

2015

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Citation Details

Thorne, C.R., Lawson, E.C., Ozawa, C., Hamlin, S.L. and Smith, L.A. (2015), Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management. *Journal of Flood Risk Management*.

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Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management

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DOI: 10.1111/jfr3.12218

Key words

Best management practices; blue-green cities; confidence; sustainable drainage systems; uncertainty; urban flood risk management.

Abstract

Blue-Green Infrastructure (BGI) and Sustainable Drainage Systems (SuDS) are increasingly recognised as vital components of urban flood risk management. However, uncertainty regarding their hydrologic performance and lack of confidence concerning their public acceptability create concerns and challenges that limit their widespread adoption. This paper investigates barriers to implementation of BGI in Portland, Oregon, using the Relevant Dominant Uncertainty (RDU) approach. Two types of RDU are identified: scientific RDUs related to physical processes that affect infrastructure performance and service provision, and socio-political RDUs that reflect a lack of confidence in socio-political structures and public preferences for BGI. We find that socio-political RDUs currently exert the strongest negative influences on BGI decision making in Portland. We conclude that identification and management of both biophysical and socio-political uncertainties are essential to broadening the implementation of BGI and sustainable urban flood risk management solutions that are practical, scientifically sound, and supported by local stakeholders.

Introduction

This paper examines the sources of uncertainty responsible for current concerns and challenges to widespread adoption of Blue-Green Infrastructure (BGI) in urban flood risk management. This is significant because many urban flood risk management professionals still perceive uncertainties concerning service delivery to be greater for BG compared with grey infrastructure, whereas decision makers and urban planners question the appetites of communities and their elected representatives for increasing a city or neighbourhood's reliance on BGI. The fact is that uptake of BGI, in the form of Sustainable Drainage Systems (SuDS) or Best Management Practices, remains stubbornly sluggish, despite the proven advantages of BG over grey infrastructure (Ellis, 2013; Casal-Campos *et al.*, 2015).

These issues were investigated through research conducted in Portland, Oregon, United States. We hypothesized that: 1) adoption of BGI in Portland is currently limited by concerns fuelled by the perception that scientific uncertainty (in hydrological processes) is greater for BG than the equivalent grey infrastructure; and 2) uncertainties associated with

forecasting future social conditions, and challenges related to the lack of confidence that beneficiary communities recognise, value, and are willing to pay for the additional benefits of using BGI, are likely to inhibit action to a degree equal to, or greater than, scientific uncertainties.

Encompassing the social dimensions of urban flooding is essential to enable effective environmental-technical discourse concerning sustainable stormwater management (Cettner *et al.*, 2014) and consideration of the environmental and social uncertainties generated outside the engineered system (Geldof, 1995a, b). These issues are manifest in the form of technical barriers to uptake that cite uncertainties concerning the long-term performance of BGI versus grey infrastructure and the perception that maintenance of BGI is more expensive and difficult to deliver. These issues are compounded by doubt in the minds of project designers and decision makers that future leadership and community buy-in can be relied upon to champion, support, accept, and take ownership of BGI. Overarching these challenges, which relate specifically to BGI, are broader challenges related to the impacts of climate change, the need to deliver urban flood risk management that is socially equitable and the

difficulty of communicating with publics on the complex technical and planning issues that relate to all infrastructure projects.

In researching these issues, we use the outcomes of semi-structured interviews to identify key concerns and challenges faced by a range of institutional stakeholders working in different governmental departments and bureaus in the City of Portland. We draw out the uncertainties and classify them as relating to hydrological and biophysical processes or socio-political factors, based on the Relevant Dominant Uncertainty (RDU) approach pioneered by Smith and Petersen (2014). We define a new type of RDU; the socio-political RDU (RDU_s), which reflects the lack of confidence that the current high levels of political backing, public support and community willingness to pay for BGI in Portland will continue into the future. We then discuss the importance of overcoming such socio-political uncertainties

to successfully broaden implementation of BGI: a course of action that is physically/scientifically optimal. Finally, we apply the knowledge created and insights gained from our research to address how decision makers can reduce their levels of concern and overcome the associated challenges to widen the implementation of BGI. In essence, this requires reducing those RDUs that are reducible, accounting for the irreducible ones, and building the confidence necessary to unlock Portland's currently unfulfilled potential to become a *Blue-Green City*.

Study location and governance

Portland is located at the confluence of the Columbia and Willamette Rivers (Figure 1). It is the largest city in Oregon, with an area of around 376 km² and population of *circa* 609 456 (US Census Bureau, 2013). The city falls primarily

