Food Action Plan also needs to address the impacts of gardening on water quality and water consumption, which it currently does not.

2.3.3 Seattle Department of Transportation

Though the purveyor of decidedly 'un-green' but necessary transportation network (1,540 lane-miles of arterial, and 2,412 lane-miles of non-arterial streets), SDOT is also an important partner and provider of green infrastructure in all three areas already mentioned: drainage, forestry and urban agriculture. SDOT manages more than 35,000 street trees, plants approximately 800 new ones per year, and collaborates with SPU to develop NDS in the ROW and to retrofit road culverts for fish passage and sediment control. Its Complete

[35] The CNT's guide, while useful, defines green infrastructure narrowly as only GSI. The guide is available from http://www.cnt.org/repository/gi-values-guide.pdf. Accessed on 10/01/13.

Streets Checklist[36] includes options for GSI and forests, and its ROW management also allows gardens and orchards. SDOT maintains 47 miles of off-street trails with plans for expansion in fulfillment of the Bicycle and Pedestrian Master Plans. The vegetation along these trails, while perhaps not optimized for green infrastructure benefits (e.g. drainage, food production, canopy), still contributes to Seattle's green infrastructure, as do the landscaping features in their on-going sidewalk improvements. SDOT also maintains 22 miles of seawalls, expanding the department's reach to the nearshore, and is currently replacing the Elliott Bay Seawall in downtown Seattle. The seawall, a critical piece of grey infrastructure, is being improved with elements to support juvenile salmon migration like a habitat bench and habitat shelves and seawall textures that mimic the sea life that lives at each tide level.[37] The seawall, in particular, is a reminder that green infrastructure doesn't necessarily have to be vegetated, and, more generally, that a department whose primary mission is transportation and public safety does not preclude green infrastructure.

2.3.4 Seattle Parks and Recreation

Parks are integral to Seattle's green infrastructure, and are inherently a multi-functional landscape and network. SPR's system includes 485 parks and natural areas, 25 miles of park boulevards, and 120 miles of trails that total 6,414 acres - 12% of Seattle's land area. By 1937, the city had 37 Olmsted parks, playgrounds and boulevards, which were designed with the landscape and ecological function at the fore and set the tone for the future. Today,

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[36] City of Seattle. 2011. Complete Streets Checklist. Available from http://www.seattle.gov/transportation/docs/ctac/2011_04_19Final%20Draft%20Checklist.pdf. Accessed on 10/30/13.
[37] City of Seattle. 2012. Seawall face treatments. Available from http://www.seattle.gov/transportation/seawall_face.htm. Accessed on 10/30/13.

the Parks Legacy Plan[38] emphasizes recreation and community services, while still continuing the tradition of environmental stewardship.

In addition to managing an estimated 600,000 trees, 20% of Seattle's canopy, SPR works on wetland restoration, creek daylighting, habitat protection (e.g. Great Blue Heron nesting grounds and beaver dams), and beach re-nourishment and nearshore habitat improvements. The Green Seattle Partnership, a public-private collaboration between SPR, SPU, OSE, non-profits, and individuals, is also working to re-establish 2,500 acres of healthy forested parkland by 2025, and has already restored 1,000 acres in 70 parks and trained 140 citizen forest stewards.[39]

SPR's green infrastructure must co-exist with a wide-variety of recreation and community facilities: 185 athletic fields, 130 playgrounds, 151 outdoor tennis courts, 26 community centers, four education environmental centers, two craft centers, five golf courses, a rock climbing site, boat ramps, moorages, and fishing piers, as well as a classical Japanese garden, zoo, and waterfront aquarium). To balance multiple users and use, SPR uses a classification scheme based on park use, purpose, and size to serve as basis for policies about programming; facility and planting design standards; and future development options.[40] Table 2 summarizes the classifications, with a focus on the 'Natural

[38] City of Seattle. 2013. Parks Legacy Plan. Available from http://www.seattle.gov/parks/legacy/. Accessed on 10/30/13.
[39] Ibid.
[40] City of Seattle. 2015. Park Classification System. Available from http://www.seattle.gov/parks/Publications/policy/parks_classification_policy.pdf. Accessed on 02/25/15.

Environment' aspect of the classification description, which has been reframed as GI potential for the purposes of this research.

Table 2. SPR Park Classification System and GI Potential

Park Type	Description	Size	GI Potential
Mini Parks, Pocket Parks	Small parks transformed from developed urban sites to "provide a little green", "sometimes jointly operated for recreational and utility/infrastructure purposes"	< 0.25 acre	• Native plants • GSI
Neighborhood Parks	Usually occupy an area equivalent of 1 city block, supports multiple uses	.25 – 9 acres	• May have natural areas, creeks, lakes • Native plants, habitat • GSI • Forestry
Downtown Parks	Small, developed sites in Seattle's center, many have historic significance	.1 – 5 acres	• Native plants • GSI
Community Parks	Serve multiple neighborhoods, may preserve unique landscapes	5 – 60 acres	• May have natural areas, creeks, lakes • Native plants, habitat • GSI • Forestry
Regional Parks	Serve citywide recreation needs, have large natural areas and/or historic or landmarked significance	10 – 500 acres, average is > 100 acres	• May have natural areas, creeks, lakes, wetlands, shoreline access • Native plants, habitat • GSI • Forestry
Natural Area, Greenbelt	Established for protection and stewardship of wildlife, habitat and other natural systems support functions (like erosion	Any	• Riparian corridor • Native plants, habitat • GSI

	control), often serve as buffers between incompatible land uses		• Forestry
Boulevards, Green Streets, Greenways	Many are part of Olmsted plan, provide safe pedestrian and cycling routes	Any	• Shoreline, Riparian area • Native plants • GSI
Special-Use Parks, Specialty Gardens	Stand-alone parks designed to serve one particular use (e.g. Woodland Park Zoo, West Seattle Stadium, Kubota Gardens, Camp Long)	Any	• Native plants, habitat • GSI

At minimum, native plantings and GSI are foreseen in every type of park, which bodes well both from a wildlife and stormwater management perspective. Currently, however, while most parks have native landscaping according to SPR and nearly 67% of park parcels are at least 90% vegetated[41], only 22[42] out of 465 parks have dedicated GSI with a total of 980,172sf. This demonstrates that SPR has unrealized potential for stormwater management, and must be a key partner in achieving the City's Green Goal.

2.3.5 Department of Neighborhoods

The DON is responsible for 88 P-Patches[43] throughout the city, mentioned previously in the OSE section. While these only constitute a small chunk of the cityscape (less than .03% of the land area), the P-Patches are a highly visible and beloved program with over 6,000 participants and multi-year waiting list. Gardeners contributed over 32,690 volunteer hours

[41] Percent vegetation calculated per park parcel using the 2013 USDA National Agriculture Inventory Program's (NAIP) 1m^2 resolution aerial imagery. See Section 2.4 for more details about the NAIP analysis.
[42] Information source: SPR GSI Web Map, available from http://uw-geog.maps.arcgis.com/home/webmap/viewer.html?webmap=3c10182b920147ec8464c150a4dda9a3# (ArcGIS Online).
[43] The P stands for the Picardo family who farmed the area that became the first P-Patch in 1973.

in 2012 (equivalent to 15.7 full time workers) and in 2014 donated over 29,000 pounds or 58,134 servings of fresh produce with a value of approximately $73,249 to local food banks and feeding programs.[44]

Beyond the obvious benefit of nourishment, these gardens are hotbeds of community building and citizen engagement (as, over the decades, several groups have had to fight to keep their gardens in the face of development), thus broadening the typical list of GI benefits directly into the social realm. Other individual and social benefits cited for gardening include stress reduction, crime reduction (by both activating urban spaces and directly engaging at-risk youth and adults), education and self-empowerment. The P-Patch Program also supports two market gardens, together with the Seattle Housing Authority, in low-income communities through a community supported agriculture program and on-site farm stands, where food is communally grown and P-Patch staff help manage the gardens and market the produce. At the other end of the spectrum, Seattle Farms is a recently (2014) launched pilot program, together with OSE, to help experienced farmers (currently 3 participants) grow and sell food in the city.

From an ecological perspective, these gardens and farms also mitigate urban heat islands, improve air quality, reduce stormwater runoff and provide pollinator habitat (Lin et al. 2015). Seattle's program requires organic methods and fertilizers; which should increase water and nutrient retention in the soil as well as increasing microbial activity and nutrient

[44] City of Seattle. About the P-Patch Program, Available from http://www.seattle.gov/neighborhoods/p-patch-community-gardening/about-the-p-patch-program, Accessed on 7/28/2015.

uptake (Pimentel et al. 2005, The Freshwater Society 2013). However, nutrient runoff does still occur, albeit more slowly, and current consensus is mixed as to what degree urban agriculture can be used as a stormwater management strategy. Much hinges on individual fertilizer application strategies and plot management practices like winter cover crops (The Freshwater Society 2013). Even without the added function of GSI, urban agriculture is still a valuable asset in the green infrastructure portfolio for the other social and ecological benefits described in this section.

2.3.6 Department of Planning and Development

The DPD is an enabler of green infrastructure planning and implementation both through the comprehensive plan and through site-specific land use, subdivision and landscaping regulations. The comprehensive plan serves as a policy framework, and is mandated by the State of Washington's Growth Management Act as well as guided by the Puget Sound Regional Council's Vision 2040 and King County's planning policies. *Seattle 2035 – Your City, Your Future*, was adopted in 2016 and replaces the city's first comprehensive plan *Toward a Sustainable Seattle* (1994-2014). From 2004-2014, the city added an average of 4,000 housing units each year and a total of about 70,000 people. Over the next twenty years, an additional 70,000 housing units, 120,000 residents and 115,000 additional jobs are predicted.[45]

The comprehensive plan continues to emphasize urban villages as the primary means to accommodate growth and support transit. Since 1994, the strategy has captured 75% of all

[45] City of Seattle. Seattle's Comprehensive Plan. Available from https://www.seattle.gov/opcd/ongoing-initiatives/seattles-comprehensive-plan#projectdocuments. Accessed on 10/4/2017.

new housing and business development on about 17% of the city's total land area. These urban villages (differentiated in the comprehensive plan as urban centers (6), urban hub villages (6) and residential urban villages (18)) are prime targets for strategic green infrastructure planning to optimize functionality in denser areas of the city. At the other end of the spectrum, large portions of the city will remain single-family residential – areas that also include most of the city-owned parks, public schools, cemeteries, small institutions as well as environmentally sensitive and critical areas, all of which may contribute to the city's green infrastructure and can supplement or enhance the GI functionality in the denser urban villages.

Green infrastructure, it should be noted, is now[46] fully mainstreamed in the city's planning agenda, with several plan elements making specific reference to it, including: Growth Strategy, Transportation, Utilities, and Environment. Both the Growth Strategy and Transportation elements emphasize street design as a means of promoting and accommodating green infrastructure. The Utilities element focuses on coordination and co-location of infrastructure in the city's ROW, which also relates to street design considerations. The Environment element emphasizes the maintenance and restoration of natural ecosystem function, wildlife habitat and contiguous urban forest. It also highlights the importance of green stormwater infrastructure and includes the 'Green Goal' policy of managing 700MG of stormwater annually with GSI by 2025.

[46] In the previous comprehensive plan only two of the included neighborhood plans made specific reference to green infrastructure. There was no reference made in the main plan document.

Other plan elements like Parks and Open Space and Land Use are also directly related to green infrastructure though they do not make specific mention of it. The Parks and Open Space element addresses the city-owned park system (ca. 11 percent of the city's land area), as well as the federal Chittenden Locks, Port of Seattle waterfront access areas, University of Washington campus, Seattle Center, Seattle Schools and private developments with public access such as Waterfall Park in Pioneer Square, and serves as a reminder of the diversity of the city's green infrastructure portfolio. When considered strategically, partnerships and policies can be crafted to achieve maximum functional benefit across jurisdictional boundaries.

The Land Use element includes an Environmentally Critical Areas (ECA) section, which defines development controls on or near wetlands, floodplains, riparian areas, shoreline habitat, additional priority habitats and species areas (all of which are designated Fish and Wildlife Habitat Conservation Areas) and steep slopes, in addition to liquefaction, landslide, peat settlement, seismic and volcanic hazard areas as well as abandoned landfills. While an ECA designation does not prevent development, regulations are in place to buffer critical areas from disturbance. Approximately 26% (47,260)[47] of the city's 179,145 parcels carry an ECA designation, with 6% (11,495) contributing to the city's green infrastructure network (specifically wetlands, floodplain, riparian, and habitat areas).

[47] All of the layers from the DPD's ECA dataset were merged and overlaid with Seattle parcels, all parcels were then selected that intersected an ECA.

Beyond the Comprehensive Plan and associated regulations, the DPD is responsible for the Seattle Green Factor, a score-based, functional systems approach to landscaping requirements in different land use zones and a regulatory approach for expanding GI in private development. Implemented in January 2007 and revised in early 2009, it was the first program of its kind in the US. Minimum scores range from .30 in commercial, industrial and mixed-use zones to .50 for mid- and high-rise residential, and .60 for low-rise residential. Three out of the six benefits listed for the program are related to the environmental benefits typical of green infrastructure: stormwater runoff reduction, urban heat reduction, and habitat.[48] Bonus credits are given for sidewalk and publicly visible plantings, drought-tolerant or native plants, rainwater harvesting and irrigation, and food cultivation. The Green Factor Worksheet provides higher scores for vegetation planted with a soil depth of more than 24", trees, permeable paving, green roofs, vegetated walls, water features and rain gardens. Figure 6 is an example worksheet from the Pinehurst Safeway Grocery, which scored .322.

[48] See 'What is the Seattle Green Factor'. Available from http://www.seattle.gov/dpd/cityplanning/completeprojectslist/greenfactor/whatwhy/. Accessed on 8/31/2015.

Revised 12/28/10

Green Factor Score Sheet

SEATTLE×*green factor*

Project title:

		enter sq ft of parcel			
	Parcel size *(enter this value first)* *	143,175		SCORE	0.322
	Landscape Elements**	**Totals from GF worksheet**		**Factor**	**Total**
A	**Landscaped areas (select one of the following for each area)**				
1	Landscaped areas with a soil depth of less than 24"	enter sq ft: 0		0.1	-
2	Landscaped areas with a soil depth of 24" or greater	enter sq ft: 26781		0.6	16,068.6
3	Bioretention facilities	enter sq ft: 2152		1.0	2,152.0
B	**Plantings (credit for plants in landscaped areas from Section A)**				
1	Mulch, ground covers, or other plants less than 2' tall at maturity	enter sq ft: 3112		0.1	311
2	Shrubs or perennials 2'+ at maturity - calculated at 12 sq ft per plant (typically planted no closer than 18" on center)	enter number of plants: 1934	23208	0.3	6,962
3	Tree canopy for "small trees" or equivalent (canopy spread 8' to 15') - calculated at 75 sq ft per tree	enter number of plants: 38	2850	0.3	855
4	Tree canopy for "small/medium trees" or equivalent (canopy spread 16' to 20') - calculated at 150 sq ft per tree	enter number of plants: 48	7200	0.3	2,160.0
5	Tree canopy for "medium/large trees" or equivalent (canopy spread of 21' to 25') - calculated at 250 sq ft per tree	enter number of plants: 18	4500	0.4	1,800.0
6	Tree canopy for "large trees" or equivalent (canopy spread of 26' to 30') - calculated at 350 sq ft per tree	enter number of plants: 7	2450	0.4	980.0
7	Tree canopy for preservation of large existing trees with trunks 6"+ in diameter - calculated at 20 sq ft per inch diameter	enter inches DBH: 84	1680	0.8	1,344.0
C	**Green roofs**				
1	Over at least 2" and less than 4" of growth medium	enter sq ft: 0		0.4	-
2	Over at least 4" of growth medium	enter sq ft: 0		0.7	-
D	**Vegetated walls**	enter sq ft: 563		0.7	394.1
E	**Approved water features**	enter sq ft: 0		0.7	-
F	**Permeable paving**				
1	Permeable paving over at least 6" and less than 24" of soil or gravel	enter sq ft: 0		0.2	-
2	Permeable paving over at least 24" of soil or gravel	enter sq ft: 17181		0.5	8,590.5
G	**Structural soil systems**	enter sq ft: 0		0.2	-
		sub-total of sq ft =	*91,677*		
H	**Bonuses**				
1	Drought-tolerant or native plant species	enter sq ft: 28933		0.1	2,893.3
2	Landscaped areas where at least 50% of annual irrigation needs are met through the use of harvested rainwater	enter sq ft: 2152		0.2	430.4
3	Landscaping visible to passersby from adjacent public right of way or public open spaces	enter sq ft: 10,000		0.1	1,000
4	Landscaping in food cultivation	enter sq ft: 1,694		0.1	169
				Green Factor numerator =	*45,111*

** Do not count public rights-of-way in parcel size calculation.*

*** You may count landscape improvements in rights-of-way contiguous with the parcel. All landscaping on private and public property must comply with the Landscape Standards Director's Rule (DR 6-2009)*

Figure 6. Pinehurst Safeway Green Factor Worksheet. Note the use of vegetated walls, permeable paving, and food cultivation to meet their requirements.

Another Green Factor project, the Joule Apartments, included nearly 15,000sf of ground cover, drought-tolerant plantings, 330 shrubs, 31 trees, a 10,683sf green roof (covering 25% of the roof), and a 238sf water feature that uses harvested rainwater. Both the Pinehurst Safeway and the Joule Apartments demonstrate how much landscaping is required to fulfill the Green Factor and how much the program could contribute to the city's green infrastructure as new properties are developed. Although, the city does not track Green Factor implementation (re: personal communication with program coordinator David LeClergue), a review of building permits issued between January 2007 and October 2015 indicates that 1,070 buildings would have triggered Green Factor requirements.[49]

2.4 Green Infrastructure Synthesis

The previous sections summarized green infrastructure planning by responsible Seattle department. This section synthesizes across departments and green infrastructure types, first through a spatial perspective to identify potential synergies and then through a planning lens to address potential barriers to collaboration. It begins with a brief look back in time to sketch both the positive and negative, material and imagined drivers and constraints for Seattle's green infrastructure, which help shape green infrastructure planning policy and implementation. This historical, biophysical context is followed by an analysis of current land cover conditions, which provide a baseline for mapping specific green infrastructure types.

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[49] See the Green Factor zones described here: http://www.seattle.gov/dpd/codesrules/codes/greenfactor/default.htm. Each building permit includes latitude and longitude, and could be converted to a point feature. Those in applicable zones were selected, and all duplex, and 2-4 unit residential buildings were eliminated unless sited as a larger group of buildings. Only those buildings with a final permit were included in the final count.

2.4.1 Historical, Biophysical Context

Seattle is situated in the Puget Lowland, an area of roughly 10,000 square miles in Western Washington bounded by the Cascade Mountains to the East and the Olympics to the West (Kruckeberg 1991). The region, though shaped by many millennia of complex tectonic, volcanic and glacial interactions, owes much of its modern biophysical character to the last glaciation, specifically the Vashon Stade, which ended 15,000 years ago (Booth et al. 2003). The resulting topography and geology affect watershed size, runoff patterns, sediment sources, fluvial dynamics, and aquatic habitat features. Glacial sediment deposits that are several thousand feet thick - collectively referred to as Vashon Drift and divided into several categories with different permeability and consolidation characteristics, blanket most of the region. Till – unsorted and compact sand, gravel, silt and clay deposited beneath the ice sheet, is most common but just three to six feet thick, followed by sandy and permeable Vashon advance outwash in areas where till is thin or absent (Booth et al. 2003).

Seattle's dominant geology is characteristic of the region, though there are diverse non-glacial and older glacial deposits throughout the city as well (Figure 7), along with extensive artificial fill at the mouth of the Duwamish and the eastern and northern portions of the Elliott Bay (Figure 8). Much of this fill came from the re-sculpting of downtown Seattle's hills (Figure 9), made possible by the malleable glacial geology, and accelerated by the diversion of Cedar River water to Seattle in 1901 and the adaptation of hydraulic sluicing techniques developed for gold mining on the Pacific Coast (Karvonen 2010). Over the course of three decades, more than 60 regrading projects were undertaken, the

elevations of over 20 downtown streets were altered and several large hills were removed (Klingle 2006). Over 10 million cubic yards of soil was removed from three hills alone, and an estimated 50 million cubic yards altogether (Karvonen 2010), enough to fill nearly 2800 stadiums 100 yards long, 50 yards wide and 8 stories tall.

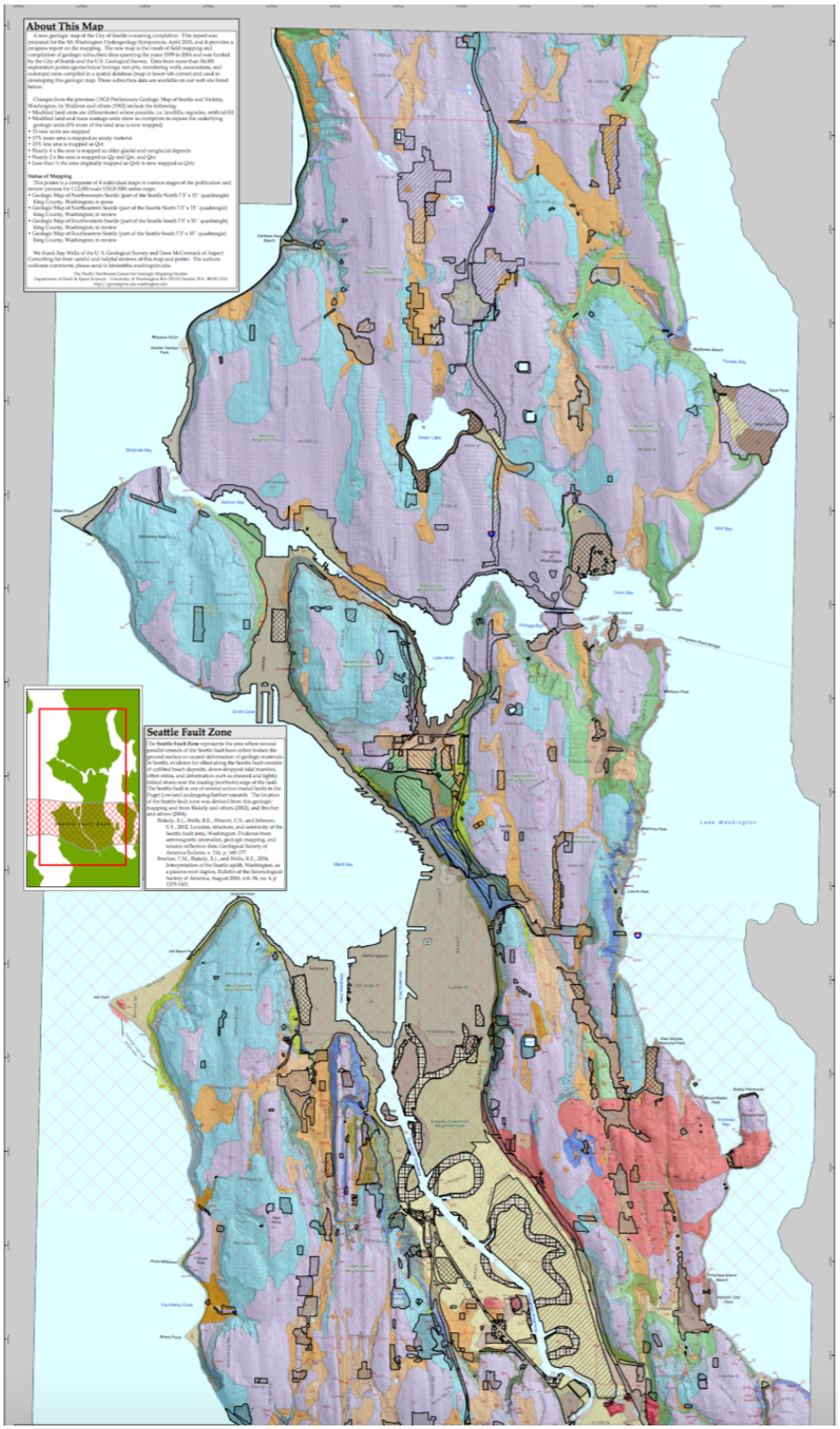

Figure 7. Seattle's geologic map. The detailed map is too large to include at full scale, but is provided to give an impression of the dominant glacial till (lavender) and outwash (light blue) geology, as well as the distribution of other geologic types through Seattle (Troost et al. 2006).

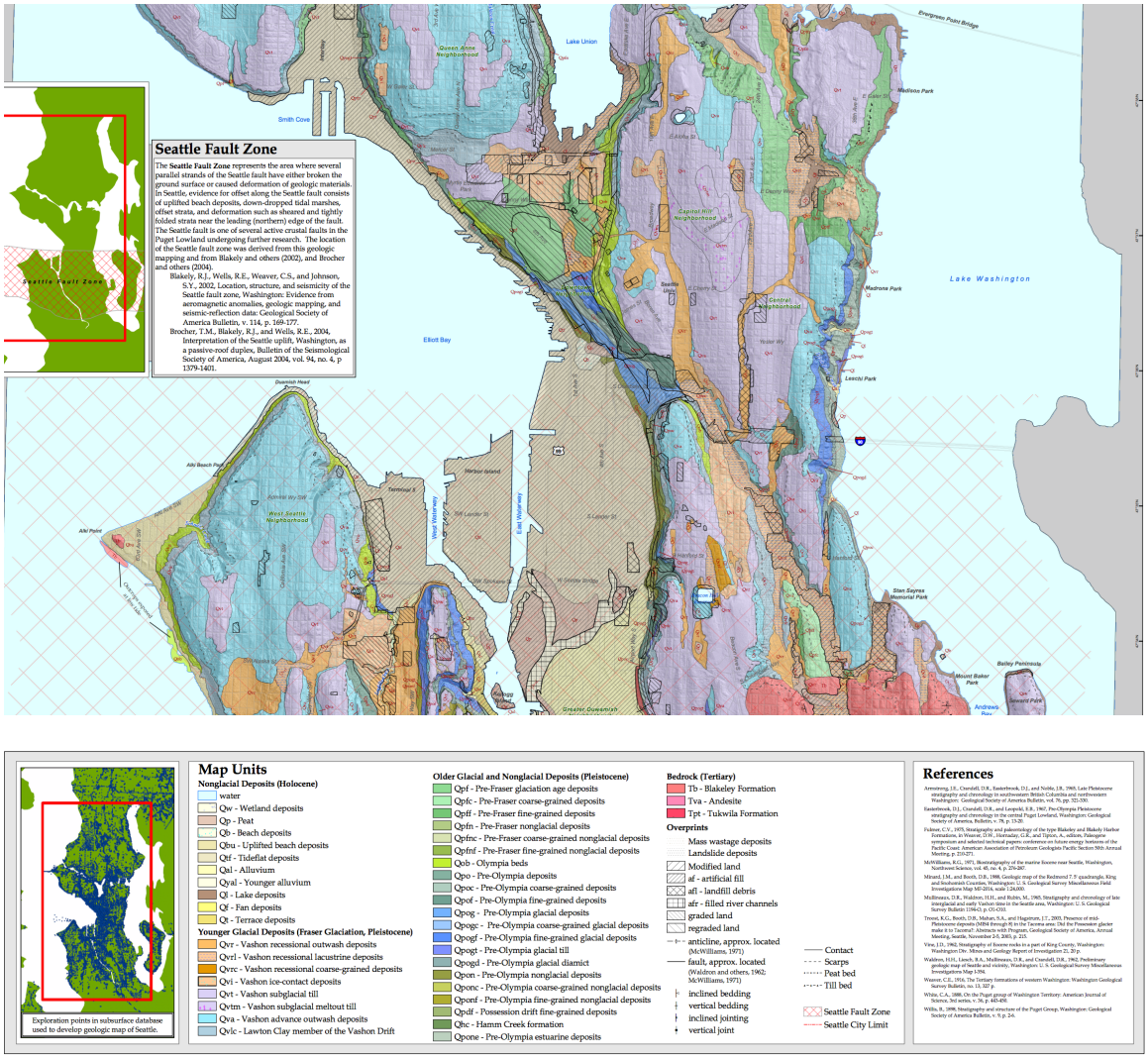

Figure 8. Downtown and South Seattle show more geologic diversity, and extensive modified land (wide diagonal), artificial fill (narrow diagonal) and regrading (left-leading diagonal) (Troost et al. 2006).

Figure 9. Regrading at Bell Street and Fourth Avenue. Hydraulic nozzles called 'Giants' were modified to allow for vertical and horizontal movement, and with a diameter of 2.5-3.5 inches created water pressures of 75-100 pounds per square inch. The Giants could consume up to 12 million gallons of water a day, a third of the Cedar River supply (Karvonen 2010). Image Source: University of Washington Libraries Special Collections, Lee 20022 (in Karvonen 2010).

The Seattle we know today was carved out of the landscape by both glacial retreat and human advances in engineering and technology. The geologic legacy of these activities impact present green infrastructure strategies, particularly related to stormwater and floodplain management. In undisturbed watersheds in the Puget Sound, the three to six foot soil layer that has developed since deglaciation has an infiltration capacity that greatly exceeds typical rainfall intensities (Booth et al. 2003). However, where natural erosion or human disturbance has thinned, compacted or stripped the surficial soil, the permeability of the subsurface geology determines both water and sediment delivery. Typical rainfall

intensities will readily exceed the infiltration capacity of glacial till and bedrock, while they are easily absorbed by the highly permeable glacial outwash (Booth et al. 2003).

According to the *Low Impact Technical Guidance Manual for the Puget Sound*, in medium (4-6 dwelling units/acre) to high-density settings (> 6 dwelling units/acre), pre-development hydrologic conditions can be met on soils with low infiltration rates when a full suite of LID practices are employed and the site is 40-50% open space (Hinman 2012). Most of the practices are related to GSI including soil enhancement, bioretention, open conveyance, dispersion to open space, aggregate storage under permeable paving and roof water harvesting. The underlying geology determines the type of infiltration tests that needed are needed when designing site-specific LID implementations (Hinman 2012).

Climate is the other major determinant of the region's environmental character. Seattle receives an average of approximately 38 inches of precipitation annually, mostly in the form of low-intensity, high frequency rainfall between October and March. June through August is typically dry, thus Seattle is considered a temperate marine and dry summer Mediterranean climate according to the Trewartha and Koeppen climate classifications respectively. Temperatures range from an average low of 36 degrees Fahrenheit to an average high of 76 degrees Fahrenheit.[50]

[50] City of Seattle. 2015. Seattle Monthly Averages and Records. Available from http://www.seattle.gov/living-in-seattle/environment/weather/averages-and-records. Accessed on 12/21/2015.

Geology together with climate conspired to shape the region's pre-settlement vegetation in which evergreen forests of Douglas-firs, western red cedar and western hemlock were punctuated by oak prairies, wetlands, and salt marsh estuaries.[51] The evergreens began to predominate the region after the last glacial retreat 15,000 years ago as the climate warmed and grew wetter (Klingle 2007). The wetlands, estimated in the tens and possibly hundreds, emerged in areas where springs existed, created by water trapped between the permeable glacial layer and impermeable clay. These springs, commemorated in place names throughout the city like Spring Street, Lichton Springs and Ward Springs Park, also provided Seattle's early water supply (Williams 2006). The oak groves and prairies were limited to areas of well-drained soil, directly atop of bedrock and can be found today along Lake Washington in Martha Washington and Seward Parks (Williams 2006). By the late 1800s, most of Seattle's forests were turned into lumber; however, remnant trees reseeded small forest patches, and by the early 1900s people began replanting trees as well for aesthetic rather than commercial value.[52]

Though the region's vegetation and food web still supports a diversity of large terrestrial mammals such as black bear, Roosevelt Elk, and black-tailed deer these have been virtually extirpated in urbanized areas due to habitat limitations.[53] However, a diversity of smaller mammal, reptilian, avian and marine species can still be found within Seattle's city limits.

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[51] City of Seattle. 2013. Urban Forest Stewardship Plan. Available from http://www.seattle.gov/trees/docs/2013%20Urban%20Fores%20Stewardship%20Plan%20091113.pdf. Accessed on 10/30/13.
[52] Ibid.
[53] Washington Wildlife Connectivity Working Group. Coastal Washington Analysis. Available from http://waconnected.org/coastal-washington-analysis/. Accessed on 12/21/2015.

According to SPR's Urban Habitat and Wildlife Management Plan over 250 terrestrial vertebrate species (21 mammal, 225 bird, 7 reptile and 8 amphibian) and 10 marine mammal species are known to occur within the park system. There are also over 200 saltwater fish species and 3,000 marine invertebrates, as well as an estimated 10,000+ terrestrial invertebrates. [54]

Of these, seven are designated special status species at either the state or federal level and known to depend on habitats within Seattle to a significant degree: Chinook salmon, hooded merganser, bald eagle, peregrine falcon, great blue heron, green heron and pileated woodpecker. Other special status species are also found in the Seattle area (e.g. gray whale, harbor seal), but their use of habitats in Seattle is not considered crucial to their survival. The presence of special species with protected legal status requires management provisions that influence green infrastructure planning and implementation in Seattle. Water quality, native vegetation, natural plant community structure, and habitat connectivity are all important to sustaining these species, to which the following from other green infrastructure activities contribute – either intentionally or inadvertently: the native plant palette for GSI, Green Factor and urban forestry; organic cultivation requirements for P-Patches; the management of street trees; the removal of stormwater and sewer outfalls from known habitat areas; the new Elliott Bay seawall face design; the daylighting of streams;

[54] City of Seattle. 2007. Urban Wildlife and Habitat Management Plan. Available from http://www.seattle.gov/parks/Publications/UrbanWildlifeandHabitatMngtPlan2000.pdf. Accessed on 12/22/2015.

habitat enhancing in-channel and off-channel modifications in streams and rivers; and recreational trail connectivity.[55]

Though the Puget Lowland, with its urbanized areas like Seattle, is the most highly modified ecoregion in Western Washington[56] – its underlying geology, climate envelope, remnant native vegetation and remaining biodiversity all play direct and indirect roles in shaping the region's green infrastructure. Geology determines the drainage capacity of the landscape and provides the soil structure for vegetation, which in turn affects stormwater infiltration and evapotranspiration, as well as terrestrial and aquatic species health. Species protection, especially for flagship species like salmon, whales, bald eagles, and Great Blue Heron provide a legal framework for green infrastructure and fuel popular support for conservation related activities.[57] In 1999, the US National Marine Fisheries Service put Seattle on notice that eight wild salmon species and steelhead trout would be listed as threatened and a ninth (Chinook salmon) as endangered under the Endangered Species Act (ESA). The listing, which included the metropolitan regions of Portland and Seattle, was the broadest in the 26-year history of the ESA both in terms of geography and affected urban populations. A year prior to the listing, Paul Schell, the newly elected mayor of Seattle, wrote an op-ed piece for *The Seattle Times* titled 'Saving Salmon May Save Ourselves' in which he declared:

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[55] Ibid.
[56] The Puget Lowland Ecoregion. Encyclopedia of Puget Sound. Available from http://www.eopugetsound.org/articles/puget-lowland-ecoregion. Accessed on 12/28/15.
[57] According to the World Wildlife Federation, flagship species are those that act as an ambassador for a defined habitat, issue, campaign or cause. Examples in Seattle include the "Great Blue Heron Sit" – a citizen monitoring project; salmon and whale adorned manhole covers; and the city's storm drain stenciling project.

> The reasons for a declining salmon population can be summed up easily: We humans create too many competing uses for our rivers, streams and oceans. If you're looking for something to blame, it's the growth and development that surround us…In short, millions of people have crowded out millions of fish. It is time to strive for a better balance…Our wild salmon connect us to the land we live on, to the people who were here before us, to the people who will be here when we are gone. We can save this wonderful creature, and by doing so, we may very well save ourselves (Karvonen 2010).

Seattle's 'environmental turn' can be largely traced back to the formation of the Municipality of Metropolitan Seattle in 1958 (now King County Metro), following several years of citizen activism, to address Lake Washington's declining water quality due to sewage discharges from Seattle and surrounding cities (Karvonen 2010). Within a year, before any new infrastructure has been put into place, Metro earned Look magazine's All-American City Award for "progress through intelligent citizen action".[58] When the interceptor sewer was completed around the lake in 1968, and visibility improved almost immediately from less than 1m to 3m, it was recognized internationally as one of the most successful lake cleanups ever (Karvonen 2010). However, it wasn't until the late nineties under Paul Schell that green infrastructure began to emerge as an alternative to conventional (grey) infrastructure for improving ecological function of Seattle's waterways. In 1999, congruent with the ESA listings, the Urban Creeks Legacy Program was launched to restore four creeks in the city – Longfellow, Piper's, Taylor and Thornton, and SPU staff first piloted the NDS approach to address the stormwater-related pollution affecting the creeks at the source of the problem (Karvonen 2010), departing from the

[58] King County. 2015. The birth of Metro. Available from http://www.kingcounty.gov/environment/wtd/About/History/BirthOfMetro.aspx. Accessed on 12/28/2015.

capture, convey and dump ethos that had dominated urban drainage management for decades.

2.4.2 Present-Day Land Cover Analysis

Today, green infrastructure is fully entrenched in Seattle's management mainstream, with a wide-variety of implementations throughout the city as discussed in section 2.3. Seattle's land cover provides a baseline for quantifying vegetated versus impervious surface, independent of specific green infrastructure types, which is useful for identifying landscape patterns that support the social and environmental or ecological function that the green infrastructure is intended to augment. Land cover analysis also reveals how much of a particular type of green infrastructure is actually vegetated, and contributing to a particular ecosystem service – this is especially important for types of green infrastructure with a larger spatial footprint like parks, floodplains and riparian zones.

The Landsat derived National Land Cover Database (NLCD)[59] is commonly used for land cover analysis to determine the predominate land cover type (Wickham et al. 2010). NASA's Landsat program, co-managed by USGS, launched in 1972 and provides the longest archive of spectral information from the Earth's surface. Landsat 7 ETM+ (Enhanced Thematic Mapper Plus), launched in 1999, is a moderate resolution satellite (30m) with a high-resolution panchromatic band (15m) that catalogs the Earth into 57,784 scenes, each 183km wide by 170km long, every 16 days. All Landsat data is free to the public and has been orthorectified, which removes erroneous image displacements caused

[59] See NLCD 2011 for more information. Available from http://www.mrlc.gov/nlcd2011.php. Accessed on 11/2015.

by the interaction of terrain relief or local elevation changes and sensor orientation variations (Tucker et al. 2004, 313).

The NLCD is useful for detecting land cover change over time, and its moderate resolution (900m^2 or approximately 9688sf) is adequate for differentiating among development intensities, agriculture and basic ecosystem types (forest, shrub/scrub, wetland, etc…). However, these land cover categories do not indicate the vegetated structure of the urban landscape, and the resolution is also too coarse to capture many green infrastructure types, especially linear implementations like swales, trails and even most bioretention/biofiltration areas, which are typically smaller than 900m^2. For example, 74% of Seattle's green roofs, with the exception of reservoir lids, range between 110sf and 9,113sf.

Because vegetation is highly reflective in the near-infrared band (Figure 10), the NDVI (Normalized Difference Vegetation Index), which is calculated from the near-infrared (NIR) spectral band subtracted by the red (R) band, divided by the sum of the two reflectances (NDVI=NIR-R/NIR+R) and represented on a scientific scale of -1 to +1, is a better measure. It has been widely used because it accounts for variations in shadows and is least influenced by topography (Singh 1989, Lyon et al. 1998, Stefanov 2001).

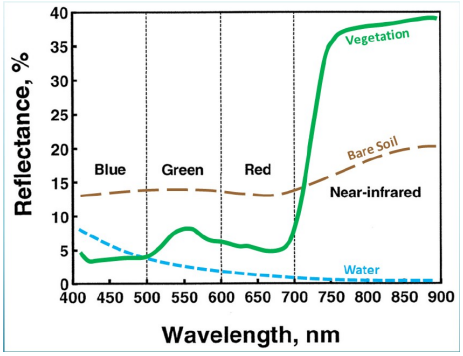

Figure 10. Four-band aerial image reflectance signatures of different land covers (Behee 2012).

The USDA's National Agriculture Imagery Program (NAIP) provides a high resolution, publicly available alternative to Landsat from which the NDVI can be calculated. The NAIP collects aerial imagery during the agricultural growing season at a $1m^2$ resolution.[60] Figures 11 and 12 compare Seattle's land cover using NLCD versus NDVI. Based on the NLCD, only 13.5% of Seattle's land cover is in a vegetated category, or 43% if including low-intensity development, which is 20%-49% impervious. By contrast, Seattle's vegetated land cover using NDVI, calculated from 2013 NAIP imagery, is approximately 38% based on a threshold of .06 on a scientific scale of -1 to 1.

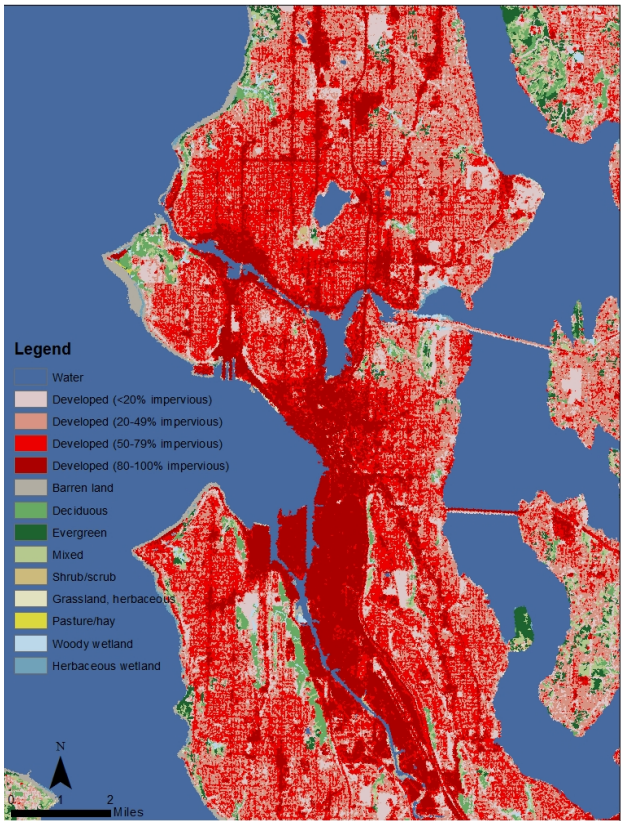

Figure 11. Seattle's land cover using NLCD 2011 ($30m^2$ resolution). Only 13.5% falls into a primarily vegetated category, including developed open space (<20% impervious), or 43% if low-intensity development is included. Data source: USGS NLCD web page. Map source: Author.

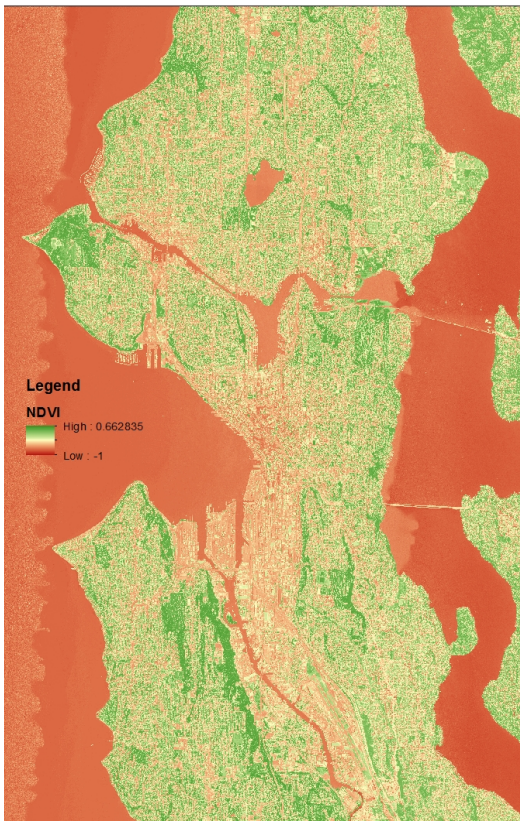

Figure 12. Seattle's NDVI calculated from NAIP imagery ($1m^2$ resolution) using ArcGIS Desktop image analysis. Based on a threshold of .06 for vegetation, Seattle is 38% vegetated. NAIP source: USDA ArcGIS Server. NDVI and map source: Author.

[60] See NAIP Imagery for more information. Available from http://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/. Accessed on 10/15/2015.

It is important to note that there are is not a clear standard for what represents vegetation in the NDVI. According to published literature, values less than zero contain no chlorophyll, and values zero and greater represent increasing chlorophyll (Morawitz et al. 2006 citing Deerfield 1975). Esri's technical documentation for the NDVI Image Analysis function provides the following ranges: very low values (0.1 and below) of NDVI correspond to barren areas of rock, sand, or snow; moderate values (0.2 to 0.3) represent shrub and grassland; and high values (0.6 to 0.8) indicate temperate and tropical rainforests.[61] Various publications actually report a wide range of values for forests, anywhere from .08 (Zhou 2008) to .7-.9 (Morawitz et al. 2006). Because of these conflicting sources, zonal statistics for the NDVI of different green infrastructure types (which define the zones) were calculated in ArcGIS Desktop, and used to determine the threshold for vegetation in Seattle (Table 3). The zonal statistic 'maximum range' was chosen because all of the green infrastructure zones also include impervious surfaces and thus non-vegetated values would be included in other zonal statistics such as minimum and mean. The minimum value, .06, from the maximum zone ranges was chosen as the vegetation threshold.

Table 3. Maximum NDVI range for selected green infrastructure types.

NDVI Zone	Max NDVI Range
Green Roof	.06 - .54
Parks	.12 - .61
Biofiltration/retention	.32 - .53
P-Patches	.37 - .60

[61] NDVI Function. 2014. Available from http://resources.arcgis.com/EN/HELP/MAIN/10.1/index.html#/NDVI_function/009t00000052000000/. Accessed on 11/15/2015.

Once the threshold for vegetation was established, the NDVI layer was reclassified as either vegetated (1) or non-vegetated (0) to determine the total percentage of vegetated land cover in Seattle (38% or nearly 32 out of 83mi^2). Figures 13 and 14 show examples of the final vegetation classification, overlaid on aerial imagery. Figure 13 is the densely vegetated Discovery Park, and Figure 14 - the urban Bill and Melinda Gates Foundation campus, which features a large green roof on the parking garage as well as a few smaller green roofs on the buildings.

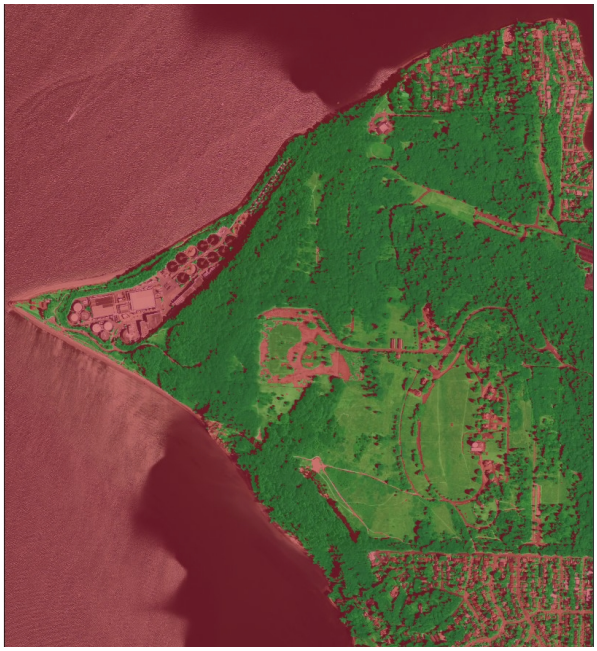

Figure 13. Discovery Park with a maximum NDVI value of .57. Note also the King County Wastewater Treatment Plant near the coast.

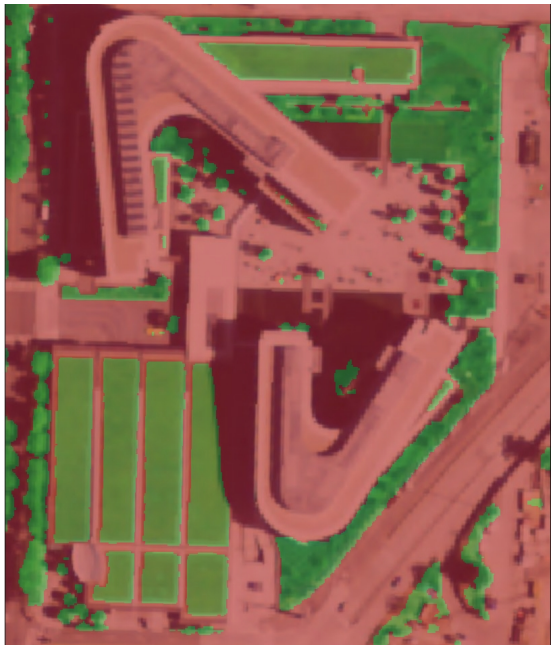

Figure 14. Bill and Melinda Gates Foundation campus - the parking garage green roof is in the lower left, the other green roofs are also rectilinear. The max NDVI value is .37.

Both of the figures illustrate the need to consider land cover and land use, when assessing green infrastructure, particularly from an environmental or ecosystem function perspective. Even the densely vegetated Discovery Park includes impervious surfaces and structures that can interrupt natural processes, while facilitating important social functions like wastewater treatment and park access. Figures 15 and 16 summarize the amount of

vegetation in Seattle's parks and floodplains – two types of green infrastructure with the largest spatial footprint and widest distribution in the city. Of the 477 park properties (which include park boulevards as well as parks), 75% are at least 50% percent vegetated, but 12 are entirely impervious, and another 55 are less than 30% vegetated, which greatly reduces the potential for a range of typical green infrastructure benefits such as stormwater runoff management, urban heat island reduction, carbon sequestration and habitat provision. While most of Seattle's floodplains, or more specifically those parcels designated in the 100-year flood hazard zone, are at least 50% vegetated, 18% are covered in predominantly impervious surfaces, which impedes flood attenuation.

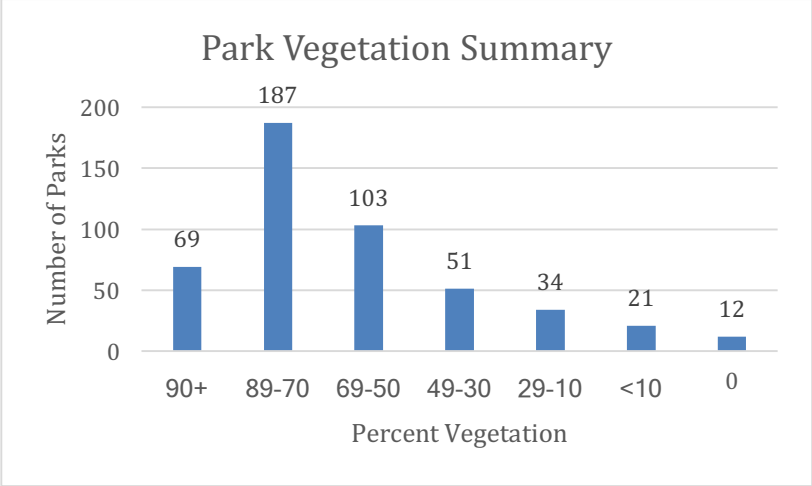

Figure 15. Summary of vegetated land cover in Seattle's parks based on NDVI analysis.

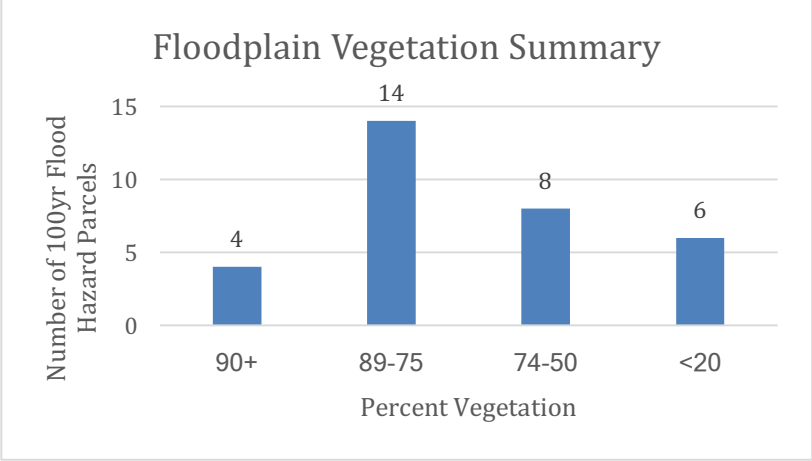

Figure 16. Summary of vegetated land cover in Seattle's Special Flood Hazard Areas based on NDVI analysis.

Both land cover and NDVI analysis provide a bird's eye view of green infrastructure potential and limitations throughout the city, but this is incomplete for the purposes of strategic green infrastructure planning, which is constrained by jurisprudence: property ownership, budgetary responsibility, regulatory restrictions and policy mandates. The next section puts City of Seattle's green infrastructure on the map to establish a baseline for further analysis through the geodesign framework.

2.4.3 Green Infrastructure Map

The first step to planning for the future is knowing what you have in the present and, ideally, how it is influenced by the past. The previous two sections provided insights into both, while this one locates specific types of green infrastructure in the Seattle landscape and in spatial relation to each other. Green infrastructure mapping initiatives typically take a 'natural' lands approach at county, state or even national levels, primarily identifying habitat hubs and corridors in the vein of Benedict and McMahon's definition of green infrastructure as "interconnected network of waterways, wetlands, woodlands, wildlife habitats and other natural areas; greenways, parks and other conservation lands; working farms, ranches and forests; and wilderness and other open spaces…" (2007). A few of these approaches will be highlighted for potential strategies that can also be used in an urban environment. At the urban scale, green infrastructure mapping is not yet de rigueur in the United States. When done, it usually focuses specifically on green stormwater infrastructure (e.g. Philadelphia's Big Green Map[62], NYC's Green Infrastructure Map[63])

[62] City of Philadelphia. 2015. Big Green Map. Available from http://www.phillywatersheds.org/BigGreenMap. Accessed on 1/29/2016.
[63] New York City Department of Environmental Protection. 2016. Green Infrastructure. Available from http://maps.nyc.gov/doitt/nycitymap/template?applicationName=GREEN_INFRA. Accessed on 1/29/2016.

identified as point features rather than two or three-dimensional areas, or it emphasizes tree canopy coverage (see Jefferson and Moskal 2014 for a review).

Maryland's Green Infrastructure Assessment (GIA), developed by the MD Department of Natural Resources, is exemplary of the habitat hub and corridor approach, which prioritizes large contiguous areas of natural lands (at least 98 acres (40ha)), interconnected by natural corridors (at least 1147 feet (350m) wide) for species dispersal and migration (Weber et al. 2006). Maryland was one of the early pioneers in smart growth planning[64] and has aggressively pursued land conservation with one of the oldest programs in the country, launched in 1969 as Project Open Space (The Conservation Fund 2004). The GIA has been used at multiple scales – at the multi-state level to set priorities for the Chesapeake Bay clean-up, regionally to rank areas for state land conservation, and at the county level for green infrastructure initiatives (Weber et al. 2006). Figure 17 illustrates the hub delineation process, with the notable step to exclude human intensive land uses after the natural areas composite layer has been created. However, most of the base features that make up the natural areas composite can also be found in the urban environment, including the interior forest, which the GIA designates as 247 acres (100ha). Seattle's Seward Park is 294 acres – much of it forested with 120 acres designated as old growth (the Magnificent Forest in the northern two-thirds of the peninsula) and home to a variety of wildlife including bald eagles.[65]

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[64] National Center for Smart Growth Research and Education. Smart Growth in Maryland. Available from http://smartgrowth.umd.edu/smartgrowthinmaryland.html. Accessed on 2/1/2016.
[65] Friends of Seward Park. The Magnificent Forest. Available from http://www.sewardpark.org/index.html. Accessed on 1/29/16.

