Info-Gap robustness pathway method for transitioning of urban drainage systems under deep uncertainties

Jonatan Zischg, Mariana L. R. Goncalves, Taneha Kuzniecow Bacchin, Günther Leonhardt, Maria Viklander, Arjan van Timmeren, Wolfgang Rauch and Robert Sitzenfrei

ABSTRACT

In the urban water cycle, there are different ways of handling stormwater runoff. Traditional systems mainly rely on underground piped, sometimes named 'gray' infrastructure. New and so-called 'green/blue' ambitions aim for treating and conveying the runoff at the surface. Such concepts are mainly based on ground infiltration and temporal storage. In this work a methodology to create and compare different planning alternatives for stormwater handling on their pathways to a desired system state is presented. Investigations are made to assess the system performance and robustness when facing the deeply uncertain spatial and temporal developments in the future urban fabric, including impacts caused by climate change, urbanization and other disruptive events, like shifts in the network layout and interactions of 'gray' and 'green/blue' structures. With the Info-Gap robustness pathway method, three planning alternatives are evaluated to identify critical performance levels at different stages over time. This novel methodology is applied to a real case study problem where a city relocation process takes place during the upcoming decades. In this case study it is shown that hybrid systems including green infrastructures are more robust with respect to future uncertainties, compared to traditional network design.

Key words | city transformation, green/blue infrastructure, hybrid systems, Info-Gap robustness pathway method, network transitioning, SWMM

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INTRODUCTION

Recent endeavors in urban water management aim to avoid piped (so-called 'gray') infrastructure and the related rapid discharge of stormwater. By mimicking the natural hydrological cycle, so-called 'green/blue' concepts are expected to be more flexible and more robust when facing future changes like climate change and urbanization (De Vleeschauwer *et al.* 2014; Kirshen *et al.* 2014). From the technical point of view, a reduction of the peak flow and the runoff volume as well as the protection of the receiving waters is sought. Furthermore, socio-economic factors, like the creation of attractive living space in urban areas, the positive effects on the micro-climate and the sustainable management of water resources are of high interest (Bach *et al.* 2013). Such green/blue strategies can include the realization of an ecosystems-services-based approach (Van Bueren *et al.* 2011), with additional green spaces, green roofs, infiltration systems, wetlands or retention ponds, also known as 'best management practices', 'sustainable urban drainage systems', 'water sensitive urban design' or 'low impact development' (Fletcher *et al.* 2015). In the following the term LID is used in this context.

By bringing the nature into the city not only hydraulic and environmental benefits are observed, but also social preferences of a liveable and sustainable future city can be addressed. From a technical point of view, the implementation of decentral stormwater treatment measures within the existing or newly constructed systems is a gradual, rather than a single-stage process, and can follow different pathways (e.g. climate, population or policy scenarios). In literature this process is defined as system transition (Pahl-Wostl 2007; Brown *et al.* 2008). A helpful planning tool for engineers is a city's masterplan, which describes the

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temporal and spatial development of such system transitions and lays out a strategic direction, which can be used as an expected ('baseline') scenario for future system design.

However, future developments are highly uncertain and exact predictions are not possible. Uncertain urban developments, the raising challenges of climate change and uncertainties in forecasting require the investigation of different scenarios (Willems *et al.* 2012). Conventional studies focused on the analysis of a few individual scenarios, with the drawback that they are highly dependent on the quality of their assumption (Gersonius *et al.* 2012; Urich & Rauch 2014). With the Info-Gap (IG) decision theory variations from a baseline scenario (e.g. the design rain and expected land use) can be analyzed under deep uncertainty and allows for statements on weak points and robustness of the systems and the pursued strategy (Herman *et al.* 2015). Furthermore, in sustainable urban planning the topic of 'system adaptation' has gained a high significance, posing the question of how to cope best with the upcoming challenges of (disruptive) change, like urbanization or climate change. With the *IG robust pathway method* future adaptation measures can be directly estimated by determining the performance level through combination of uncertain parameters until achieving the desired system efficiency.

During transition processes from an existing system to a desired final stage, changes in the system's structure and function occur. Cities and their water infrastructure are changing over time (e.g. network growth) and lately sustainable decentralized water treatment measures (e.g. LID controls) are becoming more popular (Sitzenfrei *et al.* 2013). Usually, the design of water infrastructure systems corresponds to a single design stage, describing a baseline scenario at the end of an assumed life-cycle and using state-of-the-art guidelines. However, for engineers and primarily for the main stakeholders like responsible public (or private) bodies, users and citizens, an efficient and safe operation at all stages of a system transition is crucial. Previous studies mostly focused on the topics of *network transitioning* and *phasing of construction*, however with emphasis on water distribution systems (Sempewo 2012; Creaco *et al.* 2013). Here we combine the topics of phasing of construction and IG robustness analysis in the transition of urban drainage systems for the first time.

