Table of contents:

Overview

What is Stormwater?

One of the primary terrestrial pressures on the Salish Sea estuarine and marine environment is urban stormwater runoff. When rainfall runs across hard, impervious surfaces, rather than soaking into the soil, it picks up and delivers toxic contaminants directly to nearby streams, rivers, and eventually the Salish Sea. In fact, for most toxic substances, surface runoff is the largest contributing source of loading to Puget Sound (Washington State Department of Ecology 2011).

Unfortunately, the Salish Sea's relationship with stormwater effluent is no outlier; stormwater is the fastest growing cause of surface water impairment in the United States as urbanization transitions forested and other natural landscapes to hard, impervious surfaces (United States Environmental Protection Agency 2019). Given that the Salish Sea is expected to house another 5 million people by 2040, stormwater interventions will be necessary in order to break the relationship between urbanization and stormwater-caused ecological degradation.

Fortunately, researchers have uncovered a variety of successful techniques to reduce stormwater impairment of surface and receiving waters, including street sweeping, pervious pavement, and green stormwater infrastructure wherein stormwater is filtered by soil and plant mixtures on its way between the streets and the sea. These interventions are costly (~$65-132 billion is needed to restore Puget Sound to hydraulically function like a forest), but the costs of stormwater pollution are high as well: the sickening and deaths of Salish Sea organisms. Annual losses due to one contaminant (polycyclic aromatic hydrocarbon exposure) alone are estimated to be between $4.4 to $12.1 billion (King County 2014; Washington State Department of Ecology and Washington Department of Health 2012).

> **URBAN STORMWATER RUNOFF IS A TWO-FOLD PROBLEM.**
>
> It impacts the quantity of water pulsing off the land, as well as the quality of that water.
>
> As a result of stormwater's twin problems, urban watersheds and marine receiving waters suffer from "urban syndrome"- a condition that results in low abundance and survival of sensitive aquatic and coastal species (Walsh et al. 2005). Virtually all urban streams and rivers in Puget sound have been harmed by stormwater pollution (Booth et al. 2004).

Water Quantity

Watersheds with as little as 5-10% impervious surface area- such as rooftops, roads, and paved parking areas- exhibit aquatic habitat degradation as a result of increased surface runoff (Walsh et al., 2005). This changes the timing, magnitude, and frequency of high flow events, making urban streams “flashier” than those with natural surrounding landcover conditions. These hydrological changes cause combined sewer overflow events, flooding, erosion, and scouring of stream and riverbeds. Flashy hydrology disrupts habitat structure and alters the ecology of freshwater ecosystems themselves, but also disrupts larger ecosystem processes in marine environments such as nutrient flux, organic matter processing, and ecosystem metabolism (Palmer and Ruhi 2019). While coastal food webs rely on rivers to deliver organisms, nutrients, and detritus from the land to the sea, these fluxes increasingly result in negative impacts, such as eutrophication, hypoxia, and harmful algal blooms.

Water Quality

In addition to altering hydrological flow regimes in watersheds contributing to the Salish Sea, urban stormwater also delivers a suite of contaminants that severely impact the water quality of streams, rivers, estuaries, and the Salish Sea itself. Urban runoff contains complex and unpredictable mixtures of chemicals, including persistent organic pollutants (i.e. PCPs), heavy metals (i.e. copper, zinc), hydrocarbons (i.e. motor oil, tailpipe emissions, rubber tire particles), nutrients (i.e. nitrogen, phosphorous), pesticides, and pharmaceuticals. Toxic pollutants entering the Salish Sea may be metabolized in plant and animal tissues, bioaccumulated in tissues, incorporated into sediments, volatized, degraded, or conserved in marine waters.

