swmmr - an R package to interface SWMM

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ABSTRACT
The stormwater management model SWMM of the US EPA is widely used toanalyse, design or optimise urban drainage systems. To perform advanced analysis and visualisations of model data this technical note introduces the R package swmmr. It contains functions to read and write SWMM files, initiate simulations from the R console and to convert SWMM model files to and from GIS data. Additionally, model data can be transformed to produce high quality visualisations. In accordance with SWMM’s open source policy the package can be obtained through github.com or the Comprehensive R Archive Network (CRAN).

1. Introduction
Modelling urban drainage systems has become essential to develop and assess resilient urban stormwater management strategies. Analysing the impact of different climatic or demographic scenarios on urban water infrastructure or optimising urban drainage networks are only some of the applications. Various software products are available to model urban drainage systems. Amongst others, the stormwater management model SWMM (Rossman 2010) is widely used by researchers and practitioners to simulate dynamic hydrology-hydraulic water quality processes. Its source code is released under public domain specification and online available from the US EPA.1 Besides the availability of the open source engine of SWMM, a pre-compiled software for Microsoft Windows operating systems is available. The software also provides a graphical user interface (GUI) to design drainage networks and to assign attributes to elements of the system. While the open source software facilitates basic analysis and visualisation of model data, advanced features such as time series data management, parameter uncertainty analysis or extended statistics are reserved to commercialised versions of SWMM, only.

In this respect, the free software environment for statistical computing and graphics R (R Core Team 2017) is frequently used by both scientists and engineers. It provides a huge variety of add-on packages which also cover issues related to hydrology in general and urban water modelling more specifically. For example, hydrology specific packages support process-based modelling (e.g. reservoir – Turner and Galelli (2016)), spatial data processing (e.g. Watersheds – Torres-Matalana (2016)), model performance analysis (e.g. hydroGOF – Zambrano-Bigiarini (2017)), or data exploration (e.g. wq – Jassby, Cloem, and Stachulek (2017)). Moreover, packages epanet2toolkit (Arandia and Eck 2018) and epanetReader (Eck 2016) interface R with EPANET2 (Rossmann 2010), a widely used water distribution systems model. A more comprehensive list is given in the CRAN Task View ‘Hydrological Data and Modeling’.

Further packages – not explicitly related to (urban) hydrology – provide functions to perform model parameter optimisation (e.g. Déoptim – Ardia et al. (2016)), visualise data (e.g. dygraphs – Vanderkam et al. (2017); ggplot2 – Wickham (2016)), or manage time series data (e.g. xts – Ryan and Ulrich (2017)). Additionally, with the development of the packages sp (Pebesma and Bivand 2005) and sf (simple features) (Pebesma 2018), R’s spatial data processing capabilities have been significantly advanced. Consequently, as modelling in general involves both pre- and post-processing of different types of data such as spatial or time series data, the availability of these packages enables an efficient model data management and allows various modelling tasks of diverging complexity to be addressed.

To bridge the gap between urban drainage modelling and advanced model analytics, we herein introduce the freely available R package swmmr which provides functions to interface SWMM. Core functions of the package comprise fast reading and writing of SWMM files, conversion between GIS data and the SWMM input file format as well as model data transformation to produce expressive visualisation. This technical note describes design principles of the swmmr package and exemplifies its usage. This includes a demonstration of how to produce high quality figures of model results and model structures enabled by further R packages.

2. What is the package useful for?
The main purpose of the swmmr package is to assist the modeller during the modelling process. Typically, this includes processing and visualisation of measurement and spatial data, which the R ecosystem provides matured packages for. However, its capabilities of interactively creating and modifying spatial data are limited and should not yet be compared to
a specialised GIS software, though remarkable progress can be observed (mapview – Appelhans et al. (2018); mapedit – Appelhans and Russell (2017)). Thus, the package is especially useful to modellers who use R for model data management and/or need to perform advanced analysis, visualisation or optimisation tasks of a given model or model results, respectively.