In this work we consider the dynamics of changing drainage systems by investigating discrete intermediate stages between the existing and final systems. Originally, the system is designed for final stage; however a re-design is considered at the intermediate stages in case a required performance is not fulfilled. Furthermore, the assessment of different planning alternatives (strategies) of future stormwater handling, comparing traditional approaches of gray infrastructure with new hybrid concepts including green/blue infrastructures, is addressed. Beyond the synthetic design rainfalls used for design purpose, real rain events are applied to investigate hydraulic, ecologic and economic performance indicators. In addition, the IG robustness analysis is applied to all stages of the system transition, aiming to support engineers and decision makers in planning and operating the systems. The investigations are based on a case study in Sweden where a huge city-scale transformation occurs during the upcoming decades. Major parts of the current town, including its entire infrastructure, have to be relocated and therefore this highly defined city relocation is well suited to present our methodology (Leonhardt *et al.* 2015).

MATERIALS AND METHODS

Phased system design

For the system design a suitable level of spatial implementation of LID structures is to be pursued. It is assumed to start from a completely pipe-based system stage and transition to a desired future stage by integrating different LID structures. In this work, three *strategies* (planning alternatives) are systematically compared for this transitioning. Strategy 1 follows a traditional approach of solely underground piped infrastructure. In Strategy 2 and Strategy 3 LID structures are stepwise implemented at suitable and desired sites within the existing new city framework. In Strategy 2, possible central retention ponds are integrated in the (adapted) city landscape, whereas in Strategy 3 decentralized structures like infiltration trenches and bio-retention cells of smaller size are distributed over the catchment areas in such an adapted city landscape. Strategy 1 is investigated for the purpose of comparing the potential planning alternatives. The two objectives for the conduit and LID design for all strategies are (1) to avoid flooding for design rain events and (2) to maximize their utilized capacity at the same time.

The sole design of the *final stage* is usually insufficient, neglecting possible performance deficits at *intermediate stages*. Therefore, it is also necessary to investigate the intermediate stages defined in a city's masterplan (e.g. network construction and deconstruction phases) to guarantee sufficient performance levels at all times (Creaco *et al.* 2013). The performance objective for the design of the intermediate stages, containing network parts of the final stage, is to prevent surface ponding. In case the criterion is not fulfilled, a network re-design is considered and applied to the subsequent stages to minimize upgrade costs. In doing so, each planning alternative is checked at various time points between the initial system stage and the 'desired' final system stage (see Figure 1).

Performance assessment

For a successful network design and operation, hydraulic, ecologic and economic performance criteria must be fulfilled. Helpful tools to evaluate the system's efficiencies are global performance indicators (Alegre *et al.* 2006; Mair *et al.* 2012). For the developed method, basic indicators were chosen for simplicity. Using different, more complex performance indicators would not require the method to be changed. The normalized *hydraulic* performance indicators are calculated as follows:

$$PI_{flooding} = 1 - \frac{V_{flooding}}{V_{runoff}} \; (-) \; [0, 1] \tag{1}$$

and

$$PI_{flooding,n} = 1 - \frac{\# N_{flooding}}{\# N} \; (-) \; [0, 1] \tag{2}$$

$PI_{flooding}$ considers the normalized flooding volume, while $PI_{flooding,n}$ observes the number of flooded nodes ($\#N_{flooding}$) with respect to the total number of nodes ($\#N$). In both cases a performance value of one indicates the best performance and a desired system stage.

Furthermore, *economic* performance indicators are assessed by considering the capacity utilization of the system components, and are as follows:

$$\eta_C = \sum_{j=1}^{N_l} \frac{h_{max,j}}{h_{full,j}} * \frac{l_j}{l_{tot}} \; (-) \; [0, 1] \tag{3}$$

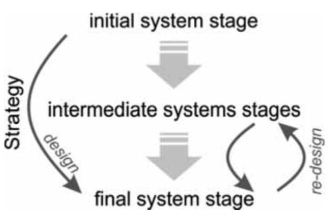

Figure 1 | Multi–stage design scheme.

and

$$\eta_{LID} = \sum_{k=1}^{N_k} \frac{h_{max,k}}{h_{LID,k}} * \frac{A_k}{A_{tot}} \; (-) \; [0, 1] \tag{4}$$

where η_C is the accumulated, length-weighted ratio (length l_j of conduit j and l_{tot} as the sum of the lengths of all conduits) of the maximum filling level ($h_{max,j}$) and the diameter ($h_{full,j}$) of the conduit j. On the other hand η_{LID} is the accumulated, area-weighted ratio (area A_k of LID structure k and A_{tot} as the sum of LID areas) of the maximum storage level ($h_{max,k}$) and the berm height ($h_{LID,k}$) of the LID structure k. Both factors indicate fully used capacities when reaching a value of 1. In terms of economic considerations, values close to 1 for the utilized capacity are desired.

Finally, the normalized LID overflow volume ($r = V_{over}/V_{in}$) and the discharge to the receiving water Q [m³/s] are determined to assess the *ecological* performances. In case an LID overflow occurs ($r > 0$), the water is not treated in the LIDs and has a negative effect on the downstream water quality.

