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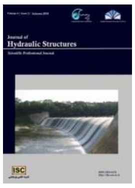

Sustainable Stormwater Management: A Holistic Planning Approach for Water Sensitive Cities

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Abstract

The planning of sustainable stormwater infrastructures for future water-sensitive cities requires new holistic methods. In the Indo-German research project SMART&WISE, a structured approach was developed to improve the planning processes for water infrastructure systems. The developed approach attempts to map the entire decision-making process when planning suitable infrastructures. A basic distinction is made between retrofit and greenfield planning. Four analyses form the basis of the planning approach: (1) Flood Protection, (2) Water Balance, (3) Water Scarcity and (4) Heat Islands. An indexation of different analyses results enables to overlay and visualize the overall result. The approach was tested successfully in two pilot projects: An Indian pilot case in a semi-arid climate zone and a German pilot case in an arid climate zone. It could be shown that the approach is suitable to cope with heterogeneous population and settlement development, climate change and increasing resource scarcity. The approach can help to facilitate interdisciplinary collaborations (especially urban planners and engineers for urban drainage). Increase in evaporation and a decrease in heat is the decisive advantage of low impact development measures (LIDs) for a sustainable stormwater management. However, an increase in evapotranspiration is not recommended in semi-arid or arid regions, since it would further increase water stress. For regions at risk of water scarcity, a balance between water sources, storage, reuse and demand must be achieved.

Keywords: Sustainable Stormwater Management, Planning Approach, Water Balance, Heat Islands, Flood Protection, Water Scarcity.

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1. Introduction

Planning of urban water infrastructure faces three major challenges: Spatially heterogeneous development of population and settlements, climate change and growing scarcity of resources [1][2][3]. The ongoing digitization is often considered as a key to tackle these challenges [4][5]. The goal of the Indo-German research-project SMART&WISE was to improve planning processes for smart and reliable water and wastewater infrastructure systems facing these challenges. The project team dealt with the question of what is meant by a smart city when it comes to water infrastructures [6][7][8]. It has been concluded that a smart city does not necessarily have to be a digital city. Rather, it should be committed to the benefit of the citizens, and it must be sustainable in dealing with resources. Therefore, a holistic approach for a water sensitive city was developed. While dealing with stormwater management, the developed approach considers the flood risk, the impact on the water balance, the use of rainwater to mitigate water scarcity and measures to reduce heat islands. This article describes the holistic planning approaches for dealing with rainwater in water-sensitive cities.

2. Methodology: Development of an approach for a holistic planning

A structured approach for holistic planning of future water sensitive cities was developed. It is based on the idea that sustainable stormwater management should, on the one hand, guarantee the safe drainage of rainwater and, on the other hand, consider rainwater as a valuable water resource. Four analyses form the basis of the planning approach: (1) Flood Protection, (2) Water Balance, (3) Water Scarcity and (4) Heat Islands. The procedure was first described from a German perspective and then adapted for Indian climate conditions. In analogy to the guidelines for innovative storm water management practices for water-sensitive cities in Germany and India [9], not only conventional measures should be planned, but also low impact development measures (LIDs: e. g. infiltration swales, green roofs) should be implemented. These measures should be planned in an iterative process, in which they are evaluated using the analyses during each iteration and subsequently improved upon. When planning the stormwater management infrastructure, a distinction is made between the use case retrofit, for the planning regarding the renewal and improvement of existing infrastructure, and the use case greenfield, for new planning or for planning in areas without functioning or very poor infrastructure. The two approaches are shown in Figures 1 and 2 and are described below. Although the involvement of the decision-makers is not explicitly mentioned, it is a prerequisite for the application. For example, the stakeholders must define weights for overlaying the individual analyses.

