



Research article

Meeting sustainable development challenges in growing cities: Coupled social-ecological systems modeling of land use and water changes

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ABSTRACT

Ongoing urban expansion may degrade natural resources, ecosystems, and the services they provide to human societies, e.g., through land use and water changes and feedbacks. In order to control and minimize such negative impacts of urbanization, best practices for sustainable urban development must be identified, supported, and reinforced. To accomplish this, assessment methods and tools need to consider the couplings and feedbacks between social and ecological systems, as the basis for improving the planning and management of urban development. Collaborative efforts by academics, urban planners, and other relevant actors are also essential in this context. This will require relevant methods and tools for testing and projecting scenarios of coupled social-ecological system (CSES) behavior, changes, and feedbacks, in support of sustainable development of growing cities. This paper presents a CSES modeling approach that can provide such support, by coupling socio-economically driven land use changes and associated hydrological changes. The paper exemplifies and tests the applicability of this approach for a concrete case study with relevant data availability, the Tyresån catchment in Stockholm County, Sweden. Results show that model integration in the approach can reveal impacts of urbanization on hydrological and water resource, and the implications and feedbacks for urban societies and ecosystems. The CSES approach introduces new model challenges, but holds promise for improved model support towards sustainable urban development.

1. Introduction

Urbanization poses a number of challenges to sustainably meeting needs for new housing, transport infrastructure, and other urban services, while also handling and minimizing negative impacts on environment and health (e.g., by air, water, soil pollution) under budgetary constraints (Keivani, 2010). Social challenges, e.g., associated with demographic and financial variability and change, affect urban policy, regulations, planning, and management in ways that may not adequately consider natural resource and ecosystem changes and impacts (OECD, 2011). However, impacts of socio-economic developments on urban environments and ecosystems have been widely documented. These include decreased biodiversity (e.g., Guetté et al., 2017); urban heat island effects and enhanced greenhouse gas emissions driven by increased urban energy use (Gunawardena et al., 2017); and water resource availability and quality changes associated with reduced water infiltration and groundwater recharge, increased peak

flows of surface water (Kalantari et al., 2017a), soil erosion (Ferreira et al., 2015, 2017), and pollutant loads (Ferreira et al., 2016). However, ecosystem changes also impact human societies, whose wellbeing relies to some degree on presence of nearby natural vegetated/water area (Goldenberg et al., 2018) and associated ecosystem services (Goldenberg et al., 2017), such as water supply and flood and landslide hazard regulation (e.g., Kalantari et al., 2017b; Wu and Li, 2019). The links between social and ecosystem changes are also affected by other processes, such as climate change (e.g., increasing flood and drought risks), which must be considered to achieve long-term urban sustainability (Grimm et al., 2008a; Michielsen et al., 2016; Karlsson et al., 2017; Ahlmer et al., 2018; Kalantari et al., 2018).

The idea of long-term sustainability dates back more than 30 years and the concept of sustainable development has been evolving since then. Sustainable development principles are increasingly included in the political agenda, e.g., through the goal of “sustainable cities and communities” (UN, 2015) and the New Urban Agenda of the United

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Nations Development Program (UNDP, 2018). In Europe, the report ‘Sustainable Urban Development in the European Union: A Framework for Action’ (EU, 1998) and the Leipzig Charter (EU, 2007) present strategies and policies for sustainable urban development to be applied by national and local governments. Many countries also have their own national urban sustainability targets, such as that in Sweden of a ‘good built environment’ (Swedish Environmental Protection Agency, 2017), the Fifth National Policy Document on Spatial Planning in the Netherlands (VROM, 2001), and Planning Policy Statement 1 in the UK (DCLG, 2005). The latter two set sustainable urban development as the first goal of planning and development in those countries. There is also increasing attention to applying sustainable development principles at municipal and regional level (Gibbs and Krueger, 2012).

However, implementation of urban sustainability policies is complex, considering the multitude of urban interdependencies between economics, culture, infrastructure, natural resources, and other social and environmental challenges, with associated public and private actors on local-national-regional levels. Handling this complexity requires integration of multi-scale decision-making systems through new forms of governance that can engage a wide range of stakeholders (Jenkins, 2018) in the broad dialogue needed to foster planning for sustainable urban development (Swedish Delegation for Sustainable Cities, 2012). Such integration efforts must be supported by novel methods and tools for integrated assessment and evaluation of environmental, social, economic, and cultural qualities in urban areas (Zheng et al., 2017).

Sustainable planetary management also demands a move beyond both ‘business as usual’ and ‘politics as usual’ (Adams, 2006). For the rapidly expanding built environment under current urbanization, sustainability involves designing and locating buildings and infrastructure in accordance with sound environmental principles, and protecting soil, water, and other natural resources (Kalantari and Folkeson, 2013; Kalantari et al., 2019). Urban development projects, e.g., for infrastructure, have thus become increasingly complex over recent decades (Pinz et al., 2018), as they require long-term whole life cycle sustainability (Lenferink et al., 2013; Yang et al., 2017; Hendricks et al., 2018). A number of methods and tools for handling various sustainability aspects in urban planning are presented in the literature (e.g., Bentivegna et al., 2002; Brandon and Lombardi, 2010; Abu Bakar and Cheen, 2013; Gibbs and O'Neill, 2015; Pan et al., 2018). However, the complexity of urban development means that no single method or tool is generally most appropriate to use across all urbanization stages and for all sustainability issues. There is general awareness among researchers of the need to integrate human societal and natural ecosystem aspects in sustainability studies (Liu et al., 2007; An, 2012; Okpara et al., 2018). However, development and application of relevant models for such integration still remains a key research challenge to achievement of long-term urban sustainability (Garcia et al., 2016; Fu and Wei, 2018).

Growing cities thus still require support in the form of novel methods and tools for their urban planning, in order to consider, compare, and decide among various possible pathways to reaching compliance with environmental regulations and to meeting other environmental and social sustainability challenges (Fu and Zhang, 2017; Jang et al., 2018). In light of these major challenges to achieving long-term urban sustainability, this paper refines a previously reported approach for modeling urban coupled social-ecological systems (CSES). The basic CSES modeling approach is the “Land use Evolution and impact Assessment Model” (LEAM) (Deal et al., 2013; Pan et al., 2018), which accounts for socio-economically driven land use changes and their feedbacks to urban and socio-economic development. Here, the CSES approach is extended to consider and model linked hydrological and water resource changes by use of the hydrological model “Hydrological Predictions for the Environment” (HYPER) (Arheimer et al., 2008). This model extension allows for examination of: (a) how population and socio-economic changes drive land use changes, and (b) associated hydrological and water resource changes. This study tests the applicability of the extended CSES modeling approach by

examining these questions for a concrete case study, Tyresån river catchment and its nested sub-catchments within Stockholm County, Sweden.

2. Materials and methods

2.1. CSES modeling approach and extension

Although urban areas face major challenges in terms of sustainability, they also have great opportunities to address these challenges through efficient solutions (Swedish Delegation for Sustainable Cities, 2012). Until recently, the fact that ecosystems are important components of cities, providing relevant services and benefits, has largely been ignored. However, to understand and influence urban development towards a sustainable future, it is necessary to consider these urban interdependencies (Wang et al., 2018), by integrating various social and ecosystem aspects in assessment and planning of urban development scenarios.

Conventional modeling approaches do not explicitly consider main links between social and ecosystems aspects, and are thereby unable to assess how various system changes propagate through urban CSES (Garcia et al., 2016). Modeling methods for such coupled assessment have been developed and refined recently (Goldenberg et al., 2017; Mörtberg et al., 2017). These are based e.g., on Geographical Information System (GIS) data and model tools (De Groot et al., 2012; Burkhard et al., 2013; Wolff et al., 2015), landscape structure analysis (Zetterberg et al., 2010), and remote sensing techniques (Haas and Ban, 2017). In a further development of social-hydrological modeling, a coupled modeling study has linked urban expansion to changes in blue and green water availability in New Jersey, USA, and has produced results that could be helpful in decision making on urban planning (Giri et al., 2018).