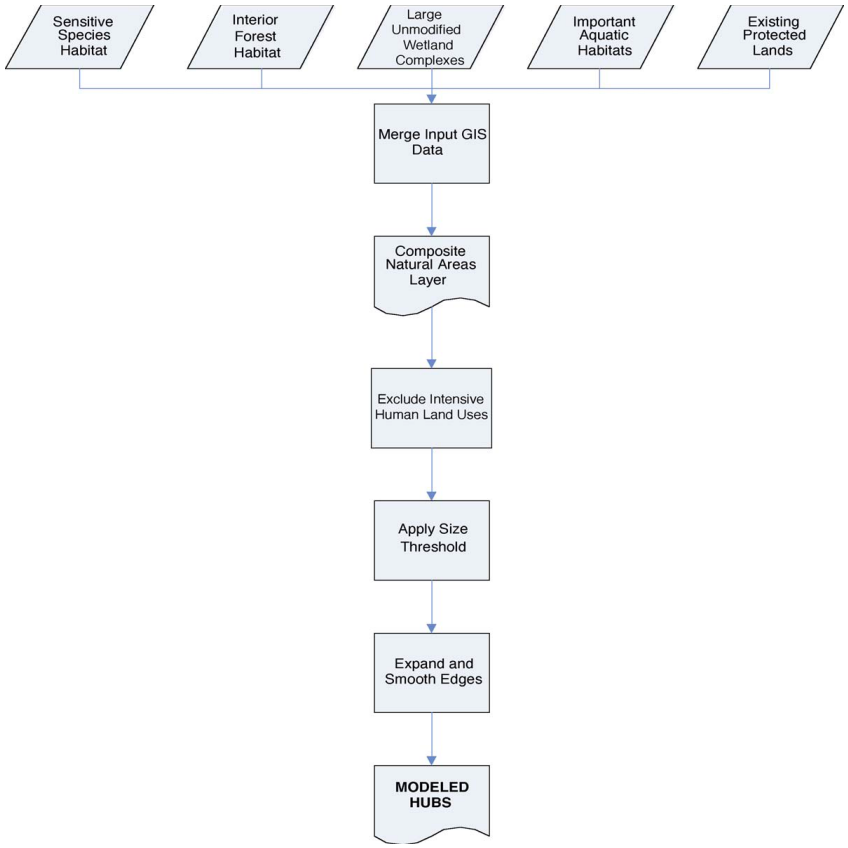

Figure 17. Maryland's Green Infrastructure Assessment's hub delineation process (Weber et al. 2006).

The GIA was developed to identify areas with the greatest ecological importance to help guide conservation priorities, so the exclusion of human dominated land uses is understandable. Weber et al. detail natural land cover losses, habitat and water quality degradation and urban growth projections to communicate a sense of urgency for the application of the GIA, "In the face of continuing urbanization, it is important that land conservation programs be directed toward conserving the most valuable of our natural assets." (2006, 95). However, land conservation alone will not restore already damaged ecosystems, nor do species necessarily recognize the distinction between *natural* and urban, as demonstrated by the 560 vertebrate and 13,000+ invertebrate species that inhabit Seattle's open space. Thus urban green infrastructure, and its relationship to the larger conservation context, should also be accounted for.

Karen Firehock, director of the Green Infrastructure Center (GIC) and author of *Strategic Green Infrastructure Planning: A Multi-Scale Approach* (2015), also subscribes to the Benedict and McMahon definition of green infrastructure and emphasizes the importance of mapping a community's natural assets, "We introduce the term *natural asset evaluation and mapping* to more directly reflect the GIC's focus on evaluating *natural* landscape resources and conserving them first, before seeking engineered solutions to mitigate impacts from the built environment [author emphasis]." (2015, 10). Perhaps, though, because of her shift in scale to community, she also includes nature-based recreation areas, historic and cultural features with landscape settings, street trees and parks (2015).

The distinction of natural versus engineered deserves special attention, especially in the urban environment where it may present a false dichotomy. Take for example the Olympic Sculpture Park Beach and habitat bench in Seattle. Prior to restoration, the site was an 800ft timber and steel seawall and riprap embankment (Figure 18). Following restoration, it mimics the gravel beaches that were part of Seattle's natural Elliott Bay shoreline, remnants of which can be found at Discovery Park and Golden Gardens Park (Figure 19). The restoration was undertaken as part of the Olympic Sculpture Park development on the site of an abandoned fuel storage and transfer facility. Preliminary design documents for the seawall portion of the site used the same behind-the-wall stabilization approach (with an estimated cost of $50-80 million) being used for the rest of the downtown seawall to avoid disrupting the piers that line much of the Elliott Bay shore. However, since there were no piers along the park's section of waterfront, and because its seawall was not adjacent to the Alaska Way Viaduct, designers had some flexibility to explore less

expensive alternatives (Conchar 2007). Their solution was to reinforce the existing seawall with an in-water buttress (at a cost of $5.5million), but in order to obtain permits for shoreline modification, the team had to develop a system that would mitigate impacts on the aquatic environment (Figure 20), particularly the juvenile salmon who migrate up the shoreline from the Duwamish River.

Figure 18. OSP shoreline before restoration.

Figure 19. OSP beach after restoration.

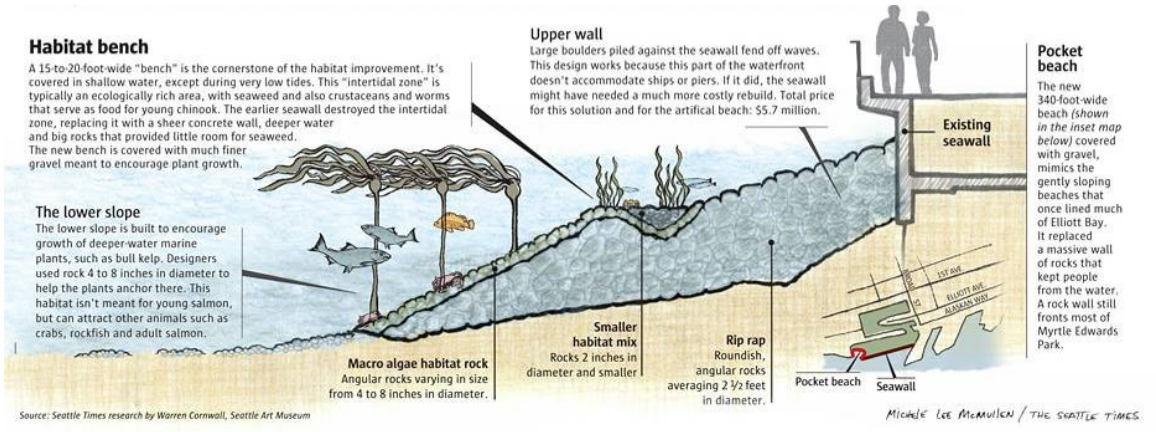

Figure 20. OSP seawall buttress was designed to do double duty as a habitat bench to give migrating juvenile salmon relief from the 80+ft drop-offs along most of the rest of the downtown shoreline.[66]

Of course, it seems logical to preserve what you have rather than undertaking costly restoration, this is one of the basic arguments used by environmental activists for

[66] Warren Cornwall. Seattle trying to woo salmon back downtown with park's seawall makeover. *Seattle Times* 1/17/2007.

conservation and against restoration (Higgs 2003). However, in an already highly modified environment that is part of an endangered species' migration path restoration is the only viable, and perhaps most efficient, option - especially when it can multi-task like the OSP habitat bench at a fraction of the cost of a conventional, purely structural solution. According to pre- and post-construction monitoring results (2005 versus 2007-2009), there was rapid development of aquatic and terrestrial biota within the newly created habitats. Many of the invertebrate and fish indicators had much higher values than baseline conditions measured before construction, or adjacent sections of seawall and riprap. Remarkably, juvenile, and most significantly larval, fish species (salmon plus more than a dozen others) in the area increased 530-fold from just over 500 in 2007 to 265,000 in 2009 (Toft et al. 2010). Because engineered solutions can readily become naturalized when designed well, they may be included in a GIA or GIC-typical assessment by accident, which is why their explicit exclusion seems amiss in a comprehensive GI inventory.

Although Seattle does not yet have a comprehensive green infrastructure mapping program, and SPU has just begun the process of parcel-level, code-driven green stormwater infrastructure mapping[67], much of the information needed for a green infrastructure map is already available from various city sources. Table 4 lists the features and data sources included for an initial representation of Seattle's green infrastructure. Figure 21 presents a city-scale overview of these features, while Figure 22 provides an example of localized detail.

[67] Based on personal communication (10/19/15) with Rodney Young, GIS Professional for SPR.

Table 4. Seattle Green Infrastructure Feature Overview

Feature	Area/Count	Data Source (Filename)
Priority Habitats and Species Areas	5538 acres	City of Seattle environmentally critical areas (DPD_ECA)
Hydrography		
Wetland	547 acres	City of Seattle environmentally critical areas (DPD_ECA), all but 9 are from the US Fish and Wildlife National Wetlands Inventory
Riparian Corridor	14 acres	City of Seattle environmentally critical areas (DPD_ECA)
Floodplain	1252 acres	City of Seattle environmentally critical areas (DPD_ECA)
Green Stormwater Infrastructure*		
Linear Swale	11 miles	Selected from SPU (dww_surface_drainline_ln)
GSI Tree	658	SPR (GSI_Trees)
Green Roof	Ca. 36 acres	**Derived** – Green roof points from SPU 700 Million Gallons[68] inventory overlaid on building roof outlines (BLDG2012) and digitized using Esri's World Imagery map service.[69] Combined with SPR (GSI_Facilities). Additional green roof locations discovered through imagery inspection and online searches.[70]
Bioretention / Biofiltration	Parks: 71 facilities = 2.4 acres SPU: 492 facilities, acreage unknown	**Derived** – Bioretention/biofiltration points from SPU 700 Million Gallons inventory joined with parcels and combined with SPR (GSI_Facilities)
Residential Rain Gardens	446 facilities, acreage unknown	**Derived** – Rain garden points from SPU 700 Million Gallons inventory joined with parcels
Additional GI		
Street Tree	98,716	SDOT (Seattle_terrain_sttree)
Pedestrian / Bike Trail	46.9 miles	SDOT (Street Network Database)
P-Patch	Ca. 350 acres	**Derived** – P-Patch points joined with parcels
Park	6414 acres	SPR (ParksBND)

*Rain barrels, cisterns and permeable pavement not included in GI Map because of their one-dimensional function.

[68] SPU and King County. 700 Million Gallons. Available from http://www.700milliongallons.org/ Data from website acquired from SPU's Pam Emerson.
[69] Esri. 2016. World Imagery. Available from http://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9. Accessed on 11/2/2015.
[70] Online sources included pacificearthworks.com and greenroofs.com, as well as the websites for individual buildings that promote their sustainability features.

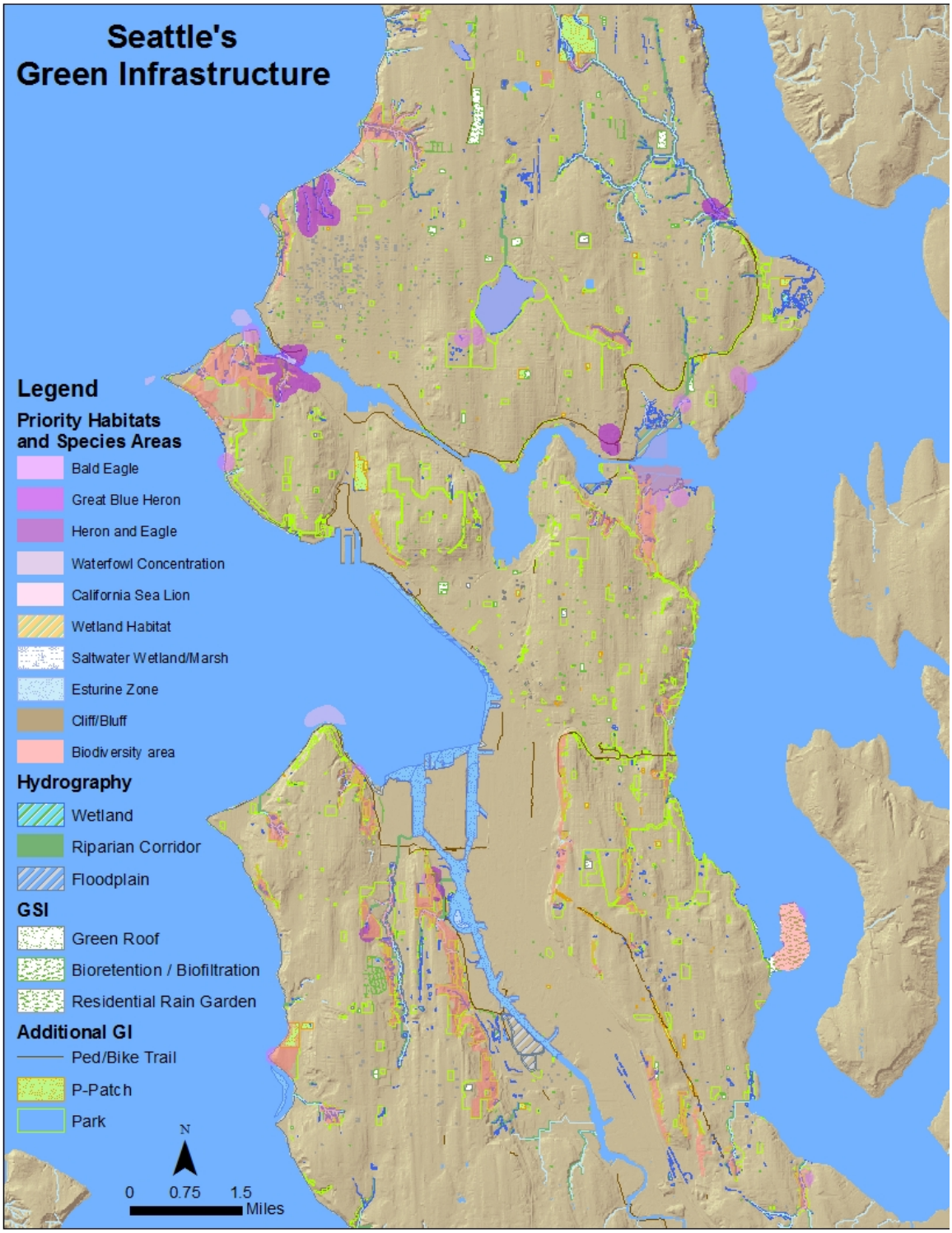

Figure 21. Overview of Seattle's GI, excluding street and GSI trees. At the city scale, the map is hard to read, and relationships between different types of infrastructure are not clear, aside from some areas of overlap. See Table 4 for map data sources.

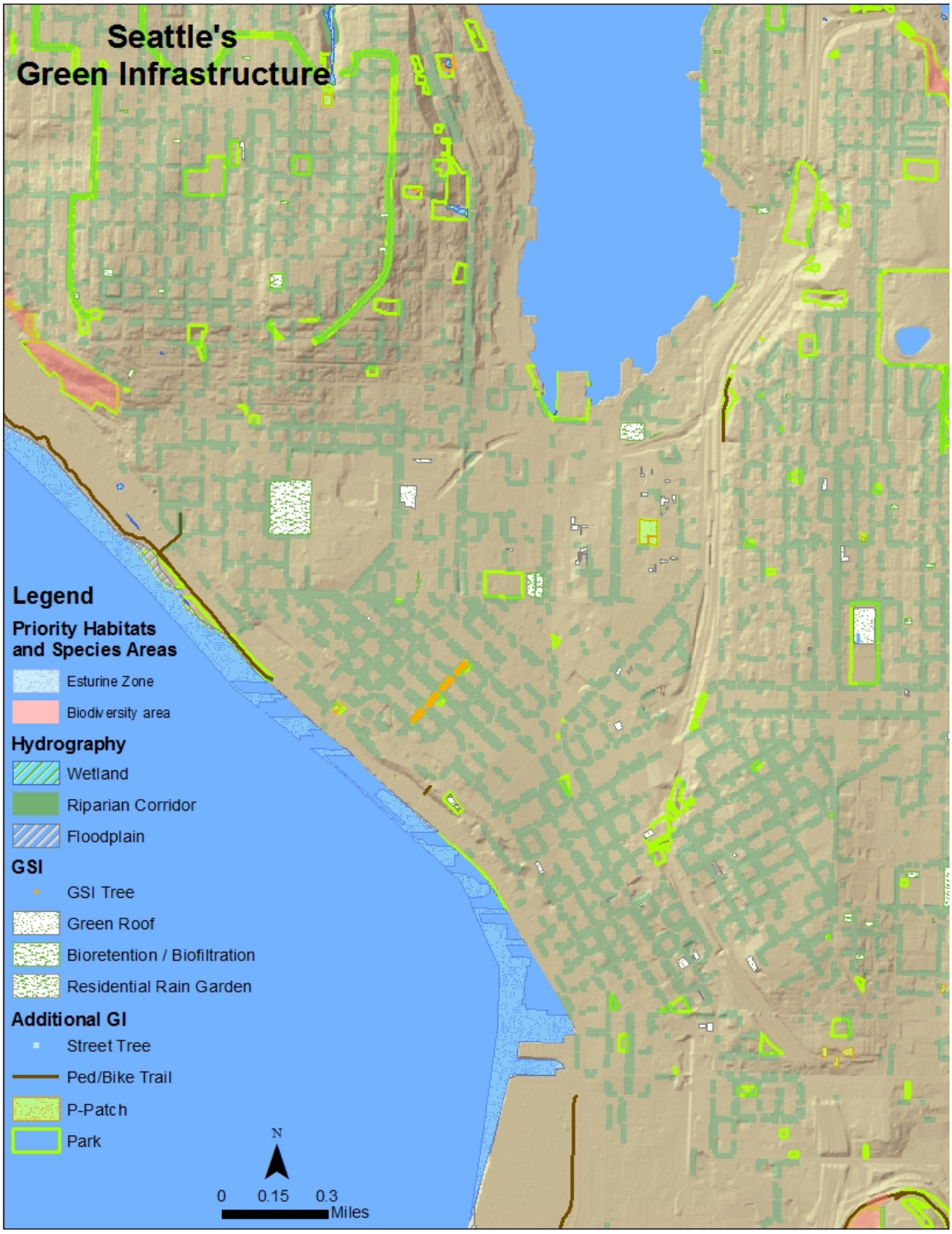

Figure 22. Seattle GI, including street and GSI trees, in the downtown core and adjacent neighborhoods. At the localized scale, different types of GI are readily discernable but relationships are still not obvious. See Table 4 for map data sources.

To reiterate the captions for Figures 21 and 22, mapping Seattle's green infrastructure is a necessary first step in strategic planning, but does not provide deeper insight into the relationships among various types of green infrastructure. Even various types of spatial statistics and spatial proximity analyses like distance, neighborhood and overlay only provide a starting point for strategic planning to achieve multi-functionality. In their analysis of two types of green infrastructure functionality in Porto, Portugal, Madureira and Andresen insist that "green infrastructure cannot remain an automatic and simplistic synonym of multi-functionality […] Deciding how to mediate between the different and potentially conflicting demands of multi-functionality is a major challenge for green infrastructure planning" (2014, 39). They emphasize the need for a "proper and systematic methodological assessment" (2014, 39) that looks at the spatial interaction of green infrastructure functions and assigns spatial priority for interventions.

In their approach, they first analyze two different functions (local temperature regulation and population access to public green space) and assign each parcel a priority for the respective GI function on a scale of 1-10 to demonstrate that there are both synergies and conflicts among areas prioritized. They then overlay and average each parcel's ranking to "mediate" between the different functions (2014, 47), and demonstrate how priorities may be redefined when taking in account more than one GI function. In their conclusion, they acknowledge a need for including more GI functions in their assessment, but do not address their assumptions that averages really capture the nature of spatial interactions among GI functions. They want to see a move from "general consensuses to designed policies" and "generic assumptions to local assessments" (2014, 48), but I posit that a more robust

analytic framework is needed that accounts for multiple system dynamics, not simply spatial co-location and averages from an ordinal ranking system. Geodesign addresses both the need for design policies and local assessments raised by Madureira and Andresen, and the geodesign framework provides a systematic methodology for green infrastructure planning.

Chapter 3. Integrating Across Dimensions: A Geodesign-based Approach to Green Infrastructure Planning

3.1 Introduction

In many ways, people have always been geodesigners- adapting their modes of survival (e.g. shelter, food, defense) to their environment, and, to the extent possible with the resources at hand, transforming their environment to better serve their needs. As social organization, technology and energy sources evolved, so too did the transformative power of people - to the point that today many consider us to be living in the Anthropocene – the epoch where people, not planetary forces, significantly shape Earth's systems. The term, coined by Paul Crutzen and Eugene Stoermer in 2000, generally connotes the time period since the Industrial Revolution in which many geologically significant conditions and processes have been fundamentally altered by human activities including: erosion and sediment transport due to colonization, deforestation, agriculture, and urbanization; the chemical composition of the atmosphere, oceans and soils, with significant perturbations of the cycles of elements such as carbon, nitrogen, phosphorus and various metals; environmental conditions generated by these perturbations including climate change, ocean acidification and hypoxic zones; the biosphere, as a result of habitat loss, predation, species invasions and the physical and chemical changes noted above.[71] Though not yet formally adopted as a geologic unit within the Geologic Time Scale, there is an Anthropocene Working Group currently developing a proposal for consideration by the

[71] Subcommission for Quaternary Stratigraphy. 2016. Working Group on the Anthropocene. Available from http://quaternary.stratigraphy.org/workinggroups/anthropocene/. Accessed on 3/24/16.

International Commission on Stratigraphy, which reinforces just how dramatic the force of humans has become.

Thus geodesign- changing geography by design (Steinitz 2012), is neither new nor inherently positive. It is this specter of anthropogenic force that motivates the exploration of geodesign more narrowly defined as a "design and planning method, which tightly couples the creation of design proposals with impact simulations informed by geographic contexts, systems thinking and digital technology"[72], and applied to the complex task of multi-functional and multi-scalar green infrastructure planning. This chapter and the next explore Seattle's green infrastructure using the six questions and related models (representation, process, evaluation, change, impact, decision) of the Steinitz geodesign framework, and traverse the framework three times – first for scoping the geodesign study, secondly for designing the study, and finally for implementing the study (Nyerges et al. 2016). Figure 23 illustrates the framework and the idealized progression through each phase and iteration; however, Steinitz (2012) emphasizes that in practice the framework is not linear and should to be flexible to accommodate the circumstances of the particular study and needs of the participants.

[72] Steinitz attributes this definition to Michael Flaxman as amended by Stephen Ervin (2012, 12).

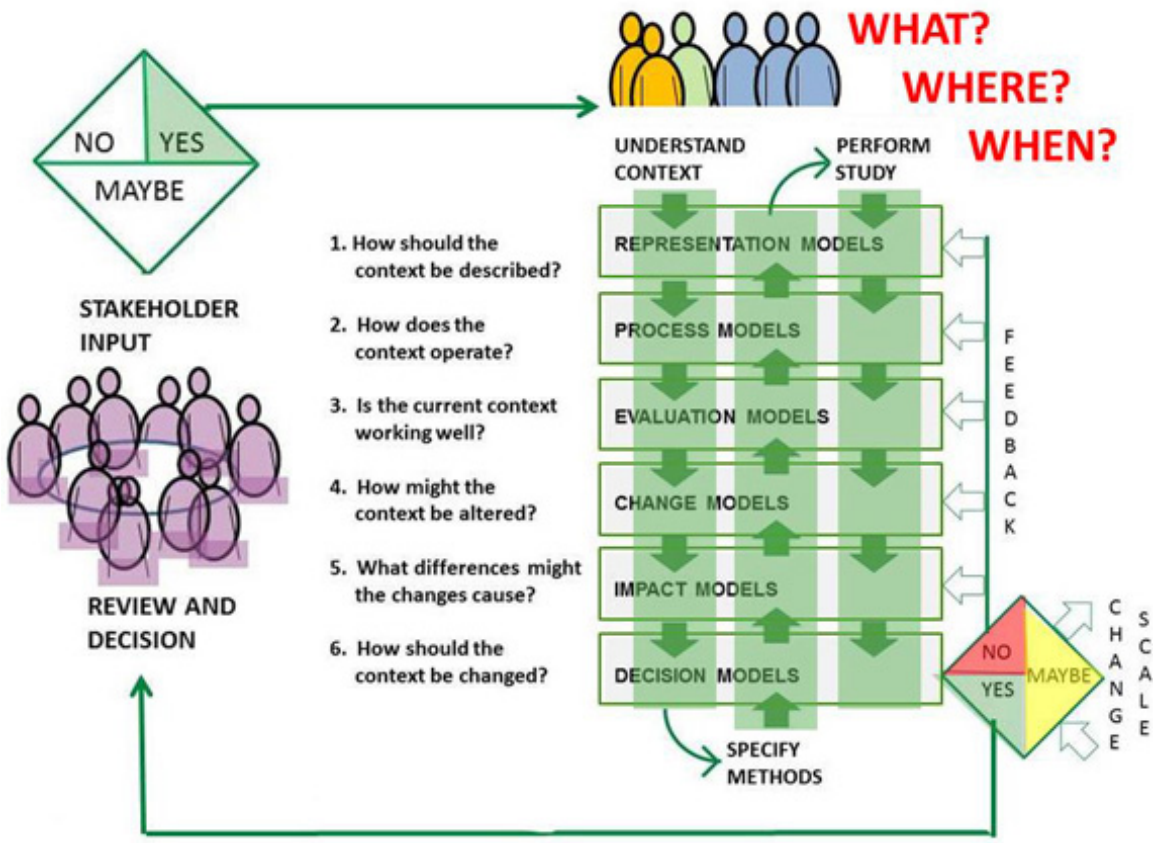

Figure 23. The Steinitz Geodesign Framework consisting of six questions and related models, refined with increasing levels of information and detail in three iterations (graphic from Steinitz in McElvaney and Rouse (2015). Note: the term 'context' is meant as the 'context for the design'. In *A Framework for Geodesign* (Steinitz 2012), the term 'study area' is used instead.

Two aspects of geodesign, which are not immediately apparent in Figure 23, make the approach well suited to multi-functional and multi-scalar green infrastructure planning. One important aspect is the inclusion of multiple systems - both their present and relevant historical conditions, in the analyses. Steinitz generally suggests 10 systems, drawing on research on cognitive overload (Miller's Law of seven plus or minus two (1956) referenced in Nyerges et al. 2016), that represent the physical, ecological, economic and social geographies of the study area (Steinitz 2012). Other research suggests the 'rule of hand', or three to five variables (which can also be construed as subsystems) influence the overall

system of interest based on empirical studies that fewer than five variables are dominant in observed system dynamics (Walker et al. 2006). Even without specifying a predetermined number, it is clear that multi-functional green infrastructure must consider the interactions of the green infrastructure system with multiple other systems – both biotic and abiotic.

Close attention to scale is another important aspect of Steinitz's geodesign methodology. Figure 23 illustrates a need to change the scale of analysis if the project stakeholders are not convinced that the interventions suggested by the study should be implemented. Steinitz, however, goes into far more detail regarding scale in *A Framework for Geodesign* because it is the differences in the scales at which the design professions and geographic sciences normally work that he seeks to bridge through geodesign. For example, landscape architects and civil engineers typically work at parcel and neighborhood scales, planners at community to regional scales, and geographers at regional to global scales (Steinitz 2012). These differences in scale are important because the methods of analysis and scope of interventions often vary significantly.

Figure 24 depicts these scale ranges as well as areas of overlap at the neighborhood to regional scale. It is these areas of overlap that create the greatest opportunity for collaboration among the broadly defined design professions and geographic sciences using the geodesign framework (Steinitz 2012). A third aspect of geodesign - the role of information technology in supporting this multi-disciplinary collaboration, will be treated in more detail Chapter 5. However, the geodesign definition formulated by Mike Flaxman and revised by Steve Ervin is useful for framing the research that follows: "Geodesign is a

design and planning method which tightly couples the creation of design proposals with impact simulations informed by geographic contexts, systems thinking, and digital technology." (Steinitz 2012).

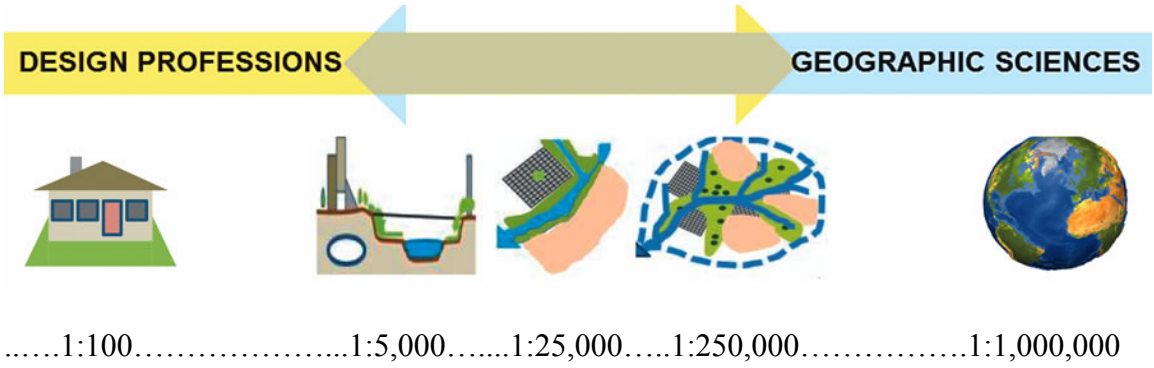

Figure 24. Scales at which design professions and geographic science typically work. Areas of overlap generally occur at the neighborhood to regional scale. Source: Carl Steinitz (2012).

The rest of this chapter focuses on demonstrating how the geodesign framework can be applied to planning green infrastructure that is both multi-scalar and multi-functional by design, which provides the basis for the use of the term 'strategic' throughout this dissertation. There are many definitions of strategy, of which Nickols provides a good overview as well as the following synthesis: "Strategy, in general, refers to how a given objective will be achieved. Consequently, strategy in general is concerned with the relationships between ends and means, that is, between the results we seek and the resources at our disposal".[73] The geodesign framework helps both understand and organize the means (i.e. organizational and capital resources) and the ways for how these resources can be deployed to achieve the end of multi-scalar, multi-functional green infrastructure.

[73] Fred Nichols. Strategy: Definitions and Meanings. Available from http://www.nickols.us/strategy_definitions.pdf. Accessed on 3/15/2016.

3.2 First Iteration – Scoping the Study

The first iteration through the geodesign framework focuses largely on gaining enough background to understand a particular study area, in this case the City of Seattle, and determine WHY intervention or change is needed (Steinitz 2012). Figure 23 lists the series of general questions that are asked in relation to each modeling phase. Steinitz also poses several sub-questions that vary for each iteration, which provide more insight and nuance to the general question set. While chapters 1 and 2 addressed to some degree all of the questions needed for scoping the study; the most salient points will be repeated as a direct response to the questions for the sake of consistency across iterations.

Q1. How should the study area be described in content, space and time?
Q1a. What are the boundaries of the study area's major systems?

The Seattle municipal boundary is the most fundamental due to the nature of decision making and funding for green infrastructure implementation. Other important jurisdictional boundaries include King County and Washington State. King County directly influences the management and restoration of aquatic systems that flow through Seattle (the Green/Duwamish River) or affect Seattle's water supply (the Cedar and Tolt Watersheds). The county is also a partner in the Protect Our Waters program to eliminate combined sewer overflows in the city. State-level regulations and funding affect things like wildlife and critical area protections. Neighboring jurisdictions and their regulations or lack thereof also affect the quality of shared ecological systems; however, these will not be treated from the green infrastructure planning perspective except in the context of larger multi-jurisdictional collaborations such as the Puget Sound Partnership (PSP) and Puget Sound Regional Council (PSRC).

Important ecological boundaries include the state-designated water resource inventory areas (WRIAs 8 and 9), which correspond to the USGS HUC-8 watershed scale and encompass large areas outside of the city from the Cascade Mountains to the Puget Sound, as well as the sub-watersheds, both natural and manufactured throughout the city. These watersheds, together with climate, vegetation and soil conditions discussed in section 2.4 determine the hydrologic response of the Seattle landscape. The Georgia Basin-Puget Sound airshed is relevant from the perspective of air quality management, another important green infrastructure function. The boundaries of habitat areas and migration pathways are also of interest including those of salmon, sea lions and diverse waterfowl.

Q1b. What is the area's physical, economic, and social geography?

Section 2.4 discussed the relevant aspects of Seattle's physical geography for green infrastructure planning. Both the economic and social geographies are far too diverse to treat in detail for the entire city; however, a few meta-categories are likely interesting and potentially overlapping: 1) water-based like the port, central waterfront, commercial fishing, houseboats, marinas 2) recreation-related like park and trail users and neighbors 3) local food-oriented and 4) eco-friendly (including traditional advocacy groups like the Green Building Council and Forterra, as well high-profile tech companies like Microsoft, Amazon, and Google who have integrated a wide range of green infrastructure into their campuses).

Q1c. What is the area's physical, economic, social history?

Again, Section 2.4 delved into Seattle's physical history, which continues to shape the hydrologic response and landslide risk of today's landscape. The persistence of 11 federal superfund sites[74], concentrated along the lower Duwamish Waterway and southern portion of Elliott Bay, are a modern reminder of several key historical industries in the region including logging and wood processing; aviation; lead smelting; and asphalt production. Cleanup efforts have included riparian restoration, off-channel habitat creation, and park and trail development – all of which contribute to the city's green infrastructure. Modern day commercial fishing continues to be affected by the legacy of contamination in the Duwamish and Elliott Bay as it affects the health of migrating salmon and trout. Though currently not a federally recognized Native American tribe, the Duwamish people contributed significantly to the survival of the first settlers in the area, and are important constituents in their namesake river's cleanup. A quote often attributed to the Duwamish leader and city's namesake Chief Si'ahl serves as the environmental ethos for Seattle: "This we know, the earth does not belong to man, man belongs to the earth. This we know, all things are connected like the blood which unites one family. All things are connected."[75]

The Olmsted brothers' legacy is another important determinant in modern Seattle's green infrastructure, and represents the confluence of socio-economic forces. The city's first

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[74] See EPA's listing of Washington's superfund cleanup sites available from https://yosemite.epa.gov/r10/cleanup.nsf/webpage/Washington+Cleanup+Sites. Accessed on 3/2/2016.

[75] Though the origin of this quote is debated, the Duwamish Tribe also reference it on their website, see http://www.duwamishtribe.org/.

public park was donated by its founder David T. Denny in 1884. Three years later, the Board of Park Commissioners was established to oversee the development of the city's park system and the Olmsted brothers were hired in 1903 to develop a comprehensive park plan, in part to prepare for the 1909 Alaska-Yukon-Pacific Exhibition.[76] Altogether, 74 of the city's parks, playgrounds and boulevards were either designed (25), influenced (20), or recommended (29) by the Olmsteds, in addition to the University of Washington campus, which also evolved out of their plan for the 1909 Exhibition.

Q1d. Are there prior plans and designs for this geographic study area?

Several plans referenced in chapter 2 provide the basis for Seattle's green infrastructure including:

- Cedar River Watershed Habitat Conservation Plan
- South Fork Tolt Watershed Management Plan
- Protecting Seattle's Waterways
- Long-term Control Plan
- NPDES Phase 1 Municipal Stormwater Permit Stormwater Management Plan
- Green Stormwater Infrastructure Implementation Strategy 2015-2025
- Urban Forest Stewardship Plan
- 2016 Seattle Tree Canopy Assessment
- Seattle Food Action Plan
- Complete Streets Checklist
- Parks Legacy Plan
- 2017 Parks and Open Space Plan
- Seattle Comprehensive Plan 2035
- Urban Wildlife and Habitat Management Plan
- Climate Action Plan
- All-Hazards Mitigation Plan

[76] SPR. 2015. Park History – Olmsted Brothers. Available from http://www.seattle.gov/parks/parkspaces/olmsted.htm. Accessed on 4/6/2016.

Q2. How does the study area operate?

Q2a. What are the area's major physical, ecological, and human geographical processes?

A few important processes that both shape and result from Seattle's physical and ecological geography were mentioned in the previous section – hydrologic, atmospheric, and biotic. Beyond the day to day and long-term management processes of each of the city departments described in chapter 2, other notable human processes that affect the city's green infrastructure include real estate development (e.g. triggering the Green Factor requirements) and an emphasis on transit, cycling and pedestrian infrastructure, which affects streetscape and greenway development throughout the city.

Q2b. How are they linked to each other?

Concerns about the impacts of stormwater runoff, combined sewer overflow, and urban flooding (hydrologic processes) are driving both GSI development in the public ROW as well as requirements, such as the Green Factor, for real estate development. Air quality improvement and carbon sequestration, together with stormwater management and habitat provision, are important motivations for urban forestry – thus linking hydrologic, atmospheric and biotic processes. Seattle's Complete Streets Checklist incorporates water and air quality considerations into street designs that prioritize pedestrian, cyclist and transit safety and mobility. From a process perspective, the linkages are readily discernable, and even acknowledged from a management perspective as demonstrated by SDOT's Complete Streets program and OSE's Urban Forest Stewardship Plan.

Q3. Is the current study area working well?

Q3a. Is the area seen as attractive?

Yes, both population and employment are on the rise in Seattle, and growth is projected to continue (Figure 25). Following the 2007-2009 US recession and subprime mortgage crisis, residential housing development has also reached an all-time high (Figure 26), with new multi-family housing leading the market.

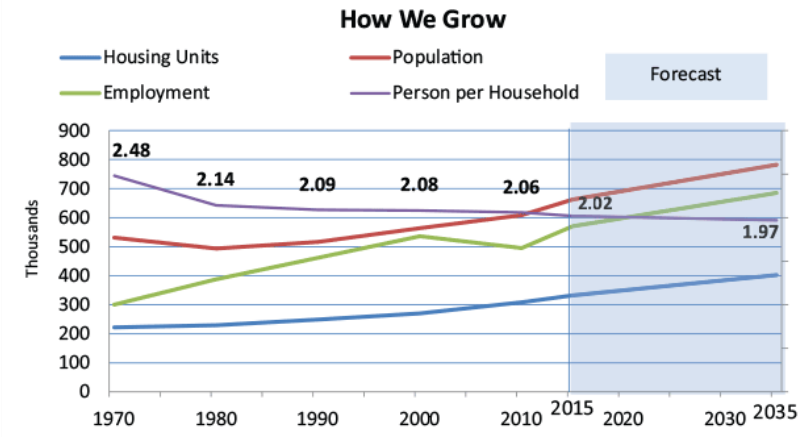

Figure 25. Seattle population and demographics 1970-2035. Graphic source: Seattle DPD.

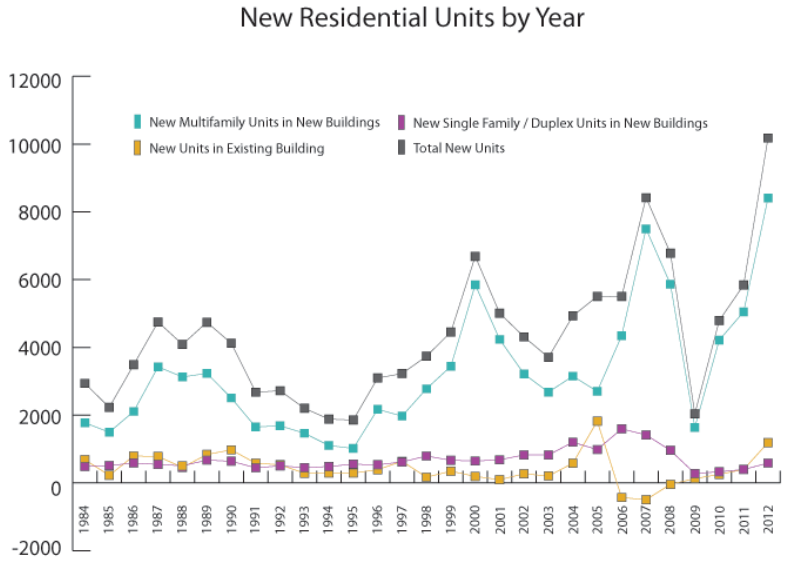

Figure 26. Seattle housing growth 1984-2012. Source: DPD.

Q3b. Is the area seen as vulnerable?

Part of the area's draw is its scenic beauty with dramatic volcanoes to the north and south, mountain ranges to the east and west, fresh and saltwater abundance, and wildlife. Volcanic and earthquake dangers aside, the main threats to these social and economic assets are

related to human activities, which is why environmental stewardship and green infrastructure are so important.

Q3c. Are there current environmental and other problems?

Some of the localized issues have are already been mentioned including toxic superfund sites, polluted stormwater runoff, and combined sewer overflows; however, the Puget Sound serves as a litmus for the health of the entire region. Puget Sound Partnership, the lead state agency formed to coordinate the efforts of hundreds of partners including local, county and tribal governments and non-profits, has identified the following three priorities as critical to improving the overall health of one of the nation's largest and most productive estuaries: stormwater pollution prevention, habitat restoration and protection, and shellfish bed improvements (PSP 2015). Between 2011 – 2014, 39 floodplain projects improved 14,500 acres of habitat, 24 projects restored estuaries to tidal inundation, and shoreline armoring has declined. However, the number of wild spawning Chinook salmon are still declining compared to 2006-2010; the Orca whale population, which depends on the Chinook, has decreased to 82; and toxic chemicals in sediments and fish, while slightly lower, are still high enough to cause mortality and morbidity, especially in Pacific herring which are an important part of the Puget Sound food web (PSP 2015). The 2014 Puget Sound Pressures Assessment reinforces the aforementioned priorities, and indicates the primary stressors, narrowed down from a list of 47, in the Puget Sound watersheds and marine basins (Figure 27) (PSP 2014).

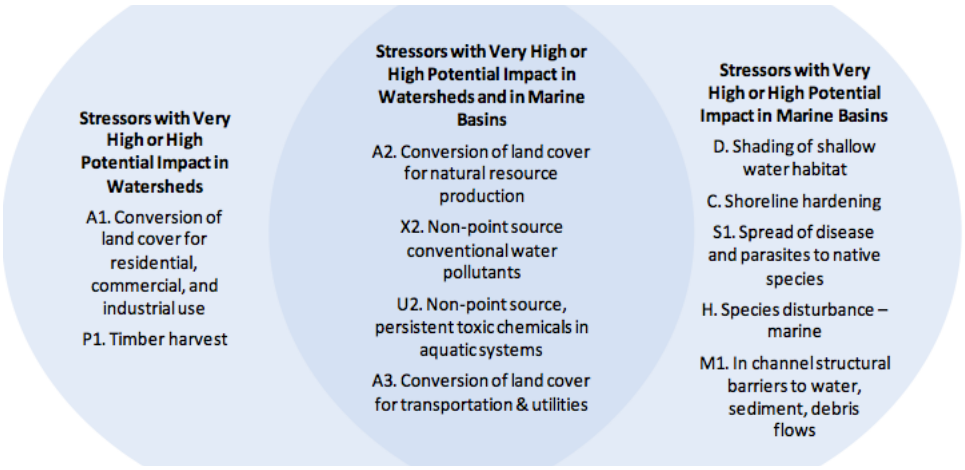

Figure 27. Stressors that ranked very high or high across multiple assessment units. Source: PSP 2014.

Note: Questions 4 and 5, as well as the related sub-questions are addressed together in this iteration so the major changes to the region and related impacts can be considered simultaneously.

Q4. How might the study area be altered?

Q4a. What major changes are foreseen for the region?

Q4b. Are they related to growth or decline?

Q4c. Are they related to development or conservation (or both)?

Q5. What difference might the changes cause?

Q5a. In which ways are foreseen changes seen as beneficial or harmful?

Q5b. Are these impacts seen as serious? As irreversible?

Climate change is one of the biggest issues facing the planet, although it is not included in the highest priority stressors listed in Figure 27 because these were rated based on present functional impact. Of the 47 stressors assessed, six were related to climate change: altered peak flows, altered low flows, changing air temperature, changing precipitation patterns, sea level rise, and changing ocean condition (PSP 2014). Based on the highest greenhouse

gas concentration "business as usual" trajectory, Representative Concentration Pathway (RCP) 8.5, the Pacific Northwest will warm approximately 5.5°F by the 2050s relative to 1970-1999, and has already warmed 1.3°F (Manger and Snover 2015). This increase is already affecting snowpack, which has declined by about 25% between 1950 and 2006, and is expected to decline by 80% by 2040 in the headwaters of the Tolt and Cedar (Seattle's two water supply sources), as well as the Green and Sultan rivers (Scigliano 2015). Though only small changes in annual precipitation are expected (-2% to +13%), precipitation extremes are expected to increase (Manger and Snover 2015), which will mean more flooding in the fall and winter and lower stream flows in the spring and summer that are further exacerbated by reduced snowpack (Scigliano 2015). While riverine flooding is not currently an issue for the Seattle landscape due to flood control measures, more flooding leads to higher sediment loads entering the Elliott Bay - a major source of toxic pollution especially in the industrialized Lower Duwamish Waterway, and lower stream flows will mean increased pollutant concentrations from stormwater runoff.

Another important change, particularly from a water resource and infrastructure management perspective and in part related to climate change, is the "death" of stationarity - the idea that "natural systems fluctuate within an unchanging envelope of variability" (Milly et al. 2008, 573), as a basis for planning. Stationarity applied to hydrology means that "any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function, whose properties can be estimated from the instrument record" (Milly et al. 2008, 573). In other words, stationarity implies that the mean and degree of variability of the hydrologic time series do not change over time.

Stationarity assumptions are used, for example, to determine flood recurrence intervals for water infrastructure planning, and planners have tools to adjust these calculations for known human interventions such water infrastructure, channel modifications, drainage works, and LULCC. However, the variability of two other influences – natural climate change and low-frequency, internal variability (e.g., the Pacific multi-decadal oscillation), enhanced by the slow dynamics of the oceans and ice sheets, has been assumed small enough to ignore (Milly et al. 2008). Observed changes in precipitation frequency and intensity as well as evaporation due to climate warming challenges these assumptions of predictability, and paleo-hydrologic studies indicate a nonlinear relationship where small changes in mean climate variables might produce large changes in hydrologic extremes (Milly et al. 2008).

Vogel et al. (2011) applied a nonstationary flood frequency model to nearly all of the USGS gaging stations in regulated (T=4,537), non-regulated (T=14,893) and Hydro-Climatic Data Network (HCDN) (T=1,588) basins (2011, 471). They found significant ($p < 0.05$) positive decadal flood magnification factors[77] (2-5) in all regions of the U.S. and for all types of basins. The HCDN basins, which have been screened to exclude human activities in or near the stream channel that could affect natural flow, showed the smallest positive trends, followed by basins affected by regulation or diversion, and non-regulated basins showed the highest trends. Increases were also highest in heavily urbanized regions such as the northeastern coastal corridor, Los Angeles and Chicago. These flood magnification

[77] The decadal flood magnification factor is the ratio of the *T*-year flood (e.g. 100-year) in a decade to the *T*-year flood today.

factors correspond to large, nonlinear, decreases in the 100-year flood recurrence interval for all stations with positive trends (Figure 27).

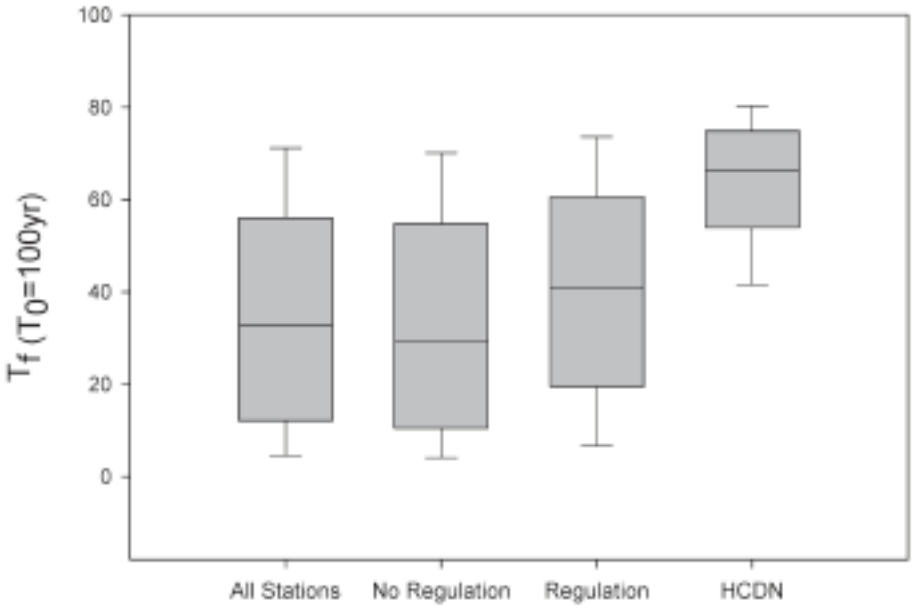

Figure 28. Reduction in the average recurrence interval of the 100-year flood for all sites with positive flood trends (Graphic source: Vogel et al. 2011). The 100-year flood is actually a 30-year, 40-year or 70-year flood in non-regulated, regulated and HCDN basins respectively.

Vogel et al. (2011) go on to further emphasize that while their findings seem to confirm increased flood recurrence due to climate change, anthropogenic influences appear more significant for flood magnification and recurrence intervals, and both contribute to nonstationarity, though their relative influence and interactions are not yet clear. This further highlights the importance of mitigating the effects of LULCC identified as stressors in the Puget Sound Pressure Assessment.

The perspective of nonstationarity requires a paradigm shift in water infrastructure planning and management away from engineering resilience that emphasizes efficiency, constancy and predictability and towards ecological resilience that emphasizes persistence, change and unpredictability (Holling 1996, 33). While scientists are still seeking

statistically significant trends, and nonstationarity is not yet state-of-the-art in water management, cities, already feeling the effects of weather extremes and urbanization pressures, are beginning to take action. Toronto experienced eight 25-year storms since 1986, and most recent, in 2005, caused an estimated Can$500 million in damages – the most expensive disaster on record for Ontario. Toronto subsequently adopted a 100-year storm design standard for their storm sewer infrastructure (versus the typical 2 to 5-year design) (Kessler 2011). In 2011, the city approved a Can$3.5 billion Wet Weather Flow Master Plan, which includes several green infrastructure projects and 1km of stream restoration per year, as well as a new sanitary sewer and constructed wetlands (Kessler 2011). Other cities are following suit. Philadelphia adopted a 25-year Green City, Clean Waters plan in June 2011, and allocated 70% of the $2.4 billion budget to green infrastructure.

Seattle is adding 6% to the volume of planned combined sewer storage tanks, and investing in "no-regrets" measures like hiring a meteorologist and developing a real-time weather system, RainWatch, to forecast rain accumulation and coordinate strategic responses to both adapt to and address existing pollution issues (Kessler 2011). Seattle has also invested heavily in retrofitting urban areas with green infrastructure, and is now requiring green stormwater infrastructure for all single-family residential projects, any project 7,000sf or greater, and any project with 2,000sf or more of new plus replaced impervious surface.[78]

[78] Seattle Municipal Code, Chapters 22.800-22.808. Available from http://www.seattle.gov/dpd/cms/groups/pan/@pan/@codes/documents/web_informational/dpdp022090.pdf .

Q6. How should the study area be changed?

Q6a. Who are the major stakeholders? Are they from the public or private sector?

While every individual carries responsibility for climate change, and clean energy and transportation are essential to put the planet on a lower RCP trajectory, climate change is already occurring and requires both large-scale mitigation and adaptation measures. Governments ultimately have to be the first-responders as exemplified by the actions that cities are already undertaking to address flooding and stormwater management issues. Local governments in particular, because of their regulatory mandates and funding mechanisms, are on the frontline, often in partnership with counties, as in the case of Seattle and King County. State and federal policies, legislation and funding also play a role, but cities and city departments must carry out the day to day and long-term planning and implementation. Chapter 2 detailed the primary departments in Seattle responsible for shaping the Seattle land and hydroscape with respect to green infrastructure: SPU, OSE, SPR, SDOT, DPD, and DON. These departments also work in partnership with non-profits and citizens to raise issue awareness and support for both interventions in the public sphere and regulations that affect private property owners and developers.

Q6b. Which consequences of change are considered most important?

Here the concept of change shifts from the externally driven perspective described in Q4 and Q5 to the intentional changes undertaken by the key stakeholders to address the critical issues facing the community. Both through the regional lens of the Puget Sound and the local concerns of the City of Seattle, water quality improvement and water quantity security are important outcomes of any action taken by city departments in fulfilling their functional

mandates. Reaching the interim goal of managing 400M gallons of stormwater with GSI by 2020, on the way to the 700MG goal in 2025, requires a 300% increase in GSI implementations over 2012 levels, and the development of new strategies and partnerships as illustrated in Figure 4.

From a broader perspective, the geodesign study should demonstrate the potential benefits from a strategic multi-functional, multi-scalar GI planning approach over a piecemeal/opportunistic/single function approach. Seattle has already started the process of multi-functional planning to some degree with the incorporation of GSI in the ROW and the Complete Streets' inclusion of forests and GSI; however, adding geographic prioritization through different types of spatial-temporal analyses can help identify areas of maximum benefit both for GSI and other forms of green infrastructure such as parks, habitat, forests/tree canopy, floodplains, and trails and greenways. The outcome of the geodesign study should be both a broader and a deeper understanding of the relationships among the various types of green infrastructure across scales and functions as well as a systematic assessment of their synergies and trade-offs to support strategic planning.

Although Steinitz recommends the development of scenarios as "an outline for a hypothetical future of the geographical context of the study" (2012, 40) at this point of the scoping process, the emphasis here is on geographically informed green infrastructure portfolio and network design to maximize its effectiveness. Green infrastructure has already been recognized as an important strategy for addressing multiple issues in the city and region, there is no foreseeable future without it. Geographic analysis can identify

potential synergies and tradeoffs between types and scales of green infrastructure. Scenarios, however, could support the decision modeling phase in third iteration of the framework to sort through various combinations of compatible green infrastructure for a particular site or to explore the potential long-term effects of drivers like climate change and land use policy on the GI portfolio.

3.3 Second Iteration – Designing the Study

The second iteration addresses HOW questions – how should the study be carried out, which methods and technologies should be used. It is performed in reverse order, with the decision model driving the rest of the analysis. An important caveat is that this geodesign study is not geared toward a single final best outcome (i.e. the most optimal green infrastructure portfolio and network), but rather it is intended to explore connections across systems and scales and spatialize synergies and trade-offs to support strategic planning.

Q6. Decision Models

Q6a. What are the objectives and requirements of the decision makers and thus of the geodesign study?

Each of the city's departments has a primary mission to fulfill, while also meeting multi-level jurisdictional regulatory requirements for stormwater management and critical area and wildlife protections. Aspirational goals like managing 700MG of stormwater with GSI, increasing local food production, and improving the urban tree canopy further shape intra-departmental plans and programs as well as inter-departmental cooperation. As discussed in Chapter 2, there are multiple points of intersection described in various planning

documents; however, a decision support environment to support collaborative planning is still missing.

Q6b. What do decision makers need to know in order to implement changes?

At the most fundamental level, all departments need to know where all of the existing green infrastructure is and what functions it fulfills. They also need a shared perspective of the major issues or impairments that need to be addressed through green infrastructure, as well as the decision criteria that drives each department's implementation choices.

Q6c. What are the relative levels of importance of their requirements?

The departmental requirements, which can also be framed as GI planning decision criteria, range from those that are legally mandated including those related to fines (e.g. the EPA's CSO consent decree) to those that are politically motivated and/or related to specific funding sources (e.g. SPR's Parks and Green Space Levy). Each of the department's plans as well as the city's capital improvement budget and comprehensive plan provides insight into these criteria and their relative ranking in importance. Table 5 summarizes departmental requirements by GI category. Priorities for the requirements have been assigned based on the requirement source and regulating authority: high – legal requirement driven by a higher-level jurisdiction; medium – legal requirement established by city ordinance or on-going program managed at the city level; low – aspirational goal that is not formalized through a specific program or funding source.

Table 5. Summary of department requirements by GI theme.