When applying the **Retrofit Planning Approach** (see Figure 1), the first step is to determine the need for action by overlaying the results from the four analyses[4]:

- **Water Scarcity Analysis:** The water scarcity analysis compares future water demand with water availability. Several different future scenarios are set up in the process. This analysis forms the link to water supply and wastewater treatment, as recycled wastewater must also be considered as a water resource.
- **Water Balance Analysis:** The water balance analysis compares the hydrological budget for the built-up area with a reference state and identifies deficits [10]. In Germany, the natural water balance is recommended as a reference for new developments [11]. It can also serve as a reference for retrofit planning for a water-sensitive urban development. However, this approach is not recommended in semi-arid or arid regions, where it further increases the water stress. Therefore, a balance between water sources, storage, reuse and demand should be further explored.
- **Heat Island Analysis:** A two-step process is recommended to identify heat hotspots. The first step is to locate areas that reach or exceed a defined threshold temperature. This temperature must be chosen on a case-specific basis. The perceived daily maximum temperatures for strong or extreme heat stress (>35°C or >38°C) [12][13], but also lower air temperatures [14], as well as threshold values depending on the length of a heat period, can serve as limit temperature. The second step is a vulnerability analysis [15]. Thereby the city-specific urban structure (population density, vulnerable population groups, accessibility of green spaces, etc.) is examined in order to define hotspots. By overlaying the results from both steps, the need for action can be quantified and localized.
- **Flood Protection Analysis**: The flood protection analysis describes the process for a step-wise hydrodynamic rainfall-runoff-modeling depending of available spatial data. The analysis aims to identify flooding hotspots. It is crucial to analyze the cause (e.g. high runoff coefficients) of these flooding hotspots and to identify connected areas. Depending on data availability, a 1D channel/sewer network model, a 2D surface model or a coupled 1D/2D model can be created. If the data basis is poor, a (manual) flow path analysis can also be applied as a first step. To check the quality of the results through verification or validation, site inspections must be carried out.

The results from each analysis are converted into index values, which indicate the need for action at any specified location. The index values from each of the analyses are then weighted and added. Following the observance of the water quality requirements as well as the emission limits must be considered (Stormwater Load Analysis). If necessary, treatment measures must be provided.

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[4] The detailed flowcharts are available online: smart-water.solutions

