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D441.3.3 Urban hydrology ECV and impact indicator data for historical conditions

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Introduction

The goal of UrbanSIS is to develop and demonstrate a method to downscale climate and impact indicators to the urban scale, delivering the information with a space/time resolution and format that makes it useful for consultants, urban planners, engineers and scientists dealing with intense rainfall, heat waves, and air pollution hazards. Within the project, WP3 targets the downscaling of climate, air quality and hydrology over three selected urban landscapes: Stockholm, Bologna, and Amsterdam/Rotterdam. Simulations are carried out for historical and future time periods.

The current deliverable (D441.3.3) addresses specifically the hydrology downscaling over a 5-year time window representing the historical period. Two other reports, D441.3.1 and D441.3.2, complete the work description for past conditions, respectively with the urban climate and the air quality components. Sector-related impact indicators are included in each one of the deliverables. Future hydrology data will be delivered with reports D441.3.4 to D441.3.6.

The downscaling modelling chain consists of three numerical models as depicted in Figure 1: the meteorological/climate model HARMONIE-AROME, the air quality model MATCH and the hydrological model HYPE. The latter is driven by bias-corrected output data from HARMONIE-AROME.

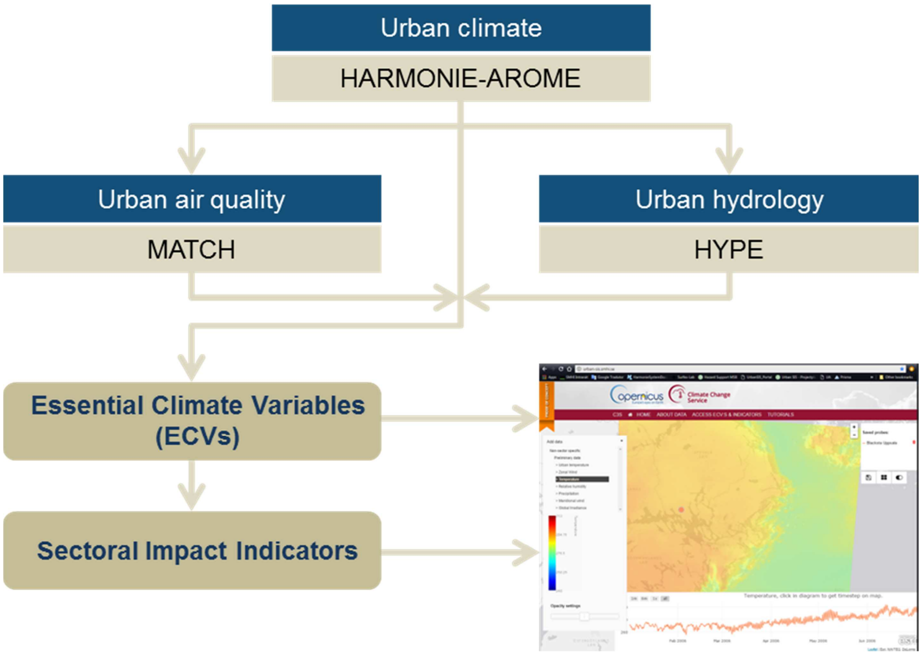


Figure 1 – General flowchart representing the numerical downscalling approach applied in UrbanSIS. More detailed information about the hydrological model HYPE will be given in the following sections.

This report summarizes relevant information about the main characteristics of the model, specific assumptions, computational domain, and input/output data. More details about the models and the numerical techniques applied can be found in the literature listed at the end of the document. Examples for hydrology-related ECVs and indicators are also given.

The last section of the report intends to share some experiences from the hydrology downscaling within UrbanSIS that can be useful for the end-users exploiting the data or for those willing to replicate this method in other European cities, in agreement with the proof-of-concept nature of this project.

