Simplifying impact of urban development on sewer systems

Manfred Kleidorfer, Robert Sitzenfrei and Wolfgang Rauch

ABSTRACT

Linking urban development and urban drainage models is a more and more popular approach when impacts of pavement of urban areas on sewer system performance are evaluated. As such an approach is a difficult task, this is not a feasible procedure for everyday engineering practice. We propose an alternative method, based on a developed simple near-quadratic relationship, which directly translates change (increase or decrease) of paved area into a change in the return period (RP) of the design rainfall event or design rainfall intensity. This formula is simple to use and compatible with existing design guidelines. A further advantage is that the calculated design RP can also be used to communicate the impact of a change in impervious areas to stakeholders or the public community. The method is developed using a set of 250 virtual and two real-world case studies and hydrodynamic simulations. It is validated on a small catchment for which we compare system performance and redesigned pipe diameters. Of course such a simplification contains different uncertainties. But these uncertainties have to be seen in the context of overall uncertainties when trying to predict city development into the future. Hence it still is a significant advantage compared to today's engineering practice.

Key words | design guideline, flooding, hydrodynamic model, rational method, urban development, urban drainage

Manfred Kleidorfer (corresponding author)
Robert Sitzenfrei
Wolfgang Rauch
University of Innsbruck,
Technikerstrasse 13,
A6020 Innsbruck,
Austria
E-mail: manfred.kleidorfer@uibk.ac.at

INTRODUCTION

To account for upcoming developments in urban water management, the linkage of different models receives increasing attention (Bach *et al.* 2014). Recent developments show the implementation of climate change and/or urban development models, which provide the input for traditional urban drainage models. Such inputs are rainfall data, which represent rainfall characteristic under future climate change scenarios, and paved areas, which represent conditions under future urban development scenarios While climate change scenarios expect an increase in rainfall intensities and longer dry weather periods between the events (Ashley *et al.* 2005; Butler *et al.* 2007; Arnbjerg-Nielsen 2008; Arnbjerg-Nielsen & Fleischer 2009), the impact of urban development can be both increase of paved areas (to account for city growth, densification and urban sprawl) and decrease of paved areas (to account for shrinking cities, disconnection of

paved areas or transformation of impervious surfaces into pervious surfaces) (Martinez-Fernandez *et al.* 2012; Miko-vits *et al.* 2014). In the context of this paper the term 'paved area' is used for all impervious surfaces, which are connected to the drainage system, sometimes also referred to as 'effective impervious area' (Dotto *et al.* 2011). Several authors present case studies investigating either impact of climate change or impact of urban development or combinations of both. For example, Semadeni-Davies *et al.* (2008) analyse the impact of both climate change and urbanization on the performance of a combined sewer system. Climate change impact comes from a regional climate model; urbanization is considered by adapting model parameters related to paved area and demographics. The sewer system performance in that study is evaluated using a hydrodynamic model. Urich *et al.* (2013) present an application in which an urban development model is

linked to an urban drainage model to account for changes in the paved area. Again, for performance assessment of the urban drainage system, a hydrodynamic model is used. Kleidorfer *et al.* (2013) consider both climate change and urbanization effects when planning rehabilitation strategies for sewers.

The problem is that such results can hardly be transferred into practical engineering solutions. The coupling of different models is not an easy task, requiring not only specific modelling but also programming skills (Rauch *et al.* 2012). So, it cannot be expected that such approaches will soon find their way into small and medium sized consultancies.

Mailhot & Duchesne (2010) propose a revision of design criteria of urban drainage systems to account for climate change impacts. Their approach is based on the statistical evaluation of rainfall intensities and leads to a simplified approach to consider such changes in design guidelines. This requires information about climate projections, expected level of system performance and expected infrastructure lifetime. Finally, a new return period (RP) which should be used in the design is calculated by multiplying the present RP with a factor. That factor can be estimated from lifetime and expected increase of rainfall intensities. Of course such a simple approach contains different sources of uncertainties, but these uncertainties have to be seen in the context of overall climate change prediction uncertainties.

For consideration of urban development such a simple approach is still missing. Different integrated urban drainage modelling studies, in which urban development models are coupled with urban drainage models, show that urban development might outreach impact of climate change or at least have similar importance (Lee & Heaney 2003; Semadeni-Davies *et al.* 2008; Willems *et al.* 2012). Although such studies are very case specific, this shows that it is even more important to develop easy to use methods which can be implemented into existing design guidelines. Starting from these findings, we propose a simple approach to account for changes in paved area in urban drainage engineering.

