4. Stormwater management tool

4.1. INTRODUCTION

The stormwater modelling tool is based on the two open-source modelling platforms, Stormwater Management Model (SWMM) and PHREEQ-C that could be employed for evaluating the processes governing the performance of NWRM and their potential long-term behaviour.

The Stormwater Management Model (SWMM)[1] is a widely used open-source tool to simulate urban water balance components, i.e., surface runoff, flooding, infiltration, and evapotranspiration for both event-based[2] and long-term periods[3]. SWMM is used to model the interactions between hydrological, hydraulic and water quality processes in urban areas. In addition, the model supports simulation of stormwater quality and generation of loads from urban areas (*Figure 1*). SWMM is a computation engine that also is included in commercial packages, such as PCSWMM (https://www.pcswmm.com/) and MIKE-URBAN (https://www.mikepoweredbydhi.com/products/mike-urban).

The objective of this document is to present summary of information related to urban hydrological modelling in the northern high latitudes using SWMM based on recent studies from Finnish climatic conditions. It summarizes the sources of data and established parameters needed for model building as well as established methodology for subcatchment delineation method based on homogeneous surface types. The document also summarises setup of PHREEQ-C for assessing geochemical processes of natural water retention measures (NWRM).

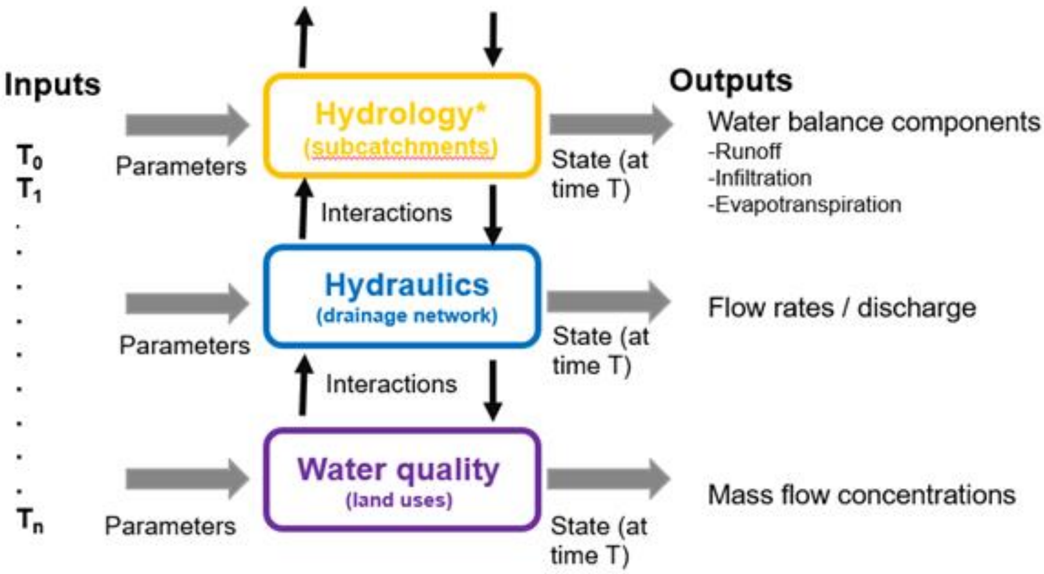

Figure 1: Illustration of Stormwater Management Model (EPASWMM), open-source (1D) tool (Source: https://www.epa.gov/water-research/storm-water-management-model-swmm)

[1] Rossman, L. A., & Huber, W. C. (2016). Storm Water Management Model Reference Manual Volume I – Hydrology. U.S. Environmental Protection Agency, I(EPA/600/R-15/162A), 233. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100NYRA.txt

[2] Niemi, T. J., Kokkonen, T., Sillanpää, N., Setälä, H., & Koivusalo, H. (2019a). Automated Urban Rainfall-Runoff Model Generation with Detailed Land Cover and Flow Routing. Journal of Hydrologic Engineering, 24(5). https://doi.org/10.1061/(ASCE)HE.1943-5584.0001784

