On the sensitivity of geospatial low impact development locations to the centralized sewer network

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ABSTRACT

In the future, infrastructure systems will have to become smarter, more sustainable, and more resilient requiring new methods of urban infrastructure design. In the field of urban drainage, green infrastructure is a promising design concept with proven benefits to runoff reduction, stormwater retention, pollution removal, and/or the creation of attractive living spaces. Such 'near-nature' concepts are usually distributed over the catchment area in small scale units. In many cases, these above-ground structures interact with the existing underground pipe infrastructure, resulting in hybrid solutions. In this work, we investigate the effect of different placement strategies for low impact development (LID) structures on hydraulic network performance of existing drainage networks. Based on a sensitivity analysis, geo-referenced maps are created which identify the most effective LID positions within the city framework (e.g. to improve network resilience). The methodology is applied to a case study to test the effectiveness of the approach and compare different placement strategies. The results show that with a simple targeted LID placement strategy, the flood performance is improved by an additional 34% as compared to a random placement strategy. The developed map is easy to communicate and can be rapidly applied by decision makers when deciding on stormwater policies.

Key words | hybrid stormwater systems, hydrodynamic simulation, LID, performance assessment, sensitivity maps, stormwater control

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INTRODUCTION

In urban water management, the implementation of green/blue infrastructure has increasingly gained importance due to its multiple benefits. Rather than rapidly discharging stormwater runoff through conduits, the retention and treatment of stormwater at the surface is sought in order to mimic the natural 'pre-development' process. The resultant increase in infiltration, evapotranspiration, and water at the surface in a controlled environment leads to multiple benefits. Increased biodiversity, improvement of the city's climate by reduction of the 'urban heat island effect', pollution removal, flood protection, increasing the attractiveness of neighborhoods and amenity values are only a few examples, which can be achieved with the implementation of green/blue infrastructure (Bach *et al.* 2013a; Kuzniecow Bacchin *et al.* 2014). Moreover, these surface structures are more flexible than the underground pipe network, due to eased accessibility, gradual implementation, and shorter lifespans (Sitzenfrei *et al.* 2017). The term green/blue infrastructure refers to above-ground stormwater control measures at different scales and is a combination between 'Green' (near-nature) and 'Blue' (water-related) urban infrastructure, shifting the focus of stormwater runoff management from a problem-centered to an opportunity-based approach.

In the literature, different terminologies for the overall concept of green/blue infrastructure exist: e.g. best management practice (BMP), sustainable urban drainage system (SUDS), low impact development (LID), water sensitive urban design (WSUD), green infrastructure (GI), and integrated urban water management (IUWM) (Fletcher *et al.* 2015). However, from a hydrologic perspective, these concepts are very similar, leading to the reduction and retention of stormwater runoff by reducing the surface imperviousness and providing temporary storage.

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Hereinafter, we use the term low impact developments (LIDs) as used by the US Environmental Protection Agency (EPA) for site and regional scale green/blue infrastructure (Rossman 2010).

Recent challenges, such as increases in surface imperviousness and rainfall intensities, stress existing, mainly piped, stormwater systems. Often these systems fail because of traditional design approaches, which relied on past performance trends, and long lifespans of several decades, resulting in infrastructure that is rigid and incapable of adapting to changing conditions (Ashley *et al.* 2005). To reduce the risk and frequency of surface flooding and consequently to guarantee the safety of the population as well as the protection of the natural water system, sustainable adaptation strategies are required. So-called 'hybrid approaches', using the combination of LIDs at the surface and a pipe system at the subsurface, are expected to be more resilient when facing changing conditions such as climate change and urbanization. LID placement is not only an option for newly built systems, but also a suitable 'adaptation option' to improve the robustness of existing systems. A prerequisite to enhance the performance of urban water infrastructure is a detailed understanding of the systems' vulnerabilities, weak points, and recoverability from extreme events. State-of-the-art methods for understanding such system properties encompass sensitivity (Mair *et al.* 2012), risk (Ashley *et al.* 2005) and global resilience analyses (Mugume *et al.* 2015).

LIDs can be divided in central units, which aim for large scale treatments (e.g. wetlands, ponds), and decentralized LID units or site control practices, which are of smaller dimension and treat the runoff at-source (e.g. raingardens, sand filters). Such LIDs are usually distributed over the catchment area in small scale units. The spatial distribution of LID units, however, alters the flow pattern of the existing stormwater network due to retardation effects and altering discharge. By identifying the most hydraulically favorable positions of LID structures, the performance of the stormwater network (e.g. 'reserve capacity' to surface overflow) can be increased with little effort.