Multi-stage IG robustness analysis

With the IG robustness analysis the planning alternatives are determined, which work under the greatest uncertainty horizon while still fulfilling desired performances (Herman *et al.* 2015). While initially presented for robust analysis for water supply networks, in this work this concept is applied for drainage systems and enhanced to take into account the temporal development. The initial system design is based on a baseline scenario $\tilde{u}(t)$, referring to a design rain event and the most likely city development over time t with regard to the surface imperviousness. However, an accurate prediction of these influencing factors is not possible. To consider all uncertainties, a robustness analysis is performed where deep uncertain model parameters (U1 and U2) are varied (Figure 2(a)).

With this non-probabilistic method, perturbations of a given estimate (baseline scenario) are investigated and routed to the limit of system functioning and failure by reaching the so-called 'critical reward level' (see Figure 2(b)). This method is called the IG robustness pathway method and has the benefit of searching the robustness level $\hat{a}$ until each scenario reaches the critical reward level (Roach *et al.* 2016). Here, the robustness level $\hat{a}$ is defined as the normalized area that delimits sufficient system performances over different system stages (see Figure 2(c)).

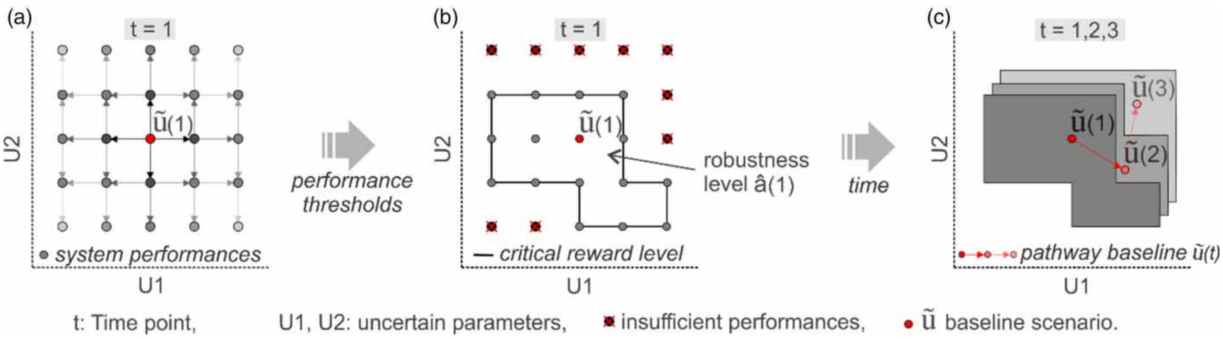

Figure 2 | General procedure of the IG robustness analysis: (a) deviations from baseline scenario ũ and performance analysis, (b) definition of the critical reward and robustness levels by setting (contrasting) performance thresholds, and (c) investigation of the robustness level over time *t* including the baseline scenario ũ(t). Modified from Roach *et al.* (2016).

In general, the criteria for efficient system performances that define the critical reward levels can be any indicators and thresholds chosen by the user. The results allow for a comparison between planning alternatives (strategies), but also quantify possible adaptation strategies by determining the trade-off between the unknown factors that ensure the same performance within the same system stage (Kleidorfer *et al.* 2014).

In this study, variations of the surface imperviousness and future rainfall depths are used as the uncertain variables U1 and U2, respectively. The main motivation for varying the rainfall depth (changing of the design rain) is the future climate change, but it can also present a change in future design guidelines. On the other hand, a changing surface imperviousness (modelled as deviation of the baseline scenario) may originate from different developments of population, policy making or city planning. Changing the surface imperviousness is only a simple but easily applicable approach to consider city development and could be related to the changing of population densities or land use. Factors like vulnerability to flooding, available funding for infrastructure or the price of land are not considered in this analysis.

The contrasting performance criteria that define the critical reward levels are chosen with user-defined thresholds of the flooding performance $PI_{flooding}$ (Formula (1)) and the utilization of the network capacity η_C (Formula (3)). While the former indicator represents a safety requirement to prevent damage caused by pluvial flooding, the latter factor can be seen as an economic indicator that prescribes a minimum utilization of the installed system capacity, assuming that higher capacities are more cost-intensive. For each system variation both performance values are determined based on Storm Water Management Model version 5.1 (SWMM5.1) simulations. With this method the robustness level can be determined for each stage of the system transition.