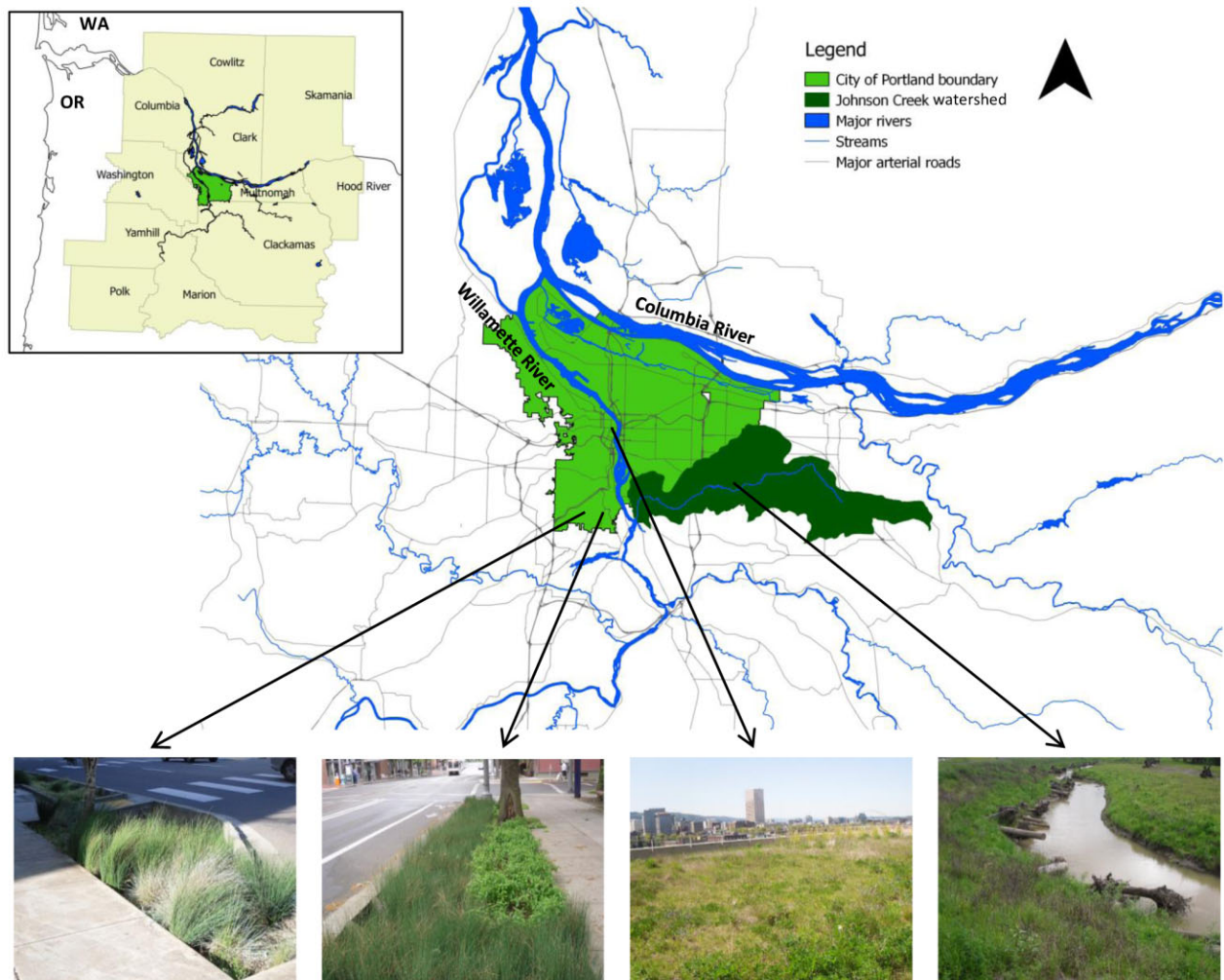


Figure 1 Study area: Portland, OR. Photographs from left to right; City of Portland green street installations, Multnomah County Ecoroof, Foster Floodplain natural area. The maps were created using QGIS Desktop software v2.2.0. Photo credits: Emily Lawson.

within Multnomah County, though small portions are in Clackamas and Washington counties, all within the wider Portland Metropolitan Area. The climate features wet, mild winters and dry, warm summers. Between 1950 and 2009, annual precipitation in Portland averaged 1401 mm/y (Velpuri and Senay, 2013), generating about 450 000 m³/y of stormwater runoff (BES, 2015a). Climate projections for the Pacific Northwest predict wetter, warmer winters and drier summers, with a trend towards greater annual precipitation that will become noticeable by the 2040s (Mote and Salathe, 2010). It has also been predicted that Portland will experience reduced snowmelt runoff, more frequent extreme rainfall events, and a stressing of the water supply system during hotter, drier summers (Chang *et al.*, 2010). Here, we focus on the City of Portland's jurisdictional area, which is becoming increasingly vulnerable to the potential impacts of climate and land-use change.

City of Portland bureaus with specific roles in city governance and the provision and maintenance of services are presided over by the mayor and four elected commissioners. The adoption and implementation of BGI spans multiple agencies, each with specific approaches to dealing with uncertainties. The Bureau of Environmental Services (BES) is tasked with providing sewage and stormwater collection and treatment services, managing water quality and the environment, and promoting healthy ecosystems. BES currently accounts for uncertainty in urban drainage and flood risk management projects using conventional approaches based on 'design standards', which apply simplified hydrologic and hydraulic analyses and factors of safety, coupled with experience, sound engineering judgement, and guidance from the Oregon Department of Environmental Quality (DEQ). The Bureau of Planning and Sustainability (BPS) is charged with enhancing liveability by planning for a resilient future and leads development of the long-range Comprehensive Plan (BPS, 2011), the Climate Change Preparation Strategy (BPS, 2014), and the Climate Action Plan (BPS, 2015). Uncertainties related to future population and economic growth are dealt with in the Comprehensive Plan. With respect to uncertainty resulting from climate change and its environmental impacts when planning and designing urban flood risk management projects, both BPS and BES rely on climate change predictions provided in the Climate Action Plan, which has been updated twice since 1993 (Dalton, 2013). The Bureau of Transportation (BoT) provides the transport infrastructure to meet the demands of a growing city. Maintenance of streets and sidewalks comes under the remit of BoT and overlaps with BES when stormwater systems are installed or updated. Working in partnership with these city bureaus is Metro, an elected regional government organisation responsible for land-use planning and coordinating city and county plans to ensure a continuing supply of land suitable for development.

BES and BPS work together, and with other bureaus, to plan, design, and deliver Portland's BGI and other natural assets. BGI has long featured in urban water management in Portland and expanded during the 1990s to help reduce the frequency of Combined Sewer Overflows (CSOs) into the Willamette River, a key watercourse for listed and endangered species of salmonids (DEQ, 2010a; BES, 2012). In 1991, the City of Portland and DEQ reached an agreement that the frequency of CSO events would be substantially reduced by 2011. Specifically, this required the City to reduce annual CSO volume into the Willamette River by 96% and reduce the number of CSO events from about fifty to four annually during the rainy season, and one every three years during the dry season. Part of the solution involved major investment in grey infrastructure through the \$1.2 billion Columbia Slough and Willamette River CSO Projects, designed to convey storm and wastewater to improved treatment facilities instead of discharging into natural watercourses (BES, 2012). This included the three 'Big Pipe' Projects (East Side, West Side and Columbia Slough) that collectively were designed to control 48 outfalls to the Willamette River. Subsequently, DEQ, under advisement of BES, forecasted that Green Infrastructure (GI) could further reduce the frequency of CSOs to only two per rainy season (DEQ, 2010b), and the City responded by implementing GI projects to manage stormwater while providing a range of biophysical, ecological, and social benefits (BES, 2010a, 2012). In this context, GI is defined by the US Environmental Protection Agency (US EPA) as '*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*' (US EPA, 2008), which embraces the *Blue-Green* ideals of reconfiguring the urban water cycle to more closely resemble the natural water cycle and using urban green spaces to help manage stormwater.

