Sustainable Flood Risk and Stormwater Management in Blue-Green Cities; an Interdisciplinary Case Study in Portland, Oregon

O'Donnell, E.C., Thorne, C.R., Yeakley, J.A., Chan, F.K.S.

University of Nottingham
UK | CHINA | MALAYSIA

University of Nottingham Ningbo China, 199 Taikang East Road, Ningbo, 315100, China

First published 2020

Sustainable Flood Risk and Stormwater Management in Blue-Green Cities; an Interdisciplinary Case Study in Portland, Oregon

Emily C. O'Donnell, Colin R. Thorne, J. Alan Yeakley, Faith Ka Shun Chan

School of Geography (O'Donnell, Thorne), University of Nottingham, University Park, Nottingham, NG7 2RD, UK; Department of Geography & Environmental Systems (Yeakley), University of Maryland Baltimore County, Baltimore, Maryland, USA, School of Geographical Sciences (Chan); University of Nottingham Ningbo China, Ningbo, China (Correspondence to O'Donnell: emily.o'donnell@nottingham.ac.uk)

Research Impact Statement: Interdisciplinary research in Portland, Oregon USA, provides an enhanced evidence base to justify adoption of Blue-Green Infrastructure (BGI) for sustainable flood risk and stormwater management.

ABSTRACT: Blue-Green Infrastructure (BGI) is recognized as a viable strategy to manage stormwater and flood risk, and its *multifunctionality* may further enrich society through the provision of multiple co-benefits that extend far beyond the hydrosphere. Portland, Oregon USA, is an internationally-renowned leader in the implementation of BGI and showcases many best practice examples. Nonetheless, a range of interdisciplinary barriers and uncertainties continue to cloud decision-making and impede wider implementation of BGI. In this paper, we synthesize research conducted by the 'Clean Water for All' (CWfA) research project and demonstrate that interdisciplinary evaluation of the benefits of Portland's BGI, focusing on green street bioswales and the East Lents Floodplain Restoration Project, is essential to address biophysical and socio-political barriers. Effective interdisciplinary approaches require sustained interaction and collaboration to integrate disciplinary expertise towards a common problem-solving purpose, and strong leadership from researchers adapt at spanning disciplinary boundaries. While the disciplinary differences in methodologies were embraced in the CWfA project, and pivotal to providing evidence of the disparate benefits of multifunctional BGI, cross-disciplinary engagement, knowledge co-production, and data exchanges during the research process were of paramount importance to reduce the potential for fragmentation and ensure research remained integrated.

KEYWORDS: Blue-Green Cities, Blue-Green Infrastructure, Green Infrastructure, Portland Oregon, Stormwater, Sustainable Urban Flood Risk Management

INTRODUCTION

Municipalities across the United States are increasingly using Green Infrastructure (GI) as a cost-effective measure to manage stormwater and improve water quality (McPhillips and Matsler, 2018; Shandas et al., 2020). Several factors have helped drive the transition from a traditional approach using centralized gray stormwater management infrastructure towards more decentralized GI facilities that retain or reuse stormwater on-site. This includes; the federal endorsement of GI as a primary stormwater management technique (EPA 2008); the recognition that GI can deliver a variety of environmental, societal and economic co-benefits and ecosystem services (Kremer et al., 2016), and; the need for water resource management systems that are adaptive to change and resilient to extremes (Rijke et al., 2013). Exemplar GI programmes further demonstrate the potential for GI to meet a range of challenges, e.g., in Portland, Seattle, New York City, North Carolina and San Francisco (City of Seattle, 2015; Kremer et al., 2016; Trogrlić et al., 2018; Shandas et al., 2020) and Philadelphia, the first city in the United States to attempt an entirely green approach to meeting federal regulations (Fitzgerald and Laufer, 2016).

The city of Portland, Oregon, has one of the oldest and most successful GI programs in the United States and is an internationally-renowned leader in the implementation of GI to manage stormwater for the promotion of sustainable development practices, climate change adaptation, and improved liveability (Lukes and Kloss 2008; Rottle 2015). An excessive burden on the City's drainage system and repeat discharge of sewage into the Willamette River due to frequent combined sewer overflow (CSO) events in the 1990s led the Portland municipal authority to search for an alternative to using conventional 'gray' infrastructure to supplement the 'Big Pipe' Project needed to substantially reduce the frequency of CSOs (BES 2019a, accessed November 2019). In its "Grey to Green" initiative, the City invested widely in GI implementation to help alleviate loadings on the piped infrastructure system and reduce adverse impacts on urban watercourses. These ongoing efforts have, to date, delivered over 2000 street bioswales, more than 600 ecoroofs and tens of thousands of street trees. The City of Portland, and notably the Bureau of Environmental Services (BES), have promoted a variety of best management practices and embraced *Blue-Green principles* of reintroducing elements of the natural water cycle into urban environments. BES have invested in widespread culvert removal, purchasing of properties at high flood risk from willing sellers, reconnecting and restoring urban streams and floodplains, and reintroducing native vegetation and wildlife (including beaver (*Castor canadensis*) and several species of Pacific salmonids (*Oncorhynchus*)) (BES 2019b, accesssed November 2019).

Portland is clearly progressing towards becoming a *Blue-Green City*; where a naturally-oriented water cycle that mimics pre-development hydrology is created through reduced imperviousness, increased infiltration, enhanced surface storage, reintroduction of native water retentive plants, restoration of urban watercourses, and improvements to water quality and aquatic environments (Novotny et al. 2010). In a *Blue-Green Cit*y, the hydrological and ecological values of the urban landscape are protected while providing resilient and adaptive measures to deal with flood events and improve the amenity of the city (Hoyer et al. 2011). Blue infrastructure includes the flowing waterways, ponds, wetlands and wet detention basins that exist within the drainage network. Green infrastructure is "*an approach to wet weather management that uses soils and vegetation to utilise, enhance and/or mimic the natural hydrological cycle processes of infiltration, evapotranspiration and reuse*" (EPA 2019, accesed December 2019). In this context, we define the Blue-Green Infrastructure (BGI) adopted in pursuit of Blue-Green ideals as a combination of the two; an interconnected network of natural and designed landscape components that includes blue and green spaces, and green spaces designed to turn 'blue' during rainfall and flood events.

BGI is increasingly recognized as enriching society through the provision of multiple co-benefits beyond water and flood risk management, and its *multifunctionality* is fundamental to its growing appeal. In addition to stormwater abatement, BGI can support climate change adaption (to, for example, extreme storms, heatwaves, and droughts); lengthen the useful life of ageing, gray infrastructure; improve wildlife, biodiversity, air and water quality; increase landscape connectivity and access to greenspace; improve health and wellbeing, and; create attractive landscapes that enhance quality of place (Demuzere et al., 2014; Netusil et al., 2014; Kabisch et al., 2016; Fenner, 2017; Hoang et al., 2018; Venkataramanan et al., 2019). Despite this, BGI is typically implemented from the perspective of a single benefit, often stormwater management (Kabisch et al., 2016).

An interdisciplinary approach is therefore needed to comprehensively evaluate the multiple co-benefits of Blue-Green approaches to flood and water management that extend beyond the hydrosphere, and facilitate the development of strategies to overcome the barriers to implementation that are known to encompass the biophysical, social and political spheres (Thorne et al., 2018). The natural and societal components of stormwater management interact in complex ways and desired societal results are rarely achieved by addressing the scientific aspects in isolation (Morss et al., 2005). Interdisciplinary research emphasises interaction and joint working to integrate disciplinary expertise towards a common problem-solving purpose and avoids partial framing of key societal challenges (Bruce et al., 2004; Lowe and Phillipson, 2006). The objective is to create knowledge that is solution-oriented, socially robust and more easily adopted by policy makers and practitioners (Gibbons, 1999).

However, the development of an interdisciplinary approach challenges our disciplinary training and ways of thinking (Klein, 2008). In this paper, we introduce the interdisciplinary approach adopted by the 'Clean Water for All' (CWfA) research project (2014-2015), that brought together disciplinary scientists from academic institutions in the UK, US and China, under the themes of Water Engineering, Resilience and Sustainability, to tackle questions posed by the interactions between humans and landscapes. Through collaborative research, this project co-produced solution-oriented, transferrable knowledge, focusing on evaluating the multiple co-benefits delivered by BGI in Portland, Oregon. As a result, long-term collaborative partnerships were formed between academics working on; the UK Engineering and Physical Sciences Research Council (EPSRC) funded 'Blue-Green Cities Research Project' (www.bluegreencities.ac.uk) (Lawson et al. 2014); the US National Science Foundation (NSF) funded 'Portland-Vancouver ULTRA (Urban Long-term Research Area) research project' (www.fsl.orst.edu/eco-p/ultra) (Chang et al. 2014), and; academics at the University of Nottingham Ningbo China, researching sustainable flood risk and urban water management in Chinese 'Sponge Cities' (Chan et al. 2018).

The overarching aim of the interdisciplinary CWfA research project was to build a substantive evidence base to justify adoption of BGI, while developing a greater understanding of design modification to co-optimise the multiple benefits of a conurbation choosing to become a *Blue-Green City*. The hypothesis underpinning the research is that implementing multifunctional BGI that delivers co-benefits can help multiple stakeholder organizations and departments meet their strategic objectives not only in relation to flood and water management, but also climate change adaption, urban heat island reduction, greenspace development, biodiversity improvement, public health and wellbeing, and recreation and amenity.

We frame this paper around the interdisciplinary barriers, or ‘Relevant Dominant Uncertainties’ (RDUs), which continue to cloud decision-making and impede wider implementation of BGI in Portland (Theme 1), and show how research into flow and suspended sediment dynamics (Theme 2); sediment-related, heavy metal contaminants and river habitats (Theme 3); community perceptions and acceptance of BGI (Theme 4), and; multiple co-benefit evaluation (Theme 5), can reduce some of these uncertainties. The insights of our disciplines were used in the context of stormwater management in Portland to co-produce the evidence base to support BGI as a means of enhancing the environment and society. The disciplinary differences in methodologies were embraced but of primary importance was the cross-discipline engagement and data exchanges during the research process to marry the interdisciplinary appeal with the disciplinary mastery (Klein, 2008). We synthesize the key research findings of the CWfA research project and illustrate the importance of multidirectional communication, sustained interactions among researchers, and an iterative approach to co-produce knowledge and tools in delivering interdisciplinary research outputs (Morss et al., 2005). We close with recommendations for researchers and practitioners involved in interdisciplinary flood risk and stormwater management projects.

STUDY LOCATION

Portland is situated near the foothills of the Tualatin Mountains, at the confluence of the Columbia and Willamette Rivers, west of the Cascade Range, Oregon. The maritime climate is typical of the Pacific Northwest, being marked by cool, wet winters and hot, dry summers. Average annual precipitation in Portland is about 1400 mm (Velpuri and Senay 2013), which generates approximately 450 000 m^3/y of stormwater runoff (BES, 2015).