Case study

The developed methodology is presented with the Swedish northernmost town of Kiruna (18,000 inhabitants) where a necessary city displacement provides the opportunity to stepwise improve the city's urban water infrastructure towards more robust, sustainable and near-natural systems during the next decades. The driving force behind this city transformation is the expansion of mining activities below ground, which threatens the current city due to settlements and subsurface erosion. Based on the city's masterplan, construction of a new city center started in 2016, at approximately 3 km distance, and people will be relocated step by step within the next decades (Zischg *et al.* 2015). Other parts of the city (see restricted areas in Figure 3(a)) and also their existing water infrastructures have to be disconnected from the remaining system. This city transformation (or 'flipping' of the system layout) is seen as an opportunity to realize the new town center (see Figure 3(a)) as an attractive city with high urban amenity, considering the integration of green infrastructures, like bio-retention cells and infiltration trenches, within the future stormwater system. The newly connected catchment size is approximately 120 hectares. Figure 3(b) illustrates potential sites for LID structures in the new town center. The construction progress unit 2018, including the newly build stormwater system by following Strategy 1, is presented in Figure 3(c). The existing stormwater network is operated as a separate system, which will be retained in the future.

Figure 4 illustrates the strongest recorded rain events in Kiruna with durations from 30 minutes to almost 2 days. It shows the classification with the average return period T (according to Formula (5)). The shaded area represents the decisive duration D (i.e. highest return period) for the rain

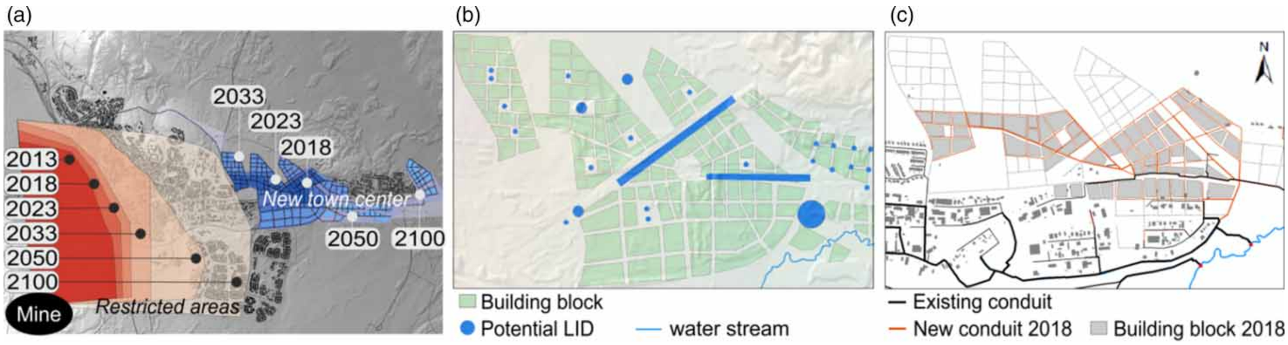

Figure 3 | (a) Masterplan describing the phased town transformation, (b) possible sites for future LID implementation, and (c) exemplary time point 2018 (Strategy 1) with constructed and existing stormwater network.