Consequently, the aim of this paper is to search for simple expressions of the relationships between urban development and parameters used in the design of urban drainage systems. We present an approach which translates change of paved areas (increase or decrease) into a change of the RP of the rainfall event that is used for the design. The main benefit of this simplification is that the result is compatible with existing design guidelines. We believe that this is the

way to bring results from scientific climate change impact assessments into practice.

METHODS

The role of the RP in sewer system design

Although design standards for urban drainage systems vary from country to country (Kleidorfer & Rauch 2011), the basics are always similar. European standards define a design RP of rainfall events for which flooding has to be prevented (CEN 1997). For example, $RP = 2$ means that such a rainfall event on average happens every 2 years. The actual design of pipe diameters in engineering practice (especially used for small areas) still often uses simple approaches such as the rational method (Butler & Davies 2004). This method needs catchment area, rational runoff coefficient and rainfall intensity as input and calculates peak runoff from catchments (i.e. flow in pipes). Consequently, the required pipe diameter is calculated from flow, roughness and pipe slope using flow formulas (Butler & Davies 2004).

Hydrodynamic models are used in larger, more complex (i.e. meshed) systems. They run with rainfall data (measured time series or design storm events) as model input, need a more detailed description of the urban area (paved area, soil characteristics), and calculate runoff from catchments and consequently flow in pipes. The main difference is that non-steady effects and surcharge in pipes can be considered. As such, it is possible to calculate ponded volume, which can be used to estimate flood risk. Again the RP of design events for which flooding has to be prevented is chosen according to guidelines (usually depending on the land use for a specific area) or the RP of flooding events is directly calculated from simulation results (in cases a time series is chosen as rainfall input instead of design events).

Thus for both approaches the RP of the rainfall intensity used is an important point. Further, the RP is also used in communicating design standards to decision makers and the public (as the RP is a term which is also known from different fields, e.g. to communicate risk of fluvial flooding). Such a successful consideration of urban development in the best cases translates any change in urban areas to a change in RP. This has the advantage that the existing design methods still can be used and that it is easy to communicate impact of a change in paved area. Further, this approach is compatible with the possibility to consider climate change effects as, for example, shown by Mailhot & Duchesne (2010).

Building the reference system

As a first step, a reference system is required, which can be used to search for a relationship between urban development and sewer system performance. It is clear that the use of measurement data is unfeasible for this as this would require measurements of the entire system performance in different states of city development. Both are impossible to acquire as system performance is always assessed only at limited points (at measurement sites) and never for the entire system. Furthermore, long-term measurements covering an extensive period of city development (e.g. 50 years) are not available for a representative set of case studies.

Instead this approach is based on a reference set of model simulations. Therefore, the approach shown in Kleidorfer *et al.* (2009) is enhanced. As reference system a set of 250 virtual case studies (Möderl *et al.* 2009) and two real-world case studies is used. All case studies are drained by combined sewer systems. The virtual case studies are used to make this approach less case specific and to ensure that the results can be transferred to other drainage networks. The two real-world case studies are used as reference points to ensure realistic interpretations.

The size of the 250 virtual case studies ranges from 200 to 4,000 ha of connected impervious (or paved) area, 50 to 500 nodes and five to 10 combined sewer overflow (CSO) facilities, and hence covers a broad range of system sizes. The virtual case studies are branched networks with pipe sizing according to Austrian design rules (ÖWAV-RB II 2009), i.e. based on the rational method described above. The two real-world case studies are both situated in Austria. In case study A, the catchment area is approximately 2,500 ha (774 ha impervious), the sewer network used consists of 246 nodes, 200 subcatchments and 34 CSOs. In case study B, the total catchment area is 12,709 ha, 3,608 ha are impervious and the hydrodynamic model consists of 397 nodes and 192 subcatchments.

For these case studies the sewer system performance is evaluated using the hydrodynamic simulation software SWMM (Gironás *et al.* 2010) with its parallel solver (Burger *et al.* 2014). The hydraulic performance is expressed as flooding performance P_F, which is calculated from ponded volume V_P and total catchment runoff V_R according to

$$P_F = 1 - \frac{V_P}{V_R} \tag{1}$$

This normalized description has the advantage that the values range from 1 (no flooding occurs) to 0 (total runoff is flooded) and hence the performance of different systems can be compared. This would not be possible if we compare the flooded volume directly as this value highly depends on the size (catchment area, number of nodes) of the case study.

