Supplementary Materials: The Applied Software KalypsoNA and KalypsoHydrology

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1. Introduction

The published article presents methods to integrate local scale drainage measures (LSDM) in catchment modelling. The implementation of these methods is done in the computation code of the semi-distributed rainfall-runoff model (RRM) KalypsoNA and the User Interface (UI) KalypsoHydrology. The computation code is written in FORTRAN and the UI is written in JAVA. FORTRAN is one of the programming languages used for scientific and numerical computing and supports e.g., complex data structures. JAVA contains standardized and platform independent constructs for creating user interfaces and application packages (e.g., GIS applications). KalypsoNA is a hydrologic model for the simulation of the land-based water balances in catchments and has been enhanced to include the differentiated description of LSDM in the form of overlay data objects. The hydrological model supports the simulation of surface runoff, precipitation, snow, evapotranspiration, evaporation from water surfaces, soil moisture, interflow, base flow, 1D-groundwater flow processes, etc.

A major issue for the model application in practice is a UI supporting the data management and the import of spatial data. The presented RRM in this paper is part of the open source project Kalypso which comprises a set of applications and client specific developments based on Java technology (e.g, see Figure S1). It is developed according to modern information and communication technologies (ICT): WMS-, WFS-Client, WPS-Server, GML (GML = Geography Markup Language)-3 Parser, Time Series Service, Report Service [1]. The application is available on the open source applications and software directory: SourceForge.net [2].

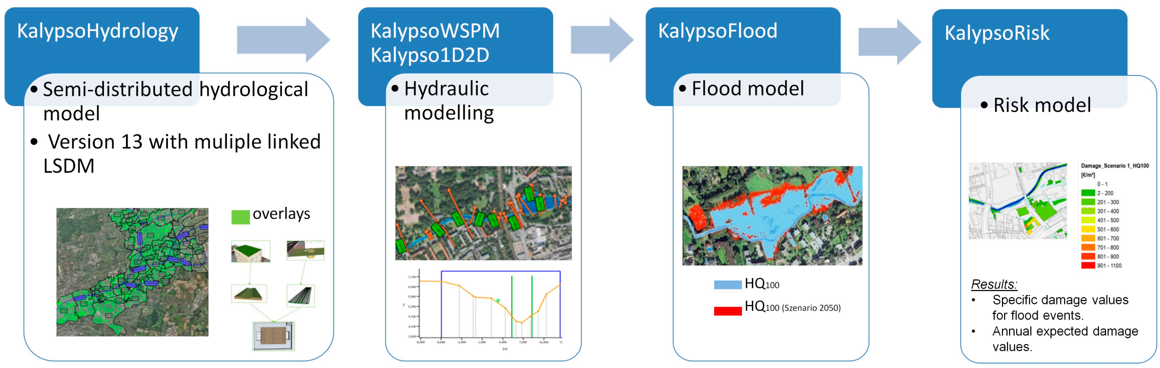

Figure S1. Kalypso modules for water management and flood risk modelling [3].

The Kalypso applications include modelling systems in the areas of rainfall-runoff modelling (KalypsoHydrology), hydraulic modelling (Kalypso1D/2D), eco-morphological modelling, flood forecasting, flood inundation modelling (KalypsoFlood), flood risk assessment (KalypsoRisk) and the evacuation modelling of flooded areas (KalypsoEvacuation). The modules are provided with a strong functionality on spatial geographical information system (GIS) analysis, time series management and data processing features. These are important functionalities in recent data management practice and software application.

2. Data Management in the User Interface

Since KalypsoHydrology Version 13 the user is supported to build up a model via workflow. Multiple layer elements like LSDM are defined in profile tables and layer setup definitions. A modular setup of multiple layer elements is enabled. Some predefined standard setups illustrate the usability as shown in the Figures S2 and S3.

The following parameters are defined per overlay type, whereas optional parameters are marked with (*):

- Hydrological soil parameters (e.g., Figure S2):
  - Wilting point (mm)
  - Field capacity (mm)
  - Maximum pore volume (mm)
  - Hydraulic conductivity (mm/d)
  - Initial soil moisture (mm) *
    (Alternatively the initial soil moisture may be calculated from continuous long-term simulations)
- Drainage parameters (e.g., Figure S3):
  - Layer thickness (dm)
  - Pipe diameter of the outlet (mm) *
  - Roughness (mm) *
  - Longest flow path (m) *
  - Gradient of the structure (%) *
  - Overflow crest height (mm) *
  - Index of the coupled soil layer (-) *
  - Area drained per outlet (m^2) *
  - Layer sealing (Yes/No) *

The following parameters are optionally replaced per overlay data object:

- Vegetation type parameters (monthly set parameters) *
  - Crop factor (-)
  - Interception storage (mm)
  - Root depth (mm)
- Landuse type parameters*
  - Sealing rate (%)
  - Maximum groundwater recharge rate (mm)

KalypsoHydrology supports a GIS based data management and basic GIS based functions (e.g., intersection of shape files). An example is illustrated in Figure S4.