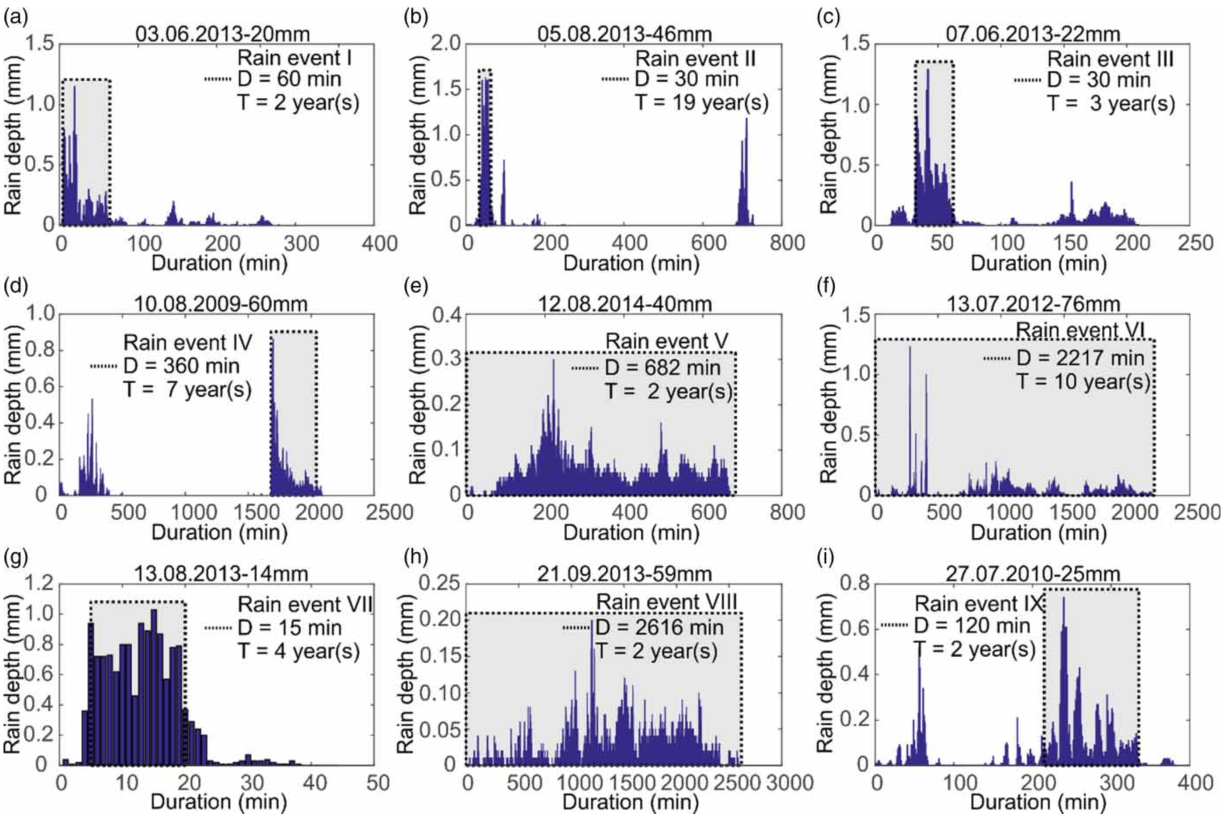

Figure 4 | Classification of nine real rain events recorded during the last 7 years in Kiruna.

classification. During the recording time of 7 years, one remarkable thunderstorm with $T = 19$ years is observed (Figure 4(b)). These rain events are used for the performance analysis to verify the system design.

These observed rainfall events are classified according to Dahlström (2010) as follows:

$$RI = 190 * \sqrt[3]{T * 12} * \frac{\ln(D)}{D^{0.98}} + 2 \quad \left(\frac{l}{s * ha}\right) \tag{5}$$

where RI is the rain intensity, D is the rain duration [minutes] and T is the average return period [years]. This equation is valid for any place in Sweden.

The Swedish design guideline defines the protection of the ecology of the receiving water by limiting the maximum outflow Q_{max} to 15 l/(s*ha). This value corresponds to the natural runoff for a 10-year event. The design rainfall event for the stormwater system corresponds to a 15-min block rain with a return period of 10 years (SWWA 2016).

RESULTS AND DISCUSSION

Phased system design

Altogether, 15 possible future stormwater models (five time points and three strategies) were created and iteratively designed with the hydrodynamic software SWMM5.1 (Rossman 2010), by following the baseline scenario that defines the expected impervious area. The system design was based on Austrian and Swedish state-of-the-art requirements (ÖWAV 2009; SWWA 2016). First the fully constructed final stage system (year 2100) was designed. In addition, intermediate state models (years 2018, 2023, 2033 and 2050) were created on the basis of the masterplan and assessed with the performance indicator $PI_{flooding}$. In case the performance was insufficient ($PI_{flooding} < 1$) at these states, the conduit diameters were increased and assigned to the subsequent state models.

Figure 5 presents the results of the model creation, including pipe and LID design for the three proposed strategies at the final stage (year 2100). The LID structures were implemented at the years 2018, 2023 and 2033 associated with the construction process (see Figure 3(a)). By following Strategy 2 or Strategy 3, about 40% of the runoff from the new city will be treated in LIDs for the design rain at final stage 2100. With the usage of LIDs and the correlated retention effect, the (averaged and length-weighted) peak flow in the conduits, determined based on SWMM5.1 simulations, could be almost reduced by a factor of 2 for the design rainfall. As a result, the conduits of Strategy 2 and Strategy 3 had much smaller diameters, to achieve the same flooding and utilization performances. For the traditional strategy a retention tank had to be applied, to limit the outflow to the receiving water. Overloaded conduits of the existing system were upgraded, to sufficiently guarantee the connection of the new system to it.

Performance assessment

Beyond the simple hypothetical rainfalls used for design purpose, various performances of the drainage systems were investigated with real rain events recorded for this case study (IRF 2016). This allowed for the consideration of the local climate, a verification of the system design and a prediction of the system operation (Seo *et al.* 2015), in particular the interaction of piped network and temporal storage structures (e.g. LIDs).

The performance of the system was evaluated for the final design stages of the three planning alternatives and the baseline scenario, describing the expected and 'most-likely' urban development. The system was investigated with the presented performance indicators and the nine real rainfall events (see Figure 4). Resulting performance indicators describing the hydraulic, ecological and economic performances can be obtained from Figure 6. A drop in the hydraulic performance can be seen for rain event II, where about 40–50% of the nodes were flooded (Figure 6(d)). The flood volume was highest for Strategy 1 (Figure 6(a)). The performance drop can be explained by the high rainfall intensity, even exceeding the design event with an average return period of 10 years. Furthermore, for this rain event the threshold of maximum outflow to the receiving water was (by definition $Q_{max} = 1.8\ m^3/s$) exceeded for Strategies 1 and 2 (see Figure 6(e)). When looking at Figure 6(b), an overflow at the LIDs for the rain events II, IV, VI and VII occurred, where the water was conveyed through the subsequent piped network as soon as the LID capacity was fully used (see Figure 6(c)). However, except for the rain event II, no flooding occurred. This is due to the higher volume but lower rain intensity for these events with durations from 6 to 44 hours. Finally, Figure 6(f) shows the global utilization of the network capacity η_C. A value of 1 would have indicated a completely pressurized system