### 3. Package design and core functions

At its core, the package relies on the tidy data concept (Wickham 2014) which is expressed through a set of harmonised packages sharing common data representation principles (‘tidyverse’ – Wickham (2017)). Although most tasks could have been addressed with base R, packages from the ‘tidyverse’ tend to simplify both the programming and the data analysis. For example, `swmmr` uses tibbles (Müller and Wickham 2017) instead of R’s built-in data.frame to represent SWMM sections because tibbles have a convenient print method which only shows the first 10 rows of data, and all the columns that fit on screen (Wickham and Grolemund 2016). This becomes especially useful when dealing with large SWMM data using functions such as `read_inp()`, `read_rpt()` and `read_lid_rpt()` (Table 1) as the console output remains readable in case large data have been printed. Generally, these functions take the path to a corresponding SWMM file (*.inp or *.rpt) and parse its content to a named list of tibbles or a single tibble, respectively. `read_inp()` creates an object of class `inp`, whose list element names are identical to the names of SWMM input sections available in lower letters (e.g. options, subcatchments, etc). To print a summary or to quickly visualise the model structure of the `inp` object, two generic functions `summary()` and `autoplot()` for `inp` objects are implemented. `read_rpt()` creates a named list of class `rpt` containing summary sections from the report file of SWMM (e.g. subcatchment_runoff_summary). While both of the aforementioned functions maintain the original SWMM file structure, `read_lid_rpt()` interprets text files from specific LID elements. A single `tibble` or index-based time series data as `xts` object is returned accordingly. The latter option is provided because `xts` objects, which are introduced with the `xts` package and build upon R’s built-in matrix data type, efficiently represent time series data and offer index-focused data subsetting methods.

Reading simulation data from the binary `.out` file is supported by `read_out()`. Because `.out` files can become very large, the function design aims for fast data processing and embeds modern C++ code through Rcpp (Eddelbuettel and Francois 2011). Output data per system element and model variable is always represented as an `xts` object and conveniently stored in a list environment.

The function `write_inp()` writes an `inp` object to disk, which addresses cases where an `inp` object has been modified within R and changes need to be saved back to disk (e.g. model parameter calibration). Thus, it takes an existing `inp` object and creates a model file on disk which can be read and run by the original SWMM executable. However, a SWMM simulation run can also be initiated from the R console with `run_swmm()`. It requires the path to an `inp` file to be specified and calls the SWMM executable. The function conveniently returns a 3-element list containing paths to the `inp`, `rpt` and `.out` file.

Moreover, converting SWMM input sections with spatial reference to `sf` objects is supported with `*_to_sf()` functions. Based on the conversion of SWMM input sections to `sf` objects, an `inp` object can be converted to the popular `.shp` format with `inp_to_files()`. Additionally, `.txt` files containing simulation settings, storage and pumping curves are returned as well as files containing SWMM time series data. As a counterpart the function `shp_to_inp()` converts spatial data given in `.shp` files into an object of class `inp`. Information on simulation settings, rainfall time series etc. can be given in `.txt` files to complete the model data. While the conversion to `sf` objects already enables common spatial analysis of SWMM model data in R, this also allows using the plotting interface of `ggplot2` through `geom_sf()`.

| Name               | Inputs                                                  | Description                                                                 | Description                                                                 |
|--------------------|---------------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------|
| model run          |                                                         | Initiate a SWMM run from the R console                                    |                                                                           |
| run_swmm()         |                                                         | Reads a SWMM model as list of tibbles (i.e. inp object)                     |                                                                           |
| reading files      |                                                         | Reads SWMM simulation results (time series) as list of xts objects          |                                                                           |
| read_inp()         | path to .inp file                                       | Reads SWMM simulation results (summary) as list of tibbles                  |                                                                           |
| read_rpt()         | path to .rpt file                                       | Reads a SWMM LID Report File as tibble or xts object                       |                                                                           |
| read_lid_rpt()     | path to LID report file                                 | Writes an inp file to disk which can be read and run by SWMM               |                                                                           |
| writing files      |                                                         | Converts SWMM objects as tibble with simple feature geometries             |                                                                           |
| write_inp()        | inp object (optionally modified) and filename            | (supported objects are junctions, links, orifices, outfalls, pumps,        | Converts an entire inp object as list of tibbles with simple feature      |
| simple feature conversion |                                                         | rainfallages, storages, subcatchments, weirs)                              | geometries                                                                 |
| *_to_sf()          |                                                         |                                                                           |                                                                           |
| inp_to_sf()        | inp object                                              |                                                                           |                                                                           |
| _shp file conversion |                                                         |                                                                           |                                                                           |
| inp_to_files()     | inp object, model name and directory path                |                                                                           |                                                                           |
| shp_to_inp()       |                                                         |                                                                           |                                                                           |
| generic functions  |                                                         |                                                                           |                                                                           |
| summary()          |                                                         |                                                                           |                                                                           |
| autoplot()         |                                                         |                                                                           |                                                                           |
4. Example usage