CWfA research focused on the City of Portland administrative area and, particularly, Johnson Creek, a 42 km long tributary of the Willamette River (Figure 1). The 134 km^2 Johnson Creek watershed is subdivided into numerous, smaller rural, peri-urban and urban catchments of varying size (0.006-0.7 km^2) and comprises mixed land-use, with forest, agriculture and rural residential characterising the upper watershed and urban development in the middle and lower reaches (Sonoda et al., 2001). In approximately 75% of the catchment, stormwater is conveyed to Johnson Creek through a piped network and a series of outfalls, without treatment. During the 1980s, high concentrations of heavy metals, the presence of E. coli *(Escherichia coli),* and elevated stream temperatures led to many reaches of Johnson Creek being classified as 'impaired' under article 303(d) of the Clean Water Act (EPA 1972). BES, with assistance from the Johnson Creek Watershed Council (JCWC) and multiple other private organizations, subsequently invested in extensive river restoration, riparian planting, and installation of BGI to gradually restore and reconnect the creek to its remaining floodplains, reduce local flood risk (JCWC 2012), and improve water quality through, for example, installation of set-back stormwater outfalls and pocket wetlands designed to trap pollutants (Janes et al. 2016). A total of 209 restoration projects were undertaken between 1990 and 2014, producing positive impacts ranging from the return of native salmon (*Oncorhynchus*) to increases in the values of nearby residential properties (Jarrad et al. 2018). The East Lents Floodplain Restoration Project is a good example of urban stream restoration and floodplain re-creation. This project regenerated the 28 ha 'Foster Floodplain Natural Area' in lower Johnson Creek (Figure 1) (BES 2013, accessed November 2019). Briefly, this extensive project (implemented over a 15 year period) was designed to reduce 'nuisance flooding' (by events with return periods between <1 and 10 years) that had for decades inundated low-lying homes and businesses adjacent to Johnson Creek and blocked Foster Road, causing widespread traffic disruption and associated impacts on local residents, commuters, and businesses (The Oregonian 2012, accessed March

2019). Families were moved out of 66 private properties within the 1-in-100 year floodplain, under the Willing Seller Land Acquisition Program, to re-create a natural basin for flood storage, conservation and recreation.

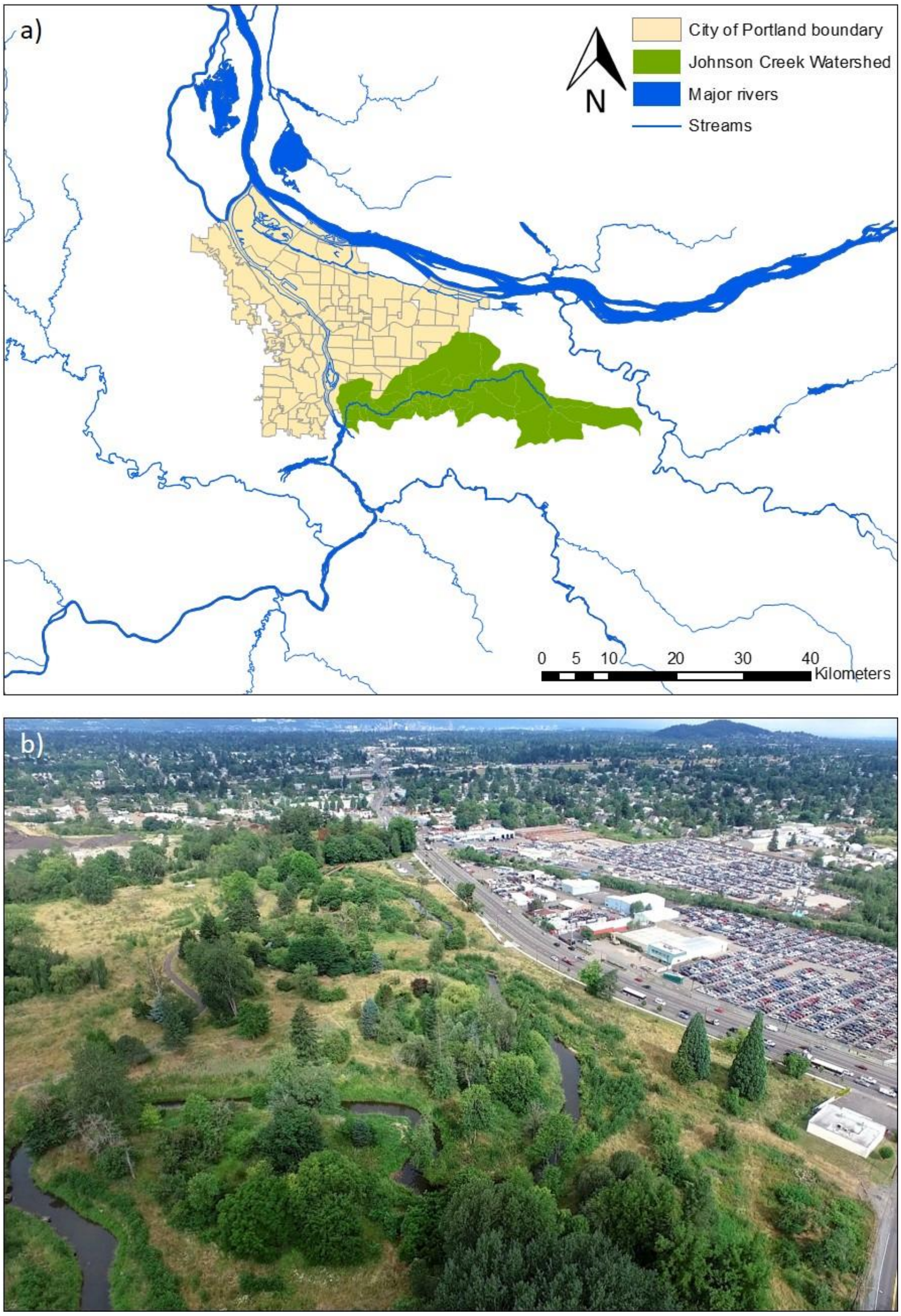

Figure 1. a) Study area in Portland, Oregon, and b) aerial photograph of the East Lents Floodplain Restoration Project on Johnson Creek (photo by Naim Hasan Photography 2016, © City of Portland, courtesy of the Bureau of Environmental Services (BES)).

During the last two decades, the City of Portland invested $1.4 billion in CSO control through 'Big Pipe' projects (East Side, West Side and Columbia Slough), aimed at improving water quality in the Willamette River. Pipe construction completed in 2011 and has eliminated 94% of CSOs to the Willamette River and 99% of CSOs to the Columbia Slough (BES 2019a, accessed November 2019). The monetary cost, and indeed the size of the required pipes, would have been much larger were it not for parallel investment in numerous GI projects, especially those implemented under the $55 million "Grey to Green" program conducted between 2008 and 2013 (BES 2010). This program included several Cornerstone Projects that help keep billions of gallons of stormwater runoff out of the combined sewer system annually, significantly contributing to the huge reduction in CSOs (BES 2019c, accessed November 2019), while generating a wide range of environmental, ecological and social co-benefits. For example, approximately 1.2 billion gallons of stormwater runoff reduction can be attributed to the Downspout Disconnection project (1993-2011) (Figure 2a), which provided financial incentives to residents to encourage them to disconnect their roof drainage from the combined sewer system and redirect runoff into their gardens. In total, 56,000 disconnections were made.

The City of Portland has an impressive portfolio of GI assets, including street trees, ecoroofs, deculverted watercourses, areas of re-introduced native vegetation, and restored and reconnected streams and floodplains. Over 2000 "green streets" transform impervious street surfaces into landscaped, green spaces featuring stormwater curb extensions, bioswales, and street planters that manage stormwater runoff at source (BES 2019c, accessed November 2019) (Figure 2b-d). Through these and other efforts, Portland has begun to make the urban water cycle more like the natural hydrological cycle, while meeting targets for urban regeneration, growth, and promoting the aesthetic appeal of the GI.

Figure 2. Blue-Green Infrastructure (BGI) and stream restoration activities in Portland. a) Downspout disconnection in a residential area of East Portland, b) large wood structure constructed in Johnson Creek as part of the East Lents Floodplain Restoration Project, c) rain garden at Mount Tabor primary school, d) typical green street bioswales. (Photos: E. O'Donnell, April 2013 (a, c, d), May 2014 (b)).

INTERDISCIPLINARY RESEARCH THEMES AND PROCESS

The CWfA research project adopted an interdisciplinary approach with the integration of disciplines driven by interactions and joint-working amongst CWfA consortium members motivated by a common, problem-solving intent. Relationships between the research themes were identified as being interactive and complex, and so a range of methodologies and routes to problem solving were developed and applied. However, as the goals were to jointly address the research questions and co-evolve understanding and knowledge, it was essential to maintain close integration between members of the consortium. As the project progressed, the team developed a research program in which disciplines were not the focal points. Instead, the inputs of the researchers were distributed and blended to ensure that each theme had the disciplinary-based experiences, skills and competencies necessary to address the specific research question at hand.

CWfA research was performed through a carefully sequenced series of actions, arranged in five themes that ran concurrently, providing a stable framework for executing the project (Figure 3). The framework was designed to address discrete elements of the complex issues surrounding urban flood risk and stormwater management. It further demonstrates the range of disciplines necessarily involved in BGI projects that move beyond analyses of their hydrologic, hydraulic and engineering performance to identify and evaluate the multiple co-benefits that may accrue. The specific methods used to meet the objectives of each research theme were not necessarily wholly innovative within a disciplinary context; rather when taken collectively they result in innovative research (i.e. the sum is greater than the parts).

Theme 1 sought to identify barriers that continue to hinder implementation of BGI, a topic central to the project as uncertainties impact all aspects of BGI research. Geographically, this theme spans the entire Portland administrative area. Themes 2, 3 and 5 focused on the East Lents Floodplain Restoration Project, which was selected because its implementation included large-scale floodplain reconnection, urban stream restoration and creation of multifunctional

BGI. Theme 4 investigated public attitudes to bioswales, which are a fundamental component of Portland's Green Streets Policy.

Interdisciplinary research was made possible by strong linkages between research themes through which knowledge and expertise were shared. For example, particle size distribution data collected in Johnson Creek as part of Theme 3 (sediment, contaminants, morphology and riparian restoration) were also used in Theme 2's sediment transport model, to simulate sediment dynamics in Johnson Creek and the reconnected East Lents floodplain. The questions developed by Theme 4 to determine community perceptions of bioswales received input from the interdisciplinary team who highlighted functional and aesthetic aspects that may influence public attitudes. We continue to refer back to the importance of interdisciplinary research as we synthesize the key outputs from each research theme. Brief descriptions of the methods are given, and the source databases, reports and publications are signposted. The synthesis presented here shows the necessity of interdisciplinary research to tackle the myriad barriers to widespread implementation of BGI, and to co-develop the evidence base that demonstrates the multiple benefits of BGI.