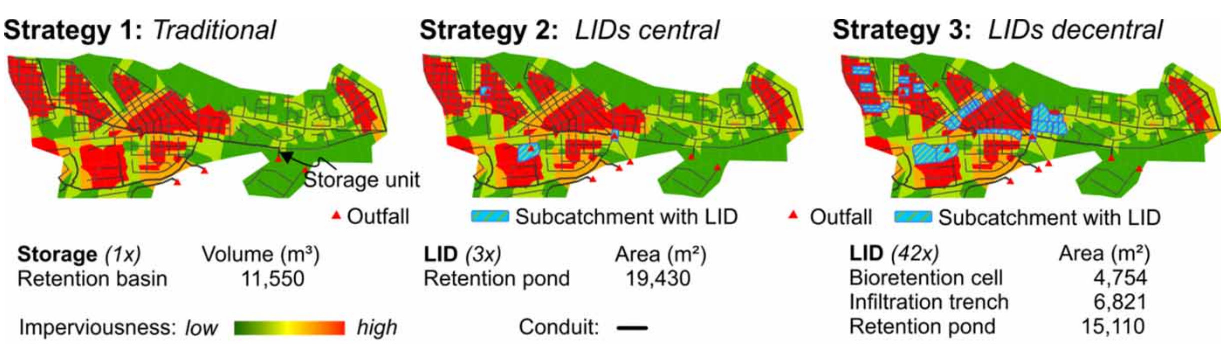

Figure 5 | Designed and optimized planning alternatives (strategies) for the future stormwater system.

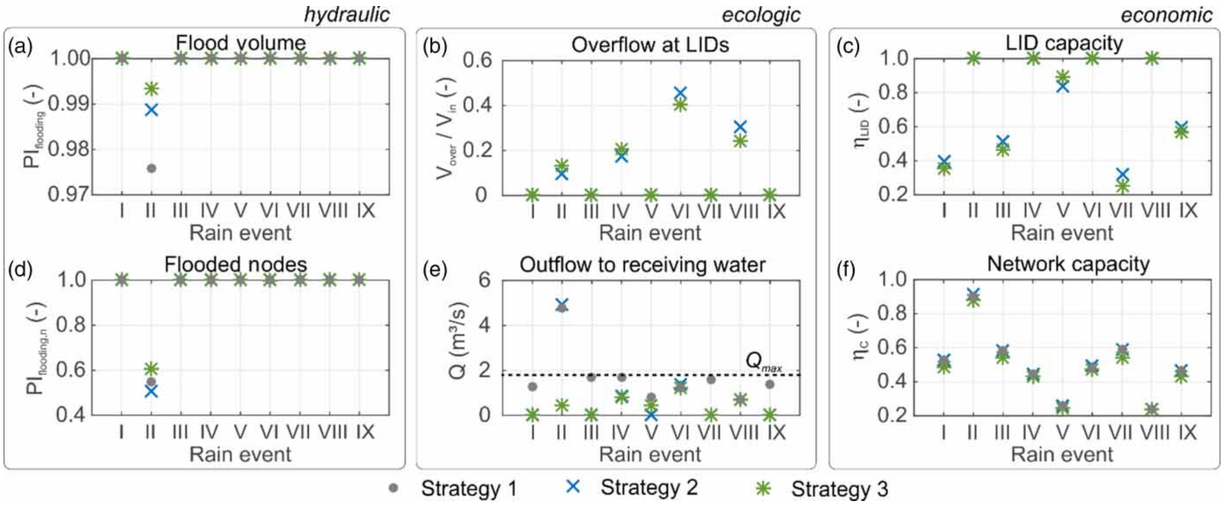

Figure 6 | (a) Hydraulic, (b) ecologic and (c) economic system performances for the three strategies and nine recorded rain events in Kiruna in accordance to Figure 4.

during the peak flow. In the design process a value of η_C close to 0.7 could be achieved without causing flooding.

IG robustness analysis

To consider unforeseen events a robustness analysis under deep uncertainty was performed for the presented case study. By incrementally sampling the uncertain space, performance levels of chosen indicators were interpolated. The uncertain space was defined by alterations of the baseline scenario ũ used in the design process and consisted of the uncertain variables U1 (area-weighted mean imperviousness of 601 subcatchments) and U2 (rainfall depth), and was therefore two-dimensional. Such an example is seen in Figure 7, where two performance indicators, namely $PI_{flooding}$ and η_C, are shown for Strategy 3 and time point 2050. According to the masterplan the starting point of U1 was the 'most likely' surface imperviousness of Kiruna's new town center of about 36% at time point 2050. U2 was initially set to the design rain event of 16.3 mm/15 minutes. Gunn et al. (2016) developed extreme scenarios for the population development of Kiruna, depending on the development of the mining industry (multipliers of 0.7 and 1.4 until year 2040). The bandwidth of the U1 parameter variation was set to 20 and 50%. According to Chabaeva et al. (2004), these thresholds would suppose changing population densities by the factors of 0.35 and 2.5, which include both extreme scenarios. The parameter U2 was varied from 8 to 28 mm with an unchanged pattern and duration. This corresponds to rain return periods of 1 to 50 years. The sampling distances of U1 were chosen from 0.5 to 1% and from 0.4 to 0.8 mm for U2 accordingly. The gradual darkening of

