Urban ecosystems and heavy rainfall – A Flood Regulating Ecosystem Service modelling approach for extreme events on the local scale

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Abstract

Increasing urbanisation in combination with a rise in the frequency and intensity of heavy rain events increase the risk of urban flooding. Flood Regulating Ecosystem Services (FRES) address the capacity of ecosystems to reduce the flood hazard and lower damage. FRES can be estimated by quantification of supply (provision of a service by an ecosystem) and demand (need for specific ES by society). However, FRES for pluvial floods in cities have rarely been studied and there is a gap in research and methods on FRES supply and demand quantification.

In this study, we assessed FRES of an urban district in the City of Rostock (Germany) for a one-hour heavy rainfall event using the hydrological model LEAFlood. The hydrological model delivered the FRES supply indicators of soil water retention and water retained by canopies (interception). An intersection of the potential demand (based on indicators of population density, land reference value, monuments and infrastructure) and the modelled surface water depth revealed the actual demand. Comparing the actual demand and supply indicated the budget of FRES to identify unmet demand and supply surplus.

Results show highest mean FRES supply on greened areas of forests, woodlands and green areas, resulting in a supply surplus. Whereas, sealed areas (paved surface where water cannot infiltrate into the soil), such as settlements, urban dense areas, traffic areas and industry, have an unmet demand resulting from low supply and relatively high actual demand.

With the hydrological model LEAFlood, single landscape elements on the urban scale can be evaluated regarding their FRES and interception can be considered. Both are important for FRES assessment in urban areas. In contrast to flood risk maps, the study of

FRES gives the opportunity to take into account the contribution of nature to flood regulation benefits for the socio-economic system. The visualisation of FRES supply and demand balance helps urban planners to identify hotspots and reduce potential impacts of urban pluvial flooding with ecosystem-based adaptations.

Keywords

supply and demand, unmet demand, mismatch, hydrological modelling, LEAFlood

Introduction

The sixth report of working group I of the Intergovernmental Panel on Climate Change (IPCC) (Arias et al. 2021) highlighted the past and future development of extreme weather events. This includes heavy precipitation events, which are projected to become more frequent and intense in the future. Urban areas in particular are vulnerable to these events because of the high degree of sealing, the presence of critical infrastructure and high population densities. Besides technical solutions, ecosystems and their structures, processes, resulting functions and services play an important role in urban flood regulation. The concept of Ecosystem Services (ES) can be used to quantify and map the links of the social and environmental systems to estimate benefits that people obtain from ecosystems (Millennium Ecosystem Assessment 2005). ES are the direct and indirect contributions of ecosystems to human well-being (TEEB 2010). Thereby, flood regulating ecosystem services (FRES) address the capacity to lower flood hazards by reducing water run-off (Stürck et al. 2014), reduce economic and social damage (Vallecillo et al. 2019) and protect property, houses, infrastructure and human life (Nedkov and Burkhard 2012). Relevant ecosystem processes, such as interception by vegetation, water storage in surface water bodies, infiltration in soil and percolation to the groundwater, contribute to flood regulation by storing water, distributing the run-off in time and reducing the peak discharge (Albert et al. 2015, Burkhard and Maes 2017).

To assess ES, the matrix method is a widly known and simple method that classifies ES, based on land-use classes from 0 to 5 (Burkhard et al. 2009, Burkhard et al. 2014, Goldenberg et al. 2017). Other, more quantitative, forward approaches are based on a purely spatial evaluation of data on land use, topography and soil to estimate FRES (Liyun et al. 2018, Vallecillo et al. 2020).

Additionally, the indicator framework developed by the German working group of "Mapping and Assessment of Ecosystem an their Servies" (MAES), in the context of the EU Biodiversity Strategy to 2020, included a FRES supply indicator to quantify water storage capacity, based on the area of floodplains (Albert et al. 2015).

Although a more comprehensive picture is given by quantitative models, which are increasingly being used in ES research (Syrbe and Walz 2012), the number of such studies is still comparatively small (Campagne et al. 2020). Quantitative modelling of ES helps to estimate supply and demand, to fill spatial and temporal data gaps and supports the extrapolation of measurements and observations. For regulating ES, such as FRES, modelling is often the best option to quantify the actual supply and demand of ES (Burkhard and Maes 2017). InVEST, for instance, is a dedicated model toolbox for the estimation of ES with the "Urban Flood Risk Mitigation model" (Natural Capital Project 2020), which is simple to use for FRES assessment (Gaglio et al. 2019).

The use of hydrological models, instead, is more complex, but more accurate in its depiction of reality. Depending on the research question, different hydrological models can be used (Nedkov and Burkhard 2012, Logsdon and Chaubey 2013, Stürck et al. 2014, Lüke and Hack 2018, Wübbelmann et al. 2021). The study by Nedkov and Burkhard (2012) is one of the first that exclusively focuses on FRES for river catchments using a combination of hydrological modelling and the matrix method (Burkhard et al. 2009) by classifying the results per land use and soil classes from 0 to 5.

The MAES-Indicators, as well as many methods based on models that determined FRES, focus on fluvial floods and on gauged catchment areas (Nedkov and Burkhard 2012, Boyanova et al. 2014, Stürck et al. 2014, Li et al. 2019). Although urban areas, in particular, are vulnerable to pluvial flood events caused by heavy precipitation and the prediction of FRES on the city scale is important for adaptation planning, pluvial FRES have so far been little investigated in urban areas (Shen et al. 2019, Wang et al. 2019). It is important to highlight that pluvial flooding – as addressed here – differs significantly from riverine flooding regarding the following aspects: (i) pluvial flooding can occur everywhere, even far away from rivers, (ii) its occurrence is local, mainly caused by convective events that can cause a very high hydrological response in terms of run-off (also referred to as flash flood). In this respect, the MAES-indicator and other indicators derived by land-use or catchment hydrological modelling with focus on fluvial flooding and floodplains have limited suitability for use in heterogenic urban areas (Kremer et al. 2016) and, in addition, disregard some crucial parameters (Wübbelmann et al. 2021), such as interception, infiltration, surface roughness and slope (Burkhard and Maes 2017). For pluvial FRES assessment in urban areas, other indicators and methods should be used, which consider the spatial heteorgenity and important hydrological retention processes, such as the interception or infiltration capacity.

Flood regulating supply only has a societal value and turns into an ES if there is an according demand (Stürck et al. 2015). However, most studies focus on the supply side and there is a gap in research on ES demand (Campagne et al. 2020). Furthermore, qualitative differences exist for ES demand assessments, since they are mainly assessed by comparably simple statistical or literature data and the multidisciplinary complexity of the demand has rarely been mapped (Dworczyk and Burkhard 2021). For a simple estimation, the matrix approach can be chosen, based on land-use/land-cover data with urban areas, settlements or traffic areas classified as ES demand areas (Burkhard et al. 2009, Syrbe and Walz 2012). Vallecillo et al. (2019) presented a more quantitative approach using the area as the unit for defined demand land-use classes. This can be extended to a more comprehensive assessment using demographic, topographic, economic and statistical data (Nedkov and Burkhard 2012, Dworczyk and Burkhard 2021

). Others define the demand for FRES by the flood risk as the function of hazard, exposure and vulnerability, while the flood hazard is defined by the extent and depth of inundation (Stürck et al. 2014, Shen et al. 2019). Dworczyk and Burkhard (2021) recommend to consider different methods and user groups to increase the knowledge and diversity of ES demand. For instance, the flood risk management plan of the European Union suggested different protection goods, such as the number of inhabitants or economy activities (European Parliament 2007).