Urban development scenarios

To account for changes in P_F caused by urban development the connected impervious area is increased and decreased, respectively. The increase expresses additional pavement of urban areas in cases of city growth or densification. The decrease expresses transformation of impervious surfaces into pervious surfaces, as can be the case in shrinking cities. Further decrease also expresses disconnection of paved areas from the drainage system, for example when decentralized stormwater management is introduced (Bach *et al.* 2013a, b). The variation of impervious area happens by multiplying connected impervious area A_i with an area factor f_A. This area factor ranges from 0.4 to 1.6 in steps of 0.1 to cover a range in the change of the connected area from $\Delta A_i = -60\%$ to $\Delta A_i = +60\%$.

As rainfall input Euler II design storm events are used, which are commonly used in the design of urban drainage system in Germany (DWA-ATV-A 118E 2006) and Austria (ÖWAV-RB II 2009). We assessed the system performance (evaluation of P_F) for different RPs ($RP = 0.5$; 1; 2; 3; 5; 10). Altogether there are 16,380 hydrodynamic simulations (252 case studies × 5 RPs × 13 area deviations).

Translation into a simple relationship

For each simulation we calculate P_F which varies with changing input ($P_F = f(RP, A_i)$) when assuming that the system characteristics are constant. By keeping either RP or A_i constant and finding simulation runs with the same system performance ($P_F = f(RP = \text{const}, A_i) = f(RP, Ai = \text{const})$), the variation in one parameter can be expressed as a change in the other one, $RP = f(A_i)$. A more detailed description is available from Kleidorfer *et al.* (2009) in which impact of a change in rainfall intensities resulting from climate change is expressed as a change in paved area. The result of this evaluation is a database of the P_F results of multiple hydrodynamic simulations with varying RP and A_i.

The next step is the investigation of whether the function $RP = f(A_i)$ can be expressed using a simple analytic relationship. Therefore, different functions are tested and optimal parameter sets are determined using the method of least squares.

Validation on a case study

The final step is a validation of the identified expression in a case study. Therefore, a third real-world case study is used, which was not used in the development of the reference system in the 'Building the reference system' section. This case study is a small semi-urban catchment with a total area of 21.9 ha (11.9 ha impervious, i.e. the fraction imperviousness is 0.54). The hydrodynamic model consists of 211 subcatchments, 231 nodes and one CSO facility at the outlet of the catchment. This network was chosen because of its simple layout (branched system, only circular cross-sections) which allows automatic pipe sizing for the different validation scenarios.

For validation purposes we determined the pipe sizes for capturing a design storm event of $RP = 2$ (a design rule for this municipality) in a way that no flooding occurs (only surcharge). Then we assumed a yearly city growth rate (representing increase of paved area) of 1.1% and calculated the future performance $P_{F,25}$ (the planning horizon is 25 years).

For validating the formula we determined a new design RP ($RP*$), and evaluated $P_{F,RP*}$ by using an event with $RP*$ as rainfall input. Then we compared the future scenarios $P_{F,25}$ and $P_{F,RP*}$. Finally both future systems are redesigned to capture runoff from increased catchment area (and original RP) and runoff from $RP*$ (and original catchment area), respectively. Then the new pipe diameters of future scenarios were compared piece by piece.

RESULTS AND DISCUSSION

Performance and impact assessment

Figure 1 (left) presents examples of the simulation results. For the 250 virtual case studies the cumulative distribution of P_F is shown for $RP = 1$ (grey lines) and $RP = 10$ (black lines). Simulation results of the real-world case studies are shown as markers. In addition, the impact of a change in paved area on P_F is shown for the cases of a reduction of 60% and an increase of 60%. Figure 1 (right) shows the relationship between the area factor f_A and the RP. In this figure we present the results of the real-world case studies as well as the median value of the virtual case studies. From this diagram one can see that, for example, the increase of impervious area of 30% ($f_A = 1.3$) has the same effect on system performance as using a rainfall event of $RP = 1.5$ (instead of $RP = 1$).

Translation into a simple relationship

For the relationship between f_A and RP as shown in Figure 1 (right) different mathematical expressions have been tested. Aiming for a simple expression not to over-parameterize the equation, we found that the formula

$$RP* = a \cdot f_A^b \qquad (2)$$

describes this relationship appropriately. For this function parameters a and b were determined using the trust-region method, a nonlinear least-squares formulation (Conn *et al.* 2000) implemented in Matlab. This parameter determination was done for each RP separately. Results including coefficient of determination (R^2) are shown in Table 1.