Toxic Stormwater Impacts

Researchers have documented toxic effects of stormwater exposure for a diverse range of aquatic and marine species, ranging from primary producers to high trophic-level predators. Some effects are sublethal, reducing species fitness and long-term survival. For example, heavy metal accumulation is common among marine macroalgae and eelgrass (Zostera Marina), reducing photosynthetic function (Jarvis and Bielmyer-Fraser 2015; Lyngby and Brix 1984). Other sublethal impacts of stormwater on marine organisms include the reduction of byssus strength in marine mussels (Gaw, Thomas, and Hutchinson 2014), reduced olfactory function in juvenile salmonids (Baldwin, Tatara, and Scholz 2011), reduced growth and lipid storage in juvenile Chinook (Meador, Sommers, and Ylitalo 2006), reduced pathogen resistance in juvenile salmon (Arkoosh et al. 2001), cardiotoxicity in juvenile fish (Incardona, Linbo, and Scholz 2011), decreased reproductive function and immune response in benthic fishes (Rice et al. 2000), seals (Anan et al. 2002), and Southern Resident Killer Whales (Kayhanian et al. 2012; Ross et al. 2000; WDFW 2011).

Some effects are acutely lethal, as is the case for adult coho salmon, where pre-spawn mortality rates in urban streams can be as high as 90% (Scholz et al. 2011). These fish end their years-long journey to the ocean and back with their bellies still full of unfertilized eggs, missing their single chance to spawn the next generation.

For coho, it appears that pre-spawn mortality is linked to the transportation network, where contaminants, like tire wear leachates, are generated (Feist et al. 2017). Thus, development expansion and increasing use intensity of the built environment is significantly impacting the long-term viability of local Coho populations, with far-reaching ramifications for both freshwater and marine food webs alike. And while it is tempting to focus on lethal impacts to iconic species such as coho, road runoff is similarly lethal to lower trophic level organisms, such as mayfly larvae, sea urchins, and amphipods, which all play important roles in upholding marine, freshwater, and terrestrial food webs (Anderson et al. 2007; Kayhanian et al. 2012; McIntyre et al. 2015).

Moving forward

Identifying where stormwater pollution is generated on the landscape

A much repeated phrase from stormwater managers is “how much and where” do we need to implement stormwater BMPs (Best Management Practices)? This is a difficult question to answer until we identify our ecological and social goals for stormwater management. The amount and spatial configuration of stormwater interception techniques will look very different depending on whether the goal is to meet permit regulations, recover coho salmon, or recover Southern Resident Killer Whales because biological organisms are susceptible to stormwater contaminants for different reasons, in different locations, at different scales, and at different points in time according to their life history traits (Levin, Howe, and Robertson, n.d.). Answering the “how much and where” question will therefore require integrating ecological data with stormwater monitoring and pollution loading data.

However, a promising starting place to answer the “how much and where” question is to build a predictive map quantifying levels of stormwater pollution loading across the landscape. This type of ‘threat’ heatmap can be coupled with ecological data to produce action maps for stormwater intervention.

To build the predictive stormwater pollution heatmap, we focused on three major steps:

1. Landcover Refinement: we generated a high resolution landcover dataset enabling landcover mapping at the 1-m^2 resolution. This is a critical level of resolution for urban runoff modeling because impervious surfaces so strongly drive hydrologic response, and therefore pollution loading. Thus, accurate mapping of impervious surfaces was needed to accurately calculate surface runoff.

2. Hydrology: we conducted continuous hydrology simulations for the 32 different hydrologic response units (HRU = combination of landcover, soils, & slope) found within the Puget Sound domain. Using regional precipitation datasets provided by the Climate Impacts Group, we modeled both current and future hydrology in order to assess how climate change will impact stormwater pollution loading across the landscape, generating more than 311 billion rows of data. This dataset alone provides an efficient way to quickly model rainfall-runoff relationships across Puget Sound using the Western Washington Hydrology Model (WWHM).

3. Pollution Statistics: We used Bayesian statistical modeling to link stormwater monitoring data to land use and land cover characteristics to predict pollution concentrations across the landscape. These concentration predictions were then combined with hydrology output to generate the pollution load across the Puget Sound landscape at a 1-m^2 spatial resolution.

The resulting interactive tool enables users to visualize and aggregate stormwater pollution loading data at several spatial resolutions for local, watershed, and regional-scale planning. The project reveals that areas with high percent cover of impervious surfaces, such as hard cityscapes, as well as industrial and commercial zones, tend to produce higher pollutant loads than high-density residential, low-density residential, and rural areas. Transportation networks- roads and highways- generate very high levels of stormwater contaminants, especially those with higher traffic intensity. These high intensity roads can cut through lower-density areas, lighting up as pollution hotspots. Traffic behavior (i.e. congestion points) also plays a role, indicating that a combination of a static landscape structure and dynamic anthropogenic behavior layered atop that structure can combine to create stormwater pollution hotspots throughout the landscape.