Lead Department	GI Theme	Requirement	Requirement Source	Type	Regulating Authority	Priority	Geographic Priority	Collaborators
SPU	Stormwater	Control discharges to and from MS4	NPDES Phase I Municipal Stormwater Permit Stormwater Management Program (2015)	L	EPA	High	Areas with separated and partially separated storm sewers	DPD, SPR, FAS, SCL, SDOT
	Stormwater	Reduce CSO to one/year/outfall	SPU Consent Decree (2013)	L	EPA	High	Areas with combined sewers; NDS planned for Ballard, North Union Bay, Delridge; Early Action CSOs: 44, 45, 46, 47/171	King County
	Stormwater/ Urban Flooding	Use GSI (On-Site Stormwater Management) to MEF	City Ordinance (2009) Stormwater Code (2009, 2016 - SMC 22.805)	O	SPU/DPD	Med	New construction and redevelopment (>1500sf of impervious surface or >750sf if parcel plat created or amended after 1/1/2016 or 7000sf land distrubance), see code for more detail	DPD, SPR, FAS, SCL, SDOT
	Stormwater	Retrofit private development	Rainwise Program	P	SPU	Med	See basins here: http://www.700millionngallons.org/rainwise/eligibility-map/	Private property owners

	Habitat/Water Supply/Riparian /Shoreline	Restore terrestrial and aquatic habitat in municipal watersheds and migration pathways	Cedar River Habitat Conservation Plan (2000), South Fork Tolt Watershed Management Plan (2011)	L	EPA	High	Cedar River Watershed, South Fork Tolt Watershed	King County, Muckleshoot Indian Tribe
OSE/SPU	Stormwater	700MG with GSI by 2025	GSI Executive Order (2013)	A	SPU	Med	Creek and CSO basins	DPD, SPR, FAS, SCL, SDOT
OSE	Food	Increase urban food production	Food Action Plan (2013)	A	OSE	Low		
	Tree Canopy	30% tree canopy by 2037	Urban Forest Stewardship Plan (2013)	A	OSE	Low	Preserve, maintain, restore existing canopy; targets also set by management unit	DPD, SDOT, SPR
DPD	Food /Forest/Urban Open Space	Protect regional agriculture, improve city infrastructure	RCW 39.108 Landscape Conservation and Local Infrastructure Program (LCLIP)	L	WA	High	South Lake Union, Commercial Core, Denny Triangle	SDOT, SPR
	Stormwater /Food/Habitat	Landscaping minimums for new commercial and multi-family residential development	Green Factor	O	DPD	Med	Commercial, Mixed Use and Multi-family residential zones	Private property owners
	Tree Canopy	Protect and preserve trees on private property	SMC 25.11	O	DPD	Med	City-wide	

	Wetlands/Flood /Riparian/ Shoreline/ Habitat	Buffer environmentally critical areas from development	ECA Code (SMC 25.09)	L	DPD, WDFW, FEMA*	High	Areas with ECA designations	Private property owners
SPR	Open Space	3.33 acres/1000 residents (SPR proposes changing to 8 acres/1000, currently has 9.34 acres/1000); All residents within 1/4 mile or 5-minute walk of a park within an urban village, and ½ mile or 10- minute walk outside of an urban village	Seattle Comprehensive Plan (2005), Parks and Recreation Development Plan (2006), Parks and Open Space Plan (May Draft, 2017)	A	SPR	Low	Areas not meeting target, see Parks and Open Space Plan (May Draft, 2017) and 2017 Gap Analysis Update Vol 1	
	Forest	2500 acres of forest restoration by 2025	Green Seattle Partnership 20 Year Strategic Plan (2005)	A	SPR	Med	Parks	SPU, OSE
	Habitat/ Wetlands/ Riparian/ Shoreline	Protect and restore wildlife habitat	Parks Legacy Plan	A	SPR	Low	See Seattle Shoreline Park Inventory and Habitat Assessment (2003) and Urban Wildlife and Habitat Management Plan (2000)	
SDOT	Stormwater / Tree Canopy	Increase/protect tree canopy; fulfill GSI code requirements	Complete Streets City Ordinance (2007)	O	SDOT	Med	All new transportation improvements; GSI for 2,000+ sf of new plus replaced hard surface or 7,000+ sf of land disturbing activity	SPU, OSE

	Tree Canopy	Regulate planting, maintenance, and removal of trees and shrubs in all public places except SPR and FAS properties	Street Tree Ordinance (2013)	O	SDOT	Med	City-wide	
	Habitat	Improve salmon migration corridors	Waterfront Seattle	P	SDOT	Med	Elliott Bay seawall	
	Trails	Increase off-street trails from 46.9 to 78.9 miles by 2035	Seattle Bicycle Master Plan (2014)	P	SDOT	Med	See bicycle network map to id missing segments	
DON	Food	Maintain P-Patches	Parks & Green Space Levy (2008)	O	DON	Low	Fulfilled and far exceeded levy requirements already (28 new/expanded P-Patches, only 4 required by levy)	
	Habitat	Develop pollinator pathways; preserve habitat	Neighborhood Matching Fund	P	DON	Low		

SMC – Seattle Municipal Code; RCW – Revised Code of Washington

*The city's environmentally critical areas also include those that are mandated and regulated on a state level by WDFW (Washington Department of Fish and Wildlife) such as wetlands, riparian and shoreline areas or on a federal level by FEMA (Federal Emergency Management Agency) such as special flood hazard zones.

Steinitz recommends prioritizing requirements to help guide the design process and change models however, this is not necessarily a clear-cut process when requirements are nested, overlapping, or otherwise intertwined. For example, the federally mandated, NPDES permit driven requirement to control discharges to and from the MS4 in turn has led, in part, to the adoption of both the GSI to MEF requirement in the city's Stormwater Code and to the aspirational goal of managing 700MG of stormwater with GSI. All of these also relate to the high priority goal of controlling CSOs in fulfillment of the city's consent decree. OSE's aspirational goal of increasing the city's tree canopy to 30% by 2037 seems to be of low priority because there is not a legal mandate, clear program or funding source. However, the OSE is in fact leveraging the efforts of other departments such as SDOT's Complete Streets Program, SPR's 2500-acre forest restoration, and both SDOT and DPD's tree regulations.

From a systems perspective, a simple count of the green infrastructure-related themes described in the above departmental requirements to support prioritization is also problematic (Figure 29). While water supply is only highlighted in the Cedar and South Fork Tolt Municipal Watershed plans, it is affected by both stormwater and wetland management. Habitat also corresponds to forests, open space, wetlands, riparian/shoreline zones. Parks (open space) also generally includes trails. Food and open space are also intersecting themes. Rather than separating and ranking requirements, it becomes clear that there are many areas of overlap and that an explicit multi-functional and multi-scalar approach to planning is needed.

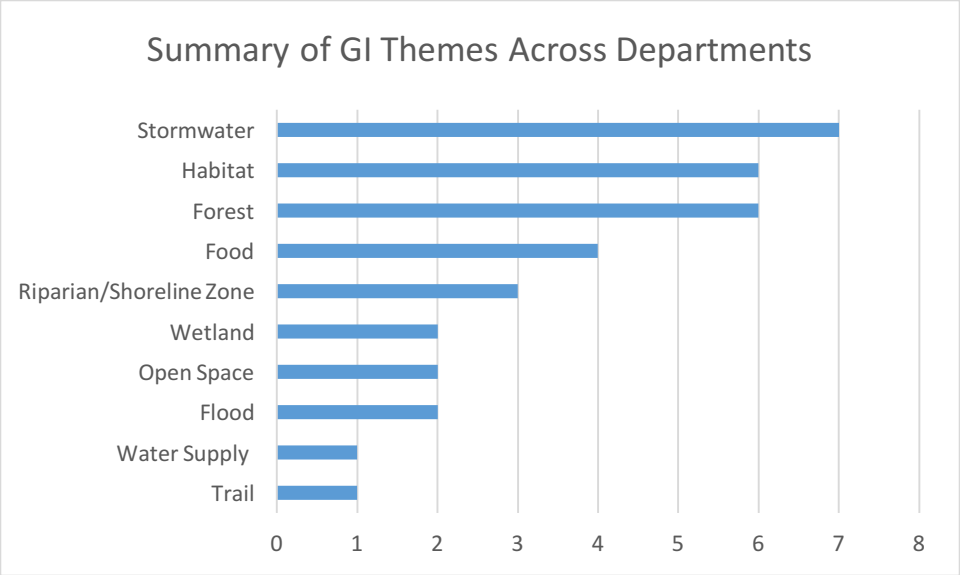

Figure 29. Summary of GI themes across departments. Derived from requirements listed in Table 5. The horizontal axis represents the number of requirements from all of the departments related to that particular theme.

Q5. Impact Models

The impact models are used to assess the potential benefits and costs of the green infrastructure portfolio and network, which can be more generally expressed during the strategic planning phase as the positive and negative impacts of proposed changes on the systems of interest. The types of impact models that are needed derive from the decision requirements, and instruct the process models, which, when combined with the change models, should demonstrate the impacts in such a way that decisions can be made.

Q5a. Which impact models are needed by the decision model to assess and compare changes?

Continuing with the systems' perspective discussed above, the impact models should both capture the effects of the intervention on the GI theme of interest (e.g. stormwater quantity and quality; habitat; forest; food; etc…) as well on any related themes. In lieu of mechanistic process models for each theme, spatial relationships can be used to extrapolate

positive and negative influences of interventions among various types of green infrastructure. Geographic priority areas (see Table 5) help determine the mix of green infrastructure that is desirable or necessary for any given location. For example, in areas that have been prioritized for CSO reductions, GSI could take precedence over food production. If parks/open space or trail connectivity are needed in these areas, then they can be designed to incorporate GSI even if the projects would not otherwise trigger the stormwater code requirements. Subwatersheds with designated aquatic habitat could also be good candidates for GSI even if CSO is not an issue in that catchment. Areas that need parks could also be good food producing locations if there is a dearth of these as well.

Since stormwater management is a high priority and high frequency theme among several city departments, the impact and related process models should be based on the city's subwatersheds and manufactured drainage basins. Other types of green infrastructure relationships and interactions can be assessed within and across these including: habitat, forests, wetlands, riparian/shoreline zones, floodplains, parks, P-Patches, and trails. Since Seattle's water supply comes from municipal watersheds outside of the city, and is not affected by other types of green infrastructure, a water supply-specific impact model is not needed. However, since Lake Washington, Portage Bay, Lake Union and the Ballard Locks are part of the Five Links (Figure 5) connecting Cedar River salmon with the Elliott Bay, interventions in these areas will be assessed for their aquatic habitat impacts, thus establishing the regional connection. All of Seattle's species of concern are either aquatic or avian, so a broader regional landscape-based habitat hub and corridor impact analysis, beyond the aquatic network, is also not necessary.

Q5b. Which impacts are not part of the decision models but should be considered nevertheless?

Climate change mitigation and adaptation have been treated as important but secondary or even tertiary drivers for green infrastructure implementations. Although increased cycling and walking, green roofs, and tree canopy have all been mentioned as ways to reduce energy consumption, the city has focused instead on other strategies related to road transportation (e.g. electric vehicles), building energy (e.g. energy efficient lighting and appliances) and waste (e.g. construction and demolition recycling) to reduce the city's greenhouse gas production.[79] Climate change adaptation, however, does have a direct influence on future priorities for Seattle's green infrastructure network and will also be considered in the impact analysis. Precipitation extremes that result in non-stationarity will affect both stormwater and flood management, as well as drought mitigation. Periodic coastal storm surge and daily high tides will also be affected by precipitation extremes and both will exacerbate base sea level rise, which threatens both built and natural infrastructure.[80] The GI portfolio and network will be assessed for how it facilitates climate change adaptation.

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[79] City of Seattle. 2013. Seattle Climate Action Plan. Available from http://www.seattle.gov/environment/climate-change/climate-action-plan. Accessed on 4/21/16.

[80] City of Seattle. 2015. Climate Preparedness: A Mapping Inventory of Changing Coastal Flood Risk. Available from http://www.seattle.gov/environment/climate-change/planning-for-climate-impacts. Accessed on 4/22/16.

Q5c. How precise must the impact assessments be?

For city-wide portfolio and network planning, the impact assessment does not need to be so detailed that it demonstrates, for example, the exact level of water quality improvement at a specific stormwater outfall, amount of energy reduction for a specific building, or increase in bicycle traffic for a new trail segment. These types of detailed analyses would be done at the site level during the design, implementation and monitoring phases of a specific project. As long as the process is appropriately contextualized (e.g. subwatershed-based stormwater runoff estimates), then desired benefits can initially be assumed (e.g. adding GSI will reduce runoff quantity and improve water quality).

Q4. Change Models

In the first iteration, questions related to both change and impacts were more from an external perspective to help establish the broader context within which the green infrastructure planning will take place. In the second iteration, the change model-related questions help define the parameters for the desired changes that are intentional outcomes of the planning process. Steinitz describes the development of change models as a continuum from the vision for change (why? where?) to strategies to achieve the vision (what? where?) that needed to be translated into specific tactics (where? how?) and finally implementing actions (how? when?) (Steinitz 2012). Because this study does not result in one specific green infrastructure design, the change model will focus more on the vision and strategy for change (why? where? what?).

Q4a. What are the assumptions and requirements for change?

One major assumption is that the City of Seattle will continue to aggressively pursue both environmental and equity-oriented planning that is amenable to green infrastructure, rather than pursuing a purely property-tax generating approach to development that would sacrifice all buildable land to the highest source of tax revenue. Another assumption is that city departments will continue and increase collaboration on green infrastructure development. A requirement for change is that the city move towards a more robust enterprise GIS strategy and shared platform for green infrastructure planning. Some steps have been made in this direction with the websites data.seattle.gov and performance.seattle.gov, as well as more specialized information portals like the Seattle Natural Hazard Explorer and DPD's GIS data explorer; however much more is needed to support collaborative, operational planning. Chapter 5 discusses these requirements and possible solutions in more detail.

Q4b. How shall change be visualized and communicated?

This question is related to the point above. A web-based, spatial, and ideally temporal, platform to visualize the green infrastructure portfolio, network and related systems would support collaborative planning as well as facilitate participation and education for Seattle citizens. Chapter 5 will make the case for why and how.

Q4c. Which change models, or ways of designing, are most appropriate for this geodesign study?

Steinitz (2012) describes eight ways of designing (or planning): anticipatory, participatory, sequential, constraining, combinatorial, rule-based, optimized, and agent-based – all of which may also be combined. The following is an abbreviated description of each, adapted from Steinitz (2012) and substituting plan/planner for design/designer:

- Anticipatory (A) – initial plan based on instinct (and/or professional knowledge and experience), later tested and refined through deductive logic
- Participatory (P) – multiple plans with different concepts that need to be negotiated and merged
- Sequential (S) – begins with current conditions and extrapolates a future plan based on a series of systematic choices
- Constraining (C) – decision models are uncertain, requirements are linearly distributed from most to least important but there are many options for each
- Combinatorial (CO)– appropriate choices in sequence of decisions is uncertain, a few requirements are equally important and must be addressed before considering less important ones, alternative scenarios need to be investigated
- Rule-based (R) – a set of formal rules guide the plan, the rules are combined in a sequence of planning decisions similar to the sequential approach
- Optimized (O) – relative importance of requirements is understood and decision criteria can be compared using a single metric
- Agent-based (AG) – future is projected rather than planned based on independent agents acting and interacting according to a set of pre-defined rules, generally computer simulated.

Table 6 summarizes which approaches are or could be used for GI planning in Seattle. The anticipatory approach is reserved for GI that is primarily human-related, and can benefit from, but does not require, scientific data. Participatory approaches have similar application areas; however, since stormwater management through GSI and forest stewardship also depends heavily on private property owners and even acceptance of the location and designs in the public ROW, these are also often participatory. GSI, because of the large range of implementation options, lends itself well to a combinatorial approach.

Each individual GI type, but especially those that fulfill a primarily natural ecosystem function, can and often must be planned using sequential and rule-based approaches. Optimization approaches can also be applied to each type, though in practice this is usually not the case. Nor are agent-based models commonly used for green infrastructure planning; however, species' habitat usage and migration pathways, residential and commercial water demand, and cyclists' travel demand all readily lend themselves to this type of modeling.

Table 6. Summary of current or possible GI planning approaches based on author's assessment of planning documents.

GI Type	Planning Approach
GSI	P,S,CO,R,O
Habitat	S,R,O,AG
Forest/Tree Canopy	P,S,R,O
Food	A,P,S,R,O
Riparian/Shoreline Zone	S,R,O
Wetland	S,R,O
Open Space	A,P,S,R,O
Municipal Watershed	S,R,O,AG
Trail	A,P,S,R,O,AG
Floodplain	S,R,O

The constraining approach was not included for single-purpose GI planning, because each of these generally have a clear decision model. In a multi-functional and multi-scalar setting where multiple decision models have to be reconciled, the constraining approach can be useful to identify overarching requirements. However, in the Seattle context, stormwater management has already been identified as a primary GI focus (Figure 29), and other priorities are clear as well. One major takeaway from Table 6 is that multiple planning approaches are applicable and are likely used, especially as the spatial scale of the plans increase, thus a mix of approaches for GI planning is needed.

Q3. Evaluation Models

The evaluation models are intended to assess the current state of the systems of interest to inform the change models, and are generally grouped into those that are vulnerable to change and those that are attractive for expansion. The green infrastructure network is made up of both vulnerable systems with mandated protections, e.g. habitat, wetlands, floodplains, riparian/shoreline zones, and systems intended for expansion like trails, parks, and GSI. Others, such as forests/tree canopy and urban agriculture, could fall into either category. For the purposes of this study, both forests/tree canopy and food-producing areas will also be evaluated with respect to their attractiveness for further development since the city wishes to increase these capacities. Typically, when highly vulnerable areas coincide with highly attractive areas for development, the risk to both systems is greater (Steinitz 2012). However, in the case of the green infrastructure network, this may simply indicate an increase in potential functional synergies if the impacts from development can be mitigated (e.g. elevated trails through habitat and pathways that avoid nesting areas).

Steinitz poses several questions related to evaluation that can be summarized together (Table 7):

- Q3a. What are the measures of evaluation across distinct but relevant fields, and their spatial, temporal, qualitative, and quantitative metrics?
- Q3b. Are they scientifically or judgmentally based?
- Q3c. Are they related to legal requirements?

Table 7. Summary of evaluation criteria for GI categories.

GI Category	Possible Measures/Metrics	Evaluation Basis	Legal Requirement (Y/N)
Vulnerable Systems			

Habitat	Spatial: Designated habitat areas, parks >.25 acres (see SPR parks classification)	Scientific	Y
Wetlands	Spatial: Designated wetlands Qualitative: Differentiated by whether or not in a priority habitat area	Scientific	Y
Floodplains and flood prone areas	Spatial: FEMA designated SFHA, urban flood zone Qualitative: Differentiated by whether or not in a habitat area or along a migration pathway	Scientific	Y
Riparian/Shoreline Zones	Spatial: Adjacent to water Qualitative: Differentiated by whether or not in a habitat area or along a migration pathway	Scientific	Y
Development-oriented systems			
GSI	Spatial: In a critical CSO or NPDES permit basin, or in an area of urban flooding; hydrologically connected to aquatic habitat or creek basins	Policy & Scientific	Y
Trails	Spatial: Extension of the city-wide trail network rather than a discreet local segment	Policy	N
Parks	Spatial: Areas with gaps in accessibility: 1/4 mile or 5-minute walk of a park within an urban village, and ½ mile or 10-minute walk outside of an urban village; areas adjacent priority habitat areas Qualitative: In one of 16 urban villages prioritized by SPR as underserved[81]	Policy & Scientific	N
Forests/Tree Canopy	Spatial: Target areas for expansion including industrial zones and downtown,	Policy	N

[81] City of Seattle. 2017 Parks and Open Space Plan – Draft 5/15/2017. Available from http://www.seattle.gov/parks/about-us/policies-and-plans/2017-parks-and-open-space-plan. Accessed on 6/20/2017.

	neighborhood business districts, major institutions, ROW- especially along riparian corridors Qualitative: In a socially vulnerable neighborhood, in an urban heat island		
Urban Agriculture	Spatial: Publicly-owned parcels identified in Growing Green [82] community garden suitability analysis Qualitative: In a socially vulnerable neighborhood	Policy	N

Table 7 highlights key criteria that will be considered for determining maximum vulnerability and attractiveness for development in the next iteration. Other criteria will be added to identify areas of medium and low vulnerability and attractiveness. Note the vulnerable systems' evaluation focuses on the current state of the landscape with respect to these features. The evaluation for the development-oriented systems emphasizes potential spatial opportunities for expansion, and social vulnerability is considered for systems with direct, localized community benefits.

GIS is an essential tool for creating the evaluation models. Each system of interest is mapped individually and the entire study area is then categorized from least to most risk or least to most attractiveness for development for that particular system using green (least at

[82] Megan Horst. 2008. Growing green: an inventory of public lands suitable for community gardening in Seattle, WA. Available from http://www.seattle.gov/Documents/Departments/Neighborhoods/PPatch/Growing-Green.pdf. Accessed on 5/9/16.

risk, most attractive for development) and red (most at risk, least attractive for development) symbology. These categories can be further refined into lowest, low, high and maximum risk or attractiveness, and a medium/marginal category (yellow) can also be included. For this study, a three-level evaluation will be used – low, medium and high risk or attractiveness. Figure 30 illustrates an evaluation model for agriculture in the Lower and Middle Green River subwatersheds developed for the 2015 UW Geodesign Workshop with Carl Steinitz (Nyerges et al. 2016).

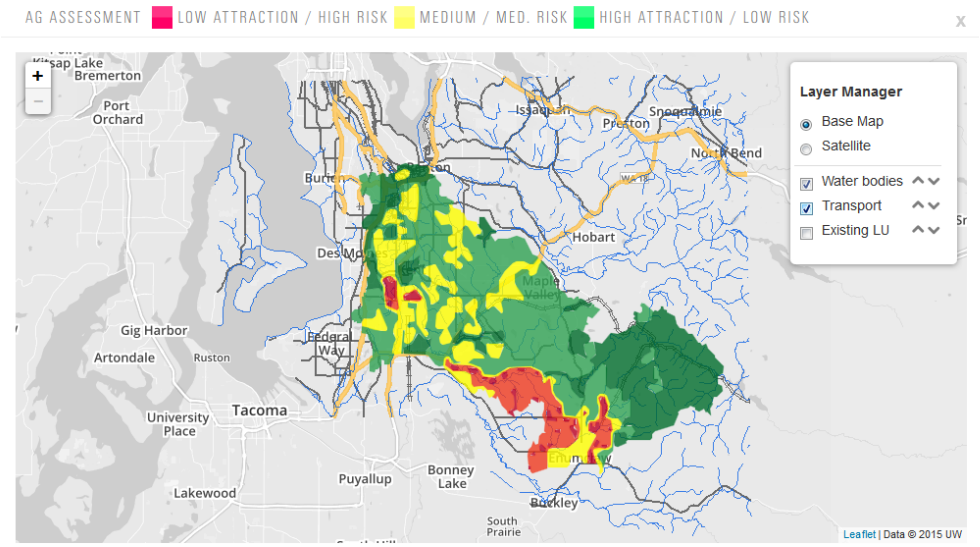

Figure 30. Example of an agricultural evaluation model for the Lower and Midde Green River subwatersheds developed by John Ritzman.

The combination (spatial overlay) of multiple system evaluations will identify both synergies (overlapping greens) and potential trade-offs (overlapping red and green) among different types of green infrastructure, though depending on the infrastructure type this relationship may not be so clear cut as discussed previously in this section.

Q2. Process Models

Process models provide the basis to assess the impacts of proposed changes (Steinitz 2012); however, these models, no matter how sophisticated, are still a simplified version of how

the world works. In their essay "Strategies of Abstraction", scientists Richard Lewontin and Richard Levins assert basic principles that serve as precautions for any modeling effort:

- "The truth is the whole (Hegel).
- Parts are conditioned and even created by their wholes.
- Things are more richly connected than is obvious.
- No one level of phenomenon is more "fundamental" than any other. Each has a relative autonomy and its own dynamics but is also linked to other levels.
- Things are the way they are because they got that way.
- Things are snapshots of processes. They remain the way they are long enough to be recognized and named because of opposing processes that perturb and restore them.
- The dichotomies into which we split the world – physiological/psychological, biological/social, genetic/environmental, random/deterministic, intelligible/chaotic – are misleading and eventually, obfuscating" (2007, 149-150).

They present these principles not to deny the value of abstraction, but to improve the quality thereof. While we cannot really look at the "whole" and all of the nuances of its dynamics in any given model, Hegel's assertion reminds us that the problem we are examining needs to be posed broadly enough for the model to fit. Lewontin and Levins caution:

> "It is usually better to present a problem too big and then reduce it than to start with a problem too small. For in that case, we may never be able to expand it enough. If we fail to do so, we are either condemned to ingenious solutions to trivial questions or to explanations that are mostly external: some external influence caused what we observe, but we have no explanation for the external influence. It is merely a given, perhaps observed and measured" (2007, 150).

Since any model for any problem, no matter how broadly defined, is still only partial, they also recommend using multiple, independent models "to converge on the truths we are looking for" (2007, 150).

Steinitz (2012) describes eight levels of increasing process model complexity: direct, thematic, vertical, horizontal, hierarchic, temporal, adaptive and behavioral. Conceptualizing the GI systems and systems' relationships across these levels increases

our ability to capture key dynamics, and perhaps avoid being overly reductionist. Direct models are experiential and answer the question "What is going on here?"[83] These can be applied to all of the spatial and qualitative measures described in the previous section, and are enhanced by thematic models which answer the questions "How much? Where?" Vertical process models add or infer overlain data and ask "What else is below or above and how do they combine? Vertical process models are implicit in the relationships among vulnerable and development-oriented GI systems. Horizontal models add consideration for adjacency and connectivity, and apply to floodplains (e.g. including or adjacent to high risk assets), trails (e.g. part of a larger network), parks (e.g. within a 1/4mile walking distance), and tree canopy (e.g. along waterways).

Hierarchic models look at relationships across nested scales and primarily apply to stormwater runoff, urban flooding and migration pathways. Temporal models explore process dynamics over time, and while implicit in the hydrologic and migration models, they can be used explicitly, for example, to look at the impacts of climate change on GI systems. Adaptive models ask, "From what and where to what and where?" and are useful for inherent successional and evolutionary dynamics. While the development of the GI portfolio and network involves landscape transformation and reflects human adaptation to diverse circumstances (pollution, species endangerment, flooding, food deserts, etc…), these actions are the outcome of decision making processes rather than some mechanism emergent from the GI system itself, and thus will not be modeled. Behavioral models add the dimension of agency - "From whom doing what, where, and when to whom doing what,

[83] All process model questions are from Steinitz 2012, 65-72.

where, and when?", and could be used to model the decision-making that leads to changes in the GI portfolio. Other types of behavioral dynamics could be modeled as well, e.g., trail usage, urban agriculture participation, salmon migration. This, however, is beyond the scope of the dissertation, and these behaviors will be assumed.

Table 8 summarizes the following questions:

- Q2a. Which models should be included?
- Q2b. How complex should the models be?

Table 8. Summary of GI process models and their associated level of complexity that will be included in the study.

Process	**Systems Included**	**Level of Complexity**
Stormwater Runoff and Combined Sewer Overflow	GI: GSI, Forests, Parks, Habitat, Riparian/Shoreline Zones, Wetlands, Floodplains Additional: Subwatersheds, Manufactured Drainage Basins, Priority Basins, Storm and Combined Sewer Mainlines, Watercourses and Waterbodies, Land Cover, Streets, Soils, Topo, Census	Hierarchic
Urban Flooding	GI: GSI Additional: Subwatersheds, Manufactured Drainage Basins, Floodplains, Urban Flood Prone Areas, Parcels, Buildings, Streets, Critical Infrastructure (WWTP, Transportation, Energy, Water Supply), Census	Hierarchic
Aquatic Migration	GI: Riparian/Shoreline Zones, Habitat, Wetlands, Municipal Watersheds	Hierarchic

	Additional: Regional Watersheds, Watercourses and Waterbodies, Migration Pathways	
Forest/Tree Canopy Increase	GI: Forest/Tree Canopy Additional: Zoning/Land Use, Geographic Priority Areas, Riparian/Shoreline Zones, Census	Horizontal
Riverine Flooding	GI: Floodplains, Riparian/Shoreline Zones, GSI, Habitat Additional: Parcels, Buildings, Streets, Critical Infrastructure (WWTP, Transportation, Energy, Water Supply), Census	Horizontal (Note: in this case only looking at adjacency, would be hierarchic if creating a hydraulic model)
Trail Connectivity	GI: Trails, New Trail Segments, Parks	Horizontal
Park Accessibility	GI: Parks, Trails Additional: Geographic Priority Areas, Streets, Census	Horizontal
Urban Agriculture Expansion	GI: Existing Food-Producing Areas Additional: Growing Green Parcels, Census	Thematic
Climate Change (Related to sea level rise, storm surge, and increased urban and riverine flooding – drought and fire will not be included)	GI: GSI, Parks, Habitat, Riparian/Shoreline Zones, Wetlands, Floodplains, Trails, Urban Agriculture Additional: Parcels, Buildings, Critical Infrastructure (WWTP, Transportation, Energy, Water Supply)	Temporal

Q2c. Which process models are beyond the modeling capabilities of the geodesign team?

As discussed in the previous section, adaptive and behavioral models will not be included in the study, though this dissertation could inform such models related to green infrastructure planning (who are the agents, what drives their decision making, how is the landscape being adapted?). However, such agent-based models are generally more interesting when applied to generic outcomes (e.g. Michael Batty's urban growth pattern simulation) or anonymous actors (Michael Flaxman's fire spread and homeowner fire management model) (Steinitz 2012). There are also so many contextual factors that shape green infrastructure planning, from the specific regulatory environment to the local biogeophysical opportunities and constraints, that a generalizable behavioral model is unlikely.

The following are other process models, which, based on the decision requirements from Table 5, would be warranted, but are beyond the scope of this dissertation:

- Forest restoration – Restoration of forested parklands is underway throughout Seattle, led by the public-private Green Seattle Partnership. Restoration phases for all of the parks currently being managed are documented on the GSP Reference Map available from http://greenseattle.org/information-for/forest-steward-resources/gsp-restoration-map/. While there is an overall goal of restoring 2,500 acres of forest by 2025, the actual process for choosing what gets restored where is largely determined by the volunteer forest stewards and volunteer organizations involved. These choices would require further study to detect patterns of behavior that could possibly be modeled and predicted.

- Stormwater Code-triggered GSI implementation – Both new development and redevelopment trigger GSI to the maximum extent feasible. New development potential could be projected from vacant lots. However, these only make up 5% of the city's current land use,[84] which means that redevelopment is the primary catalyst

[84] City of Seattle. 2016. Land Use Quick Statistics. Available from http://www.seattle.gov/dPd/cityplanning/populationdemographics/aboutseattle/landuse/default.htm Accessed on 5/19/16.

for increasing GSI. While general rates of annual redevelopment can be estimated, and building permit applications indicate where redevelopment is taking place in the near-term, the type and amount of GSI that would be implemented would be largely conjecture without more rigorous study of developer and builder preferences and practices.

Q1. Representation Models

The representation models consist of the data needed to develop the process and evaluation models that support the change, impact and decision models. The existing GI portfolio described in Table 4 serves as the basis for further data collection and analysis.

Q1a. Which data are needed? For which geography? At what spatial scale? For which times? From which sources? In which mode of representation?

Most of the data will collected for the City of Seattle, except for models requiring regional context, and will be the most current data available. The spatial scale and level of detail for each feature depends on the type of information being represented. Land cover has a $30m^2$ spatial resolution. Networks (e.g. streets) are represented as simple lines, objects (e.g. stormwater outfalls) as points, and areas (e.g. waterbodies) as polygons. Maps can be zoomed in and out to see more or less detail at different spatial scales. The structure of representation will either be vector or raster feature data types organized in a geodatabase. Table 9 lists the additional datasets needed, and potential data sources. Table 8 described the associated models.

Table 9. Additional GI model data.

Dataset	Potential Data Source
Forest/Tree Canopy	City of Seattle
Regional Watersheds	WA ECY WRIAs
Watercourses and Waterbodies	King County

Migration Pathways	Derive from SPU Urban Blueprint[85]
Subwatersheds	City of Seattle
CSO & NPDES Priority Basins	Extract from drainage basins
Storm and Combined Sewer Mainlines	City of Seattle
Geographic Priority Areas	Derive from LCLIP and Green Factor requirements
Census	Census 2010 Geodatabase & ACS 2011-2014 5 Year Estimates
Land Cover	USGS
Soils	WA DNR Geologic Information Portal
Topography	City of Seattle
Streets	City of Seattle
Parcels	King County
Buildings	City of Seattle
Critical Infrastructure (WWTP, Transportation, Energy, Water Supply)	City of Seattle
New Trails	Derive from SDOT's Bicycle Master Plan
New Urban Agriculture Areas	Derive from *Growing Green* report (Table 5)
Climate Change-related Inundation Areas	City of Seattle

Q1b. What are the appropriate data management and visualization technologies?

GIS will be used both for data management and data visualization. If this were a team project then an enterprise GIS solution could be used, like ArcGIS Server, to enable shared access to data.

[85] Seattle Public Utilities. 2003. Urban Blueprint. Available from http://www.seattle.gov/util/EnvironmentConservation/OurWatersheds/ProtectOurWaters/SalmonFriendly/UrbanBlueprint/index.htm. Accessed on 5/18/2016.

To conclude the second iteration, keeping track of how the models relate to each other and if each successive model was congruent with the previous ones required constant consultation across tables. In theory, Steinitz conceptualizes the second iteration as a master chart with diagrams and specifications (Figure 31). In reality, he recommends everyone meet in the same room, and use a large board for posting ideas, with columns representing different models (Figure 32). Chapter 5 will explore digital technologies to support the conceptual phases of the geodesign process that enable linkages across iterations and models and that strike a balance between the highly structured and informal.

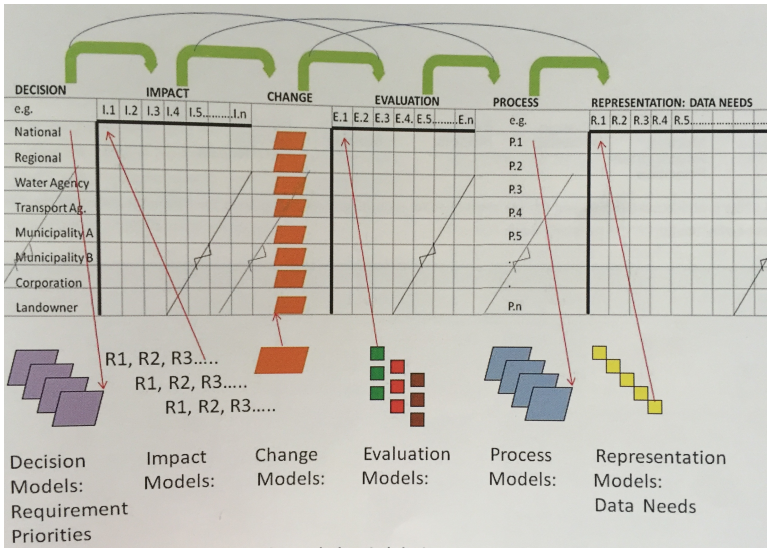

Figure 31. Theoretical approach to organizing multiple models and specifications (Steinitz 2012).

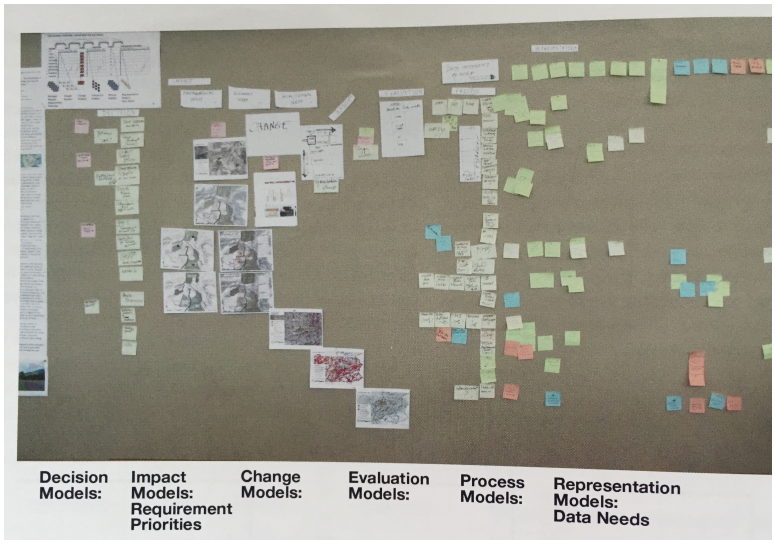

Figure 32. Model and specification organization approach in practice (Steinitz 2012).

Chapter 4. Implementing the Study: The Third Iteration

The third iteration through the framework focuses on exploring the WHAT, WHERE and WHEN questions, and involves obtaining the data and analyzing relevant processes and conditions in order to propose changes, compare impacts, and arrive at decisions about the future. Steinitz emphasizes that the culmination of this iteration is the decision – yes, no or maybe, whether the study provided a basis for future action, or whether more study is needed in whole or in part, and perhaps at a different scale or with different information (2012). He does not elaborate this iteration in much detail, preferring to demonstrate the framework through case studies. The case studies generally focus on alternative future growth scenarios for a region, and entail balancing clearly competing land uses and stakeholders to accommodate economic development and population growth while conserving ecologically important areas and functions. This was also the nature of the 2015 University of Washington Geodesign Workshop, led by Carl Steinitz and Tim Nyerges, that provided an experiential basis for this study (Nyerges et al. 2016).

This study differs in a number of ways, which simplifies some aspects of the following analysis. There is a strong municipal commitment to both developing green infrastructure and protecting vulnerable ecological systems, illustrated through the executive orders, plans and requirements described in the previous chapters. Most types of green infrastructure can be integrated with other types of development if thoughtfully planned, and there are already regulations and processes in place, like the Seattle Green Factor, GSI to the maximum extent feasible, and the Complete Streets Checklist, to ensure that this occurs. Finally, there are a number of mechanisms to support collaboration among

departments for specific systems like the GSI Implementation Plan and the Urban Forest Stewardship Plan, or for specific spaces like the ROW. The CIP budget and review/approval process by the mayor and council is also a common forum for negotiation and priority-setting. However, a shared geospatial understanding of the city's green infrastructure is missing, which is addressed through the following models.

4.1 Representation Models

The representation models are developed by combining the existing GI portfolio described in Table 4 with the additional datasets listed in Table 9, and serve as the basis for the process models and evaluation models described in Tables 8 and 7 respectively. Five out of the nine process models are water related – thus a natural-constructed water system model is foundational to the study. Land cover/land use, community assets, critical infrastructure and socio-economic information are key pieces of additional information in many of the process models. The following maps show snapshots and excerpts of this information.

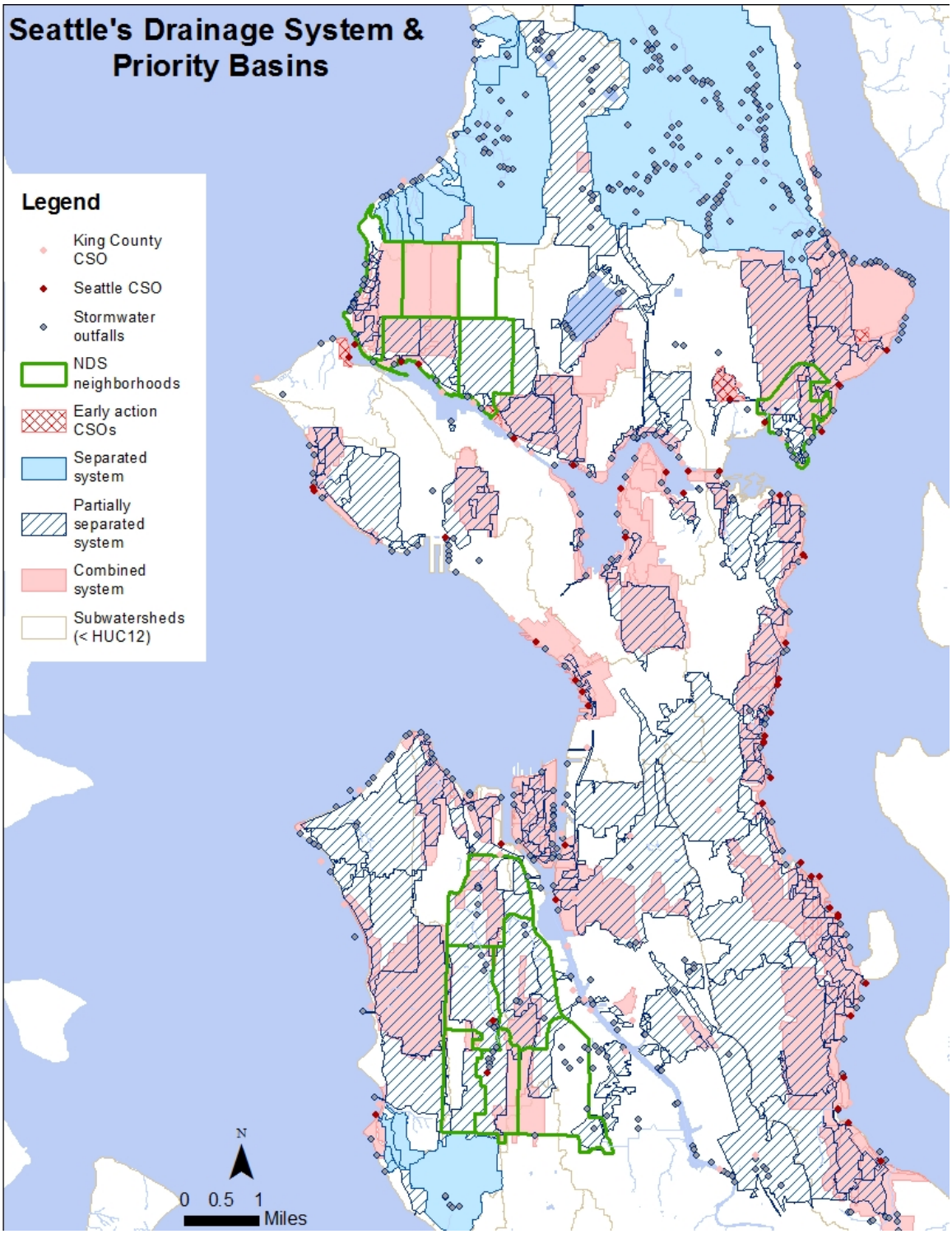

Figure 33. Seattle's natural-constructed drainage system. The topographic subwatershed boundaries are included to illustrate the frequent mismatch between the natural hydrography and constructed drainage basins, which is important when calculating stormwater runoff potential. Areas of high priority for intervention (early action CSOs, NPDES basins and NDS neighborhoods), derived from SPU planning documents, will be used in the evaluation modeling phase. Map source: author, data source: City of Seattle.

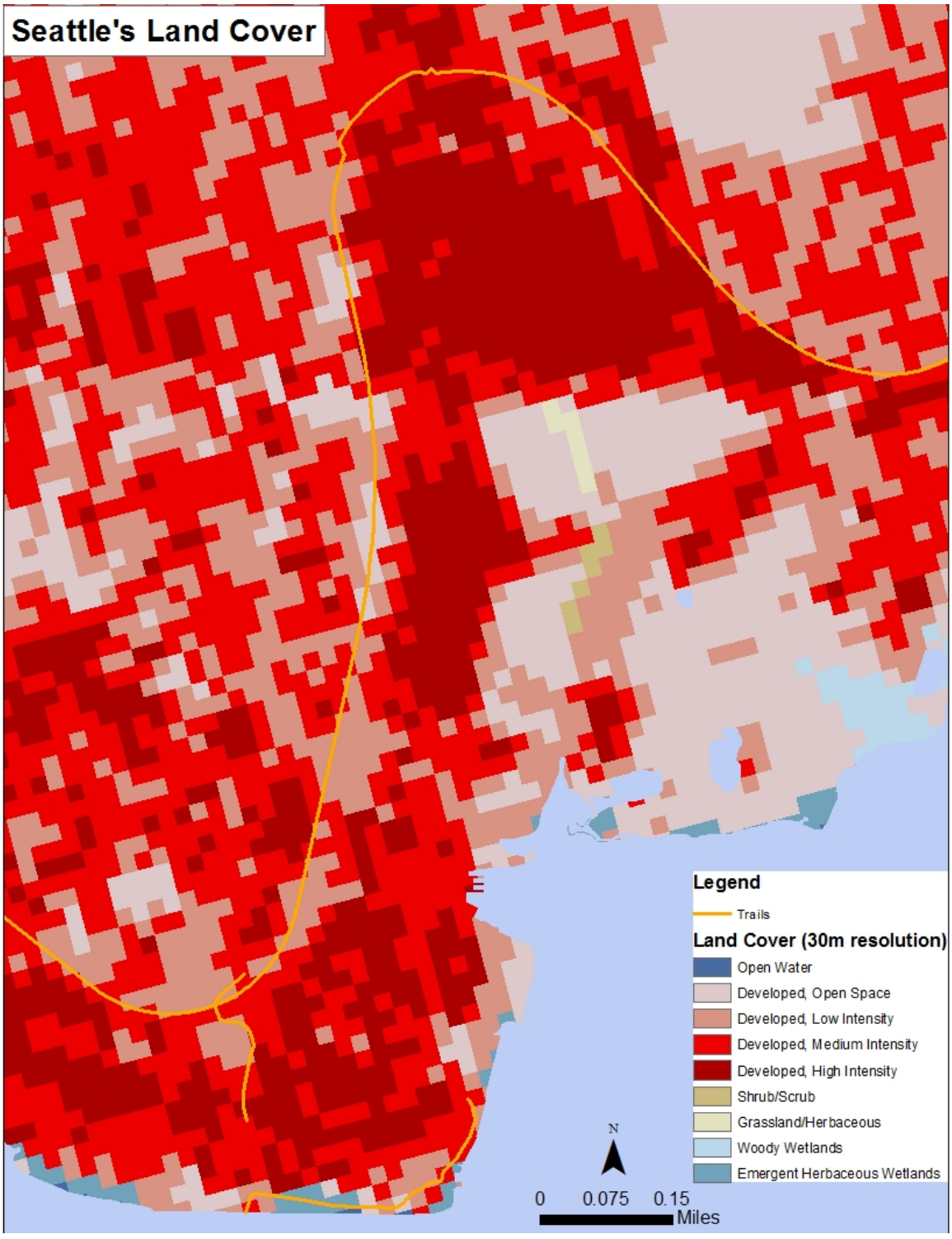

Figure 34. NLCD-based land cover excerpt at the University of Washington. Land cover is important for stormwater runoff calculations and other process models including urban flooding, riverine flooding, and forest connectivity. The NLCD is useful for general land cover classification; however, Figure 35, based on the NAIP, provides a better representation of land cover surrounding linear features like trails and streets. Map source: author, data source: USGS, City of Seattle.

Figure 35. NAIP-based NDVI excerpt at the University of Washington. The high-resolution of the NAIP provides a better representation of linear features and of the NLCD's developed, open space category. Note, however, the identification of forests using the NDVI requires additional context information, as the NDVI values of the UW sports fields and the adjacent woody wetlands in the Union Bay Natural Area are the same (.45). Street trees are included because these belong to Seattle's urban forest according to the Urban Forestry Stewardship Plan. Map source and NDVI analysis: author, NAIP source: USDA.

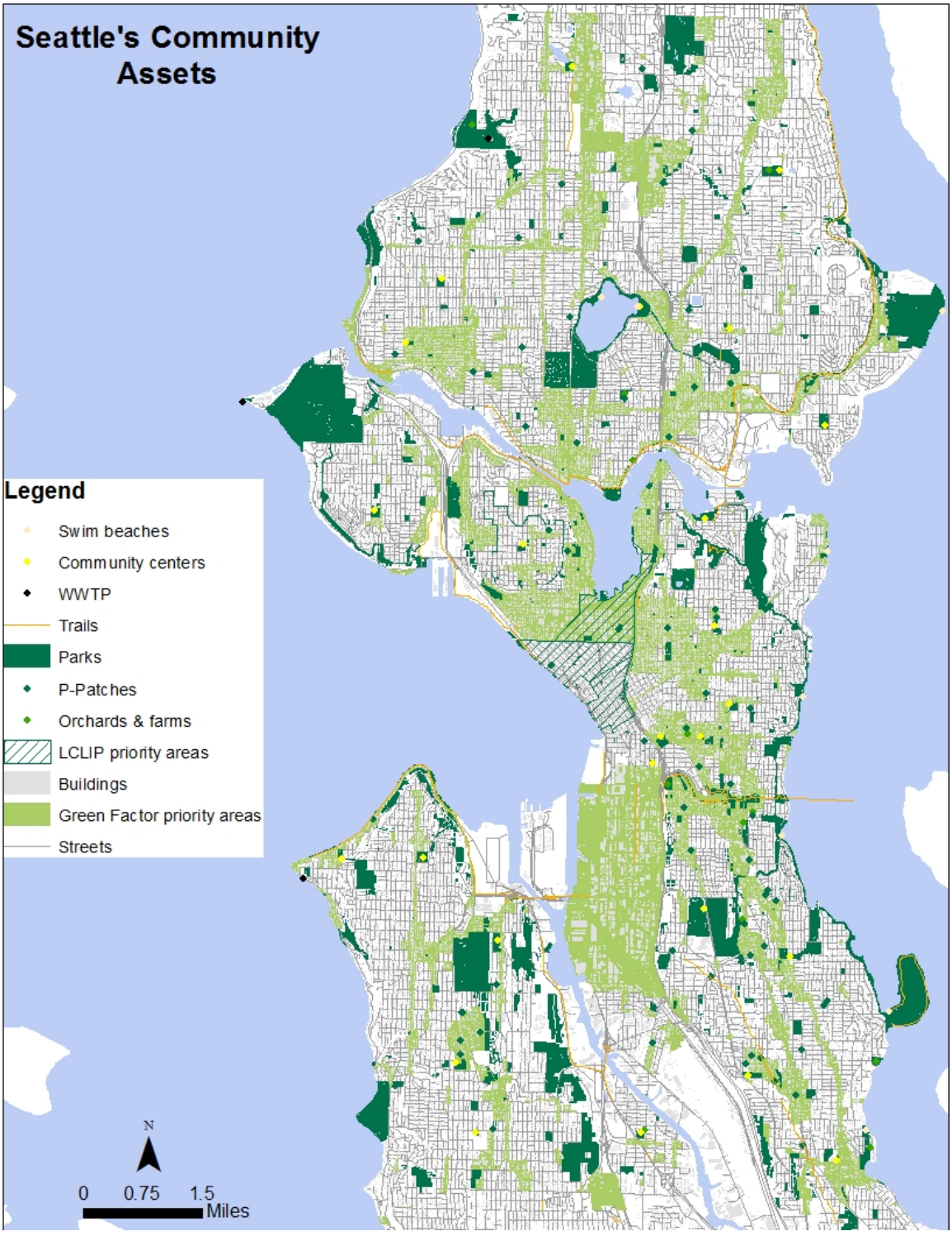

Figure 36. Overview of some of Seattle's community assets and planning priority areas, which will be used in several of the process models. Map source: author, data source: City of Seattle.

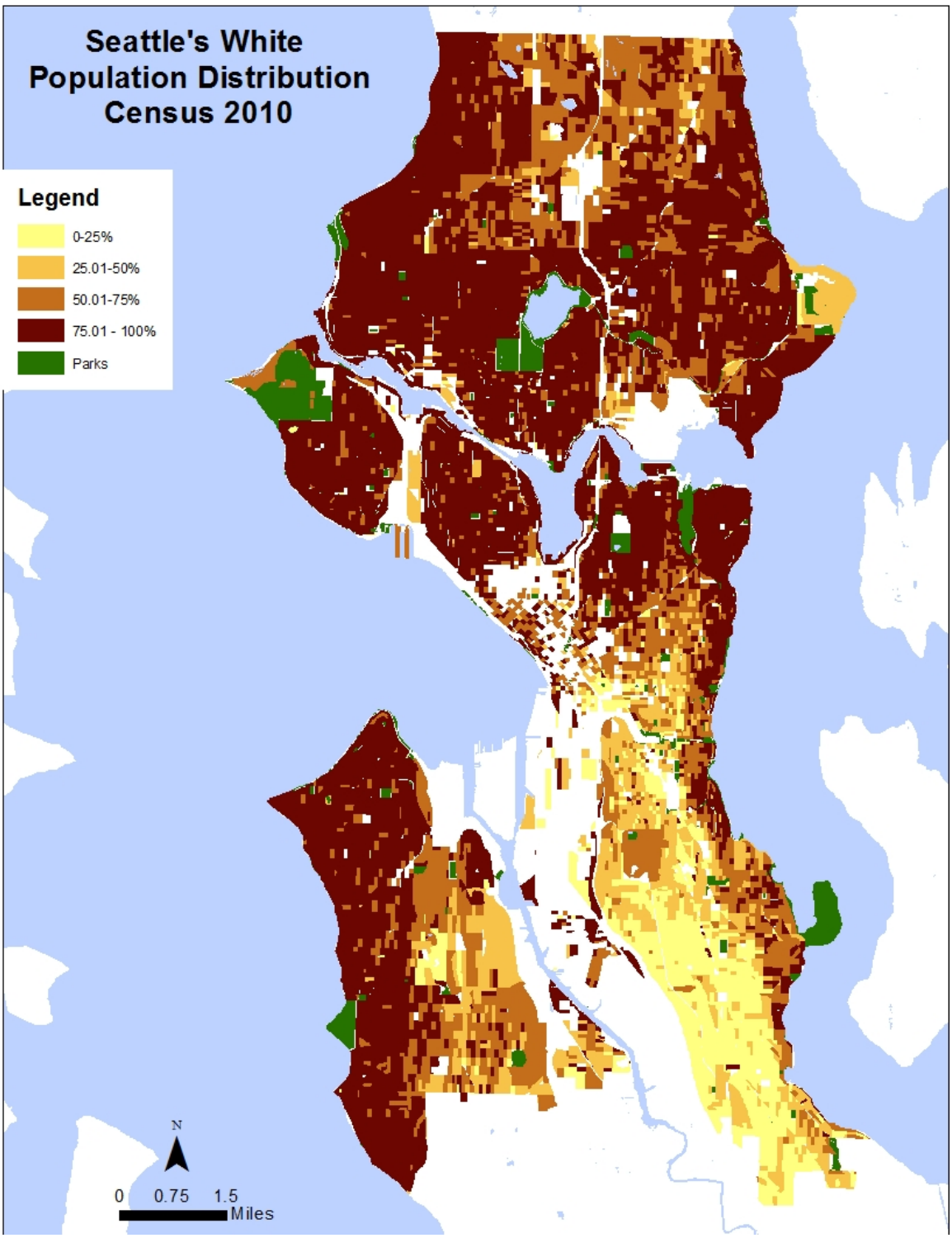

Figure 37. Seattle's dominant race (white) distribution throughout the city, by block group. The racial makeup of the city is: 69% white, 14% Asian, 8% black, 0.8% American Indian or Alaska native, 5% two or more races, and 7% Hispanic. Map source: author, data source: US Census Bureau 2010 Census.