1. Hydrological model used for downscaling

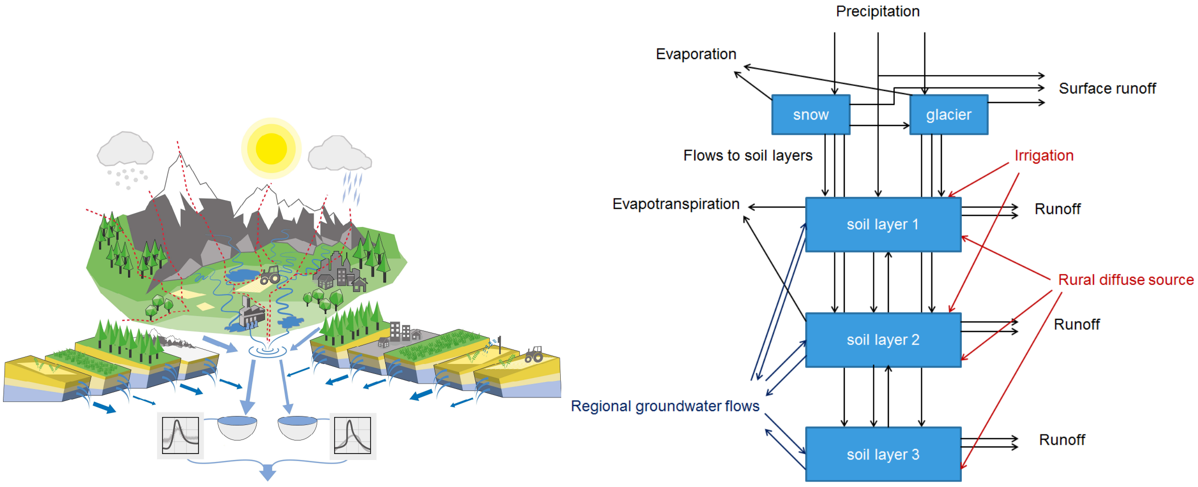
1.1 The HYPE model

The hydrological model HYdrological Predictions for the Environment (HYPE) (Lindström et al., 2010) is employed to model the land surface hydrological processes and derive a set of hydrological variables. The model is a continuous process-based model, which simulates components of the catchment water cycle at a daily or hourly time step. It is a semi-distributed conceptual model, in which a river basin may be subdivided into multiple subcatchments, which are further subdivided into homogeneous hydrological response units (HRUs) based on combined soil type and land use classes (see Figure 2). Normally, model outputs are generated at the subcatchment outlet.

The model has conceptual routines for most of the major land surface and subsurface processes (e.g. snow/ice accumulation and melting, evapotranspiration, surface and macropore flow, soil moisture, discharge generation, groundwater fluctuation, aquifer recharge/discharge, irrigation, abstractions and routing through rivers, lakes and reservoirs) that are controlled by a number of parameters that are often linked to physiography to account for spatial variability. Many of the parameters need to be estimated through calibration. The snow accumulation and melt process is modelled using the degree-day method with land use dependent parameters. A fraction of rainfall or snowmelt infiltrates into the topsoil, which is limited by a soil type dependent maximum rate. If the soil moisture in the upper soil layer exceeds a threshold for macropore flow, part of the remaining water forms macropore flow that is controlled by a soil type dependent runoff coefficient. Part of the remaining water is transformed into surface runoff using a soil dependent coefficient. The remaining water forms a surface pool and overland flow is computed using a land use dependent recession coefficient. Potential evapotranspiration (PET) is estimated using a simple threshold temperature approach, where PET increases linearly above a threshold air temperature at a rate controlled by a land use dependent parameter. PET is achieved only if the actual soil moisture exceeds a certain proportion of the soil field capacity and for soil moisture below this limit, the actual evapotranspiration decreases linearly to zero at wilting point. Runoff from the soil zone is computed when the soil moisture exceeds field capacity using soil type dependent recession coefficients. Water percolates from upper to lower soil layers when the soil moisture in the upper layer exceeds field capacity and the rate is determined using a soil type dependent percolation parameter. The ground water level is estimated based on the level in the soil zone where the pore space is filled.

The generated discharge is routed through each subcatchment and between subcatchments using a river routing routine which simulates attenuation and delay. If lakes and reservoirs are present within a subcatchment, the flow is routed in the lake or reservoir using a rating curve with parameters that need to be calibrated.

To setup the HYPE model, a set of spatial data are required. River networks and subcatchments are delineated from digital elevation models. Hydrological response units (HRUs) are derived from land use and soil data. Maps of lakes and reservoirs are also required to correctly locate them. Land management data, such as irrigation, can also be incorporated in the model setup.



(a) (b)

Figure 2 – Structure of HYPE model [a) schematic representation; b) model process interaction].

Subcatchment average precipitation and temperature corresponding to the time step of the model simulation are the main forcing data required to run HYPE. To calibrate the model and validate the model performance, discharge data at the outlet locations of one or several subcatchments are required.

2.2 Developments within UrbanSIS

HYPE computes the different hydrological variables such as runoff, evapotranspiration, etc. for the HRUs, but provides subcatchment average outputs. For UrbanSIS users, however, it is useful to have hydrological variables for different land uses within the subcatchments. Furthermore, the subcatchments are normally polygons of irregular shapes. To match the 1x1 km^2 scale in UrbanSIS, however, there is a need to provide model simulations on regular grids. In this section we describe developments implemented to render the model such capabilities within the UrbanSIS framework.

2.2.1 Model output distribution to different land uses

In order to enable the model deliver simulation outputs for different land uses within a given subcatchment, the subcatchments were further divided into smaller pseudo-subcatchments. Technically, it is possible to subdivide each subcatchment into as many smaller pseudo-subcatchments as the number of HRUs within each subcatchment. However, in the present work, each subcatchment was divided into up to three pseudo-subactchments by grouping HRUs with impervious urban areas, green areas, and all the remaining land uses, respectively (see Figure 3). It should be noted that the newly defined pseudo-subcatchments are not geographically contiguous since they are formed by grouping similar land use classes. Therefore, flow routing between subcatchments is not possible. However, this version of the model is used only to deliver simulation results of distributed hydrological variables and not discharge. Discharge is simulated using the original version of the model.