This poses the question of the optimal location of such infrastructure (Cunha *et al.* 2016; Wang *et al.* 2017). Existing studies have mainly focused on computationally expensive optimization algorithms based on only a few objectives and have primarily addressed a small number of central storage units (large scale treatment). However, the optimal adoption and the spatial distribution of decentralized, at source, treatment options is highly uncertain, depending on future climate, policy, urban development, and socio-economic trends. Such influencing factors might be the availability of space, urban amenity, the effects on the existing stormwater system, soil conditions, the treatment of pollutants, or the willingness of people to invest in LIDs at their private property. Often, restricted budgets additionally emphasize the importance of providing a useful and easily applicable planning tool when placing LID units. Bach *et al.* (2013b) developed a decision support tool called 'UrbanBEATS', where suitable locations of WSUD placement are investigated, based on a multi-criteria assessment algorithm considering aspects such as land use, population density, topological and geological characteristics, urban heat islands, etc. Kuller *et al.* (2016) investigated the optimal choice and location of green/blue infrastructure assessing biophysical factors (e.g. natural waterways) and socio-demographic factors (e.g. income in certain districts). However, these studies focus on large scale implementations and do not consider the local effects on the pipe network.

In this paper, we present a simple method to create spatially referenced GIS-maps for efficient LID placement based on a sensitivity analysis without expensive mathematical optimization. For a targeted LID placement, the developed maps for global performance and adaptation can be used and easily intersected with other spatial criteria (e.g. availability of space) resulting in performance improvements with respect to the entire system or local weak points. Finally, we show an application to a case study and compare different placement strategies: a targeted placement based on the determined sensitivity maps, a placement based on the flood map of the reference state, a placement referring to the surface imperviousness and randomly distributed placements of LID units. It is shown that with the developed adaptation map, the most beneficial strategy is achieved when improving the performance of one specific weak point in the network. By using the global performance map, the global flood performance was improved by an additional 34% as compared to a random placement strategy.

MATERIAL AND METHODS

Sensitivity analysis

In urban drainage modelling, the implementation of LID structures at the surface influences the performance of the connected underground stormwater sewer. Runoff reduction and retention effects change the flow pattern due to backwater effects and different flood locations in the network. Sensitivity analyses are carried out to assess the variation of model parameters on the model results and help to understand complex model processes. A simple local screening approach is to change one single parameter at a time (e.g. one-factor-at-a-time method) and analyze the impact on the results (Mair *et al.* 2012). The advantage of such a method is that the number of simulations required is small compared to a global sensitivity analysis and the results are easier to present and communicate. A disadvantage is that interactions of parameters are neglected.

In Figure 1 we show an example of the principle of the local sensitivity analysis used in this work. For the performance assessment, different performance indicators (*PIs*) are used. It summarizes the procedure as follows: First, the reference state of the system, without any LID structure, is evaluated and referred to $PI_{i,0}$ ($n \times 1$) at each subcatchment i, where n is the total number of subcatchments and 0 indicates the reference state. Second, consecutively on each subcatchment j, a single LID with consistent type and size is applied (parameter variation) and simulated for performance with an appropriate software tool, here SWMM5.1. The effects (parameter sensitivity) on each node of the network due to a variation at subcatchment j are assessed with $PI_{i,j}$ and assigned to the connected subcatchment i.

Impact matrix

The outcome of the sensitivity analysis can be stored in the $n \times n$ Impact Matrix M_{ij}, where all nodal performance values (parameter sensitivity) of every parameter variation (LID position) are collected (see Figure 2). While the column j of M_{ij} indicates the variation of the LID position, the row $i = 1 \ldots n$ refers to the nodal *PIs* of all possible LID positions j with respect to subcatchment i. For assessing the hydraulic efficiency of the stormwater network, various performance indicators are calculated (Zischg *et al.* 2017a). Examples are the total nodal flood volume, the flood duration or the 'reserve capacity' of the conduits. A similar principle was introduced by Wu & Song (2014), who created an impact matrix to optimize the selection of hydrants for fire flow tests in water distribution systems.

Global performance and adaptation maps

Based on the Impact Matrix M_{ij}, a global performance map can be created. The performance values $PI_{i,j}$ ($n \times n$) of the rows are therefore aggregated to a set of global PI_j ($1 \times n$), which are subsequently mapped to the corresponding subcatchment j (see Figure 2(a)). The colors of the subcatchments indicate the level of sensitivity of the mapped PI_j (dark colors indicate high sensitivity and light colors indicate low sensitivity).