As can be seen from Table 1 parameter a is always a value close to the original RP. Parameter b varies between 1.22 ($RP = 1$) and 2.04 ($RP = 10$). This clearly shows that the impact of a change in the connected impervious area increases with higher rainfall intensities. This is to be expected as in such cases the sewer system capacity is already close to its maximum and any additional runoff directly contributes to flooding volume (expressed as P_F). However, as the general approach contains significant uncertainties from different sources (e.g. prediction of the urban development), it is reasonable to define $a = RP$. Then we repeated the parameter search for b and found the best fit for $b = 1.92$ ($R^2 = 0.9776$). Finally we came to the solution

$$RP* = RP \cdot f_A^{1.92} \qquad (3)$$

As changing impervious area is related to long-term developments the time scale is still missing in Equation (3). With introducing a city growth rate g (% per year) and the planning horizon t (years), Equation (3) can be written as

$$RP* = RP \cdot (1 + g)^{1.92t} \qquad (4)$$

In practical applications g should be chosen according to urban development projections; t is the planning horizon which should be chosen according to the life expectancy of the infrastructure facility which has to be designed. Negative values for g can account for a decrease in paved area, for example, due to shrinking cities, disconnection of paved areas or other measures which reduce the stormwater runoff into a drainage system. Practical recommendations for a decreasing paved area are difficult as it would be
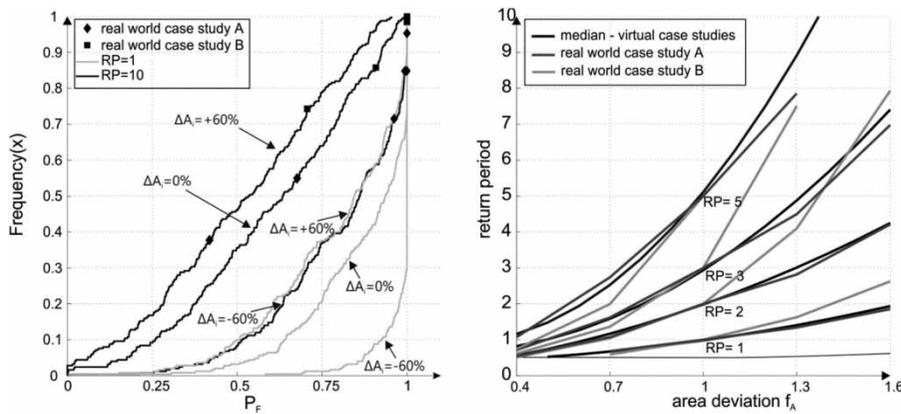
Figure 1 | Presentation of cumulative distribution of P_F for $RP = 1$ and $RP = 10$ (left) and relationship between area factor f_A and RP (right).

Table 1 | Identified parameters a and b with best fit for Equation (2)

RP	a	b	R²
1	1.04	1.22	0.8990
2	2.06	1.62	0.9608
3	3.06	1.92	0.9719
5	5.26	1.98	0.9816
10	9.97	2.04	0.9930

hardly accepted to purposely undersize a drainage system and wait for the flooding to slightly decrease. However, in cases of existing flooding problems it might be an adaptation option to boost decentralized stormwater management (Urich et al. 2013).

Equation (4) can also be interpreted in a way to estimate change of flood risk (expressed as change of RP) for an unchanged system (i.e. a system that is not adapted). This means, the occurrence of flooding event changes from RP_0 (RP at the time of the design) to RP_T (at time t in the future)

$$\frac{RP_0}{(1+g)^{1.92t}} = RP_t \tag{5}$$

Figure 2 compares $RP*$ calculated from hydrodynamic simulation and $RP*$ calculated from Equation (4). It can be seen that the agreement is sufficient although the developed formula shows a slight underestimation for high RP.