After evaluating FRES supply and demand, a budget analysis can be applied to identify mismatches of ES supply and demand to discover unmet demand besides the benefiting areas with a supply surplus (Syrbe and Walz 2012, Lorilla et al. 2019, Dworczyk and Burkhard 2021).

Therefore, the main aim of this paper is to fill the research gap of a comprehensive FRES assessment of natural supply and demand and their mismatches at the urban scale with a focus on heavy precipitation events. Accordingly, we applied the methodological approach to an exemplary area and heavy precipitation event. We tested indicators of soil water storage and interception for FRES supply using the hydrological Model LEAFlood that is based on the Catchment Modelling Framework (CMF). After we identified FRES supply areas, we carried out a comprehensive FRES demand analysis that takes into account different demand types. Finally, we conducted an analysis at the urban scale to uncover the unmet demand.

We, therefore, address the following research questions:

- Which (eco)system elements and structures have high natural FRES supply in urban areas?
- Which areas have a high FRES demand and how can we identify the level of unmet demand?
- What are the strengths and weaknesses of the LEAFlood model for the assessment of FRES in urban areas for heavy rainfall events?

Material and Methods

The basis for the following analysis was the hydrological model LEAFlood. The model was designed by Wübbelmann and Förster (2022) for scales well below the catchment scale, which allows for resolving features of urban districts (such as parks, buildings, streets) in a distributed way, in order to predict urban flooding at the neighbourhood scale, scaled up to a few square kilometres. It considers vertical hydrological processes, incorporating rainfall interception by tree canopies, infiltration and surface run-off either from rainfall intensities that exceed the infiltration rates or soil saturation excess, respectively. The spatial resolution is flexible in order to represent spatial elements - such as landscape elements - of arbitrary size. Lateral connectivity of landscape elements is accomplished through a simplified representation of 2D hydrodynamics for surface run-off, which meets the objectives of the small-scale FRES analysis of pluvial flooding in urban areas.

In the following, the results of the model and other spatial data used in the FRES analysis were analysed with ArcGIS Pro 2.8 from ESRI and Python 3.7. For the FRES analysis, we partly followed the approaches of existing studies (Nedkov and Burkhard 2012, Biota 2014) and adapted these to our research question related to the analysis of unmet demand (Dworczyk and Burkhard 2021). A district in the City of Rostock, Germany served as the test area for the approach.

Study Area

The study area covers partially the city districts Hansaviertel, Reutershagen and Köpeliner-Tor-Vorstadt in Rostock (northeast Germany) at the estuary of the River Warnow at the Baltic Sea (Fig. 1). The city and its surroundings cover an area of 181.5 km². The elevation ranges from 0 m to a maximum height of 54.64 m a.s.l. (Landesamt Mecklenburg-Vorpommern n.Y.).

Due to its proximity to the Baltic Sea, the climate in Rostock is mild-maritime. The annual mean temperature is 9.2°C (1981-2010). The annual precipitation sum is 730 mm with a maximum monthly precipitation of around 70 mm in July (DWD Climate Data Center 2022). Several heavy precipitation events occurred in the past (Fig. 2). Especially, the summer of 2011 was very wet and floods occurred more frequently (Miegel et al. 2014) .

The study area with a size of 4.5 km² is located in the southwest of Rostock (Fig. 1). This area was chosen because of the variety of different land uses. Approx. 50% of the area comprises green areas (parks, forests and woodland), 23% consists of traffic areas and 25% contains sealed areas (settlements, urban dense areas and industry) (Steinbeis-Transferzentrum Geoinformatik 2017). The soil types in the study area are mainly luvisol-pseudogley and regosol. The texture of the substrate is sandy loam and loamy sand with wet characteristics (Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz 2019a, Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz 2019b).

Data

The hydrological model requires an appropriate dataset of meteorological, land use, soil and elevation information. The main meteorological input dataset is precipitation. We used the data of the DWD climate station Rostock-Warnemünde at one minute resolution (DWD Climate Data Center 2021a). The selected event (6.8.2011 13:40 – 14:40 h) covers a rain duration of one hour, with a total amount of 21.74 mm and a maximum intensity of 2.93 mm/min (see small figure in Figure 1).

Other required meteorological data that are used if (canopy) evaporation is activated, are the minimum and maximum temperature (DWD Climate Data Center 2019a), wind speed (DWD Climate Data Center 2019b), solar radiation (DWD Climate Data Center 2021b) and relative humidity (DWD Climate Data Center 2019c). These data are only provided in 10 minute resolution. To resample these data to the one minute interval, we keep the 10 minute value constantly for all one minute values of the intervals.

Spatial data of the land use includes soil-sealing information (Steinbeis-Transferzentrum Geoinformatik 2017) and, in addition, a point shapefile of the tree locations with information on the tree diameter and tree type was available (Hanse- und Universitätsstadt Rostock - Amt für Stadtgrün Naturschutz und Friedhofswesen 2017). Spatial data on soil type (Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz 2019a) were used to set up the geometry. A digital elevation model was provided by the State of Mecklenburg-Vorpommern at one metre resolution (Landesamt Mecklenburg-Vorpommern n.Y.).

The FRES demand analysis also required a set of spatial data. In addition to the land-use data, which was used to identify the traffic infrastructure (Steinbeis-Transferzentrum Geoinformatik 2017), a map with land reference values (the average economic value for a majority of areas of mainly the same use and value characteristics (Lenzen 2014)) (Hanse- und Universitätsstadt Rostock – Kataster- Vermessungs- und Liegenschaftsamt 2021) and a map with the location of monuments (Hanse- und Universitätsstadt Rostock – Amt für Kultur Denkmalpflege und Museen 2017) were integrated. In addition, a collection of spatial data on critical infrastructure including hospitals (Hanse- und Universitätsstadt Rostock – Kataster- Vermessungs- und Liegenschaftsamt 2017), fire stations (Hanse- und Universitätsstadt Rostock – Brandschutz- und Rettungsamt 2017), schools (Hanse- und Universitätsstadt Rostock – Schulverwaltungsamt 2017), care facilities (Hanse- und Universitätsstadt Rostock – Amt für Jugend Soziales und Asyl 2017b) and institutions for the disabled (Hanse- und Universitätsstadt Rostock – Amt für Jugend Soziales und Asyl 2017a) were used in the analysis.

Hydrological Model LEAFlood

For the hydrological modelling, we used LEAFlood (Landscape vEgetAtion and Flood model) (Wübbelmann and Förster 2022), which is based on the Catchment Modelling Framework (CMF) (Kraft et al. 2011). CMF is an open source programming library for hydrological modelling. The modular structure of this Python package provides high flexibility and is adaptable to different research questions. Hydrological processes can be selected from a range of different approaches depending on the question, as demonstrated by Förster et al. (2021) for physically based hydrological modelling of green roofs.