In this work, the basic usage of the package is demonstrated using the model ‘Example1’ which is included in the SWMM software for Microsoft Windows. The model file is usually located at ‘C:/Users/../Documents/EPA SWMM Projects/Examples/Example1.inp’. Alternatively, it is also attached to the package (cf. Listing 1). In addition, the reader is referred to three package vignettes which cover topics beyond the scope of this technical note. For example, instructions on how to auto-calibrate a SWMM model with `swmmr` or how to convert GIS and SWMM model data with `swmmr` are given.

4.1. Setup and model execution

To install `swmmr` from CRAN and to add its namespace to R’s search list, the following commands need to be executed from the R command line (Listing 1). In this example, the model file attached to the package is used and its path is assigned to the variable `inp_path`. Subsequently, `run_swmm()` initiates a model run.

```r
if (!require("swmmr")) install.packages("swmmr")
library(swmmr)
library(tidyverse)
inp_path <- system.file("extdata", "Example1.inp", package = "swmmr")
swmm_files <- run_swmm(inp = inp_path,
    rpt = tempfile(),
    out = tempfile())
```

Listing 1 Installation and model execution.

4.2. Analysis of model data

SWMM’s model files (.inp, .rpt and .out) can be accessed from the named list variable `swmm_files`. Since the results of both the `read_inp()` and `read_rpt()` function comprises a list of named tibbles (Listings 2 and 3), elements can be accessed via R’s common extracting mechanism.

```r
inp_object <- read_inp(swmm_files$inp)
summary(inp_object)
```

```r
#> 
#> ** summary of swmm model structure **
#> infiltration : horton
#> flow_units   : cfs
#> flow_routing : kinwave
#> start_date   : 01/01/1998
#> end_date     : 01/02/1998
#> raingages    : 1
#> subcatchments: 8
#> aquifers     : 0
#> snowpacks    : 0
#> junctions    : 13
#> outfalls     : 1
#> dividers     : 0
#> storages     : 0
#> conduits     : 13
#> pumps        : 0
#> orifices     : 0
#> weirs        : 0
#> outlets      : 0
#> controls     : 0
#> pollutants   : 2
#> landuses     : 2
#> lid_controls : 0
#> treatment    : 0
#> ********************************************
```

`inp_object$subcatchments`
Listing 2 Reading and analysing model data.

```r
rpt_object <- read_rpt(swmm_files$rpt)
summary(rpt_object)
```

Listing 3 Reading report of model results.

Time index-based model results from an .out file are imported as given in Listing 4. Here, model variables total rainfall (in/hr or mm/hr, vIndex = 1) and total runoff (in flow units, vIndex = 4) from the system (iType = 3) are read. A general dictionary covering the mapping between variable and index number is included in the package documentation.

```r
sim <- read_out(swmm_files$out, iType = 3, vIndex = c(1,4))
sim$system_variable %>%
do.call(merge, .) %>%
summary
```

Listing 4 Reading and statistical analysis of model results.
4.3. Convert between GIS and SWMM model data

`inp_to_files()` utilises the conversion functions `*_to_sf()` for all SWMM sections containing spatial data (Table 1). Sections without spatial information are returned and saved separately. Thus, sub-folders containing `.shp`, `.txt` and `.dat` files are created in a specified directory (Listing 5). Information on supported SWMM sections for both `inp_to_files()` and `shp_to_inp()` is given in the package manual.

```r
out_dir <- tempdir()
inp_to_files(x = inp_object, name = "Example1", path_out = out_dir) c("dat", "shp", "txt") %>%
  map(list.files(file.path(out_dir, .), pattern = .))
#> [[1]]
#> [1] "Example1_timeseries_TS1.dat"
#>
#> [[2]]
#> [1] "Example1_link.shp" "Example1_outfall.shp" "Example1_point.shp"
#> [4] "Example1_polygon.shp"
#>
#> [[3]]
#> [1] "Example1_options.txt"
```