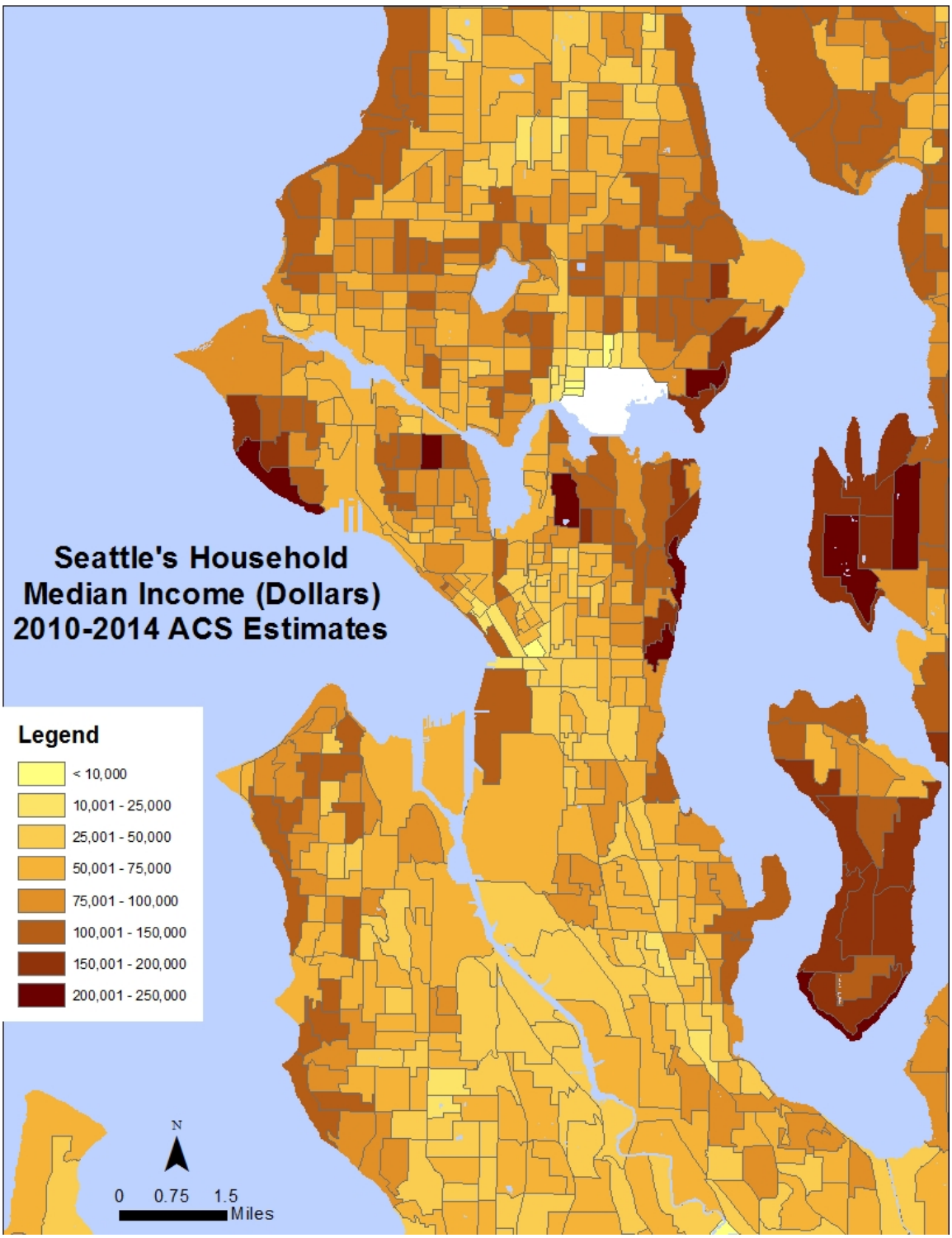

Figure 38. Seattle's household median income, by census tract. Map source: author, data source: US Census Bureau 2010-2014 American Community Survey estimates.

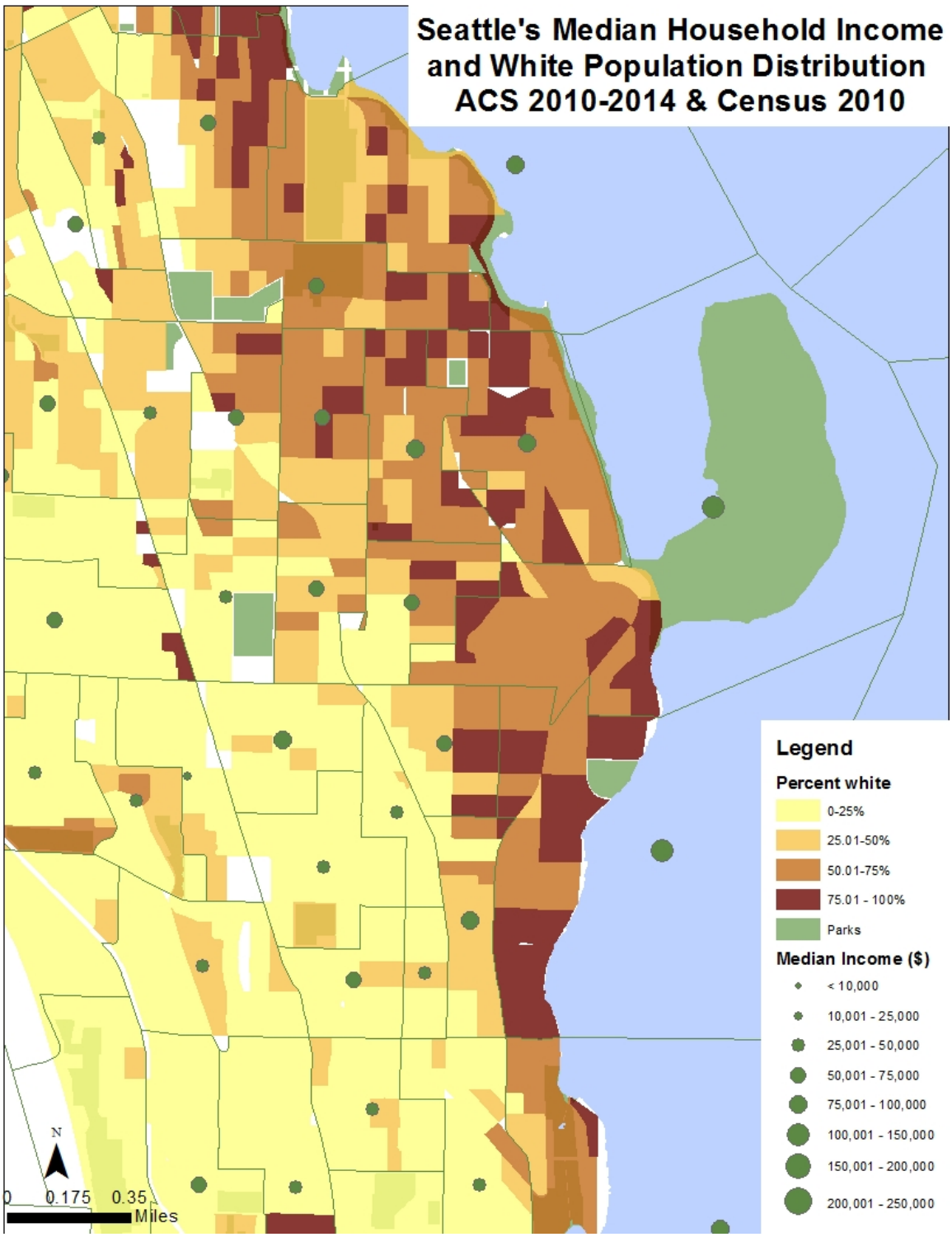

Figure 39. Seattle's race (white) and median household income distribution, by block group and census tract respectively. Lower median incomes occur in predominantly non-white census tracts, with the exception of the University District. Map source: author, data source: US Census Bureau 2010-2014 American Community Survey estimates and US Census Bureau 2010 Census.

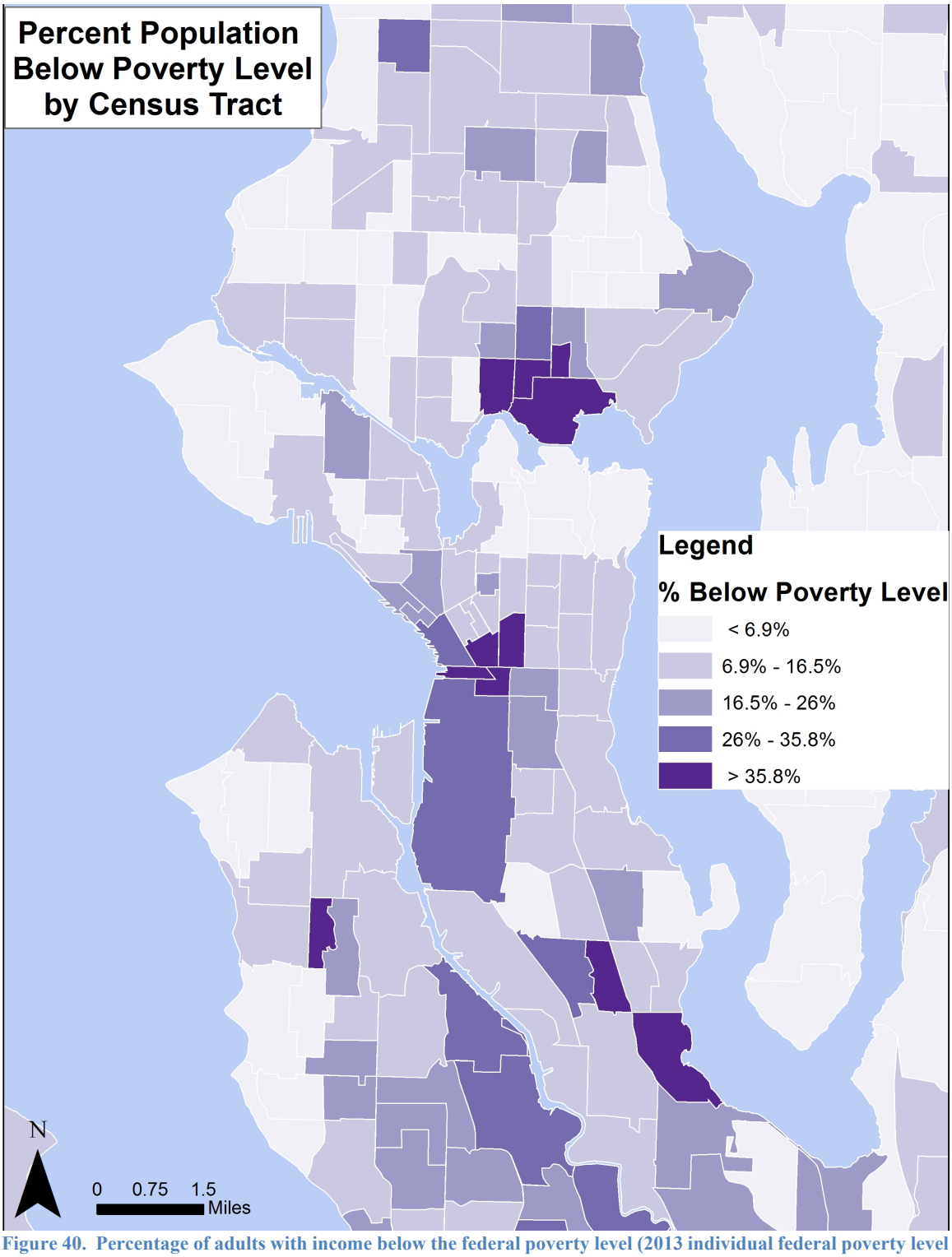

Figure 40. Percentage of adults with income below the federal poverty level (2013 individual federal poverty level = $11, 490). Map source: author, data source: US Census Bureau 2013 American Community Survey 5 Year Estimates.

4.2 Process Models

Stormwater

The natural-constructed water system forms the basis for most of the process models of interest for Seattle's GI planning, since stormwater runoff and combined sewer overflow are the highest priority issues across multiple city departments (Figure 29). Ideally, a full stormwater runoff simulation model would be developed for the city and contributing watersheds that also accounts for all existing green and grey infrastructure. However, there are several limitations to achieving this with today's technology. The EPA recommends several models and tools[86] for runoff modeling with green infrastructure; however, most of these are designed for site specific, rather than watershed scale, hydrologic analyses, with the exceptions of i-Tree, which only evaluates the impact of urban forests on runoff, and SWMM and WERF BMP SELECT, both of which requires drainage areas to be defined by homogenous land uses and require all infrastructure elements in the drainage network to be modeled individually.[87] SWMM will support the command line import of some data, but Seattle's drainage network GIS files do not have all of the required attributes.

Simple runoff models that do not include network routing could be developed instead using either the Rational Method or NRCS TR-55. However, the city's Stormwater Manual

[86] EPA. 2015. Green infrastructure modeling tools. Available from https://www.epa.gov/green-infrastructure/green-infrastructure-modeling-tools. Accessed on 8/29/2016.
[87] WERF BPM SELECT User's Guide. 2013. Available as part of tool (SWC1R06c) download from http://www.werf.org/Search. Accessed on 8/21/2016. See also https://www.epa.gov/water-research/storm-water-management-model-swmm for a description of SWMM modeling requirements.

Hydrologic Analysis and Design (Appendix F)[88] only recommends the Rational Method for drainage basins less than 10 acres where short intense storms would generate high peak flows, and only 90 of the city's 323 pre-defined manufactured drainage basins meet this criteria. TR-55 is only recommended for 24-64 hour design storms, which are not actually characteristic of Seattle, but the method is allowed for some types of volume-based stormwater control facilities.[89]

A GIS-based approach was also evaluated from University of Southern California's GIS Research Laboratory, which modeled watershed-scale recharge suitability for the Upper LA River and includes runoff, flow accumulation and flow direction (Swift et al. 2007). However, this approach assumes that natural topographic boundaries define drainage areas, which is not the case in an urbanized area like Seattle. The city's Stormwater Manual notes that the manufactured drainage systems often cross topographic divides, which is illustrated in Figure 41. Based on personal communication with a Seattle Municipal Stormwater Specialist[90], the city is still developing a basin-scale modeling strategy to address the complexities of basin-scale stormwater runoff modeling that accounts for both natural and manufactured systems, and currently only has a small number of basins modeled using a hodge-podge of approaches.

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[88] City of Seattle. 2015. Stormwater Manual Appendix F Hydrologic Analysis and Design. Available from http://www.seattle.gov/dpd/cs/groups/pan/@pan/documents/web_informational/p2358272.pdf. Accessed on 8/21/2016.
[89] Ibid.
[90] Personal communication via email and telephone on 9/8/2016.

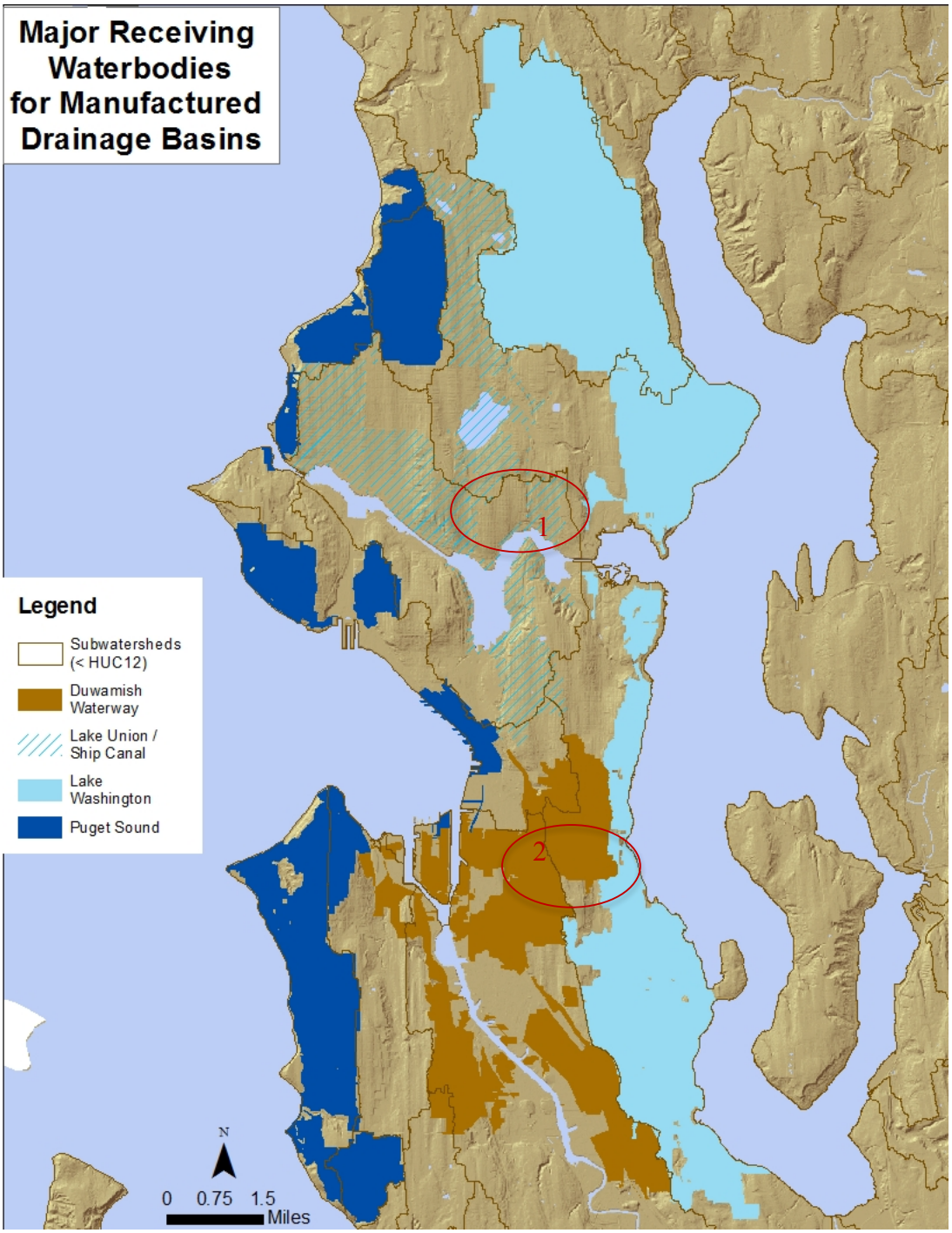

Figure 41. Major receiving waterbodies for Seattle's drainage systems. The red circles highlight large areas where manufactured drainage systems defy gravity and topographic boundaries: 1) a 2170 acre partially separated and 333 acre combined sewer system drain to Lake Union and the Ship Canal instead of Lake Washington, 2) a 2618-acre partially separated sewer system crosses three subwatershed boundaries to drain to the Duwamish instead of Lake Washington. Smaller mismatches can also be found throughout the system. Map source: author, data source: City of Seattle.

In the absence of a citywide runoff modeling approach, NPDES stormwater monitoring reports for multiple water years (2010, 2012, 2014) were reviewed to supplement the process picture. Additional caveats to modeling stormwater runoff at the city scale were indicated in particular by Seattle's *WY2010 NPDES Stormwater Monitoring Report*[91], which evaluated first-flush toxicity from three areas that were identified as characteristic of the non-combined sewer drainage conditions of the three main land uses in Seattle – residential, commercial, industrial. Note that toxicity monitoring is only required once during a five-year permit cycle, and has not yet been done for the 2013-2018 permit.

The first notable difference between monitoring and modeling approaches is that the drainage area for monitoring is defined by the catch basin and pipe network for a single outfall, and thus is typically smaller than the drainage basins provided through the city's GIS data, especially in the fully separated portion of the system. For example, the monitored residential area, which drains to Venema Creek, a tributary of Pipers Creek, in NW Seattle, is only 85.4 acres, whereas the entire manufactured drainage basin for Pipers Creek is 1604 acres, and the topographically defined subwatershed is 1795 acres. Figure 42 illustrates the relationships among the three, and further exemplifies a case where the manufactured drainage and topographic drainage boundaries do not match. These mismatches are important to consider when modeling runoff behavior because they affect

[91] City of Seattle. 2011. 2010 NPDES Phase 1 Municipal Stormwater Permit Stormwater Monitoring Report. Available from http://www.seattle.gov/util/cs/groups/public/@spu/@drainsew/documents/webcontent/01_012402.pdf. Accessed on 8/22/2016.

the land cover, land uses, soil, and slope as well as the existing infrastructure and potential pollutant sources and sinks included in the analysis.

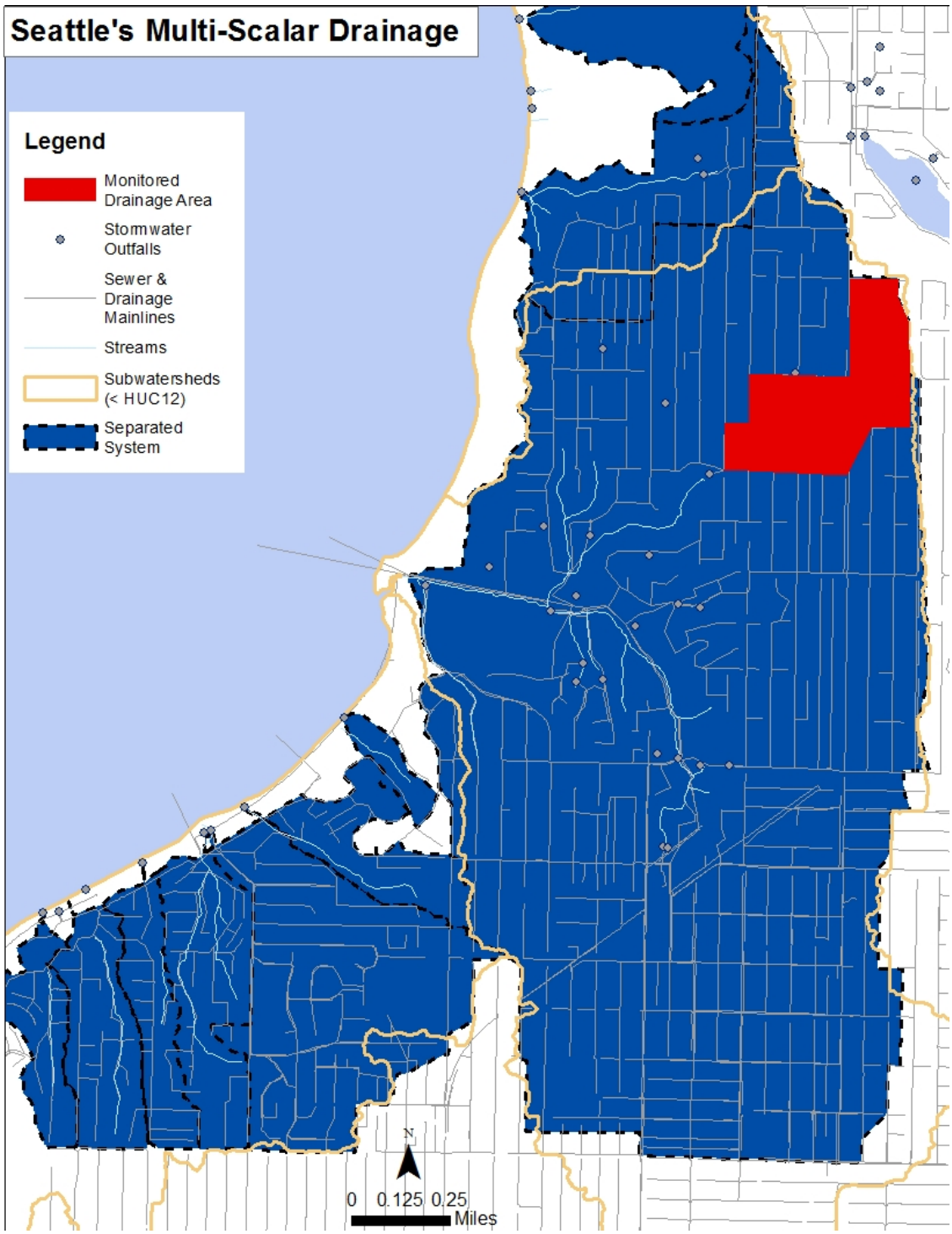

Figure 42. The monitored residential drainage area in relation to the larger manufactured and topographic drainage basins. Note the boundary mismatches, which influences the model input parameters as well as the estimated runoff volume, flow conditions and pollutant loads. Map source: author, data source: City of Seattle.

Monitoring also indicated a sudden spike in fecal coliform values in the sample industrial area, and the resulting investigation revealed that a contractor had connected a newly constructed wash pad to the storm drain rather than to the sanitary sewer. The wash pad was used for both washing the bus fleet and emptying the fleet's septic holding tanks. This incident is a reminder that most models only emulate known or expected behaviors, and illustrates the importance of monitoring as well.

Table 10 summarizes the rainfall, runoff, and a few pollutants for each storm event in the residential, commercial, and industrial sites to further characterize stormwater runoff processes in Seattle. Samples were analyzed for:

- 4 nutrients: Nitrate + Nitrite, Total Nitrogen, Total Phosphorus, and Ortho-phosphate
- 29 semi-volatile organics including multiple types of phthalates, which are considered carcinogenic and are possibly endocrine disruptors
- 4 metals in total and dissolved form: Cadmium, Copper, Lead, and Zinc
- 3 miscellaneous organics
- 7 conventionals: conductivity, pH, total suspended solids (TSS), turbidity, Chloride, biological oxygen demand, and surfactants
- Petroleum Hydrocarbons – diesel and gasoline
- Bacteria – fecal coliform

While all three sites passed toxicity tests on rainbow trout gametes (reproductive cells) for both survival and development, and pH levels stayed within the regulatory range of 6.5-8.5[92], several dissolved metals[93] and fecal coliform bacteria exceeded levels that would be permitted in receiving waterbodies. It is important to note, however, that the regulatory

[92] WA ECY. 2012. Water quality standards for surface waters for the State of Washington. Available from https://fortress.wa.gov/ecy/publications/documents/0610091.pdf. Accessed on 8/28/2016.
[93] WA ECY. 2014. Stormwater Management Manual for Western Washington Vol. IV Source Control BPMs. Available from https://fortress.wa.gov/ecy/publications/summarypages/1410055.html. Accessed on 9/8/2016.

limits only apply to the receiving waterbody and not to the discharging outlet for the municipal stormwater permit (this varies by permit type). WA ECY does provide guidance on some discharge limits, and all three sites did stay well under the suggested limits for petroleum hydrocarbons, BOD and TSS[94] with the exception of TSS at the industrial site during SE-07, which had the highest amount of rainfall (1.35") and one of the largest flow volumes (154,440 cf). Figure 44 provides an overview of the 2012 water quality assessment for the entire city and adjacent waterbodies. Only Category 2 and higher were included for the sake of clarity. Figure 45 summarizes the listing categories by waterbody.

[94] WA ECY. 2011. Guidance Manual for Developing Local Discharge Limits. Available from https://fortress.wa.gov/ecy/publications/documents/1110056.pdf. Accessed on 9/8/2016.

Table 10. WY2010 Monitoring Site Summaries

Residential (Venema Creek) – 85.3 acres – 50.2% Impervious – Separated storm sewer, ditch and culvert system											
Storm Event	SE-01	SE-02	SE-03	SE-04	SE-05	SE-06	SE-07	SE-08	SE-09	SE-10	SE-11
Storm Event Month	Oct	Nov	Dec	Jan	Feb	Feb	Feb	Mar	Mar	Aug	Sep
Duration (hrs)	19.5	18.3	30.3	35.8	44.9	15.8	26.2	38.8	25	15.2	33.2
Rainfall (inches)	.4	1.02	.79	1.12	.5	.32	.22	1.31	.28	.49	.58
Rainfall Max (in/hr)	.22	.42	.15	.19	.13	.13	.09	.11	.13	.13	.17
Rainfall Mean(in/hr)	.009	.019	.010	.017	.009	.006	.007	.009	.006	.004	.013
Flow Max (cfs)	2.20	14.24	1.67	1.93	2.22	1.37	.44	1.24	3.13	.036	2.63
Flow Mean (cfs)	.05	.21	.05	.15	.08	.06	.03	.06	.03	.01	.06
Flow Volume (cf)	1983.82	15400	8552.89	26455	6426.03	6864.5	1367.55	29410	2197.71	3291.22	3156.2
Fecal Coliform (cfu/100ml)	640	1020	10600	528	43	512	184	19500	8	35300	3760
TSS (mg/l)	25.8	288	50.9	80.2	76.5	43.9	6.2	31.6	35.5	54	68.3
Commercial (University District) – 152 acres – 61.1% Impervious – Partially separated storm sewer											
Storm Event	SE-01	SE-02	SE-03	SE-04	SE-05	SE-06	SE-07	SE-08	SE-09	SE-10	SE-11
Storm Event Month	Oct	Dec	Dec	Jan	Jan	Feb	Feb	Mar	Mar	Aug	Aug
Duration (hrs)	24.1	24.6	42	33.4	21.2	44.3	24.1	33.9	27.3	9.5	16.3
Rainfall (inches)	.5	.71	.95	1.12	.45	.54	.28	1	.39	.14	.5
Rainfall Max (in/hr)	.25	.16	.11	.17	.13	.16	.11	.1	.12	.07	.15
Rainfall Mean(in/hr)	.012	.009	.010	.016	.003	.012	.007	.007	.007	.001	.003
Flow Max (cfs)	20.80	18.35	27.24	39.74	24.60	13.58	8.70	14.17	57.25	2.21	13.58
Flow Mean (cfs)	1.26	1.14	2.06	3.46	.86	1.29	1.01	1.16	1.21	.27	.54
Flow Volume (cf)	194770	220970	506520	739120	289150	180500	91718	434600	145040	16710	133950

Fecal Coliform (cfu/100ml)	4080	2760	1680	1000	1300	1020	2000	7180	ND	NM	22700
TSS (mg/l)	23.1	74	72	50	42.7	46.6	32.2	35.9	45.6	26.3	50.8
Industrial (Norfolk) – 137.2 acres – 51.2% Impervious – Partially separated storm sewer											
Storm Event	SE-01	SE-02	SE-03	SE-04	SE-05	SE-06	SE-07	SE-08	SE-09	SE-10	SE-11
Storm Event Month	Oct	Dec	Dec	Jan	Mar	Mar	Mar	Apr	Apr	Aug	Sep
Duration (hrs)	22.3	15.1	45.8	16.9	33.3	23.4	34.3	38.7	17.3	5.7	6
Rainfall (inches)	.38	.56	.81	.47	1.31	.62	1.35	1.06	.42	.36	.19
Rainfall Max (in/hr)	.25	.13	.13	.13	.13	.26	.27	.19	.19	.14	.45
Rainfall Mean(in/hr)	.011	.010	.011	.004	.009	.009	.015	.012	.006	.003	.016
Flow Max (cfs)	15.76	4.46	5.39	3.85	8.24	10.09	12.47	10.86	7.07	2.68	17.20
Flow Mean (cfs)	.33	.13	.40	.12	.34	.27	.59	.54	.17	.05	.39
Flow Volume (cf)	31963	23889	72990	54154	168400	48727	154400	154400	34022	19811	7070.37
Fecal Coliform (cfu/100ml)	820	440	680	372	720	3200	488	762	91900*	1220	1800
TSS (mg/l)	106	120	69	37.7	43.4	74	398	73.1	16	50.2	48.5

* Industrial SE-09 fecal coliform spike revealed the illicit discharge issue.

Note: The highlighted values show that comparable precipitation can result in significantly different volumes and velocities of runoff, even for similar amounts of impervious area, due to differences in drainage area. In terms of runoff characterization, just these 11 storm events with rainfall ranging from 6.58 to 7.53 inches in 3 small drainage areas produced 3,827,979 cubic feet or 28,635,274 gallons of runoff, so the city's annual estimate of 13 billion gallons of runoff is foreseeable.

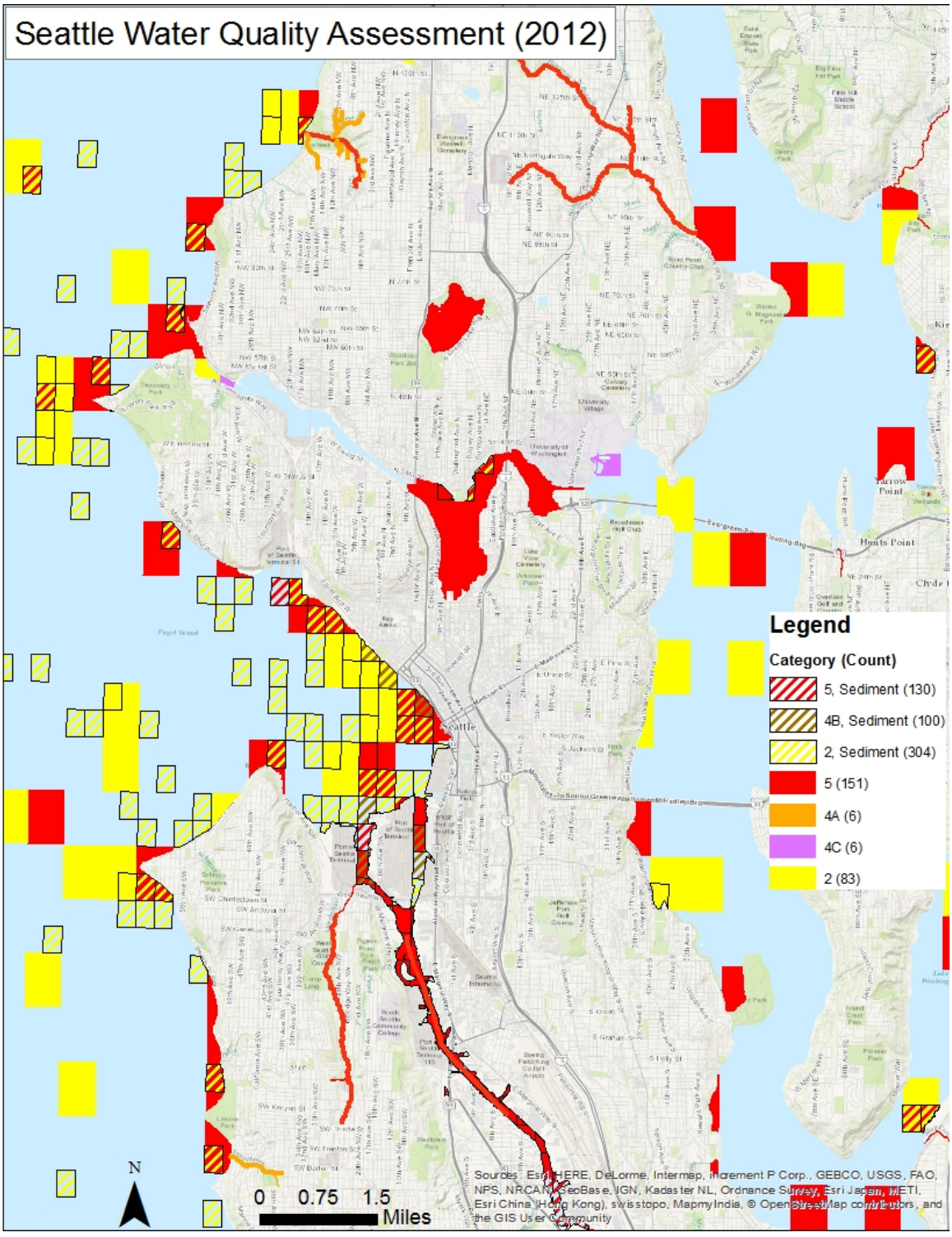

Figure 43. Seattle's 2012 water quality assessment. The worst/highest listing is symbolized, but waterbodies often have multiple listings for multiple categories. The number of listings for each category are included in parentheses. Category 5 are 303d listings, which require a TMDL or water quality improvement project. Category 4A listings also have a TMDL although it is not required, while 4B listings have some other regulatory and funded pollution control program in place. Category 4C listings are impaired by a non-pollutant, e.g. low flows, channelization, dams, or exotic species as in the case of the wetlands next to the University of Washington. Category 2 are waters

of concern, which means that while polluted, the levels do not violate water quality standards or there is not enough evidence to support a listing.

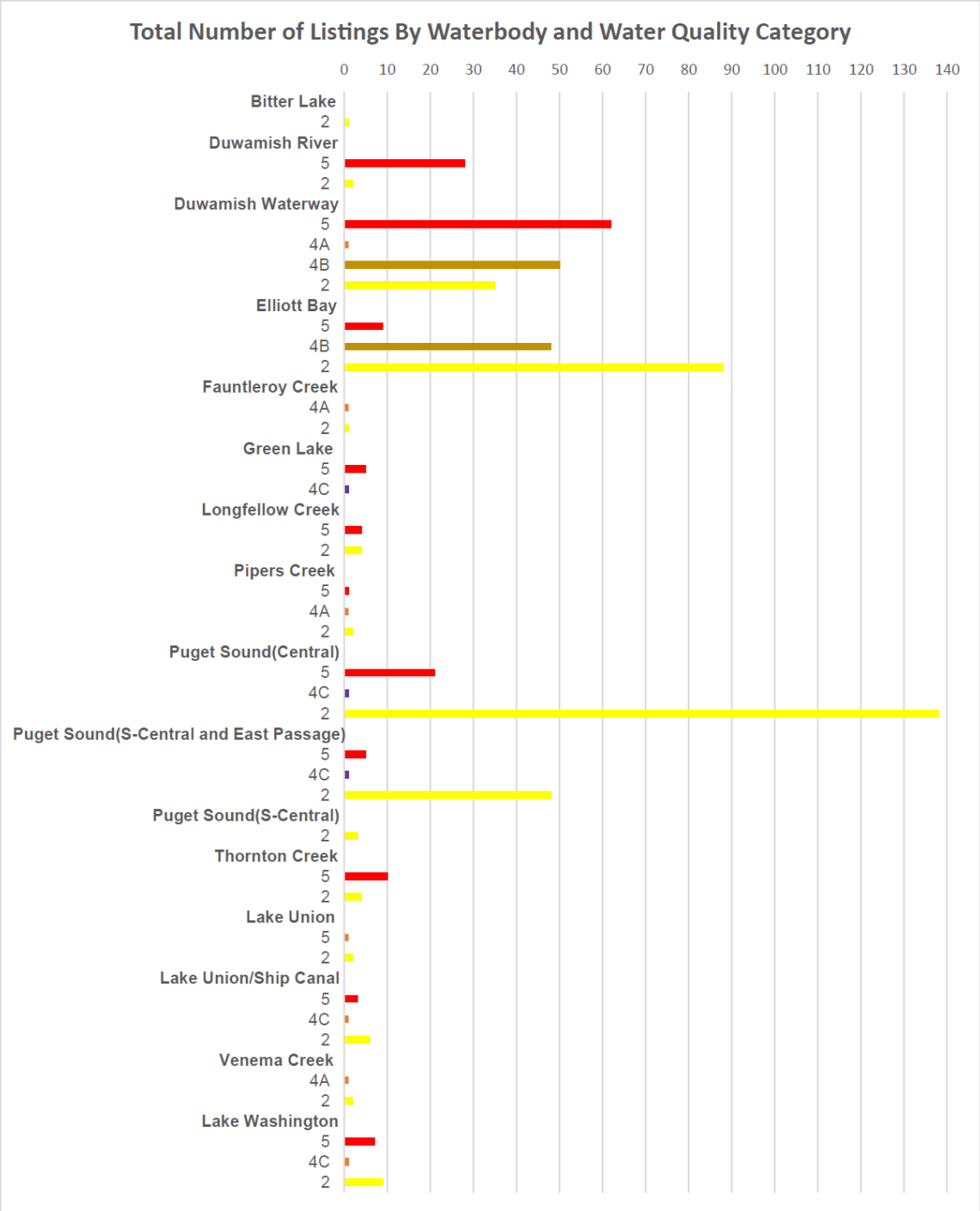

Figure 44. Summary of listings by waterbody and water quality category (including sediment). The large waterbodies have significantly more listings, which is a function of both their size and their role as a sink for runoff from multiple sources.

Table 11 lists the most common water quality and sediment issues by water quality category. A total of 71 different issues are listed in the 2012 water quality assessment for Seattle. Some issues, like heavy metals and PCBs, are largely concentrated in current or former industrial areas like the Duwamish and the Ship Canal. Other issues, like fecal coliform bacteria and dissolved oxygen, are pervasive across the city. Figure 45 shows the total volume of combined sewer overflows, a major source of bacteria and reason for low dissolved oxygen, from 2010-2014, as well as the number of incidents and whether the volumes are increasing or decreasing over time. Evaluation models will incorporate both water quality assessments and CSO incidents to identify vulnerable aquatic areas and areas attractive for GSI development.

Table 11. Summary of common water quality issues.

Water Quality Category	Common Water Quality and Sediment Issues (Count)
5 – 303d	Bacteria (30), PCB (15)
4A	Bacteria (4)
4C	Invasive Species (4)
2	2,4 – Dimethylphenol (33), Dissolved Oxygen (25), Benzoic Acid (17), PCB (14)

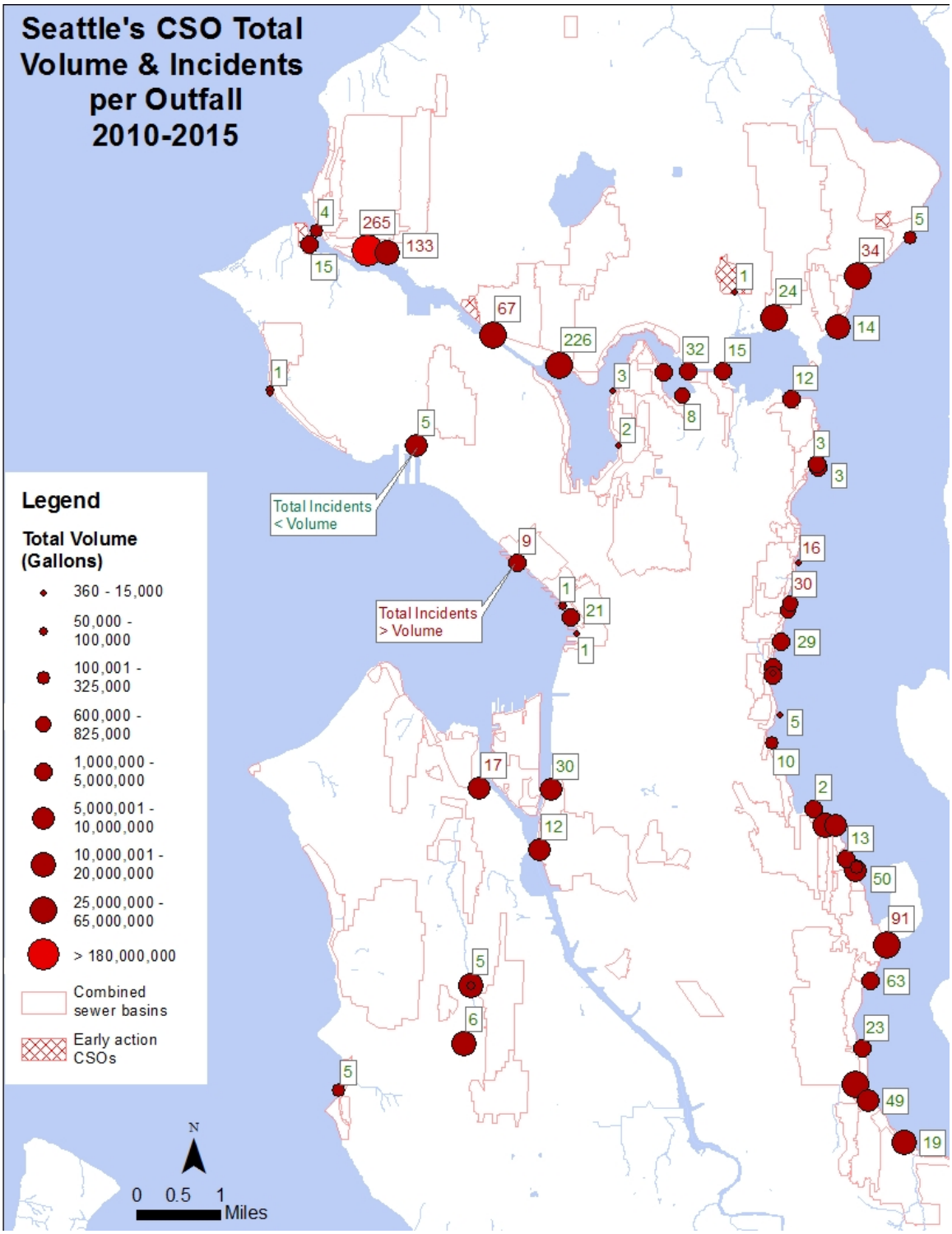

Figure 45. Total combined sewer overflows from 2010-2014, with number of incidents and annual increase/decrease trends. The number of incidents with increasing annual volume are labeled red, and those with decreasing annual volume are labeled green. Map source: author, data source: City of Seattle.

Urban Flooding

Stormwater management is also directly related to urban flooding, and is especially prevalent in the northern part of the city due to the open ditch and culvert drainage system (see Figure 46). Currently 152 areas are identified as problematic for recurring flooding and 28 of those are classified as major. Only 217 acres of the 2,609 acres affected by urban flooding also lie within the city's 100-year floodplains, and are instead largely related to capacity and maintenance issues within the drainage system. While most of the areas, with the exception of the Longfellow Creek area in West Seattle, are not prioritized for NDS projects through the city's CSO control plan ('Protecting Seattle's Waterways'), 10 are recommended for NDS/GSI and a further 4 for floodplain and wetland restoration. These areas will be also be included in the GSI evaluation model.

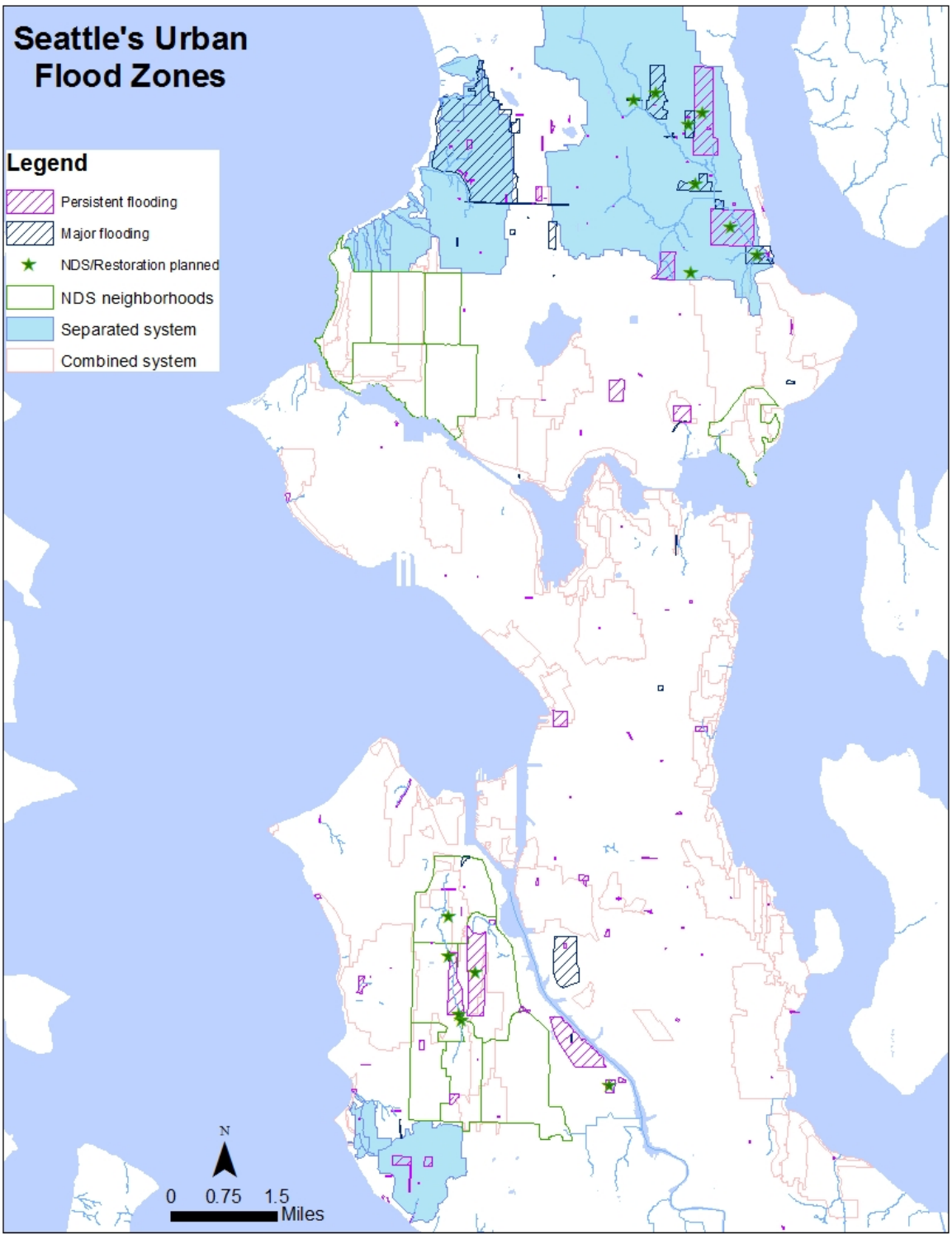

Figure 46. Urban flooding in Seattle. Most major flooding (blue hatch) occurs in the north of the city due to the ditch and culvert system. Minor flooding (pink hatch) occurs throughout the city due to infrastructure capacity or maintenance issues. NDS or restoration is only prioritized for 14 out of 152 areas. Map source: author, data source: City of Seattle.

Aquatic Migration

While several species - aquatic (vertebrate and invertebrate), avian and human, are impacted by water quality in Seattle's streams, rivers and waterbodies, anadromous fish species like Chinook salmon and Steelhead trout, which migrate between fresh and saltwater are key species of concern due to their cultural significance; federal and state endangered or threatened status; and Western Washington Treaty Tribes requirements. All of the city's major waterbodies are migration routes for these and other salmon and trout species; however, only the Cedar River to Puget Sound route illustrated in Figure 3 is regulated by a habitat conservation plan under the Endangered Species Act, largely due to the potential for "takings" due to SPU and SCL dam operations. The Green-Duwamish River to Elliott Bay route is also used by anadromous species, but is guided by a voluntary recovery plan under the ESA rather than a regulatory document.[95]

Five of Seattle's urban creek watersheds – Fauntleroy, Longfellow, Piper's, Taylor, and Thornton, also have year-round flow and support salmon and trout (Figure 47). Of approximately 35 miles, 20 miles have been classified as potentially fish-bearing and resident fish have been recorded in 11 of the 20 miles, with anadromous fish accessing four miles for spawning.[96] However, several aspects important to their survival, from water

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[95] The WRIA 9 Salmon Habitat Plan is a chapter in the Puget Sound Salmon Recovery Plan. See here for an overview: http://www.westcoast.fisheries.noaa.gov/protected_species/salmon_steelhead/recovery_planning_and_implementation/. Accessed on 9/27/16.

[96] SPU Urban Creek Watershed Analysis Appendices. Available from http://www.seattle.gov/util/cs/groups/public/@spu/@conservation/documents/webcontent/spu01_002692.pdf. Accessed on 9/27.16.s

temperature and dissolved oxygen to habitat diversity and accessibility, vary across the city. Figures 48-50 summarizes these characteristics for each creek watershed based on several years of monitoring and assessment that culminated with the *City of Seattle State of the Waters* report in 2007.

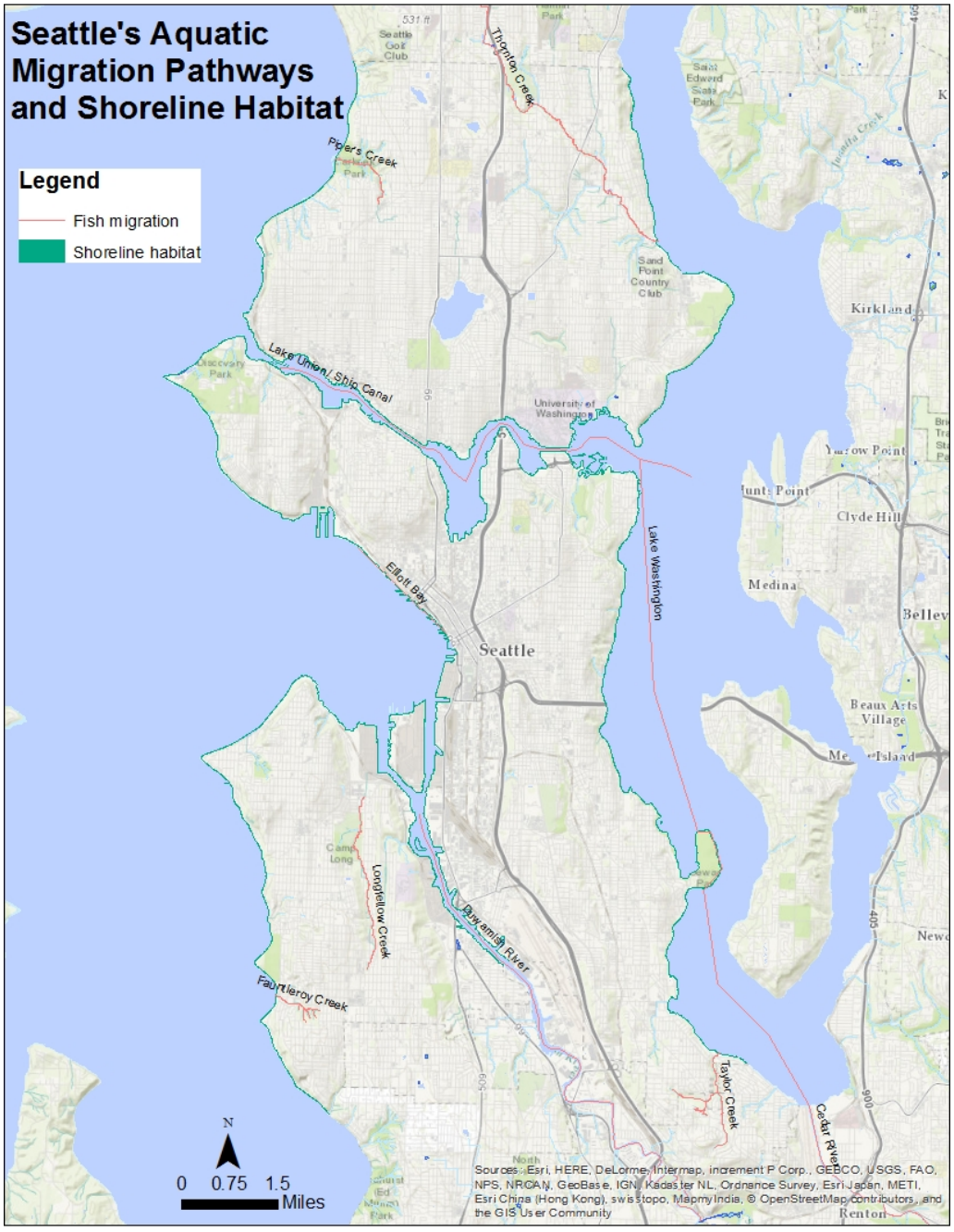

Figure 47. Seattle's urban creeks and aquatic migration pathways. Map source: author, data source: City of Seattle.

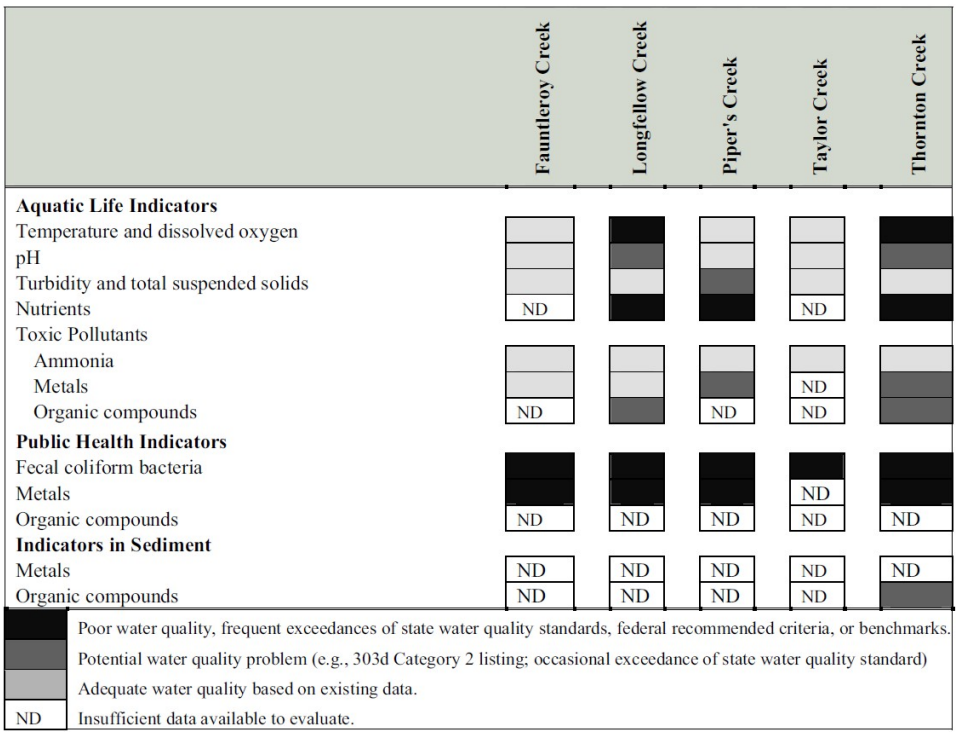

Figure 48. Urban creek aquatic life water quality assessment. Source: *City of Seattle State of the Waters 2007* report.