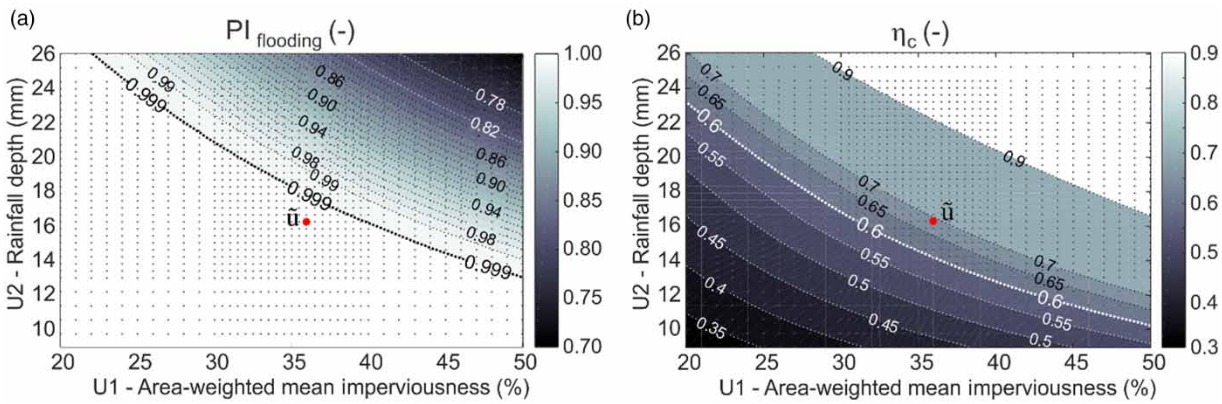

Figure 7 | Interpolated performance levels by incrementally sampling the uncertain space (U1 – area-weighted mean imperviousness (%) and U2 – rainfall depth (mm)) for Strategy 3 and stage 2050: (a) flooding performance $PI_{flooding}$ and (b) network utilization factor η_C.

the area corresponds to a performance decline in both illustrations, while the lines reveal constant performance levels.

Figure 8 exemplarily presents the IG robustness model for the stage 2050 and Strategy 3 derived from Figure 7. It shows the efficient area A_t, depending on the combination of the uncertain variables U1 and U2, where both constraints, flooding performance ($PI_{flooding} = 1$ means no flooding) and pipe utilization ($\eta_C = 1$ means capacity fully utilized), were still satisfied. The efficient area A_t can be interpreted as the robustness level $\hat{a}_t$ of a strategy at a certain time point t, where $\hat{a}_t = A_t/\max A$ and $\max A$ is the maximal element of the set A of all efficient areas at the time points and all strategies ($A_t \in A$). In this analysis a flooding performance indicator $PI_{flooding}$ of 0.999 and a pipe utilization factor η_C of 0.6 were used to define the critical reward levels. While the latter was chosen to consider economic conduit diameters (with regard to calculated values around 0.68 at the design condition), the threshold value for $PI_{flooding}$ was a safety factor to minimize surface flooding. The robust pathway method allowed not only for a robustness assessment, but also quantified possible adaptation measures (i.e. change in surface imperviousness) to achieve a required performance level. For example, an increase of the design rain intensity of 30% at stage 2050 (equivalent to a 20-year event and similar to the rain event II presented in Figure 4(b)) could be compensated for with a decrease in mean imperviousness of 6% following this strategy.

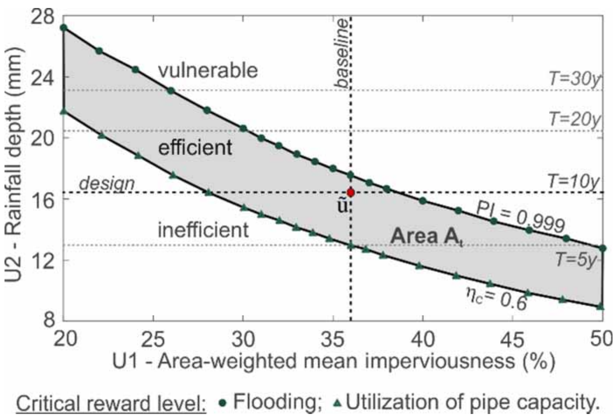

Figure 8 | Efficient area A_t of satisfying performance (limited by critical reward levels) when altering the baseline scenario (ũ) for Strategy 3 and stage 2050.