**Listing 5** Converting SWMM model data into shape files.

Column names of the `.shp` file attribute table correlate with the original SWMM encoding or its abbreviation to seven characters. `shp_to_inp()` reads `.shp` and `.txt` files and converts them to an `inp` object (Listing 6). Missing values are completed with default values or can be specified separately. The package vignette provides more information of the conversion details.

```r
converted_inp <- shp_to_inp
  (path_options = file.path(out_dir, "txt/Example1_options.txt"),
   path_line = file.path(out_dir, "shp/Example1_link.shp"),
   path_outfall = file.path(out_dir, "shp/Example1_outfall.shp"),
   path_point = file.path(out_dir, "shp/Example1_point.shp"),
   path_polygon = file.path(out_dir, "shp/Example1_polygon.shp"),
   path_timeseries = file.path(out_dir, "dat/Example1_timeseries_TS1.dat")
})
summary(converted_inp)
```

```r
#>
#> ** summary of swmm model structure **
#> infiltration : horton
#> flow_units : cfs
#> flow_routing : kinwave
#> start_date : 01/01/1998
#> end_date : 01/02/1998
#> raingages : 1
#> subcatchments : 8
#> aquifers : 0
#> snowpacks : 0
#> junctions : 13
#> outfalls : 1
#> dividers : 0
#> storages : 0
#> conduits : 13
#> pumps : 0
#> orifices : 0
#> weirs : 0
#> outlets : 0
#> controls : 0
#> pollutants : 2
#> landuses : 2
#> lid_controls : 0
#> treatment : 0
#> **************************************************
5. Usage with other R packages

5.1. Visualisation with ggplot2 and mapview

Modelling involves visualisation of spatial and temporal data. With base (R Core Team 2017), lattice (Sarkar 2008) and ggplot2 (Wickham 2016), R currently offers three different plotting systems. Because of ggplot2’s flexibility and declarative way of constructing graphics, a demonstration of how to create expressive and customisable figures of model data is given in Listings 7 and 8.

Listing 7 aims to visualise rainfall and simulated runoff data. Temporal data is read from an .out file, initially merged to one single xts object with two columns (’total_rainfall’ and ’total_runoff’) and converted to tibble which can be processed by ggplot2. Both variables are plotted as different geometric objects (geom_col(), geom_line()) and separated into facets. The result is shown in Figure 1.

```r
library(ggplot2)  # ggplot2 ≥ 3.0.0 required
library(broom)    # to convert an xts/zoo object to tibble

sim$system_variable %>%
do.call(merge, .) %>%
tidy(.) %>%
{
  ggplot(mapping = aes(x = index, y = value)) +
  geom_col(data = filter(., series == "total_rainfall")).
  geom_line(data = filter(., series == "total_runoff")).
  scale_x_datetime(date_breaks = "3 hour", date_labels ="
  facet_wrap(
    series, ncol = 1, scales = "free_y", strip.position = "left",
    labeller = as_labeller(c(
      total_rainfall = "total rainfall (in/hr)",
      total_runoff = "total runoff (CFS)"
    )))
  )

  theme_light() +
  theme(
    strip.placement = "outside",
    strip.text = element_text(colour = "black"),
    strip.background = element_rect(fill = "white"),
    panel.grid.major = element_blank(),
    panel.grid.minor = element_blank()
  )