The global performance map shows the effect of a possible LID placement on the subcatchment, with respect to the global stormwater network performance. Furthermore, the resulting global performance values PI_j are normalized with the reference performances $PI_{i,0}$ to present the relative changes in comparison with the reference (existing) state of the stormwater network (see Figure 2(b)). For example, a normalized performance value of 1 indicates no effects of the LID placement on the global system performance.

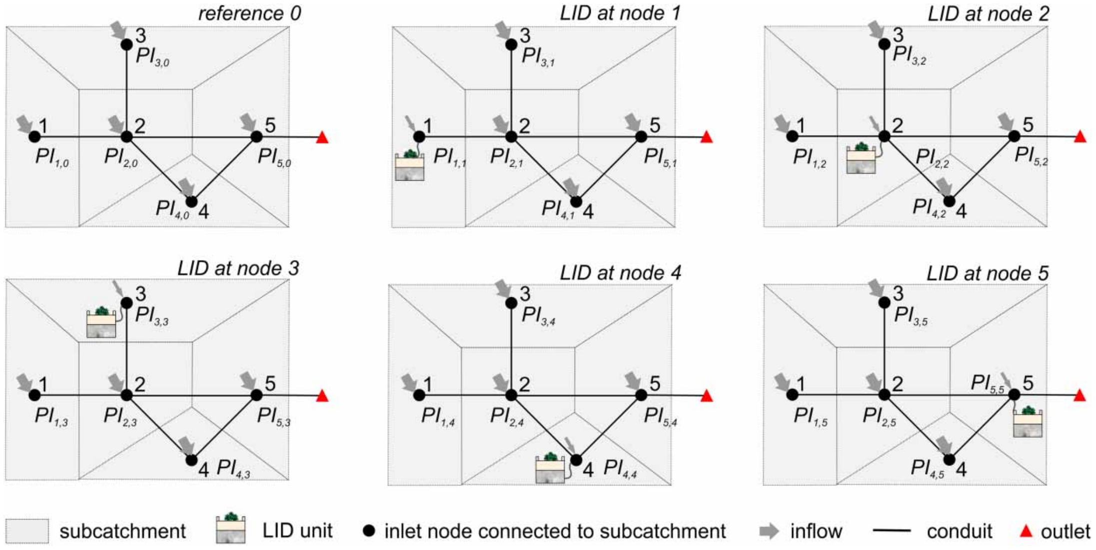

Figure 1 | Concept of the sensitivity analysis. Variation of the LID unit placement within the system and performance assessment (PI) at the inlet nodes.

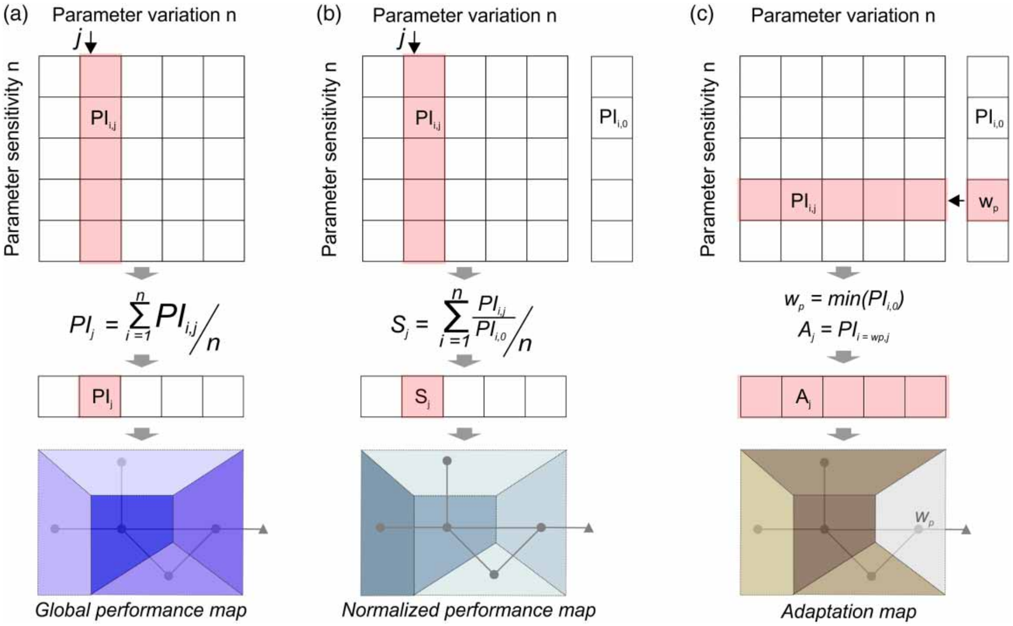

Figure 2 | Impact Matrix M_{ij}: (a) derived global performances PI_j, (b) normalized performance values S_j and (c) effects of LID placement A_j with respect to a weak point w_p.