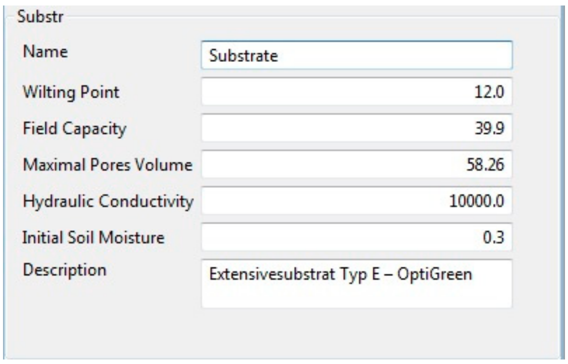

Figure S2. Hydrological soil parameters.

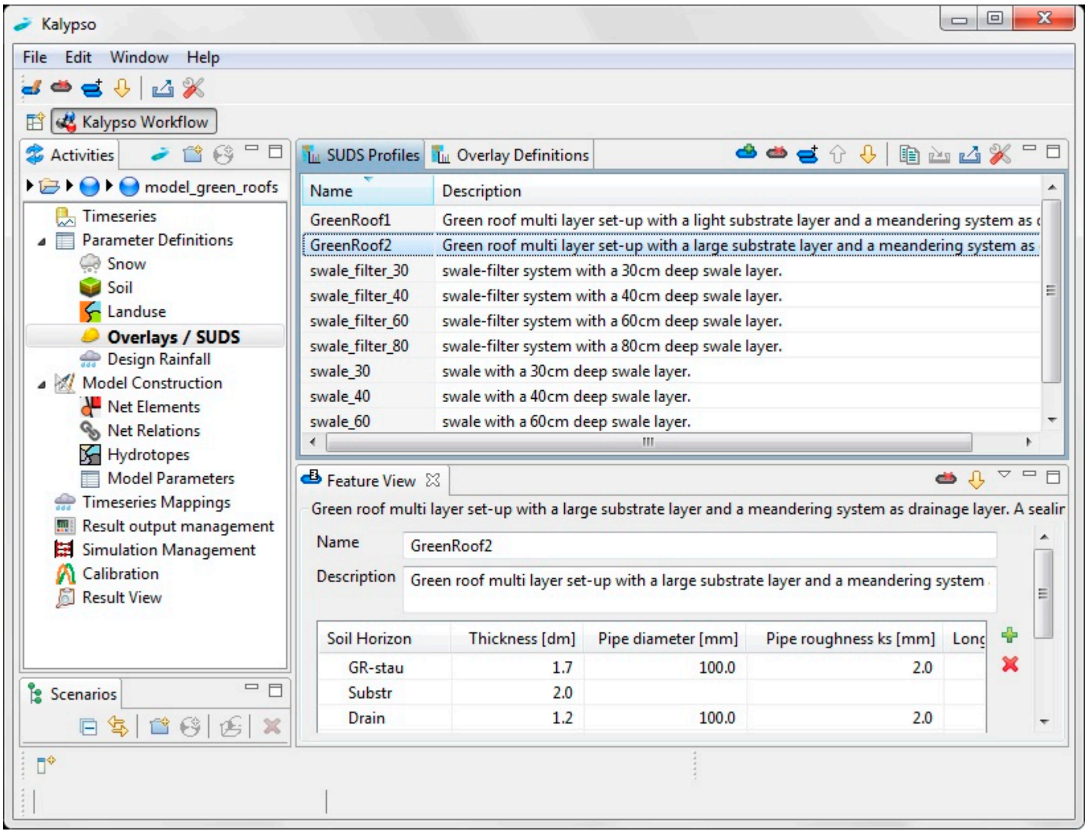

Figure S3. Workflow of KalypsoHydrology and parameter setup for multiple layer elements (e.g., LSDM).