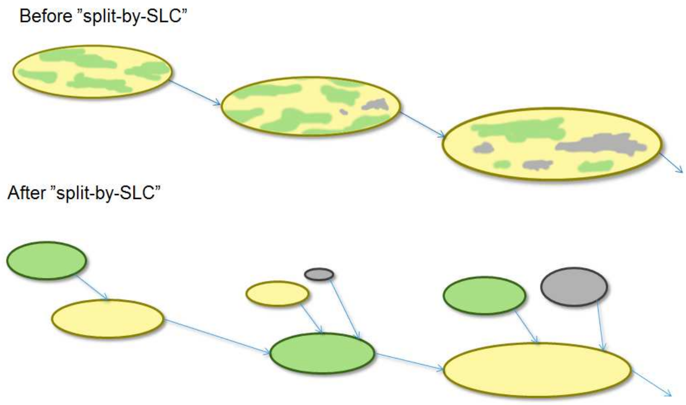


Figure 3 – Subdivision of subcatchments into smaller pseudo-subcatchments.

2.2.2 Development of a grid based HYPE model

As HYPE is a subcatchment based semi-distributed model, subcatchment average forcing data are used to run the model and the model outputs are also delivered as subcatchment average values. The subcatchments are basically irregular polygons and their sizes may be orders of magnitude larger than the forcing data grid cell. This may lead to incorrect representation of the spatial variability of the forcing data, especially precipitation. To avoid this, a grid-based model was developed. The model grids are defined to match the HARMONIE-AROME forcing data grid and each grid cell is treated as a subcatchment. The flow routing between the grids is established based on the flow concentration from the digital elevation model (see Figure 4).

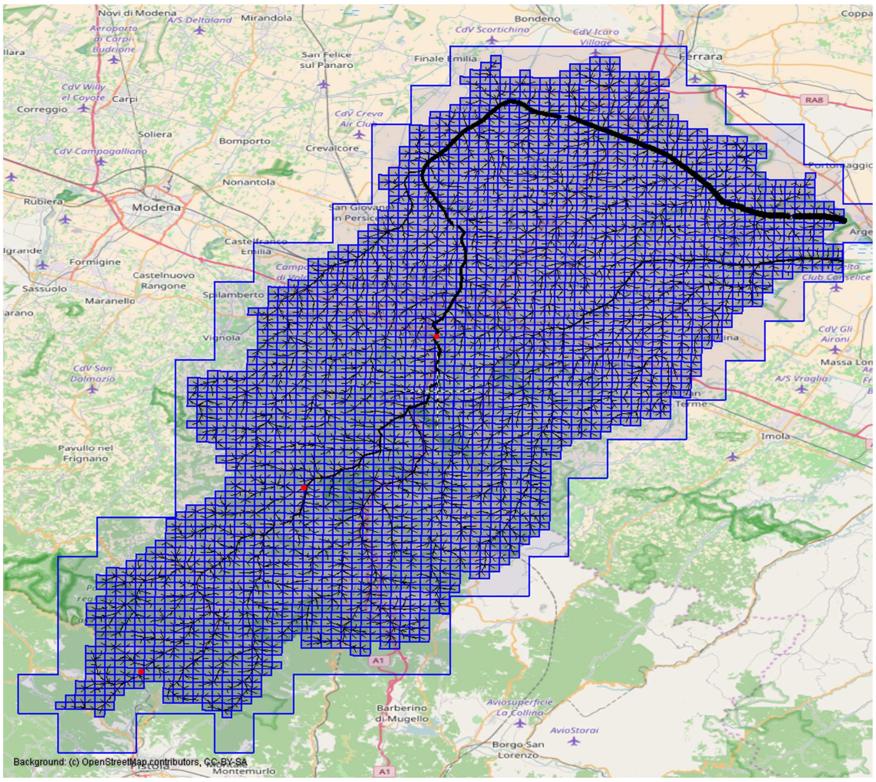


Figure 4 – Grid based model setup for Bologna.

The grid based model works exactly in the same way as the polygon based model. HRUs are defined based on land use and soil types. Note that if the grids of the land use and soil map coincide with the model grid, each model grid will have a unique HRU.

This version of the model was set up for Bologna. For Stockholm, the polygon based model was already developed in previous projects and was refined for UrbanSIS by using Urban Atlas for land use description. A grid based model is under development for Amsterdam/Rotterdam.

2. Input to the hydrological downscaling

2.1 Time period of simulation

The 5-year historical period selected is comprised of the following years: 2006, 2007, 2012, 2013, and 2014. The same period is considered for the 3 use cases. The criteria for the selection were mainly the availability of data needed by the models (namely boundary conditions from UERRA and observations for assimilation and/or validation), and the project´s goal of addressing the end-user requirements and expectations. In particular, this time window responds to a specific request from Bologna end-users to consider more recent conditions, including the year 2012, which was particularly warm in the summer. More information about the time period selection process can be found in D2.1.