LEAFlood adopts CMF features to create the geometry, based on polygon cells out of GIS shapefiles on the spatial resolution that is required for adequate hydrological modelling on the city scale. Most models designed for urban areas focus on urban drainage with a simplified representation of vegetation (Iffland et al. 2021). LEAFlood considers hydrological processes of canopy interception, through-fall, canopy evaporation, soil infiltration and surface run-off (see Fig. 3). It accounts for a detailed representation of interception and a lateral surface run-off simulation through a 2D kinematic wave approximation. The model was described and tested in detail by Camarena et al. (2022). They compared measured run-off data with LEAFlood model results and verified the good representation of both interception by tree canopies and run-off at the quarter scale. In the present study, neither run-off nor interception measurements were available for Rostock, but model comparison and on-site inspections confirm the plausibility of computed spatial inundation patterns. In general, models should be calibrated for new sites, whenever possible. Even though some parameters are site-specific, the results demonstrated by Camarena et al. (2022) highlight that the model is capable of representing pluvial flooding for landscape elements, which is why we chose the model.

The geometry for our study was created on the basis of an irregular polygon shapefile consisting of 4750 cells with an average size of approximately 1000 m², in order to best possibly resolve relevant urban landscape elements on the one hand side and numerical stability on the other. The canopy closure, which defines the amount of through-fall and canopy interception, was given by the quotient of the projected canopy area and cell area. Each tree was assigned a Leaf Area Index (LAI) value and an interception capacity, based on its species-specific attributes using the datasets of Breuer et al. (2003) and Iio and Ito (2014). After that, for each cell, a mean LAI and interception capacity was calculated from all trees included in that cell. For missing values, a mean of all existing values was used. Since literature values of interception capacity, like those compiled by Breuer et al. (2003), cover a broad range of precipitation events in terms of precipitation total and event duration, they do not necessarily represent the maximum retention governed by interception during heavy rainfall events, as demonstrated by Asadian and Weiler (2009) and Alves et al. (2018). Therefore, supported by the validated modelling experiments conducted by Camarena et al. (2022), a scaling factor of 5 was applied to the literature values to compensate the mismatch in temporal scale and to acknowledge the higher possible interception load of trees during heavy rainfall events.

LEAFlood uses a one soil layer approach, assuming that only the upper layer is relevant for infiltration and that percolation does not play a role due to the time delay. The used infiltration approach is Green-Ampt, which is an approximate theory adaptation of the Darcy equation (Rawls et al. 1993). Except for saturated conductivity (Ksat), all other parameters were the same throughout the study area (Table 1). The base value for Ksat was 0.3 m/d resulting from the soil property sandy loam (Sponagel et al. 2005). Depending on the degree of soil sealing, Ksat was reduced by the following function: $K_{sat,reduced} = (1 - \frac{sealing}{100}) * K_{sat}$

A higher degree of sealing, therefore, resulted in a lower Ksat value (Table 2). The porosity of sandy loams, given in literature (0.45) (Sponagel et al. 2005), was lowered to 0.3 due to urban compaction and resulting reduced infiltration rates (Gregory et al. 2006). The Manning roughness coefficient was assigned for each land-use class (Table 2).

Flood Regulating Ecosystem Services (FRES) analysis

The FRES analysis was undertaken with Python and ArcGIS Pro using an intersection of spatial information of population, economy, land use and hydrological model results. Fig. 4 gives an overview of the workflow and Table 3 shows the definitions of the used FRES terms and the used indicators. The potential demand was determined by a GIS analysis of various economic and social indicators. The output of LEAFlood was the water storage on the surface, the soil water and the intercepted canopy water. While the last two variables were used as indicators for the supply of FRES, the surface water, together with an intersection of the potential demand, indicated the actual demand. Finally, the FRES supply and demand budget was calculated by the difference of the supply and actual demand.

FRES supply

The FRES supply indicators were the soil water depth and the intercepted water depth on the canopies. They were defined by the difference of the maximum over the time and the initial water column at the first time step. The values were derived from the output of the hydrological model. The total supply resulted from the sum of both indicators (Fig. 4).

The supply and its indicators were individually classified into a relative scale from 0 to 1 by dividing the water depth of the cell by the maximum of all cells. Thereby, 0 to 0.2 indicates a very low supply, 0.2 to 0.4 a low supply, 0.4 to 0.6 a medium supply, 0.6 to 0.8 a high supply and 0.8 to 1.0 a very high supply with the 1.0 as maximum supply, according to the suggested 0 to 5 classification by Burkhard et al. (2009).

FRES demand

For the demand analysis, we used the proposed indicators of the INTEK project in Rostock (Biota 2014). This approach was based on the vulnerability for different protected assets, which we transferred to ES. Protected assets can be referred to as potential demand and the intersection with the flood hazard, as actual demand.

Five different indicators were selected, covering different potential demand types of population density [people/100 m²], cultural heritage [-], economy by the land-reference value [€] and the infrastructure sectors [-] (see Table 4); (Biota 2014). Additionally, we added an indicator for critical infrastructure elements that includes, for instance, the presence of hospitals, fire stations and social institutions. The associated point shapefiles of these were buffered by a 100 m radius around the institutions. All indicators were classified into a relative scale from 0 to 1.0 (see Table 4). For the indicators with units (population density and land reference value), the cell value was divided by the maximum of all polygons. The indicators of cultural heritage and infrastructure were dimensionless as they depict the occurrence of the elements and are referred to as an entire polygon. The occurrence of cultural heritage and critical infrastrucutre were indicated with 1.0, station, main streets and railway tracks with 0.6, streets with 0.4 and ways with 0.2. A very low potential demand ranges from 0 to 0.2 and a very high potential demand from 0.8 to 1.0. For the total potential demand, all indicators were intersected and the maximum for each polygon was taken out of all potential demand indicators in order to present the most vulnerable variable.

The actual demand is understood to be the area that has a potential demand or need for flood protection (for instance, by population or economy) and that was actually flooded by the observed event, according to our hydrological simulation. This means that, if an area is flooded and has a potential demand, this turns into an actual demand. Accordingly, this indicator resulted from the intersection of potential demand and flood hazard (Fig. 4). The surface water depth, an output of the LEAFlood model, defined the flood hazard. Equally, for the supply indicators, the difference of the maximum water depth over the time and initial surface water at the beginning of the event was scaled from 0 to 1.0. Due to some single values with very high water depth in terrain depressions, the 90% quantile (31.4 mm) was chosen here instead of the maximum. This means that everything above the 90% quantile was indexed with 1. The product of the flood hazard and the potential demand yielded the magnitude of the actual demand (Biota 2014). Again, 0 to 0.2 indicates a very low actual demand, 0.2 to 0.4 a low actual demnad, 0.4 to 0.6 a medium actual demand, 0.6 to 0.8 a high actual demand and 0.8 to 1.0 a very high actual demand with the 1.0 as maximum actual demand.