Portland is recognised as a leader in green stormwater management (Lukes and Kloss, 2008; Water Environment Research Foundation, 2009; Rottle, 2015). Portland's experience in using GI alongside grey infrastructure demonstrates the significantly lower cost of GI compared with grey assets. For instance, the 'Grey to Green' project (2008–2013) was allotted \$55 million for stormwater management, including planting trees, installing eco-roofs, purchasing land to create green assets, removing culverts, and citywide construction of green streets (BES, 2010a; US EPA, 2010). The City estimated that investment of \$9 million on GI for stormwater management saves ratepayers (who are currently still paying for the 'Big Pipe' projects) \$224 million in CSO maintenance and repair costs (US EPA, 2010). However, the City's implementation of GI has been largely opportunistic and voluntary. For example, in the city's largest project, 'Tabor to the River', sites selected for GI assets were quickly revised if a property owner opposed a planned installation. Portland's GI has also

been demonstrated to deliver ancillary benefits not generated by grey infrastructure including: improved air quality, enhanced physical and mental health, energy savings, reduced greenhouse gas emissions, amenity and aesthetic improvements, higher property values, enhanced community cohesion and community relationships, decreases in crime, improvements in environmental equity, and better access to nature (BES, 2010b). The City's Charter, however, only recognises some of these ecosystem services benefits (e.g. clean air and temperature moderation) and hence, the full scope of benefits cannot be used as first-tier criteria for funding GI schemes (City of Portland, 2015). GI for stormwater management must meet conditions set in the Stormwater Management Manual (City of Portland, 2014); yet there is still no formal requirement to implement anything better than standard 'most economical' solutions.

Methods

RDU conceptual framework

We framed our investigation of barriers to the implementation of BGI by a heuristic developed from work by Smith and Petersen (2014): the notion of a hierarchy of uncertainty and identification of 'Relevant Dominant Uncertainties' (RDUs). Smith and Petersen originally cast RDUs purely in terms of uncertainties in physical science, using climate modelling as an example. They define an RDU as the most likely known unknown limiting our ability to make a more informative scientific probability distribution for an outcome of interest. An RDU may be (or may be thought to be) reducible or irreducible, but it is always an uncertainty related to physical processes and their impacts (Smith and Petersen, 2014). This type of RDU is referred to here as an RDU_{Physical} (RDU_P). Our research suggests this definition of an RDU is incomplete. We build on the original approach by recognising the RDU_{Socio-political} (RDU_S). An RDU_S is *addressable* if it can be reduced by education, confidence building exercises, or

trusted legal sanctions. However, an RDU_S may be *unaddressable* when it hinges on future political governance, valid differences of opinion, or community values. Independently, RDUs may also be *reducible*, when enhanced research could yield the findings necessary within a practical time-scale, or *irreducible*, when arising from the inherent natural variability (Samuels *et al.*, 2009; Smith and Stern, 2011).

Interviews

A semi-structured interview approach (Wengraf, 2001) was adopted to allow respondents to talk around a set of open-ended questions designed to elicit understanding of their perspectives on urban stormwater management and BGI. Interviews were conducted with twelve respondents from BES, BPS, BoT, and Metro (Table 1). Interviewees were selected based on their knowledge and involvement in stormwater management, climate change adaptation, urban planning, and/or BGI design. The sample population consisted of mid-level managers and BGI practitioners with diverse educational backgrounds and professional remits, providing a wide range of perspectives on the uncertainties associated with BGI. A core set of overarching questions was put to all respondents, including questions about their experience and perception of BGI, challenges and uncertainties that they associate with BGI (based on past projects or future implementation), and the principal risks and uncertainties for future urban water management, climate change adaptation and city growth, together with additional questions specific to the respondents' professional remit. The 45- to 75-min interviews were conducted between 7th May and 30th June 2014. To maintain confidentiality, respondents are referred to according to their professional remit and employer, e.g. *Green Streets Designer*, *BES*.

Intersubjective construct validity approach to classify RDUs

Four of the five researchers listened to the recorded interviews and/or read the transcripts in order to identify and

Table 1 Summary of the interview respondent's characteristics

Employment	Profession and educational background	Professional remit	Number of respondents
Bureau of Environmental Services (BES)	Hydraulic modelling and engineering	Stormwater system modelling, and water resource engineering	3
	Landscape architecture	Green streets designer	1
	Environmental law, regulations and policies	Portland climate change preparation strategy	2
	Environmental management and planning	Watershed manager/programme coordinator	2
Bureau of Planning and Sustainability (BPS)	Urban planning	Portland Comprehensive Plan	2
Bureau of Transportation (BoT) Metro	Infrastructure management	Transport asset manager	1
	Urban planning	Planning and development	1

rank RDUs. Rankings were based on the frequency and intensity with which each interviewee referred to each RDU. This independent assessment allowed each researcher to identify RDUs based on their individual interpretations of the interviews without the crosswinds of influence inevitable in a more interactive approach. The researchers then shared and discussed their findings through a Delphi-like sequence of exchanges and debates, where individual data analysis was followed by collective discussion that was repeated until consensus was reached regarding uncertainty classifications and rankings. This enabled the geographically dispersed researchers to systematically classify uncertainties and gradually refine their views. The outcome was classification and ranking of RDUs that the researchers recognised as achieving an acceptable level of intersubjective construct validity. The fifth researcher then separated the RDUs into RDU_{PS} and RDU_{IS}. All five researchers then re-examined the outcomes. This intense, discursive process led the researchers to conclude that many of the uncertainties were not RDUs *per se* but were better defined as recurring *concerns* (issues

respondents are worried about) or *challenges* (which result from these concerns and may act as barriers to implementation of BGI).

Results

Thirteen concerns, eleven challenges, and fifteen RDUs were identified, ranked from high to low and classified as being *widely recognised* or *recognised* based on the frequency and intensity with which they were mentioned during the interviews (Table 2). The concerns and challenges that influence implementation of BGI fall into two categories:

1. general project management issues that affect all aspects of local governance and infrastructure management, such as future maintenance and service provision (shaded orange in Table 2); and
2. issues specific to BGI, e.g. community perceptions and understanding of its particular costs, benefits and risks (shaded blue in Table 2).