2.2 Computational domains

It was aimed to perform modelling of the hydrological processes using detailed urban land use information for each case study city. The land use database employed in this study is Urban Atlas 2012 (http://land.copernicus.eu/local/urban-atlas). The computational domain for the hydrological modelling of each case study city was, therefore, established based on delineation of a catchment that covers the selected cities where land use information from Urban Atlas 2012 is available. However, Urban Atlas 2012 may not cover the entire upstream drainage area for each city. Furthermore, scenarios of hydrological variables are modelled using the HARMONIE-AROME downscaled forcing data, whose domain may not cover the entire upstream drainage area. Nevertheless, modelling the entire upstream drainage area is required to estimate river discharge for the river reach that drains the upstream area. Other local hydrological variables can be estimated as long as the local model can be calibrated using discharge gauging stations at subcatchments that do not drain upstream areas.

For Stockholm, the model domain was chosen as the drainage area that covers the Stockholm County (see Figure 5). The entire drainage area includes the Lake Mälaren and its upstream drainage area. However, the lake has two outlets and is regulated, which makes modelling of the outflow difficult. Therefore, the lake and its upstream area are excluded from the model domain.

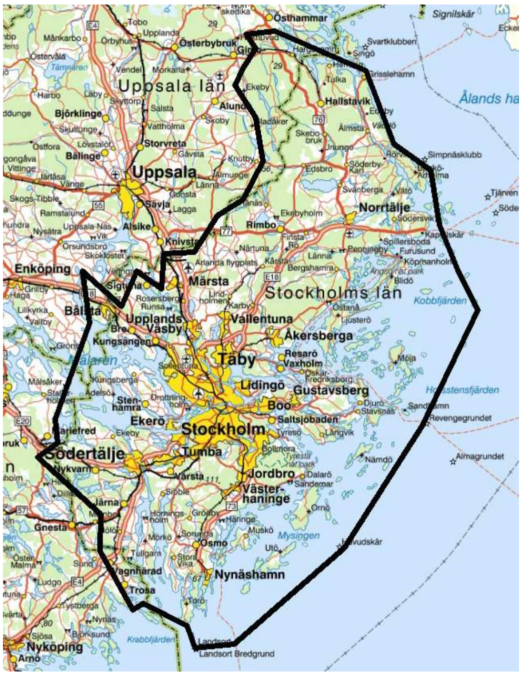


Figure 5 – Outline of the Stockholm model domain.

For Bologna, the model domain was chosen as the entire drainage area upstream of the city of Bologna. For Amsterdam the model domain is chosen as the drainage area for local flows covering the Amsterdam/Rotterdam area.

2.3 Boundary conditions

The meteorological output from HARMONIE-AROME (described in D441.3.1) are used as forcing data for the HYPE simulations.

For model setups where the entire upstream drainage area is not included, simulated river discharge for river reaches that drain the upstream area need to be estimated in some way. Models set up for the upstream area are run using daily climate forcing data from the UERRA project (http://www.uerra.eu/). The hourly discharge data are approximated as if the simulated daily discharge were uniformly distributed throughout the day. Detailed land use information may not also be available for the entire upstream area and the CORINE land use data is used for the upstream area. For UrbanSIS this will only be applicable for the Amsterdam setup.

For the Bologna model, modelling the upstream area in the way described above is not necessary since the entire upstream drainage area is within the model domain. For the Stockholm model, flow from the upstream drainage area is the outflow from Lake Mälaren, which is regulated. The outlet from the lake is, therefore, not included in the model simulations.

2.4 Surface description

As described in section 2.2 above, land use information is of importance for the hydrological model descriptions. For the city area we use the same land use data source, Urban Atlas 2012, as the meteorological and air quality models used in UrbanSIS.

2.5 Observations

Hourly observed meteorological forcing data (precipitation and temperature), as well as discharge data at different locations within the model domain, are required to calibrate and validate the hydrological model. Data from different sources were employed for the different case study cities. For Stockholm, radar based hourly precipitation data and hourly temperature from the MESAN reanalysis system, were used as forcing (see below for description of data synthesis). Hourly discharge data from four stations from SMHI’s hydrological measurement database (WISKI) were used. In addition, high resolution discharge data from three stations were obtained from Stockholm Vatten, which were synthesized into hourly series by averaging the inter-hourly values.

For Bologna, hourly precipitation from stations within and around the model domain, were obtained from Arpae Emilia-Romagna. Similarly, hourly temperature data measured from automatic weather stations were obtained. Furthermore, 5 km gridded hourly operational analysis data were obtained for precipitation and temperature. The gridded analysis data were used for model calibration and validation. Hourly discharge data were also obtained at two stations along the Reno River.