[3] Khadka, A., Kokkonen, T., Niemi, T. J., Lähde, E., Sillanpää, N., & Koivusalo, H. (2019). Towards natural water cycle in urban areas: Modelling stormwater management designs. Urban Water Journal. https://doi.org/10.1080/1573062X.2019.1700285

4.2. MATERIALS AND METHODS

4.2.1. SWMM components

The SWMM description of water flow in the stormwater drainage network (hydraulics) is fed by a set of subcatchments (hydrology) represented in 1 dimension (1D). Conceptually, subcatchments in SWMM are treated as nonlinear reservoirs, which receive inflows from precipitation and adjacent subcatchments and generate different components of outflows and losses including surface runoff, infiltration, and evaporation. The model can also simulate Low Impact Development (LID) structures, where each LID structure is represented with a combination of vertical layers such as surface layer or pavement, soil layer, and storage layer (*Figure 2*). LID module is part of the Hydrology component of SWMM. The LID module support simulation of structures, such as permeable pavements, bio-retention areas, rain barrels, infiltration trenches, and vegetative swales.

There is an abundance of practical guidance on using SWMM for practice and research, e.g., SWMM user's manual version 5.1[4], SWMM Reference Manual Volume I- Hydrology[5], and SWMM Reference Manual Volume II- Hydraulics[6].

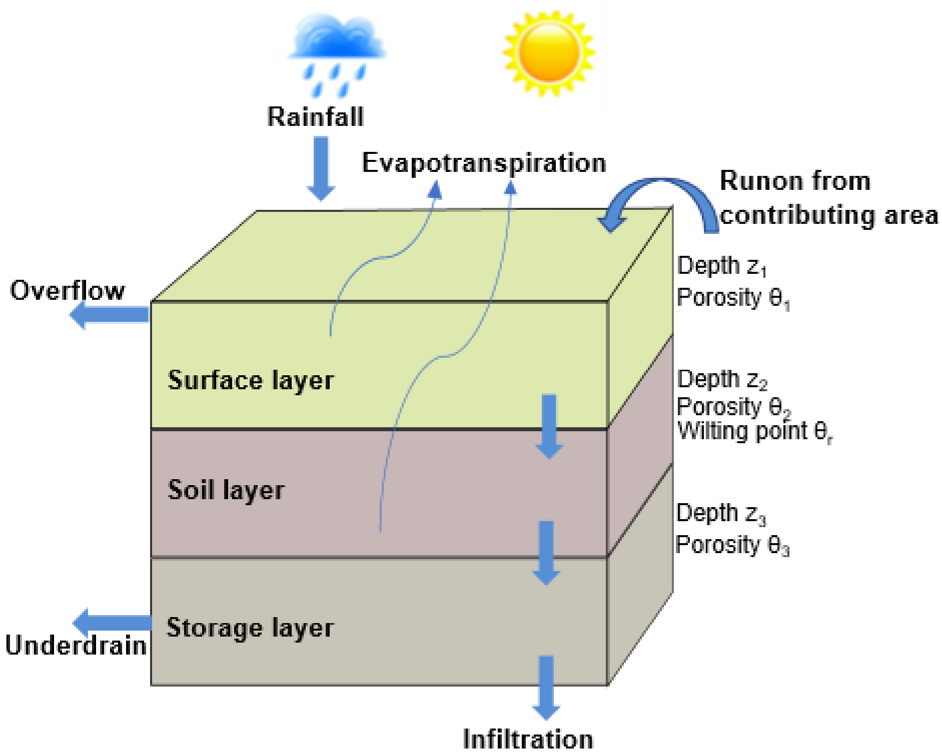

Figure 2: Generic illustration of an LID solution (Khadka et al. 2021).