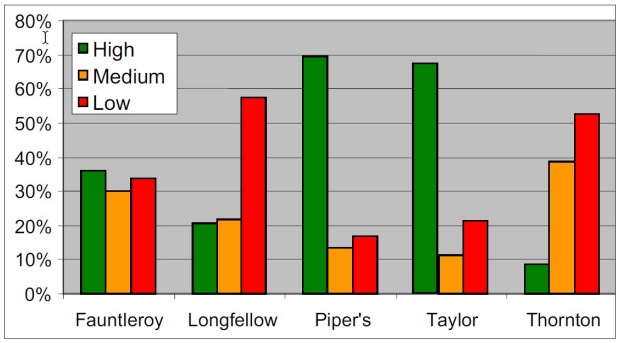

Figure 49. Riparian habitat quality by percent of high, medium and low quality. Piper's Creek and Taylor Creek have largely high-quality riparian habitat because 60% of their extent is bordered by mature forest.

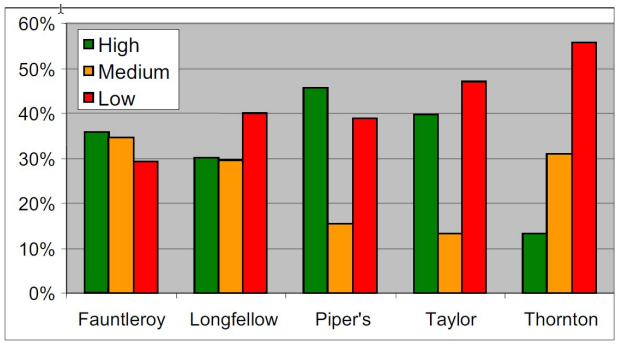

Figure 50. Instream habitat quality by percent high, medium and low quality. Higher quality areas are usually located within park lands.

Forest/Tree Canopy Increase

In 2013, the Urban Forest Stewardship Plan re-affirmed the 2007 goal of reaching 30% tree canopy by 2037. In 2016, the city completed a new LiDAR and NAIP-based tree canopy study (Figure 51) and determined that the city currently has 28% canopy cover.[97] The 30% canopy goal was further differentiated and distributed among eight management units (i.e. land use types) as well as the ROW to help focus specific stewardship strategies, and several management units are exceeding or nearly meeting these goals (Table 12). As can be expected, single-family, parks, and ROW have the most canopy cover in the city, and industrial areas and downtown the least. Both, however, are sources of urban heat islands, thus canopy increase in these areas must remain a priority.

Table 12. Seattle's canopy cover by management unit (Source: City of Seattle).

Management Unit	Land area (% of city)	2016 canopy cover	2037 canopy goal (set in 2007)	% contribution to city's canopy cover
Single-Family Residential	56%	32%	33%	63%
Multi-family Residential	11%	23%	20%	9%
Commercial/Mixed-use	8%	14%	15%	4%
Downtown	1%	10%	12%	<1%
Industrial	11%	6%	10%	2%
Institutional	2%	25%	20%	2%
Developed Parks	4%	34%	25%	6%
Parks' Natural Areas	7%	89%	80%	14%
City total	100%	28%	30%	100%
Right-of-way (runs through all other MUs)	27%	23%	24%	22%

Forest function is also a stewardship priority, so the canopy assessment identified groves of trees (stands of eight or more, each with a 12in. minimum DBH (diameter at breast

[97] Jarlath O'Neil-Dunne, University of Vermont, Spatial Analysis Laboratory. 2016. Seattle Tree Canopy Assessment. Available from http://www.seattle.gov/trees/docs/Seattle2016CCAFinalReportFINAL.pdf.

height)), and differentiated between coniferous and deciduous trees. Large trees (at least 30in. DBH) were also identified because they provide the most cooling, carbon sequestration and stormwater management benefits. The assessment identified an estimated 6,338 large trees and 3,188 tree groves (Figure 52). Just over a quarter (28%) of the trees are coniferous. The city would like to increase their numbers, in part because Seattle was dominated by lowland coniferous forests, and because they provide benefits year-round.

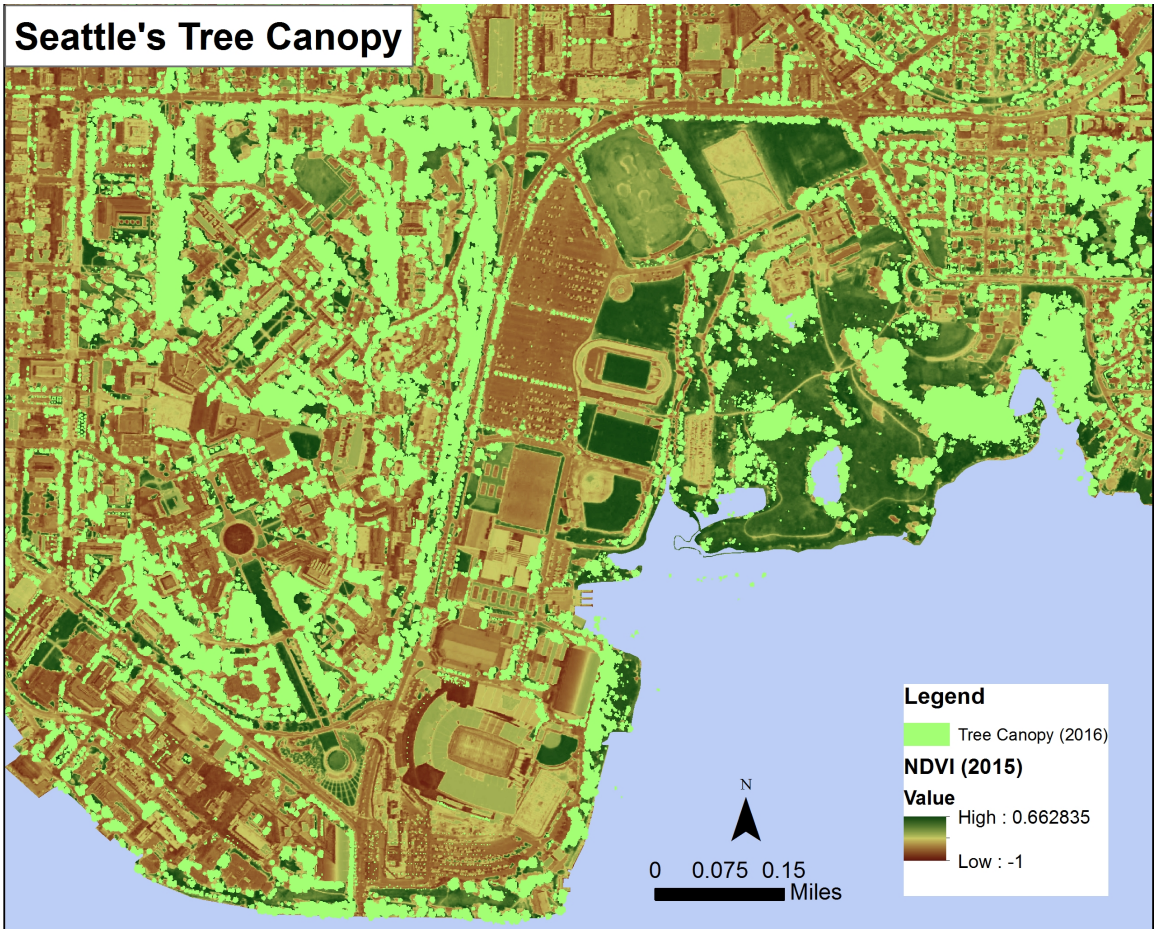

Figure 51. Seattle's tree canopy compared to NDVI. The 2016 canopy assessment used LiDAR under leaf-off conditions for its vertical accuracy, which helps separate tree canopy (trees 8ft. and above) from shrubs. This was combined with 2015 NAIP color-infrared, leaf-on imagery, the same basis for the previously discussed NDVI analysis. As Figure 35 noted, the NDVI values for the UW sports fields and the adjacent woody wetlands in the Union Bay Natural Area are the same (.45), and thus cannot be used alone to determine canopy cover. Map source: author, data source: City of Seattle.

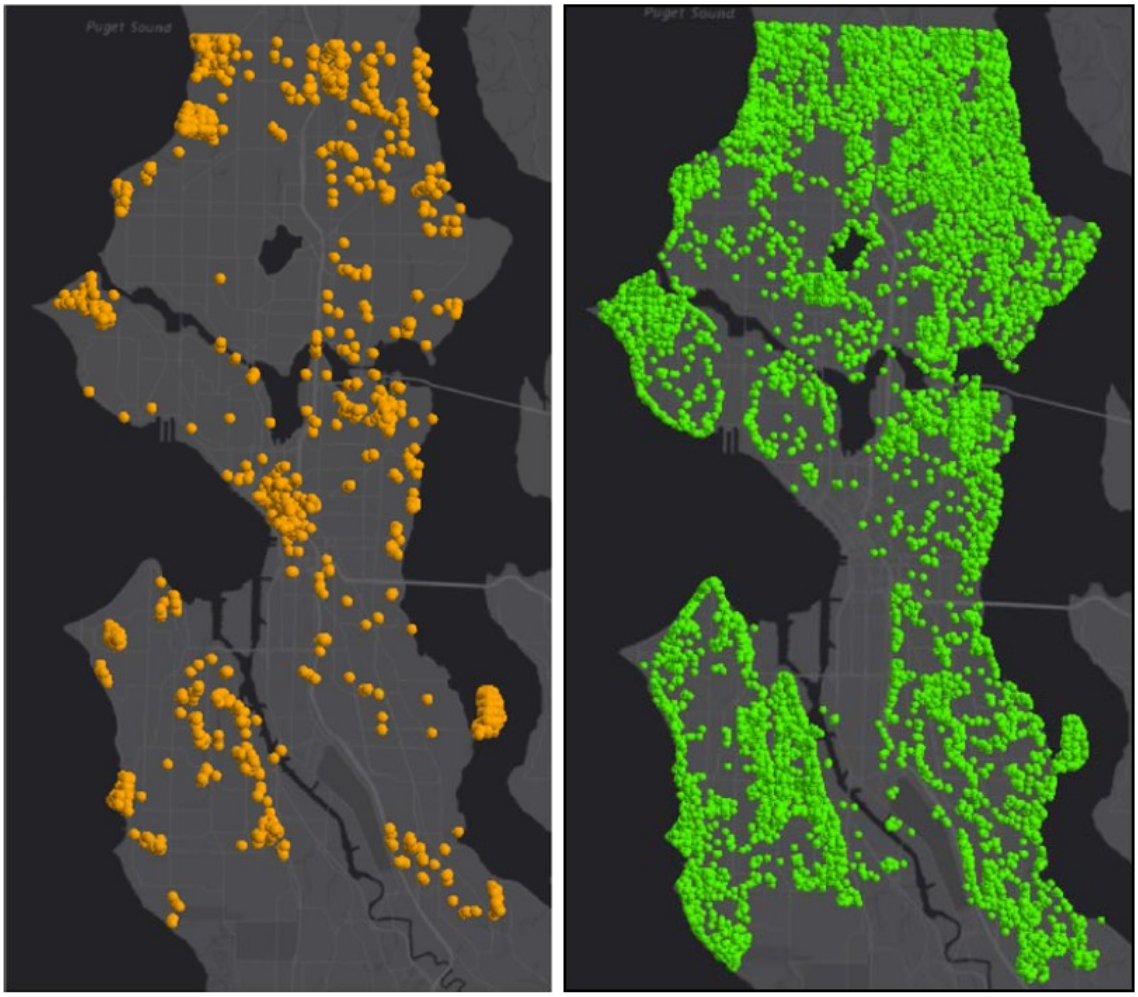

Figure 52. Distribution of large trees (left) and tree groves (right) in Seattle. Image source: Jarlath O'Neil-Dunne, University of Vermont, Spatial Analysis Laboratory.

Riverine Flooding

Due to the Howard Hanson Dam upstream on the Green River and the extensive channeling and armoring of the Duwamish River, Seattle is not significantly affected by riverine flooding. Areas in the 100-year floodplain, excluding the coastline, comprise 388 acres and include the South Park neighborhood and the Thornton and Longfellow Creek drainage basins, all of which have flood controls in place. Seattle has fewer than 10 buildings that

have experienced more than one flood loss.[98] Table 12 lists the land uses that can be potentially flooded, including nearly 73 acres of parks and open space and 60 acres of right of way, which could be used for mitigation measures.

Table 13. Land use in flood prone areas.[99]

	Acres	% Seattle	% Area
Seattle	53178.37	100%	
Flood Area (1996 FIRM & other)	388.39	0.73%	100.00%
Property in area	**328.81**	**0.62%**	84.66%
Commercial/Mixed-Use	18.35	0.03%	4.72%
Easement	0.00	0.00%	0.00%
Industrial	50.06	0.09%	12.89%
Major Institutions	47.45	0.09%	12.22%
Multi-Family	13.82	0.03%	3.56%
Parks/Open Space	72.77	0.14%	18.74%
Reservoirs	0.81	0.00%	0.21%
Single Family	69.90	0.13%	18.00%
Unknown	0.62	0.00%	0.16%
Vacant	55.03	0.10%	14.17%
Right of Way in Area	**59.58**	**0.11%**	15.34%

Seattle's Puget Sound coastline is also included in FEMA's Special Flood Hazard Area, but does not extend inland. Much of Seattle's coastline consists of bluffs, and the low-lying areas in downtown are heavily armored with a seawall. Coastal flooding can occur during large storms, eroding the toes of coastal bluffs and creating the potential for landslides. Sea-level rise associated with climate change is expected to exacerbate coastal flooding and will be treated in the Climate Change subsection.

[98] Seattle Office of Emergency Management. 2014. Seattle Hazard and Vulnerability Analysis. Available from https://www.seattle.gov/Documents/Departments/Emergency/PlansOEM/SHIVA/2014-04-23_Flooding.pdf. Accessed on 2/7/2017.
[99] Ibid.

Trail Connectivity

This process model simply looks at current and future connectivity of dedicated, off-street trails (referred to as multi-use trails in Seattle Bicycle Master Plan) and does not include the street network since roadways limit additional GI benefits related to habitat corridors, air quality and stormwater management. The current multi-use trail network spans 46.9 miles, and an additional 32 are planned (no target date is specified).[100] Nearly 64 miles will be interconnected rather than isolated trails in the planned network (Figure 53).

[100] City of Seattle. 2017. Seattle Bicycle Master Plan: 2017-2012 Implementation Plan. Available from https://www.seattle.gov/transportation/docs/BMP_Imp_Plan_2017_vr32.pdf. Accessed on 9/30/2017.

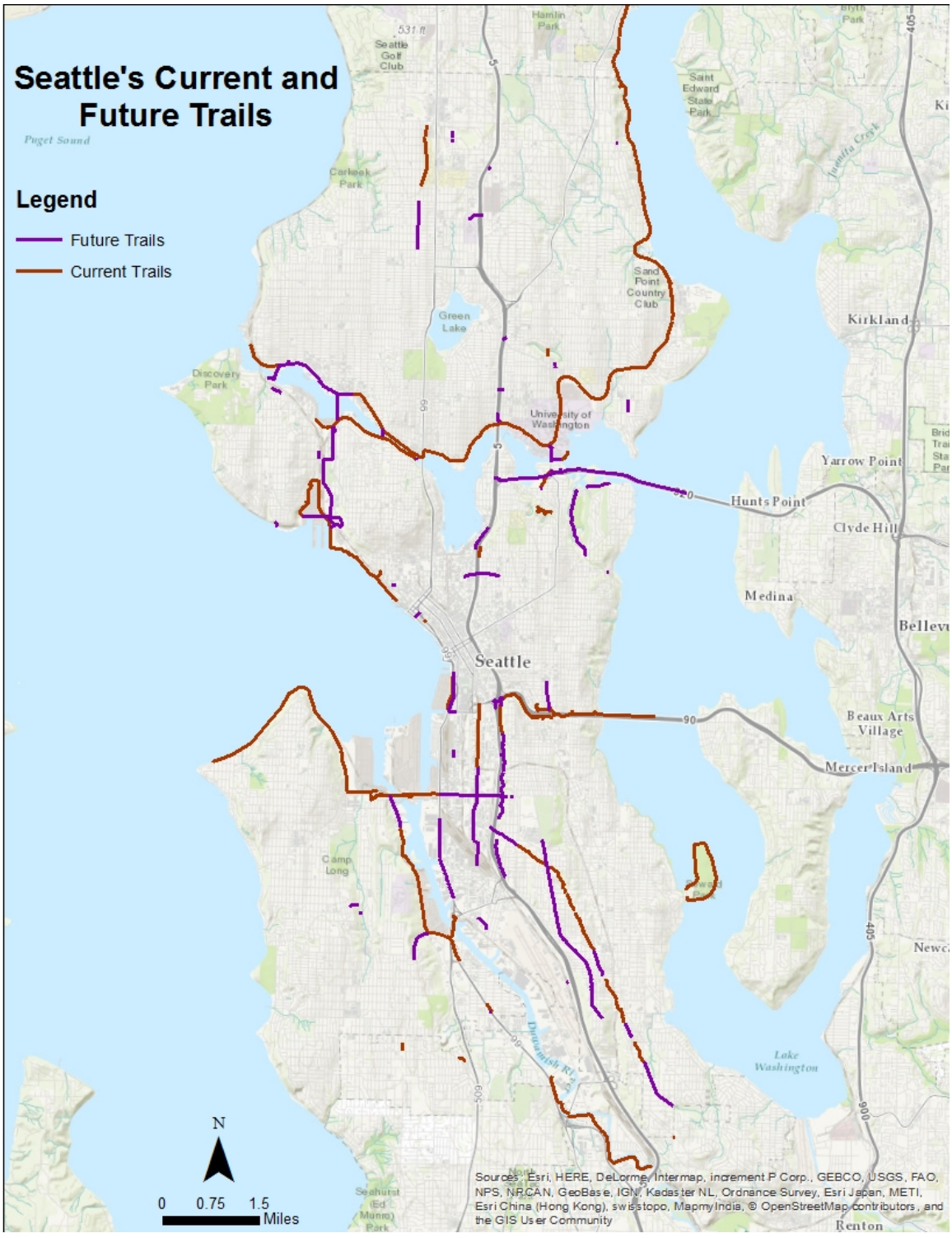

Figure 53. Seattle's current and future trails. Map source: author, data source: City of Seattle.

Park Accessibility

For the 2017 Parks Development Plan, which guides improvements and facilities for the next 6 years, SPR conducted an open space gap analysis that measured walkability, and overlaid socio-economic data to help prioritize investments based on equitable access and future population growth projections (an estimated 120,000 increase over the next 20 years). SPR uses the Trust for Public Lands and National Park Service definition of walkability – the distance a person walks in 10 minutes, ½ mile, but has reduced it to 5 minutes, ¼ mile within Urban Villages. They also consider the urban design aspects of walkability – safety, traffic, road conditions, sidewalks, and other public amenities.

SPR mapped over 1000 park entry points and joined these to SDOT's walking network layer, which discounts barriers such as waterbodies, ravines, unconnected streets, and streets without sidewalks. They then buffered each park by its 5-minute, ¼ mile and 10-minute, ½ mile access areas to identify gaps in walkability within and outside of Urban Villages. SPR published their analyses as the 2017 Gap Analysis Update Volume 1 using Esri's Story Map platform, which combines mapping and spatial analytics with narratives, images, and multimedia. Figure 54 just highlights the open space gaps in walkability, since these are the areas where future parks may be developed or extended.

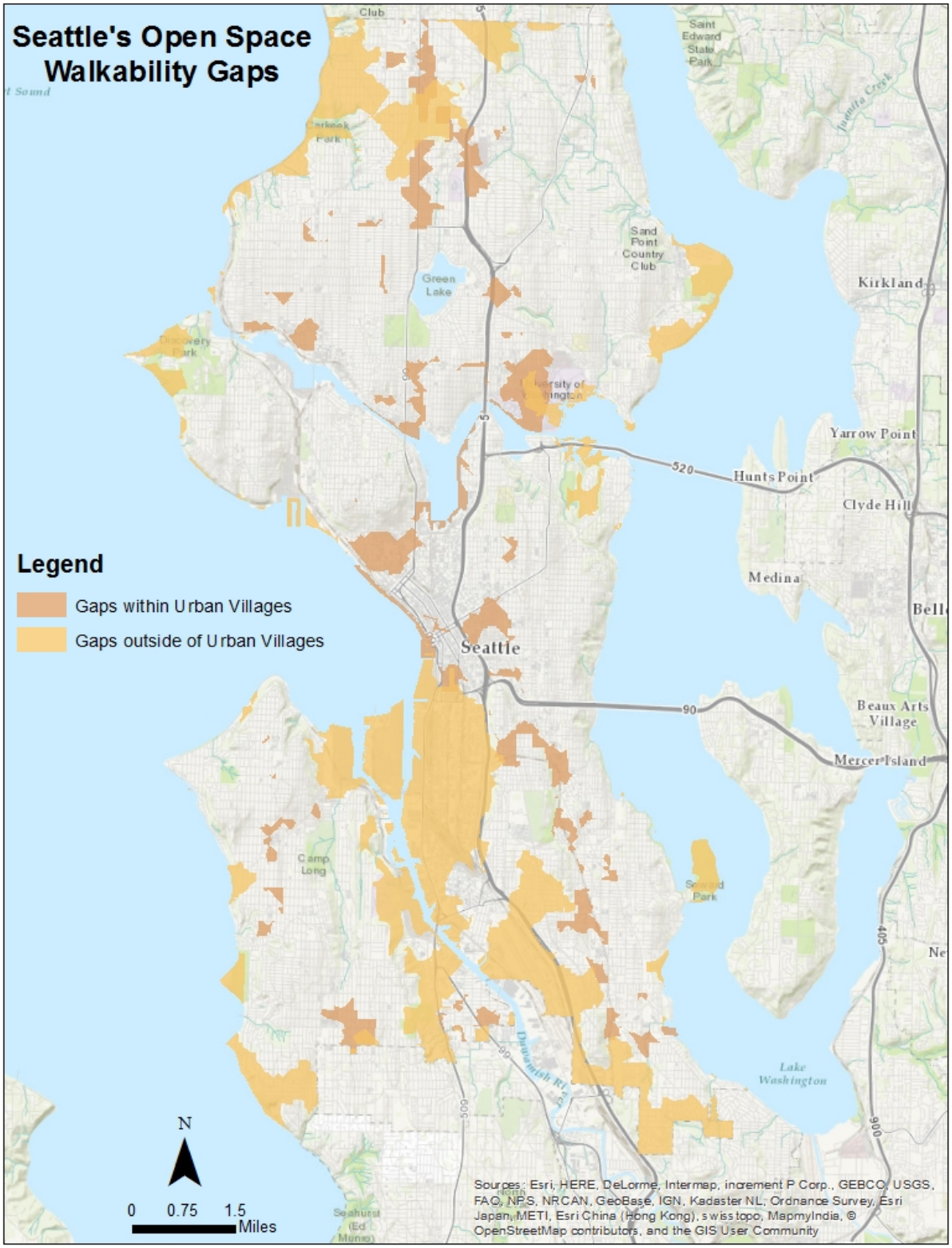

Figure 54. Seattle's open space walkability gaps. Note: these gaps do not account for non-SPR owned open spaces such as Seattle Center, Hiram Chittenden Locks, Olympic Sculpture Park, portions of the Burke-Gilman trail, P-patch gardens, publicly accessible street-ends, plazas in the downtown core, Seattle Public School property and major universities. Map source: author, data source: City of Seattle.

Urban Agriculture Expansion

The Seattle Farms initiative, launched in 2014 to support commercial urban agriculture, only added one new additional plot of approximately 16,000sf in the Central District. The other two plots are located at the Marra Farms P-Patch in the Marra-Desimone Park, and are thus accounted for in the 33 acres of DON's P-Patches and other community gardens and orchards. There are currently no plans for further expansion of the program. Instead, current programs to increase food production in the city based on the Food Action Plan focus more on homeowners. The Urban Garden Square program matches homeowners with garden space to gardeners. Residents are also being encouraged to grow food in their planting strips (the space between the sidewalk and street in front of their property).[101] There is currently no tracking of this activity, however, so it is not included in this analysis.

The DON P-Patch program used funds from the 2008 Parks and Green Spaces Levy to develop 28 new and expanded gardens. There are also no further plans for expansion, but rather the program is experimenting with different gardening models such as collective gardens, giving gardens and food forests to increase community access to urban agriculture. Due to the popularity of the gardens and the long wait list and wait times (as of December 2016 there were 1000+ people waiting between 3 months and 4 years[102]), it is highly likely that new gardens will be developed in the future. The most recent analysis of

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[101] City of Seattle. 2016. OSE Food > Programs and Policies. Available from https://www.seattle.gov/environment/food/programs-and-policies. Accessed on 4/6/17.

[102] Seattle DON. 2017. P-Patch Fact Sheet. Available from http://www.seattle.gov/Documents/Departments/Neighborhoods/PPatch/P-Patch_Fact-Sheet_ENG.pdf. Accessed on 4/6/2017.

public land available for expansion was completed in 2008 by Megan Horst - then a Master of Urban Planning student at the University of Washington, and now an Assistant Professor at Portland State University. Her analysis identified 44 parcels for a total of approximately 526,000sf or 12 acres that met her criteria: public land classified as vacant, unused, or excess right-of-way; 2,000sf minimum area; 40% maximum slope; no streams or wetlands. She also considered future developments plans, available parking, shading, and building coverage. These parcels have been mapped and will be included in the urban agriculture evaluation model. Figure 55 shows all of the current and potential future locations as points, since the parcels are too small to be visible at the city scale.

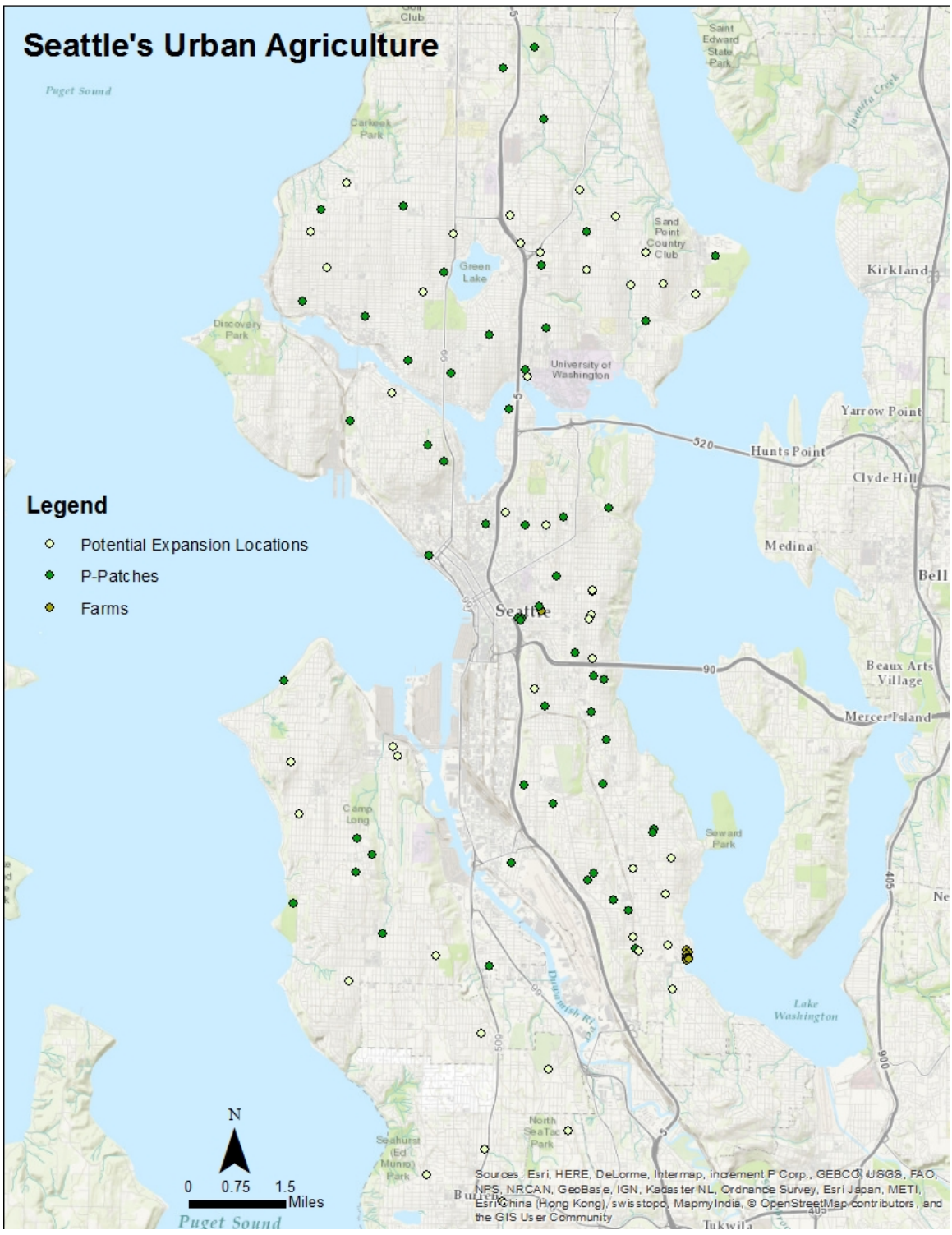


Figure 55. Current and potential urban agriculture locations. Map source: author, data source: City of Seattle and Megan Horst.

Climate Change

Climate change affects many of the processes described previously and must be factored into planning decisions. Table 13 summarizes the most significant changes projected for the PNW, some of which are already detectable. For example, in 2015, the largest wildfire season in Washington's history burned more than a million acres and caused over $250 million in damages, and 30% of the PNW experienced a greater than normal proportion of extreme precipitation events.[103]

Table 14. Summary of climate change in the PNW.[104]

Variables	Projected Changes
Temperature	• Increasing average annual temperature • More frequent extreme heat events (days over 92 degrees F)
Precipitation	• Wetter winters and dryer summers • More extreme heavy rainfall events • Declining snowpack • Shifting streamflow timing and levels with more winter rain and earlier snowmelt • Increasing stream temperatures
Sea Level	• Rising sea levels • Higher storm surges and high tides

Aside from sea level rise (SLR), most of the city's current climate change analyses and planned strategies are aspatial; areas of potential increased flooding and urban heat islands (UHI), for example, have not been mapped. Without more detailed information about the drainage system capacity, it is difficult to identify where new flooding may occur. However, it can be assumed that areas already prone to flooding will continue to do so. For UHI, the *Preparing for Climate Change* report generally identifies the International

[103] Seattle OSE. 2016. Preparing for Climate Change (Draft). Available from http://www.seattle.gov/environment/climate-change/planning-for-climate-impacts. Accessed on 5/11/2017.

[104] Ibid.

District, South Park and Georgetown as problem areas, mainly due to existing air pollution levels, which would be exacerbated by increased temperatures. A study by Climate Central researchers confirms that Seattle does experience the urban heat island effect, and is in fact on the top ten list of cities with urban/rural daytime average summer temperature differences (+4.1 degrees F).[105] The study actually used the weather station at SEA-TAC, which though geographically distant from downtown, shares key characteristics, according to the authors, that contribute to UHI: impervious surfaces that retain and reflect heat, low levels of vegetation, and reduced evapotranspiration. Satellite thermal imagery used in the study confirmed the temperature similarity between SEA-TAC and downtown Seattle. Unfortunately, the study was spatially coarse, and did not identify specific UHI hotspots within Seattle. For the sake of simplicity, the three neighborhoods identified by OSE and downtown will be considered potential urban heat islands.

SLR and potential infrastructure and community impacts have been mapped as a part of a screening tool for city-internal planning purposes, and made available for this research as well. The OSE's Climate Preparedness Mapping Inventory describes several caveats to the data including: uncertainties in climate projections and timing, limits of LiDAR vertical accuracy (1 foot), and changes to elevation due to grading since the LiDAR data collection in 2001.[106] The screening tool is meant to provide a better understanding of potential coastal flooding across the city and in general geographic areas, not to determine risk at a specific

[105] Climate Central. 2014. Summer in the City: Hot and Getting Hotter. Available from http://www.climatecentral.org/news/urban-heat-islands-threaten-us-health-17919. Accessed on 5/15/2017.
[106] Seattle OSE. 2015. Climate Preparedness: A mapping inventory of changing coastal flood risk (Section 1). Available from http://www.seattle.gov/environment/climate-change/planning-for-climate-impacts. Accessed on 5/11/2017.

site. The projections and scenarios are based on the 2012 National Research Council report *Sea-level rise for the coasts of California, Oregon, Washington: Past, present, and future*. The projected values were added to the highest water level observed in Seattle over the last century for 100-year, annual and monthly events to determine potential water levels for different flood intervals. Thus, the flood levels shown on the map (Figure 57) are a combination of the above average daily high tide (also referred to as the mean higher high water (MHHW)) and the projected SLR, illustrated in Figure 56. The analysis uses NAVD88 as the base vertical datum, and MHHW is currently 9ft, so the projected water levels are 11-14ft above the city's base vertical datum. For context, the National Geodetic Survey Benchmark (for tidal station 9447130) is set 3ft above the sidewalk in the granite cornerstone of the National Building at the NE corner of the intersection of Western Ave and Madison Street in downtown Seattle. The elevation of the disk is 19.26ft above 0ft NAVD88.[107]

FREQUENCY	NOW	2035		2060	
	A Water Level*	B Projected Sea Level Rise	C = A + B Water Level	D Projected Sea Level Rise	E = A+D Water Level
100 Yr Storm (Surge)†	3'	1'	4'	2'	5'
Annually	2'	1'	3'	2'	4'
Monthly	1'	1'	2'	2'	3'
Daily	0	1'	1'	2'	2'

** Above average daily high tide (MHHW)*

† Current projections do not show a change in storm surge as a result of sea level rise.

Projected water levels associated with different flood intervals based on National Research Council 2012 data and observed water levels over the last century in Seattle. Data are rounded for ease of use.

Figure 56. Overview of Seattle's coastal flooding projections for 2035 and 2060, which combines the MHHW and future SLR. Source: GGLO Design.

[107] City of Seattle. 2014. Standard Plans for Municipal Construction. Available from https://www.seattle.gov/util/cs/groups/public/@spu/@engineering/documents/webcontent/01_029210.pdf Accessed on 5/15/2017.

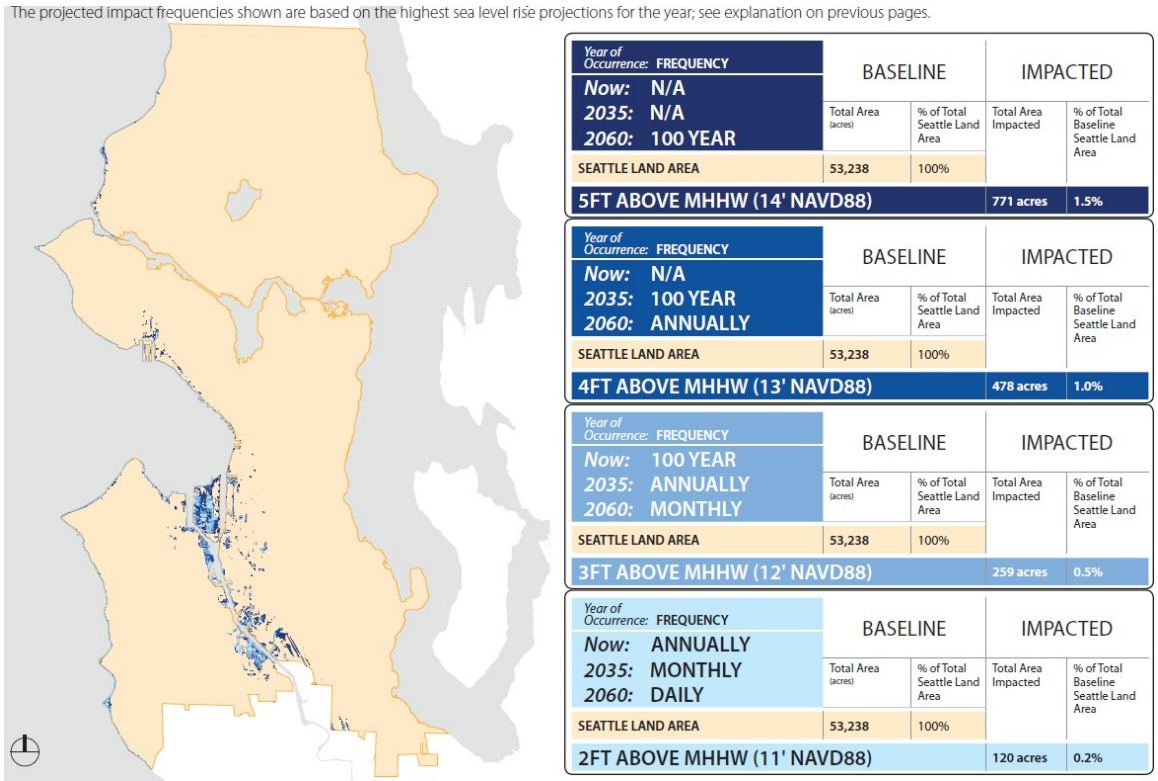


Figure 57. Overview of the areas affected by coastal flooding (the combination of SLR and high tides). Each inundation level (2-5ft) describes the frequency of occurrence and total land area affected. Source: GGLO Design.

Figure 58 combines the areas already identified at risk for urban and riverine flooding, as well as those that are potential heat islands, with those affected by coastal flooding to provide a climate change process model. Note that drought and wildfire risk are not included; however, the city is also planning for these issues, particularly in the water supply watersheds, as well as in the selection and maintenance of urban forests, street trees, and landscaping.

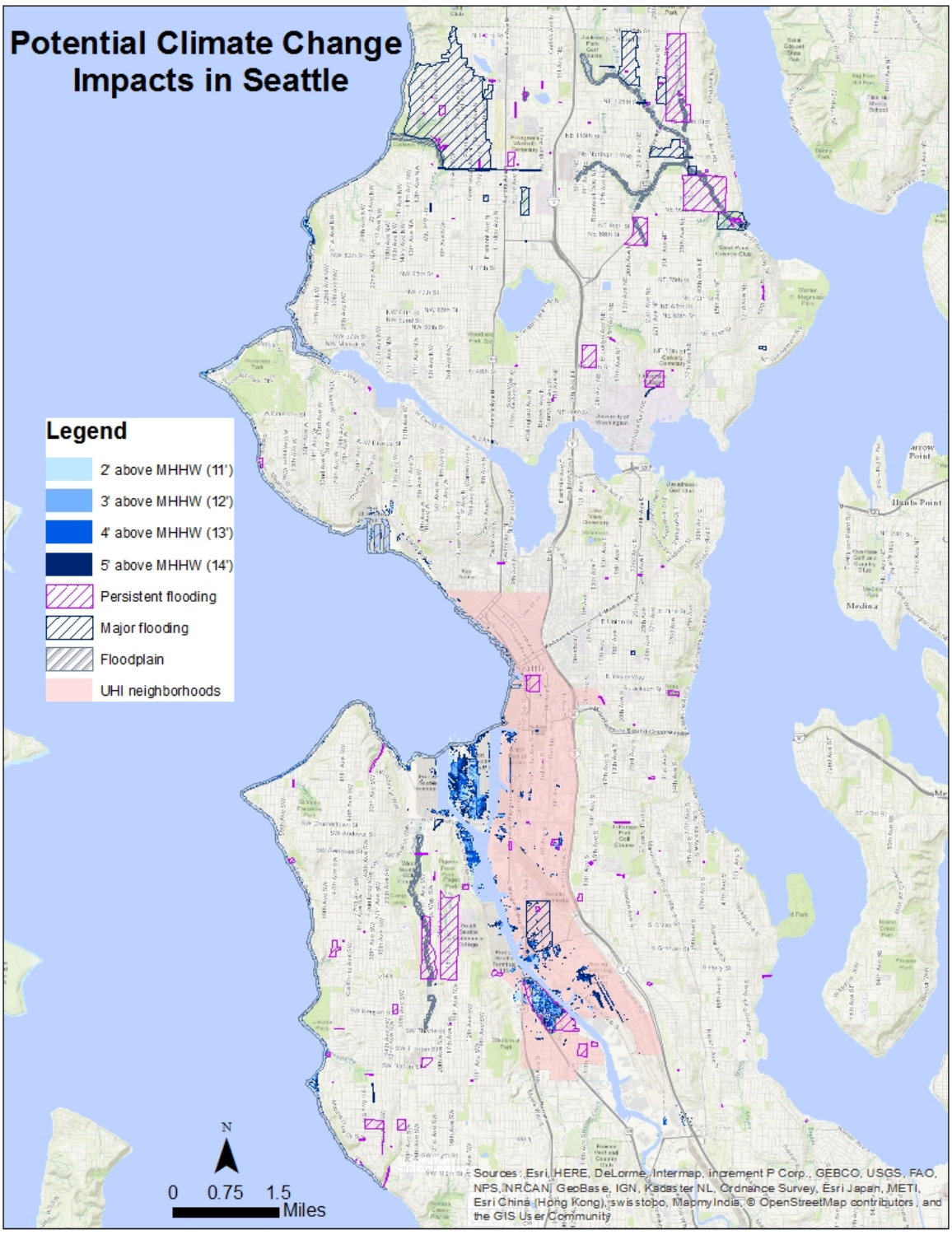


Figure 58. Potential areas affected by climate change. As expected, there are some areas of overlap between current floodplains, and areas that experience urban flooding as well as potential coastal flooding. Map source: author, data source: City of Seattle and GGLO Design.

Table 14 summarizes the land area affected by current and potential flooding, and identifies areas of overlap between different types of flooding. The areas identified in the climate change process model are added to other system evaluation models when evaluating their vulnerability or attractiveness for development.

Table 15. Summary of Seattle land area affected by different types of flooding.

Issue	**Total/Percent Land Area**
Floodplains	388 acres / 0.73%
Urban Flooding	2609 acres / 4.9%
Coastal Flooding (SLR)	**5' 100 year in 2060:** 771 acres / 1.5% **4' 100 year in 2035, annually in 2060:** 478 acres / 1.0% **3' 100 year now, annually in 2035:** 259 acres / 0.5% **2' now annually, daily in 2060:** 120 acres / 0.2%

It is notable that the city's climate preparedness strategy emphasizes three priorities:

- Equity – Reduce risk and enhance resilience in "frontline communities", e.g. communities of color, lower income communities, immigrant and refugee communities, disable residents and seniors.
- Co-benefits – Enhance physical spaces and services in ways that support "quality/livable urban environments, health and social cohesion."
- Natural Systems – Use nature-based solutions that "leverage ecosystem services and foster natural systems resilience"[108]

All three of these priorities are integral to the research presented herein, and are supported by the geodesign planning approach.

[108] Seattle OSE. 2016. Preparing for Climate Change (Draft). Available from http://www.seattle.gov/environment/climate-change/planning-for-climate-impacts. Accessed on 5/11/2017.

4.3 Evaluation Models

As discussed in Section 3.3, the evaluation models assign a level of *vulnerability to* or *attractiveness for* development for each system of interest. The evaluation models are based on the process models, and the evaluation criteria are derived from the second iteration decision models (Table 5). Depending on the evaluation criteria (Table 16), the colors green, yellow or red are assigned to each record in each feature used for the system's evaluation model, which serve as the raw input to the Evaluation Model Simplification Toolkit developed by John Ritzman for the 2015 UW Geodesign Workshop (Nyerges et al. 2016). The toolkit was initially designed to reduce the size of feature classes covering a large geographic area so that they could be processed by the Geodesignstudy.com platform. However, the toolkit is also useful for combining multiple feature classes to be used in the evaluation, and resolving conflicts between overlapping or conflicting feature boundaries. For vulnerable systems, the feature priority is red>yellow>green, and the order is reversed for the attractive systems. Figure 59 illustrates the evaluation models developed for each system described in Table 16.

Table 16. Evaluation model descriptions and criteria.

Evaluation Models

To Be Sustained/Vulnerable Systems - Evaluated By Risk To System From 'To Be Developed' Systems		
System 1. Habitat		
Habitat areas designated by City of Seattle, including parks larger than .25 acres per SPR park classification; non-habitat areas differentiated by land cover.		
Low Risk	Medium Risk	High Risk
NLCD highly developed land: · Developed (Medium Intensity) · Developed (High Intensity)	Shoreline, Parks > .25 acres, NLCD developed open space (<20% impervious), NLCD low intensity development (20-49% impervious)	Priority habitats and species areas
System 2. Wetlands		
Wetlands designated by the City of Seattle, note the city's wetland delineation is more detailed than the NLCD so it is not necessary to use.		
Low Risk	Medium Risk	High Risk
Areas that are not a wetland	Wetlands that are not considered priority habitat	Wetlands within priority habitat areas

System 3. Floodplains and Flood Prone Areas		
FEMA designated floodplains, areas prone to urban flooding.		
Low Risk	Medium Risk	High Risk
Not a floodplain	Floodplains that are not habitat	Floodplains that are habitat or areas prone to urban flooding, areas projected to be inundated due to climate change (2'-5' above MHHW)
System 4. Riparian/Shoreline Zones		
Areas adjacent to rivers, streams and open water bodies.		
Low Risk	Medium Risk	High Risk
All non-riparian areas	Riparian areas that are not a salmon migration pathway	Riparian areas that are salmon migration pathways
To Be Developed Systems - Evaluated By Attractiveness For Development or Expansion		
System 5. Green Stormwater Infrastructure		
Areas to prioritize GSI retrofits, since the Stormwater Code now requires it for new and replaced impervious surfaces 1500 sqft and greater, or 750 sqft and greater if platted after 1/1/2016.		
Attractive	Marginal	Not Attractive
Areas in a critical CSO or NPDES permit basin, prone to urban flooding, or in a creek basin; NLCD medium and high intensity developed land	Parks - while DPR is implementing GSI when required, there has been resistence to prioritizing GSI over other park uses; NLCD developed open space (<20% impervious), NLCD low-intensity development (20-49% impervious)	Designated habitat, wetlands, and floodplains; P-Patches and farms - all of which help manage stormwater but are not optimized for this purpose.
System 6. Trails		
Future multi-use trails designated in the Bicycle Master Plan.		
Attractive	Marginal	Not Attractive
Part of the city-wide network	Discreet local segment, not connected to city-wide network	Existing trails and non-trail areas
System 7. Parks		
Gaps in accessibility. SPR has mapped over 1000 park access points and determined areas with accessibility gaps using SDOT's walkability network. Accessibility gaps occur outside of a 1/4 mile or 5-minute walk of a park within an urban village, and ½ mile or 10-minute walk outside of an urban village.		
Attractive	Marginal	Not Attractive
Gaps in 16 urban villages prioritized by SPR, described in the 2017 Parks and Open Space Plan (May Draft), gaps in Georgetown outside of an urban village, gaps intersecting priority habitat areas	Gaps within the city's other 14 urban villages, gaps outside of urban villages	Existing parks, open water, non-gap areas
System 8. Forests/Tree Canopy		
Areas where tree canopy should be increased.		
Attractive	Marginal	Not Attractive
Management units not meeting canopy goals, areas affected by the UHI, riparian/shoreline zones, areas adjacent to existing tree groves and large trees, areas in socially vulnerable census tracts (>26% population below poverty level)	ROW (limited space for large trees, conifers, tree groves)	Existing tree and tree groves, note: that these should be maintained and trees should be planted adjacent to these if possible, open water
System 9. Urban Agriculture		
Publicly-owned parcels identified in Growing Green community garden suitability analysis. Climate change induced sea level rise (2ft and 3ft) also considered (occuring annually or monthly through 2035); however, no parcels were located potentially inundated areas.		
Attractive	Marginal	Not Attractive
Parcels in socially vulnerable census tracts (> 26% population below poverty level)	Remaining parcels throughout Seattle	Non-suitable parcels from Growing Green analysis

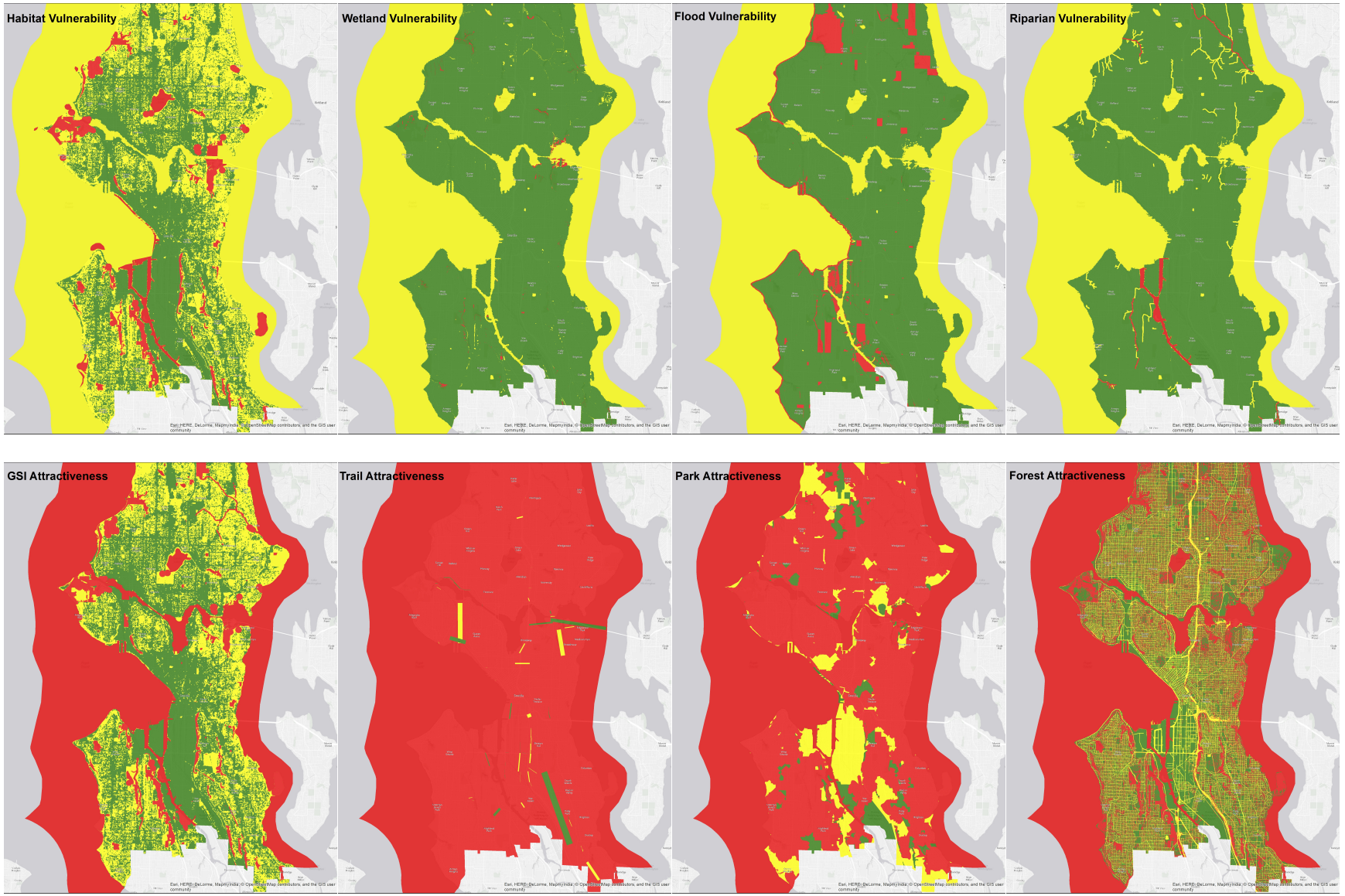


Figure 59. Evaluation models for green infrastructure systems which are vulnerable to and attractive for development. Note, the agriculture system is not pictured because the individual parcels, which are attractive for food production, are not visible at the city scale. Map source: author.

4.4 Change and Impact Models

In this step, change and impact models will be considered concurrently. Both utilize the evaluation models, and both draw from the overlay methods formalized and described by Jacqueline Tyrwhitt in Chapter 7 of the *Town and Country Planning Textbook* (1950), which she also edited, and popularized for suitability analysis by Ian McHarg in *Design with Nature* (1967), both of whom were influenced by Scottish botantist and bio-regional planner Patrick Geddes (Shoshkes 2013, Spirn 1985). Geddes proposed "place-work-folk" as an organizing concept for regional planning in 1915, and contributed to the broader theoretical discourse on the relationship between people and the natural environment, recognizing that "The types of people, their kinds of styles of work, and the whole environment become represented in the community, and these react upon the individual, their activities, and their place itself." (Ndubisi 1997, 13-15). Fifty years before him, geographer George Perkins Marsh expressed his alarm at the extent of environmental degradation stemming from industrialization in *Man and Nature, or Physical Geography as modified by Human Action* (1864). He was an early proponent for designing with nature and, as a geographer, implicitly, for geodesign: "in reclaiming and reoccupying lands laid waste by human improvidence and malice…the task...is to become a co-worker with nature in the reconstruction of the damaged fabric" (Spirn 1985, 42).

In this vein, Tyrwhitt, one of the first graduates (in 1939) of the School of Planning and Research for National Development (SPRND) at the Architectural Association in London and later director (1941-1948) of the Association for Planning and Regional Reconstruction (APRR), the research arm of SPRND, sought to develop multi-disciplinary survey methods

and visualization and mapping techniques to explore the interactions between planning, industry, agriculture and nutrition, population, housing and recreation, health and education, and uses for waste (Shoshkes 2013). The goal of the APRR was to apply Geddes' ideas to post-war reconstruction and to standardize information across specializations to create the 'composite mind'- SPRND founder E.A.A. Rowse's metaphor for the shared intelligence needed for comprehensive and collaborative regional planning espoused by his mentor Geddes (Shoshkes 2013).

The manual overlay method (also referred to as sieve-mapping) detailed by Tyrwhitt had precursors in American landscape architecture and was described in the biography *Charles Eliot, Landscape Architect* (1902). Eliot, partner in Olmsted, Olmsted and Eliot, and his apprentice Warren Manning used the approach (initially 'sun-prints', taped to the office windows) for designing the Boston Metropolitan Park (Steiner 2008). Manning later collected hundreds of national maps, had them redrawn to the same scale, and using the overlay technique and a light table, created a landscape plan for the entire continental US in 1923 (Steinitz 2012). Tyrwhitt, however, provided the theoretical explanation for using the technique in planning. McHarg, who took a APRR correspondence course offered by Tyrwhitt and was involved in new town planning in Scotland in the 1950s, evolved the overlay method by photographing each map layer and creating transparent prints of light to dark values, which could be overlain to develop an X-ray-like composite land use suitability map (Steiner 2008), where light = suitable, least cost and dark/black = not suitable, highest cost (Figure 60).