As for meteorological data in the Rotterdam area, we are receiving data from TU Delft and KNMI. TU Delft is operating a network of weather stations in the city. KNMI operates an automatic weather station at Rotterdam airport with hourly data and 10-min data available. Furthermore, KNMI provides a climatological dataset for their rainfall radar network.

As an additional source of precipitation data we use the NORDRAD radar composite (Carlsson, 1995), which includes radars from both Sweden and Denmark for the area of interest. The original resolution of the composite is 2×2 km², and the temporal resolution is 15 min. Although the NORDRAD product contains several corrections to the radar echoes, such as beam blockage, systematic range-dependent bias and removal of false precipitation regions according to satellite images, there are still systematic errors which are clearly visible at longer accumulation intervals.

Berg et al. (2016) investigated the NORDRAD product and its suitability for hydrological simulations over several years, and found that the systematic errors were too large and a correction was necessary. They proposed a mixture of the NORDRAD composite and the PTHBV data base. PTHBV consists of daily gauge-based observations in a 4×4 km² national grid, obtained by an optimal interpolation procedure taking altitude and winds into account (Johansson and Chen, 2003). The new product called HIPRAD (HIgh-resolution Precipitation from gauge-adjusted weather RADar) uses the transient 1-h information of NORDRAD, but scales it with the monthly accumulations of PTHBV, such that systematic errors in the radars are removed. HIPRAD was evaluated against 1-h gauge observations in southern Sweden, and was shown to perform well, besides some problems with the very lowest intensities and the most extreme events. The latter is partly due to the re-gridding of the data to a 4×4 km² grid, but also due to possible underestimations in the PTHBV product.

For the hydrological modelling in UrbanSIS, HIPRAD data were mapped to HYPE catchments by weighted interpolation. Hourly temperature data for the modelling was taken from the MESAN reanalysis system (Häggmark et al., 2000), which assimilates gauge observations with the operational weather prediction model system of SMHI.

3. Post-processing of model output

3.1 Transformation of gridded time series to NetCDF

HYPE output are generated as ASCII files, using the standard HYPE output formats and need to be converted to NetCDF. For this we use software developed for the HYPE modelling system. For Stockholm the conversion includes recalculation of the subbasin based output into the UrbanSIS output grid.

3.2 Statistical post-processing of hydrological ECVs

The statistical post-processing of hydrological variables is made using the same methods and software as for the meteorology and air quality related ECVs. These have been calculated using the Climate Data Operators (CDO) software, version 1.8 (CDO 2017: Climate Data Operators. https://code.zmaw.de/projects/cdo/). For each parameter, the following statistical processing is performed: mean; yearly mean; yearly max; yearly min; monthly mean; monthly max; monthly min; annual monthly mean; annual monthly max; annual monthly min; mean of yearly min; and mean of yearly max.

Note though that some combination of parameter and statistical operators are not shown in the final results, since they are not meaningful. One such combination is yearly minimum of precipitation.

3.3 Calculation of hydrological indicators

One main justification for the very high-resolution downscaling performed in UrbanSIS is to obtain a more realistic description of small-scale rainfall extremes (cloudbursts), and thereby also their future changes, than what is attainable in lower-resolution climate models. Three hydrological indicators are specifically designed for representing small-scale rainfall extremes:

1. Maxprec. This is a complement to the general ECV post-processing statistics (section 3.2). In *maxprec*, monthly maxima are calculated not only for the highest resolution of the precipitation (15 min) but also for longer durations (i.e. accumulation periods) up to 24 h. In each month, the *maxprec* value for a certain duration D min is identified using a moving time window that successively accumulates the rainfall over D/15 time steps and stores the maximum value. The result is a time series of monthly maximum intensities that may be used to evaluate intra-annual as well as spatial/geographical patterns.

2. Intensity-Duration-Frequency (IDF) curve. The IDF curve is a compact statistical description of short-duration rainfall extremes that is widely used in engineering design. There are many ways to calculate IDF curves and in UrbanSIS we use one of the standard approaches to obtain a robust estimation. The approach is based on annual maximum values for different durations between 15 min and 24 h (which may be obtained from the above calculations of maxprec). Then a Gumbel/GEV distribution is fitted to these values in order to estimate intensities associated with different return periods.

For a specific grid cell, the 5-year time series in UrbanSIS generates five annual maxima, which is not a sufficient number for distribution fitting and IDF analysis by this approach. To overcome this limitation, and produce a long enough time series for meaningful analysis, 5-year time series from different grid cells are merged (concatenated) into a time series long enough for IDF analysis. For this purpose, a sub-grid inside the 240×240 km² UrbanSIS domain is defined (see Figure 6). In this sub-grid, the cells are spaced 50 km apart and the entire sub-grid is located 20 km away from the boundary. At 50 km spacing, the short-duration precipitation extremes are expected to be statistically independent, and thus the time series from the sub-grid may be regarded as different realization of the same climate. This approach also requires that the entire domain is statistically homogeneous with respect to the short-duration precipitation extremes, which is a reasonable assumption considering their stochastic nature.