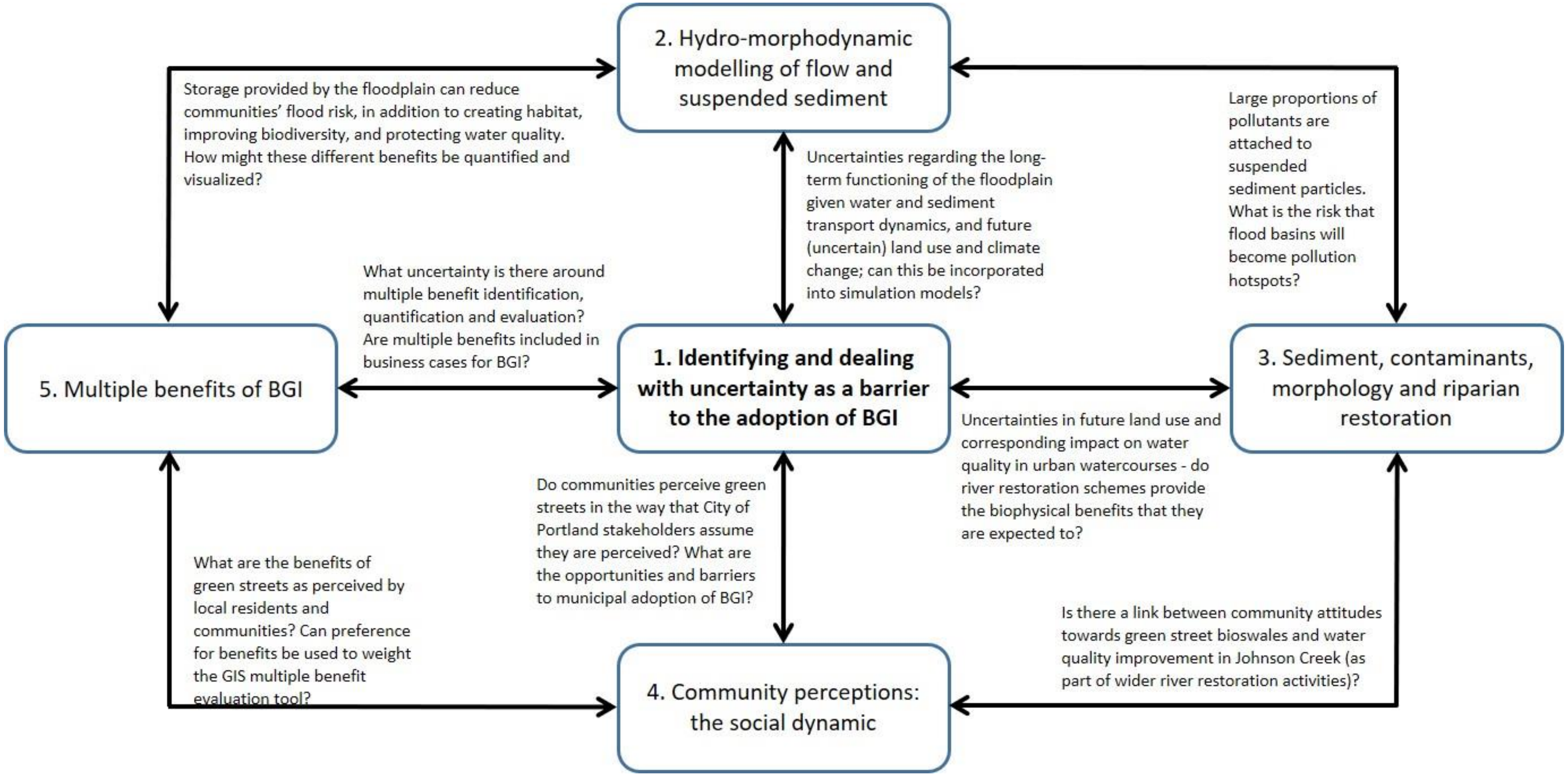

Figure 3. Populated workflow illustrating the links between the five Clean Water for All (CWfA) research themes and examples of where the themes may jointly address research questions and generate interdisciplinary outputs. BGI = Blue-Green Infrastructure, GIS = Geographical Information System.

Theme 1. Identifying and dealing with uncertainty as a barrier to the adoption of BGI

Implementation of BGI projects requires alignment of planning frameworks, engineering design, construction practices, maintenance strategies, ownership/adoption agreements and community acceptability. Despite the successes of the 'Grey to Green' transition, diversity of BGI already built in Portland, and proven advantages of Blue-Green over equivalent gray infrastructure (Casal-Campos et al. 2015), uncertainties remain within each stage of the implementation process that collectively hamper further innovation in stormwater management. In Portland, known uncertainties relate to the hydrologic performance of BGI and a lack of confidence among decision-makers that BGI will be publicly acceptable. Typically, socio-institutional barriers are believed to exert more of a negative influence on sustainable drainage decision-making than hydrological factors (Carlet 2015). These specific uncertainties nest within broader, interdisciplinary challenges that affect all infrastructure projects, including the impact of climate change, delivery of socially-equitable schemes, and communicating complex technical and planning issue to communities.

Theme 1 investigated these uncertainties through a series of semi-structured interviews with institutional stakeholders in the City of Portland (hereafter referred to as 'City of Portland stakeholders'). Twelve respondents in total were interviewed, from the Bureau of Environmental Services, Bureau of Planning and Sustainability, Bureau of Transport, and Metro. The Relevant Dominant Uncertainty (RDU) approach was applied to identify known unknowns most likely to limit the capacity for decision-makers to make more informed choices (Smith and Petersen 2014), in this case, around BGI. The full methods and outputs are presented in Thorne et al., (2018) and briefly described here.

First, the CWfA researchers involved in this theme individually listened to the recorded interviews and/or read the transcripts in order to identify and rank the RDUs (based on frequency and intensity with which each interviewee referred to each RDU). The findings were then shared and discussed through a Delphi-like sequence of exchanges and debates until consensus regarding the RDU classifications and rankings were reached. In addition to identifying fifteen RDUs, sub-divided into biophysical and socio-political RDUs (Figure 4), thirteen concerns (issues respondents are worried about) and eleven challenges (which result from aforementioned concerns) were identified. Socio-political RDUs were found to exert the strongest negative influences on BGI decision-making in Portland. The strongest RDU resulted from lack of confidence on the part of City officials and technical leaders that the public and their elected representatives would continue to understand, support, and be willing to pay for BGI. Fewer biophysical RDUs were identified by the stakeholders interviewed, with the most prominent being the impact of climate change on the current and future performance of BGI.

Overcoming uncertainty as a driver for interdisciplinary research. The range of biophysical and socio-political RDUs identified by the City of Portland stakeholders show the importance of an interdisciplinary approach to generate the evidence that is clearly needed to reduce these uncertainties and support widespread implementation of BGI. This is because the RDUs are not unique to a single research discipline. Decision-makers must have greater confidence that BGI assets are both scientifically sound, and understood, accepted and supported by communities and their elected representatives. This means addressing the biophysical RDUs related to asset performance and maintenance, modeling, and downscaling climate projections, through collaborative research conducted by teams of professional researchers and BGI practitioners (Thorne et al., 2018). Central research themes should be the development of improved technical and scientific analyses of BGI functionality, coupled with long-term, post-project monitoring and evaluation to establish the maintenance regimes and adaptive management needed to ensure that BGI functions at its design capacity throughout its useful life. Research conducted under Themes 2, 3 and 5 addressed some of these biophysical RDUs. In parallel, research is required to address socio-economic RDUs related to, for example, public preferences, stewardship, effective inter-agency working and economic resilience. Determining public perceptions of BGI, as investigated under Theme 4 using Point of Opportunity Interaction methods to identify attitudes towards bioswales, is the first step to understanding local awareness and satisfaction which ultimately impact the potential for effective and long-term local stewardship.

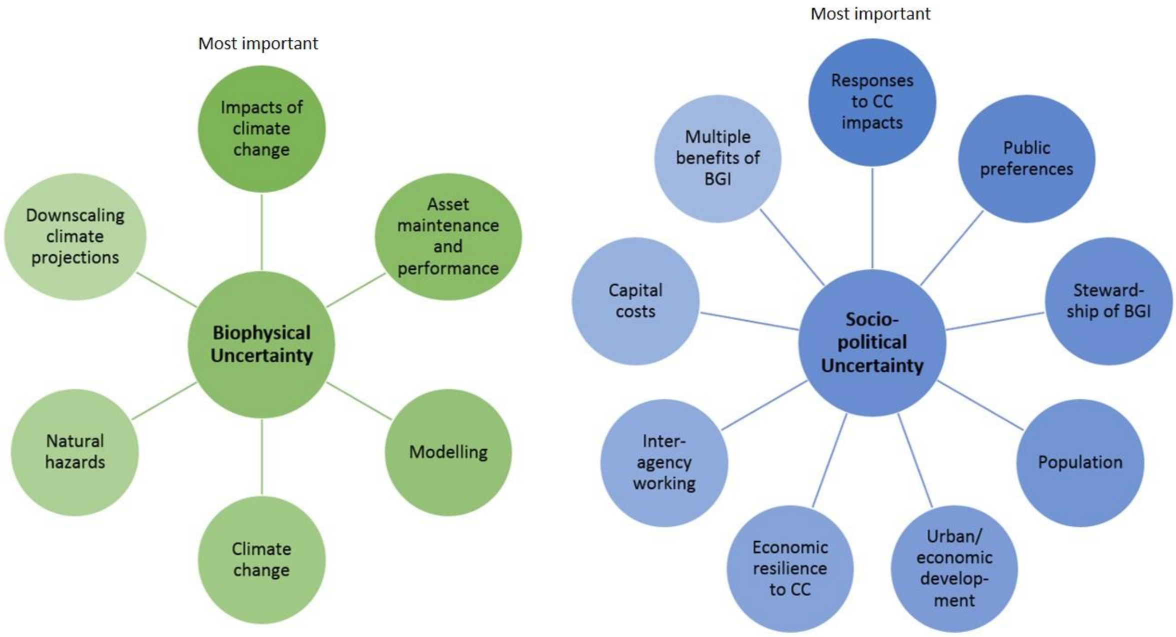

Figure 4. Biophysical and socio-political challenges and concerns that constitute significant 'Relevant Dominant Uncertainties' (RDUs) impeding implementation of Blue-Green Infrastructure (BGI) in Portland. RDUs are presented in order of importance, as identified by the interview respondents, beginning at the top and moving clockwise. Socio-political RDUs (e.g., public preferences, stewardship and equitable delivery of BGI) have a greater impact on Portland decision making than biophysical uncertainties. CC = climate change.

Theme 2. Floodplain restoration in East Lents

A biophysical RDU that impedes implementation of BGI in Portland (and other cities) relates to concerns about long-term performance and service provision, particularly as assets age and environmental loadings change. Using the East Lents project as an example, Theme 2 used a 2-dimensional hydraulic, sediment and morpho-dynamic model (Guan et al. 2015) to investigate concerns expressed by City of Portland stakeholders regarding uncertainties surrounding how the lowered, reconnected floodplain functions during a range of storm events with different peak discharges. The model also forecast sediment deposition and retention within the floodplain, evaluating the risk that gradual accumulation of storm-generated sediments over a period of decades might significantly reduce the future capacity of the floodplain to detain stormwater (Ahilan et al. 2018).

Although designed primarily to reduce the frequency of flooding by events with short return periods, the restored East Lents floodplain was found to reduce downstream flood peaks for the modeled 500-year flood event (115 m^3/s) by over 25% (Figure 5). This challenges the common assumption that floodplain reconnection is only effective during low and medium return period flow events (Woltemade and Potter 1994). The floodplain was also found to act as an effective sediment sink, trapping ~20-30% of the sediment generated further upstream and considerably reducing the cumulative sediment loading into the Willamette River. However, the volume of deposited sediment is small when compared with the large storage capacity of the floodplain, showing that there are minimal long-term impacts on downstream flood resilience.

Theme 2 research addressed a further concern of the City of Portland stakeholders regarding infrastructure performance and maintenance requirements. The fact that the elevation of the floodplain will not substantially change over a range of flood events suggests that minimal maintenance is required to maintain functionality to the design standard, allowing the scheme to deliver its environmental and social co-benefits without requiring significant investment in frequent or complex maintenance activities.