Therewith, by placing LIDs based on the global performance map, the overall performance of the system can be improved.

On the other hand, the Impact Matrix M_{ij} also allows for the creation of sensitivity maps, where specific locations of the stormwater network are addressed. Such specific locations can be particularly important facilities at the surface (e.g. schools, hospitals) or a specific weak point w_p at location i (e.g. lowest performance in the reference system – $min(PI_{i,0})$). As illustrated in Figure 2(c), to create the so-called adaptation map, M_{ij} can be used by choosing the row A_j where the respective weak point is located. The resulting global performance and adaptation values for each subcatchment can again be assigned to GIS maps. Therefore, by placing LIDs based on the adaptation map, the performance at a specific weak point in the system can be improved. For performance assessment, different performance indicators can be defined/used depending on the aim of the study. A suitable performance indicator should be chosen based on the reference system. For example, the flood PI applied to a system where no flooding occurs with and without LID placement would result in a global performance map where no improvements are indicated.

Case study

The methodology is tested for the case of Kiruna, Sweden (Zischg *et al.* 2017b). The investigated stormwater network consists of 601 subcatchments (32% mean imperviousness) with a catchment size ranging from 13 ha to 0.05 ha. Each network node is connected to a subcatchment (see Figure 3(a)). Neither pumping stations nor LIDs are present in the existing stormwater system. The new Swedish design standard SWWA (2016) requires newly constructed stormwater systems to resist a 10-year design storm event without causing surface ponding. However, when applying this design rain (16.3 mm/15 min) to the existing system, flooding occurs in 27% of the network nodes (see Figure 3(c)). Therefore, the total nodal flood volume V_{flood} is used as a performance indicator for the existing system. The weak point w_p in this reference performance map, represents the node of the stormwater network with the highest flood volume and is indicated by the magenta-colored dot (see Figure 3(b) and 3(c)).

On the other hand, a new city center (see dotted area in Figure 3(a)) including a new stormwater network will be built (Leonhardt *et al.* 2015). Due to the fact, that this system is designed according to the new standard, neither flooding nor surcharging occurs for the 10-year and 5-year design storm, respectively. The subcatchments and the stormwater network of the new city center are shown in Figure 4(a) and 4(b). In Figure 4(c), the performance of the initial system is shown as 'reference map'. To derive the reference performance map, a performance indicator describing the 'reserve capacity' of the node is calculated and mapped to the connected

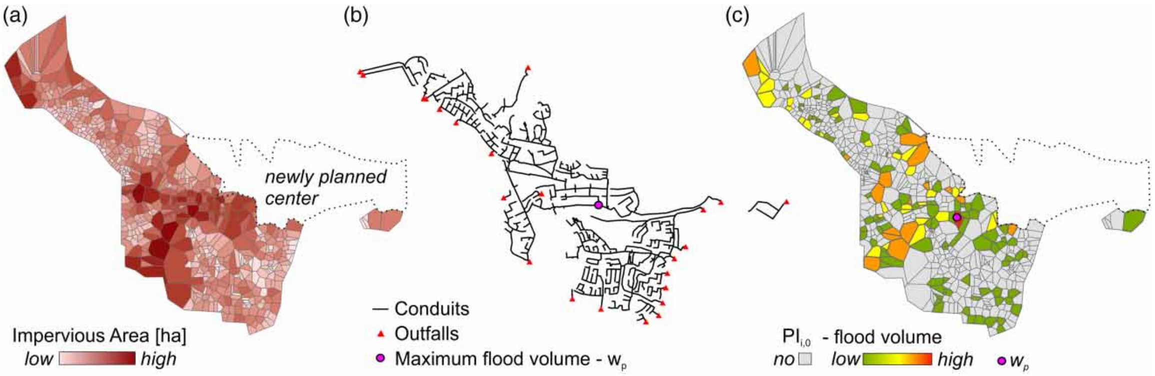

Figure 3 | Existing system: (a) map of the surface imperviousness, (b) the stormwater network and (c) the reference performance/flood volume map of Kiruna. The weak point (maximum flood volume) is indicated by the magenta-colored dot. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wst.2018.060.