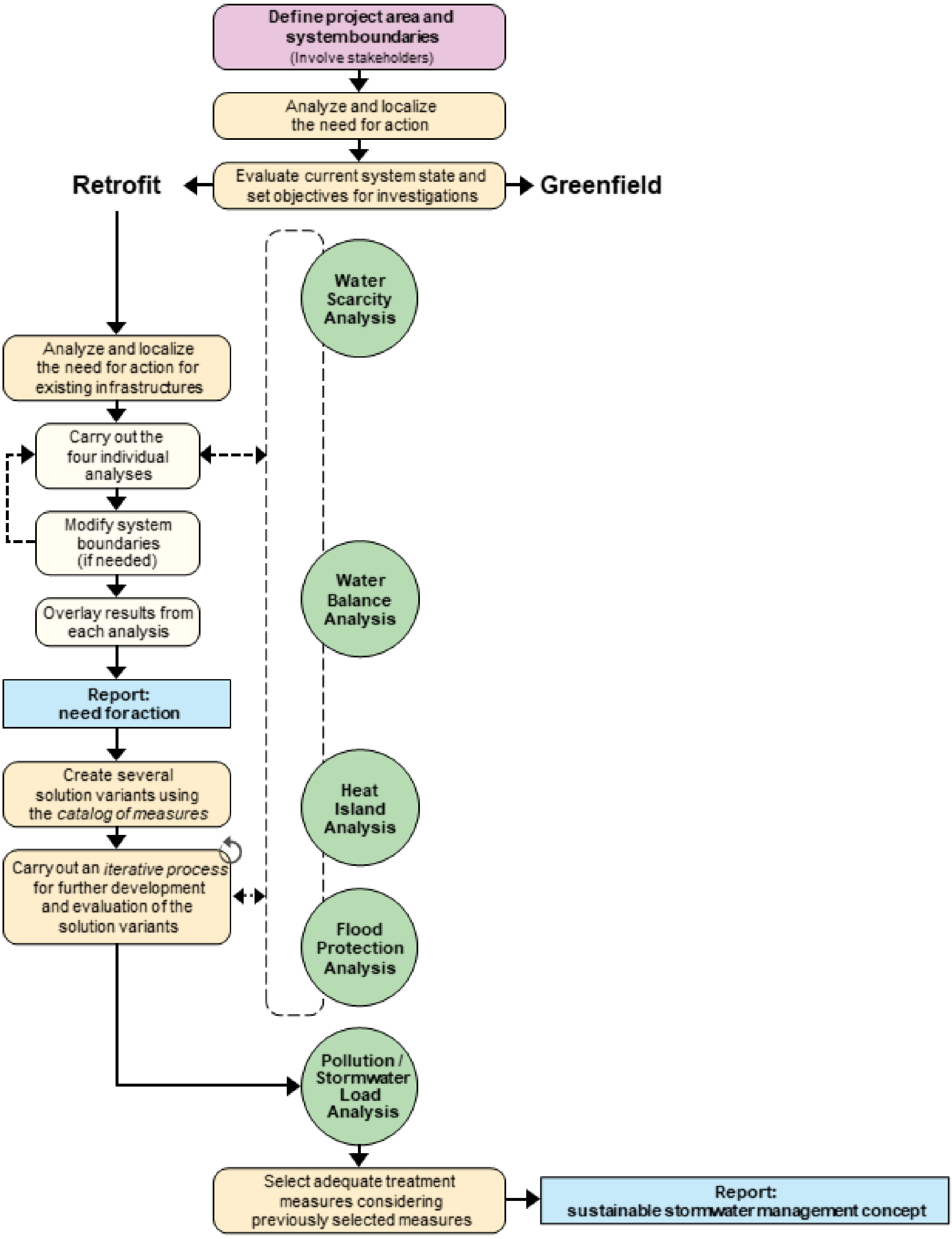

Figure 1. Sustainable Stormwater Management – Retrofit Approach [16]

When applying the **Greenfield Planning Approach** (see Figure 2), it is recommended that the analyses are applied in a specific order. Thus, it must first be checked whether storage and use of rainwater is necessary due to (1.) water scarcity. Subsequently, (2.) a water balance must be drawn up and (3.) potential heat islands in the planning area must be identified. Stormwater management measures must be implemented until the reference state (e.g. natural hydrological water balance) is achieved in terms of infiltration and evapotranspiration. The results of the heat analysis should be taken into account when selecting locations and measures (e.g. tree trenches, green roofs, green facades). In areas where water shortage is expected, irrigation of these plants should be considered. For this purpose, the water resource *treated wastewater* should be considered. After completing this rough planning and the distribution of measures in the planning area, the conventional drainage planning (including the dimensioning of the sewer network) is to be carried out. The design aspect of visible waterways should be considered. For the resulting overall concept, a heavy rain analysis is then to be carried out, as envisaged in the (4.) flood protection analysis. Based on this, retention areas and measures for the storage of rainwater runoff are to be planned if the need arises. In addition, the water quality and emission limit values must be considered and if necessary, treatment measures must be provided. Doing the pollution load analysis, combined and separate sewer systems must be distinguished. For combined sewer systems the analysis deals with the qualitative determination of emissions by overflow. In the case of separate systems, the degree of stormwater pollution is determined based on a categorization of the sealed areas of the catchment. From this result, a need for action can be derived according to the country-specific legal conditions. It should be pointed out, that separate sewers are always recommended for greenfield planning. The procedure corresponds to the procedure from the German guideline DWA-A 102-2/BWK-A 3-2 [17].