The CSES model extension in this study links hydrological conditions, changes, and feedbacks (through HYPE modeling; Arheimer et al., 2008) with the basic land cover/use-focused CSES modeling of LEAM (Fig. 1). This extension follows the lines discussed previously by Pan et al. (2018). It is essential if urban CSES modeling is to consider and meet model needs and planning challenges related to water, which is a key resource for urban-regional development and its sustainability (BIO Intelligence Service, 2014; Chen et al., 2017; Engström et al., 2017).

2.2. Case study application of the CSES approach

The extended CSES modeling approach (Fig. 1) was used to explore two main questions, related to the general issues outlined in section 1 of this paper, for the specific case study example of the Tyresån catchment in Stockholm County, Sweden. These were: (a) What land use changes are driven by projected population and socio-economic changes in the study area? and (b) What are the associated hydrological and water resource changes, and their social and ecosystem implications?

In Sweden, the average population growth rate was 4.4‰ per year in the period 1960–2008 and is projected to decrease to 2.8‰ per year in the period 2009–2060 (SCB, 2009). In 2005, which is used as the base year in this study, approximately 1,803,000 people lived in Stockholm County (TRF, 2012), out of a total Swedish population of 9,747,355 (SCB, 2014). Stockholm county includes the capital of Sweden, Stockholm, which is the most populous city in Scandinavia and the most attractive residential location in Sweden. Thus Stockholm County has seen a steeper population increase than the rest of Sweden in recent years, and this trend is expected to continue in the future. Although population forecasts differ, the Swedish Growth and Regional Planning Administration (TRF) projects a future population range of between 3.0 and 3.7 million for Stockholm County by 2050 (TRF, 2018).

The most likely projected population growth in Stockholm County

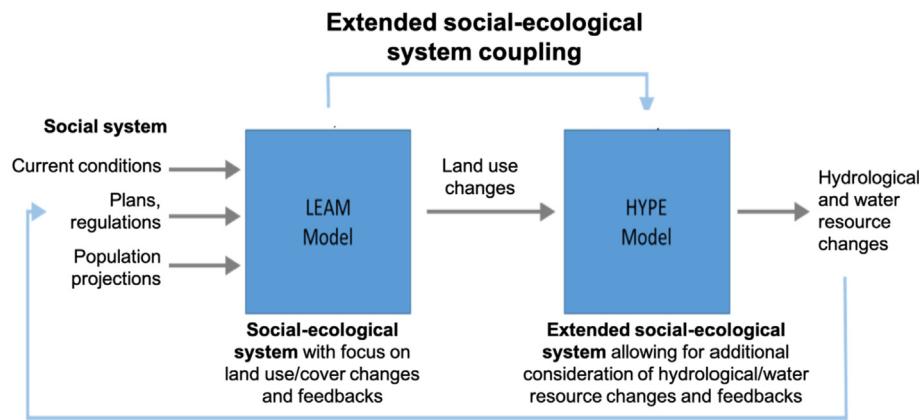


Fig. 1. Schematic illustration of the Coupled Social-Ecological System modeling approach, with the basic land cover/use focused model LEAM and the coupling to the hydrological model HYPE.

will be from 2.23 million in 2015 to 3.39 million in 2050. This is the ‘base’ population growth value calculated by the Stockholm planning authorities and used by them in planning for future development in the county (TRF, 2018). This significant population increase will require urban development in terms of additional houses, schools, and other infrastructure. While the planning authorities of Stockholm County and Stockholm City are concerned with the sustainability of urban development, the scale of development required for the projected population expansion is also expected to affect regional ecosystems.

Within Stockholm County, we chose the Tyresån river catchment with its seven nested sub-catchments (1–7) as a case study (Fig. 2). This catchment is located 10 km south of Stockholm City, covers approximately 109 km², and is part of a larger Tyresån Lake System (total drainage basin of approximately 240 km²).

The Tyresån catchment is mostly composed of coniferous forests and the urban areas of Huddinge, the second largest municipality after Stockholm in terms of population, and Farsta. Farther south, the catchment landscape contains coniferous and small deciduous forests, grasslands, agricultural areas, and wetlands. The elevation in the study area ranges between 30 and 50 m above sea level.

2.3. Model description

The basic CSES model LEAM (e.g., Pan et al., 2018), developed at the University of Illinois (<http://www.leam.uiuc.edu>), is based on a cellular automata approach to simulating urban growth, using 30 m by 30 m cells as basic landscape units that give relatively high spatial resolution. The model is designed to project patterns of urban growth based on causal mechanisms between human activities and land use changes. In general, a probability surface, defined by social, economic, and biophysical factors, evolves over time and drives the land use transformation. This probability is determined by the local attributes of each cell, interactions between neighboring cells, and global information available to the model. Rules for calculating probabilities are based on a dynamic set of sub-models which, combined with the spatial allocation process, produce spatial changes in the landscape. A comprehensive description of LEAM can be found in Deal (2001) and Deal et al. (2013), with a detailed technical description in Deal et al. (2005) and Pan et al. (2018). The LEAM model is calibrated using a Stochastic Greedy Algorithm (SGA) and validated using past development data as far as possible, and through visual comparison with actual development scenarios. A more detailed description of this process can be found in Deal et al. (2017), and in the comprehensive LEAM papers cited above. LEAM can be used to test various future development scenarios, in order to assist in making policy decisions to guide development towards a desired future scenario.

For the specific case study of Tyresån catchment, LEAM was first set

up and used to simulate projected land use changes over the whole of Stockholm County, based on initial spatial and non-spatial data drivers, for the horizon 2050. Current land use conditions and projected land use changes, derived from a specific urbanization scenario example developed in LEAM (Fig. 3), were then used as input data for the hydrological model HYPE, as illustrated in Fig. 1.

The model HYPE, developed and maintained by the Swedish Meteorological and Hydrological Institute (SMHI, 2019), is an open-source, semi-distributed, integrated hydrological and nutrient transport model (Arheimer et al., 2008). The model structure is based on a multi-catchment approach, with each main river catchment divided into sub-catchments and each sub-catchment divided into a set of soil type/land use classes called SLC (Soil type Land use Combination) representing different hydrological response units (Flügel, 1995; Strömqvist et al., 2012). Thus, different land use types and soil types have different parameters that are combined as SLCs, which have different (hydrological) responses. To each sub-catchment is assigned a record of the relative proportion (% of coverage) of all different SLC types that exist in the catchment. More information is available here:

http://www.smhi.net/hype/wiki/doku.php?id=start:hype_model_description:hype_land

Data for each sub-catchment are processed sequentially, from headwaters to outlet, to consider individual contributions following the water flow pathway. A thorough description of the conceptual structure and details of model equations can be found in Lindström et al. (2010), with up-to-date information available in the model documentation pages (<http://www.smhi.net/hype/wiki/doku.php>). HYPE has been calibrated and validated by SMHI for the whole of Sweden, including the catchment in this study (for more information, visit <https://www.smhi.se/en/research/research-departments/hydrology/hype-1.7994>). The first version of the national set-up (called S-HYPE) is described in Strömqvist et al. (2012), with new and improved versions being released continuously. The main objective of S-HYPE is to obtain an overall good model performance and a model capable of predicting in ungauged basins. In addition, regional parameter adjustment factors are employed for certain regions to describe spatial variations that cannot be accounted for by the forcing data or process formulations.

S-HYPE is calibrated and validated using some 300 discharge observation stations that are rather evenly distributed throughout the country. For the category small catchments (< 200 km²) with a minor degree of regulation (< 5%), to which the Tyresån catchment belongs, 71% of the catchments have a relative error in mean discharge of $\pm 10\%$ and 96% an error of $\pm 30\%$. In the nearest discharge station, located just east of the main Tyresån catchment (Fig. 2), the model error is -1.3% . This justifies extracting the Tyresån local HYPE model from S-HYPE and using it for hydrological simulation in this study.