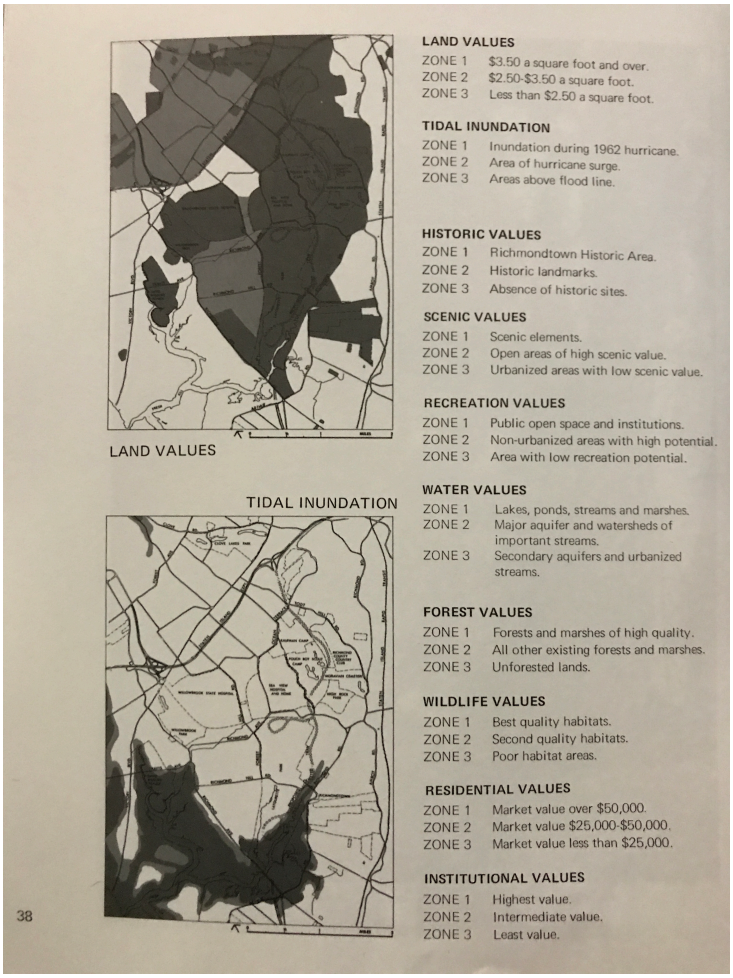
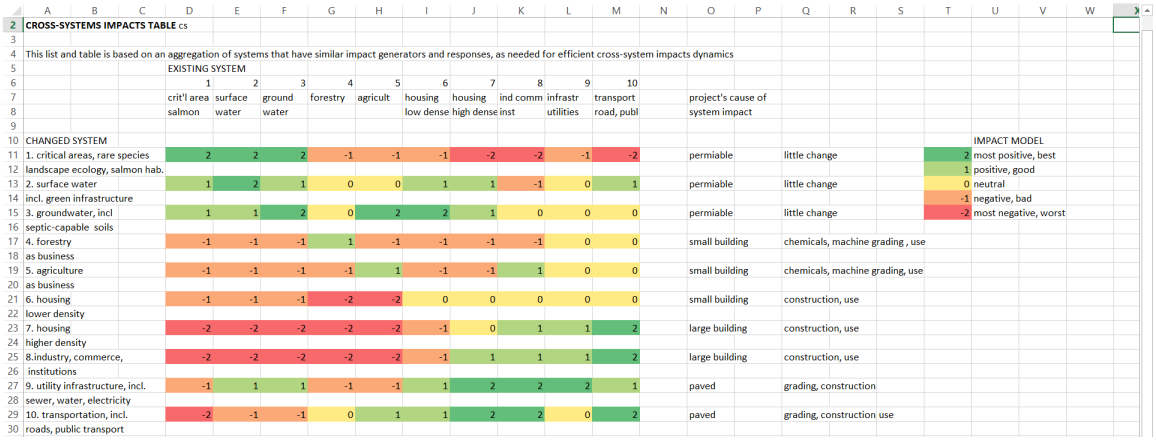


Figure 60. Excerpt from the individual map layer classification and suitability representation used by McHarg to determine the Richmond Parkway highway route "that provides the maximum social benefit at the least social cost (1992, 32).

He also emphasized social processes and values, and felt these values could be applied to all other dimensions: physiographic, ecological, and economic – likely driven by the nature of the subject of analysis to which he first applied the overlay analysis – highway corridor alignment. McHarg laments "Who are as arrogant, as unmoved by public values and concerns as highway commissioners and engineers? …Give us your beautiful rivers and scenic valleys, and we will destroy them: Jones Falls in Baltimore, the Schuylkill River in Philadelphia, Rock Creek in Washington…Give us your cities, your historic areas and buildings, their precious parks, cohesive neighborhoods, and we will rend them – in New Orleans and Boston, and Francisco and Memphis." (1992, 31). He contends that highways "can no longer be considered only in terms of automotive movement within its right of way, but in the context of the physical, biological and social processes within its area of influence" since they are

“a major public investment, which will affect the economy, the way of life, health and visual experience of the entire population within its sphere of influence.” (1992, 32).

The evaluation and impact models used in the Steinitz geodesign method disaggregate the information presented in McHarg’s suitability layers. The evaluation models assess the intrinsic quality of the system of interest, independent of a particular type of change, and the impact models numerically characterize change risk or attractiveness for each system. Steinitz also uses impact models to explore cross-system dynamics. For the 2015 UW Geodesign Workshop, he assigned a range from -2 to +2 to the cross-system impacts between each pair of the ten systems considered in the watershed-based growth management study (Figure 61). Note, the ordinal scale allows the same impact range to be applied to all systems so they can be combined in change models.



CROSS-SYSTEMS IMPACTS TABLE cs

This list and table is based on an aggregation of systems that have similar impact generators and responses, as needed for efficient cross-system impacts dynamics

	EXISTING SYSTEM												
	1	2	3	4	5	6	7	8	9	10			
	crit'l area salmon	surface water	ground water	forestry	agricult	housing low dense	housing high dense	ind comm inst	infrastr utilities	transport road, publ	project's cause of system impact		
CHANGED SYSTEM													IMPACT MODEL
1. critical areas, rare species landscape ecology, salmon hab.	2	2	2	-1	-1	-1	-2	-2	-1	-2	permiable	little change	2 most positive, best
													1 positive, good
2. surface water incl. green infrastructure	1	2	1	0	0	1	1	-1	0	1	permiable	little change	0 neutral
													-1 negative, bad
3. groundwater, incl septic-capable soils	1	1	2	0	2	2	1	0	0	0	permiable	little change	-2 most negative, worst
4. forestry as business	-1	-1	-1	1	-1	-1	-1	-1	0	0	small building	chemicals, machine grading , use	
5. agriculture as business	-1	-1	-1	-1	1	-1	-1	1	0	0	small building	chemicals, machine grading, use	
6. housing lower density	-1	-1	-1	-2	-2	0	0	0	0	0	small building	construction, use	
7. housing higher density	-2	-2	-2	-2	-2	-1	0	1	1	2	large building	construction, use	
8.industry, commerce, institutions	-2	-2	-2	-2	-2	-1	1	1	1	2	large building	construction, use	
9. utility infrastructure, incl. sewer, water, electricity	-1	1	1	-1	-1	1	2	2	2	1	paved	grading, construction	
10. transportation, incl. roads, public transport	-2	-1	-1	0	1	1	2	2	0	2	paved	grading, construction use	

Figure 61. Example of a cross-system impact model. Source: Carl Steinitz, 2015 UW Geodesign Workshop.

This study also uses a negative to positive ordinal impact scale; however, the system impacts are computed as a part of the overlay process rather than being set in advance, and encompass multiple system interactions rather than pairwise relationships. Systems that are

attractive for development (GSI, trails, parks, forest/tree canopy, urban agriculture) are assigned positive values, while systems that are vulnerable are assigned negative values. Areas where multiple vulnerable systems overlap have a higher negative impact score, and will reduce the positive impact of incompatible green infrastructure uses. For example, if the expansion of a system is proposed (e.g. GSI) into an area that is highly vulnerable (e.g. priority habitat in a wetland within a floodplain), that change will have a lower positive impact score than an area where there are no vulnerable systems.

Table 17 summarizes the range of impact values assigned to the evaluation categories for each system. These values are assigned based on the departmental requirements (Table 5) used for each model's evaluation criteria. Note, medium risk/marginal attractiveness is differentiated by whether the requirement is encoded in a city ordinance, part of a funded program or currently just an aspirational goal. The highest ranked criteria at both ends of the scale are those driven by regulations set at a higher jurisdictional level.

Table 17. Green infrastructure system impact values.

Impact Value	Evaluation Category	Department Requirements (Table 5): Priority and Source (Law, Ordinance, Program, Aspiration)
3	Attractive	High Priority – Law
2	Marginal	Medium Priority – Ordinance, Program
1	Marginal	Low Priority - Aspiration
0	Not Attractive	None
0	Low Risk	None
-1	Medium Risk	Low Priority - Aspiration
-2	Medium Risk	Medium Priority – Ordinance, Program
-3	High Risk	High Priority - Law

It is clear from the department requirements summarized in Table 5 that not all green infrastructure systems are afforded the same importance or resources, in part due to the types of requirement drivers and in part due to the number of departments involved in some

aspect of the system's implementation or protection. To reflect this variability in the impact models, an additional multiplier has been included in the impact calculations based on the number of requirements for each system across all departments (Table 18).

Table 18. System impact multipliers.

System	Multiplier (Figure 29)
Habitat	6
Wetlands	2
Floodplains and Flood Prone Areas	2
Riparian/Shoreline Zones	3
GSI	7
Trails	1
Parks	2
Forest	6
Urban Agriculture	4

While GIS is instrumental in all modeling phases, it is especially useful for the impact models and calculations. Each evaluation model (a composite feature class) can be converted to a raster with the same size cells (10sf in this case, but that is determined by the size of the study area and scale of analysis), and then the impact value for each evaluation category (base x multiplier) can be assigned to each cell that falls within that category. The 'raster calculator' can then be used to overlay all of the relevant systems and calculate the change impacts of interest. Although the change models precede the impact models in the third iteration, the systems have to be initialized with impact values before changes are made. Figure 62 provides a combined overview of the vulnerable systems considered in this study. The sum of the system impact values for the different evaluation categories (highest to lowest possible range) were used to classify risk.

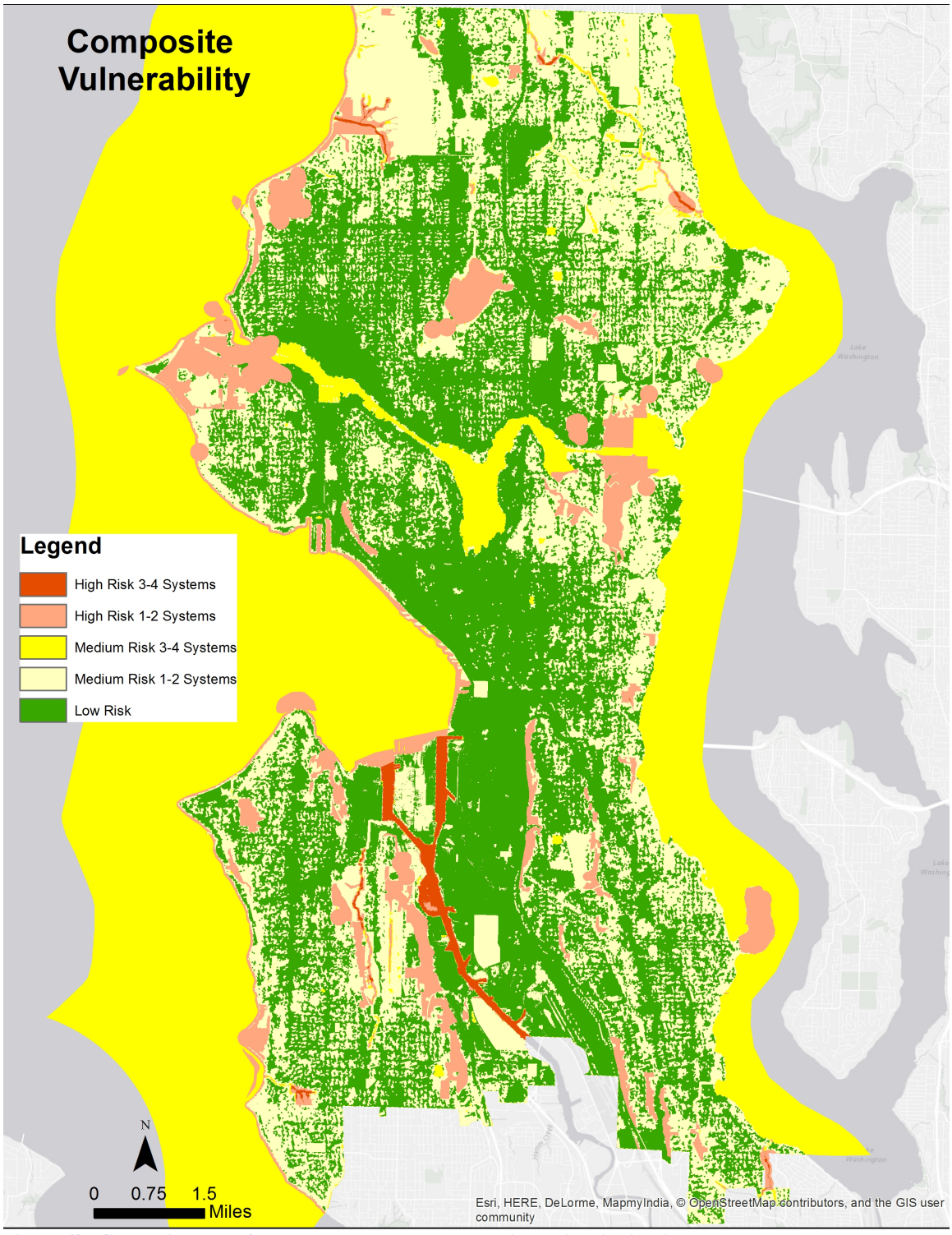


Figure 62. Composite map of all vulnerable systems and their spatial distribution. Map source: author.

Before exploring the change and impact models, it is also useful to consider the cross-compatibility between green infrastructure systems vulnerable to and attractive for change, in the vein of McHarg who employed an "intercompatibility matrix" (Figure 63) when analyzing a landscape for multiple compatible land uses (1992, 144). The impact values that result from the weighted overlay show similar trends, but this overview (Table 19) is helpful to identify potential conflicts and synergies before developing the change models.

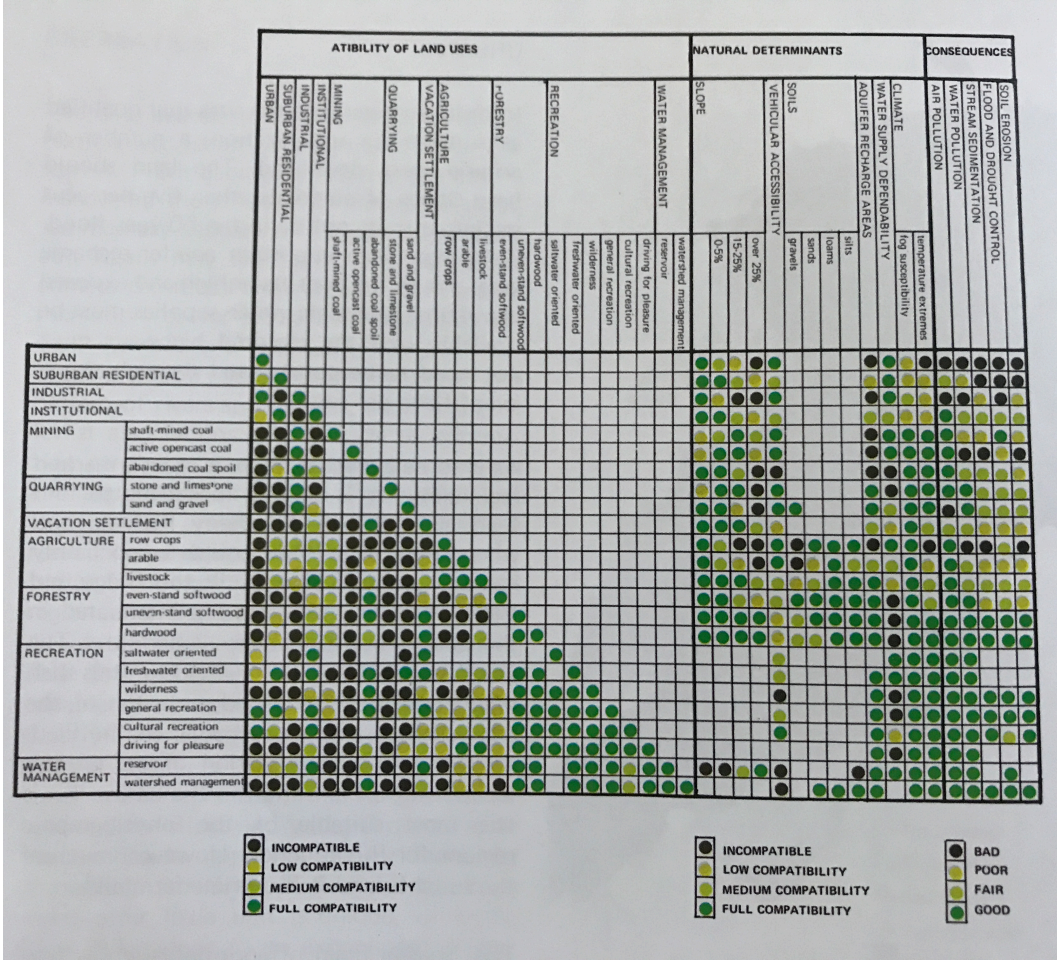
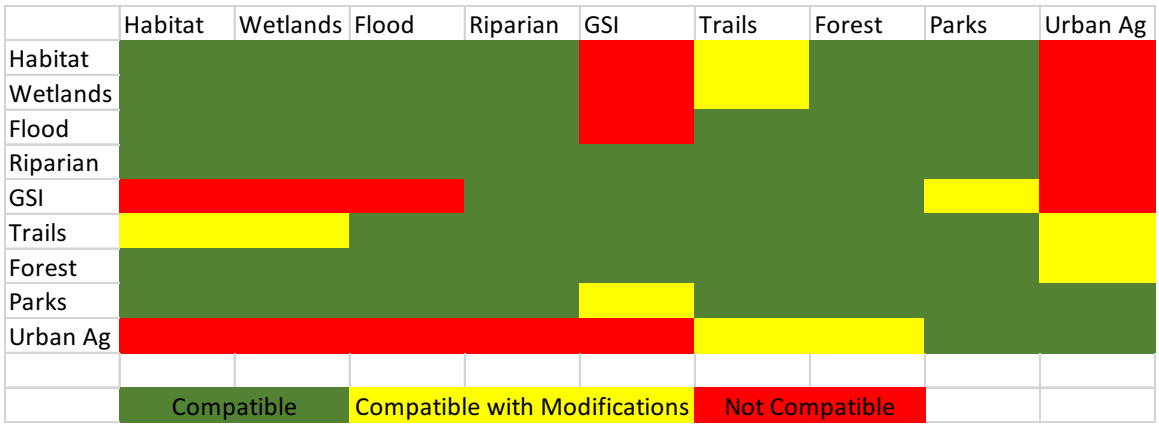


Figure 63. McHarg's intercompatibility land use matrix (1992, 144).

The vulnerable systems largely overlap; floodplains and wetlands are in riparian zones and are the habitat of priority species: bald eagles, great blue heron, waterfowl, California sea lions, salmon. Systems attractive for expansion like forests and parks are compatible and

often coincident with the vulnerable systems. Others, like trails can be integrated in vulnerable systems but negative impacts from their construction and use must be managed. Urban agriculture and GSI should not be integrated due to nutrient and pollutant loading (although GSI can be beneficial in riparian zones that are not habitat or natural wetlands, and also beneficial in the same hydrologic basin as flood prone areas, habitat and wetlands). Parks can accommodate GSI, but SPR has resisted using park space for permanent stormwater management utilities beyond the stormwater code requirements[109] (a topic not addressed in the EPA's recently published "Green Infrastructure in Parks: A Guide to Collaboration, Funding and Community Engagement"[110]), thus parks received low priority in the stormwater project selection process used when developing the 'Integrated Plan' alternative for Seattle's CSO consent decree.[111]

Table 19. Cross-system compatibility matrix.



[109] David Graves, SPR Senior Planner. 2013. Email to Betty Meyer, SEPA Responsible Officer for SPU. Excerpts included in Appendix A Scoping Summary Report available from https://www.seattle.gov/UTIL/cs/groups/public/@spu/@drainsew/documents/webcontent/01_030103.pdf. Accessed on 10/7/2013.

[110] EPA. 2017. Green Infrastructure in Parks: A Guide to Collaboration, Funding and Community Engagement. Available from https://www.epa.gov/sites/production/files/2017-05/documents/gi_parksplaybook_2017-05-01_508.pdf. Accessed on 9/16/2017.

[111] City of Seattle. 2015. Volume 3 Integrated Plan Appendices (Appendix C). Available from http://www.seattle.gov/util/cs/groups/public/@spu/@drainsew/documents/webcontent/01_030104.pdf. Draft accessed on 10/7/2013.

The cross-system compatibility matrix helps clarify which change models need to be developed. Since GSI and urban agriculture are the primary systems where conflicts with vulnerable systems and with each other occur, these are the most important to explore. Potential conflicts between GSI and parks also require analysis, although park policies can be adapted to increase GSI.

4.4.1 GSI and Urban Agriculture

For the purposes of this analysis, which is based on ground-level rather than rooftop urban agriculture, GSI and urban agriculture are considered mutually exclusive. Like any pervious surface, urban agriculture does mitigate the volume of stormwater runoff leaving the site; however, garden plots are not planned and optimized to receive catchment-wide runoff (Figure 64), nor should they be due to the wide range of pollution found in urban runoff (Table 20). Also, as discussed in section 2.3.2, the compost-amended soils and organic fertilizers used for gardening are themselves a source of nutrient-loading that needs to be managed to protect surface water quality (Pimentel et al. 2005, The Freshwater Society 2013), which is likely the reason that Horst's Growing Green suitability analysis excluded parcels with streams or wetlands.

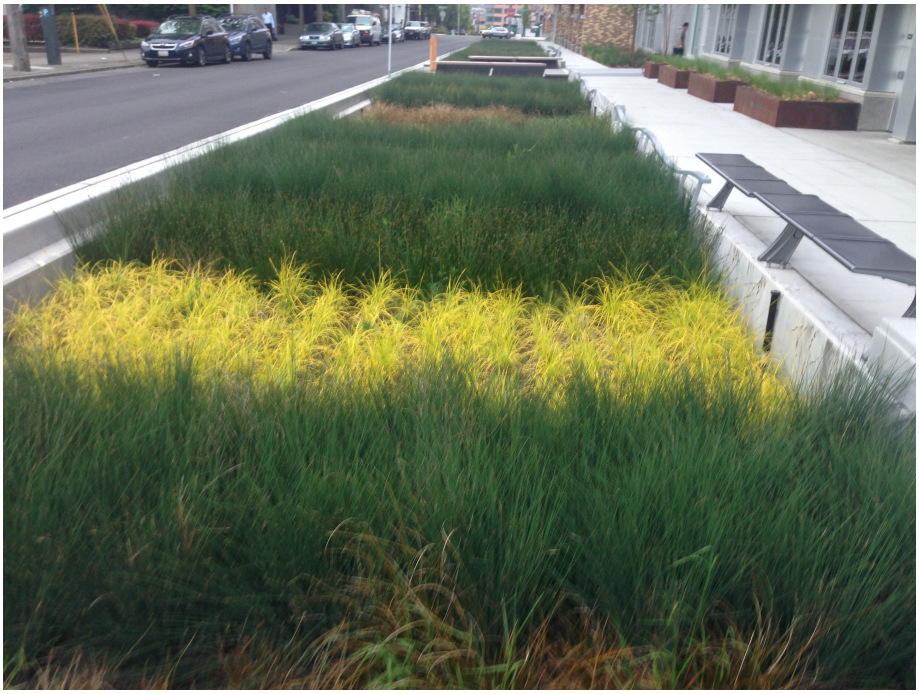


Figure 64. The Swale on Yale is an $11M biofiltration system in South Lake Union that will consist of four biofiltration swales, a pre-treatment swirl concentrator, a diversion vault, and 2000ft of new storm drain when completed. Two swales were completed in 2013, and two more will be constructed 2017-2018 after two years of monitoring and possible design modifications. The system will treat an average of 190 million gallons of runoff from 630 acres annually in one of the most densely urbanized areas of the city. Each swale is 270-feet long by 10.5 to 16.5-feet wide. The diversion vault is a large underground tank that diverts the stormwater into the biofiltration swales. The swirl concentrator spins the stormwater to create a vortex, which separates large solids and trash into a sump that has to be cleaned regularly.[112] Image source: author.

Table 20. Typical stormwater runoff pollutants and sources.[113]

Pollutant Type	Examples	Common Sources
Metals	Zinc, cadmium, copper, chromium, lead	Industrial waste, roofs, automobile parts and fluids
Nutrients & Biochemical Oxygen Demand (BOD)	Nitrogen, phosphorus	Grass clippings, fallen leaves, fertilizers, farm-animal waste, faulty septic systems

[112] City of Seattle. 2013. Swale on Yale – Capitol Hill Water Quality. Availabe from http://www.seattle.gov/util/EnvironmentConservation/Projects/SwaleonYale/index.htm. Accessed on 10/3/2017.

[113] Minnesota Stormwater Manual. 2014. *Pollutant fate and transport in stormwater infiltration systems*. Available from https://stormwater.pca.state.mn.us/index.php?title=Pollutant_fate_and_transport_in_stormwater_infiltration_systems. Accessed on 9/24/2107.

Pathogens	Viruses, bacteria, protozoa	Domestic sewage, animal waste
Polycyclic Aromatic Hydrocarbons (PAHs)	Compounds found in soil, and also created by the incomplete combustion of organic chemicals	Auto emissions, elicit discharges, asphalt, coal tar sealants
Sediment	Sand, soil, and silt	Grading, construction, vegetation removal
Salts	Sodium chloride, calcium chloride	Road salt, fertilizer
Volatile Organic Compounds (VOCs)	Large group of carbon-based chemicals that easily evaporate at room temperature	Crude oil, insecticides, varnishes, paints, gasoline products, degreasers

Since the two systems are considered mutually exclusive, overlaying their impact models indicates where conflicts exist based on the sums of their unique impact values (Figure 63). Areas with the highest impact values are optimal for both, and other combinations show which areas are optimal for GSI and marginal for urban agriculture and vice versa, as well as which areas are marginal and not attractive for both (which means other GI like forests/tree canopy could be prioritized). Since the urban agriculture parcels considered in this analysis have such a small footprint (44 parcels for a total of approximately 526,000sf or 12 acres), the decision could be made to always prioritize food production; however, the city's Green Goal and USEPA CSO consent decree could shift the priority to GSI. Overlaying the two systems reveals that 63,900sf (1.5acres) are optimal for both; 101,700sf (2.3acres) are optimal for GSI and marginal for urban ag; 37,800sf (.9acres) are optimal for urban ag and marginal for GSI; and 68,700sf (1.6acres) are marginal for both.

Figure 65. Intersection of GSI and urban agriculture. Map source: author.

4.4.2 Urban Agriculture and Vulnerable Systems

When evaluating parcels suitable for urban agriculture, Horst excluded those with wetlands or streams immediately on the parcel, which will avoid conflicts with two of the vulnerable systems. While floodplains and habitat overlap with these areas, their extent is often larger, so need to be considered separately. In the case of habitat, there are no overlaps with the highest risk areas, and since the marginal risk areas are not designated habitat, just amenable to it due to low levels of impervious surfaces, agriculture can be prioritized. A nominal area of the suitable parcels lies in flood prone areas, 12,200sf, and can be eliminated to prevent both destruction to the gardens and water pollution from their nutrient-rich soils.

Hydrologic connectivity with aquatic habitat areas also needs to be considered, since nitrogen and hydrogen combine to create ammonia, which is extremely toxic to fish, mussels and benthic macroinvertebrates (The Freshwater Society 2013). The city's shoreline code (23.60A.190.J) prohibits the application of pesticides, herbicides and synthetic fertilizers within 200 feet of wetlands, riparian watercourses, and other water bodies. It also states that organic fertilizers should be hand mixed with ingredients that reduce their solubility. A 200-foot buffer applied to the shoreline and streams shows that none of the suitable parcels are located within these areas.

4.4.3 GSI and Vulnerable Systems

GSI is generally suited for all land uses and can be designed to work within most physical contexts. However, it is designed to collect pollutants, sediment and inevitably trash, thus it is not appropriate directly within sensitive areas like habitat, natural wetlands,

floodplains, P-Patches and farms - all of which were included in the evaluation model as ‘not attractive’ for GSI. The change model broadens the analysis to also address hydrologic connectivity with these systems. However, unlike urban agriculture, well-designed GSI should clean stormwater before it reaches the vulnerable systems, and is desirable in the same drainage basins. Figure 66 highlights those drainage basins with outfalls upstream from or directly discharging to aquatic habitats, or stream-based salmon migration routes. The neighborhoods prioritized for NDS overlap many of these basins.

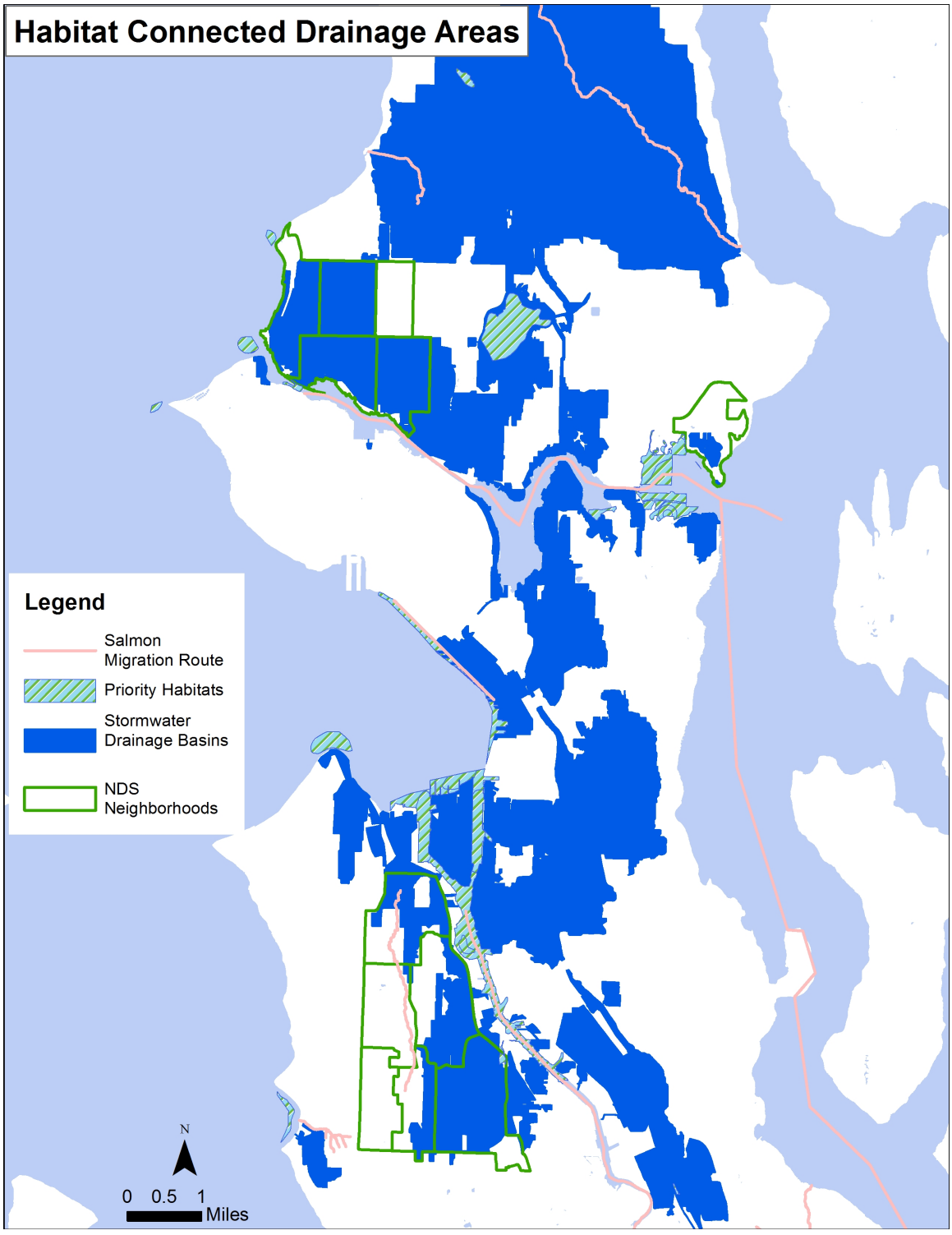


Figure 66. Stormwater drainage basins that impact aquatic habitat and salmon migration routes. Map source: author, data source: City of Seattle.

4.4.4 GSI and Parks

The areas identified by SPR's open space gap analysis accounted for many urban design aspects of walkability, but did not discount private property and buildings, which means that some of the areas identified for future park development may not actually be available. GSI, on the other hand, can be integrated into the streetscape, incentivized on private property, or even included in the park landscape if SPR's concerns about stormwater utility siting can be addressed:

> Shoreline parks are not "free" land within which to site utilities. Shoreline parks are a precious commodity; a finite resource. Free and open access to the shores of Lake Washington and Puget Sound is a necessary component of sustainable urban living in Seattle. The ability of a shoreline park to provide a variety of active and passive recreational opportunities is paramount. Siting a utility in a park limits the park's adaptability for future needs, both of people and the environment.
>
> Parks' central concern is that the placement of a CSO facility within Park's property forever constrains the use of this area, regardless of whether or not it is under paved and/or unprogrammed areas. Parks will be forever precluded from changing the use of the site to provide a different park amenity and/or recreational opportunity due to the underlying utility facility.[114]

It should be noted that the lifecycle costs for the CSO storage tanks and pipes are calculated for 100 years, and the NDS projects have a projected 50-year lifespan.[115] Although stormwater infrastructure will not, in fact, last "forever", if SPR's perspective remains unchanged, there are large areas of overlap and potential conflict between future parks and GSI: 956,210,000sf (2195.2 acres) are optimal for both; 234,707,700sf (5388.1 acres) are optimal for GSI and marginal for parks; and 16,881,800sf (387.6 acres) are optimal for

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[114] David Graves, SPR Senior Planner. 2013. Email to Betty Meyer, SEPA Responsible Officer for SPU.
[115] City of Seattle. 2015. Volume 3 Integrated Plan. Available from http://www.seattle.gov/util/cs/groups/public/@spu/@drainsew/documents/webcontent/01_030099.pdf. Accessed on 9/30/2017.

parks and marginal for GSI (Figure 67). Areas where SPR interests and stormwater management converge, such as urban flood zones and LTCP-deferred combined sewer basins that discharge to shoreline areas, could provide opportunities for cooperation since neither flooding nor sewer overflows are conducive to the recreation opportunities SPR seeks to protect, Figure 68 illustrates these spatial relationships; however, none of the area corresponding to the deferred basins and just a small fraction of the urban flood zones are optimal for both (3,983,800sf (91.5acres)), so a different basis for decision-making is needed that includes other GI priorities and will be addressed in the next section.

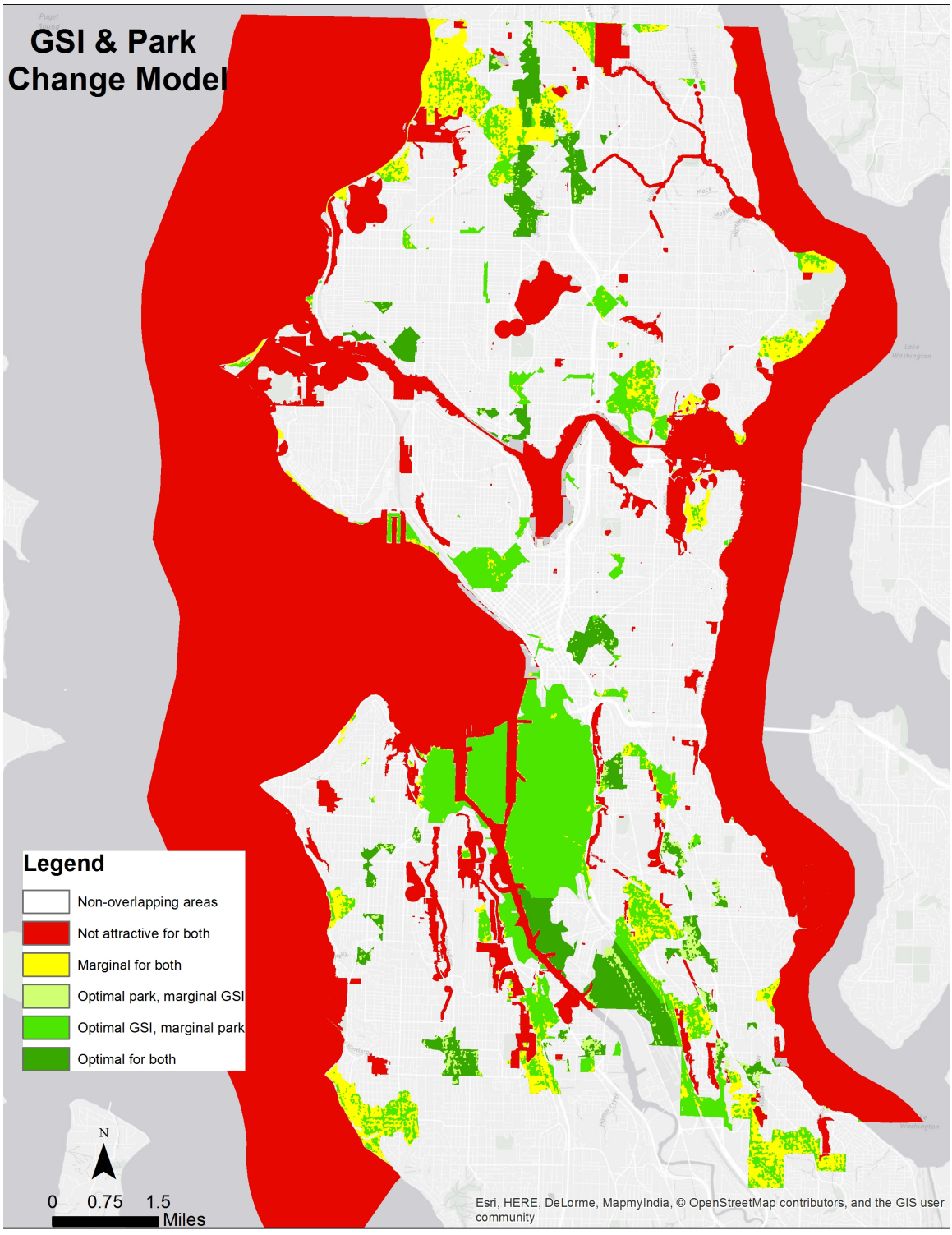

Figure 67. Intersection of GSI and parks. Map source: author.

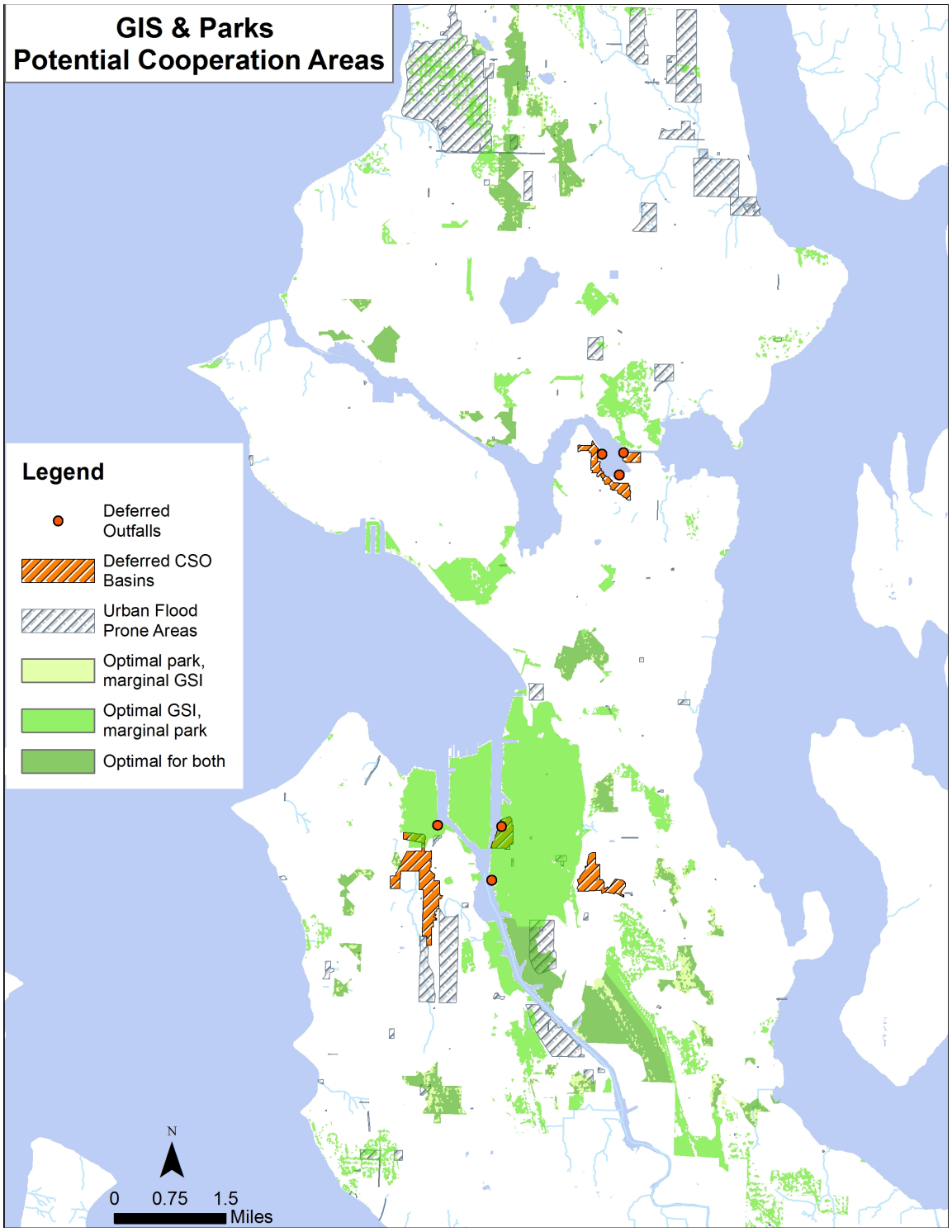

Figure 68. Areas where stormwater management could benefit future park development. Map source: author.

4.4.5 Impacts Refined: System Development Targets

The previous sub-sections analyzed cross-system impacts to highlight potential conflicts between systems that are attractive for development, and to ensure that risk to vulnerable systems is minimized. The cross-system impact analysis confirmed that there are overlapping areas that are attractive for incompatible GI uses. To recap:

- **GSI and Urban Agriculture -** Of the 44 parcels, 12 acres identified in Horst's Growing Green analysis, only 1.5 acres are optimal for both GSI and urban agriculture, 0.9 acres optimal for urban ag, 0.28 acres of which are in a flood prone area, leaving 0.6 acres. For comparison, the largest urban farm is 8 acres (Rainer Beach), and smallest is 0.37 acres (Yesler).
- **GSI and Parks -** Over 2000 acres are optimal for both GSI and parks, 388 acres are optimal for parks and marginal for GSI, and 5,388 acres are optimal for GSI and marginal for parks. To put these numbers in perspective, the Swale on Yale GSI (Figure 64) is approximately 13,500sf or 0.3acres, and is designed to treat 190MG of stormwater annually.

One approach to making choices between systems is to review the development targets for each system and determine if these can be satisfied first by the land available in non-conflict areas. If that is not the case, additional change models, essentially scenarios, need to be developed that represent different target fulfillments as advised by Steinitz: "When there are numerous requirements or objectives, and some of the more significant ones and their options are in conflict, the study will need to generate and communicate alternative futures for the geographical study area which reflect these varied positions" (2012, 48).

While departmental requirements (Table 5) related to each system informed the assessment of risk or attractiveness in the evaluation models, and the importance of the requirements (i.e. legally mandated versus aspirational) further weighted by the frequency of the requirement across different departments provided the basis for the cross-system impact models, development targets are a guide to the future. Table 21 summarizes the development targets described in several planning documents including the 2014-2019 CIP budget, 2017 Parks and Open Space Plan, 2013 Urban Forest Stewardship Plan, Street Tree Maintenance Plan, Seattle Bicycle Master Plan 2017-2021 Implementation Plan, Food Action Plan, and P-Patch Community Gardening Program Parks and Green Spaces Levy Update. Note that although DPD is responsible for the broad planning and policy framework detailed in the city's comprehensive plan as well as for a number of system-related regulations (i.e. floodplains, ECA, landscaping, tree protection), they do not directly implement capital projects and are not represented in this portion of the analysis.

One of the immediate takeaways from the various systems with physical targets when compared to the previous cross-system impact analysis, is that the spatial footprint of the future planned infrastructure is very small compared to the land potentially suitable for their development. For example, in the case of parks, SPR only needs 40 acres of the 388 identified as optimal over GSI uses. Performance rather than physical targets are specified for GSI, but the Swale on Yale demonstrates that a relatively compact GSI implementation (0.3acres) can manage nearly a third of the city's Green Goal target. The targets for trails and forests (7.5 miles and 2% canopy respectively) can easily be accommodated in conjunction with other GI. Finally, urban agriculture beyond the P-Patch program does not

have clear development mandate. When compared with the explicit targets and large budgets of other types of green infrastructure, it is apparent that urban agriculture will need more dedicated support to expand beyond current levels.

Table 21. System development targets.

System	Target	Target Type	Timeframe	Current Status	Target Increase	Lead	Capital Budget	Primary Funding Sources
GSI	700MG/yr stormwater 400MG/yr stormwater	Performance Performance	2025 2020	192MG	265% 108%	OSE/SPU	$21,330,000	Utility Rates (2014-2019)
	35 MG/yr (NDS Partnering for CSO control)	Performance	2025	Not Specified	Not Specified	SPU	$35,992,000	
Forest	30% canopy cover 2500 restored acres	Physical Physical	2037 2025	28% 1000 acres	2% 150%	OSE	$9M total	SDOT Levy to Move Seattle
							$20,930,000	SPR Forestry Budget (2014-2019)
							$183,000	SPU reLeaf Program (annually)
							Not itemized	SCL Tree Replacement Program
Parks	8 acres/1000 people (40 new acres to	Physical	2035	9.34 acres/1000*	0.6% (6414 acres currently)	SPR	$4M annually	City's General Fund (10%

	accommodate future population growth)							allocation - $37M annually) + CIP $110M (2014-2019)
	All residents within 1/4 mile, 5-minute walk All residents within 1/2 mile, 10-minute walk	Performance Performance		77% 94%	23% 6%			Park District ($48M annually) REET ($16-20M annually) Bonds & Levies
Urban Ag	Increase urban food production	Aspirational	Not specified	3 farms	Not specified	OSE/SPR/ DON	Not itemized	NA
	Increase P-Patches (4 mandated, 28 built)	Physical	2008	88	Exceeded Target	DON	$2M total	Parks and Green Space Levy
Trails	7.5 miles multi-use (off-road) 32 miles multi-use (off-road)	Physical Physical	2021 2035	46.9	16% 68%	SDOT	$41.7M (all types)	Levy to Move Seattle

* Although target currently exceeded, population projections show that additional space needed to maintain desired level of service.

4.5 Decision Models

The system targets described in the previous section help ground the analysis generated through change and impact modeling. Although green infrastructure planning is not fraught with the same types of conflicts that McHarg addressed in determining the optimal highway corridor through vulnerable social and ecological landscapes, nor as contentious as growth management – the focus the 2015 UW Geodesign Workshop (Nyerges et al. 2016), when targets for competing types of GI (GSI and parks/GSI and urban agriculture in this study) exceed the land designated as optimal for one use over another, a basis for choosing among them is required.

McHarg, in exploring the social values represented by natural processes and the conflicting demands placed upon them, reflects "These apparent conflicts can be resolved in a number of ways. Because of their scarcity and vulnerability, certain resources may represent such high value for conservation that other uses should be excluded. Multiple uses of some areas may be permitted if it is assured that intrinsic values are not compromised. Yet in other cases where two uses are coequally suitable, it remains with society to make the choice." (McHarg 1992, 104). McHarg's suitability analysis addresses the former and illustrates the latter, but does not detail *how* to choose among multiple suitable yet competing land uses, which is not an oversight, but rather a limitation of designing with nature.

Steinitz addresses this limitation by including explicit decision models in the geodesign framework. In the first iteration, the decision model questions are related to who the primary stakeholders are and what influences are driving their decisions. In the second

iteration, the focus is on detailing their system related requirements and priorities. In the final iteration, the emphasis is on determining whether the study has produced an adequate basis for choosing among various change models based on their impacts. In the case of this study, the previous modeling phases revealed that potential conflicts between some types of green infrastructure, when viewed through the lenses of cross-system compatibility and system-specific targets, can easily be avoided and departments can proceed with their planned GI implementations based on the evaluation and impact models.

Table 22 summarizes the impact analysis for the three systems with potential conflicts. The table should be read across for optimal versus marginal relationships. Parks, the only system with a defined physical target, should be able to accommodate 40 acres within the 388 acres that are optimal for parks and marginal for GSI. Likewise, there is significant acreage available for GSI where both parks and urban agriculture can be avoided. Although the optimal parcels for urban agriculture have a far smaller footprint, GSI conflicts can also be avoided, especially since urban agriculture can be and already often is integrated into park landscapes.

Table 22. Summary of cross-systems impacts. Same system intersections (e.g. GSI/GSI) are the total attractive acres for the system independent of cross-system interactions.

Optimal Systems	**Marginal Systems**			**Targets**
	GSI	Parks	Urban Ag	
GSI	28936	5388	2	open
Parks	388	3141	NA	40
Urban Ag	0.6	NA	12	open

The previous modeling phases demonstrated that the other systems attractive for development, forests and trails, can readily be integrated with GSI and parks, and with their modest targets, can avoid conflicts with urban agriculture. Finally, the vulnerable systems

must be included in the analyses to avoid negatively impacting them, in the vein of McHarg's *Designing with Nature*. However, the decision model in their case is simple. The city departments, by virtue of their role as stewards of the vulnerable systems, will protect them using ordinances and restoration programs.

By iterating through the geodesign framework, the complex picture of green infrastructure planning across multiple scales, functions, and departments with a broad range of requirements driven by many different influences has been successively simplified to narrow in on a few key systems and questions. However, geodesign should be transparent, collaborative and accessible to multiple groups of stakeholders, not just the outcome of a single person's analysis. The next chapter reviews enabling technologies and tools to demonstrate how this study could be carried out in a real planning context.

Chapter 5. Cyber-Enabling Collaborative Geodesign: Technologies and Tools

5.1 Introduction

The Steinitz geodesign framework has in fact been 'cyber-enabled' from the outset. This chapter briefly reviews the geodesign-related technological evolution, as well as the current technologies and tools that add support for collaboration across space and time. It also summarizes the gaps that still need to be filled to support an end-to-end geodesign process (from the initial problem definition to the final stakeholder review and assessment), as well as specific considerations for collaborative geodesign within a municipal context.

In 1965, architect Howard T. Fisher founded the Harvard Laboratory for Computer Graphics, leveraging the capabilities of his Synagraphic Mapping System (SYMAP) programmed by Betty Benson – the first automated computer mapping system with spatial-analytic capabilities. Fisher was in turn inspired by a computer mapping course he took at the University of Washington from urban planning and civil engineering professor Edgar Horwood in 1963. Steinitz used SYMAP for his dissertation, an analysis of factors that make some parts of Boston more memorable than others as described in Kevin Lynch's seminal book on urban design *Image of the City* (1960), and became an initial member of the Harvard Lab along with urban planner Allan Schmidt, water engineer and economist Peter Rogers, and architect Allen Bernholtz. In this interdisciplinary environment, Steinitz began developing and applying the geodesign framework, using SYMAP, within the context of regional and urban development (Steinitz 2012). The early simplicity of the

maps (Figure 69) belies the complex mathematical equations and algorithms that needed to be developed to render them, which are largely described in the *Harvard Papers in Theoretical Geography* (1967) organized by William Warntz (who also added 'and Spatial Analysis' to the Harvard Lab's name). The collection included 57 papers with titles like "Hyper-surfaces and Geodesic Lines in 4-D Euclidean Space and The Sandwich Theorem: A Basic One for Geography".[116]

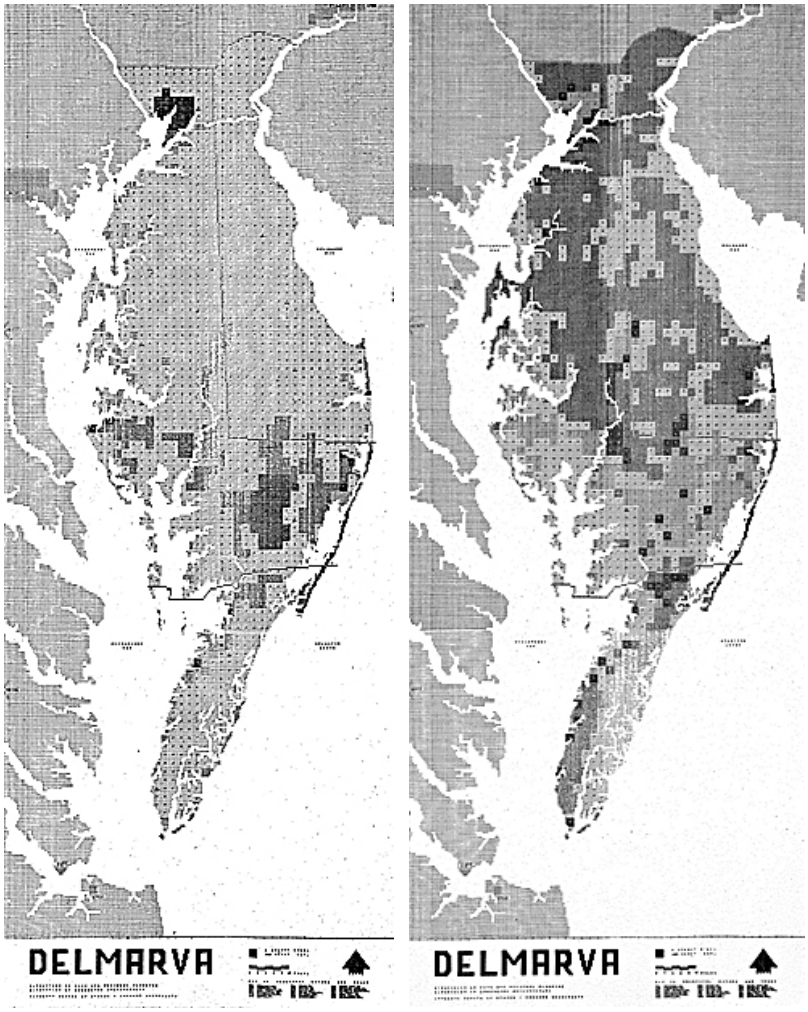

Figure 69. Maps generated for DELMARVA – a regional study of conservation and development for the peninsula shared by Delaware, Maryland and Virginia (Steinitz 2012).

[116] Hessler, John. 2013. History of GIS and early computer cartography. Available from http://www.esri.com/esri-news/arcnews/winter1314articles/history-of-gis-and-early-computer-cartography-project. Accessed on 10/8/2017.

In 1969, Jack Dangermond, who also worked in the Lab, graduated with an MLA from the GSD and started the Environmental Systems Research Institute, today known as Esri. Esri was initially a land-use consulting firm; software development was a means to an end. In mid-1970, building on the capabilities of SYMAP, the company developed the polygon information overlay system for the San Diego Comprehensive Planning Organization. By the early eighties, Esri needed to manage multiple projects more efficiently, and sought to automate mapping and analyses. By 1982, ARC/INFO, the precursor to ArcGIS, was released as the first commercial GIS and was quickly adopted by government and researchers for a wide-array of applications. The increasing speed and accessibility of personal computers and the Internet in the 1990s led to Esri's first desktop release-ArcView GIS. ArcGIS 9 added server capabilities and a developer framework in 2004, and the software continued to evolve into a broad platform across the desktop, server, cloud and mobile devices with the launch of ArcGIS Online (AGOL) in 2010.[117]

Today there are other commercial and open source GIS available, but Esri is the primary heir to cyber-enabled geodesign started at the Harvard Lab and promulgated by Steinitz. The Esri product portfolio is extensive, and offers many tools useful for the analytical aspects of geodesign (representation, process and evaluation models); however, true design capabilities (change, impact and decision models) had been largely missing or limited until GeoPlanner was launched in 2014.[118] Bill Miller, former head of Esri's GeoDesign Services

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[117] Esri. 2015. History up close. Available from http://www.esri.com/~/media/Files/Pdfs/about-esri/esri-history-up-close. Accessed on 10/4/2017.
[118] Bill Miller. 2012. Introducing geodesign: the concept. Available from https://www.esri.com/library/whitepapers/pdfs/introducing-geodesign.pdf/. Accessed on 10/14/2017.

and avid geodesigner, describes the verb *design* generically as "the thought process comprising the creation of an entity." Typically, the design context is analyzed separately and the information provided in a variety of formats to the designer/design team, who must mentally integrate this information into their design. At scale of the city or region, this 'design' is usually some sort of plan like those referenced throughout this document. At the block or site scale these plans or concepts are eventually translated into buildable designs with CAD – computer-aided design tools. GeoPlanner can support multiple spatial and temporal resolutions of analysis and design; however, it is still primarily a tool for exploration and conceptualization, and does not replace CAD for buildable designs. Steinitz, Miller and Dangermond initially collaborated on the development of GeoPlanner before Steinitz joined forces with Hrishi Ballal to develop Geodesign Hub - an open source alternative to GeoPlanner that will be evaluated in the next section.