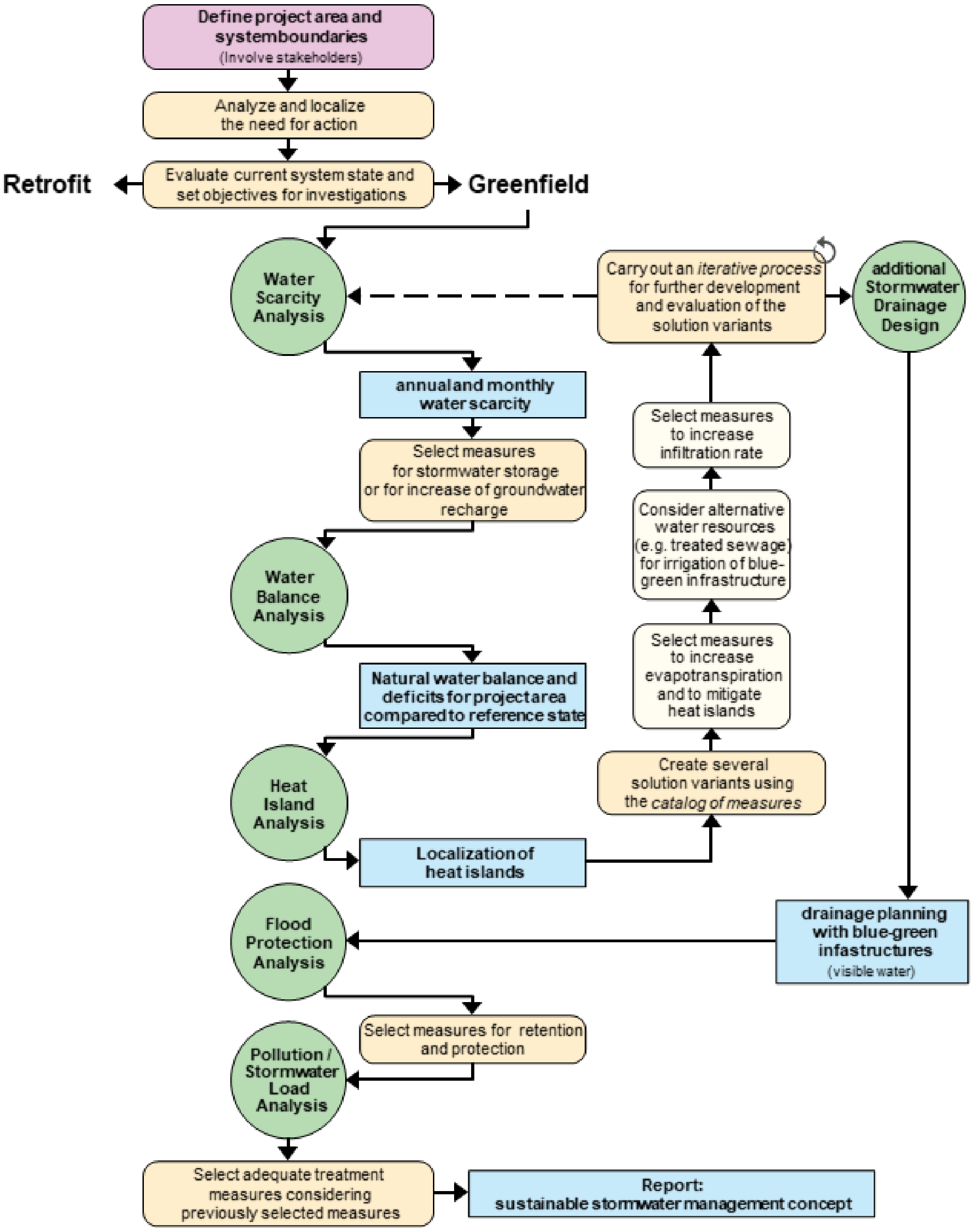

Figure 2. Sustainable Stormwater Management – Greenfield Approach [16]

3. Results and Discussion: Proof-of-Concept

The flowcharts for sustainable stormwater management developed with the project team were checked for their applicability as part of master projects at the University of Kaiserslautern. The pilot areas were Kurichi in Coimbatore (City Municipal Corporation) in Tamil-Nadu in India and the city Ochsenhausen in Baden-Württemberg in Germany.

3.1. Test-Case in India

Kurichi has an existing stormwater drainage system. The system consists of rectangular open drains, which were built in the course of road construction. Secondary data on the position and width of the drains is partially available. However, no data was readily available on the slope of the drains. Determining the flow direction via terrain maps was possible but showed several obvious data errors. Initially, it was planned to collect missing data during field trips and to check questionable data and faulty drain connections on site. Unfortunately, this was not possible due to the start of the pandemic in April 2020. In consultation with the stakeholders and the project partners in India, it was decided that the objective of the planning should be a complete redesign of the stormwater management infrastructure. This assumes that the existing stormwater infrastructure can be completely replaced. This was also proposed because a previous field trip to the pilot area revealed that the infrastructure, which is in part very old, is in poor condition (clogged with sediment, some sections were destroyed) and a new construction of the entire water infrastructure in the pilot area is planned anyway.