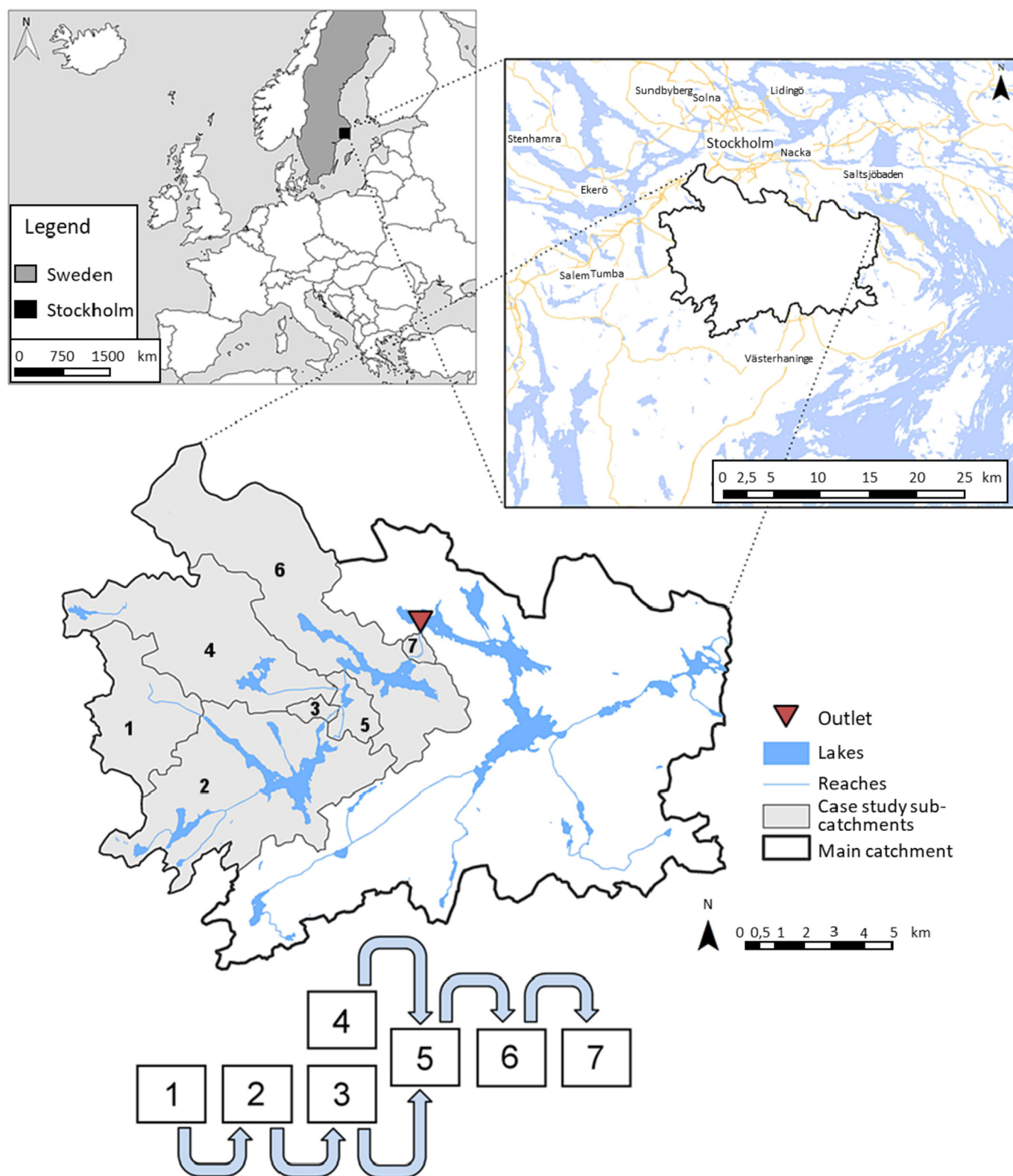


Fig. 2. Location of Stockholm, the total drainage basin of Tyresån Lake System (thick line), and the main Tyresån catchment (gray) with seven nested sub-catchments (1–7) considered in this case study. The diagram at the bottom shows the flow directions between sub-catchments.

2.4. Data processing

2.4.1. LEAM

For exemplifying and illustrative purposes in this study, only one future scenario was considered in the basic CSES modeling with LEAM

for providing the land use output (Fig. 3) required as input for the HYPE modeling extension for the Tyresån sub-catchments. The LEAM simulation was run for 2005 and 2050, considering the most likely development scenario and its regional land use/cover effects for Stockholm County.

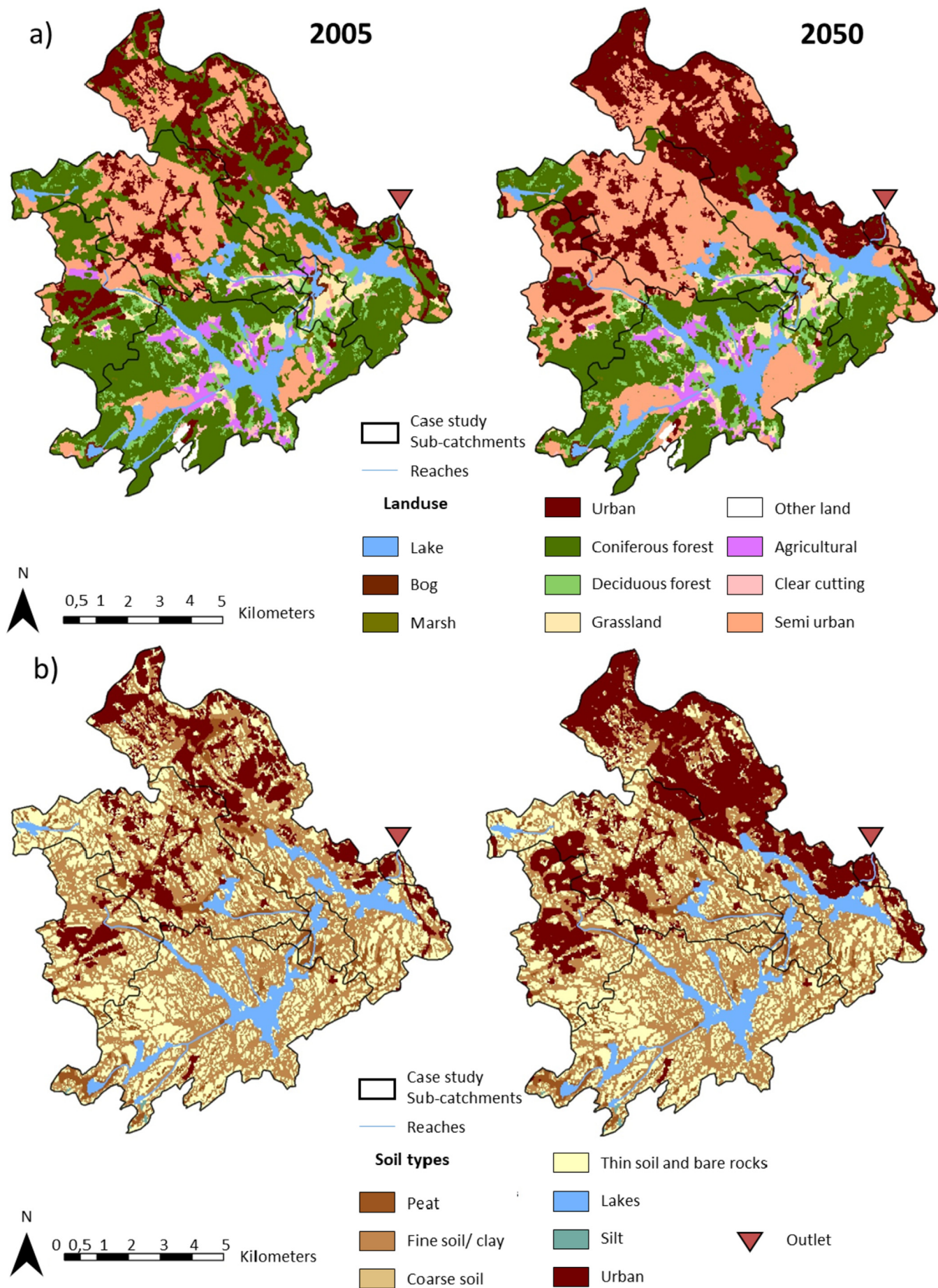


Fig. 3. (a) Land cover map and (b) soil map for the Tyresån catchment in the initial situation (2005, left) and the future scenario (2050, right).