subcatchment as follows:

$$PI = 1 - \frac{h_{max}}{h_{depth}} \quad [0; 1],$$

where h_{max} is the maximum filling height in the manhole and h_{depth} is the manhole depth. The conduits of the new city center are planned with a circular cross section. A PI of 1 indicates no capacity usage or no flow in the conduit, while a PI of 0 indicates fully used capacities and likely occurrence of surface flooding. To show the applicability of the proposed approach also to such a design case without any flooding, a weak point w_p in the new city center is defined (see Figure 4(c)) in which the water level is closest to utilizing the full manhole depth.

To create a global performance map and adaptation maps, the impact matrix as described before is created for the existing system and the newly planned system. For parameter variation, a uniform LID type with a size of 500 m^2 (limited by the minimum subcatchment size) is successively applied to each subcatchment and the performances are assessed with SWMM5.1. The LID unit is a bioretention cell with surface storage, infiltration, underdrain, and overflow structure. Due to the fact, that flooding occurs in the existing part of the city, the total flood volume is chosen as *PI* for that part. Moreover, the network performance is only evaluated at inlet nodes of the sewer network. However, for the presented study this is irrelevant because each node of the network relates to a subcatchment.

LID placement strategies

To show the usability of the created sensitivity maps we finally compare five LID placement strategies for the presented case study, where LID placement is sought to improve the performance of the piped network. The following placement strategies are investigated:

(1) LID units are randomly distributed over the catchment area, e.g. representing a voluntary installation by land owners.
(2) LID units are distributed on catchments with the highest flood volume based on one SWMM5.1 simulation, representing the reference system.
(3) LID units are distributed on catchments with the highest impervious surface.

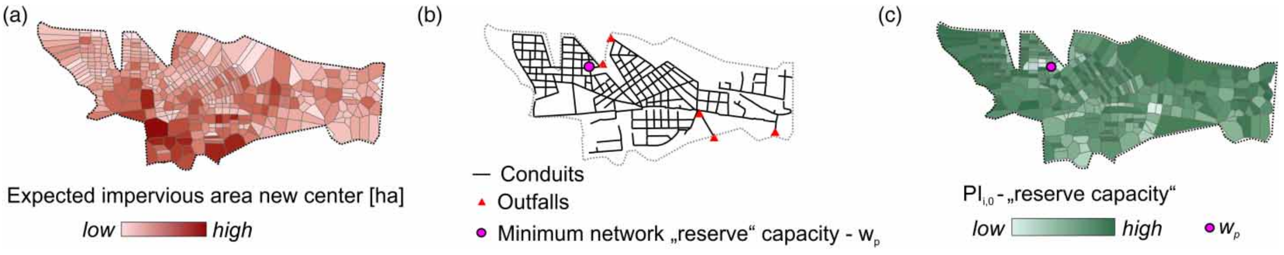

Figure 4 | Newly planned system: (a) map of the expected surface imperviousness, (b) the stormwater network and (c) the reference performance/flood volume map of Kiruna. The weak point (maximum flood volume) is indicated by the magenta-colored dot. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wst.2018.060.

(4) LID units are distributed using the previously developed 'global performance map'.
(5) LID units are distributed using the previously developed 'adaptation map'.

RESULTS AND DISCUSSION

Sensitivity maps for case study application

In Figure 5 the calculated Impact Matrix M_{ij} for the existing system is shown. It indicates the relative performance changes (flood volumes) when applying LID structures compared to the reference system. From Figure 5 it can be seen that about 99.3% of the matrix entries reveal an unchanged performance, i.e. no sensitivity (see gray pixels). This implies that a specific LID location does not affect the entire system. One reason for this effect is due to only investigating surface flood volume. The dark blue pixels indicate a performance improvement (reduced flood volume). Most of the diagonal matrix entries (M_{ij}, for $i = j$) show performance improvements, which indicates that a potential LID placement on subcatchments with surface flooding is beneficial. However, a performance decline at some network parts cannot be avoided due to synchronization of peak flows, mainly due to LID overflow at an unfavorable moment.