[4] Rossman, L. A. (2015). Storm water management model user's manual version 5.1 (EPA/600/R-05/040). United States Environment Protection Agency, September, 353. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100N3J6.TXT

[5] Rossman, L. A., & Huber, W. C. (2016). Storm Water Management Model Reference Manual Volume I – Hydrology. U.S. Environmental Protection Agency, I(EPA/600/R-15/162A), 233. https://doi.org/10.1016/S0021-9290(00)00018-X

[6] Rossman, L. A. (2017). Storm Water Management Model Reference Manual. Environmental Protection, II(EPA/600/R-17/111), 37–46. www.epa.gov/water-research

4.2.2. Data sources

This section lists the key data sources of the and provides examples of available data for the construction of SWMM parameterization. There are three main spatial datasets required as input for SWMM model setup. They are:

1. Topography data: Digital Elevation Model (DEM)

A 2m resolution DEM is freely available from a file service of open data by National Land Survey of

Finland (NLS), http://www.maanmittauslai-tos.fi/en/e-services/open-data-file-download-service .

Open-source QGIS tool can be used to compute slope and areas of subcatchments.

2. Land use / landcover data:

High-resolution land cover dataset for Helsinki Region is freely available from HSY (WFS) (https://kartta.hsy.fi/geoserver/wfs).

For larger city areas, a low-resolution pan-European land use and land cover data set known as Urban Atlas is provided by the European Environment Agency. It is available at http://www.eea.europa.eu/data-and-maps/data/urban-atlas .

In addition, land use spatial data can be constructed manually using online municipal map services, orthophotos (the NLS file service of open data, municipalities), satellite images in online services such as Google Maps (https://maps.google.fi) and Open Street Map (https://www.openstreetmap.org/).

3. Stormwater network data

Existing drainage/ storm sewer networks can be available from water utility or municipalities-

4.2.3. Catchment delineation

Urban catchment can be delineated based on the topographic data (DEM). First, the DEM is pre-processed to remove depressions because DEM with no depressions help to create a continuous flow and it is easy to delineate catchments. Pipe network can be burned into DEM to allow the water to flow along the pipes and to the outlet. The outlet can be where the measurement has been done. The r.watershed tool in QGIS or pyshed package (https://github.com/mdbartos/pysheds) in python can be used to delineate the urban catchment.

4.2.4. Automated subcatchment delineation using GIStoSWMM'

The manual construction of high-resolution urban hydrological models, where each contributing surface is individually described as shown in *Figure 3*[7], is only practical when study area is small. For large urban catchments, it is a slow and laborious task. An automatic subcatchment generator (GisToSWMM5) has been developed[8] to automate the model construction process by connecting the subcatchments together and into the stormwater network on a uniform grid based on input data. The

[7] Krebs, G., Kokkonen, T., Valtanen, M., Koivusalo, H., & Setälä, H. (2013). A high resolution application of a stormwater management model (SWMM) using genetic parameter optimization. Urban Water Journal, 10(6), 394–410. https://doi.org/10.1080/1573062X.2012.739631 ; Krebs, G., Kokkonen, T., Valtanen, M., Setälä, H., & Koivusalo, H. (2014). Spatial resolution considerations for urban hydrological modelling. Journal of Hydrology, 512, 482–497. https://doi.org/10.1016/j.jhydrol.2014.03.013

[8] Warsta, L., Niemi, T. J., Taka, M., Krebs, G., Haahti, K., Koivusalo, H., & Kokkonen, T. (2017). Development and application of an automated subcatchment generator for SWMM using open data. Urban Water Journal, 14(9). https://doi.org/10.1080/1573062X.2017.1325496

tool has been further improved[9] by adding an adaptive subcatchment generation routine based on actual surface flow routes according to DEM and land cover information. The adaptive subcatchment generation algorithm thus developed can be used for high-resolution description for each subcatchment. However, the adaptive routine produces number of subcatchments with same land use and a shared outlet that should ideally be merged to one resulting in 15 times more subcatchments compared to the corresponding manual high-resolution models[10]. The adaptive routine discussed above will be improved[11] by merging additional subcatchments with the same land use and common outlet into one. This improvement will reduce the subcatchment numbers to 2-4 times more than the corresponding manual high-resolution models.

Figure 3: The high-resolution subcatchment delineation. Colours represent the surface subdivision based on different surface types, land-use types, and ownership classes; subcatchment boundaries are described with white lines, black lines represent the stormwater sewer network, and black dots indicate the sewer inlets (Krebs et al. 2014).