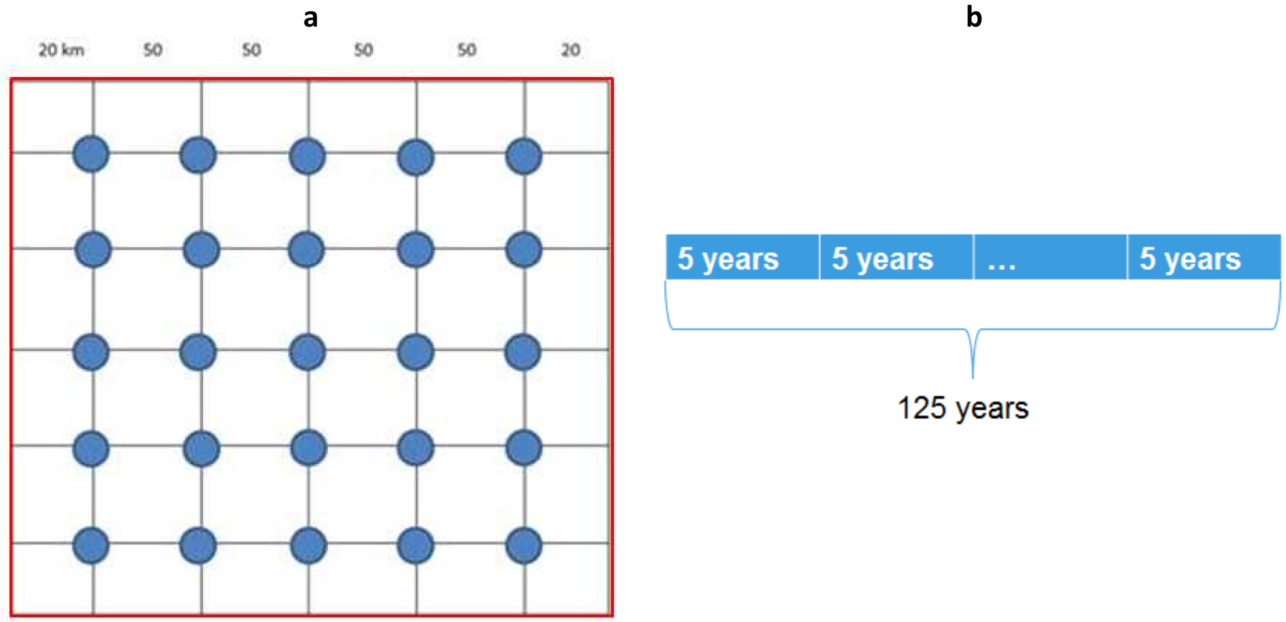


Figure 6 – The 240×240 km² UrbanSIS domain (red line) and the 5×5 sub-grid used in the IDF-analysis (a). The principle of concatenating the 5-year time series from the sub-grid into a 125-year time series (b).

From the final 125-year time series, short-duration precipitation intensities representing very long return periods (≥100 years) may be confidently estimated (provided that the HARMONIE-AROME simulated precipitation is accurate in this respect), which is expected to be a significant contribution to e.g. engineering design procedures and guidelines.

Most importantly, the future change of local precipitation extremes (as represented by the IDF-curves) will in UrbanSIS be estimated with greater confidence than in virtually all other attempts made to date. With a very few exceptions, these attempts have been based on lower-resolution, non-convective-permitting regional climate projections that are not able to properly describe the small-scale atmospheric processes behind local precipitation extremes.

3. *Areal Reduction Factors (ARFs).* The ARF describes the reduction of peak rainfall intensity when the rainfall field is averaged over gradually larger areas and durations. This averaging is attained by interpolating from the original duration D=15 min and grid cell area A=1×1 km² in the HARMONIE-AROME data to a gradually lower temporal resolution of 30 min, 60 min, etc., as well as a gradually lower spatial resolution of 2×2 km², 4×4 km², etc. For each combination of spatial (A) and temporal (D) resolution two statistics are employed: a) Intensity-Duration-Frequency (IDF) analysis (see item 2 above) b) areal reduction factors (ARF).

In this case, the IDF curve is used to derive the relationship between duration of a rainfall event and rainfall depth (*p*) with a given return period (T). Fitting a GEV distribution to annual maxima is a common method for extreme rainfall analysis. From the GEV fits we derive the depths *p* for a number of return periods T, e.g., 5, 10, 50 and 100 years.