Therefore, the **Greenfield Planning Approach** was applied to the area, which starts with three analyses (see Figure 3). First, water scarcity analysis compares the availability of water sources with water demands. Alternative water sources, such as recycled greywater and rainwater, were considered for the water supply. The analysis of the population and settlement structure intended for the Greenfield Planning Approach was carried out with students from the Department of Spatial Planning of TUK. In the process, future settlement scenarios were developed for Kurichi, which serve as the basis for calculating water demand. The water demand was estimated for the Trend (based on analysis of neighboring areas), Peak-Growth, and Green-Livable-City scenarios. When considering the Green-Livable-City scenario, a potential water shortage becomes apparent if only currently used water sources are regarded. The use of alternative water sources can ensure adequate water supply on an annual average. However, to secure the supply throughout the year without the additional import of water, stormwater must be used and stored, especially with regard to drought years. And if, as described in the green-livable-city scenario, extensive greening is planned, there will be an even greater need for water. This can only be covered by increasing water imports or by recycling the sewage (or graywater).

For the water balance analysis, the determination of the potential evapotranspiration is crucial. Kurichi is in a semi-arid climate zone. Furthermore, the calculations according to Romanenko [18] show that the potential evapotranspiration in the study area exceeds the actual annual precipitation by far. The increase in evaporation in the project area may further increase the already existing water stress. For this reason, the natural water balance was not used as a target in this test case.

Landsat 8 OLI/TIRS temperature data were used for the heat island analysis. These data were overlaid with the results of a vulnerability analysis. Many and very pronounced heat island hotspots are represented throughout the study area, and these are often found in the areas of major roads and densely built-up areas.

As proposed solutions for the problems of heat islands and water scarcity in Kurichi, two solutions variants were developed, which differ mainly in the area required for the measures. For these scenarios, water management concepts were designed for two subareas of Kurichi. In both cases, the focus is on rainwater storage and infiltration. For storage, a discharge into the nearby Kurichi Kulam lake is also included in the planning concept. The problem of heat islands and water scarcity can be reduced by the targeted purification and reuse of greywater for irrigation of horticulture and green areas. The planning of large-scale green spaces leads to an improvement of the microclimate and increases the quality of life in the area.

Both concepts nevertheless require a stormwater drainage system for the discharge of heavy rainfall events. The planning and design of this system, the subsequent review of flood protection measures and the review of water quality for discharge into natural water bodies was not yet in the scope of the investigation. However, it should be noted that the developed concept will significantly reduce runoff (during heavy rainfall) from the area.