FRES budget

In order to quantify, map and visualise the mismatches between actual demand and supply, a FRES budget map was created. The budget resulted from the spatial overlay and difference of the total supply and the actual demand of FRES (see Fig. 4) (Nedkov and Burkhard 2012). The scale ranged from -1.0 to 1.0, where 1.0 indicated a very high supply surplus, 0 showed a balance and -1.0 indicated a high unmet demand that was not covered by the supply. For instance, a polygon of high supply (0.8) and a low actual demand (0.2) has a supply surplus since the supply exceeds the actual demand. If supply and actual demand had the same score, they were in balance (0).

Results

The main results are analysis and maps for all three FRES-components – supply, demand and budget. The supply map includes the two indicators of soil water and interception, as well as the total supply (see chapter FRES supply). The demand map shows the potential and actual demand, as well as the flood hazard (see chapter FRES demand). The mismatch of supply and actual demand is displayed in the budget map and is analysed in the following chapter 'FRES budget'. It indicates the unmet demand and benefitting/ supply surplus areas. In addition, the table in the Suppl. material 2 lists the relative scale values for all FRES parameters for each land use.

The mean stored water depth of soils was highest on forest, woodlands and green areas land uses with 2.5 mm (see Suppl. material 1), while the sealed areas did not store water by soil due to the low saturated conductivity. Whereas, the interception by canopies had higher water columns for the sealed areas with an average of ~ 1 to 2 mm for settlements, traffic areas and urban dense areas. Additionally, green areas, such as parks, only had a mean water depth of 1.3 mm on canopies and woodlands stored 2 mm. As expected, forests had the highest mean water depth by interception of 6.2 mm. In general, this resulted in a total mean supply (soil + interception) of 3.2 mm in the study area. Greened spaces had higher supply water depth with ~ 9 mm on forest areas, ~ 4 mm over green areas and 5 mm on woodlands. The sealed areas had a low total water depth of soil and interception with 0.3 mm (industry) to 2 mm (traffic areas).

Over the entire study area, the surface water depth was higher than the supply by interception and soil. The surface flooding reached from ~ 16 mm on settlements, forests and urban dense areas and up to 90 mm on terrain depressions of water land-uses. Traffic areas were flooded with an average water depth of 30 mm.

FRES supply

The indicators for the FRES supply were the water depth of interception and soil. Each indicator and the total supply, which resulted from the sum of interception and soil water depth, were converted into relative scales from 0 to 1, respectively. The maximum interception depth was 7 mm, soil water depth was 3 mm and the total supply in one cell reached a maximum of 10 mm. Fig. 5 displays the indicators and the total supply in maps and a chart diagram of the area weighted mean supply of the indicators and the total supply for each land use.

In general, green areas, such as forests, parks and woodlands, had the highest supply. A very high supply was provided by forests with ~ 0.9. Both the supply through interception and through the soil were very high. The supply on green areas and woodland were mainly provided by soil (very high), while the supply by interception on this areas was low (0.2 to 0.3).

Traffic areas had a low supply, which resulted from a low supply by interception (0.3), while the supply by soil was very low. The other sealed areas had a very low supply, which was also due to the very low supply by interception (0.15).

Over the entire area, the interception supply was low (~ 0.3), the soil supply medium (~ 0.5) and the total supply low (~ 0.3) on a relative scale. However, the results also showed, if a canopy were present, the absolute amount of interception storage was higher than the soil storage.

FRES demand

The demand components of potential demand, flood hazard and actual demand are displayed in Fig. 6. While the maps show the spatial distribution of the relative scaled demand, the bar chart shows the area weighted mean demand over the entire study area grouped by land uses. The individual indicators for the FRES potential demand are mapped in the Suppl. material 3.

The potential demand (Fig. 6a), based on the indicators of population, reference land value, monuments and infrastructure, was relatively high (0.6) (see also Suppl. material 3), with maximum values on traffic areas and urban areas (~ 0.75). On green areas and settlements, the potential demand was high and, on industry and woodland, it was medium. Additionally, forest areas in the south were indicated with a high potential demand due to the cultural heritage status of the area.

The flood hazard (Fig. 6b) resulted from the surface water from the LEAFlood model and was converted to a relative scale, based on the 90% Quantile of 31.4 mm, while the maximum reached up to 2047 mm in depressions. Therefore, a very high flood hazard was indicated on water bodies (0.95). Traffic areas had a high flood hazard, while the remaining land uses of forests, green areas, industry, settlements and urban density were exposed to a medium flood hazard.

The actual demand (Fig. 6c) resulted from the product of potential demand and flood hazard on each individual cell and can be a maximum of 1. On average, there was no high or very high actual demand for any land-use. The highest actual demand were on traffic areas (0.5) and urban density areas (0.4; medium), whereas, green areas, water, woodland, industry and settlements had a low actual demand on average.

FRES budget

The budget map (Fig. 7) shows the difference between the supply and actual demand with a relative scale from -1 (unmet demand) to 1 (supply surplus) and a balance of 0.

Greened spaces, such as forests, green areas and woodlands, had an average supply surplus. Thereby, forests had a very high supply and low actual demand, which resulted in a medium supply surplus (~ 0.55). Green areas and woodlands were exposed to a medium supply (> 0.4) and a low actual demand. On average, there was a very low supply surplus on green areas (0.1) and a low supply surplus (~ 0.2) for woodlands.

On the contrary, sealed spaces were indicated with an unmet demand. While the supply was low on nearly all land-uses, the actual demand was low or medium (traffic areas, urban dense areas). This resulted in a very low unmet demand for settlements, industry, traffic areas and urban density areas.

In total, the study area had a low supply and low to medium actual demand. Therefore, the budget was calculated with a very low unmet demand of -0.1.

Discussion

The results showed local pluvial FRES supply and demand that were quantified and mapped in an exemplary urban area and heavy precipitation event. These results indicated that vegetation plays an important part in flood regulation, if the soils are saturated or sealed and, thus, should be considered in urban FRES assessments. The intercepted values of maximum 7 mm are comparable to the measurements and model results of other studies (Alves et al. 2018, Camarena et al. 2022). Therefore, green urban areas have, in general, a high FRES supply, while sealed areas are indicated with low to no supply. A mismatch of supply and actual demand could be identified. While parks and forest provided a high supply, the actual demand in this areas is relatively low and vice versa. Thus, the settlements in the east of the study area were indicated to have high unmet demand resulting from a high potential demand by critical infrastructure and land reference value and a low supply due to missing vegetation elements, such as trees or green spaces where water can be intercepted or infiltrate. Furthermore, lower lying areas, for instance, the Holbeinplatz, had a higher unmet demand, which resulted from a high flood hazard and high potential demand by traffic areas.

Over the entire study area, the surface water depth was found to be deeper than the water depth of the total supply. To counteract the high water levels on the surfaces, more storage by ecosystems can be provided (e.g. infiltration or interception). Since we investigated a single event, even changing intial conditions, such as a lower saturated depth, could lead to more supply capacity. Furthermore, we did not consider the sewerage system in the hydrological modelling, as the focus was on the possible contribution of natural ecosystems to the regulation of pluvial floods. Neglecting the drainage system is a limitation, which might overestimate the actual demand, but does not influence the FRES supply. At this point, we accept this limitation, since the study focuses on rare events of high intensities that potentially cause pluvial flooding that typically exceeds the capacity of urban drainage systems - as observed during the considered event in 2011 (Miegel et al. 2014).