The geographical data required as inputs to LEAM were obtained from the open database maintained by the Swedish Mapping, Cadastral and Land Registration Authority (Lantmäteriet). They included land cover data, a digital elevation model (DEM), orthophotos, vector maps, and a road network map (Lantmäteriet, 2018). Population and employment data obtained from Statistics Sweden (SCB, 2009) were first processed to produce results for the whole of Stockholm County. Data preparation for the 2050 scenario comprised two main parts: demographic projections and regional drivers. The population projection used in LEAM was the most likely ‘base’ projection from TRF (2018), i.e., 3.39 million people by 2050. Data for regional socio-economic drivers, including existing population, employment centers, and no-growth zones (areas where no development is allowed, such as nature reserves), were extracted from the regional plan for Stockholm County until 2050 (TRF, 2018). In processing the data for use in LEAM, the original data resolution of 25 m was adapted to the 30 m resolution of LEAM.

The LEAM simulation, conducted for a 45-year period (2005–2050), followed a ‘business as usual’ scenario. New residential areas were assumed to be developed with inhabitant densities similar to neighboring pre-existing conditions. The development attractiveness of the different population and employment centers in the region was ranked according to their initial values (based on population and employment density), with several areas being restricted for development due to their cultural, ecological, or strategic value, or due to current legislation. In summary, the scenario studied is one where urban growth is allowed in all areas except for a few no-growth zones (e.g., with nature reserve status). This growth is not limited to certain core areas, and thus results in some urban sprawl and overall urban expansion.

LEAM produces results on a cell-per-cell basis, with each new cell developed by the model representing a new residential building. For the present model extension to HYPE, this information was generalized for use as land cover input to HYPE. Cells were then locally expanded to clusters depending on housing density, and further used to produce new land cover data for the year 2050. For use in HYPE, new housing developments with low density housing (fewer than 5 inhabitants per building) were classified as semi-urban and those with higher density (more than 5 inhabitants per building) were classified as urban.

2.4.2. HYPE

Initial land cover data (Lantmäteriet, 2018) and soil data obtained from the Swedish Geological Survey (SGU, 2010) contained 49 and 28 different characterization classes, respectively. The land cover data were reclassified to 11 classes and the soil data to nine classes for use in the HYPE model. This reduction was performed to obtain a manageable amount of SLC combinations, while still maintaining significant property differences between classes (Fig. 3). These two reclassified layers were then combined to produce 65 SLC for the study area. The same process was followed for both the initial situation (2005) and the 2050 scenario, and statistics for SLC area coverage in each sub-catchment were computed for the two comparative years. The SLC themselves remained unchanged between the two scenarios (each SLC represents a particular land use and soil type combination), but the proportions assigned to each sub-catchment were changed from the initial scenario to the future scenario. For example, a sub-catchment in which urban expansion occurs might initially have 35% of the area designated as urban SLC, while in the future scenario it could have 53% urban SLC (with a corresponding reduction in other SLCs in that sub-catchment).

This spatial information was summarized in matrices used as input data to the HYPE model. The SLC were lumped over each sub-catchment, and thus not directly tied to a geographical location within it. However, dividing the whole study catchment into the seven smaller sub-catchments conserved enough of the spatial differences and change

patterns in the regional urbanization scenario considered.

The HYPE model was set up using precipitation and temperature data for an eight-year period (2000–2008) provided by SMHI. The period 2000–2002 was used for model warm-up and was excluded from further analysis. SMHI also provided calibrated parameter data for application of HYPE to the Tyresån sub-catchments. These parameters are mostly dependent on the physical properties of different soil and land use types, and were kept constant between the two scenarios. The simulated hydrological changes between 2005 and 2050 thus depended on changes in soil and land use extent, and not on changing parameterization of each soil/land use type. The HYPE modeling thus facilitated assessment of hydrological changes due to changing extents of various soil and land use types in each sub-catchment and over the whole main study catchment.

3. Results

3.1. LEAM results for urban development

The urban fabric in 2005 and 2050 simulated by LEAM for the Tyresån sub-catchments is shown in Fig. 4. In the scenario studied, urban development is most likely to occur around the large municipalities. In the southern Tyresån sub-catchments, urban development is limited due to continued forestry and agriculture.

The overall population increase in Stockholm County, from 1,803,000 in 2005 to 3,388,000 in 2050, results in an 18% increase in total urban area within the Tyresån sub-catchments (Table 1). Most of the new urban development in Stockholm County occurs in the suburbs of Stockholm City, since semi-urban areas provide the main remaining undeveloped land for such development. Major expansion of urban cover is projected to occur in sub-catchments 1, 4, 6, and 7 of the Tyresån catchment (Table 1).

3.2. LEAM-HYPE results for hydrological changes

Mean daily discharges from each sub-catchment for 2005 and 2050 are shown in Fig. 5. The highest discharges occur during the winter period (December–March), when temperatures first rise above 0 °C initiating snowmelt after periods of snow accumulation. Secondary peak discharges occur in April, when temperatures rise consistently above 0 °C and cause all remaining ice and snow to melt. A third discharge peak occurs during July and August, which have the highest monthly rainfall. Discharge in 2005 and 2050 is similar when the main water source is snowmelt, and diverges more when the main source is rainfall (Fig. 5).

Total annual runoff (discharge normalized with catchment area), surface runoff, and evapotranspiration (ET) for the seven Tyresån sub-catchments in 2005 and 2050 are shown in Table 2. A general increase in runoff and decrease in ET is seen for most sub-catchments. The runoff increase is greatest in the most downstream sub-catchment 7 (30% at the outlet), due to the combined effects of both local and upstream urbanization, but is also considerable in sub-catchment 6 (22%), with greater relative urban area in the 2050 scenario than in more upstream sub-catchments. Surface runoff increases from 2005 to 2050 for the upstream sub-catchments (1, 4, and 5) and for the most downstream sub-catchment station (7) that receives and conveys the runoff from the whole main catchment. Sub-catchments 2, 3, and 5 have stable runoff and ET fluxes, with negligible changes from 2005 to 2050 (Fig. 6). In 2005, the ratio ET/runoff ratio was > 1 for all sub-catchments, meaning that more water left the catchment via evapotranspiration than via runoff. With the increased urban development in 2050, this ratio decreases for all sub-catchments except number 2, with the greatest decreases occurring in sub-catchments 6 and 7, to ET/P < 1,

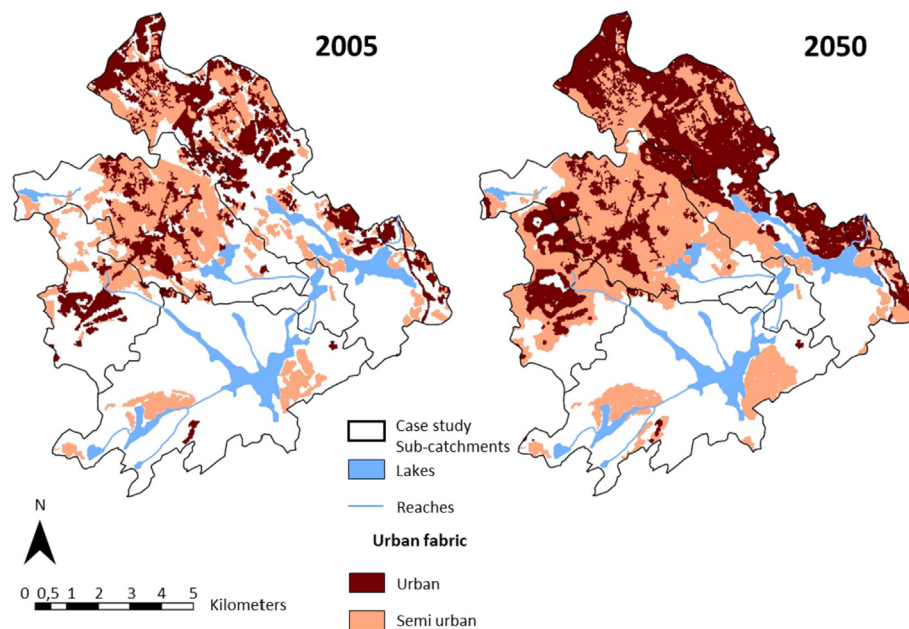


Fig. 4. Spatial distribution of urban and semi-urban areas in the Tyresån sub-catchments for the initial situation (2005) and the future development scenario (2050).

implying more water leaving as runoff than evapotranspiration.