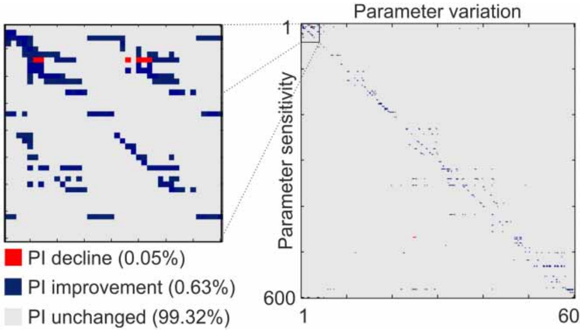

Figure 5 | Impact Matrix M_{ij} with normalized performance values for 601 subcatchments.

The global performance map derived from the aggregated Impact Matrix M_{ij} in Figure 6(a) shows the change in total flood volume of the entire system when implementing an LID in the respective subcatchment. In terms of the hydraulic performance, the LID placement in light blue areas is more beneficial than in the dark blue ones. Figure 6(b) shows the adaptation map and the location of the weak point w_p, i.e. the location with the highest flood volume at the reference state. The adaptation map illustrates the most effective locations of LID placement with respect to this weak point, indicated with brownish color. Dark brown areas are most suitable, while areas with grey color have no effect on the performance of the weak point.

The global performance map using the 'reserve capacity' as an indicator is presented in Figure 7(a) for the new city center. A possible LID placement in the green areas regarding the global 'reserve capacity' is more beneficial than a possible placement in the red areas. The adaptation map in Figure 7(b) indicates where the LID unit should be placed to improve the local performance of the weak point w_p in the network. Subcatchments with a brownish color indicated a performance improvement, while a LID placement in the light grey areas would have no effect on improving the weak point w_p. Although the illustrated adaptation maps are based on one weak point of the system, several weak points could be considered in one map. However, this requires an additional ranking of potential LID locations (e.g. identifying the locations which are beneficial to more than one weak point).

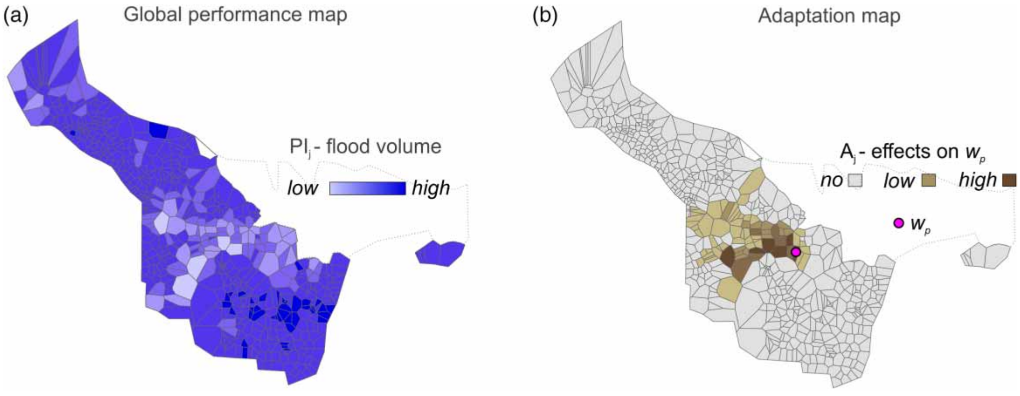

Figure 6 | Existing Kiruna: (a) global performance map and (b) adaptation map.

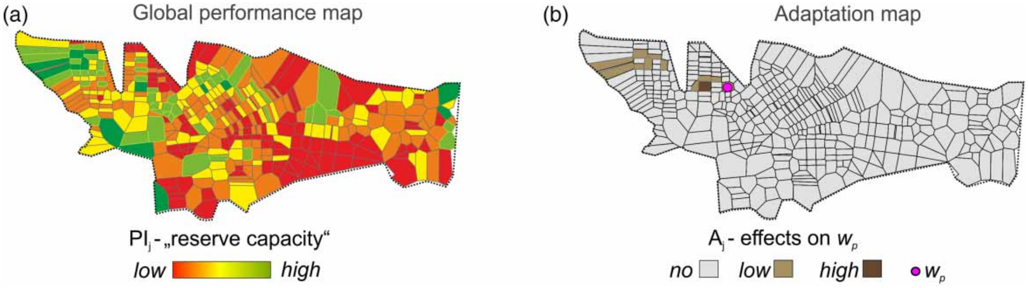

Figure 7 | New Kiruna: (a) global performance and (b) adaptation maps.