Of course this approach contains several limitations and simplifications. (1) Urban development can not necessarily be directly translated into a change of paved area (or more precisely connected paved area) g. This is especially true in city developments, in which existing areas are densified by replacing existing buildings. But also in new developments
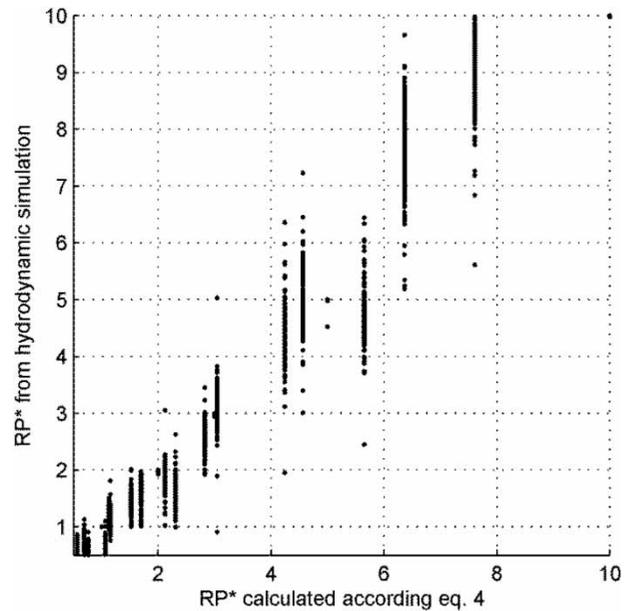

Figure 2 | Comparison between $RP*$ calculated from hydrodynamic simulation and $RP*$ calculated from Equation (4).

nowadays often decentralized stormwater management (e.g. infiltration facilities) is introduced, leading to the fact that parts of the stormwater runoff are not drained in the existing drainage system. However, the problem of predicting future impervious area that is connected to the drainage system is out of the scope of this paper and it is the same problem for model-based approaches. We assume that this assessment is possible from master plans and urban development scenarios. (2) The development of Equation (3) is based on the comparison of P_F, which is related to the change in flooding volume. Other performance indicators, example combined sewer overflow emissions, might behave differently. However, we propose this method for the design of the

hydraulic capacity, for which the prevention of flooding is the main indicator. (3) This method assumes an equal change of the paved area over the whole catchment. Impacts of connection of new areas which influence downstream network parts are more difficult to assess. However, usually new development areas are connected using CSO structures as inflow points into the existing network (Sitzenfrei et al. 2013b), meaning that the additional inflow is anyway limited to a certain value.

Conclusively we can say that the proposed formula cannot replace a detailed (coupled) urban development/ urban drainage simulation but it can help to roughly assess the expected future system performance. Hence existing design guidelines can easily be adapted to account for future situations. For such cases it would be possible to further simplify Equation (4) to $b = 2$. This still leads to a good agreement ($R^2 = 0.9758$)

$$RP* = RP \cdot (1 + g)^{2t} \tag{6}$$

Table 2 compares $RP*$ calculated according to Equations (4) and (6), respectively. As can be seen the consideration of the further simplification to $b = 2$ leads to a slight change of $RP*$ (decrease for $f_A < 0$ and increase for $f_A > 0$) but does not significantly change the results.

Validation

For validation purposes, the case study described previously is used. We assume an average city growth rate of 1.05% over 25 years, i.e. this leads to an increase of the impervious area of 30% ($f_A = 1.3$): from 11.9 to 15.5 ha. This growth rate is a hypothetical assumption, but it accords with pavement of areas which was observed in the region in the past (Umweltbundesamt 2013). This means the imperviousness fraction increases from 0.54 to 0.70. The pipe diameter of the system is currently designed to prevent flooding for $RP = 2$. Furthermore, commonly applied design rules prescribe minimum pipe diameter of 0.2 m and that pipe diameters of downstream pipes are never smaller than the upstream pipes.

In Table 3 simulation results for the different scenarios are shown. Scenario 0 is the current baseline system described above. In scenario 1 an increase of paved area of 30% is assumed. This leads to a decrease of P_F from 1 to 0.943 (i.e. the flooding volume V_F increases to 0.26 m³ for the event). In scenario 2, a new design RP is calculated from Equation (4) as

$$RP* = RP \cdot (1 + 0.0105)^{1.92 \cdot 25} = 3.3 \tag{7}$$

P_F decreases from 1 to 0.937 ($V_F = 0.29$ m³). In scenario 3, pipe diameters are redesigned to prevent flooding for $RP = 2$ and $f_A = 1.3$. In scenario 4, pipe diameters are redesigned to prevent flooding for $RP = 3.3$ and $f_A = 1.0$.