Table 2 Identifying and classifying concerns, challenges, and RDUs

Relevant Dominant Uncertainties		Concerns		Challenges	
Widely recognised	Recognised	Widely recognised	Recognised	Widely recognised	Recognised
Impacts of climate change	Modelling	Leadership, political will and vision	How to change policy to support BGI	Securing effective leadership	Multiple risk management
Appropriate responses to the impacts of climate change	Climate change	Future infrastructure maintenance requirements	Future population	Effective future governance	Delivering infrastructure
Maintaining infrastructure performance and provision of services	Natural hazards	Community perceptions and understanding of BGI	Future land-use	Delivering future maintenance and level of service	Keeping BGI on the agenda and promoting interagency working
Public preferences	Population	Community buy-in	Impact of natural hazards	Community ownership and buy-in	Communicating effectively
Stewardship of BGI	Urban/economic development	Social equity	Future governance of BGI	Including climate change in policy/design standards	Using climate science in policy making
	Economic resilience to climate change	Willingness to pay/sell	Interagency fragmentation	Ensuring social equity	
	Level of interagency working		Who benefits/who pays		
	Capital costs				
	Recognition of the multiple benefits of BGI				
	Downscaling climate projections				

Notes: Green = reducible, yellow = irreducible, orange = general project management concerns and challenges, blue = concerns and challenges specific to implementation of Blue-Green Infrastructure (BGI).

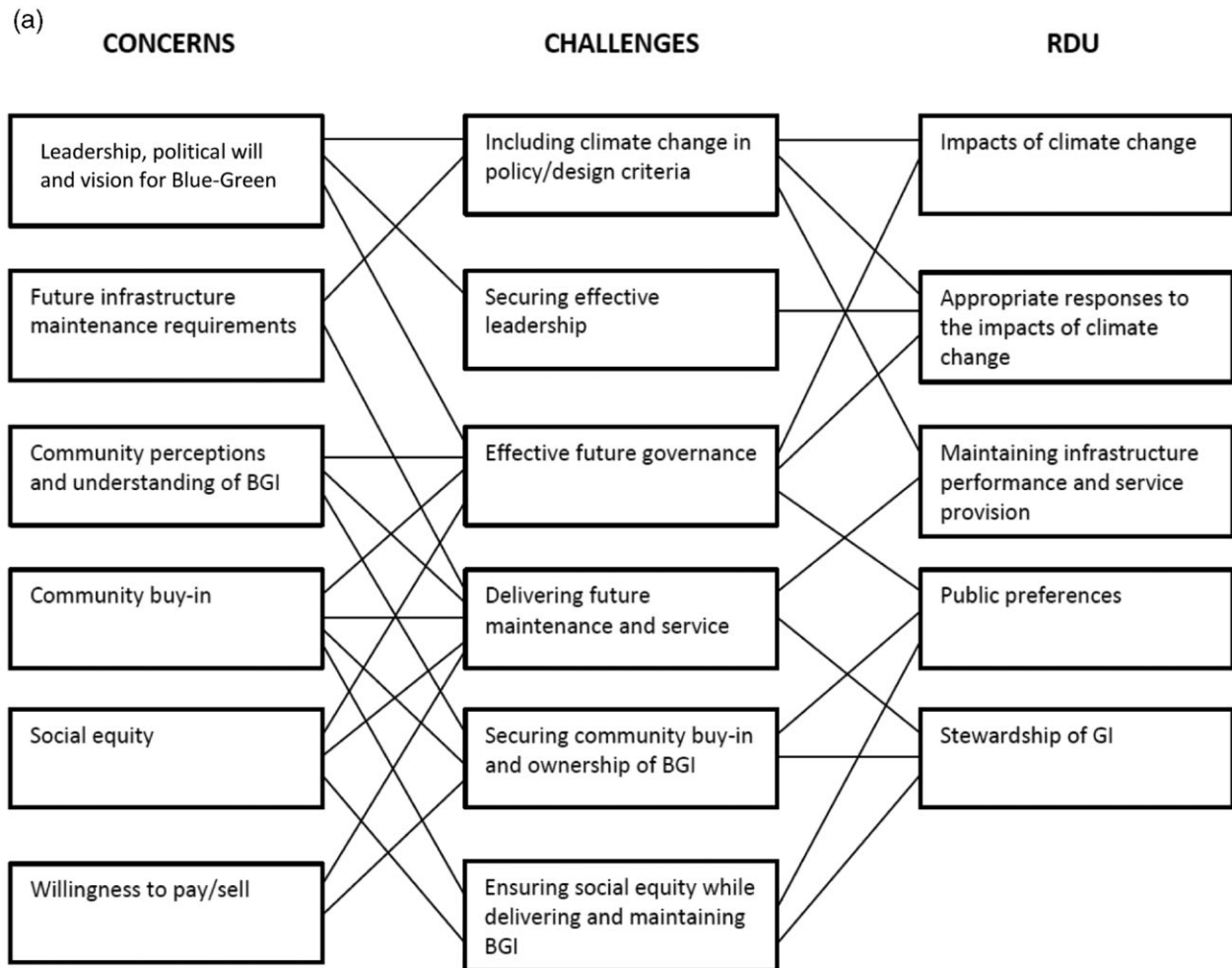


Figure 2 Linking concerns and challenges to (a) widely recognised and (b) recognised biophysical and socio-political RDUs.

Concerns and challenges that are *addressable* are those that it may be possible to resolve and overcome through investment in improving public education, social learning, and/or community engagement. This implies action, intervention, and coping capacity, and includes concerns such as understanding community preferences for stormwater infrastructure, overcoming challenges to communicating effectively, and developing engagement strategies appropriate to different demographics. *Non-addressable* concerns and challenges relate to lack of confidence on issues that we cannot expect to resolve (without a significant increase in the risk appetites of citizens) even if progress is made in better understanding them, such as lack of confidence that the individuals and parties governing Portland in the 2020s will continue to provide political support for BGI, and the ongoing challenge of delivering water and flood risk management that is socially equitable for future populations whose ethnicities and demographics are unknown. Recognising these confounding factors, Figure 2 indicates the links

through which it may be possible to reduce, or at least better understand each of the concerns and overcome the resulting challenges, by identifying and reducing the underlying RDUs.