The disciplinary expertise of the CWfA consortium in hydraulic, sediment and morpho-dynamic modeling has provided information to overcome several biophysical RDUs and demonstrated the ability of BGI, represented here by a restored floodplain, to manage local flood risk and retain sediment, without requiring extensive maintenance regimes. A final concern stated by City of Portland stakeholders referred to the risk that floodplains may become pollutant hotspots owing to the deposition of pollutants (e.g., heavy metals) attached to fine suspended sediment particles. Ahilan et al., (2018) found no evidence to suggest that pollutant hotspots occur within the East Lents floodplain, and shared these modeling results with the Theme 3 team, who investigated this further by contributing knowledge from a different disciplinary standpoint (water quality and ecology).

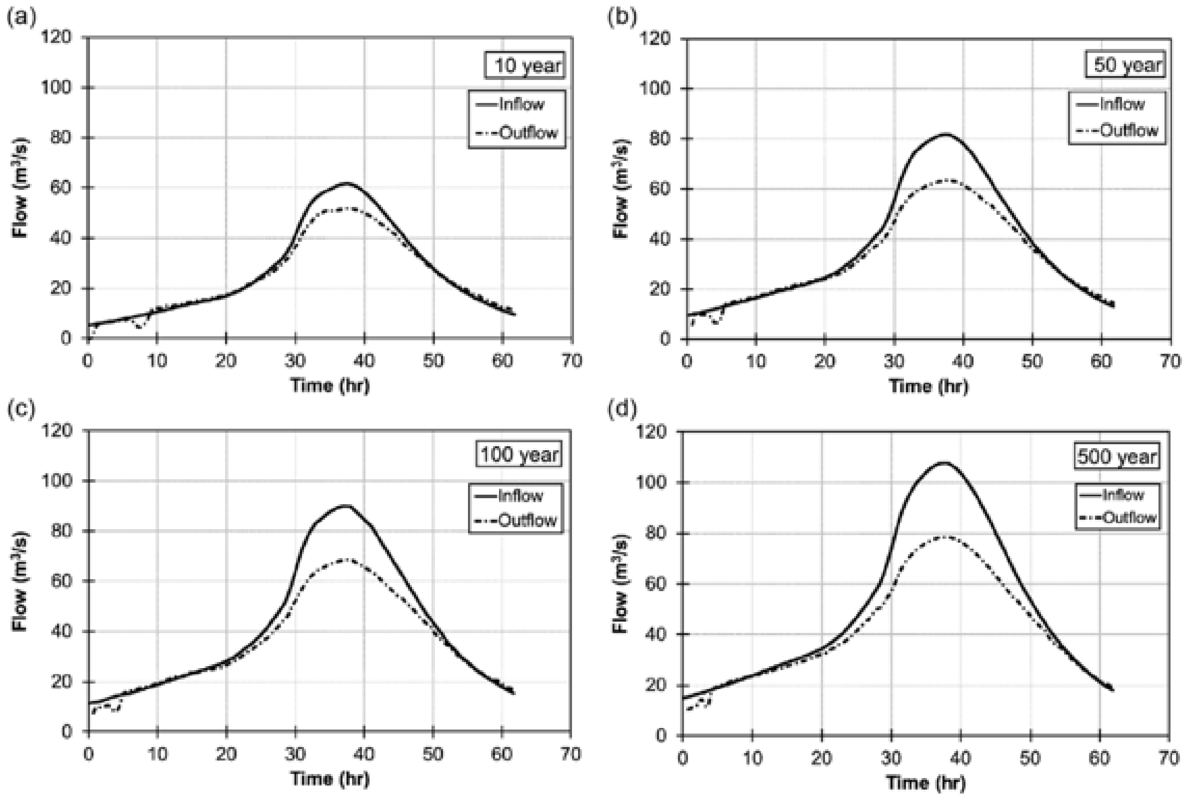

Figure 5. Figure 5 Inflow and attenuated outflow hydrographs of the (a) 10-year, (b) 50-year, (c) 100-yr and (d) 500-year flood events in Johnson Creek (from Ahilan et al., (2018)).

Theme 3. Sediment, contaminants, morphology and riparian restoration

The interdependencies among stream hydrology, hydraulics, sediment transport and water quality are a prime example of where interdisciplinary research is necessary to fully explain processes and trends observed in the field and comprehensively evaluate the environmental costs and benefits of floodplain reconnection. The sources and delivery of contaminated sediment to Johnson Creek, and the ability of natural flood management approaches (such as set-back outfalls that discharge into BGI features prior to entering the channel) to remove in-channel pollutants, were further investigated in Theme 3.

It is estimated that ~85% of heavy metal pollutants derived from urban surface (e.g., from vehicles, construction, commercial and industrial sources, and degradation of old infrastructure) are conveyed into urban watercourses adsorbed to fine ($D < 500$ μm) sediment particles (Wei and Yang 2010). In mixed rural-urban catchments, heavy metal concentrations typically increase with distance downstream and the concomitant increase in urban development, traffic and piped drainage infrastructure that generate and transport pollutants into watercourses (Sharley et al. 2016). However, the relationship between sediment heavy metal concentrations and sub-basin characteristics in Johnson Creek are more complex. Research conducted during the CWfA project, and detailed in full in Chang et al., (2018), has shown that land-use is less clearly segregated; a range of point and nonpoint sources and delivery paths of sediment-associated pollutants are influential.

Sediment samples were collected from 37 outfalls along the main stem of Johnson Creek, and analysed by Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES) for five key heavy metals; copper, zinc, lead, chromium and cadmium (full methods are given in Chang et al., 2018). Contributing sub-catchments for the outfalls were delineated using the ArcHydro tool in ArcGIS 10.4. Catchment variables derived for each sub-catchment were based on 2011 National Land Cover Data, hydrologic soil groups, and selected topographic parameters (e.g., elevation and slope) derived from a 10m Digital Elevation Model (USGS, 2015).

Contrary to expectations, heavy metal concentrations in stream bed samples were not found to increase downstream ubiquitously. In fact, copper, chromium and lead concentrations were elevated in both upstream reaches and in downstream reaches near listed clean-up sites (Figure 6a-c). This suggests that point industrial sources play a key role in heavy metal pollution in Johnson Creek, in addition to nonpoint sources such as traffic. Only zinc concentrations demonstrated a statistically significant relationship with variables defining catchment characteristics (Figure 6d). Chang et al. (2018) infer that the complicated processes of mobilizing and delivering sediment-bound heavy metals in catchments like Johnson Creek, where sub-catchment land-use is spatially heterogeneous often down to sub-decimeter scales, requires a more nuanced relationship than is currently assumed. This research has illustrated to City of Portland stakeholders that subtle changes in land-use patterns, stormwater runoff pathways (and proportion of runoff drained via pipe networks), outfall designs and BGI interventions can significantly affect the sources, pathways and delivery of heavy metals in mixed use watersheds such as Johnson Creek. Sharing of data and effective multidirectional communication, between researchers working under Themes 2 and 3, aided the CWfA research team in their evaluation of the delivery paths of sediment-associated pollutants, and subsequent interpretation of the efficacy of Johnson Creek's BGI to improve water quality.

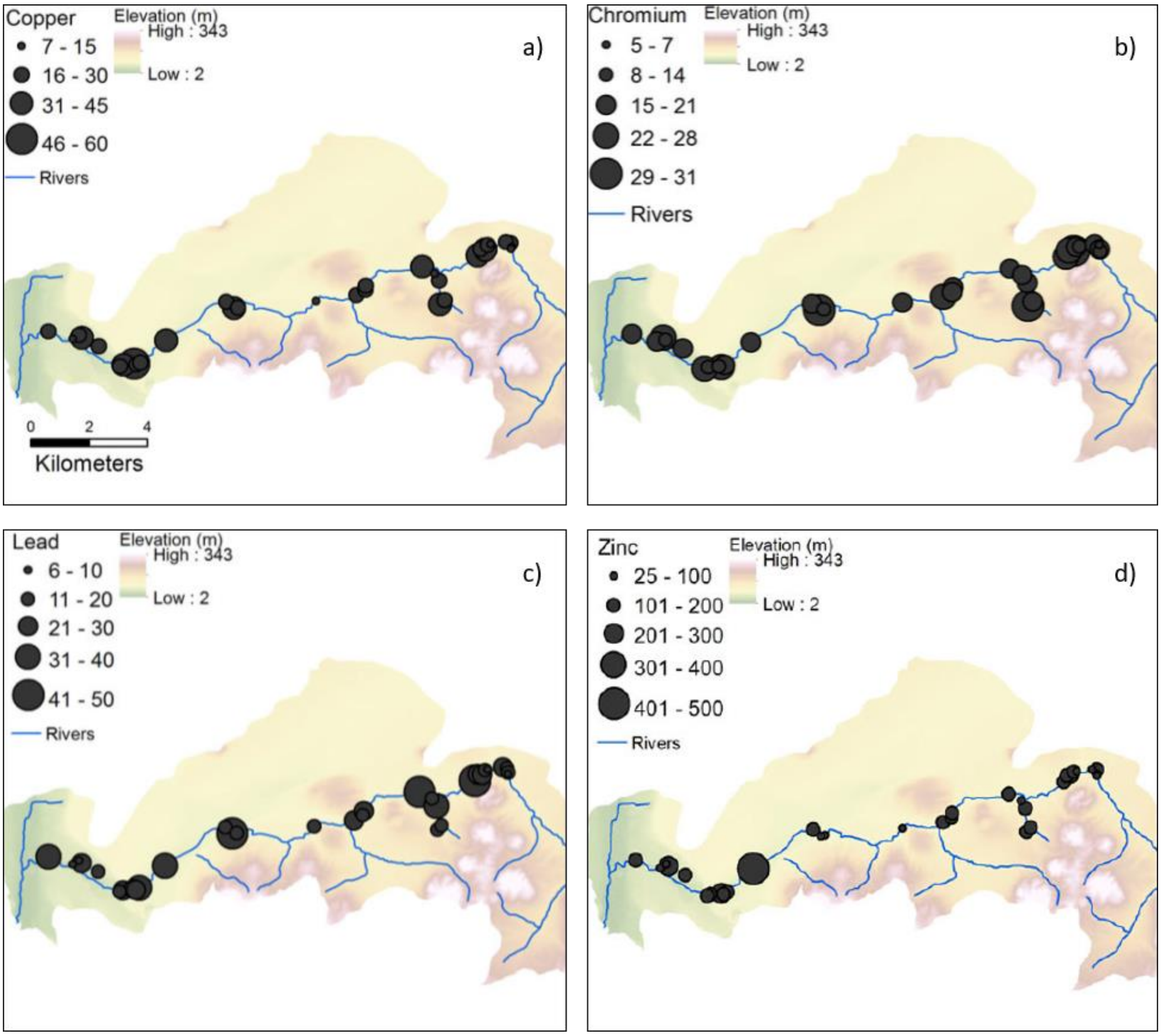

Figure 6. Downstream distributions of heavy metal concentrations (units = ppb) in bed sediments samples around stormwater outfalls in Johnson Creek a) copper, b) chromium, c) lead and d) zinc (adapted from Chang et al. (2018)). The base maps illustrate the varying topography within the Johnson Creek watershed based on the 10 m Digital Elevation Model (US Geological Survey (USGS), 2015).