Model uncertainties of LEAFlood for pluvial FRES Modeling

By using hydrological models for FRES-assessment, it is possible to take different rainfall events and initial conditions into account. Thus, the results of the actual FRES demand and budget analysis are only valid for a specific event. However, this also gives the opportunity to test different scenarios and replicate real events with different initial conditions to get a bandwith of possible impacts. Designed events and ideal (drier) soil conditions, for example, could lead to an improbably high supply and are far from reality. The total capacity would be determined rather than the actual used flood regulating capacity available to the population.

CMF fills the gap of flexible and modular hydrological modelling structure that the community is asking for (Elga et al. 2015). With this framework, it was possible to build up LEAFlood, which provides the opportunity to value single landscape structures and elements of ungauged urban areas including their lateral connectivity instead of entire catchments, while having a flexible choice of hydrological processes. This way, LEAFlood enables hydrological predictions below the scale of typical land use classifications as it allows for resolving single elements of urban districts in a distributed way such as parks, buildings, streets or even elements of green infrastructure (for instance swales or trees) (Camarena et al. 2022). It is capable of incorporating vegetation-related hydrological processes, which are an important FRES-supply element (Nedkov and Burkhard 2012, Burkhard and Maes 2017) and which is unaccounted in typical stormwater models used in urban hydrology. The use of point shapefiles for the trees, a land use dataset that resolves individual elements of a city and a 1 m DEM can, therefore, be considered as sufficient for the application in this model. However, modelling and programming experiences are required and, even if it is possible to take vegetation and individual landscape elements into account with LEAFlood, this hydrological model is - like all models - only a simplified representation of reality.

Besides the vegetation-related hydrological processes, we considered the infiltration with the Green-Ampt approach and the kinematic surface run-off. For infiltration, we only looked at the upper soil layer and did not consider percolation (water flow from the unsaturated to the saturated soil zone), because of a time delay, most of the water infiltrates into the upper layer during an short rainfall event (Markovič et al. 2014). The same applies to interflow (horizontal water flow in the unsaturated soil zone), which is not considered in LEAFlood. These limitations are acceptable for event-based modelling in urban areas, as surface run-off is the most dominant process. Furthermore, evapotranspiration is neglected. This is based on the assumption that the rate of evapotranspiration losses is at least one order of magnitude lower than corresponding rainfall intensities during a heavy rainfall event (Elga et al. 2015).

The advantage of hydrological modelling, especially of LEAFlood, for valuing FRES, is its flexibility. Depending on the available data and the research question, the complexity of the model can be adapted and extended by the processes, input data or resolution. For instance, we used a simple soil approach with regard to the spatial distribution because detailed information about soil texture distribution was unavailable. Urban soils are highly heterogeneous, which is why a dense measurement network is necessary for detailed soil mapping. In addition to the enormous measurement effort, it is difficult to obtain according permissions. Therefore, the existing level of detail is sufficient for the research question and, even with the simpler approach, good conclusions can be drawn about FRES.

A calibration of the ungauged urban study area in Rostock is not possible because of missing field measurements, which is common for urban areas since these are not demarcated catchments on this scale (Krebs et al. 2014) and high measurement efforts are required. However, the functionality of LEAFlood has been proven in the study area of Vauban (Freiburg, Germany) by showing that the model is capable to model run-off and canopy interception (Camarena et al. 2022). Both study sites in Vauban and Rostock are smaller districts within a city with a soil texture of sandy loam. Information about trees is more detailed in Rostock; however, the mean characteristics of the trees and so the settings of LAI and interception capacities are similar. Therefore, the functionality of infiltration and interception processes can be assumed as transferable from one site to the other. Nevertheless, the set and calibrated model parameters in Vauban cannot be transferred directly to other areas for hydrological modelling, as they are site and event specific (e.g. saturated depth) and, thus, reflect uncertainties. However, the results can be considered as sufficient, since an on-site inspection showed comparable flooding of past pluvial flood events in Rostock (for instance, at the Holbeinplatz) (OZ 2014) and also other modelling studies in Rostock emphasise these areas, which were indicated as hotspots in our study (Biota 2013). Furthermore, Rostock provides a comprehensive dataset, which is sufficient for the mode setup of the qualitative analysis of FRES.

Spatial Analysis of pluvial Flood Regulating Ecosystem Service modelling results

The results showed that the interception by vegetation has a large share of the total FRES supply, which is particularly true when the soil is highly saturated. This confirms the statement by Nedkov and Burkhard (2012) and Burkhard and Maes (2017) that interception plays an important role in FRES supply assessment. The importance of urban trees is further supported in other studies, which have found that urban trees have a larger canopy circumference than forest trees because they have more space to grow. Consequently, they have a greater interception capacity (Asadian and Weiler 2009, Carlyle-Moses et al. 2020). With LEAFlood, we can model the interception and the importance for FRES supply on the spatial resolution of individual landscape patterns and, therefore, perform a spatially-detailed FRES supply assessment for the indicator by modelling, instead of working with general assumptions of interception classification based on literature (e.g. Nedkov and Burkhard 2012, Liyun et al. 2018). We avoided a weighting of the two supply indicators according to their importance and influence on flood regulation by summing up the absolute water depth values of both indicators and calculating the relative scale of the total supply afterwards. Furthermore, we did not incorporate the supply by upstream areas as other studies did (Goldenberg et al. 2017, Shen et al. 2021). Since we investigated a short heavy rainfall event and the topograhy of the study area is realtively flat, it can be initally assumed that the inflow or retention from the surrounding areas is low during this short time period. Rather, the present study is concerned with the direct regulating contribution of the areas in the study area.

In addition to the common processes of interception and infiltration, smaller landscape and green infrastructure elements, such as green roofs, have great potential to contribute to flood regulation (Zölch et al. 2017, Basu et al. 2022, Twohig et al. 2022). Camarena et al. (2022) considered green roofs in LEAFlood with a simple approach by increasing the saturated conductivity. However, for a comprehensive consideration of these elements in a FRES assessment, LEAFlood should and can be adapted accordingly (Förster et al. 2021). Since no spatial information on green roofs was available for the study area in Rostock and, in addition, satellite images did not show any green roofs, we have not taken this element into account as a regulation function.

Flood regulating demand should not only be roughly estimated by land-use or population density, as it is often used in other studies (Nedkov and Burkhard 2012, Goldenberg et al. 2017, Vallecillo et al. 2019), but is multidisciplinary and multiple data types and indicators from different disciplines, such as societal, economic, ecological and cultural demand should be analysed (European Parliament 2007, Milcu et al. 2013, Dworczyk and Burkhard 2021). By taking into account economic and cultural values, a different demand results than the estimation based on land use. Monuments are classified with a high demand, which is missing in an estimation based on land use, for example, if it is a park. While most studies focus on a detailed analysis of the supply of ES, the demand is often neglected or considered by using comparably simple analysis approaches, for instance, based on land-use classifications (Campagne et al. 2020). Using different sectors and data types, including different levels of demand, increases the knowledge and details of the demand assessment (Dworczyk and Burkhard 2021). By considering various protected assets, such as population, economy, infrastructure and monuments, we are tackling this point. Nevertheless, not all aspects of demand could be taken into account and not all potential demand indicators could be quantified monetarily or biophysically. The existing data can be refined spatially and temporally by adding further information and including stakeholders. For instance, instead of the population density in 100 m grid resolution, the number of persons per building could be used. Another possibility is the intersection of the land-use with the land reference value for a more detailed damage potential built environment.