As indicated in Figure 2 and Table 2, widely recognised RDUs span both biophysical (RDU_p) and socio-political spheres (RDU_s). RDU_p s comprise six uncertainties (listed in order of ranked importance): impacts of climate change (e.g. the detrimental impact of increased air temperatures and/or changing precipitation regimes on river health), maintaining infrastructure performance and provision of services (as the asset ages and environmental conditions change), modelling, climate change, natural hazards, and downscaling climate projections. RDU_s s outnumber RDU_p s (being nine in total, listed in order of ranked importance): appropriate responses to the impacts of climate change, public preferences, stewardship of BGI, population, urban/economic development, economic resilience to climate change, level of interagency working, capital costs, and recognition of the

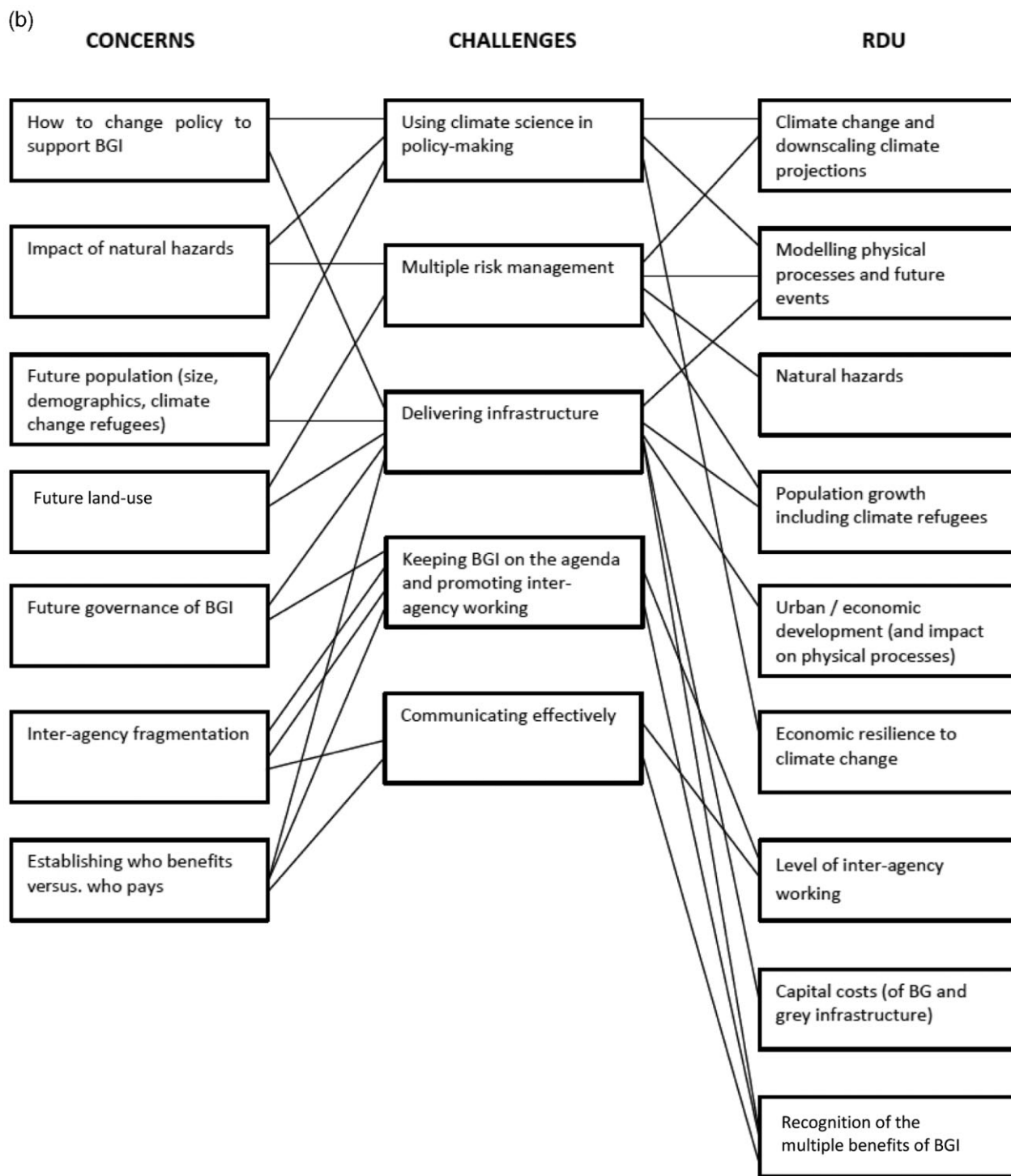


Figure 2 Continued

multiple benefits of BGI. In Table 2, RDUs are shaded as green (*reducible*) or yellow (*irreducible*) depending on whether further research would be a feasible way to reduce them, or whether infrastructure design and implementation must learn to cope with the current level of uncertainty.

The highest ranked RDU is uncertainty in the impact of climate change on the environment, society (including health), and economy, rather than the uncertainty in changes in temperature, precipitation and sea level *per se*. This RDU₁ is irreducible. Maintaining infrastructure performance and

service provision was another key RDU_p for which many respondents expressed deep concern, particularly those working in stormwater modelling and water resource engineering:

... another large uncertainty is we just don't know how these (green streets) facilities are going to function over time, our oldest one is 10 years old and we presume the design life is 30 years and so just based on other vegetative facilities, we don't know, so we are just extrapolating out to say we think it is going to last for 30 years. ...

(Water Resource Engineer, BES)

... we don't know how frequently we will have to replace the soils.

(Water Resource Engineer, BES)

This RDU is reducible, however, and it extends to grey as well as BGI. Multiple respondents mentioned a lack of knowledge of how infrastructure functionality (e.g. infiltration capacity) may change over time and in response to different magnitudes and frequencies of rainfall events. The cost of future maintenance was also highlighted as a key unknown:

I think the biggest one, and I would be surprised if not every single one of your interviewees had the same answer, is adequate funding for long term maintenance.