Consequently redesigned pipe diameter for scenario 3 and 4 are compared. Figure 3 shows this comparison in detail. The pipes marked as black thin lines were not required to be adapted, i.e. pipe diameters did not have to be changed. The pipes marked as black thick lines were identically adapted for both development scenarios 3 and 4. For the pipes marked as grey thick lines differences in pipe diameters were observed when designing for scenario (SCN) 3 and 4, respectively. For those pipes detailed information about original pipe diameter (DN) SCN 0 and both adaptation scenarios is shown in the boxes in Figure 3 (DN in mm). As can be seen in Figure 3 some differences exist (e.g. DN 1100 for SCN 3 and DN 1200 for SCN 4 in the pipe section close to the catchment outlet). But in general the developed formula successfully predicted future urban development conditions (i.e. system performance $P_F = 0.943$ in SCN 2 and $P_F = 0.937$ in SCN 3) and can be

Table 2 | Comparison of design RPs $RP*$ calculated according to Equation (3) ($b = 0.92$) and Equation (6) ($b = 2.0$)

RP	$f_A = 0.40$		$f_A = 0.70$		$f_A = 1.30$		$f_A = 1.60$	
	$b = 1.92$	$b = 2.0$	$b = 1.92$	$b = 2.0$	$b = 1.92$	$b = 2.0$	$b = 1.92$	$b = 2.0$
1	0.17	0.16	0.50	0.49	1.65	1.69	2.47	2.56
2	0.34	0.32	1.01	0.98	3.31	3.38	4.93	5.12
3	0.52	0.48	1.51	1.47	4.96	5.07	7.40	7.68
5	0.86	0.80	2.52	2.45	8.27	8.45	12.33	12.80
10	1.72	1.60	5.04	4.90	16.55	16.90	24.66	25.60

Table 3 | Results for the validation example

Scenario	Designed on scenario	Model input		Performance assessment	
		RP	f_A	P_F	V_F [m³]
0	0	2	1.0	1	0
1	0	2	1.3	0.943	0.26
2	0	3.3	1	0.937	0.29
3	1	2	1.3	1	0
4	2	3.3	1	1	0

used to adapt pipe diameters to account for upcoming changes (small differences in redesigned pipe diameters for SCN 3 and SCN 4).

The more simplified formulation of Equation (4) with using $b = 2$ as an exponent (shown in Equation (6)) does lead to only minor changes. As new design RP we get $RP^* = 3.4$ (instead of $RP^* = 3.3$).

CONCLUSION

In this paper a simple formula is developed to translate complex interactions of the impact of urban development on the performance of a combined sewer system (expressed as flooding performance P_F). This formula expresses changes in the impervious area as a change in the RP of design storm events (i.e. the same system performance is estimated by either running a model with changed impervious area or with changed RP). The aim of this study was not to find the best possible solution but to identify a simple expression which can be used together with existing design guidelines for combined or storm sewers. The near-quadratic relationship, which we identified, can be used for both increase and decrease of impervious areas. Of course this approach contains uncertainties from different sources but when applying this method these uncertainties have to be seen in the context of overall uncertainties when predicting the city development into the future. We feel confident that the advantages of this expression outbalance the disadvantages related to the uncertainties and simplifications, as now urban development can be considered in practical engineering applications in a simple way. A further advantage is that the calculated new design RP can also be used to communicate impact of urban development to stakeholders or to the public community even if no hydrodynamic model is available.