We defined the protected assets of population, economy, cultural and infrastructure as potential demand, by arguing that all vulnerable areas and activities have a demand for flood protection regardless of whether they are actually exposed to the hazard. The actual demand results from the areas of potential demand that would be flooded. Therefore, it must be noted that the actual demand calculated here is only valid for the selected precipitation event and its initial conditions. For a more comprehensive assessment, other possible extreme precipitation events and initial conditions need to be considered.

A mismatch analysis of FRES demand and supply is important to identify priority areas for adaptation with an unmet demand, which is necessary, for instance, for adaptation planning (Syrbe and Grunewald 2017). By comparing supply and demand through subtraction, areas with a balance, as well as unmet demand and areas with a supply surplus, can be identified. Such an analysis is an indication of various parameters, which visualisation with maps supports decision-makers for urban and adaptation planning (Lüke and Hack 2018). Since demand indicators are expressed in social or economic units (for instance people/100 m² or euro) and supply indicators on biophysical units (for instance mm or mm²), we transferred them to a relative scale from 0 to 1, in order to compare these different units of indicators. This means that a direct comparison of the biophysical values cannot be conducted (Czúcz et al. 2018), but it does make it possible to compare indicators from different units for the supply and actual demand mismatch analysis. Additionally, interpreting the relative scale of indicators with the same unit relies on: 1) different upper boundaries related to the maximum or 90% quantile of each parameter and 2) the fact that this value is site specific and can be computed for arbitrary sites. Therefore, the approach is an indication instead of absolute values, because they are not comparable due to different units and maxima, but still reflect the bandwith of supply or demand. Identifying mismatches or balances should, therefore, always be done with respect to scaling classification. Nevertheless, we additionally showed the imbalance between the biophysical values of supply and hazard by their quotients to draw attention to the unequal distribution of water in a cell and to illustrate the high run-off fractions over the surface.

Furthermore, the budget analysis can be strongly influenced by site-specific and short-term aspects. This is particularly true for this study, where event-based modelling was used. The results are valid for a one-hour event with a total amount of 22 mm with a saturated soil, as has already been observed in Rostock. A less saturated soil at the beginning could increase the FRES supply and consequently the supply surplus in green-related areas. However, no improvement is expected for areas with a high unmet demand since these areas are mainly highly sealed. Whereas, with a prolonged or more intense rainfall, the proportion of land with unmet demand is expected to increase.

We would like to emphasise here that the results of the mismatch analysis do not constitute a flood hazard map. Rather, it serves as an input dataset in the FRES analysis and as an indicator of hazard, which in turn, is the output of the modelling. Unlike the Flood Framework Directive (European Parliament 2007) or the IPCC's vulnerability and risk approach (Oppenheimer et al. 2014), a comprehensive FRES study, that considers and compares both supply and demand, captures the contribution of natural ecosystems to flood regulation. With this approach, missing biophysical FRES supply on demand areas can be identified. This information can help to identify adaptation areas in order to create a sustainable city by ecosystem and biophysical adaptation measures by increasing the FRES supply where the analysis highlights the need. In an area with high potential demand for flood hazards, such as a city, biophysical structures and ecosystems thus have a social and economic contribution to protect the population and reduce damage costs. Long-term consequences of FRES loss might be high economic costs and increasing vulnerability and decreasing resilience (Gómez-Baggethun and Barton 2013). Therefore, the mapping of scaled FRES demand and supply indicators and their mismatch delivers an easy-to-comunicate and important tool to identify the benefit and missing FRES supply for a sustainable urban planning.

Outlook

Since CMF is a modular python package, it is possible to connect it with other models, including models from other disciplines (Kraft et al. 2010). Against this background, it would be interesting to examine whether the hydrological model can be linked to regional climate model information. With this, the FRES assessment could be conducted for different possible future climate scenarios. An extensive spatial analysis of the soil would further improve the model. Run-off measurements are necessary for a local calibration of the model. Adding the effect of urban drainage system is an other outlook for future research. This would allow a FRES analysis with more emphasis on artificial elements (Vallecillo et al. 2019).

In terms of ES research, it is interesting to compare the results obtained in this study with the well-known and frequently used ES matrix method, based on land-use classifications

(Burkhard et al. 2009). So far, only a few studies have compared the matrix method to quantitative estimations (Campagne et al. 2020). To counteract the issue of scaling and different units, all indicators must be aligned to one unit. For this, in a next step, the ecosystem value could be converted into economic values (Constanza et al. 1997, Constanza et al. 2014).

It has already been mentioned that demand is multidisciplinary (Dworczyk and Burkhard 2021) and often neglected in ES research (Campagne et al. 2020). Besides developing, adapting and extending the demand indicators, modelling of temporal changes (e.g. land-use changes and population development) could be conducted to improve ES research on the demand side. Furthermore, the damage costs could be calculated in monetary values to add another aspect of economic value. The temporal and time aspect should also be considered on the supply side, by analysing the development of the used supply capacity and the mismatch with demand during a heavy precipitation event.

So far, we did not consider future climate and land-use scenarios. For urban planning, the method would be an interesting approach to test adaptation measures in terms of their FRES supply functionality under changing climate conditions.

Conclusions

Cities are, in particular, vulnerable to pluvial flood events caused by heavy precipitation. The prediction of FRES on the city scale is an important tool for flood risk assessment to value the contribution of natural (or near-natural) structures and processes to flood regulation and the benefits for demanding factors, such as society, economy or culture. This study proposes an approach for the quantification of FRES supply, demand and their mismatches in urban areas for short-term heavy precipitation events.

FRES supply was estimated by the soil water and canopy interception, based on the LEAFlood model. It could be shown that interception has a high FRES supply in soil water saturated or sealed areas and is, therefore, an important indicator to be considered in FRES assessment on the urban scale. Green spaces, such as forests or parks, had high FRES supply, whereas sealed areas had a low FRES supply.

We argued that an area used in a certain way has a demand for protection against pluvial flooding, since pluvial flooding can happen everywhere. Therefore, the approach to investigate the flood regulating effects cannot be reduced only to single areas which are actually flooded. With the terminology of potential and actual demand, we could consider a general demand that is always asked by different sectors of society and economy and the demand for single flood events, when the potential demand turned into an actual demand. The potential demand was conducted by considering multiple actors of economy, population, infrastructure, critical infrastructure and monuments. In our analysis, monuments and critical infrastructure had a high impact on the total potential demand. Therefore, a demand analysis, solely based on land use classification, is not sufficient. Afterwards, the actual demand was defined by a function of the hazard and potential demand. The subsequent budget analysis of supply and actual demand indicated unmet demand for the entire study area. While greened areas had a supply surplus, sealed areas and, in particular, industry, urban dense areas and traffic areas had an unmet demand. Even the existing street trees could not compensate the unmet demand over traffic land-uses. In general, the water retained by the soil and interception, which represented the supply, was smaller over the entire study area than the surface water, which was the indicator for the hazard.