Mitigating the impact of contaminated sediment in stormwater discharge through stormwater management practices. Stormwater management practices that promote infiltration and pollutant removal by routing stormwater through BGI, natural flood management structures or restored riparian zones are widely used in Johnson Creek yet many City of Portland stakeholders expressed uncertainty over how (and by whom) BGI performance and service provision would be maintained in order to deliver these benefits to water quality. Janes et al., (2016) investigated the effectiveness of setback outfalls, an example of BGI whereby piped stormwater is discharged into a wetland or swale before reaching the watercourse, to remove stormwater pollutants. This combines disciplinary research into ecological performance with water quality and hydrology.

Pollutant concentrations were found to be higher in setback outfalls when compared with background levels (upstream) due to the increased deposition of contaminated sediment and greater uptake of dissolved, or bioavailable bound contaminants, by aquatic organisms. However, recent research into phytoremediation in swales (e.g., Leroy et al. 2016) suggests that there is limited potential for long-term concentration of contaminated sediment in setback wetlands and swales, potentially mitigating the need for extensive maintenance of setback outfalls by the City of Portland and project partners. This, in line with findings reported under Theme 2 regarding the minimal maintenance required to maintain functionality of the East Lents floodplain, suggests that BGI assets in Portland have the potential to effectively manage stormwater and improve water quality, without significant investment in complex maintenance regimes. This negates some of the socio-political uncertainty surrounding costs of maintaining BGI (identified under Theme 1).

Channel modification and quality of the river habitat were also found to influence levels of sediment contamination in Johnson Creek by impacting pollutant removal efficiency. The UK River Habitat Survey (RHS) assessment method was used to determine the level of habitat diversity, and habitat modification (or artificiality), of four diverse reaches (Figure 7). Utilising the RHS scoring methodology to assess the benefits of channel restoration on water quality at stormwater outfalls is a novel application of this method. It provides a semi-quantitative assessment of the level of modification that may be used to infer the ability of the reach to reduce pollutant concentrations around stormwater outfalls. In practice, this assessment may highlight locations where restoration works may be the most effective, helping river managers focus their investments to achieve the best possible outcomes, which helps address some of the uncertainties outlined in Theme 1. Reaches adjacent to stormwater outfalls with lower habitat modification scores (HMS) were significantly correlated with greater removal efficiency of several key pollutants (Fe, Ba, Sn, Mg, P, K) (Janes et al. 2016). This reiterates the key relationship between ecological, hydrological and hydrodynamic processes in Johnson Creek in determining water and sediment quality.

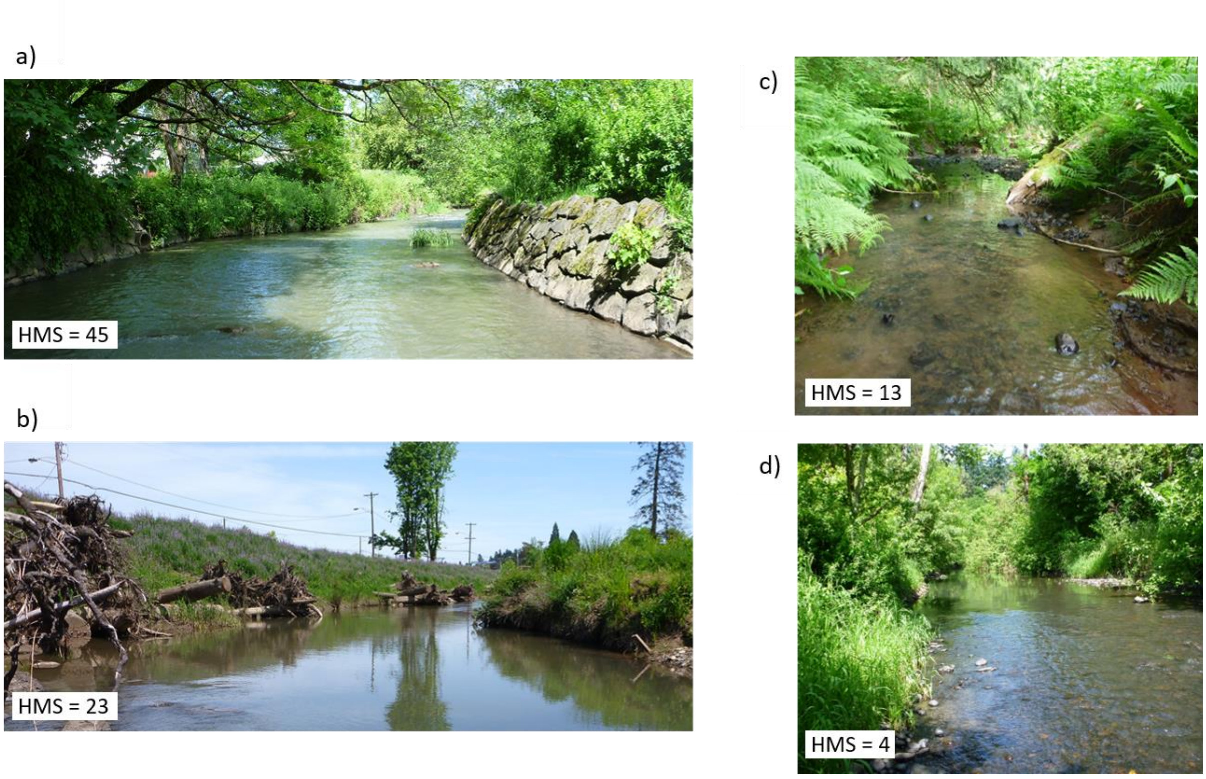

Figure 7. Habitat modification score (HMS) at four diverse reaches within Johnson Creek; a) a severely modified reach; b) a significantly modified (restored reach at East Lents two years after completion hence habitats may not be fully established); c) an obviously modified (restored reach at Schweitzer project, completed in 2009 with the reconnection of a meandering channel with a 91,000 m3 floodplain); d) a predominantly un-modified reach. HMS scores: 0 (pristine); 0-2 (semi-natural); 3-8 (predominantly unmodified); 9-20 (obviously modified); 21-44 (significantly modified); 45+ (severely modified). Adapted from Janes et al. (2016).

Theme 4. Community perceptions of BGI - bioswales

Theme 4 moved away from biophysical uncertainties to investigate some of the key socio-political issues concerning BGI design, implementation and maintenance, focusing on bioswales. Socio-political RDUs, identified by City of Portland stakeholders and acknowledged as inhibiting further implementation of BGI, include uncertainties in forecasting future social conditions, public preferences, and the lack of confidence among decision makers that beneficiary communities will value, accept and support BGI schemes (see Theme 1). The perceptions that residents and communities have of BGI has a direct impact on their understanding of the functionality and their willingness to pay for such assets (Everett et al. 2015). Residents' preferences for bioswales, as an example of a highly visible BGI intervention and key component of the citywide green infrastructure program (Figure 8a, b), were evaluated in Theme 4, using Point of Opportunity Interaction methods to collect information from 45 respondents (Everett et al. 2018). Briefly, this involved approaching people directly outside their house in order to include individuals who might not otherwise volunteer to be interviewed. Respondents were asked to talk freely around twelve key questions in a relaxed, conversational environment.

Several factors were found to influence residents' appreciation and acceptance of bioswales, including their awareness of the asset and its functionality; their community values (e.g., environmental attitudes), and; site-specific physical and aesthetic characteristics including plant choice, maintenance regime and level of perceived 'mess' and littering (Everett et al. 2018). Maintenance was a primary concern, echoing the City of Portland stakeholders with regard to questions of maintenance cost and who pays; "*If you want the public to embrace them you need to keep them looking good and keep them functional, but in order to do that you need to spend money*" (Water Resource Engineer, BES, Thorne et al. 2018).

Several residents expressed willingness to maintain the bioswales themselves (i.e. to improve aesthetics), but such uncoordinated efforts may reduce the ability of the assets to manage water quantity and quality to the design standard. This demonstrates disconnect between bioswale characteristics (e.g., plant choice) that residents prefer and the characteristics that deliver the required (optimal) functionality. Interdisciplinary partnerships between public and private stakeholders that consider both residents' preferences regarding landscape design, and knowledge of how to design bioswales to ensure maximum water retention and bioremediation potential, could address this disconnect and develop multifunctional, mutually-beneficial assets.

Improving local awareness and satisfaction of bioswales through greater consultation and co-construction of solutions during the development phase will help overcome the challenge of effective stewardship (Everett et al. 2018). Engagement was a key component of the City's Tabor to the River program and positively impacted residents' perceptions and support for bioswales (Shandas et al., 2010; Church, 2015). Such collaborations between residents, communities, nonprofit organizations and City of Portland agencies, such as BES, could greatly increase local stewardship, as exemplified by the volunteer Green Street Stewards Program. This encourages people to clear out trash and debris to improve BGI functionality, reduces the likelihood of untrained residents inadvertently damaging the bioswales (Figure 8c), and facilitates a cost reduction for the City through reducing maintenance costs. Signs explaining when incomplete bioswales will be planted (Figure 8d) also help manage residents' expectations and keeps them informed throughout the construction process.

Figure 8. Portland bioswales. a) A mature bioswale, b) a new bioswale in the early stages of plant growth, c) an incomplete bioswale with a Bureau of Environmental Services (BES) sign warning against interference with the plant, d) an incomplete bioswale with a BES sign detailing that planting will take place in the next planting season. (Photos: E. O'Donnell, April 2014 (a, b), Glyn Everett, April 2014 (c, d)).

Residents are often aware of the stormwater management and water quality improvement functions of BGI; typically, the functions that the assets were primarily designed to deliver (Kabisch et al., 2016). Awareness of other, less visible, co-benefits, such as carbon sequestration (as part of climate change adaptation objectives), air quality improvement, and noise reduction, are less widely understood, suggesting that the multifunctionality of BGI is not routinely acknowledged. This may be due to challenges in identifying and quantifying the range of BGI benefits that extend beyond water and flood risk management, which requires an interdisciplinary team to fully address. This was explored in the final CWfA research theme (Theme 5) that built on the disciplinary knowledge gained by research Themes 1-4 to develop an innovative approach to illustrate the spatial distribution of key BGI benefits.

Theme 5. Multiple benefits of BGI

Valuation of the multiple benefits of BGI in economic terms in increasingly included in business cases and a range of tools are available, including the US Center for Neighborhood Technology's Green Values Stormwater Toolbox (CNT 2013, accessed October 2019) and the New York City Green Infrastructure Co-Benefits Calculator (Jones et al., 2017). Instead of focusing on economic valuation and monetization of benefits, the CWfA research team developed a Geographic Information System (GIS) approach to illustrate and evaluate the spatial distribution of several BGI benefits. The GIS approach was developed to aid City of Portland stakeholders demonstrate multifunctionality in BGI performance, and identify the dominant, relevant benefits for a given location (Hoang et al. 2018). It complements the monetization of BGI benefits provided by other benefit calculators by illustrating the relative uplift in the case study location after an intervention, showing how the benefits may have an impact at the site of intervention and much more widely into adjacent neighborhoods. This ultimately facilitates the identification of beneficiaries of BGI schemes, and in particular, which benefits they may primarily benefit from.