The system behavior over time is shown in Figure 9. Therein, the critical reward levels and the derived robustness levels are shown for the five time points and the three strategies. The results revealed that all strategies had similar robustness when facing uncertainties, which also proved an appropriate system design for all network stages. The baseline scenario ũ(t) was within the efficient area A_t at all stages (between solid and dotted lines of each time point). Strategies including LIDs had slightly higher robustness levels $\hat{a}_t$ at most stages, due to an increased flood protection (temporal surface storage) and similar pipe utilization capacities as the traditional strategy (see insets in Figure 9). One weak point could be identified with the robustness drop at stage 2018 for Strategy 3, where the critical performance lines of flooding and capacity are intersecting for high U1 values. It can be referred to changing flow paths for higher runoff rates and the not fully implemented LID structures at that stage.

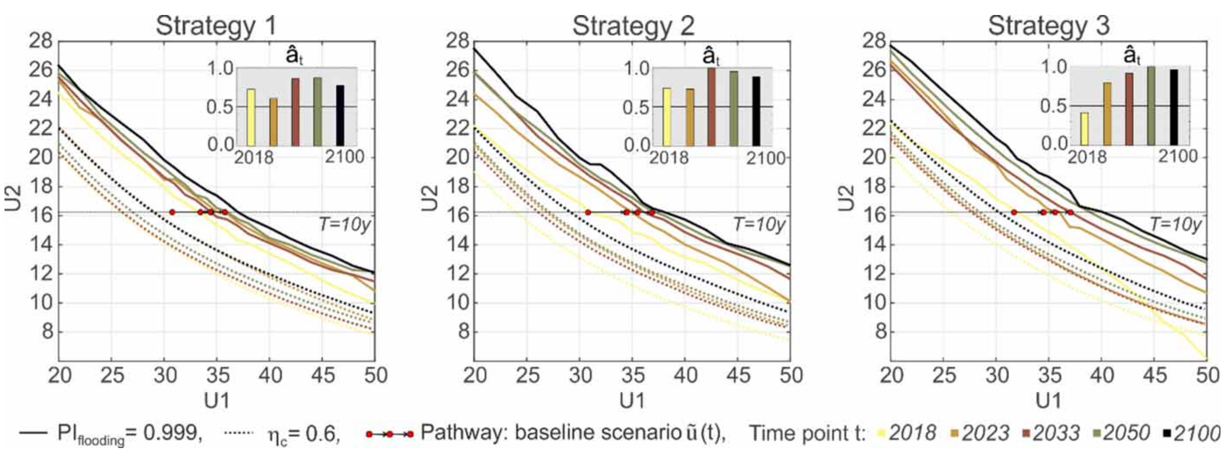

Figure 9 | IG robustness models for the three strategies presenting the critical reward levels for the five time points. The insets show the robustness levels $\hat{a}_t$ at five time points.

CONCLUSIONS AND OUTLOOK

In this work a multi-stage robustness analysis with IG decision theory to assess the drainage system behavior under deep uncertainty over time was shown for the first time. In this analysis perturbations of a given pathway (baseline scenario) were made at five network stages (time points) and then iteratively routed to the critical reward level, where defined performance criteria fulfilled the minimum requirements. Furthermore, it was shown how a masterplan of a phased city transformation was realized step by step with the focus on the design of different planning alternatives. The iterative multi-stage design of the new stormwater system was well suited when planning the expansion of the stormwater system (e.g. city growth) and ensured sufficient performances at every time point. The obtained IG-robustness models allowed for the determination of two-dimensional uncertainty regions, where future pathways will be satisfactory in terms of the predefined minimum required system performances. The 'expected' pathway of the baseline scenario was within the efficient performance region in all cases, which proves an appropriate system design during the phased network growth.

One limitation of the presented work is that the uncertain space was abstracted by two-dimensionality. This simplified approach could be extended to a high-dimensional parameter space comprising a redefinition of the robustness levels (efficient volumes). A possible third parameter with regard to green/blue infrastructure implementation could be the integration of additional surface storage (LIDs) to reach the desired performance levels. In this case the presented ecological indicators would represent useful performance criteria. A more efficient sampling method when applying this method for a high-dimensional parameter space should be considered. Furthermore, the assessment of the robust area considers all parameter combinations with the same probability, regardless of the 'distance' to the 'most likely' baseline scenario. In a further study a weighting of the efficient area could be investigated, for example with a normal distributed probability of the events around the baseline scenario. For further investigations or the application to other case studies, the sensitivity of different performance indicators and their thresholds (critical performance levels) should be addressed.

Future work will also emphasize the integration of different future pathways in the IG robustness models. By taking into account political, socio-economic, climate, population and wildcard scenarios, the city development and its influence on the system robustness will be considered in a broader context. This could, for example, include 'adoption-curves' of additional green/blue infrastructure implementation. Furthermore, this study builds the basis for a cost-benefit analysis of the different planning alternatives also taking into account the multiple benefits of green/blue infrastructures for future city developments.

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