The visualisation of mismatches in maps with indicators is an essential tool for urban planning and flood risk management. Compared to the flood risk approach, the concept of ES for flood regulation has the advantage that also the supply side of flood risk reduction is considered. In the case of ecosystem-based adaptation, the ES concept can estimate the contributions of nature to flood regulation and their benefits to the socio-economic system. This can support city planners in making sustainable decisions in order to avoid long-term consequences of ecosystem loss.

For urban areas, a catchment area-based model is not sufficient, because of the spatial and temporal scale, as well as the involved considered processes. Instead of the catchment scale, it is more important to be able to identify the flood regulation supply capacities of single landscape elements and to include vegetation related hydrological processes, which are both considered by LEAFlood. In general, ungauged urban areas face the problem of lack of data for calibration and validation for hydrological models. However, previous studies could prove the model performance of LEAFlood in urban areas regarding run-off and interception. Therefore, it can be classified as a suitable hydrological model for quantifying and assessing FRES on urban scale for heavy precipitation events.

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Conflicts of interest

The authors declare no conflict of interest.

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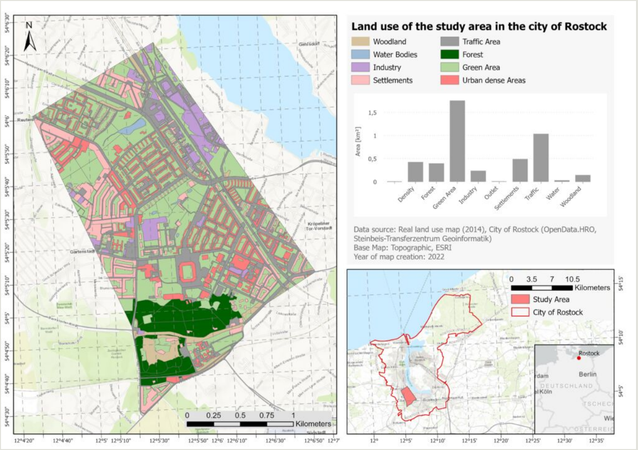

Land use of the study area in the city of Rostock

Data source: Real land use map (2014), City of Rostock (OpenData.HRO, Steinbeis-Transferzentrum Geoinformatik)
Base Map: Topographic, ESRI
Year of map creation: 2022

Figure 1.

Location and Land use of the research area in the City of Rostock.

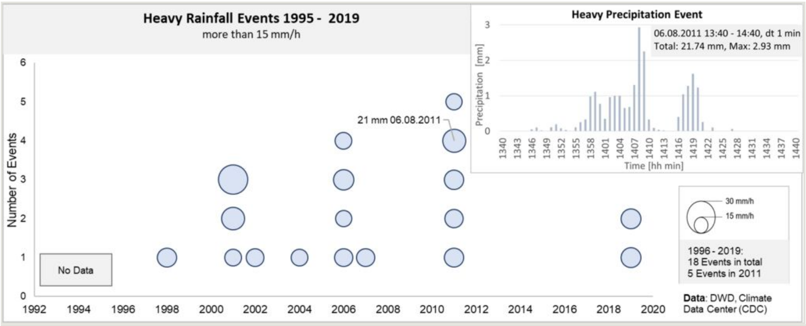

Figure 2.

Heavy Rainfall events from 1995 - 2019 with more than 15 mm/h and the chosen rainfall event on 06.08.2011 for the modelling in this study.

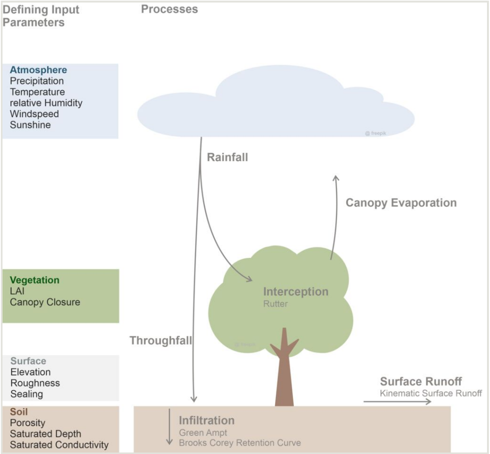

Figure 3.

The hydrological processes, defining parameters and storages in LEAFlood (Wübbelmann and Förster 2022).

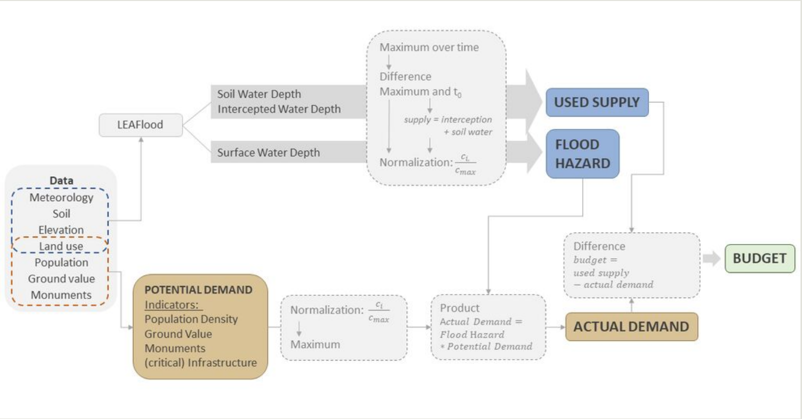

Figure 4.

Workflow of the FRES analysis.

t_0 is the starting time at the beginning of the rainfall event. c_i is the water depth of an individual polygon. c_{max} is the maximum water depth of all cells for the respective parameter or the 90% quantile for the surface water depth.

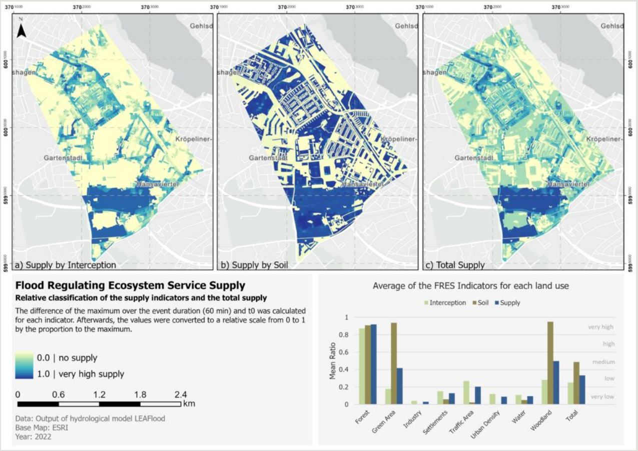

Figure 5.

FRES supply. a) Interception by canopies, b) Soil storage, c) Total supply.