This study was intentionally executed using standard desktop GIS because it is widely available, well known to the planning community, and allows the concepts and methods of the Steinitz geodesign framework, which is intended to be technology and tool agnostic, to be emphasized. However, the single-user desktop environment does not support collaborative design and decision-making, nor does it readily enable the development and assessment of different design alternatives. To assess the functionality of GeoPlanner and Geodesign Hub, the implementation of two different scenarios for urban agriculture development in Seattle will be evaluated.

The first scenario reflects the Food Action Plan's emphasis on increasing access to healthy food in low-income neighborhoods in Seattle (Scenario A: Healthy Food For All). The second scenario (Scenario B: Healthy Parks, Healthy You) explores the development potential of future gardens combined with future parks. SPR's Healthy Parks, Healthy You initiative (now split into two different programs: Get Moving and Urban Food Systems) emphasizes hand-on education and activities in parks related to cooking and gardening. Both scenarios will take in account the vulnerable systems: wetlands, habitat, riparian/shoreline, and floodplains/flood prone areas.

Table 23. Two scenarios for urban agriculture expansion.

Healthy Food For All	Healthy Parks, Healthy You
Locate new gardens in low-income areas.	Locate new gardens in areas identified by the SPR open space gap analysis.
Both: Avoid vulnerable systems – habitat, wetlands, riparian/shoreline areas, floodplains/flood prone areas.	

5.2 GeoPlanner in Focus

GeoPlanner was first released in 2014, and incorporates functionality from previous Esri applications like Landscape Modeler and Landscape Analyst as well as data and analysis services available through ArcGIS Online. The current version, released in September 2017, divides the geodesign workflow into 3 major segments: Explore, Design, and Evaluate. *Explore* includes the representation, process and evaluation models from the geodesign framework. *Design* includes the change and impact models. *Evaluate* is the decision modeling environment.

The first step, after provisioning GeoPlanner to an ArcGIS Online (AGOL) organization (note: a "personal" AGOL account is not sufficient because certain GeoPlanner functions require processing credits, which are only available to organization accounts), is to create

a project and share this with collaborators in the AGOL organization. GeoPlanner provides a small number project templates that will load commonly used design categories (for sketching features as part of the change model) and datasets for that particular topic (e.g. economic development, public safety, land use planning, green infrastructure).

The Green Infrastructure template was chosen for the urban agriculture scenario development, and includes the following design categories: recreation areas, trails, streams, habitat cores/fragments/connectors, common land uses, and a wide variety of green infrastructure including environmentally critical areas, habitat, agriculture and viewsheds (Figure 70). The default datasets include both 'representation' model features (e.g. national trails, wetlands, parks, historic sites, habitat, land cover), and 'evaluation' model features (e.g. assessments of farmland, ecological redundancy, land forms, slope, elevation, and human landscape modification). One immediate issue is that to view any of the details of the defaults datasets, aside from the simple categories included in the legend, the layer must first be opened in ArcGIS Online, and then loaded into a Map Viewer. This requires several steps, and still does not provide adequate metadata (e.g. data source, acquisition date and procedure, assessment criteria, accuracy). There are no technical limitations to loading the service metadata directly into GeoPlanner, it is simply a software design shortcoming, which limits the usability of the defaults datasets for verifiable analysis.

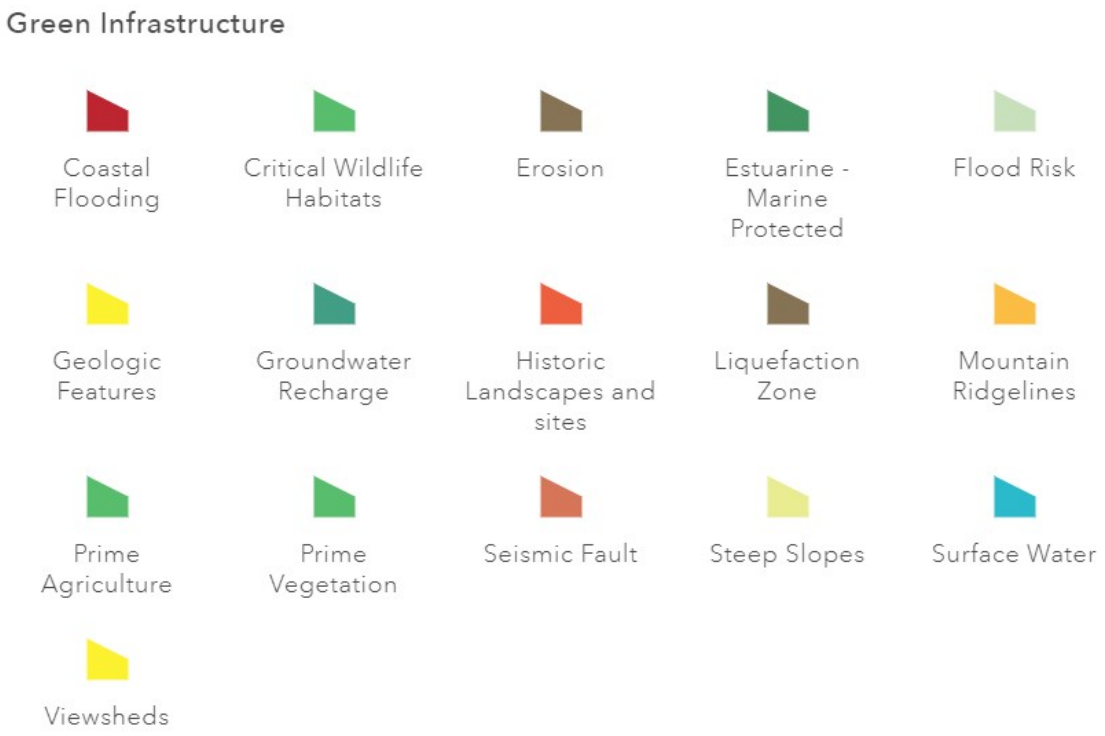

Figure 70. Green infrastructure design categories included in the GeoPlanner template. Some of these should actually be characterized as 'environmentally critical areas' rather than green infrastructure, which need to be accounted for in any type of development activity (i.e. erosion, liquefaction zone, seismic fault, steep slope) but do not contribute any social-ecological benefits. Categories like flood risk and coastal flooding are similar, but at least possibly represent wetlands and floodplains which do provide benefits. One criticism is the use of the same color for agriculture, vegetation and critical wildlife habitats, as well as for geologic features and viewsheds; however, these colors can be changed prior to sketching.

5.2.1 Explore

The next step is to set up each scenario. To add custom datasets to GeoPlanner, these need to be loaded into ArcGIS Desktop and published as a feature service to the AGOL organization provisioned for GeoPlanner. For both scenarios, all of the current urban agriculture parcels, potential parcels from Horst's Growing Green analysis, and all of the vulnerable systems need to be added. The first thing to evaluate is if any of the Growing Green parcels are within 200 feet of a vulnerable aquatic system as discussed in section 4.4.2. The 'Explore' segment has an 'Analysis' toolbox that includes a 'Create Buffer' function. After adding a 200-foot buffer to the Growing Green parcels, the 'Overlay

Layers' function identifies that none of the buffered parcels intersect the vulnerable systems.

For Scenario A, 'Healthy Food For All', the next step is to evaluate existing and future urban agriculture in relation to socio-economic conditions. While any number of refinements could be made (e.g. single-parent households with children), for the sake of demonstration, the same Census layer included in SPR's Parks and Open Space Plan analysis (Figure 40 – percentage of adults with income below the federal poverty level) was published as a feature service.[119] Using the same convention as that which was used for the evaluation models in section 4.3, the data in this layer was then classified from least attractive to most attractive for urban agriculture, based on the percent of adults below the poverty level (PovertyEvalModel). The 'Classify' tool, which is found in the context menu for each feature, actually provides a nine-level scale, but the GeoPlanner documentation (like Steinitz) recommends five or fewer categories for clarity and consistency across all features.[120] One limitation, is that there is no manual classification option like there is in ArcGIS for Desktop, so 'Natural Breaks' with three classes was chosen, which grouped the poverty percentages into 0-14.3% (lowest attractiveness), 14.3-31.3% (medium attractiveness), and 31.3-66.1% (highest attractiveness). Although the Jenks Natural

[119] Note, the 'Analysis' toolbox does have a 'Data Enrichment' function, which includes 2011-2015 ACS Poverty Level variables. Unfortunately, even though only one variable was selected to enrich the Growing Green parcels, which should have only used .044 credits for 44 parcels according to the GeoPlanner's credit estimator, I supposedly did not have enough credits to execute the job (97). Several attempts by myself and Geography's technical support could not resolve the issue, so I uploaded the data I needed instead.

[120] Esri. 2017. GeoPlanner for ArcGIS: Classify your analysis. http://doc.arcgis.com/en/geoplanner/documentation/classify-your-analysis.htm. Accessed on 10/28/17.

Breaks algorithm divides data into groups with similar values and maximizes differences between groups, which makes sense for poverty level percentages, manual classification that allows these ranges to be modified into simplified categories (e.g. 0-15%, 15-30%, >30%) is preferable for communicating information to a broad audience.

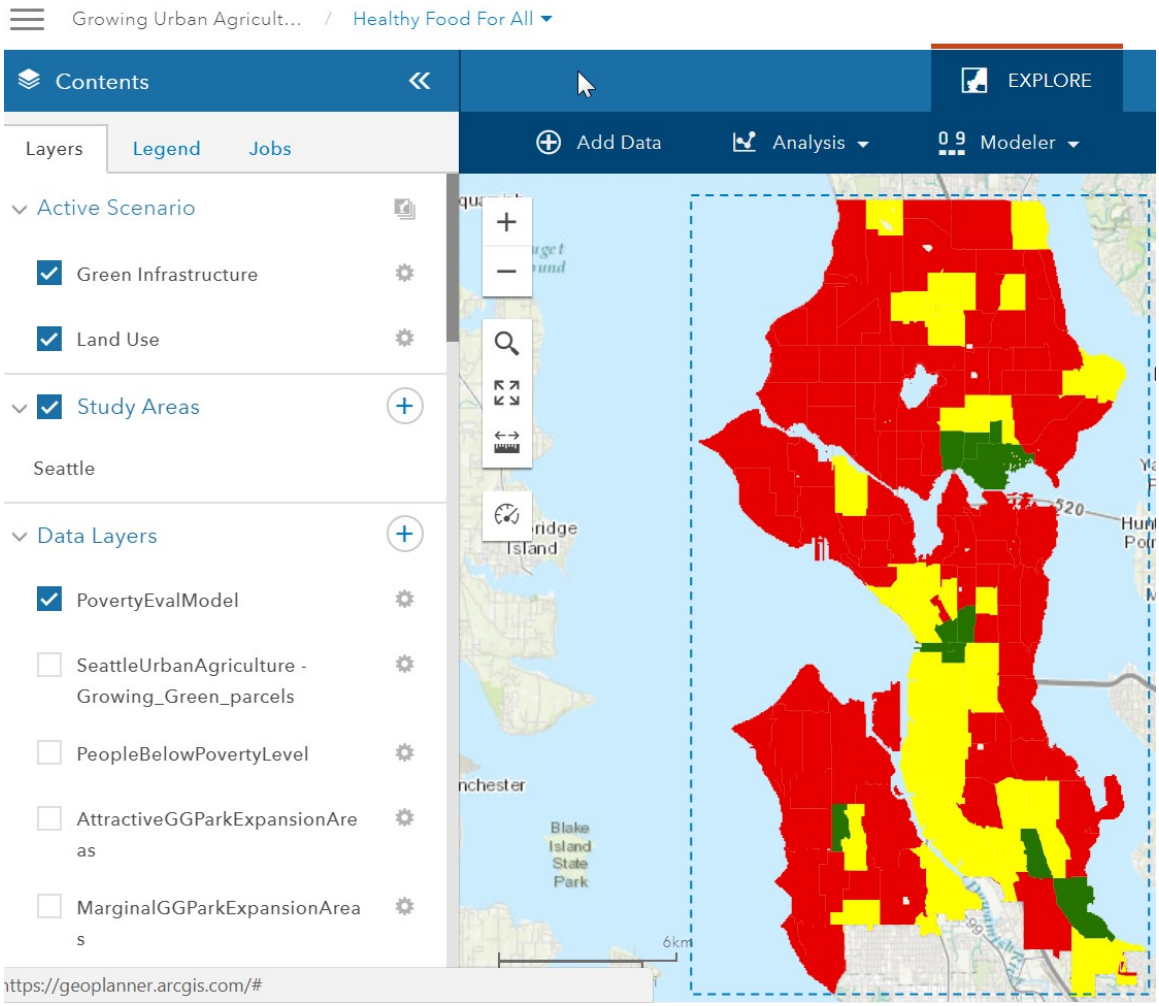

Figure 71. Scenario A evaluation model in GeoPlanner with Natural Breaks classification of below poverty level percentages: 0-14.3% (red - lowest attractiveness), 14.3-31.3% (yellow - moderate attractiveness), and 31.3-66.1% (green - highest attractiveness).

For Scenario B, 'Healthy Parks, Healthy You', none of the Growing Green parcels fell within a park gap area, either within or outside of an urban village, so a .25mile buffer was added to the Growing Green parcels to see if any were at least within a 5-minute walk of a

park gap area. The buffer was then overlaid on the park gap areas to find the intersection between the two. The results of this analysis were then classified based on the urban village type (Figure 72). In line with the city's strategy to direct development, infrastructure and services to urban villages - residential and hub urban villages were considered most attractive for new gardens because they have the greatest amount of housing.[121] Urban center villages are primarily employment centers, but also have housing, so were classified as moderately attractive, and areas outside of urban villages were considered least attractive.

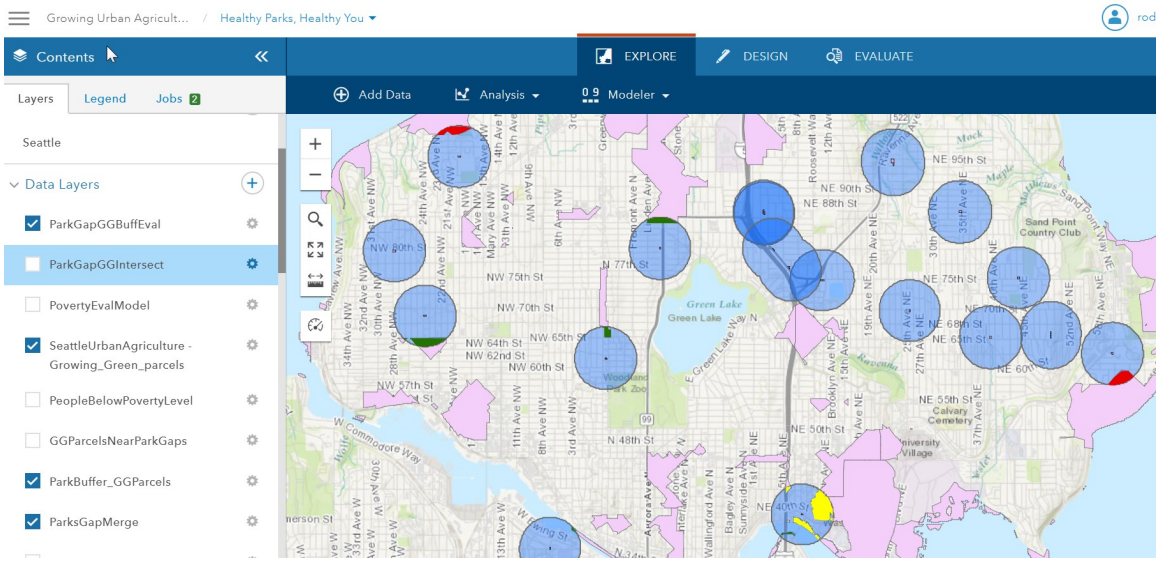

Figure 72. Scenario B evaluation model in GeoPlanner. Areas where Growing Green walkability buffers overlap park gaps are classified by the type of urban village the gaps are located within – green: residential or hub urban village; yellow: urban center village; red: outside of an urban village.

5.2.2 Design

After importing data, exploring spatial relationships, and determining suitable, or attractive, locations for urban agriculture development, the next step is to 'design' potential

[121] City of Seattle. 2016. Seattle 2035: Citywide Planning. Available from http://www.seattle.gov/Documents/Departments/OPCD/OngoingInitiatives/SeattlesComprehensivePlan/CouncilAdopted2016_CitywidePlanning.pdf. Accessed on 10/28/2017.

interventions or change models using the ‘Design’ segment. One design option is to add existing features as a design layer via the feature’s context menu. Another option is to draw new features freehand using the ‘Design’ segment’s drawing tools (Figure 73).

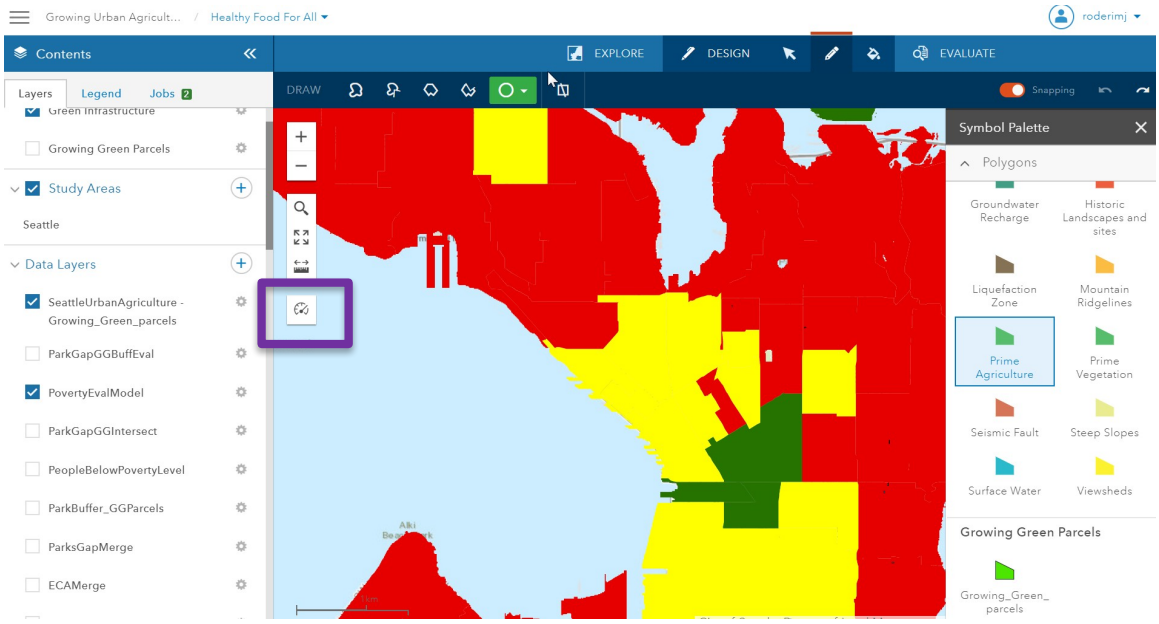

Figure 73. GeoPlanner drawing tools in the ‘Design’ segment. The design categories on the right were loaded by default with the ‘Green Infrastructure’ template. The purple square highlights the dashboard widget discussed below.

For Scenario A, the existing Growing Green parcels were added as a design layer to assess which ones fall within census tracts with more than 14.3% of adults below the poverty level (the green and yellow categories). The dashboard widget (see the purple square in Figure 73) can be opened at any time during the design process (it is also included as a main tool in the ‘Evaluate’ segment) to provide feedback about the design’s performance. The dashboard widget consists of a primary chart and a secondary chart; the primary chart quantifies information about the design feature (i.e. Growing Green Parcels – area, perimeter, or count because they are polygons). The secondary chart is configured from the

available assessment models (i.e. PovertyEvalModel), and quantifies how many Growing Green parcels fall within each poverty level category (Figure 74).

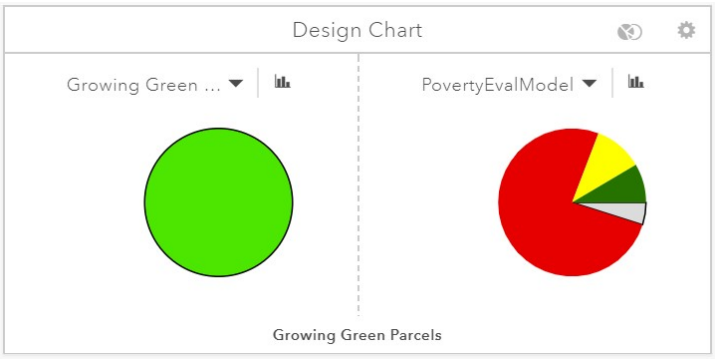

Figure 74. GeoPlanner dashboard widget for Scenario A. The chart on the left is the primary chart and is configured to show the area of the features in the design layer. While the graphic is not informative, the associated hover tooltip shows the total parcel area. The chart on the right shows the relative quantity of Growing Green parcels that fall within each 'below poverty level' category (a small area is within and area not included in the poverty analysis). The hover tooltip also provides the numeric information.

In Scenario B, the drawing tools were used to draw in urban agriculture locations in a few of the park gap areas that lay within the .25 mile Growing Green parcel buffer to demonstrate the difference between the two design approaches. The scenario dashboard widget shows how many new urban agriculture areas fall within each urban village category. The new designs can also be assessed using the poverty level model from Scenario A, demonstrating the flexibility of the GeoPlanner's assessment functionality.

Figure 75. Scenario B dashboard. The left widget shows that half of the new urban ag areas fall within the attractive and half within the moderately attractive park gap areas. The right widget shows how the new areas relate to the poverty level assessment.

Key performance indicators (KPI) are an additional dashboard feature, and show how the design relates to a goal like the system development targets discussed in section 4.4.5. In the case of parks, 40 new acres need to be added to the park system by 2035 to maintain

SPR's goal of 8 park acres/1000 people. A simple KPI is to quantify how many acres the design scenario contributes to this goal (Figure 77). Both the design/assessment charts and the KPIs are examples of impact models.

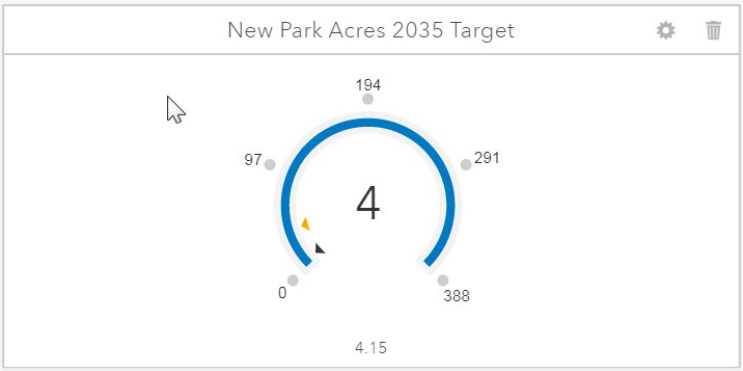

Figure 76. Contribution of new urban agriculture designed in Scenario B to the park development target of 40 new acres by 2035. The gauge endpoint, 388, represents the acres optimal for park development identified in the Chapter 4 analysis. The orange indicator is the target of 40 acres, and the black indicator and 4 in the center is the contribution of the design toward meeting the target.

5.2.3 Evaluate

The 'Evaluate' segment has several tools to compare scenarios; however, it is designed to compare different versions of the same scenario, i.e. alternative plans with the same layer (content) structure. The previous sections described an approach to scenario development based on different types of decision models (urban agriculture development based on poverty levels vs. based on park gaps), although design charts can be added to the dashboard to compare across multiple metrics (Figure 75).

To illustrate the 'Evaluate' tools, Scenario B was duplicated and an additional urban agriculture area was created in a highly attractive park gap. The two versions of the scenarios can then be loaded and compared side by side or by swiping left and right between them. Consensus between the two scenarios can also be evaluated by executing the 'Consensus' tool, which computes both a change score and a consensus score as well as visually represents areas of agreement and conflict based on these scores (Figure 77).

The change score reflects how many scenarios included changes for a particular area, and represents the relative interest or focus on making changes in that area. For example, if six out of ten scenarios have changes for the same area, the score is 6 (6/10 = .6, then multiplied by 10 to convert to 6 on the 1-9 scale).

The consensus score evaluates the types of changes for an area, summing each feature type (e.g. frequency of different land uses proposed for the same area) and then dividing the most frequent type by the total number of changes. For example, of the six scenarios that proposed a change for the same area, three were for agriculture, two for residential and one for commercial. Agriculture would 'win' and the consensus score would be 5 (3/6 = .5, x 10 to convert to 5). Higher consensus scores indicate a higher level of agreement among proposed changes.[122] The Scenario B consensus report illustrated in Figure 77 is simplified because there are only two scenario alternatives. Scenario B.2 just includes an additional feature, and no conflicting changes.

[122] Esri. 2017. GeoPlanner for ArcGIS: Consensus. Available from http://doc.arcgis.com/en/geoplanner/documentation/scenario-consensus.htm. Accessed on 10/28/17.

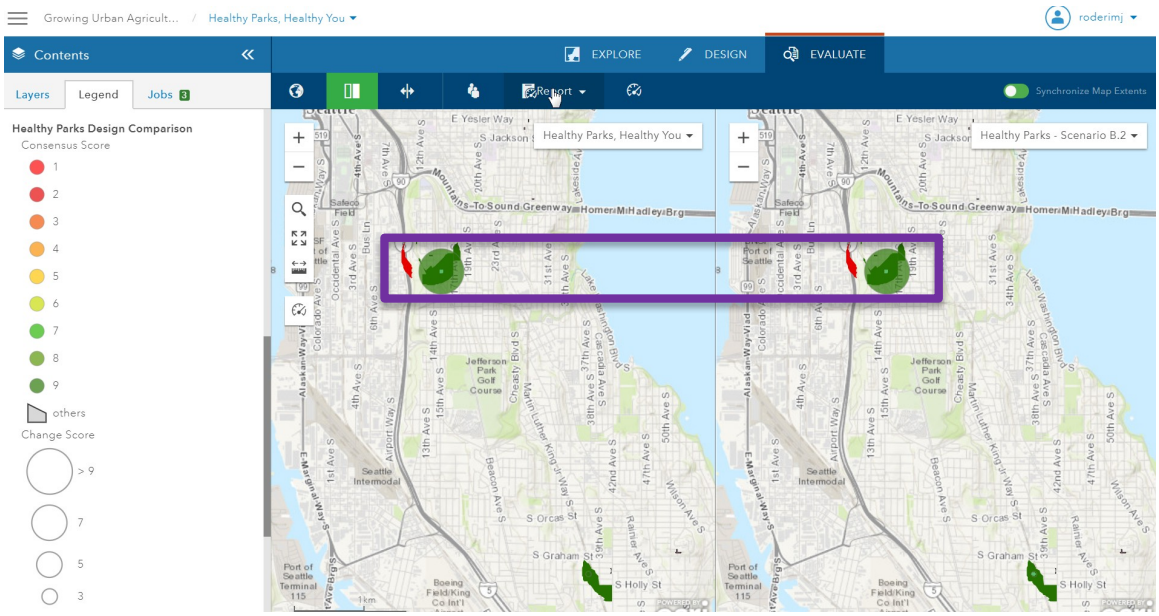

Figure 77. Output from the Consensus tool. The change and consensus scores are high for the areas in the purple box where both been designated for urban agriculture. The color of the circle indicates the degree of consensus, and the size of the circle indicates the change score (see the legend on the left).

5.2.4 Collaborate

Although it offers a far more limited set of analytical tools, and does not allow datasets and their metadata to be explored directly, GeoPlanner streamlines many aspects of the geodesign process when compared to the desktop GIS approach presented in Chapter 4, especially those related to change and impact models (e.g. simplified sketching/feature editing tools and dynamic dashboards that provide immediate design feedback). GeoPlanner also adds decision modeling functionality via the Consensus tool that is missing entirely in the desktop GIS environment. Most importantly, it supports collaboration both within the geodesign team and with external stakeholders both by virtue of being a web-based application and through a variety of information sharing features.

When the geodesign project is created, other registered AGOL users can be added as collaborators. All scenarios will be available to all project users by default; however, the

base feature representation and assessment layers need to be explicitly added to the project template as do the dashboards. This enables a project administrator to create a shared workspace for everyone, while allowing individual team members to customize the shared workspace with data and dashboards that are only visible to them. To share information with external stakeholders, both static maps and dashboard reports can be printed, and specific scenarios can be shared as a web map via AGOL. From AGOL, the map can be embedded in another website or turned into a standalone web application.

One notable collaboration feature that is missing, both in GeoPlanner and AGOL, is an integrated deliberative environment for collaborative problem-solving. Although different users can create and share different design scenarios and view degrees of agreement or conflict between design scenarios by running the Consensus tool, there is no support for group discussion and scenario selection. Users can comment on and rate individual content in AGOL by selecting it and scrolling to the bottom to leave a comment or a reply, but this is not a true deliberative and decision-making space that allows for brainstorming, synthesis and choice among alternatives (Nyerges, Roderick, Avraam 2013). The requirements and implementation options for this type of collaborative problem-solving will be discussed following the Geodesign Hub section.

5.3 Geodesign Hub in Contrast

Geodesign Hub was developed by Hrishikesh Ballal for his dissertation from the Center for Advanced Spatial Analysis, University College London with guidance from Carl Steinitz. It is intended to support digital design synthesis for complex regional planning problems and follows the Steinitz Geodesign Framework. The tool seeks to bridge the

systematic analysis common in regional planning and the creative design process (Ballal 2015). It has been used in multiple workshops, including the 2015 UW Geodesign Workshop that explored alternative futures for the Lower and Middle Green River subwatersheds in King County, Washington (Nyerges et al. 2016). The author was involved in the UW workshop from conceptualization to execution, and has hands-on experience with Geodesign Hub from which to draw upon for this assessment.[123]

One of the main differences between GeoPlanner and Geodesign Hub is the type of modeling supported by each tool. GeoPlanner supports the development of evaluation models (referred to as suitability or vulnerability analysis) from representation and process models in the 'Explore' segment. Geodesign Hub requires the evaluation models to be developed prior to beginning a new project. None of the analytical models (representation, process, evaluation) can be explored within the Geodesign Hub beyond the color-coded visualization of vulnerability or attractiveness. GeoPlanner delegates much of the exploratory functionality to AGOL, but each type of model can be loaded into GeoPlanner as a feature service and opened. These differences reflect the origin of each tool. GeoPlanner evolved out of GIS, Geodesign Hub evolved from the design studios lead by Carl Steinitz.

[123] Note: while a comparison based on the same scenarios developed for GeoPlanner would be ideal, Geosdesign Hub only offers a 'Sandbox' for general exploration due to the technical support still required to use the platform.

Design (or change models) is the real point of departure for comparing the two applications (Figure 78). In Geodesign Hub, designs are associated with a specific system (or requirement). Rather than creating a different scenario for each set of features included in a design, users create as many designs, e.g. as alternative sets of policies and project, as they wish and then select a subset of designs to assess against the evaluation models (Figure 79). The subset of selected designs are assessed visually against different evaluation models through transparent overlay (Figure 80) and through an impact scale that relates the design to the evaluated system (Figure 81). Two limitations of Geodesign Hub when compared to GeoPlanner are 1) the lack of quantified spatial information about the design's relationship to the evaluated system (i.e. how much area of the design lies within each vulnerable/attractive area of the evaluated system), which is provided by the design chart comparison in GeoPlanner's dashboard (see Figure 74), and 2) the inability to configure the impact model within the application, instead the project must be initialized with a table similar to the one depicted in Figure 61. GeoPlanner allows the user to create KPIs for each model relationship of interest, and also displays these in the dashboard.

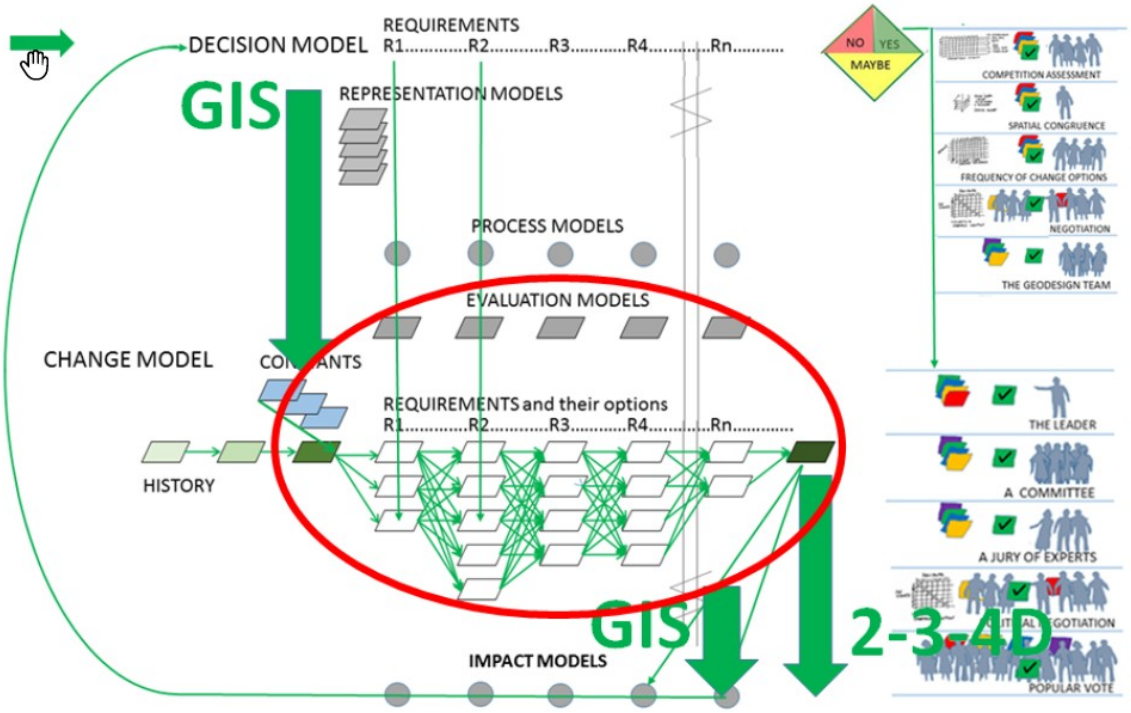

Figure 78. Geodesign Hub focuses on the iterative design and synthesis process within the geodesign framework. Analytical modeling occurs within GIS, but the evaluation models can be added to Geodesign Hub to provide design performance feedback. Image source: Ballal 2015, 136.

Figure 79. Diagrams are created by users for each system and can then be selected to develop a composite design.

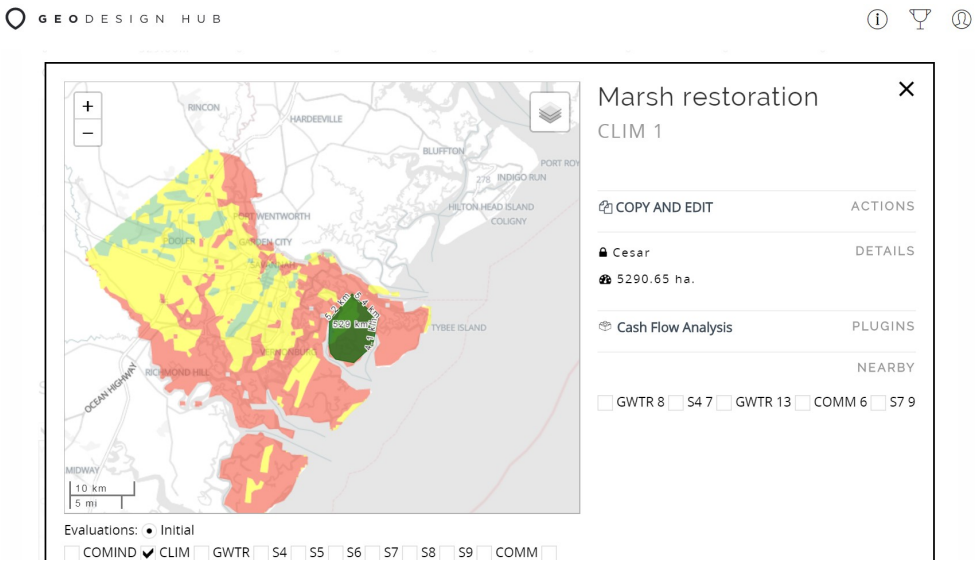

Figure 80. Design overlay example from the Geodesign Hub community sandbox project. The dark green area is a marsh restoration project selected from 'All Diagrams' in Figure 79 and overlaid on a climate change risk model.

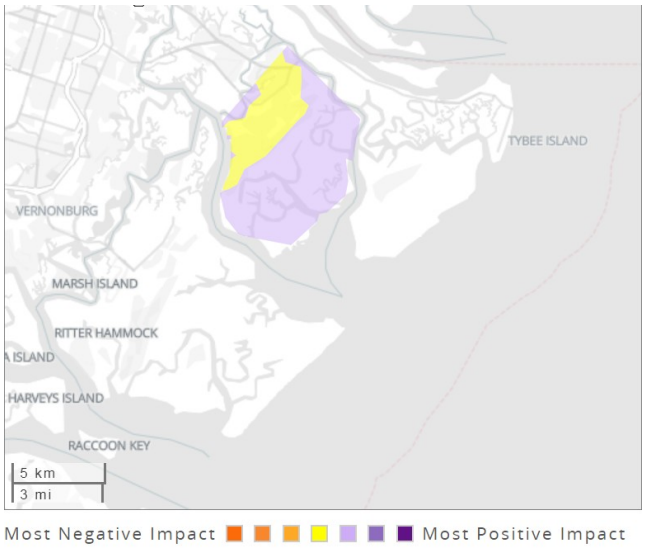

Figure 81. A separate map shows a relative impact scale for the influence of the marsh restoration on climate change vulnerability. The model does not provide any further information about the values used to determine the impact relationship, nor can these be configured by the user in the application.

Geodesign Hub does explicitly quantify the implementation costs of each design, and how much area the design contributes to the development target set for the system/requirement to which the design belongs. Both the overall system development target and the cost of each design can be configured by the user as a part of the design process. In GeoPlanner,

the cost of the design would be specified as an equation assigned to a KPI. The system development target and design target fulfillment can also be included as a KPI as illustrated by Figure 76.

True to its intent as a design synthesis tool, Geodesign Hub does provide several different ways to compare and synthesize designs. An individual designer can compare her selected diagrams with another individual's selections, and can import that person's design into her diagram set (Figure 82). The side by side comparison is similar to GeoPlanner's 'Evaluate' view of two scenarios (Figure 77); however, it is not possible to simply adopt the features from another scenario. Individuals are also part of teams, and can compare team design versions (i.e. a set of diagrams that have been selected and saved as a variant) (Figure 83).

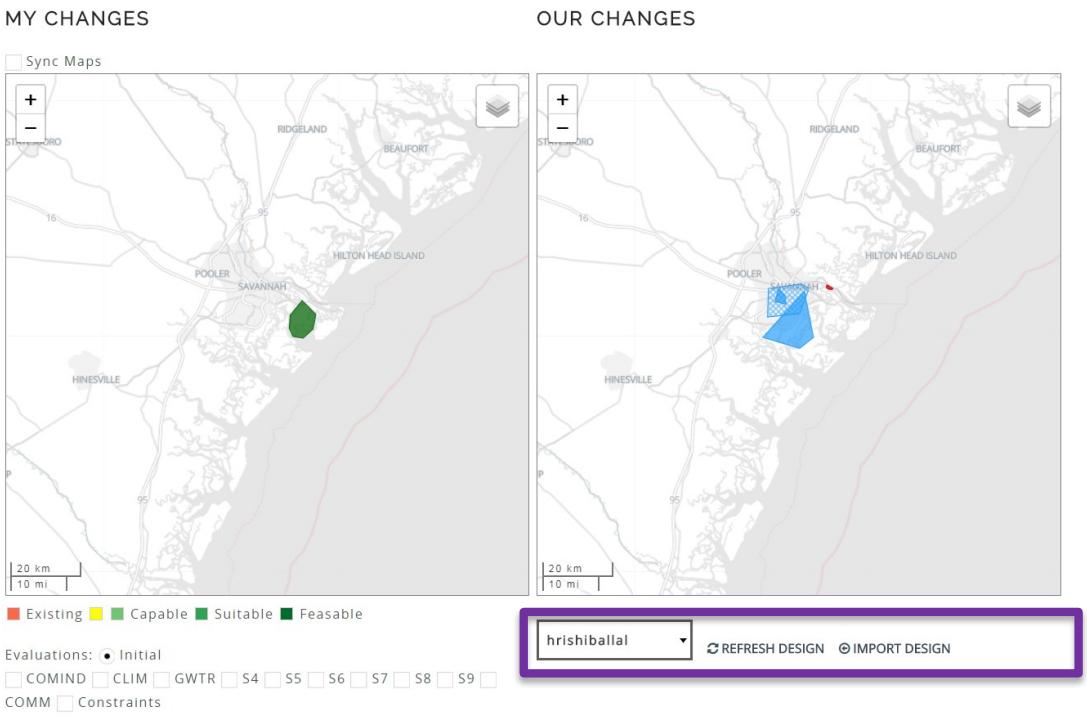

Figure 82. The individual design comparison in Geodesign Hub also allows the user to import another user's design into their own set of diagrams (see the 'Import Design' function highlighted in the purple box).

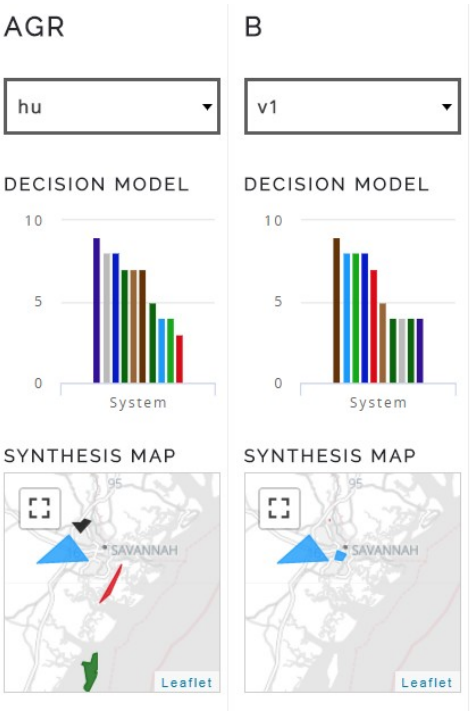

Figure 83. Users are assigned to teams and can compare both the teams' decision models (i.e. importance of each system relative to each other) and specific team design versions (AGR:hu and B:v1 in this case). The team comparison also shows the project area of all of the designs for each team, an impact summary, and costs – all categorized by the sum of the diagrams per system.

There are several combined analysis views as well. A synthesis map can be created from all of the team designs, and filtered by each system. Another view illustrates the diagram frequency across all of the team designs, and the user can choose to view the frequency of interest to build different composite designs (Figure 84).

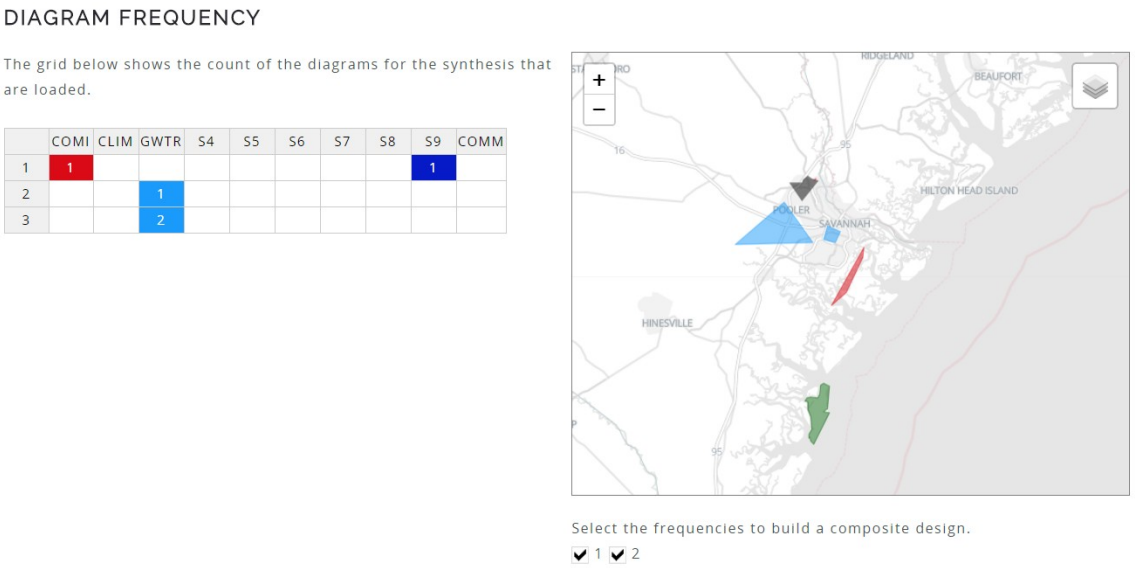

Figure 84. Composite of all team designs, and a diagram frequency grid. This figure shows all of the designs, but by deselecting the checkbox by number 1, only those that were used twice would be included in the composite design.

A further view allows the user to choose among two different team's design composites, and provides a similar composite map and diagram frequency grid comparison as illustrated in Figure 84 for each team (rather than for all teams). Comments can be posted for each team related to this view. Finally, a negotiated design view provides a more granular representation of the two selected teams and their composite designs (with only two teams, this is the same composite map and diagram frequency grid as depicted in Figure 82). The user can view both teams, or only one at a time, or only the areas of agreement or disagreement between the two teams (Figure 85). The GeoPlanner Consensus tool provides a similar view; however, enriches the visualization with quantitative information – both the degree of consensus through the color-coded consensus score on a 1-9 scale, and the similarity of changes through graduated symbols. The graduated symbols are color-coded with the consensus score and overlaid on each feature in each scenario in a side-by-side comparison (Figure 77). The 'on/off' functionality in Geodesign Hub makes the differences between team designs easy to visualize; however, the quantified and color-coded comparison provided by the GeoPlanner's Consensus tool makes the differences easier to describe.

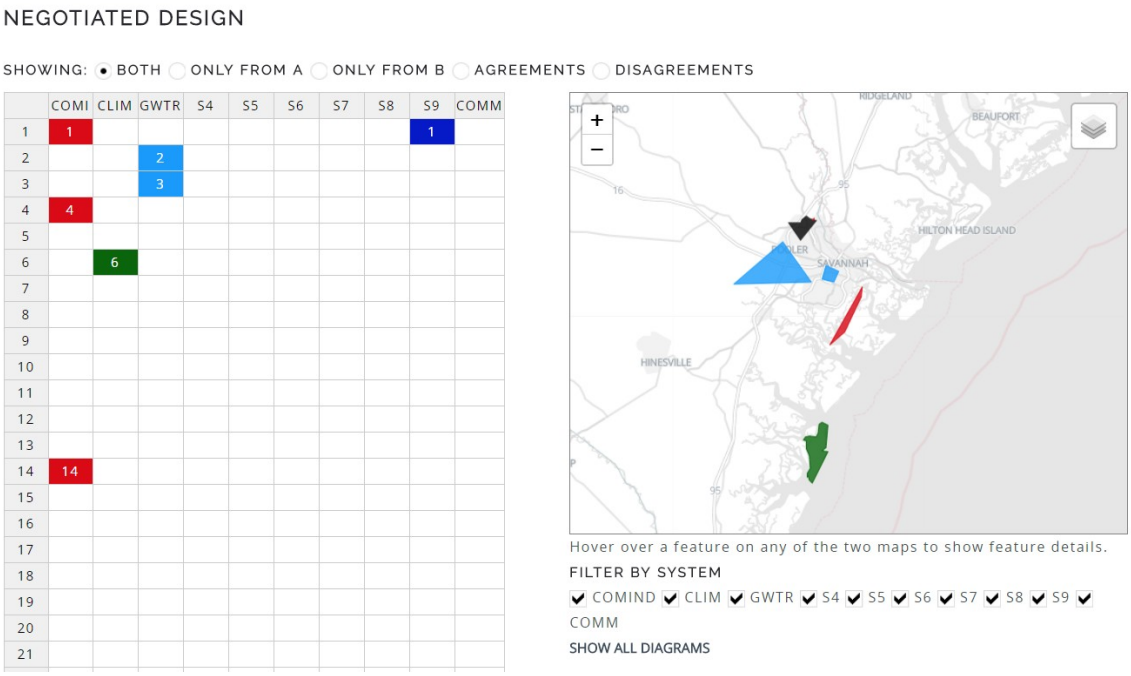

Figure 85. Negotiated design view between two teams. The user can also choose to view only one team at a time, or can view only the diagrams in agreement or disagreement between the two teams.

5.4 Application Synthesis

Both software applications can be used to implement the third iteration of the geodesign framework, and have different strengths and weaknesses. GeoPlanner leverages many years of GIS development in its analytic capabilities, and Esri has greatly improved upon the design functionality by simplifying the feature creation and editing process that is available in ArcGIS Desktop. Geodesign Hub is modeled directly on the design studio experience, which is reflected in the flexible, iterative diagram creation, comparison and synthesis process. GeoPlanner does not readily support the synthesis of different designs, although a scenario can be copied and added to or changed. GeoPlanner is more flexible in how systems are defined and how system relationships and design impacts are quantified. Geodesign Hub assumes a '10 System' structure proposed by Steinitz (2012), and does not provide the ability to configure the system impact models. Table 24 summarizes the most

fundamental high-level geodesign tasks, both modeling and collaboration, across both applications.

Table 24. GeoPlanner and Geodesign Hub high-level functional comparison.

Function	GeoPlanner	Geodesign Hub
Modeling Phases		
Representation	?	?
Process	?	?
Evaluation	C	<
Change (Design)	C	C
Impact	C	<
Decision	C	C
Collaboration Features		
Compare Designs	C	C
Combine Designs	<	C
Build Consensus	C	<
Comment	?	C

? = Not supported < = Partially supported C = Fully supported

For the purposes of this study, and more generally in the detail and data-rich, analytically driven realm of government-led planning, GeoPlanner is a better choice for supporting the geodesign process. As highlighted throughout this study, departments develop plans based on extensive research and outreach, and the metrics that serve as a basis for decisions need to be equally detailed and transparent. Geodesign Hub could, however, be used in earlier plan scoping phases to gather initial ideas and generate dialog about desirable changes, identify potential areas of conflict and assess the relative impact of choosing different development strategies.

5.5 Additional Platform Requirements

Neither application is sufficient to fully traverse the geodesign framework, and the development of a monolithic, all-in-one solution is too complex and costly to keep pace with changing technologies as well as planning and design innovations. Instead, a platform-

oriented approach, which can also leverage the vast number of existing expert systems, is more feasible to support all three of the geodesign framework iterations. In his discussion of future geodesign research, Steinitz emphasizes "I do not have *the* all-encompassing list of tools, techniques and methods that must be taught, understood, adapted, and used for effective geodesign. No one does…Diverse tools include countless combinations of computer hardware devices, information-management programs, packaged models, and many equivalent non-digital tools" (2012, 181). He also reiterates the importance of supporting and bridging the highly intuitive, experiential process of design and the detailed analytical process of geographic sciences – the crux of geodesign, as well as merging the unique workflows of both individuals and teams (Steinitz 2012), which further makes the case for a highly flexible, extensible platform.

Before delving into the additional requirements of a geodesign support system (GDSS) (Steinitz 2012), a brief look at planning support systems (PSS) helps frame the gap that a GDSS needs to fill. Like GIS, an extensive body of literature exists on both planning support systems (PSS) and, more generally, on decision support systems- both spatial and non-spatial. An oft-cited definition of PSS describes them as "geotechnology-related instruments that incorporate a suite of components (theories, data, information, knowledge, methods and tools) that collectively support all of or some parts of a *unique planning task* [emphasis added]" (Geertman and Stillwell 2003, 5). Many of these systems are specialized to a pre-defined topic such as sustainable urban development (Kapelan et al. identified over 150 systems focused on this topic alone (2005), with many exemplars covered in Geertman, Toppen, and Stillwell 2013); land use change (Deal and Pallathucheril 2008);

transportation (te Broemmelstroet 2010); and energy and material flows (Batty 2013) just to name a few. Drawing from years of professional software development and system architecture experience, this focus on a 'unique planning task' and the related proliferation of discreet, specialized applications has been one of the barriers to the widespread adoption of PSS when compared to GIS.

A 2005 study by Vonk et al. identified a variety of other issues related to the lack of utilization of PSS in planning practice. Because "geoinformation tools appear to be seldom used for those tasks that are unique to planning, such as visioning, storytelling, forecasting, analysis, sketching and evaluation" (2005, 909), the authors had expected that PSS, with the additional functional focus on planning-specific models and information visualization, would find a broader user base, which failed to materialize despite the best efforts of PSS developers to increase the number and variety of systems. The authors developed a survey to understand this deficit in demand based on an adapted version of a framework (Frambach and Schillewaert 2002) that integrated Roger's seminal work *Diffusion of Innovations* (1962; 2003) with a widely applied technology acceptance model developed by Davis (1986). The results from ninety-six respondents, largely from academia and public research institutions (58%) and some end-user groups (consulting firms (8%), public planning bureaus (16%), and combinations and other (18%)), were mapped to the Frambach and Schillewaert framework (Figure 86), and were distributed across most of the organizational and individual factors considered important for innovation adoption.

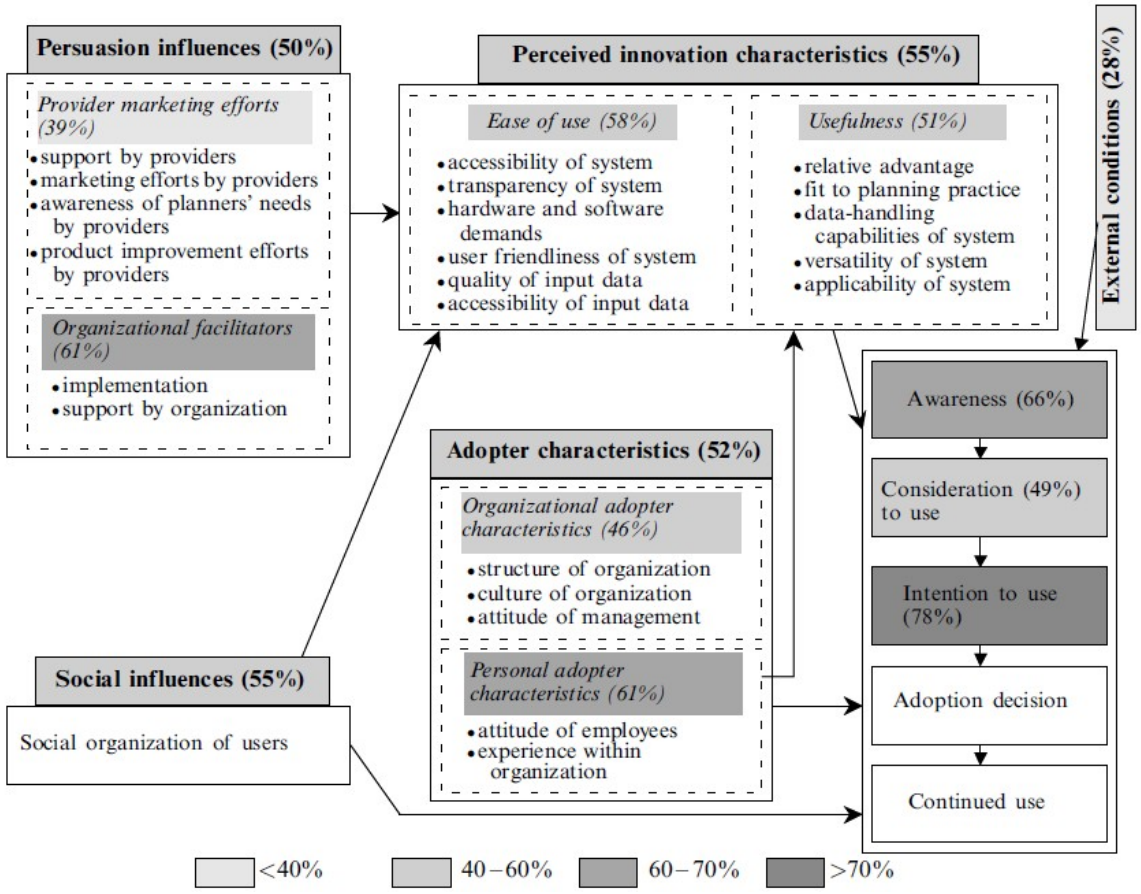

Figure 86. Factors affecting wider spread usage of PSS with importance percentages based on survey results (Vonk et al. 2005).