(Watershed Programme Coordinator, BES)

... it's not just the perception or the ability to maintain things, it is also what level of maintenance and where are the costs associated with that level of maintenance ... maintenance is a huge fraction of the cost. ...

(Water Resource Engineer, BES)

... one of the biggest things we are faced with, with these stormwater facilities, is the cost to maintain them. 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)

Uncertainty in hydraulic and hydrological modelling, climate change projections, and natural hazards (e.g. the impact of the next big earthquake and the risk interface between natural hazards) were lower ranked RDU_s:

For some people, it could be that it [climate change] seems so uncertain and so big that they don't want to deal with it. For some people it may be that they are more interested in doing near-term projects.

(Watershed Programme Coordinator, BES)

And I would say, just from observation, that we haven't yet incorporated climate change into our sort of day-to-

day planning activities ... we haven't developed the systematic approach yet for evaluating the uncertainties, the risks, the potential changes in river levels. ...

(Urban Planner, BPS)

Public preferences were a high-ranking RDU_s and can be shaped by forces external to the local context as well as by the legitimacy of local leadership and attitudes towards BGI. Uncertainties regarding public preferences were mentioned by many respondents in connection with concerns about continued political support from elected leaders for continued planning, implementation, and maintenance of BGI, especially in the context of climate change mitigation (Figure 2), demonstrating that none of these uncertainties operate independently. Concern for political leadership and social equity, which are issues applicable to general project management, were also widely recognised. The interviews revealed that local managers and planners are aware of, and highly sensitive to, the impact of local politics;

There are political uncertainties as we are working in the planning realm ... we literally can be told 'don't do that anymore, now do this, I don't want you to work with transportation anymore to do green streets, that's a waste of money'. It's a little far-fetched but it could happen.

(Watershed Manager, BES)

A contextual note must be added here: the interviews were conducted just before a hotly contested local ballot (held on 20th May 2014) on a proposal to create an independent board to oversee the City's water and sewer agencies: the Bureaus of Water and Environmental Services. Anxieties related to the ballot may have focused the minds of respondents on the political dimension of municipal water governance to some extent, bearing in mind the push by property rights activists and Tea Party followers to privatise management of these bureaus.

Social equity, which is regarded as being critical to urban sustainability and a focal point of the City's Comprehensive Plan update, was a widely recognised concern. Given that social equity is an issue universally referred to in public discourse throughout the city, it is not surprising that respondents mentioned it as a salient concern:

How do you measure whether or not you're doing your climate work in a more equitable way? We're really struggling to figure out how do we do that, how to know that we're planting trees more equitably ...?

(Urban Planner, BPS)

Additional concerns and challenges specific to BGI include community perceptions of BGI, understanding BGI effectiveness and the willingness of beneficiaries to pay for it, local support and buy-in, and ongoing commitment to

interagency coordination. These issues are influenced by factors that are beyond the City’s control, such as the political leadership, but they can be reduced to some extent by appropriate actions and interventions. For example, community perceptions, understanding, and ownership of BGI may be shaped through improving access to information and education, and as a result of experiencing benefits of BGI. Even if the political will to promote widespread uptake of BGI is lacking, the likelihood of future community support will be higher if the public are informed and engaged. Ongoing interagency coordination is similarly a challenge that is only partially contingent on strong political leadership as bureau directors, managers, and technical staff can communicate across bureaus with, or without, directives to do so. That said, identifying the incentives for cross-bureau communication, such as the sharing of technical expertise or successful mechanisms for public engagement, would certainly help overcome future challenge to interagency coordination.

In summary, in Portland, asset performance and service provision (including the uncertainty surrounding capital and maintenance costs and perceived costs), community expectations and behavioural change, and environmental change and hazards, represent the key areas of concern that adversely influence implementation of BGI. These concerns are to a degree insulated from overarching concerns about climate change by the City’s Comprehensive Plan and by the regulatory environment within which decision making takes place (Figure 3).

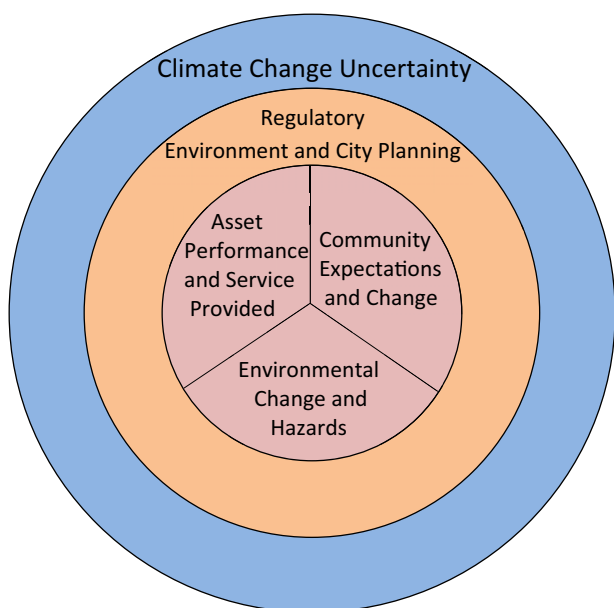


Figure 3 The factors that influence the implementation of Blue-Green Infrastructure in Portland.