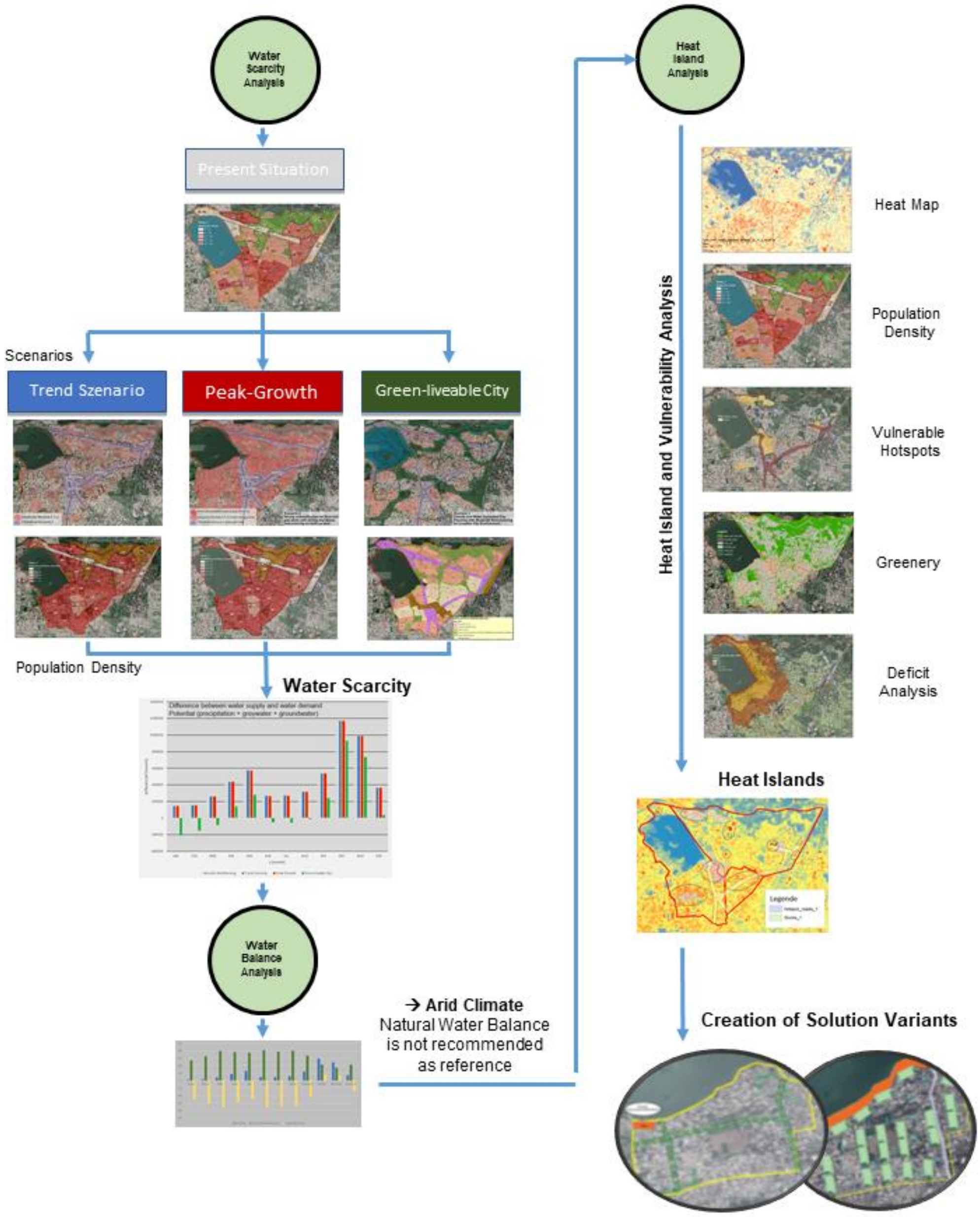

Figure 3. Application example for the part of stormwater management within the holistic greenfield planning for the pilot case Kurichi

3.2. Test-Case in Germany

The **Retrofit Planning Approach** was tested for the pilot case Ochsenhausen in Germany, where a functioning infrastructure already exists. Ochsenhausen is not affected by water shortages. Therefore, the water scarcity analysis was not considered further. Figure 4 shows the indexation created for the remaining three analyses, the resulting overlay and the corresponding holistic evaluation of the solution variants for one settlement unit.

(1.) Landsat 8 OLI/TIRS temperature data and a vulnerability analysis were used as the basis for the heat island analysis. The temperature values, available as grid values, can easily be converted into index values. The indexation shows a moderate and uniform distribution. (2.) The water balance analysis was carried out using the software WABILA[5]. It allows the determination of runoff, evaporation and infiltration depending on the specified surface and existing LIDs. In this process the natural water balance of a nearby undeveloped area is defined as the target state. The deviation of the current state from the target state was calculated for sub-areas with similar settlement structures and then converted into index values. (3.) 1D, 2D and 1D/2D simulations of extreme rain events were carried out with the software ++SYSTEMS (tandler.com). On this basis, areas prone to flooding by sewer overflow or direct surface runoff were identified. Manholes and conduits were associated with their catchment areas. These areas got an index value in relation to the sewer overflow volume of the simulated flooding. (4.) The overlay was generated by adding up the three analyses results. (5.) To improve the overall situation, two possible solution variants with LIDs were created. Variant A considered measures only in public spaces (e.g. infiltration areas, swales and surface unsealing) while Variant B considered redesign of private properties (e.g. green roofs, cisterns, swales) as well. (6.) The solution variants were evaluated again. Although evaluation has not been carried out to determine the reduction of heat islands yet, the two solution variants show a clear improvement regarding urban flooding and the water balance parameters as compared to the current situation. Compared to the status quo, Variant A already shows a strong positive change in the situation due to the measures taken in the public areas. In comparison, Variant B with the additional measures in the private properties only leads to a small further improvement.