However, of course this approach cannot replace detailed investigations when planning specific sewer infrastructure measures. This is important to avoid wrong
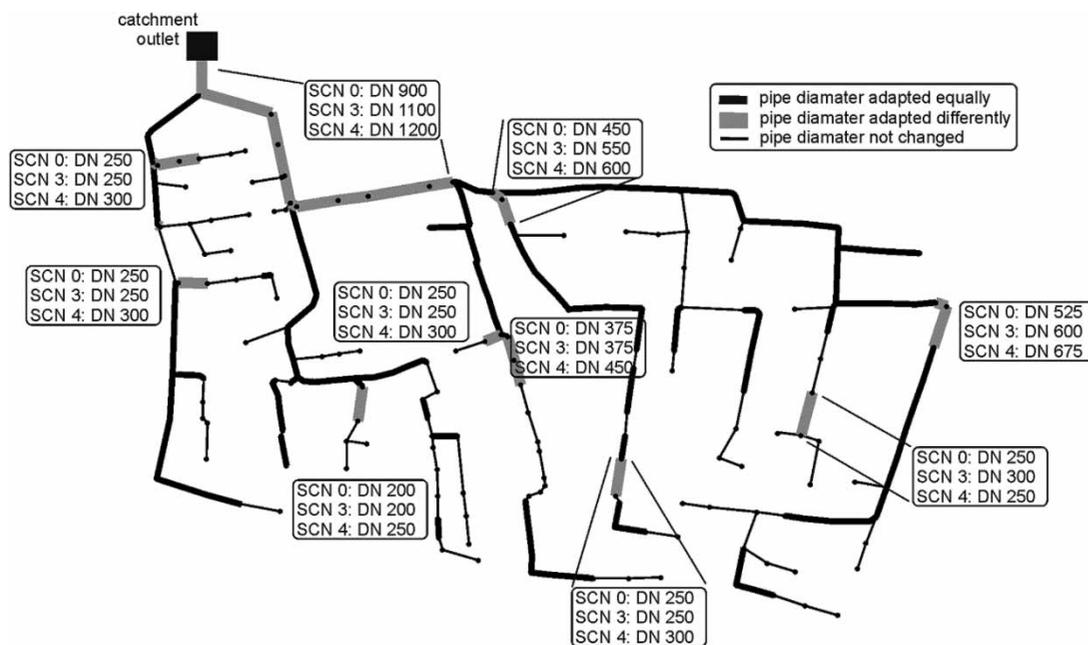
Figure 3 | Comparison of pipe diameters in the validation example for base scenario (SCN) 0, SCN 3 (pipe sizing on model with increased area) and SCN 4 (pipe sizing on model with *RP*); black thin line: pipe diameter not change; black thick line: pipe diameter changed equally for both scenarios; grey line: differences in changed pipe sizes – further details in boxes.

decisions potentially leading to wrong investments or to operational problems, for instance sedimentation problems which can occur, for example, when pipe diameters are oversized (Sitzenfrei et al. 2013a).

ACKNOWLEDGEMENTS

REFERENCES

Arnbjerg-Nielsen, K. 2008 Quantification of climate change impacts on extreme precipitation used for design of sewer systems. In: *11th International Conference on Urban Drainage, Edinburgh, Scotland, UK*.

Arnbjerg-Nielsen, K. & Fleischer, H. S. 2009 Feasible adaptation strategies for increased risk of flooding in cities due to climate change. *Water Science and Technology* **60** (2), 273–281.

Ashley, R. M., Balmforth, A. J., Saul, A. J. & Blanskby, J. D. 2005 Flooding in the future – predicting climate change, risks and responses in urban areas. *Water Science & Technology* **52** (5), 265–273.

Bach, P., Deletic, A., Urich, C., Sitzenfrei, R., Kleidorfer, M., Rauch, W. & McCarthy, D. 2013a Modelling interactions between lot-scale decentralised water infrastructure and urban form – a case study on infiltration systems. *Water Resources Management* **27** (14), 4845–4863.

Bach, P. M., McCarthy, D. T., Urich, C., Sitzenfrei, R., Kleidorfer, M., Rauch, W. & Deletic, A. 2013b A planning algorithm for quantifying decentralised water management opportunities in urban environments. *Water Science & Technology* **68** (8), 1857–1865.

Bach, P. M., Rauch, W., Mikkelsen, P. S., McCarthy, D. T. & Deletic, A. 2014 A critical review of integrated urban water modelling – urban drainage and beyond. *Environmental Modelling & Software* **54**, 88–107.

Burger, G., Sitzenfrei, R., Kleidorfer, M. & Rauch, W. 2014 Parallel flow routing in SWMM 5. *Environmental Modelling & Software* **53**, 27–34.

Butler, D. & Davies, J. W. 2004 *Urban Drainage*. Spon Press, London.

Butler, D., McEntee, B., Onof, C. & Hagger, A. 2007 Sewer storage tank performance under climate change. *Water Science and Technology* **56** (12), 29–35.

CEN 1997 EN 752 – Drain and sewer systems outside buildings – Part 4: Hydraulic design and environmental considerations. European Commitee for Standardization (CEN), Brussels, Belgium.

Conn, A. R., Gould, N. I. M. & Toint, P. L. 2000 *Trust Region Methods*. MPS-SIAM Series on Optimization, Society for Industrial and Applied Mathematics, Philadelphia, PA, USA.