4. Discussion

4.1. Water change implications and feedbacks

The greatest simulated water impacts, in terms of decreased ET and increased total runoff and surface runoff, occur in sub-catchments 6 and 7, which also have the largest urban increases, implying the greatest increases in impervious surface areas. Urban areas, with high surface sealing, dominate these two sub-catchments, which consequently also exhibit the greatest decreases in ET/runoff in the future scenario (Table 2, Fig. 6). These changes shift the hydrological regime in these sub-catchment areas into more water leaving the areas as runoff than through ET. Increased runoff and decreased ET due to urbanization have also been found in other studies (e.g., Kalantari et al., 2017a). The future water resource implications are decreased groundwater recharge, increased flooding hazard, and less water feeding vegetation and more flowing into rivers and man-made drainage systems (e.g., Shuster et al., 2014). Less water feeding vegetation and associated smaller ET also means decreased latent heat flux and less associated local cooling (Destouni et al., 2010) to mitigate the urban heat island

effect (Voogt and Oke, 2003). The changes in seasonal discharge from 2005 to 2050 (Fig. 5) further indicate that the hydrological effects of urbanization are more important for the direct rainfall contributions than the snowmelt contributions to runoff.

Other key drivers, not explored in the present study, are also important for understanding future hydrological changes. In particular, climate change effects can be expected to modify rainfall and snowmelt patterns, and associated responses of runoff (IPCC, 2013), as well as soil moisture and groundwater recharge/level (Destouni and Verrot, 2014). Climate change projections (Olsson and Foster, 2013; Strandberg et al., 2015) need to be combined with projections of socio-economically driven land use changes in order to assess future hydrological changes (Jarsjö et al., 2012; Kalantari et al., 2014). The extended LEAM-HYPE based approach to CSES modeling developed and exemplified in this study can be used for such projection combinations, in support of urban and regional development planning that accounts for changes in land cover/use and in hydro-climatic and water resource conditions.

4.2. CSES modeling for urban areas

In general, social systems and ecosystems are both highly complex, and combining the two adds further complexity. Until recently,

Table 1

Urban cover in the seven Tyresån sub-catchments and over the whole main study catchment in 2005 and 2050 (for location of sub-catchments 1–7, see Fig. 2).

Sub-catchment			1	2	3	4	5	6	7	Whole catchment
2005	Incremental area	(km ²)	12.99	32.16	0.99	23.85	2.89	35.08	0.81	108.77
		(km ²)	1.76	0.32	0.00	3.80	0.00	9.63	0.30	15.81
	Urban area	(%)	14	1	0	16	0	27	37	15
		(km ²)	2.35	2.86	0.00	9.15	0.18	7.61	0.12	22.27
	Semi-urban area	(%)	18	9	0	38	6	22	15	20
2050	Total urban fabric	(km ²)	4.11	3.18	0.00	12.95	0.18	17.24	0.42	38.08
		(%)	32	10	0	54	6	49	52	35
	Urban area	(km ²)	3.25	0.32	0	4.94	0	16.3	0.55	25.36
		(%)	25	1	0	21	0	46	68	23
	Semi-urban area	(km ²)	5.06	5.02	0.00	12.10	0.28	9.37	0.19	32.02
Increase in total urban fabric (2005–2050)	Total urban fabric	(%)	39	16	0	51	10	27	23	29
		(km ²)	8.31	5.34	0.00	17.04	0.28	25.67	0.74	57.38
	Urban area	(%)	64	17	0	71	10	73	91	53
		(km ²)	4.20	2.16	0.00	4.09	0.10	8.43	0.32	19.30
	Semi-urban area	(%)	32	7	0	17	4	24	39	18

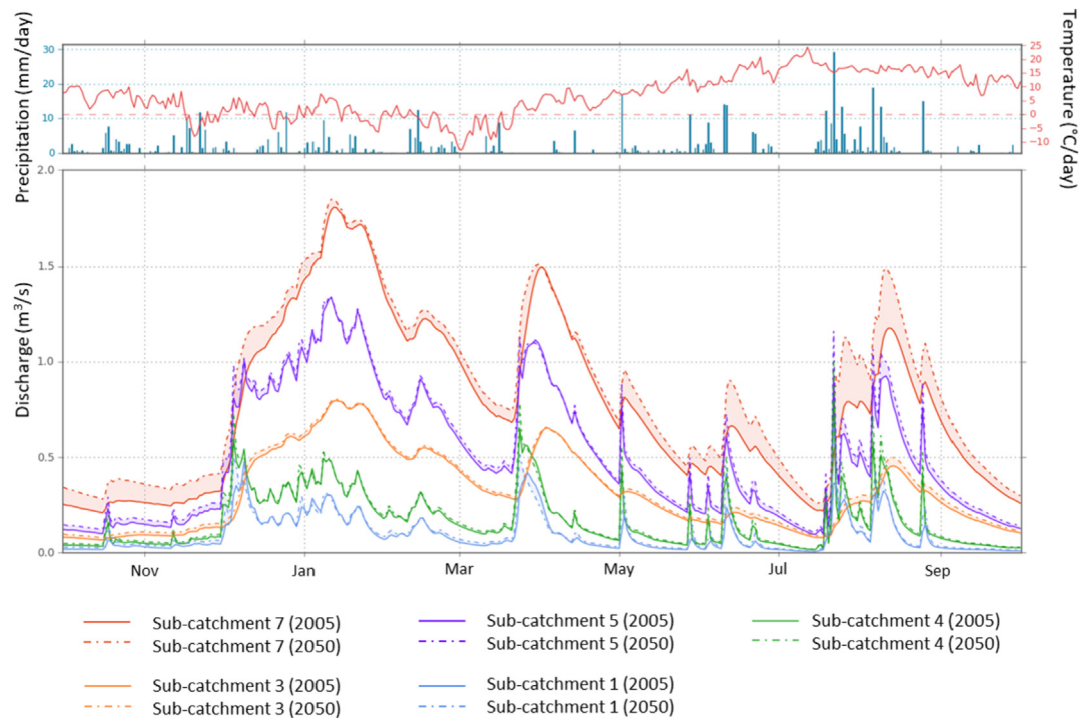


Fig. 5. Daily precipitation and average temperature for the hydrological year 2004–2005 (upper diagram) and simulated daily discharge from some of Tyresån sub-catchments (lower diagram). Solid lines represent the 2005 discharge and dashed lines represent the simulated discharge for the 2050 scenario.

ecosystems have been largely ignored as city components, even though they provide important services, such as flood mitigation (Godschalk, 2003), air cleaning (Nowak et al., 2006), and psychological benefits (van den Berg et al., 2010). Existing knowledge of how urban social systems and ecosystems interact is relatively limited, and capacity building is needed for both projecting and dealing with their combined future changes (Folke et al., 2005).

The specific need to combine social and hydrological research for improved understanding of water-related CSES links and feedbacks has been discussed in previous studies (e.g., Elshafei et al., 2014). Garcia et al. (2016) have used socio-hydrological modeling in support of water reservoir operations, considering distinct policy aspects. Tesfatsion et al. (2017) have explored the capabilities of agent-based modeling for studying temporal interactions between hydrology, climate and human decision making. Noel and Cai (2017) have coupled an agent-based model of farmers' behavior and a groundwater model for assessing the

impacts of groundwater-fed irrigation on the regional aquifer.

The coupled LEAM modeling of socio-economically driven land use/cover changes and HYPE modeling of associated hydrological changes presented in this study extends and complements previous water-related CSES modeling. LEAM can be coupled to other hydrological models instead of HYPE, as tested and suggested to be well-suited for urban planning in previous studies (Pan et al., 2018). In general, such model couplings open new possibilities to study and evaluate future urbanization trajectories and their social-ecological impacts and feedbacks across various temporal-spatial scales and parts of the world (Grimm et al., 2008b).

5. Conclusions

The CSES modeling approach developed and applied in this study couples the dynamic urban growth model LEAM with the semi-

Table 2

Mean annual precipitation (2000–2008) and total annual runoff, surface runoff, and evapotranspiration (ET) in the seven Tyresån sub-catchments (1–7), in the base case (2005) and the future scenario (2050).