Discussion

The RDUs derived in this study provide immediate new insights into the contrasting natures of the uncertainties that condition and limit implementation of BGI in Portland. Uncertainties relating to future climate, climate impacts, assumptions and inaccuracies in modelling BG (and grey) infrastructure, and long-term maintenance required to sustain maximum functionality fit within the original framework of RDUs proposed by Smith and Petersen (2014). However, other important uncertainties are unrelated to the scientific uncertainty that currently clouds our ability to forecast future BGI performance and service provision. They relate instead to local socio-political contexts, preferences, responses to impacts of environmental processes, and limited recognition of the multiple benefits of BGI. This insight led naturally to the decision to broaden Smith and Petersen’s definition of RDUs by adding a new genre: the RDU_S defined above. A further insight gained through this research is that although socio-political in nature, RDU_S may still overshadow scientific known unknowns (RDU_P) and limit effective action. This is important for (at least) two reasons. First, the research, actions, and interventions needed to reduce and thereby mitigate RDUs differ between RDU_S and RDU_P . Second, reducing RDU_P alone is insufficient to unlock the potential for wider uptake of BGI unless a parallel investment is made in resolving (or at least better understanding) concerns and challenges that stem directly from RDU_S . The implications of widening the basis for RDUs extend beyond selecting the appropriate mix of BG and grey infrastructure. Recognition and consideration of socio-political uncertainties related to, for example, citizens’ appetites to accept the risk that their lifestyles may be detrimental to future generations, demonstrate why inaction is likely to continue even if the scientific uncertainties that are the focus of current debate (RDU_P) are substantially reduced. It follows that effective action (i.e. taking the steps necessary to reduce the chance of near-certain catastrophe by making difficult decisions that benefit future generations) does not depend solely on our ability to forecast future conditions. Planners, politicians, and the publics they serve must also learn: first, to recognise socio-political uncertainties that manifest as concerns and challenges to evidence-based decision making; second, reduce those uncertainties that are reducible, and; third, address concerns and overcome challenges related to those uncertainties that are, in practice, irreducible.

Returning to decision making with regard to sustainable urban flood risk management, it emerges that consideration of *both* RDU_P and RDU_S is essential: the first in order that things are done right and the second in order that the right things are done. Stringent efforts to reduce scientific and engineering uncertainties related to the performance and

maintenance of BGI and the hydrological stresses with which urban communities will have to cope must continue. Many RDU_s are addressable and some are reducible, indicating that public engagement, education, and co-production of the knowledge upon which evidence-based decision making relies can lead to consensual decision making. Alternatively, the concept of adaptive management practices that intentionally acknowledge and embrace uncertainty could suggest a way to deal with the irreducible and non-addressable uncertainties (Pahl-Wostl, 2007). The risk appetites and tolerances of communities and their elected representatives may inform the degree to which precautionary principles are applied or future increases in flood risk are accepted. An important corollary is that these two remedies: improving our ability to forecast future flood risks and their management; and developing a common view of what levels of public investment and flood risk are acceptable, are very different undertakings. The risk is that preoccupation with the need to generate consensus on the scientific, technical, and engineering aspects of alternative stormwater management strategies may obscure other equally important determinants (Pahl-Wostl *et al.*, 2008). Accurate identification of which types and sources of uncertainty dominate is therefore crucial, and it must be recognised that these will differ not only between cities but also between neighbourhoods.

A surprising outcome of our research is that uncertainty regarding the identification of hydrological stresses that infrastructure built today will have to cope with over the next 50 years is not the highest ranking concern. We expected that engineers would be exercised by the need to implement integrated urban drainage systems with the adaptive capacity necessary to deal with rainstorms of progressively greater, but unknown, intensities and durations (i.e. a classic RDU_p). The empirical evidence that emerged indicates a deeper concern regarding the likelihood of getting *any* long-term infrastructure plans to implementation, due to socio-political uncertainties (i.e. RDU_s). The effect is to promote short-term, reactive thinking, with designers and engineers persistently responding to changes in hydrology and flood risk (and politics) rather than planning for them. Denying the space within which to conceive and refine long-term solutions negates even the possibility of delivering integrated BG and grey systems needed to ensure adequate service provision in an uncertain future. Flood risk management solutions bounded by design standards that are historically referenced leads, at best, to wasted investment in infrastructure that is abandoned early in its design life or, at worst, technical lock-in that burdens future generations with systems that have neither the hydrologic nor adaptive capacities necessary to continue delivering adequate stormwater management throughout their design lives. The wider point that this example illustrates is that it may be necessary to

address a relatively obscure RDU_s before a more obvious and tractable RDU_p can be tackled.

Building confidence in BGI

The findings of this research demonstrate that broadening the consensus on technical and engineering aspects of flood risk management and reducing the scientific uncertainties is not sufficient to trigger the public support and political backing needed to sustain actions that must be coordinated across multiple agencies, implemented over a wide area, or sustained for a long period (Morss *et al.*, 2005; Cettner *et al.*, 2014; Ashley *et al.*, 2015). The difficulties experienced in turning *Blue-Green ideals*, where the urban water cycle is reconfigured to more closely resemble the natural water cycle, into real changes to neighbourhoods and cities suggests that uncertainty related to setting priorities for public investment may be as limiting as uncertainties associated with the long-term functionality of BGI. BGI and sustainable drainage systems have typically been perceived as serving a single drainage need and judged solely on abilities to manage stormwater and contribute to reducing flood risk. Communicating the multiple benefits of BGI, which extend into the socio-cultural, ecological, and economic spheres, could greatly increase confidence in BGI as a preferred strategy, potentially opening avenues for co-funding schemes that simultaneously meet a range of City objectives (Ashley *et al.*, 2015). This presents a pivotal challenge for water management professionals in devising effective strategies for communicating the benefits of future implementation of BGI and motivating decision makers to champion such approaches (Fratini *et al.*, 2012). Moreover, although BGI is especially vulnerable, the paralysing effects of RDU_s may be pervasive, sapping the capacity of cities and the confidence of their decision makers to invest in *any* infrastructure that promises a long-term return on that investment, with preference given to schemes offering short-term benefits that are also short lived.

Although the impacts of RDU_s are similar to those of RDU_ps, there is a critical difference between them: publics can influence social-political uncertainties at the city and neighbourhood scales. Many interviewees expressed concern over community buy-in and, based on their or their colleagues' experiences, perceived gaining community support for BGI implementation as a significant challenge. This stresses the importance of initiatives involving engagement, ongoing dialogue, public education, social learning, and participatory modelling to co-produce knowledge through which citizens can develop new understandings that create the social contexts of the future (Pahl-Wostl, 2007; Pahl-Wostl *et al.*, 2008; Landström *et al.*, 2011; Everett *et al.*, 2015).