Using the stormwater heatmap as a foundation, we can begin to integrate the ecological layers to understand exactly where on the landscape stormwater interventions will be most efficient and effective at breaking the link between urbanization and aquatic degradation. Examples of spatialized biotic response data generated by robust local monitoring programs include NOAA’s MusselWatch, King County’s Benthic-Index of Biotic Integrity (B-IBI), and NOAA’s coho pre-spawn mortality monitoring. WDFW’s Salmonscape data represents another source of ecological information, showing the timing and spatial habitat use of different species of salmonids. With respect to human well-being Front and Centered’s Environmental Health Disparities Map offers data-driven insights on human health in the region.

Building an interactive tool to service stormwater manager needs

The mapping tool is especially timely because the Washington Department of Ecology recently issued a new stormwater permit which increased the number of jurisdictions required to develop and implement stormwater management plans. Historically, just 4 stormwater permittees were required to submit detailed stormwater management plans and models. Now, 85 jurisdictions must develop stormwater management plans and be able to scientifically defend their prioritization and decision-making process.

In order to help move more jurisdictions towards this goal/requirement, The Nature Conservancy embarked on a Design Thinking project to better understand what tools those smaller Phase II cities and counties would need in order to meet permit requirements. The Design Thinking approach centers on a structured interview process that is human-centered. Through interviewing stormwater planners, engineers, and leaders throughout the Puget Sound region, this process identified “pinch” and “release” points that currently prevent or promote effective stormwater management. The Design Thinking project emphasized that a tool supporting stormwater management in the region requires the following elements:

- **Compelling Visuals**: tools should help stormwater managers tell a story to different audiences.
- **Multiple Scales**: stormwater planning takes place at the parcel, neighborhood, watershed and regional scale. Data need to be flexibly aggregated at all scales.
- **Make it Mine-able**: serve as a data platform and resource for use with other tools. Land cover, soils, hydrology, and climate change impacts data would help meet multiple modeling needs.
- **Grounded in Science**: data and calculations should be apparent and meet current best practices.

For many of the smaller jurisdictions, financial, and personnel constraints are significant barriers to effective stormwater management and innovation. Most projects are opportunistic, and many stormwater management departments have only one employee.

This stormwater management tool is targeted for stormwater managers in order to 1) get the best available science and tools into the hands of decision-makers, 2) lower the costs for effective decision making and planning, and 3) improve Puget Sound water quality and recover ecological health.

Thus, in addition to the stormwater pollution loading data layer, the online mapping tool also includes data extraction capabilities and report modules that service requirements outlined by the Department of Ecology’s stormwater permit. The modules can be flexibly applied at multiple scales, and include:

- Land Use/Land Cover
  - Land cover classification (% cover)
  - Land use
  - Imperviousness
- Hydrology
  - Hydrologic response units
  - Mean annual runoff
  - Flow-control metrics

- Climate change impacts
- Pollutant loading
    - 25th, 50th, 75th concentration quantiles
    - 25th, 50th, 75th annual loading quantiles
- Other
    - Age of development
    - Estimated population

Open data helps us bound forward

Early adopters are currently testing the capabilities of the data, analyses, and approaches generated by the Stormwater heatmap project. King County is using the hydrology modeling output to prioritize and resize culverts for fish passage. Our Green/Duwamish is using the tool for stormwater management action planning, the City of Tacoma is using it for watershed prioritization, EPA's Office of Research and Development are integrating this work with the VELMA runoff model, and the City of Phoenix and Maricopa County are using it for a regional LID study.

The stormwater heatmap is an open-source tool, free for use by the public[1]. Code will be accessible on the stormwater heatamp Github repository.

The Stormwater heatmap can be used as a foundational layer to answer many social-ecological questions to benefit people and nature. It is built for you, with stormwater management in mind. Please use, modify, and distribute this work widely. See where you can take it!