Sub-catchment			1	2	3	4	5	6	7
Precipitation		(mm)	521	539	543	508	570	502	526
2005	Total runoff	(mm)	214	214	191	210	223	231	257
		(% of precipitation)	41	40	35	41	39	46	49
	Surface runoff	(mm)	43	10	4	50	5	84	106
		(% of precipitation)	8	2	1	10	1	17	20
		(% of total runoff)	20	5	2	24	2	36	41
2050	ET	(mm)	301	326	345	294	334	271	261
		(% of precipitation)	58	60	64	58	59	54	50
	Total runoff	(mm)	242	214	193	223	223	281	335
		(% of precipitation)	46	40	36	44	39	56	64
	Surface runoff	(mm)	75	10	4	64	5	138	193
2050		(% of precipitation)	14	2	1	13	1	27	37
		(% of total runoff)	31	5	2	29	2	49	58
	ET	(mm)	274	327	346	283	335	227	183
		(% of precipitation)	53	61	64	56	59	45	35
Runoff increase (2005–2050)		(%)	13	0	1	6	0	22	30

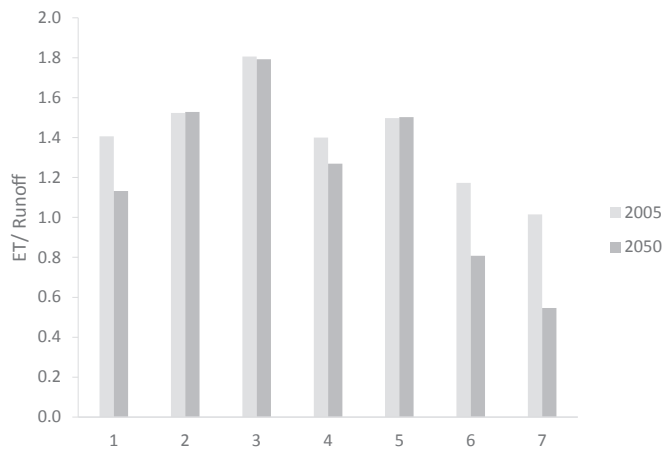


Fig. 6. Evapotranspiration (ET)/runoff ratio for the seven Tyresån sub-catchments (1–7) in 2005 and 2050.

distributed hydrological model HYPE to quantify essential urbanization links, effects, and feedbacks of socio-economically driven land use changes and hydrological changes. Application of the approach in a Swedish case study showed that it can account for spatial variations in linked land use and hydrological changes over an urban/metropolitan region, and provide insights into societal and ecosystem impacts and feedbacks on urbanization.

The coupled approach can also enable further exploration of urban development impacts and feedbacks. For example, it can be adapted to analyze various population and land use scenarios in combination with climate change projections. This would improve basic understanding and support adaptive land use planning, management, and policy in the Stockholm region and in other parts of the world.

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References

- Abu Bakar, A.H., Cheen, K.S., 2013. A framework for assessing the sustainable urban development. *Proced. Soc. Behv.* 85, 484–492.
- Adams, W., 2006. *The Future of Sustainability: Re-thinking Environment and Development in the Twenty-First Century*. The World Conservation Union.
- Ahlmer, A.-K., Cavalli, M., Hansson, K., Koutsouris, A.J., Crema, S., Kalantari, Z., 2018. Soil moisture remote-sensing applications for identification of flood-prone areas along transport infrastructure. *Environ. Earth Sci.* 77, 533. <https://doi.org/10.1007/s12665-018-7704-z>.
- An, L., 2012. Modeling human decisions in coupled human and natural systems: review of agent-based models. *Ecol. Model.* 229, 25–36. <https://doi.org/10.1016/j.ecolmodel.2011.07.010>.
- Arheimer, B., Lindström, G., Pers, C., Rosberg, J., Strömquist, J., 2008. Development and test of a new Swedish water quality model for small-scale and large-scale applications. In: XXV Nordic Hydrological Conference, Reykjavik, August 11–13, 2008. NHP Report No. 50, pp. 483–492.
- Bentivegna, V., Curwell, S., Deakin, M., Lombardi, P., Mitchell, G., Nijkamp, P., 2002. A vision and methodology for integrated sustainable urban development. *BEQUEST. Build. Res. Inf.* 30, 83–94. <https://doi.org/10.1080/096132102753436468>.
- BIO Intelligence Service, 2014. *Soil and Water in a Changing Environment, Final Report Prepared for European Commission (DG ENV), with Support from HydroLogic*.
- Brandon, P.S., Lombardi, P., 2010. *Evaluating Sustainable Development in the Built Environment*. John Wiley & Sons, London, UK.
- Burkhard, B., Crossman, N., Nedkov, S., Petz, K., Alkemade, R., 2013. Mapping and modelling ecosystem services for science, policy and practice. *Ecosyst. Serv.* 4, 1–3. <https://doi.org/10.1016/j.ecoser.2013.04.005>.
- Chen, Z., Wu, Q., Wu, G., Hu, H.-Y., 2017. Centralized water reuse system with multiple applications in urban areas: lessons from China's experience. *Resour. Conserv. Recycl.* 117, 125–136. <https://doi.org/10.1016/j.resconrec.2016.11.008>.
- De Groot, R., Fisher, B., Christie, M., Aronson, J., Braat, L., Gowdy, J., et al., 2012. Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation. In: *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*. Taylor and Francis, pp. 9–40. <https://doi.org/10.4324/9781849775489>.
- Deal, B., 2001. Ecological urban dynamics: the convergence of spatial modelling and sustainability. *Build. Res. Inf.* 29 (5), 381–393.
- Deal, B., Pallathucherial, V., Sun, Z., Terstriep, J., Hartel, W., 2005. *LEAM Technical Document: Overview of the LEAM Approach*. University of Illinois at Urbana-Champaign, pp. 76.
- Deal, B., Kim, J.H., Hewings, G.J.D., Kim, Y.W., 2013. Complex urban systems integration: the LEAM experiences in coupling economic, land use, and transportation models in Chicago, IL. In: Pagliara, F., M de Bok, D Simmonds, Wilson, A. (Eds.), *Employment Location in Cities and Regions*. Springer Berlin Heidelberg, pp. 107–131.
- Deal, B., Pan, H., Timm, S., Pallathucherial, V., 2017. The role of multidirectional temporal analysis in scenario planning exercises and Planning Support Systems. *Comput. Environ. Urban Syst.* 64, 91–102. <https://doi.org/10.1016/j.compenurbysys.2017.01.004>.
- Department for Communities and Local Government (DCLG), 2005. *Planning Policy Statement 1: Delivering Sustainable Development*. DCLG, London, UK.
- Destouni, G., Verrot, L., 2014. Screening long-term variability and change of soil moisture in a changing climate. *J. Hydrol.* 516, 131–139. <https://doi.org/10.1016/j.jhydrol.2014.01.059>.
- Destouni, G., Asokan, S., Jarsjö, J., 2010. Inland hydro-climatic interaction: effects of human water use on regional climate. *Geophys. Res. Lett.* 37. <https://doi.org/10.1029/2010GL044153>.
- Engström, R.E., Howells, M., Destouni, G., Bhatt, V., Bazilian, M., Rogner, H.-H., 2017. Connecting the resource nexus to basic urban service provision - with focus on water-energy interactions in New York City. *Sustain. Cities Soc.* 31, 83–94. <https://doi.org/10.1016/j.scs.2017.02.007>.
- Elshafei, Y., Sivapalan, M., Tonts, M., Hipsey, M.R., 2014. A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach. *Hydrol. Earth Syst. Sci.* 18, 2141–2166.
- European Union (EU), 1998. *Sustainable Urban Development in the European Union: A Framework for Action*. European Commission, Brussels, Belgium.
- European Union (EU), 2007. *Leipzig Charter*. European Council, Brussels, Belgium. https://ec.europa.eu/regional_policy/archive/themes/urban/leipzig_charter.pdf.
- Ferreira, C.S.S., Walsh, R.P.D., Steenhuis, T.S., Shakesby, R.A., Nunes, J.P.N., Coelho, C.O.A., Ferreira, A.J.D., 2015. Spatiotemporal variability of hydrologic soil properties and the implications for overland flow and land management in a peri-urban Mediterranean catchment. *J. Hydrol.* 525, 249–263. <https://doi.org/10.1016/j.jhydrol.2015.03.039>.
- Ferreira, A.J.D., Soares, D., Serrano, L.M.V., Walsh, R.P.D., Ferreira, C.M.D., Ferreira, C.S.S., 2016. Roads as sources of heavy metals in urban areas. The Covões Catchment experiment, Coimbra, Portugal. *J. Soils Sediments* 16, 2622–2639. <https://doi.org/10.1007/s11368-016-1492-4>.
- Ferreira, C.S.S., Walsh, R.P.D., Blake, W.H., Kikuchi, R., Ferreira, A.J.D., 2017. Temporal dynamics of sediment sources in an urbanizing Mediterranean catchment. *Land Degrad. Dev.* 28, 2354–2369. <https://doi.org/10.1002/ldr.2765>.
- Flügel, W.A., 1995. Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. *Hydrol. Process.* 9, 423–436.
- Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of social-ecological systems. *Annu. Rev. Env. Resour.* 30, 441–473.
- Fu, B., Wei, Y., 2018. Editorial overview: keeping fit in the dynamics of coupled natural and human systems. *Curr. Opin. Env. Sust.* 33, A1–A4. <https://doi.org/10.1016/j.coust.2018.07.003>.
- Fu, Y., Zhang, X.L., 2017. Planning for sustainable cities? A comparative content analysis of the master plans of eco, low-carbon and conventional new towns in China. *Habitat Int.* 63, 55–66. <https://doi.org/10.1016/j.habitatint.2017.03.008>.
- Garcia, M., Portney, K., Islam, S., 2016. A question driven socio-hydrological modeling process. *Hydrol. Earth Syst. Sc.* 20, 73–92. <https://doi.org/10.5194/hess-20-73-2016>.
- Gibbs, D., Krueger, R.O.B., 2012. Fractures in meta-narratives of development: an interpretive institutional account of land use development in the Boston city-region. *Int. J. Urban Regional* 36 (2), 363–380. <https://doi.org/10.1111/j.1468-2427.2011.01061.x>.
- Gibbs, D., O'Neill, K., 2015. Building a green economy? Sustainability transitions in the UK building sector. *Geoforum* 59, 133–141.
- Giri, S., Arab, N., Lathrop, R., 2018. Water security assessment of current and future scenarios through an integrated modeling framework in the Neshanic River Watershed. *J. Hydrol.* 563, 1025–1041. <https://doi.org/10.1016/j.jhydrol.2018.05.046>.
- Godschalk, D., 2003. Urban hazard mitigation: creating resilient cities. *Nat. Hazards Rev.* 4 (3), 136–143.
- Goldenberg, R., Kalantari, Z., Cvetkovic, V., Mörtberg, U., Deal, B., Destouni, G., 2017. Distinction, quantification and mapping of potential and realized supply-demand of flow-dependent ecosystem services. *Sci. Total Environ.* 593–594, 599–609. <https://doi.org/10.1016/j.scitotenv.2017.03.130>.
- Goldenberg, R., Kalantari, Z., Destouni, G., 2018. Increased access to nearby green-blue areas associated with greater metropolitan population well-being. *Land Degrad. Dev.* 29, 3607–3616. <https://doi.org/10.1002/ldr.3083>.
- Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008a. Global change and the ecology of cities. *Science* 319 (5864), 756–760. <https://doi.org/10.1126/science.1150195>.
- Grimm, N.B., Foster, D., Groffman, P., Grove, J.M., Hopkinson, C.S., Nadelhoffer, K.J.,