Recognising the different frames of reference of institutional and private actors and developing shared practices

that foster collaboration would help address the risk of interagency fragmentation and ineffective communication (Lems *et al.*, 2011). Although science education helps people and communities to understand the choices they are making, the key to helping them make better choices lies in clarifying the whole-life costs and benefits associated with each option, recognising that the values placed on costs and benefits are contingent on social context, environmental setting and, above all, *who benefits* and *who pays*. Fragmentation in social and political values and preferences must be overcome by pragmatic consensus if acceptable levels and distributions of risk, cost, and benefit are to be negotiated. Stakeholders assign numerous values to urban water infrastructure (Fratini *et al.*, 2012) and hence, engaging with citizens in developing shared understandings of the functionality and benefits of BGI provides the basis for negotiating these values, leading naturally to options appraisal that is accessible to well-informed *water literate* citizens. The outcome should be beneficiary communities that are more inclined to support implementation of BGI and increasingly willing to maintain and even take ownership of BGI in the future, both of which are key to reducing physical uncertainties related to future maintenance costs and service provision. Therefore, RDU_s are not only amenable to reduction through public engagement but capable of leveraging reductions in RDU_ps that appear to be serious barriers to BGI uptake when considered in isolation.

Addressing RDUs in order to widen implementation of BGI in Portland

Uptake of BGI in Portland demonstrates that barriers associated with biophysical and socio-political RDUs are not insurmountable. Our research highlights that, while concerns about BGI remain, BGI projects continue to be implemented despite the resulting impediments, as demonstrated by a range of highly successful initiatives and Portland's recognition as a leader in green stormwater management (Lukes and Kloss, 2008; Water Environment Research Foundation, 2009; Rottle, 2015). For instance, over 32 200 new street trees, 867 green street planters and 398 eco-roofs have been built as part of the 'Grey to Green' initiative (BES, 2015b). In designing urban drainage and flood risk management projects, uncertainty is dealt with using conventional approaches based on 'design standards', experience, and sound engineering judgement. Design standards and requirements for new and retrofit BGI defined in the Stormwater Management Manual (City of Portland, 2014) are modified as necessary to accommodate site-specific factors that would otherwise limit their utility, such as low soil infiltration capacity. Practitioners inclined to maximise uptake of BGI can thus work with the relevant design standards. Furthermore, all infiltration facilities must retain the

10-year storm, remove 70% total suspended solids, and manage 90% of the average annual runoff (City of Portland, 2014). This provides City engineers and designers with the regulatory leverage to enhance the longevity of new installations by accounting for potential changes in climate, land-use, and population that current design standards might not adequately cover. This is possible because, in Portland, planning for climate change is hard-wired into the City's Comprehensive Plan (BPS, 2011). The engineers and designers interviewed, however, do not over-rely on the Comprehensive Plan, and some climate change uncertainty does leak through the regulatory and planning membrane in Figure 3. For instance, uncertainty concerning the characteristics of future design storms and droughts affects the design of grey and BG infrastructure, and concerns about future immigration (due to unknowable numbers of climate change refugees moving to Portland) reduce the confidence in future population projections.

Conclusions and recommendations

The widespread adoption of BGI in Portland is currently limited by uncertainty regarding its hydrologic performance and lack of confidence in political acceptability and public preferences. We classified these uncertainties as RDUs and broadened the initial concept of RDUs that previously considered uncertainties purely in terms of the physical science (RDU_p) (Smith and Petersen, 2014). A range of biophysical RDUs that affect infrastructure performance are recognised by institutional stakeholders, notably the impacts of climate change on hydrological performance, service provision and infrastructure maintenance requirements. Socio-political RDUs (RDU_s), which refer to a lack of confidence that decision makers and publics will continue to support, understand, and pay for BGI (particularly in light of future climate and land-use change), were found to have the greatest adverse influences on decision making. Thus, the RDU_s significantly hinder Portland on its path towards becoming a *Blue-Green City*.

We conclude that to widen implementation of BGI, both the biophysical and socio-political RDUs must be identified and managed. This is because key stakeholders involved in designing and delivering sustainable urban flood risk management projects must have greater confidence that BGI components are both scientifically sound and supported by communities and their elected representatives. The actions and interventions needed to mitigate RDUs differ between RDU_s and RDU_ps. We may attempt to reduce those RDUs that are reducible through extended scientific research capable of yielding the findings necessary within a practical timescale, such as monitoring and modelling BGI assets, to determine long-term maintenance requirements. We may also promote initiatives that will build confidence among key

stakeholders and communities and thus account for irreducible uncertainties such as future stewardship, political leadership, and motivation for BGI. Investment in social learning and community engagement may help uncover the reasons behind differing public preferences for BGI, whereas changes in the risk appetite of citizens and communities may be needed before non-addressable challenges and concerns, such as delivering socially equitable water and management for future, unknown populations, can be addressed and confidence in BGI improved. Our research provides clear evidence of the need for stronger cross-sector integration and partnership in delivering sustainable urban flood risk management. Flood risk managers, planners, and other water-sector stakeholders must engage, together developing strategies to understand and overcome socio-political as well as biophysical challenges to broadening the uptake of BGI. Reducing scientific uncertainties alone will be insufficient to unlock the potential for widespread uptake of BGI in Portland and other conurbations aspiring to become *Blue-Green Cities*.

Acknowledgements

This research was performed as part of an interdisciplinary project undertaken by the Blue-Green Cities (B-GC) Research Consortium (<http://www.bluegreencities.ac.uk>) with the Portland-Vancouver ULTRA (Urban Long-term Research Area) project (PVU, <http://www.fsl.orst.edu/eco-p/ultra/>), as part of the 'Clean Water for All' initiative (<http://www.epsrc.ac.uk/funding/calls/cleanwaterforall/>).

The B-GC Consortium is funded by the UK Engineering and Physical Sciences Research Council under grant EP/K013661/1, with additional contributions from the Environment Agency and Rivers Agency (Northern Ireland). PVU is funded by the National Science Foundation award #0948983. We thank the City of Portland Bureaus of Environmental Services, Planning and Sustainability and Transport, Metro, and the Johnson Creek Watershed Council for their generous support and sharing of data, field equipment, time, and expertise. The Portland State University Office of Research Integrity provided approval for use of US human subjects (IRB 143040). For ethical reasons, the transcripts and audio files cannot be made openly available. Parties interested in this data should in the first instance contact the corresponding author. The associated metadata is available at <http://dx.doi.org/10.17639/nott.24>.

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