Full details of the method are provided in Hoang et al., (2018) and in the brief summary that follows. The spatial distribution and intensity of six biophysical benefits (habitat connectivity, recreational accessibility, traffic movement, noise propagation, carbon sequestration and NO_2 trapping) generated by the East Lents Floodplain Restoration Project (the 'after' condition) were evaluated under flood and non-flood condition states, and compared with the benefits that would have accrued before completion of the floodplain restoration scheme (the 'before' condition). The benefits were then normalized using a piecewise linear transformation to a common, dimensionless, scale (0 representing no benefit and 10 representing the maximum benefit) which allowed benefits to be compared across categories. The total, cumulative benefit in each grid cell, for the before and after conditions, is calculated by summing the benefit intensity in each grid cell for each benefit. This highlights where multiple benefits may accrue and whether the BGI intervention leads to specific benefit hotspots, where several of the benefits show a high intensity. By comparing the before and after condition, a value is derived that reflects whether the overall accrual of benefits at the site, following BGI implementation, has improved or worsened. This comparative approach between the before and after condition also allows disbenefits to be identified, for instance, a temporary reduction in carbon sequestration and NO_2 trapping will occur when the restored floodplain is inundated with water. This shows a temporary trade-off between benefits; when the floodplain is fulfilling its primary function of storing floodwater other environmental processes become less effective and result in a net disbenefit (Figure 9). Interdisciplinary knowledge of the site and the functions that the restored floodplain provides is essential in interpreting the results of the GIS evaluation; creation of flood storage was the primary aim of the scheme and is not a disbenefit provided that the flood water remains within the designated, flood-suitable, area. In addition to mitigating flood risk, the benefits of the East Lents restored floodplain extend beyond the project area by improving recreational accessibility and habitat connectivity, and reducing traffic across the site (due to the removal of several streets as part of the restoration) when the system is in a non-flood state (Figure 9). Carbon sequestration and noise reduction were temporarily reduced due to removal of some vegetation during construction, but should recover and then increase as the new vegetation matures.

This conceptual GIS approach to multiple benefit evaluation, and the corresponding creation of a spatial benefit intensity profile, also demonstrates the aggregated impact of BGI projects on a range of stakeholder groups and beneficiaries. The results indicate that, while most of the beneficiaries are local, the scope of beneficiaries is increased through wider (though modest) contributions to improved air quality, recreational access and habitat connectivity at the city scale. Nonetheless, there are limitation to this approach and uncertainties associated with the scale of analysis.

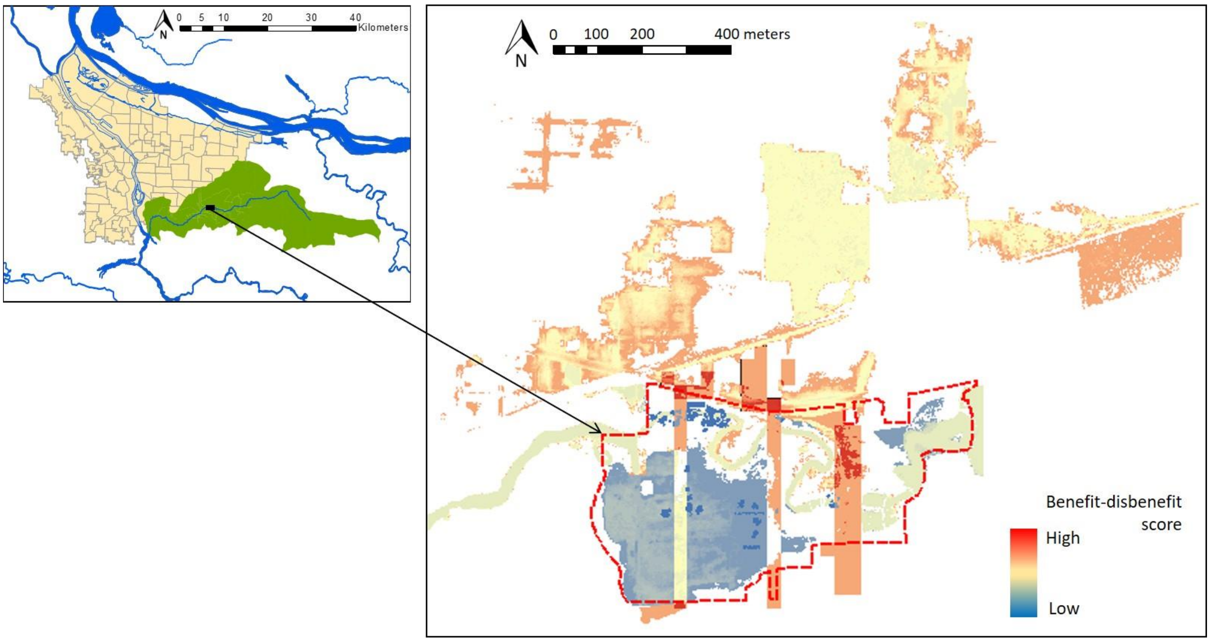

Figure 9. Cumulative benefits distribution across the East Lents floodplain restoration site, calculated according to the methods detailed by Hoang et al., (2018). The dashed outline shows the extent of the floodplain restoration. The highest benefits (red) are where flood mitigation, landscape connectivity and amenity accessibility have been improved by removal of streets and houses within the reconnected floodplain. Apparent flood disbenefits (blue) occur within the restored floodplain due to higher water levels during floods (as intended), and include reduced carbon sequestration and NO_2 trapping due to temporary loss of some trees during construction. Insert: the location of the East Lents floodplain restoration site (black rectangle) in relation to the Johnson Creek Watershed (green) and City of Portland boundary (yellow). Image adapted from BGC (2016).

Limitations. Data resolution and data availability are limiting factors in the GIS multiple benefits evaluation method; the resolution of the overall benefit intensity is restricted by the finest resolution that all benefit layers could be aggregated without further processing. The benefit determination also only represents a snapshot in time and longer-term benefit accrual during flood and non-flood conditions are not accounted for. The six benefit categories that are included in the GIS assessment are also only illustrative of the potential benefits, and disbenefits, of this project; in reality, the East Lents Floodplain Restoration Project will generate a range of additional impacts, some negative. While not concentrating specifically on East Lents, Hagerman (2007) found that the production of new greenspaces in Portland has previously forced low income housing and service agencies to fight their own displacement. BGI and Green Stormwater Infrastructure (GSI) are often associated with gentrification; poor and vulnerable communities will not receive the intended benefits of BGI if they are moved out of areas due to greenspace development (Anguelovski et al., 2019). Investigating issues of gentrification and environmental justice both in our case study areas, and more widely across Portland, were beyond the scope of this study which was designed to address discrete elements of the complex issues surrounding stormwater management. Nonetheless, these issues, and the equitable delivery of BGI, should be key considerations for planners, designers and decision-makers if Portland is to become a sustainable *Blue-Green City*.

Geographical scope of CWfA research project. Our evaluation of the multiple benefits of BGI is also limited in geographical scope. The geographically-targeted approach employed by the CWfA research project means that the exact benefits associated with the East Lents Floodplain Restoration Project (e.g., related to flow and suspended sediment dynamics (Theme 2), or river habitats (Theme 3)) are specific to this site. However, the type of benefits will likely be delivered by similar projects, such as the Schweitzer restoration project that facilitates the deposition and storage of sediment and sediment-bound pollutants (Janes et al., 2016), or the future West Lents Floodplain Restoration Project that is expected to reduce local flood risk, restore fish and wildlife habitat and improve water quality in Johnson Creek (BES 2019d, accessed December 2019). Similarly, the community perceptions of bioswales identified under CWfA research are specific to the neighborhoods surveyed. Nonetheless, common issues that we have identified are expected to affect residents' appreciation and acceptance of Portland's bioswales more widely, including environmental attitudes, awareness and understanding of functionality, and plant choice and maintenance.

INTERDISCIPLINARY RESEARCH TO OVERCOME BARRIERS TO BGI

Interdisciplinary research encourages the bridging of dominant paradigms from individual disciplines to generate new understanding. Thoms and Parsons (2002) use the example of eco-geomorphology as an interdisciplinary focus to develop new understandings of river systems. Responses to the question "what characteristics are desirable for urban rivers?" from hydraulic, geomorphological and ecological perspectives will differ; to support river flows during a 1:100 year event; maintain the structure and function of natural features in the river channel, and; maintain individuals, populations and ecosystem processes, respectively (Thoms and Parsons 2002). In order to protect and conserve the river function while mitigating against future flooding all of these answers need to be incorporated into strategies to improve urban rivers. Parallels can be drawn when asked to define characteristics that are desirable of (multifunctional) BGI systems. The key advantages of Blue-Green over traditional 'gray' infrastructure approaches relate to the creation of the environmental, ecological, social and economic benefits, in addition to meeting flood risk and stormwater management objectives (Fenner, 2017).

Multiple benefit evaluation that unifies the CWfA research themes. Effective integration of BGI into the existing urban fabric requires detailed understanding of the hydrological, ecological and social benefits, and trade-offs, plus knowledge of where they interact with other infrastructure systems (Hoang et al., 2018). Demonstration that the multiple benefits of Portland's floodplain reconnection and BGI projects extend far beyond the hydrosphere is a focal point for the CWfA interdisciplinary research project, and unifies the five research themes.

As an example, the East Lents Floodplain Restoration Project generates flood risk reduction benefits (flood peak attenuation, increased water storage and infiltration, reduced runoff velocities, sediment trapping) and the river restoration and setback outfalls in Johnson Creek have been shown to improve sediment quality and habitats, and reduce pollutant concentrations (Themes 2 and 3). Awareness of the flood risk management and water quality improvement benefits of street bioswales was common among surveyed residents (Theme 4) yet knowledge of the wider, less visible benefits was limited. Similarly, the lack of recognition and valuation of the multiple benefits of BGI in policy and practice was highlighted as a socio-political RDU by City of Portland stakeholders that inhibits progress with citywide BGI implementation (Theme 1).

The contrasting nature of the biophysical and socio-political uncertainties that limit BGI implementation highlights the importance of interdisciplinary teams. These teams are needed to design BGI that is adaptable and resilient to future (uncertain) changes in climate and land-use, while ensuring uninterrupted service delivery. They are also essential for developing and raising awareness of BGI, often by co-producing new knowledge with beneficiary communities and policy-makers. Disciplines must not be the focus of research programs, and instead, research inputs should be distributed and blended to ensure that the specific research questions can be addressed by a group with the necessary disciplinary-based experiences, skills and competencies. Collectively, the interdisciplinary CWfA research project created an evidence base for a range of environmental and social benefits of BGI as a means of helping City of Portland stakeholders overcome the barriers to BGI.

One of the challenges of interdisciplinary approaches is ensuring that projects are truly interdisciplinary, rather than allowing fragmentation into multidisciplinary research undertaken from a number of perspectives, with individuals working on their own sub-topics within a common framework, and outputs only being synthesized towards the end of the project (Massey et al. 2006). Some degree of fragmentation was unavoidable during the multifaceted CWfA research project, which involved field-based research performed using different techniques and conducted simultaneously at multiple locations. Nevertheless, we found that our commitment to mutually agreed, interdisciplinary goals, adoption of a common terminology, and establishments of a project intranet to facilitate data and information sharing, together with regular meetings, enabled us to keep our research coordinated and integrated.