- Pataki, D.E., Peters, D.P.C., 2008b. The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients. *Front. Ecol. Environ.* 6 (5), 264–272.
- Guetté, A., Gaüzère, P., Devictor, V., Jiguet, F., Godet, L., 2017. Measuring the synanthropy of species and communities to monitor the effects of urbanization on biodiversity. *Ecol. Indic.* 79, 139–154. <https://doi.org/10.1016/j.ecolind.2017.04.018>.
- Gunawardena, K.R., Wells, M.J., Kershaw, T., 2017. Utilising green and bluespace to mitigate urban heat island intensity. *Sci. Total Environ.* 584–585, 1040–1055. <https://doi.org/10.1016/j.scitotenv.2017.01.158>.
- Haas, J., Ban, Y., 2017. Mapping and monitoring urban ecosystem services using multi-temporal high-resolution satellite data. *IEEE J. Sel. Top. Appl.* 10 (2), 669–680. <https://doi.org/10.1109/JSTARS.2016.2586582>.
- Hendricks, M.D., Meyer, M.A., Gharaibeh, N.G., Van Zandt, S., Masterson, J., Cooper, J.T., Berke, P., 2018. The development of a participatory assessment technique for infrastructure: neighborhood-level monitoring towards sustainable infrastructure systems. *Sustain. Cities Soc.* 38, 265–274. <https://doi.org/10.1016/j.scs.2017.12.039>.
- Intergovernmental Panel on Climate Change (IPCC), 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jang, W., Lee, S.K., Han, S.H., 2018. Sustainable performance index for assessing the green technologies in urban infrastructure projects. *J. Manag. Eng.* 34 (2). [https://doi.org/10.1061/\(asce\)me.1943-5479.0000582](https://doi.org/10.1061/(asce)me.1943-5479.0000582).
- Jarsjö, J., Asokan, S.M., Prieto, C., Bring, A., Destouni, G., 2012. Hydrological responses to climate change conditioned by historic alterations of land-use and water-use. *Hydrol. Earth Syst. Sci.* 16, 1335–1347.
- Jenkins, B.R., 2018. Application of sustainability framework. In: *Water Management in New Zealand's Canterbury Region*. Glob. Iss. Water Pol. 19. Springer, Dordrecht.
- Kalantari, Z., Folkeson, L., 2013. Road drainage in Sweden: current practice and suggestions for adaptation to climate change. *J. Infrastruct. Syst.* 19 (2), 147–156. [https://doi.org/10.1061/\(ASCE\)IS.1943-555X.0000119](https://doi.org/10.1061/(ASCE)IS.1943-555X.0000119).
- Kalantari, Z., Lyon, S.W., Folkeson, L., French, H.K., Stolte, J., Jansson, P.-E., Sassner, M., 2014. Quantifying the hydrological impact of simulated changes in land use on peak discharge in a small catchment. *Sci. Total Environ.* 466–467, 741–754. <https://doi.org/10.1016/j.scitotenv.2013.07.047>.
- Kalantari, Z., Ferreira, C.S.S., Walsh, R.P.D., Ferreira, A.J.D., Destouni, G., 2017a. Urbanization development under climate change: hydrological responses in a peri-urban mediterranean catchment. *Land Degrad. Dev.* 28 (7), 2207–2221. <https://doi.org/10.1002/ldr.2747>.
- Kalantari, Z., Cavalli, M., Cantone, C., Crema, S., Destouni, G., 2017b. Flood probability quantification for road infrastructure: data-driven spatial-statistical approach and case study applications. *Sci. Total Environ.* 581–582, 386–398. <https://doi.org/10.1016/j.scitotenv.2016.12.147>.
- Kalantari, Z., Ferreira, C.S.S., Keesstra, S., Destouni, G., 2018. Nature-based solutions for flood-drought risk mitigation in vulnerable urbanizing parts of East-Africa. *Curr. Opin. Environ. Health.* 5, 73–78. <https://doi.org/10.1016/j.coesh.2018.06.003>.
- Kalantari, Z., Ferreira, C.S.S., Koutsouris, A.J., Ahmer, A.-K., Cerdà, A., Destouni, G., 2019. Assessing flood probability for transportation infrastructure based on catchment characteristics, sediment connectivity and remotely sensed soil moisture. *Sci. Total Environ.* 661, 393–406. <https://doi.org/10.1016/j.scitotenv.2019.01.009>.
- Karlsson, C.S.J., Kalantari, Z., Mörtberg, U., Olofsson, B., Lyon, S.W., 2017. Natural hazard susceptibility assessment for road planning using spatial multi-criteria analysis. *Environ. Manag.* 60 (5), 823–851. <https://doi.org/10.1007/s00267-017-0912-6>.
- Keivani, R., 2010. A review of the main challenges to urban sustainability. *Int. J. Urban Sustain. Dev.* 1 (1–2), 5–16. <https://doi.org/10.1080/19463131003704213>.
- Lantmäteriet, 2018. <https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/oppna-data/>, Accessed date: 15 April 2019.
- Lenferink, S., Tillema, T., Arts, J., 2013. Towards sustainable infrastructure development through integrated contracts: experiences with inclusiveness in Dutch infrastructure projects. *Int. J. Proj. Manag.* 31 (4), 615–627. <https://doi.org/10.1016/j.jiproman.2012.09.014>.
- Lindström, G., Pers, C.P., Rosberg, R., Strömqvist, J., Arheimer, B., 2010. Development and test of the HYPE (Hydrological Predictions for the Environment) model – a water quality model for different spatial scales. *Hydrol. Res.* 41 (3–4), 295–319.
- Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., Taylor, W.W., 2007. Complexity of coupled human and natural systems. *Science* 317 (5844), 1513–1516. <https://doi.org/10.1126/science.1144004>.
- Michielsen, A., Kalantari, Z., Lyon, S.W., Liljegen, E., 2016. Predicting and communicating flood risk of transport infrastructure based on watershed characteristics. *J. Environ. Manag.* 182, 505–518. <https://doi.org/10.1016/j.jenvman.2016.07.051>.
- Mörtberg, U., Goldenberg, R., Kalantari, Z., Kordas, O., Deal, B., Balfors, B., Cvetkovic, V., 2017. Integrating ecosystem services in the assessment of urban energy trajectories – a study of the Stockholm Region. *Energy Policy* 100, 338–349. <https://doi.org/10.1016/j.enpol.2016.09.031>.
- Noel, P.H., Cai, X., 2017. On the role of individuals in models of coupled human and natural systems: lessons from a case study in the Republican River Basin. *Environ. Model. Softw.* 92, 1–16. <https://doi.org/10.1016/j.envsoft.2017.02.010>.
- Nowak, D., Crane, D., Stevens, J., 2006. Air pollution removal by urban trees and shrubs in the United States. *Urban For. Urban Gree* 4 (3–4), 115–123.