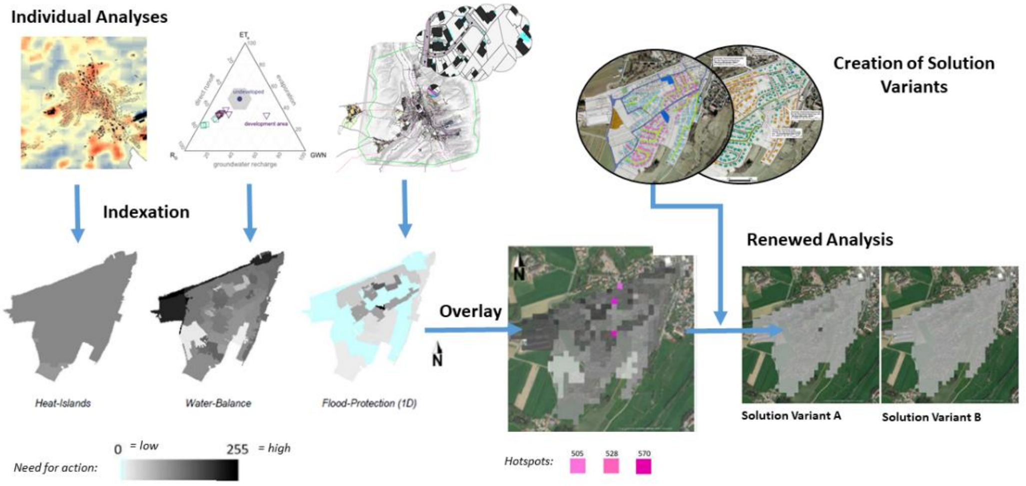

Figure 4: Application example for the part of stormwater management within the holistic greenfield planning for the pilot case Ochsenhausen [19]

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[5] https://de.dwa.de/de/Wasserbilanz.html

4. Conclusions and future work

A framework for a holistic planning of sustainable stormwater management systems for water sensitive cities was developed. It combines discharge and the use of different water sources. It tackles heterogeneous development of population and settlements, the climate change, and the growing scarcity of resources. The developed framework can serve as a guideline for planners and decision-makers to develop stormwater management concepts considering these long-term challenges. The concepts can be set up in an iterative process based on the analyses Water Scarcity, Hydrological Water Balance, Heat Islands and Flood Protection. The four analyses are to be supplemented by a detailed design of the stormwater drains or sewers and, if the stormwater is polluted, the planning of treatment plants prior to discharge into natural water bodies. The developed approaches for retrofit and greenfield planning were tested using the two pilot areas Ochsenhausen in Germany and Kurichi in India. It can be concluded that:

- The **Retrofit Planning Approach** is suitable for evaluating and adapting existing systems for water-sensitive urban development. When planning the stormwater management concept, it is important to consider urban planning, water supply, and wastewater treatment issues to find a holistic solution. This approach can help to facilitate interdisciplinary collaborations (especially urban planners and engineers for urban drainage). However, it also became apparent that the effort involved in creating several solution variants and the subsequent re-evaluation is very high. It is therefore recommended to set up only a few solution variants. This means that the planner depends on experience and empirical values to limit the number of variants in a meaningful way. In response to this deficit computer-aided optimization and decision-making can be used to generate and evaluate a large variety of solution variants. This could not yet be implemented in the present work since the methods and tools used were too different and integration of the different types of analysis results is not trivial. The conversion of the results into index values seems to be a suitable approach to solve this problem. The developed flowcharts for retrofit can serve as a basis for developing a holistic computer-aided planning tool.
- The structured approach to **Greenfield Planning** seems well suited to create sustainable concepts for dealing with stormwater. It also simplifies and strengthens interdisciplinary cooperation. In a first step, only the three analyses Water Scarcity, Water Balance and Heat Islands must be considered. The integration of the results of these analyses and the further planning of sewers or drains and the subsequent consideration of heavy rain events is easily possible with the available tools. A detailed design could not be done yet, as this would require more detailed data collection. In order to accelerate and optimize the process of "manual" planning with computer tools, the approaches for planning and designing urban drainage systems described in the literature [20][21] could be used in the future.

When looking at the country-specific differences between India and Germany, the climatic conditions must be emphasized. In Germany the deviation from the natural (hydrological) water balance is used as an argument to support LIDs. Many LIDs greatly increase infiltration but their effect on evapotranspiration seems to be small. The German test case has shown that the target condition "natural" water balance is difficult to achieve already at the planning stage using existing tools. Additional research is needed to evaluate LIDs concerning evapotranspiration and further research is required to develop appropriate models for reduction of the heat island effect by LIDs.

In addition, an increase in evapotranspiration is not recommended in semi-arid or arid regions, since it would further increase water stress. For regions at risk of water scarcity, a balance between water sources, storage, reuse, and demand must be achieved. Planning methods to support holistic considerations in this regard should be further developed.

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