Changing the BGI paradigm towards greater multifunctionality. In order to realize the multiple benefits of BGI, the ‘urban drainage’ paradigm must be supplanted by one whereby BGI is seen as the starting point for urban planning, development and regeneration. Opportunistic implementation of BGI should be at the forefront of all new city projects, in addition to the use of BGI to solve specific problems. In practice, interdisciplinary collaboration across departments and organizations on BGI projects intended to meet the respective policy and strategic objectives of those involved has several advantages. Financially, the burden on individual organizations would be reduced if collaborative BGI projects were collectively funded, as illustrated in Seattle and partnerships between Seattle Public Utilities and King County Wastewater Treatment Division (City of Seattle, 2015). Further, increased value-for-money and improved cost-benefit analyses of BGI projects are assured once the multiple benefits are included in calculations (Jones et al., 2017).

Moving the focus of BGI projects away from solely ‘stormwater management’ will increase the likelihood that organizations not typically involved in BGI projects will get involved, offering specialist knowledge and resources that may ultimately increase the realization of multiple benefits derived from a wider array of ecosystem services provided by urban streams and urban stream corridors (Yeakley et al. 2016). These types of interdisciplinary projects are more easily adopted by policy makers (Donaldson et al. 2010) and deliver benefits to a wider range of beneficiaries. Such collaborative schemes would help address wider issues of inter-agency fragmentation and ineffective communication that are common within and between institutions across the globe (O’Donnell et al., 2017; Thorne et al., 2018). Regular meetings are a prerequisite to limit potential challenges due to gaps in understanding at the interface between disciplines, and facilitate the potential evolution of sub-disciplines that may develop their own framing of a common problem (Qin et al. 1997).

Leadership in interdisciplinary projects relies on individuals who are able to span disciplinary boundaries, build trust and relationships, and successfully facilitate cognitive (integrating the different epistemics of the different team members) and structural (need for timely knowledge and information exchange) tasks (Margerum and Robinson 2015). The CWfA research project was led by Theme 1 researchers who have an excellent understanding of the physical and social science components of stormwater management, and expertise in both quantitative and qualitative data analysis. They were able to identify where cross-theme research was needed, encourage communication and data sharing, and keep the team focused on the interdisciplinary goals. Theme 1 researchers were also responsible for identifying the key contributions from each research theme that help address the overarching interdisciplinary aim involving the co-development of an evidence base to demonstrate the multiple benefits of BGI. Strategies for resolving procedural tasks, e.g., conflicts during any stage of the process, reluctance, inertia and structural obstacles, are also essential (Gray 2008) and were assigned to Theme 1 researchers. Tools, such as GIS, were also used to facilitate learning and communication activities across boundaries due to their effective visualization capabilities, providing shared visions and understandings for disciplines to converge towards, as illustrated here with the development of the GIS-based approach to evaluating the multiple benefits of BGI.

CONCLUSIONS

Designing and delivering effective flood risk and stormwater management strategies is more than a purely engineering challenge; indeed, addressing the scientific aspects in isolation can rarely achieve the desired societal results owing to the complexity of interactions between natural and societal components of stormwater management (Morss et al., 2005). Blue-Green Infrastructure (BGI) is recognized as a viable strategy to manage stormwater and flood risk, and its *multifunctionality* may further enrich society through the provision of multiple co-benefits that extend beyond the hydrosphere, including urban regeneration, climate change adaptation, recreation and public amenity, health and wellbeing, open space improvements and enhanced biodiversity. The incorporation of multifunctional BGI into the design of urban landscapes is essential if cities are to achieve higher goals for sustainable development.

Despite an abundance of BGI and international recognition as a leader in green stormwater management, a range of barriers, or 'Relevant Dominant Uncertainties' (RDUs), continue to cloud decision-making and impede wider implementation of BGI in Portland, Oregon USA. In this paper, we demonstrate how the 'Clean Water for All' (CWfA) research collaboration addressed many of the biophysical and socio-political RDUs through an interdisciplinary study of the benefits of Portland's BGI, focusing on green street bioswales and the East Lents Floodplain Restoration Project in lower Johnson Creek.

An interdisciplinary approach is advocated to comprehensively evaluate the multiple co-benefits of BGI and facilitate the development of strategies to overcome the barriers to implementation. The approach adopted by the CWfA research project was made possible by strong linkages between research themes, sharing of knowledge and expertise, and leadership by researchers who were adapt at spanning disciplinary boundaries and maintaining focus on the overarching interdisciplinary research goal. The importance of sustained interaction and collaboration to integrate disciplinary expertise in, for example, hydrology, hydraulics, ecology, hydrochemistry, sociology, geography and economics, is essential for an interdisciplinary evaluation of BGI benefits and disbenefits. While the disciplinary differences in methodologies were embraced in this project, and pivotal to providing evidence of the disparate benefits of multifunctional BGI, cross-disciplinary engagement and data exchanges throughout the research process were of paramount importance to reduce the potential for fragmentation and ensure research remained integrated. The interdisciplinary research process that was adopted is highly transferable to other urban environments facing similar development pressures and increasing demands for natural resources.

Acknowledgements

This research was performed as part of an interdisciplinary project program undertaken by the Blue-Green Cities (BGC) Research Consortium (www.bluegreencities.ac.uk) and Portland-Vancouver ULTRA (Urban Long-term Research Area) project (www.fsl.orst.edu/eco-p/ultra) as part of the EPSRC “Clean Water for All” (CWfA) initiative. This work was supported by the Engineering and Physical Sciences Research Council (grant numbers EP/K013661/1, EP/N008103/1); the US National Science Foundation (grant number 0948983); the National Natural Science Foundation of China (grant number NSFC41850410497): and the Ningbo Municipal Bureau of Science and Technology (grant number 201401C5008005). Additional contributions were received from the UK Environment Agency, Rivers Agency (Northern Ireland) and Institute for Sustainable Solutions (Portland State University, USA). We thank the City of Portland Bureau of Environmental Services and Johnson Creek Watershed Council for their kind support and sharing of data and expertise. We further thank the Reviewers for their valuable comments and suggestions, which helped us to improve the quality of the manuscript.

Literature Cited

Ahilan, S., M. Guan, A. Sleigh, N. Wright, A. Sleigh, and H. Chang. 2018. "The Influence of Floodplain Restoration on Sediment Dynamics in an Urban River." Journal of Flood Risk Management 11(S2): S986-S1001. https://doi.org/10.1111/jfr3.12251

Anguelovski, I., Connolly, J.J., Pearsall, H., Shokry, G., Checker, M., Maantay, J., Gould, K., Lewis, T., Maroko, A. and Roberts, J.T. 2019. “Opinion: Why green “climate gentrification” threatens poor and vulnerable populations”. Proceedings of the National Academy of Sciences 116: 26139-26143. https://doi.org/10.1073/pnas.1920490117.

BES (Bureau of Environmental Services, City of Portland). 2010. "Grey to Green". https://www.portlandoregon.gov/bes/article/321433.

BES (Bureau of Environmental Services, City of Portland). 2013. "Natural Area Information". https://www.portlandoregon.gov/bes/article/286175.

BES (Bureau of Environmental Services, City of Portland). 2015. "Integrating Stormwater Into the Built Environment". https://www.portlandoregon.gov/bes/article/41620.

BES (Bureau of Environmental Services, City of Portland). 2019a. "Combined Sewer Overflow Control (Big Pipe Project)". https://www.portlandoregon.gov/bes/31030.

BES (Bureau of Environmental Services, City of Portland). 2019b. "Green Infrastructure". https://www.portlandoregon.gov/bes/34598.

BES (Bureau of Environmental Services, City of Portland). 2019c. "Cornerstone Projects". https://www.portlandoregon.gov/bes/article/201795.

BES (Bureau of Environmental Services, City of Portland). 2019d. “West Lents Floodplain Restoration Project”. https://www.portlandoregon.gov/bes/78422.

BGC (Blue-Green Cities). 2016. "Green Infrastructure Evaluation factsheet." http://www.bluegreencities.ac.uk/documents/green-infrastructure-evaluation-benefit-intensity-benefit-profile-and-benefit-dependencies.pdf

Bruce, A., C. Lyall, J. Tait, and R. Williams. 2004. "Interdisciplinary integration in Europe: the case of the Fifth Framework programme". Futures 36(4): 457-470. https://doi.org/10.1016/j.futures.2003.10.003.

Carlet, F. 2015. "Understanding attitudes toward adoption of green infrastructure: A case study of US municipal officials". Environmental Science & Policy 51: 65-76. https://doi.org/10.1016/j.envsci.2015.03.007.

Casal-Campos, A., G. Fu, D. Butler, and A. Moore. 2015. "An Integrated Environmental Assessment of Green and Gray Infrastructure Strategies for Robust Decision Making". Environmental Science & Technology 49(14): 8307-8314. DOI: 10.1021/es506144f.

Chan, F.K.S., Griffiths, J.A., Higgitt, D., Xu, S., Zhu, F., Tang, Y.-T., Xu, Y. and Thorne, C.R. 2018. "Sponge City” in China—A breakthrough of planning and flood risk management in the urban context". Land Use Policy 76: 772-778. https://doi.org/10.1016/j.landusepol.2018.03.005.

Chang, H., Thiers, P., Netusil, N. R., Yeakley, J. A., Rollwagen-Bollens, G., Bollens, S. M., and S. Singh, S. 2014. "Relationships between environmental governance and water quality in growing metropolitan areas: A synthetic view through the coupled natural and human system lens." Hydrology and Earth System Science 18: 1383-1395. https://doi.org/10.5194/hess-18-1383-2014.

Chang, H., D. Allen, J. Morse, and J. Mainali. 2018. "Sources of contaminated flood sediments in a mixed rural-urban catchment". Journal of Flood Risk Management. https://doi.org/10.1111/jfr3.12496.

Church, S.P. 2015. "Exploring Green Streets and rain gardens as instances of small scale nature and environmental learning tools." Landscape and Urban Planning 134, 229-240, https://doi.org/10.1016/j.landurbplan.2014.10.021.

City of Seattle. 2015. "Green Stormwater Infrastructure in Seattle. Implementation Strategy 2015-2020." https://www.seattle.gov/Documents/Departments/OSE/GSI_Strategy_Nov_2015.pdf.

CNT. 2013. "Green Values Stormwater Toolbox." Center for Neighborhood Technology. http://greenvalues.cnt.org/.

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A., Mittal, N., Feliu, E., and Faehnle, M. 2014. "Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure". Journal of Environmental Management, 146: 107-115. https://doi.org/10.1016/j.jenvman.2014.07.025.

Donaldson, A., N. Ward, and S. Bradley. 2010. "Mess among disciplines: interdisciplinarity in environmental research". Environment and Planning A, 42(7): 1521-1536. https://doi.org/10.1068/a42483.

EPA (US Environmental Protection Agency). 1972. "Clean Water Act".

EPA (US Environmental Protection Agency). 2008. "Incorporating Green Infrastructure Concepts into Total Maximum Daily Loads (TMDLs)" https://www.epa.gov/sites/production/files/2015-07/documents/2008_12_12_tmdl_stormwater_tmdl_lid_final.pdf.

EPA (US Environmental Protection Agency). 2019. "What is Green Infrastructure?" https://www.epa.gov/green-infrastructure/what-green-infrastructure.