Placement strategies

To verify the usefulness of the created sensitivity maps, we compare various potential LID placement strategies for the existing stormwater network of Kiruna. A total LID area of 10,000 m^2 is assumed to be implemented, representing a hypothetical budget target. The area of one LID unit is chosen as 1,000, 500, and 200 m^2 per subcatchment. With that information, 10, 20 and 50 units (n^{LID}) of consistent size are distributed over 601 subcatchments based on the different placement strategies. For the random placement, 100 sampling processes are repeated (only one LID can be placed in one catchment). For the other placement strategies, the best positions are determined depending on n^{LID} and applied to subcatchments with the highest flood volume (reference performance map), the highest surface imperviousness, the global performance map, and the adaptation map. For the different placement strategies, Figure 8 demonstrates the global flood performance (total flood volume) and the local flood performance (nodal flood volume) at the weak point. It is shown that the random placement of the LID units reduces the total flood volume from 3% to 13% on average, compared to the reference situation. However, this strategy is less effective than the targeted LID placements, where additional criteria are considered. The placement of the LID units ($n^{LID} = 10$, 20, and 50) based on the reference performance map reduces the total flood volume from 15% to 35%. When applying the LID units to the subcatchments with the highest surface imperviousness, a performance improvement from 22% to 43% can be achieved. The best global performance is reached when using the previously determined global performance map (flood reduction of 23% to 47%). However, when improving the performance of one specific point in the network (e.g. weak point), then the placement using the adaptation map is the most beneficial strategy. For this case study, a performance improvement regarding the weak point from 87% to 99% is achieved. Furthermore, a higher number of LID units (n^{LID}) with lower size is shown to be more efficient compared to a lower number of LIDs of bigger size. This

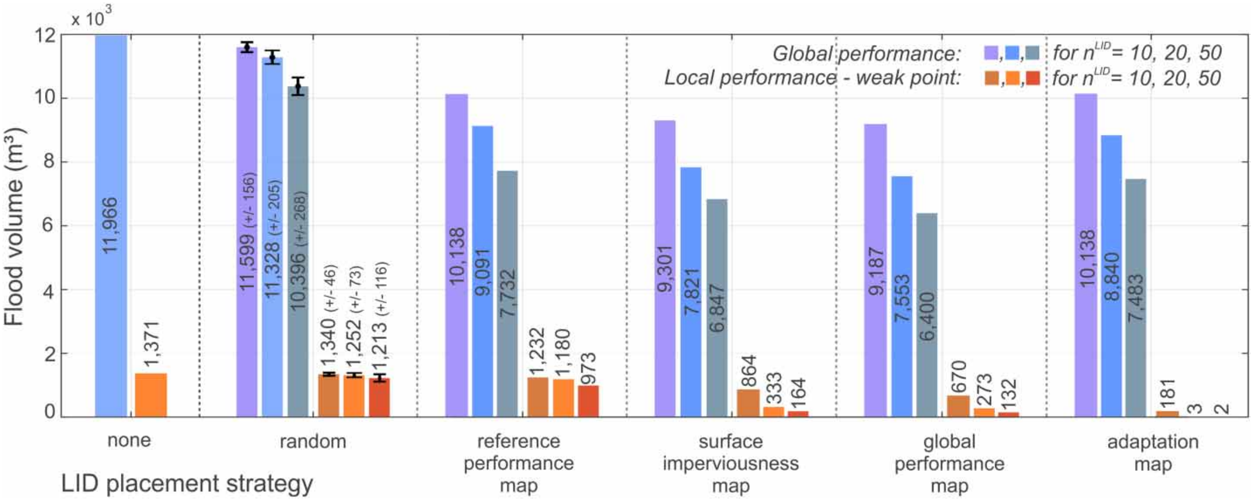

Figure 8 | Flood volumes pursuing different strategies of LID placement.

is mainly due to the higher capacity utilization of smaller units (LID size is not optimized). The results show that the best performance improvement is achieved when using the presented sensitivity maps.

The presented method is based on an a 'set' pipe network (unchanged network topology and capacity) and shows hydraulic benefits when providing additional storage and retention at the surface. However, for newly planned stormwater systems a capacity reduction (decrease of conduit diameters) or even a reduction of the centralized sewer network could be considered by applying LID structures and preserving identical hydraulic performances (cost-benefits without compromising the hydraulic performance).