  labs(
    x = "1998–01–01 01:00:00 – 1998–01–02 12:00:00",
    y = "total rainfall (in/hr)"
  )
```

FIGURE 1. Example of ggplot2-based visualisation of simulation results.
Listing 7 Creation of ggplot2-based visualisation of simulation results.

Listing 8 is used to visualise the model structure with subcatchments, links, junctions and raingages. Initially, SWMM objects to be plotted are converted as sf objects. Coordinates for labelling subcatchments and raingages are calculated afterwards. Since ggplot2 provides the geometric object geom_sf(), sf objects are directly passed to ggplot2 and interpreted accordingly. Figure 2 illustrates the result.

# initially, SWMM objects to be plotted are converted as sf objects
# here: subcatchments, links, junctions, raingages
sub_sf <- subcatchments_to_sf(inp_object)
lin_sf <- links_to_sf(inp_object)
jun_sf <- junctions_to_sf(inp_object)
rg_sf <- raingages_to_sf(inp_object)

# calculate coordinates for label position of subcatchments
# here: centroid of subcatchment
coord_subc <- sub_sf %>%
  sf::st_centroid() %>%
  sf::st_coordinates() %>%
  tibble::as_tibble()

# update coordinates to label raingage label
coord_rg <- rg_sf %>%
  sf::st_coordinates(.) + 500
  tibble::as_tibble()

# add coordinates to tibble containing sf geometries
sub_sf <- dplyr::bind_cols(sub_sf, coord_subc)
rg_sf <- dplyr::bind_cols(rg_sf, coord_rg)

# create the plot

Figure 2. Visualisation of SWMM Example1 model structure using the ggplot2 package.
ggplot() +
  # subcatchments and label
  geom_sf(aes(fill = Area), data = sub_sf) +
  geom_label(aes(X, Y, label = Name), sub_sf,
             alpha = 0.5, size = 3) +
  # links
  geom_sf(aes(colour = Geom1), lin_sf, size = 2) +
  # junctions
  geom_sf(aes(size = Elevation), jun_sf, colour = "darkgrey") +
  # rainage and label
  geom_sf(data = rg_sf, shape = 10) +
  geom_label(aes(X, Y, label = Name), rg_sf,
             alpha = 0.5, size = 3) +
  # change scales and theme
  scale_fill_viridis_c() + scale_colour_viridis_c(direction = -1) +
  theme_linedraw() +
  theme(panel.grid.major = element_line(colour = "white"))

Listing 8 Creation of ggplot2-based visualisation of model structure.

Since `sf` objects are supported by the `mapview` package, a SWMM model structure converted to simple feature geometries can also be interactively visualised. Figure 3 shows a screenshot of a browser-based visualisation of the 'Example1' model, obtained by executing Listing 9.

```r
library(mapview)
inp_to_sf(inp_object) %>%
  mapview()

Listing 9 Creation of mapview-based visualisation of model structure.

5.2. Model calibration using DEoptim

Calibration of model parameters is an essential part within the modelling chain to improve the model quality. During calibration, model parameter values are systematically modified to optimise an objective function, which numerically expresses the difference between observed and simulated data.

Because `swmmr` provides the functions `write_inp()` to save an `inp` object to disk and `run_swmm()` to potentially run the written model file afterwards, it especially facilitates autocalibration of model parameters. `swmmr`, however, does not depend on
particular optimisation packages. The package vignette ‘How to autocalibrate a SWMM model with swmmr’ exemplifies the application of the DEoptim package (Ardia et al. 2016) for single objective optimisation.

6. Conclusions

A brief introduction of the R package swmmr is given. swmmr interfaces the stormwater management model SWMM with R and bridges the gap between modelling and advanced model analytics. It offers functions to represent SWMM models in R which subsequently can be modified or visualised with modern technologies. Simulation results are efficiently read with help of Rcpp to streamline further time series analysis. This facilitates efficient model calibration and parameter uncertainty analysis. The package is freely available and is especially open to both the SWMM and R community. The authors would like to promote the open source project and welcome any contribution to the package through the project page on GitHub.

Notes

1. https://www.epa.gov/water-research/storm-water-management-model-swmm.
2. https://www.epa.gov/water-research/epanet.
3. https://cran.r-project.org/view=Hydrology.
4. ‘Base R’ refers to a set of default packages which R is actually based upon without any additional packages loaded.
5. Note that ggplot2 ≥ 3.0.0 is required.

Acknowledgements

This package has been mainly developed in the course of the project STBMOD funded by the German Federal Ministry of Education and Research (BMBF, FKZ 03FH033PK2). Its development was inspired by the work of Peter Steinberg and significantly benefits from the Interface Guide of SWMM (Rossman 2010). In the course of the review of this paper, swmmr evolved from version 0.8.1 to 0.9.0. The latter version also contains contributions by the user community, from which we especially would like to thank Malte Henrichs and Hauke Sonnenberg.

Disclosure statement

No potential conflict of interest was reported by the authors.

Highlights

- An R package to read and write SWMM files is introduced
- SWMM’s .out files are read with high performance
- Functions to convert between GIS and SWMM files are provided
- Modern plotting systems are supported to visualise model data

Software availability

swmmr is available on the Comprehensive R Archive Network (CRAN) at https://cran.r-project.org/package=swmmr and GitHub at https://github.com/dleutnant/swmmr
License: GPL-3
System requirements: R (≥3.0.0)
Installation: install.packages('swmmr') or remotes:install_github('dleutnant/swmmr')

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