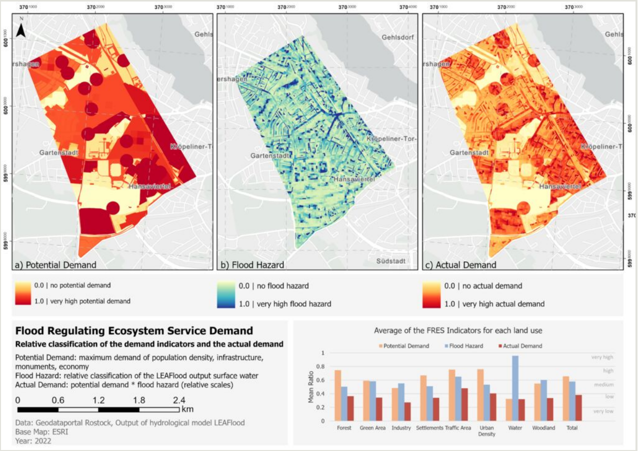

Figure 6.

ES components of FRES demand. a) potential demand, b) flood hazard, c) actual demand.

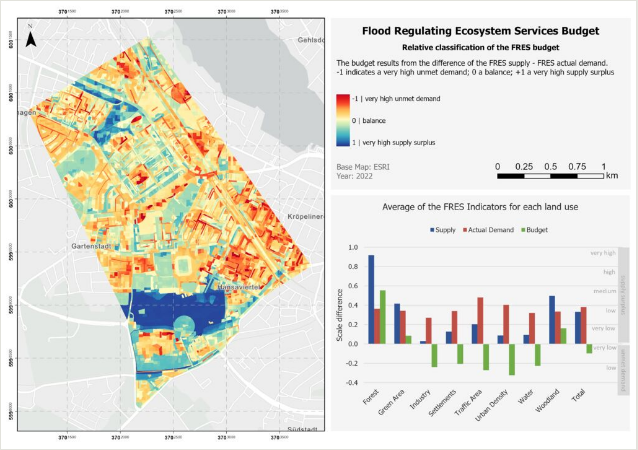

Figure 7.

Budget of the FRES supply and demand resulting in unmet demand and supply surplus.

Table 1.

Settings and processes in LEAFlood.

Process/ Parameter	Setting
Interception	Rutter Interception Through-fall Canopy Evaporation
Infiltration	Green-Ampt Brooks Cores Retention Curve
Layer depth	0.5 m
Saturated conductivity (Ksat)	0.3 m/d (base value)
Porosity	0.3 [-]
Theta_x	0.2 [-]
_b	8 [-]
Porosity decay	0.2 m^{-1}
Saturated depth	1 m
Surface Run-off	Kinematic wave

Table 2.

The roughness coefficient Manning's n and the saturated conductivity (Ksat) defined for each land use class.

Land use	**Manning's n [s*m$^{-1/3}$]** (Brunner 2021)	**Saturated Conductivity [m/day]**
Urban dense areas	0.2	0
Settlements	0.12	0.015
Industry	0.12	0
Traffic area	0.03	0.006
Green area	0.05	0.29
Woodland	0.14	0.3
Forest	0.15	0.3
Water	0.03	0.015

Table 3.

Definitions of the terms used for FRES.

Term	Definition	Indicators	Other studies
Used Supply	ES supply indicates the provision of a service by an ecosystem (Burkhard and Maes 2017). The pluvial FRES supply indicators in this study are soil water content and intercepted water by vegetation.	Interception capacity [mm] + Soil water capacity [mm] *Difference between Maximum and initial depth (t0)* = Supply [mm] *converted into relative scale 0-1*	There is no synonym from other studies, such as the vulnerability and risk approach, since they do not consider flood regulating elements, but are focused on the flooding itself.
Potential demand	An ecosystem only provides ES if there is a demand by society or other stakeholder. Therefore, the demand is the need of an ES by society or other stakeholders (Burkhard and Maes 2017, Syrbe and Grunewald 2017, Syrbe and Walz 2012) and describes the values that need to be protected (European Parliament 2007 , Biota 2014). For pluvial FRES, it refers to the need for risk reduction, prevention and security increase (Dworczyk and Burkhard 2021). This is always the existing general demand of areas that might get flooded.	Population Density [people/100 km²] Monuments [-] Land reference value [€] Infrastructure [-] (for details see Table 4)	In other concepts or approaches, the terms of vulnerability and exposure (Oppenheimer et al. 2014) or damage potential (European Parliament 2007, Biota 2014) are used. While exposure is the spatial presence of, for instance, humans or infrastructure, the vulnerability refers to the characteristics of the human and socio-economic system (Oppenheimer et al. 2014).
Flood hazard	Flood hazard indicates the surface flooding. The indicator is the modelled surface water depth.	Surface water depth [mm] *converted into relative scale 0-1*	In vulnerability and flood risk assessments, flooding is referred to as hazard and is the potential occurrence of an event (Oppenheimer et al. 2014). While these concepts are referred to as statistical design events, we consider a specific event.
Actual demand	The actual demand resulting from an intersection of the potential demand and flood hazard. It is the potential demand that was actually used for this single rainfall event (flood hazard). Therefore, the potential demand turns into a actual demand.	*Product of potential demand and flood hazard*	The actual demand can be understood as the risk and results of the function of vulnerability, exposure and hazard (Oppenheimer et al. 2014).
Budget	ES budget results from the difference of FRES actual demand and supply. It indicates the mismatches of supply and demand as benefiting areas with a supply surplus and unmet demand areas, where the FRES is not sufficient to balance the amount of precipitation (Nedkov and Burkhard 2012, Dworczyk and Burkhard 2021).	*Difference of supply and flood hazard*	Other concepts do not consider the used regulating storage capacities and balance to examine the sufficiency of FRES supply.

Table 4.

The potential demand indicators and the relative scale.

Sector	Population	Cultural Heritage	Economy	Infrastructure	
Indicator	Population density [people/100m²]	Monuments [-]	Land reference value [€]	Critical Infrastructure [-]	Traffic [-]
Scaling	*converted into relative scale 0-1: Value of scale divided by maximum of all cells*	1.0: monuments	*converted into relative scale 0-1: Value of scale divided by maximum of all cells*	1.0: hospitals, fire stations, schools, care facility, disabled institutions	0.6: station, main streets, railway tracks 0.4: streets 0.2: ways

Supplementary materials

Suppl. material 1: Ratio of FRES supply and flood hazard

Authors: Wübbelmann, T., Bouwer, L.M., Förster, K., Bender, S., Burkhard, B.
Data type: Image
Download file (1.09 MB)

Suppl. material 2: Table of the scaled Flood Regulating Ecosystem Services indicators and categories

Authors: Wübbelmann, T., Bouwer, L.M., Förster, K., Bender, S., Burkhard, B.
Data type: Table
Download file (225.34 kb)

Suppl. material 3: Maps of the individual potential FRES demand indicators

Authors: Wübbelmann, T., Bouwer, L.M., Förster, K., Bender, S., Burkhard, B.
Data type: Image, Map
Download file (1.62 MB)