Dotto, C. B. S., Kleidorfer, M., Deletic, A., Rauch, W., McCarthy, D. T. & Fletcher, T. D. 2011 Performance and sensitivity analysis of stormwater models using a Bayesian approach and long-term high resolution data. *Environmental Modelling & Software* **26** (10), 1225–1239.

DWA-ATV-A 118E 2006 Hydraulic Dimensioning and verification of drain and sewer system. DWA (German Association for Water, Wastewater and Waste), Hennef, Germany.

Gironás, J., Roesner, L. A., Rossman, L. A. & Davis, J. 2010 A new applications manual for the Storm Water Management Model (SWMM). *Environmental Modelling & Software* **25** (6), 813–814.

Kleidorfer, M. & Rauch, W. 2011 An application of Austrian legal requirements for CSO emissions. *Water Science and Technology* **64** (5), 1081–1088.

Kleidorfer, M., Möderl, M., Sitzenfrei, R., Urich, C. & Rauch, W. 2009 A case independent approach on the impact of climate change effects on combined sewer system performance. *Water Science and Technology* **60** (6), 1555–1564.

Kleidorfer, M., Möderl, M., Tscheikner-Gratl, F., Hammerer, M., Kinzel, H. & Rauch, W. 2013 Integrated planning of rehabilitation strategies for sewers. *Water Science and Technology* **68** (1), 176–183.

Lee, J. & Heaney, J. 2003 Estimation of urban imperviousness and its impacts on storm water systems. *Journal of Water Resources Planning and Management* **129** (5), 419–426.

Mailhot, A. & Duchesne, S. 2010 Design criteria of urban drainage infrastructures under climate change. *Journal of Water Resources Planning and Management* **136** (2), 201–208.

Martinez-Fernandez, C., Audirac, I., Fol, S. & Cunningham-Sabot, E. 2012 Shrinking cities: urban challenges of globalization. *International Journal of Urban and Regional Research* **36** (2), 213–225.

Mikovits, C., Rauch, W. & Kleidorfer, M. 2014 Dynamics in urban development, population growth and their influences on urban water infrastructure. *Procedia Engineering* **70**, 1147–1156.

Möderl, M., Butler, D. & Rauch, W. 2009 A stochastic approach for automatic generation of urban drainage systems. *Water Science & Technology* **59** (6), 1137–1143.

ÖWAV-RB 11 2009 Richtlinie für die abwassertechnische Berechnung und Dimensionierung von Abwasserkanälen; 2. vollständig überarbeitete Auflage (Guidelines for the calculation and design of sewer pipes, 2nd revised edition). Österreichisches Normungsinstitut, Vienna, Austria.

Rauch, W., Bach, P. M., Brown, R., Deletic, A., Ferguson, B., De Haan, F. J., McCarthy, D., Kleidorfer, M., Tapper, N., Sitzenfrei, R. & Urich, C. 2012 Modelling transitions in urban drainage management. In: *9th International Conference on Urban Drainage Modelling, Belgrade, Serbia*.

Semadeni-Davies, A., Hernebring, C., Svensson, G. & Gustafsson, L.-G. 2008 The impact of climate change and urbanisation on drainage in Helsingborg, Sweden: combined sewer system. *Journal of Hydrology* **350** (1–2), 100–113.

Sitzenfrei, R., Moderl, M. & Rauch, W. 2013a Assessing the impact of transitions from centralised to decentralised water solutions on existing infrastructures – integrated city-scale analysis with VIBe. *Water Research* **47** (20), 7251–7263.

Sitzenfrei, R., Urich, C., Möderl, M. & Rauch, W. 2013b Assessing the efficiency of different CSO positions based on network graph characteristics. *Water Science & Technology* **67** (7), 1574–1580.

Umweltbundesamt 2013 *Zehnter Umweltkontrollbericht. Umweltsituation in Österreich (Tenth Environmental Control report, Environmental Situation in Austria)*, REP-0410. Umweltbundesamt, Vienna, Austria.

Urich, C., Bach, P. M., Sitzenfrei, R., Kleidorfer, M., McCarthy, D. T., Deletic, A. & Rauch, W. 2013 Modelling cities and water infrastructure dynamics. *Proceedings of the ICE – Engineering Sustainability* **166** (5), 301–308.

Willems, P., Arnbjerg-Nielsen, K., Olsson, J. & Nguyen, V. T. V. 2012 Climate change impact assessment on urban rainfall extremes and urban drainage: methods and shortcomings. *Atmospheric Research* **103**, 106–118.