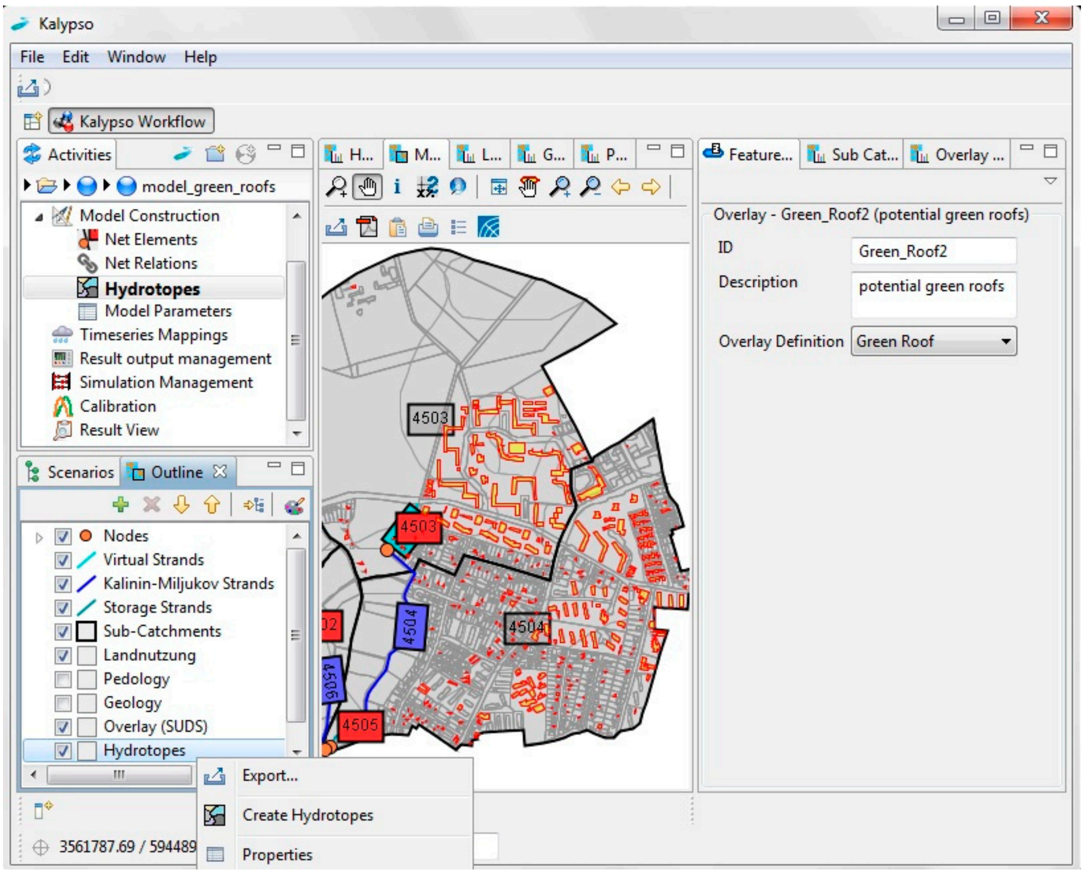

Figure S4. GIS based data management and processing functions (e.g., creation of hydrotops via intersection of shape files).

Different kinds of the same overlay type may be created with tools in KalypsoHydrology or defined in shape files as polygon themes and imported in the model. According to the needs of city planners different designs of the same decentralized measure are to be modelled within one sub-catchment. The implemented functions enable the import of the geographical location and area of diverse LSDM designs of the same type within the same sub-catchment: e.g., extensive green roofs, intensive green roofs, cisterns with rainwater harvesting attributes of detached houses and cisterns with rainwater harvesting attributes of administration buildings. The description of the data input and the data handling is shown in Figure S5.

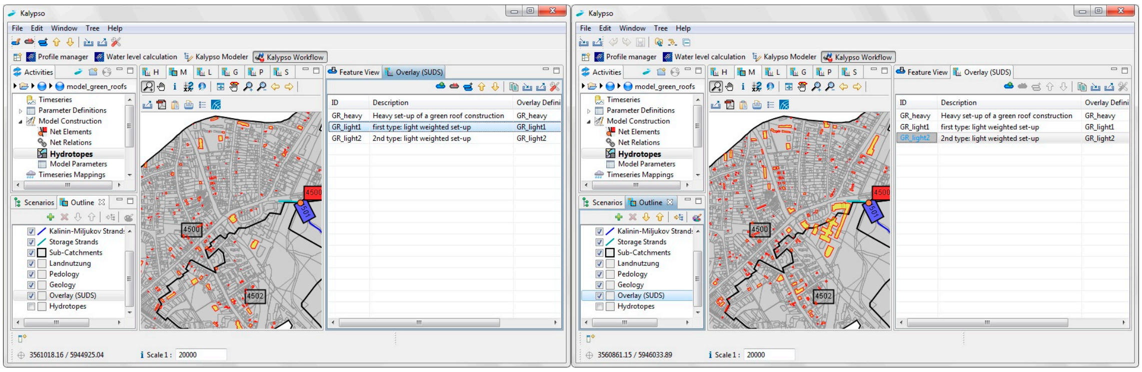

Figure S5. Different overlay data types with similar drainage functionality but different setup can be defined and imported as shape files. Selected different types (e.g., different green roof setups: heavy green roof design, light green roof design 1 and light green roof design 2) are marked in the map by activating the LSDM type in the list.