The input files for GisToSWMM5 include a DEM raster, as well as a land use raster and a flow direction raster with the resolution and dimensions corresponding to those of the DEM (*Figure 4*). A high-resolution DEM raster of 1 or 2m resolution can be used for the automatically generated SWMM models using GIStoSWMM5. The basic workflow for preparing the input files proceeded as follows: 1) Catchment boundaries are forced by raising DEM elevation outside the catchments; 2) A raster file with an index describing the land use information inside the catchment boundaries is assigned for each DEM raster cell; and 3) A flow direction grid from the DEM raster is created. The tool then forms the subcatchments by combining cells with common land use and connected flow route and routes the stormwater between the subcatchments as well as between subcatchments and the stormwater network.

The tool can be downloaded from https://github.com/AaltoUrbanWater/GisToSWMM5. The github also contains demonstration catchment with the required input files.

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[9] Niemi, T. J., Kokkonen, T., Sillanpää, N., Setälä, H., & Koivusalo, H. (2019a). Automated Urban Rainfall-Runoff Model Generation with Detailed Land Cover and Flow Routing. Journal of Hydrologic Engineering, 24(5). https://doi.org/10.1061/(ASCE)HE.1943-5584.0001784

[10] Niemi, T.J., Krebs, G., Kokkonen, T. 2019b. Automated Approach for Rainfall-Runoff Model Generation. 11th International Conference on Urban Drainage Modelling, UDM 2018. Palermo, Italy. Green Energy and Technology, 2019, pp. 597–602

[11] Khadka, A., Kokkonen, T., Niemi, T. J., Lähde, E., Sillanpää, N., & Koivusalo, H. (2021). Stormflow against streamflow – can storage capacity ensure performance efficiency and maintenance of pre-development flow regime? Manuscript under review in Journal of Hydrology.

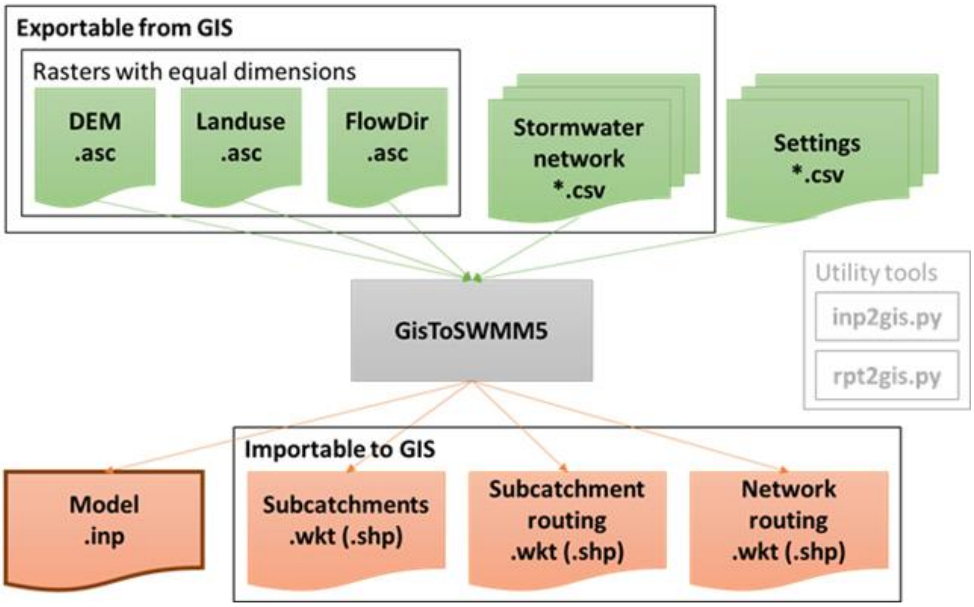

Figure 4: GISto SWMM5 Input/Output

4.2.5. SWMM parameterisations

The catchment is divided into small homogeneous subcatchments sharing the same land cover types shown in *Figure 3*[12]. This facilitates adopting parameter values from earlier hydrological studies conducted in Finland. Infiltration was simulated using the Green-Ampt equation and the flow routing in the pipe system using the dynamic wave theory. The node ponding was not allowed in the model to quantify flooding in the nodes[13]. Subcatchment characteristics, i.e., area, mean slope and flow. Flow width (W) for each subcatchment is computed using Equation:

$$W = K_w \sqrt{A}$$

where A is the subcatchment area and K_w is a parameter (with a value of 0.7). Other subcatchment characteristics, i.e., the depression storage, the Manning's roughness coefficient for the overland flow and the imperviousness of land cover are tied to the homogeneous surface types. *Table 1* shows the parameter values tied to different surface types for above subcatchment characteristics. For the soil parameter values, there are some locally calibrated values for Finnish study sites (

Table 2).

[12] Khadka, A., Kokkonen, T., Niemi, T. J., Lähde, E., Sillanpää, N., & Koivusalo, H. (2019). Towards natural water cycle in urban areas: Modelling stormwater management designs. Urban Water Journal. https://doi.org/10.1080/1573062X.2019.1700285 ; Krebs, G., Kokkonen, T., Valtanen, M., Setälä, H., & Koivusalo, H. (2014). Spatial resolution considerations for urban hydrological modelling. Journal of Hydrology, 512, 482–497. https://doi.org/10.1016/j.jhydrol.2014.03.013

[13] Khadka, A., Kokkonen, T., Niemi, T. J., Lähde, E., Sillanpää, N., & Koivusalo, H. (2019). Towards natural water cycle in urban areas: Modelling stormwater management designs. Urban Water Journal. https://doi.org/10.1080/1573062X.2019.1700285

Table 1: Values for parameters tied to homogeneous surface type[14]

Surface	Land-use type	Imperviousness (%)	Manning's roughness coeff	Depression storage (mm)
Paved surface	Asphalt driveway	95.0	0.01	0.38
	Asphalt parking	85.0	0.02	0.62
	Asphalt road	100.0	0.01	0.39
Gravel surface	Mixed yard	78.8	0.03	2.54
	Gravel yard	38.0	0.03	4.98
Roof	Roof	100.0	0.01	0.10
	Sloped roof	100.0	0.01	0.10
Train track	Train track	69.5	0.03	2.51
	Tramline	69.5	0.03	2.51
Vegetation	Road side vegetation	0.0	0.67	4.13
	Forest/ Trees	0.0	0.67	5.38
Stormwater pipe	-	-	0.01	-

Table 2: Locally calibrated infiltration parameter values for Finnish study sites

Soil condition	Hydraulic conductivity (mm/hr)	Suction head (mm)	Initial moisture deficit (-)	Source
	4.21	88.9	0.217	Guan et al. (2015)[15]
	24.965	55.839	0.350	Niemi et al. (2019)
Loamy clay type	2.0	208.8	0.416	Khadka et al. (2019)

4.3. EVALUATING NWRM PERFORMANCE WITH PHREEQ-C

PHREEQ-C is a model that can be employed for evaluating the processes governing the NWRM performance and its potential long-term behaviour. The results of PHREEQ-C support identifying the critical environmental changes (e.g., pH fluctuations or soil acidification) that may influence the

[14] Khadka, A., Kokkonen, T., Niemi, T. J., Lähde, E., Sillanpää, N., & Koivusalo, H. (2019). Towards natural water cycle in urban areas: Modelling stormwater management designs. Urban Water Journal. https://doi.org/10.1080/1573062X.2019.1700285

[15] Guan, M., Sillanpaa, N., & Koivusalo, H. (2015). Assessment of LID practices for restoring pre- development runoff regime in an urbanized catchment in Southern Finland. Water Science Technology, 71(10) (April 2016), 2015–2017. https://doi.org/10.2166/wst.2015.129

pollutant retention mechanisms. Scenarios, capturing the projected effects of climate change, can further shed light on the anticipated long-term NWRM performance.