Fitting the GEV to a single grid cell time series will cause large variance of its cumulative distribution. A regional frequency analysis is therefore applied to increase the accuracy. It assumes that certain distribution parameters are constant over the region of interest (Overeem et al., 2009). Likelihood function over all involved pixel is maximized under the assumption of spatial independence:

$$L(\mu,\gamma,\kappa) = \sum_{s=1}^{S} L_s(\mu,\gamma,\kappa)$$

where $L_s(\mu,\gamma,\kappa)$ is the log likelihood function for the annual maxima at pixel s, which is derived from the GEV cumulative distribution function F(x):

$$F(x) = exp\left\{-\left[1-\frac{\kappa}{\gamma}(x-\mu)\right]^{\frac{1}{\kappa}}\right\} \quad for\ \kappa \neq 0$$
$$F(x) = exp\left\{-exp\left[-\frac{1}{\gamma}(x-\mu)\right]\right\} \quad for\ \kappa = 0$$

The ARF is defined as a ratio of rainfall depths:

$$ARF(T;D,A) = \frac{p(T;D,A^{+})}{p(T;D,A)}$$

where A stands for the grid cell (i.e., 1 km^2) and A^+ stands for area size of every grid after data interpolation, which varies from 2×2 km² and up. The parameter *p* refers to a rainfall depth with a given return period T conditioned on duration D and spatial resolution A or A^+.

Besides the small-scale precipitation extremes, a key factor behind hydrological extremes (e.g. high flows and flooding) is the depth of the snow pack (i.e. accumulated snow). In many northern regions, the snow-melt induced spring flood constitutes a very distinct annual discharge maximum. Besides the flood risk associated with an unusually high spring flood, hydropower production is highly dependent on accurate estimations of the snow pack in order to optimize reservoir operation. Thus, there is a clear societal interest in estimating the maximum snow pack accumulated in the end of the winter season. In UrbanSIS, this is quantified by the indicator *maxsnowcover*, which is the average value of the annual maximum snow cover in the 5-year simulation period, as estimated by the HYPE model.

Another aspect of snow that is somewhat less hydrologically relevant but highly relevant for other societal functions is the frequency of time with a significant snow cover on the ground. This is of importance for e.g. traffic safety as well as the resources required for municipal snow removal activities. In UrbanSIS, this is quantified through the indicator *ndayswithsnow*, which is the average annual number of days in the 5-year simulation period with snow cover (i.e. SWED > 10 mm), as estimated by the HYPE model.

4. Summary of delivered hydrological data

4.1 Hydrological ECVs

The following table summarizes the ECVs related to hydrology.

Table 1 – List of hydrology related ECVs. The spatial resolution is 1x1 km^2 over the entire modelling domain (110x110 km^2) and the temporal resolution is 1 hour, except for precipitation that equals 15 min.

ECV name	Unit	Model
Local runoff	$mm\ h^{-1}$	HYPE
Local runoff - impervious areas	$mm\ h^{-1}$	HYPE
Local runoff - green areas	$mm\ h^{-1}$	HYPE
Local runoff - other areas	$mm\ h^{-1}$	HYPE
Surface runoff	$mm\ h^{-1}$	HYPE
Surface runoff - impervious areas	$mm\ h^{-1}$	HYPE
Surface runoff - green areas	$mm\ h^{-1}$	HYPE
Surface runoff - other areas	$mm\ h^{-1}$	HYPE
Evapotranspiration	mm	HYPE
River discharge	$m^3\ h^{-1}$	HYPE
Soil moisture	mm	HYPE
Snow cover	mm	HYPE
Air temperature (at 2 m above ground)	°C	HARMONIE-AROME
Precipitation	mm	HARMONIE-AROME

Figure 7 shows examples of local runoff data for Stockholm and Bologna.

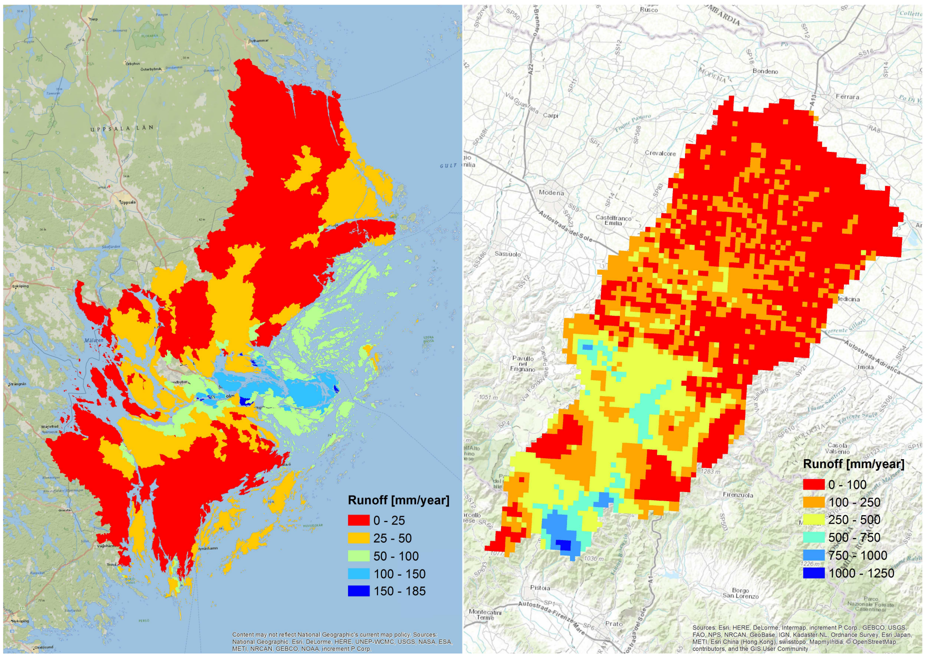


Figure 7 – Spatial distribution of local runoff data from HYPE for Stockholm (left) and Bologna (right).