3. Explicit Network Generation in the User Interface

The network structure is created with algorithms to check any closed loops and creates the respective ASCII files required for the execution of the computation code. The network structure explicitly defines the order of elements in the model. The order is given according to the river strands. Additional virtual nodes and strands are added to the network structure on the fly to fulfil the explicit order. Each strand is defined with one start and one end node. Spatial elements on the meso scale (e.g., sub-catchments) and on the local scale (e.g., LSDM) are defined optionally and linked to strands. The implementation of the methodology in Kalypso Version 13 has been done in cooperation with Björnsen Consulting Engineers [1].

The created network fulfils the following requirements:

- o Strands always have one start and one end node.
- o Sub-catchments always are linked to strands and drain to one defined downstream node.
- o The location of a sub-catchment in the network plan is explicitly defined by the strand.
- o Nodes are water distribution and control elements. Nodes may drain to any element e.g., to strands, catchments or other nodes. Several nodes may drain into one other node.

4. Code Implementation of Multiple Linked Local Scale Elements

The computation code KalypsoNA (version 3.2.0 [4]) has been revised to support the functionality of multiple linked local scale elements. The network in the hydrologic model used to describe the runoff concentration from upstream to downstream sections in a river system consists of sub-catchments, drainage strands and drainage nodes. The explicit computation is done via element-by-element, starting with the upstream hydrological element. The numerical calculation of each element is performed over all time steps before the next element downstream is calculated. In this way, the overall results of all upstream elements are available for any computation procedures of downstream network elements. The computation code has been enhanced to apply derived data types which can consist of data objects of different types. This implementation was required to record intermediate results and attributes of the network elements on the different spatial and temporal scales and to implement the method of interconnections presented in the methodology of the published main article in Section 3.2.

An additional implemented feature is the uptake and redistribution function of water between data object types (here: nodes, overlays, sub-catchments). Spatial elements (e.g., sub-catchments) are defined as "non-linear reservoirs" draining water to receiving rivers. This approach is enhanced by additional water uptake and redistribution functions. If a spatial meso scale or local scale data type object has the attribute to distribute water to another spatial data object, the explicit network generation derives additional connectors to store the water in a so called "redistribution" node of the receiving spatial data object (see Section 2 in the main article). According to the explicit network computation, several elements may distribute the water by a given percentage to any element via redistribution nodes.

5. Code Implementation of Multiple Interlinked Micro Scale Layers

The computation of the hydrological processes in multiple linked layers within local scale data objects (here: overlays) is implemented with the method described in Section 3.3 of the main article. For each spatial data object type on the local scale (e.g., LSDM) the soil moisture balance equations are solved with the presented computation loops in Figure 5 of the main article. The computation results (e.g., surface runoff, interflow, surface runoff, evaporation, etc.) are aggregated per time step and per spatial data object on the meso scale.

6. Application Studies

The RRM KalypsoNA and KalypsoHydrology with the functionality to simulate the hydrologic behaviour of different types of LSDM in a catchment model has been applied and is continuously optimised during recent application projects and case studies. The first application case study was done for a small urban catchment in Garforth, West Yorkshire in England. The focus was set on credible water balance computations of LSDM and first results have been presented in Hellmers et al. [5,6]. The implementation in the computation code has been enhanced in the second case study of the Krückau catchment area (274 km^2) in North Germany to analyse the effectiveness of green roofs, swales and swale-filter-drain systems [7–9]. The outcomes showed promising results to mitigate the flood peak discharges in small urban catchments. The third case study focused on the urban Wandse catchment (88 km^2) in Hamburg, Germany. This case study was analysed in detail within the German Research Project KLIMZUG-NORD. The model was enhanced to support a GIS based import function of overlays and the definition of different LSDM types per sub-catchment [10]. Further on, the module KalypsoHydrology was enhanced with the functionality to drain the exceedance water from one element to another. The module was applied within the overall Kalypso applications for flood risk management: KalypsoHydrology, KalypsoWSPM, KalypsoFlood and KalypsoRisk. The results demonstrate the potential to mitigate the flood risk and related damage costs (in €/a) of specific flood events (see [3]). In the project KLEE (2013–2016) ("Adaption to climate change in the Este catchment") a detailed integrated approach for the Este River was developed, which covers the complete catchment and aims to mitigate projected effects from climate change impacts. Here, the effectiveness of LSDM is analysed on a regional scale approach for the overall catchment (365 km^2). The results of this project pointed out that the effectiveness of LSDM to mitigate flood peak discharges depends highly on the catchment characteristics [11].

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