The survey confirmed that the PSS supply (expressed as "provider marketing efforts" in Figure 86) was less of an issue than the organizational facilitation of PSS adoption, which, in turn, impacted both individual awareness of the systems and intention to use. From a platform development perspective, the results for ease of use (accessibility and transparency; hardware and software demands; and accessibility and quality of input data) and usefulness (relative advantage, fit to planning practice, data-handling capabilities, and versatility) are the most telling.

In 2016, citing the continued lag in PSS adoption more than a decade later, another study tackled the topic of usefulness (defined as both usability and utility), this time within the context of the application of a PSS (Urban Strategy) to a real-world planning situation (a traffic impact study on a former industrial area identified for mixed use redevelopment (Pelzer 2016). Table 25 summarizes that aspects of PSS usefulness that the study examined.

Table 25. Different types of usefulness analyzed in the Urban Strategy case study (Pelzer et al. 2014).

Kind of usefulness	Definition
Learning about the object	Gaining insight into the nature of the planning object
Learning about other stakeholders	Gaining insight into the perspective of other stakeholders in planning
Collaboration	Interaction and cooperation among the stakeholders involved
Communication	Sharing information and knowledge among the stakeholders involved
Consensus	Agreement on problems, solutions, knowledge claims and indicators
Efficiency	The same or more tasks can be conducted with smaller investments
Better informed plans or decisions	A decision or outcome is based on better information and/or a better consideration of the information

Urban Strategy was used in a three-hour workshop with the area team responsible for the redevelopment from the City of Utrecht, Netherlands (n=9: environmental analysts, transport planners, housing experts, and urban designers), and its usefulness was studied via a combination of individual questionnaires and interviews, as well as participant observation. Urban Strategy combines a variety of impact models in a GIS environment (noise, air quality and traffic), with the ability to add different types of land uses, which in turn generate different volumes of car traffic and resulting changes in noise and air quality. It provides three views of the modeling outcomes: 1-D (tables with impact scores), 2-D (a map) and 3-D (relative massings of new land uses and resulting impacts) (Figure 87). In addition to the PSS software, participants were provided with large paper maps, a whiteboard, large screens to access Google Streetview and the municipality website. A technology 'chauffeur' operated the PSS and interpreted the results, and the city's transportation modelers prepared the impact models prior to the workshop.

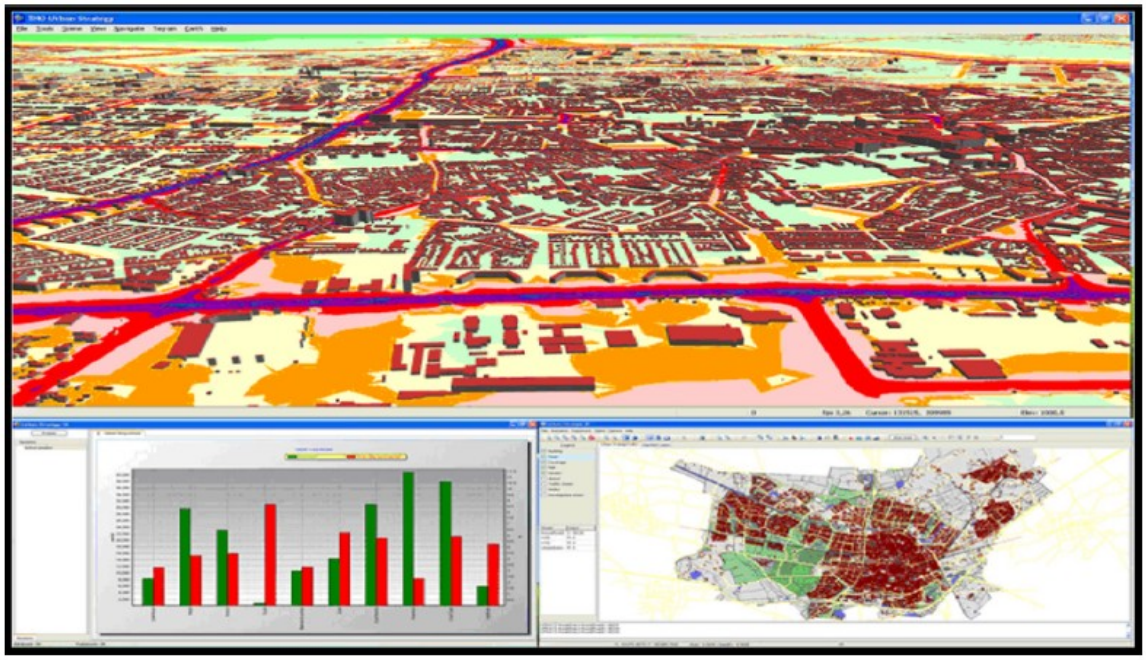

Figure 87. Three views of redevelopment changes and impacts in Urban Strategy (Pelzer 2016).

Following the workshop, participants were asked to choose the most important type of PSS usefulness from Table 26 they had experienced. Pelzer found that there was little consensus among participants, with half emphasizing substantive aspects of usefulness (learning about the planning objective, better informed decisions) and the other half choosing process characteristics (efficiency, communication, collaboration). It is, however, the negative feedback that is most telling for GDSS requirements:

- The models, analysis and calculations rules were not transparent enough, and the analytical support provided by the PSS was hard to understand.
- Other thematic dimensions were missing and could not be added on the fly (e.g. other transportation modalities like bike and rail, although both are very common for daily trips in the Netherlands and there is a train station adjacent to the plan area). Urban Strategy thus limited the substance of the workshop because only car traffic and related environmental legal restrictions could be evaluated.
- Financial analysis was missing.
- Communication about complex topics across disciplines was difficult.
- Working through the technology 'chauffeur' limited collaboration between participants, and limited users' understanding of the PSS itself (Pelzer 2016).

The common concerns from both PSS studies - transparency, versatility, accessibility and fit to planning practice, have been addressed to some degree in both GeoPlanner and Geodesign Hub. Both can be configured with the systems and impacts of interest, and these can be explored by the users while designing. GeoPlanner, in particular, provides full flexibility in the number and types of systems and KPIs that can be included in a geodesign project, and allows the user to interrogate the underlying details. Both provide simple quantitative and comparative interfaces, and can be used by anyone who knows how to open a web browser (although there is a learning curve and some advanced technical skill (and facilitation in the case of Geodesign Hub) required for configuring the systems). Both tools can also be used for most of the planning tasks that Vonk et al. (2005) emphasized, especially forecasting, analysis, sketching and evaluation. The following sections explore what is still missing in terms of technology and both of the high-level geodesign functional tasks – modeling and collaboration.

5.5.1 Technology

A platform-oriented approach to developing a GDSS depends upon a loosely-coupled, component-based, interoperable system architecture that can be flexibly integrated. Services, which were introduced in section 5.2 in conjunction with AGOL, deserve more explanation at this point, as the key enabling technology for interoperability and integration. Services, or more accurately web services, are standardized software interfaces, and can be distinguished conceptually by their role in information exchange as consumers and providers. Service consumers and providers exchange messages over a network via the same hypertext transfer protocol used by web browsers. Services are the cornerstone of SOA (service-oriented architecture), which has already been widely adopted

as a part of the enterprise IT strategy to decouple software applications, data management, and complex business algorithms (Krafzig et al. 2005). Through services, which provide an abstraction layer, any system can expose data or functionality for any other system to use, and the internal implementation or even the entire underlying software can be changed without affecting the service consumer as long as the service interface stays the same (service versioning allows for interface changes if necessary).[124]

The World Wide Web Consortium (W3C) released the original web service specification in 2000[125], and OGC (Open Geospatial Consortium) has expanded upon these to accommodate geographic information, first with a web map service specification, followed by web feature and web processing services.[126] Web feature services can be used to develop representation models, access the output of process models, and create change models. Web processing services can be used to develop evaluation and impact models, and they can be combined for decision models. GeoPlanner already partially implements this approach- all data is added via feature services and the outputs of analyses are published as feature services. Also, all of the functions in the 'Explore' segment's analysis tools are processing services, rather than 'built-in' application functionality (Figure 88).

[124] This description is purposefully very high level. As both a consultant and a developer for the Deutsche Post's SOP (Service-Oriented Platform) group (one of the case studies in the Krafzig et al. reference), I have both enterprise IT strategy experience and deep technical knowledge from which to draw upon.
[125] SOAP (Simple Object Access Protocol) 1.1. Available from https://www.w3.org/TR/2000/NOTE-SOAP-20000508/.
[126] OGC Standards. Available from http://www.opengeospatial.org/docs/is.

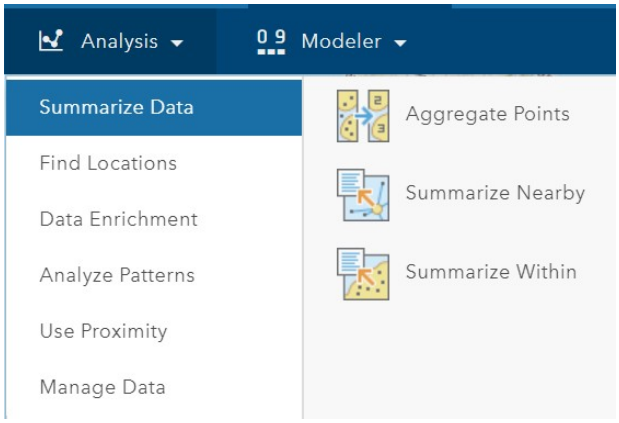

Figure 88. All of the analysis functions are processing services, hosted by AGOL, rather than 'built in' functionality in GeoPlanner.

GeoPlanner's service-oriented approach with data and analysis is definitely a step in the right direction. However, neither it nor AGOL allow users to add external processing services, which would greatly enhance the application's flexibility and usefulness for planning where expert systems are frequently used for process analysis (e.g. traffic impacts, housing demand, flooding, fire spread, species dispersal, disease vectors). More fundamentally, while many levels of government now offer data via feature services discoverable in geoportals, processing services are not yet common in the public realm. Academic and research institutions are developing and using them, see the ChainBuilder hosted by ASU's GeoDa Center, UIUC's CyberGIS Gateway, and SDSC's OpenTopo for examples; however, commercial providers will need to come online to simplify the interface designs and ensure a robust level of service.

5.5.2 Modeling

As we move from static to interactive to increasingly complex integrative models, the aphorism "All models are wrong but some are useful.", attributed to statistician George Box, is good to keep in mind. Lewontin and Levins also remind us "Different abstractions from the same wholes capture different aspects of reality but also leave us with different blindnesses" (2007, 150). The way a system is conceptualized reflects a particular

perspective or world-view, and defines the range of variables, their variability, and their relationships in more concrete modeling phases. Model assumptions and limitations need to be transparent to users and include information about gaps and uncertainty. Much of the work in the first two iterations of the framework involves conceptualization, which can be more formally supported by conceptual modeling tools. The conceptual models and cross-model relationships, from which computational models are derived, should be integrated into the geodesign platform, so they can be reviewed in relation to their computational implementation.

A digital library of conceptual models, with references to the resulting computational models would also help manage the complexity of working with large amounts of information. The GeoPlanner application discussed in section 5.2 supports attachments of documents to projects as a static solution for associating conceptual models with the geodesign context. Geoportals, mentioned in the previous section, offer a more dynamic solution where all services can be hosted, and associated metadata, additional documents, and data/model relationships can be explored.[127]

There are many different levels of granularity when conceptualizing a system, and the amount of detail to include in a conceptual model really depends on the question at hand, as well as the disciplinary perspective of the modeler. A biologist would model species lifecycle, habitat, community, and migratory behavior in far more detail than a conservation planner trying to identify areas of the landscape to protect from urban

[127] See https://www.geoplatform.gov/ for a geoportal example, hosting nearly 125,000 federal data services.

encroachment. The decision-driven scoping approach recommended by Steinitz (2012) in the first iteration of the framework can help identify which level of granularity is needed. If appropriate, expert knowledge can serve as input to a more high-level model, and that model can be annotated with source information to provide a better understanding of the generalizations being made.

There are also many different digital modeling tools available and representation 'languages'. UML (Unified Modeling Language) is a highly elaborated notation often used in software development and entity-relationship diagrams, but can be applied to other types of system representations because of it's broad 'vocabulary' (Figure 89). Other approaches are simpler in their notation, but more prescriptive in the types of models developed like the conceptual models described on Landscapetoolbox.org, which include control models for how an ecosystem is organized and functions as well as state-and-transition models and mechanistic driver or stressor models (Figure 90). Whatever the choice, both the language and the modeling tool should be easy for the geodesign team to understand and use. Teams may also find existing conceptual models that can be adapted for the geodesign context. For example, the NRCS, USGS, BLM, and Nature Conservancy are developing conceptual models that are part of an ecological site description and available through the NRCS Ecological Site Information System.[128]

[128] See https://esis.sc.egov.usda.gov/Welcome/pgESDWelcome.aspx for a searchable database of ecological site descriptions and their related conceptual models. Unfortunately, this system is not connected to a geoportal.

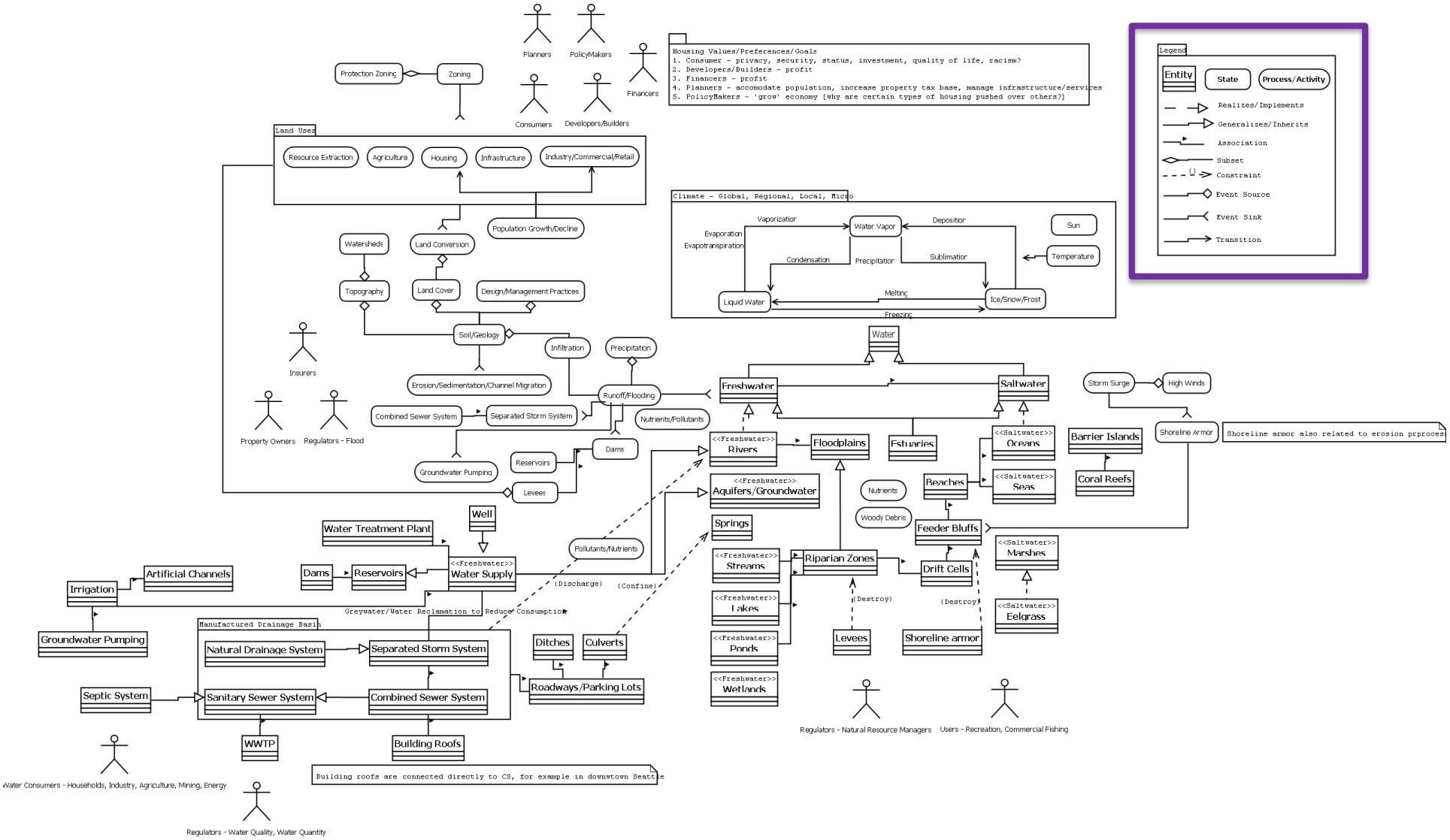

Figure 89. A conceptual model for a socio-ecological water system with actors, entities, states, processes and relationships developed in UML. The purple box highlights the legend, which describes the formal UML notation.

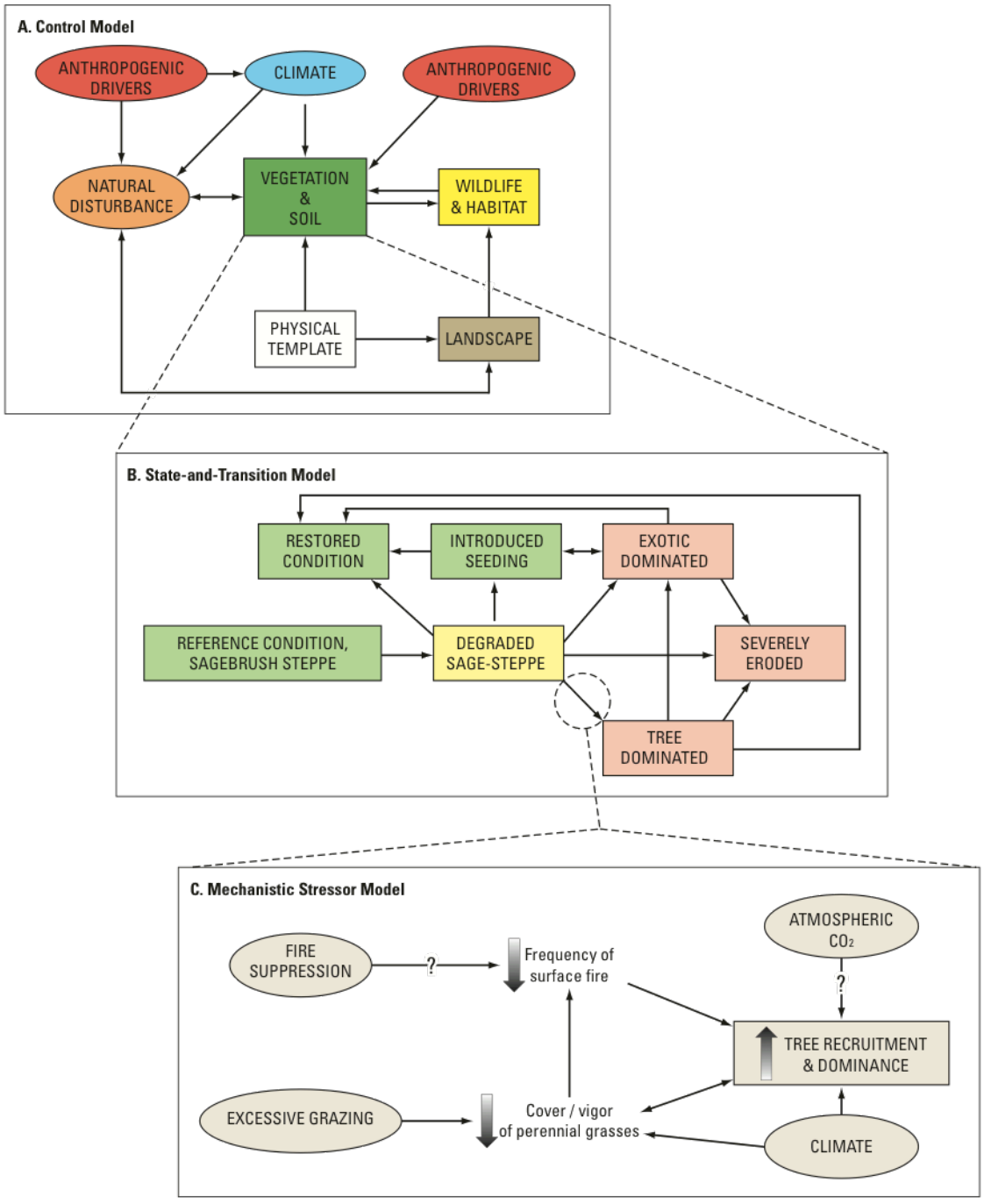

Figure 90. An example of a multi-level conceptual model used in ecosystem analysis (Landscapetoolbox.org). The notation does not follow a formal standard, but is easy to comprehend.

In both the conceptual models illustrated above, and throughout the Seattle green infrastructure geodesign study, an important model variable was implicit – time. Three-dimensional models are still uncommon outside of the design fields, although gaining broader application as software tools evolve, and four-dimensional models or time-based simulations are generally only available in advanced modeling environments (e.g. agent-based, cellular automata, and network models). In order to translate time from an implicit conceptual dimension to a computational construct in later modeling phases and improve our ability to explore complex system interactions, Nyerges et al. (2014) contend that spatial data models needs to be expanded to incorporate six types of spatial-temporal dynamics (change, process, movement, activity, event and interaction (Yuan and Stewart 2008, Goodchild et al. 2007)).

Through the MOESIR framework (Measurement-informed Ontology and Epistemology for Sustainability Information Representation), Nyerges et al. describe how space-time dynamics can be modeled as relationships between system elements to form composite objects. Drawing from Brinberg and McGrath's (1985) ten levels of information gain the relationship model would include logical order (causality of influence between elements), direction (of influence), form (linear, non-linear, or monotonic rate of influence), mechanism (deterministic, probabilistic, or rule-based), stability (random, systematic, or periodic), and external influences (on either or both of the system elements) (Nyerges et al. 2014). In computational terms, the relationships would be data types like the feature classes (points, lines and polygons) that we use to develop static representation models. ArcGIS does include a relationship class that can be added to a data model, but these simply

establish the connection between two elements and be used for simple network queries (e.g. calculate the shortest path, find connected or disconnected network elements, trace 'upstream' and 'downstream' elements). Specialized simulation models embed specific types of spatial-temporal dynamics through customized programming routines, which prevents integration among different types of models and limits the reusability of these models in different geodesign contexts. The use of a shared ontology would address these issues as well as improving epistemological value of our models as we move from concepts to computation.

5.5.3 Collaboration

Collaborative problem-solving has been characterized as workflow to achieve a joint outcome (Jankowski and Nyerges 2001, Balram and Dragicevic 2006a, 2006b, Nyerges, Ramsey, and Wilson 2006). Designing computer systems that support collaborative problem-solving like that required in a multi-system, multi-dimensional geodesign context, however, requires a deeper understanding about collaborative activity and the underlying analytic-deliberative process. Analytic-deliberative processes exhibit a balance of investigation (analysis) and discussion (deliberation), and provide a mechanism not only to make decisions, but also to enhance knowledge production for all those involved (National Research Council 1996, 2005, 2009). Geodesign Hub was modeled after the Steinitz design studio workflow (Ballal 2015), thus the collaboration features, while grounded in geodesign practice, are largely limited to design aggregation and design comparison, with final selections occurring through face-to-face, or at least, synchronous negotiation where the analytic-deliberative process is implicit and secondary to the final design outcome.

Jankowski and Nyerges (2001) describe four modes of participation – communication, cooperation, coordination, and collaboration within information technology-supported environments, as a way to decompose the various tasks and capabilities needed when individuals and teams are distributed across time and space. Communication is the simplest transfer of information between individuals and groups. Cooperation is the mutual exchange of a communicative activity, wherein participants might agree to exchange the outcomes of their separate knowledge products, without the expectation that the cooperation continues. Coordination involves sequenced turn-taking of those cooperative exchanges, thereby building upon exchanges in a systematic manner. Coordination of work activity in a teamwork context is a significant challenge, but the key in deep knowledge production (Smith 2000). Collaboration commonly makes use of highly interactive sequences of turn-taking such that within an agreed upon timeframe knowledge has been produced and decisions can be made.

Starting with the four participation modes, Nyerges, Ramsey, and Wilson (2006) outlined several principles, goals, and capabilities needed to support the four modes of participation within the context of online systems for analytic-deliberative decision support as the focus area for collaborative problem-solving. They articulated the following five principles and fourteen associated design goals for developing capabilities.

- Principle 1: participation should be open, fair, and equitable.
    - Goal 1.1: system is easy to use by all; Goal 1.2: encourage many kinds of contributions; Goal 1.3: avoid privileging any particular kind of contribution; Goal 1.4: downplay domination by a vocal few; and Goal 1.5: provide equitable access to all information.
- Principle 2: participants are free to deliberate anything that connects to the topic.
    - Goal 2.1: an agenda setting capability is needed that can absorb change upon agreement from the group.

- Principle 3: group process must be augmented with consensus-resolution capabilities.
    - Goal 3.1: polling, ranking, and other aggregative capabilities are needed to assess positioning of topics; and Goal 3.2: voting is needed to clear decision gates before proceeding to next steps.
- Principle 4: encourage transformations of perspective to move beyond entrenched positions at the start of the analytic-deliberative process.
    - Goal 4.1: recruiting participants with diverse backgrounds, interests, and perspectives encourages comprehensive consideration of issues; Goal 4.2: encourage and accommodate expressions of differences, including those of conflict; and Goal 4.3: encourage contributions that are engaging and compelling.
- Principle 5: deliberation supports and encourages analytic information contributions.
    - Goal 5.1: provide analytic information relevant to the complex problem under consideration; Goal 5.2: make experts (policy, technical, and stakeholder public) available as appropriate; and Goal 5.3: support and encourage deliberation about the meaningfulness of the relevant information.

Based on those principles and goals, Nyerges, Ramsey, and Wilson (2006) and Avraam (2011) examined structured participation methods from the strategic planning literature, and synthesized across the planning outcomes to form general strategies. Structured-participation methods are systematic approaches for coordinated turn-taking with alternating steps of analysis and deliberation in the knowledge production process. Many of the methods developed through the years (like Nominal Group Technique (NGT), Delphi, Technology of Participation (ToP), and others) provide a foundation for generating and synthesizing ideas about a common theme in an organized way, and reaching a consensus on an appropriate synthesis that addresses a stated common goal. Literature about rational (satisficing) decision making has provided insight about how consensus is reached through intelligence, design, choice, and iterative reflection (Simon 1979). Similarly, structured participation methods use techniques that resemble this sequence:

idea generation, synthesis, and consensus (Avraam 2011; Nyerges, Roderick, and Avraam 2013).

To test the hypothesis that structured participation methods are needed to support analytic-deliberative collaborative problem-solving in a distributed, online environment, the University of Washington's Participatory Geographic Information Systems Technologies (PGIST) Group developed an online decision support field experiment called Let's Improve Transportation (LIT) Challenge based on a modified moderator-driven Delphi process (Nyerges and Aguirre 2011). The aim of the experiment was to explore large-scale public participation during analytic-deliberative decision-making about proposed improvements to the regional transportation system. The LIT Challenge convened 179 people from the King, Pierce, and Snohomish counties of Washington State who participated in an online process composed of mapping daily travel, brainstorming transportation concerns, assessing different goals and factors for transportation improvement, developing personalized transportation project packages from 60+ projects worth billions of dollars, evaluating and prioritizing selected packages, and creating a group report of the agreed upon packages. Although participants did not sketch their own transportation networks and analyze resulting multi-system impacts, many aspects of the experiment mirror geodesign modeling tasks.

The PGIST Group also developed a modified ToP process for a field experiment called Voicing Climate Concerns (VCC) (Nyerges, Wright, and Aguirre 2010). The VCC field experiment supported public participation in resource management along the Oregon

Coast, focusing on climate change impacts. It involved four phases, each consisting of two steps. The design enabled individuals to work alone, then subsequently merge their work with the group during 1) idea generation, labeling, and synthesis, 2) prioritization, and then 3) complement their concerns resulting in a data specification for 4) mapping climate change vulnerability. An intermediate step enabled expert users to introduce non-binding commentary in the process that provided further information to participants if needed. The modified ToP process enabled a bilateral, participant-driven synthesis of the multiplicity of concerns about climate change conditions (hazards and receptors) and the development of vulnerability mapping recommendations – an activity that could both develop public issue awareness and help scope the decision context before beginning a formal geodesign study.

Both of these experiments led to the refinement of structured participation methods in an asynchronous, online context and demonstrated their utility in large-scale knowledge production, collaborative problem-solving and consensus-building. However, both were implemented as standalone, topic specific web applications. A pluggable and customizable user interface is needed for a GDSS to provide analytic-deliberative support through structured participation for any type of geodesign problem. Integration with the CyberGIS Gateway, a geospatial analysis environment that utilizes a parallelized and distributed supercomputing architecture and integrates data and processing services from multiple academic institutions as well as Esri, posed a similar challenge and led to the development of the Structured Participation Toolkit (SPT) (Wang 2010, Nyerges, Roderick, and Avraam 2013). The SPT is deployed as pluggable graphical user interface (GUI) widgets that can

be embedded in any web application interface, and uses remotely hosted processing and persistence layers, consistent with a service-oriented architecture approach (Figure 91).

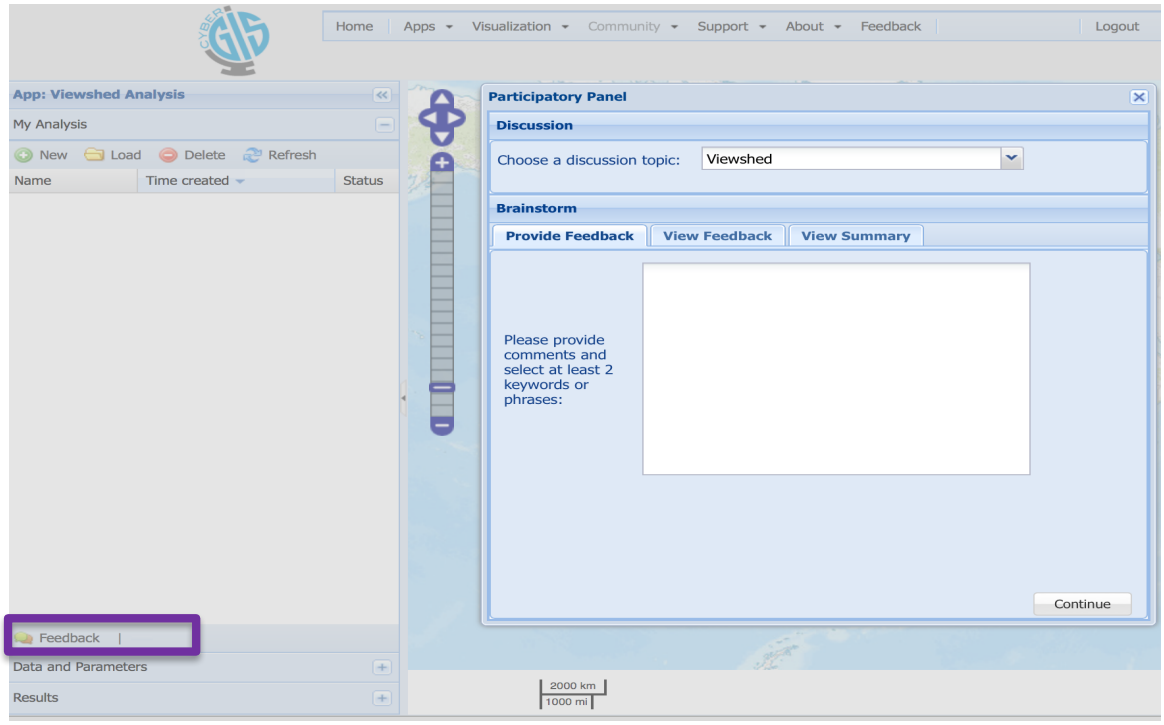

Figure 91. The SPT Brainstorming widget (triggered by the 'Feedback' function highlighted in the purple box), allows users to deliberate the analysis results or functional implementation of different CyberGIS Gateway applications (in this case Viewshed Analysis). After providing feedback and keywords, users can view and comment on other participants contributions, vote to indicate agreement or disagreement, and see a summary of the keywords and agreement or disagreement among participants.

The SPT was also integrated into ASU's Chain Builder for a watershed planning application to demonstrate the capability of both for flexibly developing a GDSS. The application allowed users to, for example, create different reforestation scenarios and see the related hydrologic impact of their designs. The workflow for the application was created interactively using a dependency editor (Figure 92) that connected data and processing services with each other and to user interface elements (e.g. maps, polygon sketching tools, buttons, text boxes). The application information, design and decision dashboards, which included the SPT, were then generated from the workflow (Figure 93) (Pahle, Roderick and Nyerges 2014)

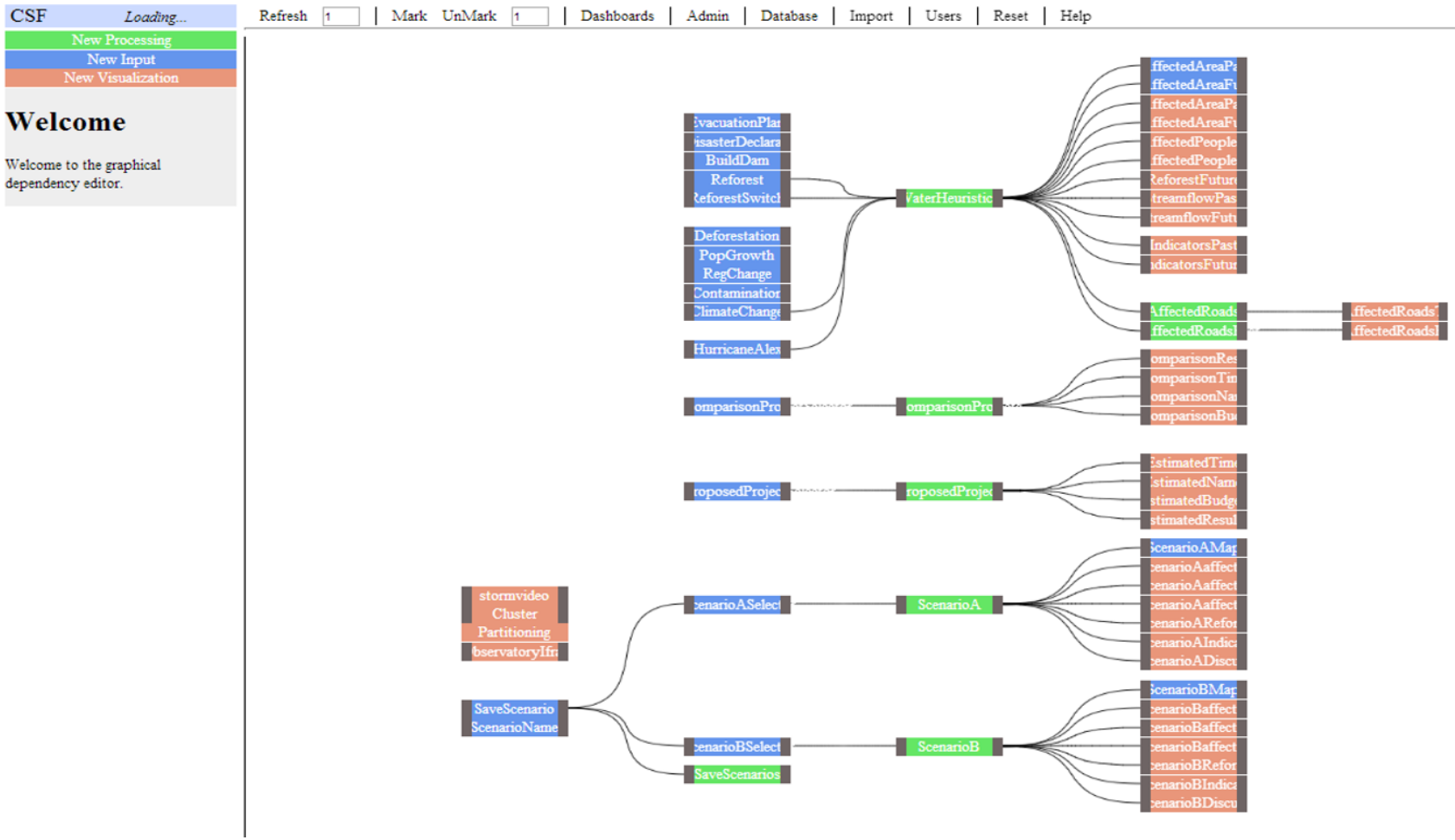

Figure 92. ChainBuilder's Dependency Editor interface and workflow for the watershed planning application. The blue boxes are inputs: either data services or user input elements that will appear in the dashboard. The green boxes are processing services, and the orange boxes are the visualizations of the analyses and design outcomes.

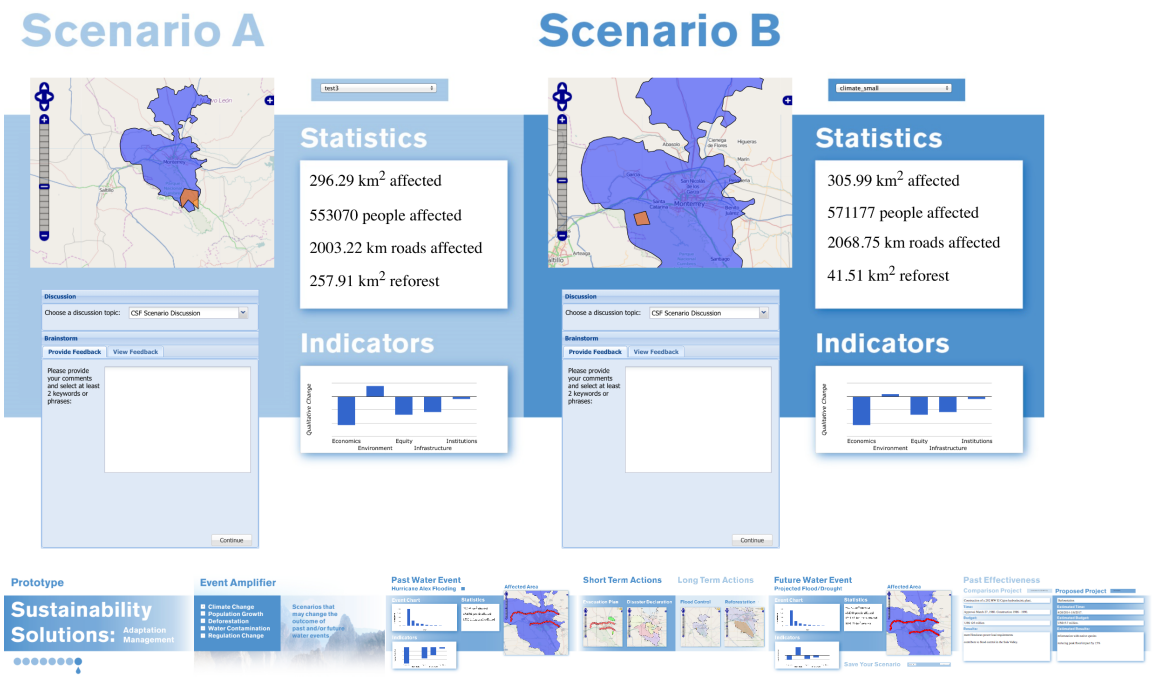

Figure 93. Excerpt from the user interface dashboard for watershed planning that was generated from the workflow depicted in Figure 92. The scenarios compare two different reforestation areas sketched by different users, and the related impacts. The SPT Brainstorming widget below the map enables users to comment and vote on each scenario.

The SPT allowed structured participation methods to be seamlessly integrated into both the CyberGIS Gateway and ChainBuilder to support large-scale, asynchronous participation; structured analytic deliberation; consensus-building and decision-making; as well as to provide an open, transparent decision repository and participation metrics for reporting and analysis. In cases where the geodesign team is accountable to a broad and diverse group of stakeholders, like publicly-funded green infrastructure projects, transparency in the analytic-deliberative process is important not only for assessing the relevance and validity of the analysis and design outcomes, but also for gaining public understanding and support for the design proposals.

5.5.4. Add-ons

This chapter focused on additional modeling and collaboration requirements for a GDSS, particularly conceptual modeling, spatial-temporal dynamics and structured analytic-deliberative participation, as well as key platform-enabling technologies and tools (e.g. service-oriented architecture, data and processing services, geoportals, pluggable GUI widgets). Steinitz (2012) and Ervin (2011) also enumerate 15 elements of a GDSS (Figure 94). While conceptual modeling is not specifically addressed, they do generally refer to the need for four-dimensional models, collaboration support, and integrated and interoperable IT systems. These and the additional elements are divided into three categories: semantics (the meaning and linkages that serve as sources of geodesign ideas), syntax (the parts and relations that are the specifics of the study), and dynamics (the tasks and activities of a geodesign study). Several aspects have already been implemented in either or both of the previously reviewed geodesign software applications including: context base (i.e. base map and representation models), objects (i.e. feature classes, entities and their relationships), modeling/scripting tools, hyperlinked information library, KPI dashboards, and design diagram and version managers.

Three other GDSS features included in the 15 elements have yet to be addressed: constraints (i.e. rule-based design generation), level of abstraction manager (i.e. a mechanism for supporting various levels of design detail from simple schematics to fully elaborated designs), and geodesign methods coach (i.e. automated design suggestions and critique). However, there are precedents for each of these in other systems that can be leveraged in a GDSS. Rule-based design generation (e.g. 3-D extrusion of building height

attributes, parking garage capacities generated from minimum parking requirements, community build-out based on zoning regulations), in particular, is already supported in many different CAD software for landscapes and buildings, as well as in Esri's CityEngine for urban design. When the design process has moved from general land use allocation and exploration to site/project-level specification, the advanced design capabilities of these tools can be used, and the outputs exported to the GDSS for broader multi-system impact analysis and decision-making. Esri's synchronization support between CityEngine and AGOL already illustrates this type of integration, and addresses the de facto management of different levels of abstraction. Through the different design capabilities of different tools, the design naturally evolves from a more general to more detailed representation. (Figure 95). Conceptual models provide another option for exploring the levels of abstraction needed throughout the geodesign study (see the multi-level ecological model in Figure 90), and for the intellectual management of these models and their relationships.

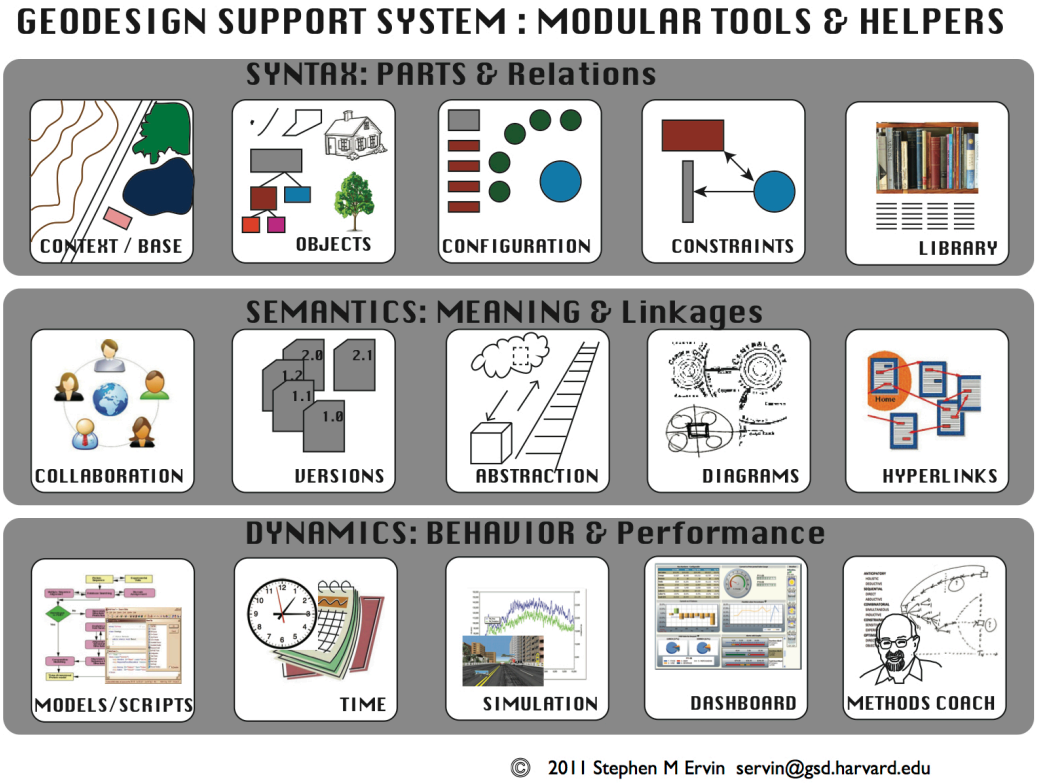

Figure 94. GDSS elements proposed by Ervin (2011). Note, Steinitz (2012) re-organizes these slightly, switching the categorization of 'Time' and 'Versions' and well as of 'Library' and 'Hyperlinks'.

Figure 95. Example of integration between systems supporting advanced design capabilities like rule-based design generation (block-scale massing based), and more generalized design representation (2-D zoning layer). Here zoning polygons can be updated in AGOL (or using other Esri tools like GeoPlanner) and replicated to City Engine.

The Geodesign Methods Coach is likely the most elusive element to implement. Ervin relates this functionality to the 'Library', which could also contain design precedent case studies in addition to information specific to the current geodesign study. The methods coach would provide interactive intelligence that would "help diagnose problem characteristics, suggest appropriate design methods, and help structure methods in the process. This module could record and classify design processes, and could learn over time, over many different geodesigners and projects, and become more and more valuable, linked up to the library described above." (2011, 155). While the full spectrum of this type of automated intelligence is not yet available, many online systems do already have 'recommendation' features that can recognize and learn patterns in user behavior and preferences, and recommend related items either from a content perspective or from the analysis of other users' choices (Isinkaye, Folajima and Ojokoh 2015).

These recommendation systems rely of various types of shared meaning that can be assigned (e.g. categories, topic keywords) or derived from implicit characteristics (e.g. artist name, era, genre). In the realm of geodesign, this type of shared meaning would need to be explicitly specified as a formalized ontology (i.e. basic terms, elements and concepts organized in a taxonomy (Li et al. 2012)) that classifies and codifies geodesign concepts, problems and related solutions so that they can be organized and managed in a GDSS. Although IT systems are increasingly capable of inference and fuzzy concepts and relationships, a formal ontology is still foundational for information management and machine learning. Li et al. also make the case for developing an ontology for geodesign, bottom-up and from multiple perspectives, to serve as a community resource that promotes

dialog and shared understanding among researchers and practitioners as the field evolves (2012).

Recognizing these ontological needs and benefits, the Spatial Decision Support Consortium (SDSC), which formed in 2008 to foster collaboration among spatial decision support researchers, technologists, and practitioners[129], created the Geodesign Knowledge Portal modeled after their Spatial Decision Support Knowledge Portal. The portal organizes the geodesign ontology, which is based up the SDSC's spatial decision support (SDS) ontology, into several sub-ontologies, many of which have been addressed in this dissertation, including problem types; context; process; design strategies, methods and techniques; technology; domain data and knowledge; people and participation; and resources (Li et al. 2012). Contributors include several of the researchers mentioned in this this paper: Steinitz, Ervin, Miller, Geertman, Nyerges, and Li, as well as many other leading thinkers in the geospatial sciences. It also includes technology developers, geodesign consultants, government agencies, and non-profits.

The geodesign ontology is organized as nodes and linkages that can be explored via an interactive web interface using different entry points and different types information structures (e.g. hierarchical and graphical). By late 2011, the ontology included over 900 classes (i.e. collections, types of objects), 500 instances (i.e. individual entities or objects), and 200 properties (i.e. attributes and relationships). The content was derived from nine

[129] Spatial Decision Support Consortium home page. Available from http://www.sdsconsortium.org/home. Accessed on 11/10/2017.

different geodesign process workflows, 100 design and analysis methods, 80 tools and models, 20 data models, 20 data sources, 15 case studies and 700 publications related to research in geodesign, planning, and spatial decision support (Li et al. 2012). A more recent count has not been summarized, nor is there delta between geodesign and SDS ontologies to identify how many topics specific to geodesign have been added. However, the status six years ago provides a perspective on how much the field has already grown, and provides a further reinforcement for the need for a geodesign ontology to track and organize the vast amount of related information so that it can be used to inform new geodesign studies, methods, tools, and technologies, fulfilling, in part, the role of the coach envisioned by Ervin and Steinitz.

Chapter 6. Conclusions

This dissertation provided an in-depth synthesis of green infrastructure planning in Seattle across multiple scales and functions. From the planning case studies presented in Chapter 2 and further detailed in Chapters 3 and 4, it is clear that the City of Seattle has embraced green infrastructure as a means to improve ecosystem function and services throughout the city, and the more recent emphasis on equity planning (particularly related to parks, trails, urban agriculture, urban forestry, water quality and climate change impacts) improves access to the benefits of these services for all of the city's residents. Through the Green Goal, the city has also made a commitment to a more integrated approach to green infrastructure planning, at least for stormwater management. The city, however, has not yet addressed how to coordinate its green infrastructure development beyond GSI in the right-of-way.

The geodesign framework was applied to the city's diverse forms of green infrastructure to demonstrate a systematic approach for developing a shared synthesis and for identifying potential synergies and trade-offs between systems based on current conditions and future-oriented plans. By iterating through the geodesign framework, the complexity of GI across multiple scales, functions, and departmental requirements was successively simplified to narrow in on clear synergies and a few potential conflicts. Some of the synergies were not surprising. The systems considered vulnerable to change – floodplains, wetlands, riparian/shoreline areas, and habitat, largely overlapped due to their shared near-shore character and previous planning efforts to protect these areas. The evaluation models for GSI and urban agriculture, systems attractive for development, accounted for their

relationship with vulnerable systems and avoided potential conflicts. Although Steinitz (2012) recommends that the systems be evaluated independently, the vulnerable systems provided the primary constraints in the case of GSI and were already included in the previous urban agriculture suitability analysis used for this study (with the exception of 0.28 acres in floodplains that were identified through the impact analysis).

The main conflicts revealed in the evaluation, change and impact modeling phases were between GSI and urban agriculture and between GSI and parks, where areas considered optimal for their development overlapped. Conceptually, these conflicts were already apparent; however, the models provided a spatially explicit perspective from which to make decisions. The additional information from the development targets further relativized the conflict potential. The overlap between areas optimal for GSI and urban agriculture were minimal (only 1.5 acres). Although the city currently does not have a concrete development target for urban agriculture, preserving this space to meet the aspirational goal of increasing food production in the city would still leave 28,934 acres optimal for GSI development (note: rooftops and other impervious surfaces were not considered a limiting factor in the GSI analysis, although these cannot be converted entirely to GSI so this number is inflated). The potential for conflict between GSI and parks is also relativized by the SPR's 2035 development target of only 40 new park acres, which can be accommodated within the 388 acres that are optimal for parks and marginal for GSI.

Although the geodesign framework provided a useful structure for a detailed investigation of Seattle's green infrastructure, which is a novel application of the framework and a

contribution to geodesign-based planning knowledge in this dissertation (Steinitz 2012, Ballal 2015), the information was difficult to manage and correlate in the narrative format of this dissertation. Digital support is needed throughout the entire framework, and, of course, is essential to enable a collaborative study among teams distributed in space and time. A further contribution of this dissertation is a detailed examination of the tools and technologies needed to cyber-enable the full spectrum of the geodesign framework. Tools like GeoPlanner and Geodesign Hub have already been developed to digitally support some of the analysis and modeling aspects of the framework, and technologies like web services and geoportals already exist to increase their flexibility and extend their data management and analytic capabilities. Other aspects like conceptual modeling, and structured participation methods for analytic-deliberative decision-making also have IT system precedents, but all of the existing tools and technologies need further development on the basis of a shared ontology for geodesign to realize the potential of a comprehensive, interoperable geodesign support system.

6.1 Future Research

This study was based on extensive analysis of existing green infrastructure plans and implementation; however, participant observation studies of actual planning processes, like the city's multi-departmental effort to integrate GSI in the right-of-way or more broadly to achieve the Green Goal, would provide much needed insight into the day to day tasks of green infrastructure planning across multiple city departments and with other stakeholders (e.g. other levels of government, developers, citizens). The geodesign framework could then be assessed against green infrastructure planning practice to identify potential mismatches or gaps and additional conceptual and functional requirements for a GDSS.

Although the framework has been used in both academic and public workshop settings, the structure of the planning process was determined by the framework, rather than assessing the fit of the framework to existing processes. From a more practical perspective, green infrastructure implementation is also driven by non-profits, private development, and other levels of government. A synthesis of these green infrastructure planning activities with those initiated by municipalities is missing. At the other end of the spectrum, it would also be instructive to evaluate the geodesign framework through the lens of different schools of planning thought (e.g. rational, strategic, collaborative, communicative, advocacy, pragmatism, incrementalism, and agonism). Planning practice certainly draws from these and more, so it would be helpful to situate the framework in this literature.

From a geographic information science perspective, there are also several areas that would also benefit from further research. At the most fundamental level, a data modeling and management approach is needed to normalize the representation of green infrastructure features and networks, much like that which has been developed for streets and water supply. SPR has started modeling their green stormwater infrastructure features and SPU is planning a full inventory as well to support hydrologic modeling. These efforts need to be evaluated and harmonized with other types of related green infrastructure models like watersheds and tree canopy assessments. The shared ontology for geodesign discussed in Chapter 5 should support these efforts to ensure cross model compatibility, and can be used to evaluate the relevance of the exiting ontology to these types of domain-specific models.

Once the green infrastructure representation model has been elaborated, the spatial-temporal relationship model described in MOESIR needs to be incorporated to enable dynamic process models to be specified rather than hard-coded in specialized programming routines. This is a broader need in geographic information science, and not specific to green infrastructure. However, the multi-functional and multi-scalar nature of green infrastructure would lend itself well for prototyping these types of model relationships. Once the representation and process models have been more fully developed, software support can be further expanded to incorporate conceptual modeling and structured participation, as well as linkages, based on the shared ontology, across all levels of modeling.

In the age of the Anthropocene and widespread, ever-increasing urbanization, coupled with the ubiquitous degradation of ecosystem services and the increasingly severe impacts of climate change, strategic green infrastructure planning will be essential for improving the adaptive capacity of our cities and citizens. While frameworks, models, technology and IT systems are not sufficient for addressing the many issues we face, they are essential for understanding the complexity of system interactions and the outcomes of planning and design decisions. We live in a world full of information, and need to learn how to harness all of our analytic and persuasive capabilities to inform the tough decisions that need to be made to improve our world for ourselves and the generations that come.

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Note: All planning documents, authoritative websites, and news articles are referenced in footnotes.

Appendix A. Seattle Employees Interviewed for Study

Each interview was conducted in person, except where noted, in September 2013, and followed a semi-structured format. See questions in Section 2.2 Research Methodology. Each interview lasted approximately one hour. Further clarification occurred via email. Interviews were not coded for content analysis as they would have been to identify common or reoccurring themes. Instead they were used as an investigative tool to supplement publicly available planning documents with more detailed information about the planning process and plan development.

- Tom Hauger, Climate Action Plan & Comprehensive Plan, tom.hauger@seattle.gov
- Susanne Rockwell, Parks Legacy Plan, susanne.rockwell@seattle.gov
- Sharon Lerman, Food Action Plan, sharon.lerman@seattle.gov
- Pam Emerson, Green Goal/GSI Implementation Plan, pam.emerson@seattle.gov
- Susan Harper, Protecting Our Waterways, susan.harper@seattle.gov
- Edward Mirabella, LCTP (Sewage Overflow Reduction Alternative), edward_mirabella@seattle.gov
- Kevin Buckley, Integrated Plan (Sewage and Stormwater Pollution Reduction Alternative), kevin.buckley@seattle.gov
- Sandra Pinto de Bader, Urban Forestry Stewardship Plan, Sandra.Pinto_de_Bader@seattle.gov
- Cyndy Holtz, Cedar River Watershed Habitat Conservation Plan, cyndy.holtz@seattle.gov
- Brent Lackey, South Fork Tolt Watershed Restoration Plan, brent.lackey@seattle.gov
- (Email Only) Karen Galt and Rodney Young, SPR Green Infrastructure GIS Mapping, karen.galt@seattle.gov and rodney.young@seattle.gov