PHREEQ-C is a physics-based tool for assessing the geochemical processes in NWRMs that are relevant for understanding their long-term behaviour. PHREEQ-C allows to assess the fate of stormwater pollutants and the principal pollutant removal mechanisms[16]. The simulations use thermodynamic principles to predict equilibrium reactions of the mineral phases. PHREEQ-C can be applied to compute mineral saturation indices (SI) based on measured pollutant concentrations:

$SI = \log[(IAP)/(K_s)]$

where IAP is the ion activity product (describing the non-equilibrium state of a solution, i.e., measured concentrations), and K_s is the solubility product (describing the relationship of the ion equilibrium in the solution). SIs indicate either oversaturation (SI > 0; mineral precipitation) or undersaturation (SI < 0; mineral dissolution) of the mineral phases. SI values not exceeding -0.5 and 0.5 represent equilibrium in the solution.

The outputs of PHREEQ-C simulations allow to evaluate which ambient conditions and qualitative changes in the NWRM influx will potentially impact the formation of more stable compounds or the release of the dissolved ones. For instance, the increased inflow to the filters system simulated with the downscaled regional climate scenarios in SWMM can be translated into the dilution or accumulation effect of stormwater pollutants that is further assessed with PHREEQ-C. Table 3 lists a set of minimum set of required qualitative and quantitative data necessary for the parameterisation of PHREEQ-C simulation.

Table 3: A set of minimum required qualitative stormwater composition data for PHREEQ-C simulations.

Stormwater physicochemical parameters	Specific chemical constituents	NWRM design details and other parameters
pH Electrical conductivity Alkalinity Redox Turbidity TOC DOC	Cations: Na, Ca, Mg, K, Zn, Pb, Cu, Cd, Al, Ni, Anions: Cl, SO4, PO4, NO3, NH4, total phosphorus, total nitrogen	Design dimensions Materials used Influent flow Effluent flow Chemical transformations Thermodynamic phases

4.4. FUTURE PROSPECTS

Regionalisation of hydrological models to areas, where no local measurements are available, is a tricky task. In the regionalisation of distributed models, the computation results are generally assumed to be valid only with outputs that have been explicitly validated against measurements[17]. The urban areas with constructed surfaces and drainage networks are easier from the modelling viewpoint than complex natural areas to gain success in model regionalisation. The detailed description of homogenous urban surface elements as subcatchments has been proposed[18] as a workable approach

[16] Appelo, C.A.J., & Postma, D. (2007). Geochemistry, groundwater, and pollution. A.A. Balkema Publishers, Leiden.

[17] Refsgaard, J.C. 1997. Parameterisation, calibration, and validation of distributed hydrological models. Journal of Hydrology 198(1–4), 69-97

[18] Krebs, G., Kokkonen, T., Valtanen, M., Setälä, H., & Koivusalo, H. (2014). Spatial resolution considerations for urban hydrological modelling. Journal of Hydrology, 512, 482–497. https://doi.org/10.1016/j.jhydrol.2014.03.013

for an urban model regionalisation to ungauged areas. Another benefit of introducing high spatial resolution of urban catchment description is the match between the LID design scale and the spatial modelling scale. SWMM readily supports simulation of LID solutions attached to homogeneous surface types. The benchmarking of SWMM to new urban settings with validation of results against measurements will provide model parameter base for applications in ungauged conditions and new design settings. The information provided in this summary is a step to support SWMM applications in new areas.

Needs for climate change assessment forms a strong incentive to apply urban hydrological models. Future projection about urban hydrological impacts of climate change rest on the application of stormwater models with future weather inputs. The main challenge is the projection of future precipitation. The projection of precipitation form is achievable, with snowfall turning into rainfall, but the projection of design rainfall intensities for high temporal and spatial resolution under future changing conditions is challenging. Still, the available scenarios for the future and clues how the current peak precipitation intensities may change, provide the necessary starting point for urban hydrological modelling and estimation of climate change impacts on stormwater processes and systems.

SWMM has been successfully embedded in environmental modelling systems as part of wider simulation platforms. The development of modelling through model integration is a prospect for tackling challenges beyond water quality and quantity, such as broadly defined sustainable urban design including biodiversity, amenity, and quality of the environment.