The following lists the limitation of the current work, which is subject to further investigations:

- All implemented LID units have a uniform size of 200, 500 and 1,000 m^2, depending on the number of LID units to be distributed over the catchment area. In all subcatchments it is assumed that 100% of the runoff of the impervious area is intercepted by the unit. This results in under- or overloaded LIDs.
- The number of LIDs per subcatchment is constant (one). In the current SWMM model that single LID could also represent more LIDs of smaller size (constant total area) without affecting the performance of the sewer network. To see such an effect a more detailed model representation (more subcatchments of smaller size) would be necessary.
- All implemented LID units are of the same type, treating the same fraction of impervious area. The LIDs are solely intercepting the runoff of the respective subcatchment (no external inflow/run-on). The main difference to the hydraulic sewer network performance when applying other LID types would be the storage volume, the retention time, and the intercepted runoff fraction from areas with different land use (e.g. green roofs only intercept rooftop runoff, while raingardens can intercept the runoff from streets, buildings, and/or parking areas). For a final decision-making process, a cost comparison between different LID types might be significant.
- For the placement strategies using the sensitivity maps, where multiple LID units are applied, the ranking of the best (single) solutions are considered.
- In this study, we neglected the possible synchronization of peak flows in the sensitivity analysis due to multiple interacting LID units ('clustering effect'). Overflow at the LID structures at an unfavorable moment can reduce the flood performance. In case no LID overflow occurs, the synchronization effect is marginal due to the relatively long retention times of the LIDs (several hours) compared to the short travel times within the pipe network (several minutes) for the design storm event (uniform distribution).
- Information of urban form patterns (e.g. availability of space, land prices, heat islands), soil information, willingness of property owners to invest in green/blue infrastructure, etc., were not considered as LID placement criteria. In further studies, such information could be intersected with the presented sensitivity GIS maps.
- The need of hydraulic performance improvement was the only objective to be considered for the creation of the sensitivity maps. It is beyond doubt that LID structures provide a multiple range of benefits, most importantly including ecological and socio-economic factors. Here we only considered the surface flood volume and 'reserve' hydraulic capacity of the conduits. However, sensitivity maps showing the effects of different (also contradicting) performance indicators (like pollutant control, outflow minimization to the receiving water, 'urban heat island effect', etc.) can be created when the required information is available without changing the approach.

Future work will focus on the integration of multiple spatially explicit placement criteria and search for a suitable location when overlapping different layers (e.g. land price distribution map). Emphasis will be put on the creation of adaption maps when combining several weak points of the network. In this sense, mathematical optimization approaches will be necessary. However, the outlined problem is very complex with a great solution space. Therefore, it is necessary to limit the investigated solutions to a manageable level. The developed sensitivity maps can provide the information to confine that search space and enable an efficient solving of that optimization problem.

SUMMARY AND CONCLUSIONS

Decentralized LID structures are usually distributed over the catchment area in small scale units to meet the objectives of a runoff reduction, stormwater retention, pollution removal, and/or the creation of attractive living spaces. In many cases such concepts interact with the existing pipe infrastructure, resulting in hybrid solutions. In this work, we investigated the effect of different LID placement strategies on the hydraulic network performance of existing drainage networks. Based on a sensitivity analysis, geo-referenced maps were created which identified most effective LID positions. With a case study, different LID placement strategies where investigated and compared. The results showed that with the usage of the two developed sensitivity maps (global performance and adaptation map), the best performance improvements were achieved. For example, the flood performance by using the global performance map was improved by an additional 34% as compared to a random placement strategy when implementing 50 LID units.

The creation of spatially referenced GIS-maps shows the hydraulic effects of a potential LID placement on the existing stormwater network. These maps can be used as an additional decision support tool when retrofitting existing systems. The developed maps are easy to communicate and rapidly assessed by decision makers when deciding on stormwater policies in the screening phase of a project. The discussed methodology represents a simple and fast engineering approach, rather than an optimal mathematical solution. On the one hand, the sensitivity maps indicate a global performance improvement by placing an LID at a specific location, but, on the other hand, also address the locations where a possible LID placement would be beneficial with respect to a specific target point (e.g. providing additional 'reserve capacity' in the stormwater system where critical facilities are located at the surface).

Further work will focus on a simple design principle where the dimensions of the LID units are estimated, and the integration of multiple spatially explicit placements criteria are integrated (e.g. land prices, availability of space, heat islands). Due to the large number of uncertainties, a mathematical optimization addressing the location of decentral LID units is often not feasible or even possible. However, the created sensitivity maps can be used to simplify an optimization analysis by reducing the number of parameters by taking only the most sensitive positions into account.

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