4.2 Hydrological impact indicators

The following table summarizes the indicators related to hydrology.

Table 2 – List of hydrology related indicators.

Category	Group		Indicator	Aggregation	Unit	Threshold
Infrastructure	**Flooding**	Short duration extreme precipitation	Maximum precipitation intensity	Selected accumulation periods (AP) from 15 min to 24 h	mm AP-1	
		Short-duration extreme precipitation intensity/duration	Intensity-Duration-Frequency (IDF) curve	Selected accumulation periods (AP) from 15 min to 24 h	mm AP-1	
			Areal Reduction Factors (ARFs)	Selected accumulation periods (AP) from 15 min to 24 h		
	Green infra-structure	Drought periods	Drought duration	yearly	days	20th percentile
Non sector specific	**Snow cover**	Snow cover indicators	Number of days (per year) with a snow cover > 1 cm	yearly	days	1 cm
			Mean annual maximum snow cover depth	yearly	cm	

Figure 8 shows an example of an Intensity-Duration-Frequency (IDF) curve based on an analysis of UrbanSIS data for Bologna.

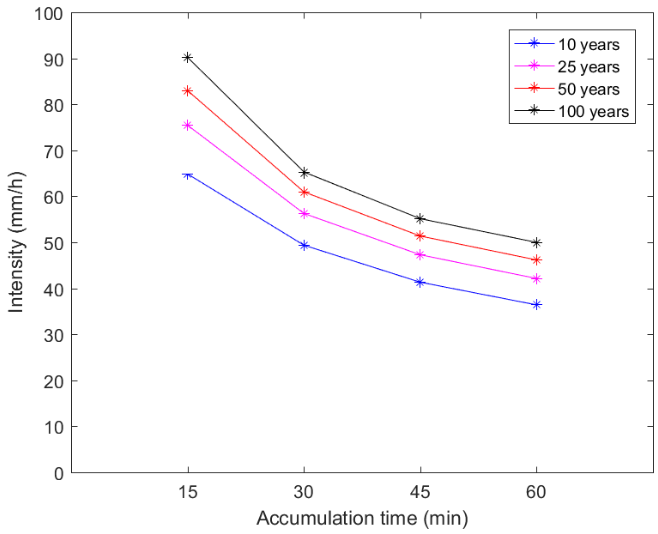


Figure 8 – Example of IDF curve based on analysis of data from HARMONIE-AROME runs over Bologna.

5. Experiences from the hydrological downscaling

As discussed in the foregoing sections, employing the hydrological model under the different settings for the different case study regions has its own challenges. While some of the issues that arose along the way have been resolved in some way, there are still issues that need to be resolved.

The employed hydrological model is a semi-distributed model with subcatchments as model units. Although HRUs are used as computational units within a subcatchment, simulated hydrological variables are at a subcatchment scale. As the study areas are built up urban areas, there is a need to supply certain hydrological variables for different land cover features. For instance, runoff from sealed areas can be considerably higher than from pervious areas and unless a given subcatchment contains only sealed areas, it is difficult to provide distribution of runoff for sealed and unsealed areas for users of the hydrological information. However, sealed areas are often surrounded by green areas in urban settings and it is not practically feasible to delineate subcatchments with exclusively sealed areas. We introduced a work around allowing model simulations for different land features that can be extended to other similar studies. However, as flow routing between different connected subcatchments is not possible since the introduced pseudo-subcatchments are not spatially continuous, two versions of model setups are required to be able to simulate discharge as well. Further work may be needed to fix this problem.

Subcatchment average forcing data are used to run the hydrological model. In the present work, the model needs to run with hourly forcing data that are finely spatially resolved. At such temporal scale, the spatial variability of especially precipitation needs to be appropriately represented in the model. Averaging the precipitation over a subcatchment may lead to smoothing of extreme local precipitation. This can be handled by delineating smaller subcatchments with sizes comparable to the forcing grid cell size. However, unless the subcatchment is not entirely contained within a single forcing grid cell, there may be a need to interpolate forcing data from grid cells whose parts are within a subcatchment. The grid based modelling approach we introduced enabled us to solve the problem, while additionally enabling us to come up with a distributed modelling framework while still keeping the original model structure. This comes at the cost of increased computational effort. However, as the employed hydrological model has a modest data demand and the model structure is not that complex; the increase in the computational effort at the scale of the study domains in this work is not that much. HYPE simulations for 5 years for a city can be made on a normal PC with a computation time of a few minutes.

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