Everett, G., J. Lamond, A. Morzillo, F. K. S. Chan, and A. Matsler. 2015. "Sustainable drainage systems: helping people live with water". Proceedings of the ICE – Water Management 169(2): 1-94-104. http://dx.doi.org/10.1680/wama.14.00076.

Everett, G., A. Morzillo, J. Lamond, M. Matsler, and F. Chan. 2018. "Delivering Green Streets: An exploration of changing perceptions and behaviours over time around bioswales in

Portland, Oregon." Journal of Flood Risk Management 11(S2): S973-S985. http://dx.doi.org/10.1111/jfr3.12225.

Fenner, R. 2017. "Spatial evaluation of multiple benefits to encourage multi-functional design of sustainable drainage in blue-green cities". Water 9(12): 953. https://doi.org/10.3390/w9120953.

Gibbons, M. 1999. "Science's new social contract with society." Nature 402: C81-C84.

Gray, B. 2008. "Enhancing transdisciplinary research through collaborative leadership." American Journal of Preventive Medicine 35(2): S124-S132. https://doi.org/10.1016/j.amepre.2008.03.037.

Guan, M., N. G. Wright, and P. A. Sleigh. 2015. "Multimode morphodynamic model for sediment-laden flows and geomorphic impacts". Journal of Hydraulic Engineering 141(6): 04015006. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000997.

Hagerman, C. 2007. “Shaping neighborhoods and nature: Urban political ecologies of urban waterfront transformations in Portland, Oregon”. Cities 24(4): 285-297. https://doi.org/10.1016/j.cities.2006.12.003.

Hoang, L., R. A. Fenner, and M. Skenderian. 2018. "A conceptual approach for evaluating the multiple benefits of urban flood management practices". Journal of Flood Risk Management 11(S2): S943-S959. https://doi.org/10.1111/jfr3.12267.

Hoyer, J., W. Dickhaut, L. Kronawitter, and B. Weber. 2011. Water sensitive urban design: principles and inspiration for sustainable stormwater management in the city of the future. Jovis, Hamburg.

Janes, V., R. Grabowski, J. Mant, D. Allen, J. Morse, and H. Haynes. 2016. "The impacts of natural flood management approaches on in-channel sediment quality". River Research and Applications 33(1): 89-101. https://doi.org/doi:10.1002/rra.3068.

Jarrad, M., N. R. Netusil, K. Moeltner, A. T. Morzillo, and J. A. Yeakley. 2018. "Urban Stream Restoration Projects: Do Project Phase, Distance, and Type Affect Nearby Property Sale Prices?" Land Economics 94(3): 368-385. https://doi.org/doi: 10.3368/le.94.3.368.

JCWC (Johnson Creek Watershed Council). 2012. "Johnson Creek Watershed Council State of the Watershed Report." http://www.jcwc.org/wp-content/uploads/2017/07/FINAL-JC-SOW-2012.pdf.

Jones, M., J. McLaughlin, and S. Mehrotra. 2017. "Accounting for the Co-Benefits of Green Infrastructure." International Conference on Sustainable Infrastructure 2017, New York. (pp. 65-75). https://doi.org/10.1061/9780784481219.006.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., and Stadler, J. 2016. "Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action". Ecology and Society 21(2):39. http://dx.doi.org/10.5751/ES-08373-210239.

Klein, J. T. 2008. "Evaluation of interdisciplinary and transdisciplinary research: a literature review". American Journal of Preventive Medicine 35(2): S116-S123. https://doi:10.1016/j.amepre.2008.05.010.

Kremer, P., Hamstead, Z. A., and McPhearson, T. 2016. “The value of urban ecosystem services in New York City: A spatially explicit multicriteria analysis of landscape scale valuation scenarios”. Environmental Science & Policy 62: 57-68. https://doi.org/10.1016/j.envsci.2016.04.012.

Lawson, E., Thorne, C. R., Ahilan, S., Allen, D., Arthur, S., Everett, G., Fenner, R., Glenis, V., Kilsby, C., Lamond, J., Mant, J., Maskrey, S., Mount, N., Sleigh, A., Smith, L., and N. Wright. 2014. "Delivering and evaluating the multiple flood risk benefits in Blue-Green Cities: an interdisciplinary approach". In Flood Recovery, Innovation and Response IV, edited by D. Proverbs and C. A. Brebbia, pp. 113-124, WIT Press. https://doi.org/10.2495/FRIAR140101.

Leroy, M.-C., F. Portet-Koltalo, M. Legras, F. Lederf, V. Moncond'huy, I. Polaert, and S. Marcotte. 2016. "Performance of vegetated swales for improving road runoff quality in a moderate traffic urban area." Science of The Total Environment 566: 113-121. https://doi.org/10.1016/j.scitotenv.2016.05.027.

Lowe, P., and J. Phillipson. 2006. "Reflexive interdisciplinary research: the making of a research programme on the rural economy and land use.” Journal of Agricultural Economics 57(2): 165-184. https://doi.org/10.1111/j.1477-9552.2006.00045.x.

Lukes, R., and C. Kloss. 2008. Managing Wet Weather with Green Infrastructure Municipal Handbook: Green Streets. US Environmental Protection Agency.

Margerum, R. D., and C. J. Robinson. 2015. "Collaborative partnerships and the challenges for sustainable water management". Current Opinion in Environmental Sustainability 12: 53-58, https://doi.org/10.1016/j.cosust.2014.09.003.

Massey, C., F. Alpass, R. Flett, K. Lewis, S. Morriss, and F. Sligo. 2006. "Crossing fields: The case of a multi-disciplinary research team." Qualitative Research 6(2): 131-147. https://doi.org/10.1177/1468794106062706.

McPhillips, L. E. & A. M. Matsler. 2018. "Temporal evolution of green stormwater infrastructure strategies in three US cities." Frontiers in Built Environment 4(26), 1-14. https://doi.org/10.3389/fbuil.2018.0002.

Morss, R. E., O. V. Wilhelmi, M. W. Downton, and E. Gruntfest. 2005. "Flood risk, uncertainty, and scientific information for decision making: lessons from an interdisciplinary project". Bulletin of the American Meteorological Society, 86(11): 1593-1601. https://doi.org/10.1175/BAMS-86-11-1593.

Netusil, N. R., Z. Levin, V. Shandas, and T. Hart. 2014. "Valuing green infrastructure in Portland, Oregon". Landscape and Urban Planning, 124: 14-21. https://doi.org/10.1016/j.landurbplan.2014.01.002.

Novotny, V., J. Ahern, and P. Brown. 2010. Water centric sustainable communities: planning, retrofitting and building the next urban environment. Wiley, New Jersey.

O'Donnell, E., J. Lamond, and C. Thorne. 2017. "Recognising barriers to implementation of Blue-Green infrastructure: a Newcastle case study". Urban Water Journal 14(9): 964-971. doi:10.1080/1573062X.2017.1279190.

Qin, J., F. W. Lancaster, and B. Allen. 1997. "Types and levels of collaboration in interdisciplinary research in the sciences". Journal of the American Society for Information Science 48(10): 893-916.

Rijke, J., Farrelly, M., Brown, R. and Zevenbergen, C. 2013. "Configuring transformative governance to enhance resilient urban water systems". Environmental Science & Policy 25, 62-72. https://doi.org/10.1016/j.envsci.2012.09.012.

Rottle, N. 2015. "Blue-Green to the Extreme in Portland and Seattle." In: Planning the Pacific Northwest, edited by C. O. J. Sterrett, D. Ryan, E. Seltzer, J. Whittington, Planners Press, Chicago, IL.

Shandas, V., Nelson, A., Arendes, C. and Cibor, C. 2010. "Tabor to the river: an evaluation of outreach efforts and opportunities for engaging residents in stormwater management." City of Portland: Bureau of Environmental Services. https://core.ac.uk/reader/37776402.

Shandas, V., Matsler, A., Caughman, L. and Harris, A. 2020. “Towards the implementation of green stormwater infrastructure: perspectives from municipal managers in the Pacific

Northwest”. Journal of Environmental Planning and Management 63(6), 959-980. https://doi.org/10.1080/09640568.2019.1620708.

Sharley, D. J., S. M. Sharp, S. Bourgues, and V. J. Pettigrove. 2016. "Detecting long-term temporal trends in sediment-bound trace metals from urbanised catchments." Environmental Pollution 219, 705-713. https://doi.org/10.1016/j.envpol.2016.06.072.

Smith, L. A., and A. C. Petersen. 2014. "Variations on Reliability: Connecting Climate Predictions to Climate Policy." In: Error and Uncertainty in Scientific Practice, edited by M. Boumans, G. Hon and A. C. Petersen. Pickering & Chatto, London.

Sonoda, K., Yeakley, J.A., and Walker, C. E. 2001. "Near-stream landuse effects on streamwater nutrient distribution in an urbanizing watershed". Journal of the American Water Resources Association 37: 1512-1537. https://doi.org/10.1111/j.1752-1688.2001.tb03657.x.

The Oregonian. 2012. "East Lents Floodplain Project wraps up, creates 70-acre natural area in East Portland." https://www.oregonlive.com/gresham/2012/12/east_lents_floodplain_project.html.

Thoms, M. C., and M. Parsons. 2002. "Eco-geomorphology: an interdisciplinary approach to river science". International Association of Hydrological Sciences 276: 113-119.

Thorne, C. R., E. C. Lawson, C. Ozawa, S. Hamlin, and L. A. Smith. 2018. "Overcoming uncertainty and barriers to adoption of blue-green infrastructure for urban flood risk management." Journal of Flood Risk Management 11(S2): S960-S972. https://doi.org/10.1111/jfr3.12218.

Trogrlić, R. Š., Rijke, J., Dolman, N., and Zevenbergen, C., 2018, Rebuild by Design in Hoboken: A Design Competition as a Means for Achieving Flood Resilience of Urban Areas through the Implementation of Green Infrastructure: Water, v. 10, no. 5, p. 553.

US Geological Survey (USGS). 2015. "National Hydrography Dataset (NHD)". http://nhd.usgs.gov.

Velpuri, N., and G. Senay. 2013. "Analysis of long-term trends (1950–2009) in precipitation, runoff and runoff coefficient in major urban watersheds in the United States." Environmental Research Letters 8(2): 024020. https://doi.org/10.1088/1748-9326/8/2/024020.

Venkataramanan, V., A. I. Packman, D. R. Peters, D. Lopez, D. J. McCuskey, R. I. McDonald, W. M. Miller, and S. L. Young. 2019. "A systematic review of the human health and social well-being outcomes of green infrastructure for stormwater and flood management." Journal of Environmental Management 246, 868-880. https://doi.org/10.1016/j.jenvman.2019.05.028.

Wei, B., and L. Yang. 2010. "A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China." Microchemical Journal 94(2): 99-107. https://doi.org/10.1016/j.microc.2009.09.014.

Woltemade, C. J., and K. W. Potter. 1994. "A watershed modeling analysis of fluvial geomorphologic influences on flood peak attenuation." Water Resources Research 30(6): 1933-1942. https://doi.org/10.1029/94WR00323.

Yeakley, J. A., Ervin, D., Chang H., Granek, E., Dujon, V., Shandas, V., Brown, D. 2016. "Ecosystem services of streams and rivers". In: River Science: Research & Applications for the 21st Century, edited by D. Gilvear, M. Greenwood, M. Thoms, and P. Wood. Wiley, UK. pp 335-352. https://doi.org/10.1002/9781118643525.ch17.