- Okpara, U.T., Stinger, L.C., Akhtar-Schuster, M., Metternicht, G.I., Dallimer, M., Requier-Desjardins, M., 2018. A social-ecological systems approach is necessary to achieve land degradation neutrality. *Environ. Sci. Policy* 89, 59–66.
- Olsson, J., Foster, K., 2013. Short-term precipitation extremes in regional climate simulations for Sweden. *Hydrol. Res.* 45, 479–489. <https://doi.org/10.2166/nh.2013.206>.
- Organisation for Economic Co-operation and Development (OECD), 2011. *Effective modelling of urban systems to address the challenges of climate change and sustainability*. OECD Global Science Forum.
- Pan, H., Deal, B., Destouni, G., Zhang, Y., Kalantari, Z., 2018. Sociohydrology modeling for complex urban environments in support of integrated land and water resource management practices. *Land Degrad. Dev.* 29 (10), 3639–3652. <https://doi.org/10.1002/ldr.3106>.
- Pinz, A., Roudyani, N., Thaler, J., 2018. Public-private partnerships as instruments to achieve sustainability-related objectives: the state of the art and a research agenda. *Publ. Manag. Rev.* 20 (1), 1–22. <https://doi.org/10.1080/14719037.2017.1293143>.
- Shuster, W.D., Bonta, J., Thurston, H., Warnemuende, E., Smith, D.R., 2014. Impacts of impervious surface on watershed hydrology: a review. *Urban Water J.* 2, 263–275. <https://doi.org/10.1080/15730620500386529>.
- Statistics Sweden (SCB), 2009. Demographic Reports, the Future Population of Sweden 2009–2060. https://www.scb.se/statistik/publikationer/be0401_2009i60_br_be51br0901eng.pdf.
- Statistics Sweden (SCB), 2014. Available at: <https://www.scb.se/hitta-statistik/sverige-i-siffror/manniskorna-i-sverige/sveriges-befolkning/>, Accessed date: 31 December 2012.
- Strandberg, G., Barring, L., Hansson, U., Jansson, C., Jones, C., Kjellström, E., Kolax, M., Kupiainen, M., Nikulin, G., Samuelsson, P., Ullerstig, A., Wang, S., 2015. CORDEX Scenarios for Europe from the Rossby Centre Regional Climate Model RCA4, vol. 116 RMK, Stockholm, Sweden SMHI.
- Strömqvist, J., Arheimer, B., Dahné, J., Donnelly, C., Lindström, G., 2012. Water and nutrient predictions in ungauged basins: set-up and evaluation of a model at the national scale. *Hydrol. Sci. J.* 57 (2), 229–247.
- Sveriges Geologiska Undersökning (SGU), 2010. Geological Map. Swedish Geological Survey, Sweden.
- Swedish Delegation for Sustainable Cities, 2012. Take Action Now! Conclusions from the Government Assignment September 2008 – December 2012. <https://www.boverket.se/contentassets/dce3f7e3d80d4bcaa06ad2071366bda/take-action-now.pdf>.
- Swedish Environmental Protection Agency, 2017. A Good Built Environment. <http://www.swedishepa.se/Environmental-objectives-and-cooperation/Swedens-environmental-objectives/The-national-environmental-objectives/A-Good-Built-Environment/>, Accessed date: 12 April 2019.
- Swedish Growth and Regional Planning Administration (TRF), 2012. Befolkning, sysselsättning och inkomster i Östra Mellansverige - reviderade framskrivningar till år 2050. Rapport 1, 2012.
- Swedish Growth and Regional Planning Administration (TRF), 2018. Regional Utvecklingsplan för Stockholmsregionen (RUF) 2050. http://www.rufs.se/globalassets/h-publikationer/2018/rufs2050_webb.pdf.
- Swedish Meteorological and Hydrological Institute (SMHI) <http://www.smhi.se>, Accessed date: 15 April 2019.
- Tesfatsion, L., rehmann, C.R., Cardoso, D.S., Jie, Y., Gutwsky, W.J., 2017. An agent-based platform for the study of watersheds as coupled natural and human systems. *Environ. Model. Softw.* 89, 40–60. <https://doi.org/10.1016/j.envsoft.2016.11.021>.
- United Nations Development Program (UNDP), 2018. Cities 2030: Implementing the New Urban Agenda. <http://www.undp.org/content/undp/en/home/blog/2018/cities-2030-implementing-the-new-urban-agenda.html>, Accessed date: 7 March 2019.
- United Nations (UN), 2015. Transforming Our World: the 2030 Agenda for Sustainable Development. <https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf>.
- van den Berg, A., Maas, J., Verheij, R., Groenewegen, P., 2010. Green space as a buffer between stressful life events and health. *Soc. Sci. Med.* 70 (8), 1203–1210.
- Voogt, J.A., Oke, T.R., 2003. Thermal remote sensing of urban areas. *Remote Sens. Environ.* 86, 370–384.
- Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM), 2001. Making Space, Sharing Space: the Fifth National Policy Document on Spatial Planning 2000/2020. VROM, The Hague, The Netherlands.
- Wang, S., Fu, B., Zhao, W., Liu, Y., Wei, F., 2018. Structure, function, and dynamic mechanisms of coupled human-natural systems. *Curr. Opin. Env. Sust.* 33, 87–91. <https://doi.org/10.1016/j.cosust.2018.05.002>.
- Wolff, S., Schulp, C.J.E., Verburg, P.H., 2015. Mapping ecosystem services demand: a review of current research and future perspectives. *Ecol. Indic.* 55, 159–171. <https://doi.org/10.1016/j.ecolind.2015.03.016>.
- Wu, S., Li, S., 2019. Ecosystem service relationships: formation and recommended approaches from a systematic review. *Ecol. Indic.* 99, 1–11. <https://doi.org/10.1016/j.ecolind.2018.11.068>.
- Yang, J., Goh, K., Shen, G.Q., Li, D., Yigitcanlar, T., 2017. Transforming communication and decision-making practices for sustainable renewal of urban transport infrastructure future challenges. In: Brandon, P.S., Lombardi, P., Shen, G.Q. (Eds.), *Evaluating and Managing Sustainable Development in the Built Environment*. John Wiley & Sons, Ltd., pp. 285–305.
- Zetterberg, A., Mörtberg, U., Balfors, B., 2010. Making graph theory operational for landscape ecological assessments, planning, and design. *Landsc. Urban Plan.* 95, 181–191.
- Zheng, W., Shen, G.Q., Wang, H., Hong, J., Li, Z., 2017. Decision support for sustainable urban renewal: a multi-scale model. *Land Use Policy* 69, 361–371. <https://doi.org/10.1016/j.landusepol.2017.09.019>.