Abstract
This paper argues that a systems' thinking and explicit modeling approach is needed to address noted weaknesses (in terms of practicality and usefulness) in integrated water resource management. A process of coupling complex regional land use, economy, and water system interactions in integrated modeling is demonstrated with proof-of-concept applications to two urban cases (Chicago and Stockholm). In this uniquely coupled systems model, urban land use scenarios are considered a complex urban system represented by dynamic systems models of land use, economics, and water with a focus on urban environments that include drivers and system feedbacks with implications focused on urban water systems. The integrated model results reveal that the physical availability of land for economic activities (forecasted via a bottom-up land use change model) and their locations differ sharply from top-down sectoral-based economic forecasts. This shows that both human systems (economic and land use planning) and natural systems (land use limitations and associated water implications) need to be considered in order to accurately account for system(s) impacts. For example, flood zone regulations divert land use to other locations, whereas land cover changes can greatly affect the water infiltration characteristics of land surfaces and thereby alter hydrological outcomes. Our results indicate that modeling social and natural processes using a systems approach can provide a more comprehensive understanding of coupled causal mechanisms, impacts, and feedbacks in applications of integrated water resource management.

KEYWORDS
hydrological modeling, integrated water resource management, land use modeling, regional economy, stormwater management

1 INTRODUCTION
Cities are complex and evolving systems. Understanding these systems and their dynamics is becoming increasingly critical as urban areas shift from relatively static determinism, toward a dynamic and entropic "edge of chaos" (Langton, 1986). We argue that understanding the evolutionary point between stasis (characterized by a lack of responsiveness to change) and chaos (where actions become "lost in the static of irregular activity"; Marion, 1999) requires a systems approach. A systems approach acknowledges that complex behaviors

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cannot be understood or reliably improved by studying the behavior of system parts in isolation; the system must be viewed and understood as a dynamic interactive whole. We contend that this approach is critical for addressing the challenges inherent in both chaotic indeterminism and urban sustainability. A systems approach is especially critical for addressing the complex interactions between urban and water system dynamics. To address these challenges, we suggest a systems approach using nature-based solution sets.

A good example of a nature-based solution methodology that bridges natural and socioeconomic processes within a sustainability framework is integrated water resource management (IWRM; Hazbavi & Sadeghi, 2017; Pires et al., 2017). IWRM considers water management issues relative to land use planning and socioeconomic development while promoting the protection of natural processes and resources (Global Water Partnership [GWP], 2017; Liu, Gupta, Springer, & Wagener, 2008; Mitchell, 2005). According to the United Nations Department of Economic and Social Affairs (UNDESA), water is critical for driving economic and social development and for maintaining the integrity of the natural environment (GWP, 2017). They also warn that water issues cannot be considered in isolation and the traditional ‘fragmented approach’ to water management is no longer viable. UNDESA considers the IWRM approach as “the way forward for efficient, equitable, and sustainable development and management of the world’s limited water resources” and the “conflicting demands” for its use (GWP, 2017).

Despite the support of UNDESA, the GWP and other prominent water-centric organizations, the IWRM framework has not been universally accepted. Some contend, for example, that a lack of clarity and an inability to guide implementation inhibit its usefulness (Biswa, 2008). Generally, a review of the literature on IWRM reveals two consistent disadvantages to the process: (a) lack of a systems approach and (b) limited implementation practicality (Biswa, 2008; Giordano & Shah, 2014; Jeffrey & Gearey, 2006).

### 1.1 A systems approach in urban environmental awareness in IWRM

Sivapalan, Savenije, and Blöschl (2012) note that traditional, anthropocentric approaches to managing (and controlling) hydrological systems have failed. They propose a bottom-up process, on the basis of sociohydrological systems modeling, to understand coupled human–water systems (Sivapalan, Blöschl, Zhang, & Vertessy, 2003). This type of modeling, constructed to estimate the physical and economic performance of alternative river basin development configurations, has been widely used since the start of the Harvard Water Program in the early 1960s (Brown et al., 2015). The models have typically included characterization of population, economics, and community interaction with water in terms of (among others): quantity and quality (Di Baldassarre et al., 2013; Elshafei, Sivapalan, Tonts, & Hipsey, 2014; Viglione et al., 2014); security and governance (Gober & Wheater, 2014); and flood risk (Di Baldassarre et al., 2013; Elshafei et al., 2014; Viglione et al., 2014).

Recent studies have considered land use dynamics and potential impacts on water systems (Weber, Fohrer, & Möller, 2001; White, Engelen, & Uljee, 2000; Wijesekara et al., 2012). Weber et al. (2001) and White et al. (2000) demonstrate the importance of including socioeconomic system variables to understand the interaction between human and water systems. Wijesekara et al. (2012) combine a land use cellular automata model and a distributed physically based (MIKE-SHE/MIKE-11) hydrological model. The study revealed that due to the complex hydrological regime (in Southern Alberta, Canada), a comprehensive physically based method is required to better represent the interaction between groundwater and surface water. In both cases, land use is the key variable that links human activities to water, although in neither case are the simulations capable or testing alternative land use scenarios that are tied to policy or infrastructure investment choices. Farjad, Pooyandeh, et al. (2017) propose an original coupled human/land use/water framework that includes a land use/land cover change model, a stakeholders’ negotiation model, and a hydrological model. The modeling framework does not include complex urban systems-based dynamics (such as regional economics) nor does it involve policy scenario integration limiting its practical usefulness in planning (human)-based processes.

In this paper, we build on previous work integrating land use and water systems dynamics with some additional questions: If socioeconomic dynamics of human systems (in large and complex urban environments) are driving land use change, what are the implications in terms of water systems? This question is important because land use changes in large urban areas are often affected by activities from outside watershed boundaries, typically due to technological advances in transportation networks and communication methods. Alternatively, how do human interactions with the water systems affect land use and socioeconomic systems? This is discussed in part by Farjad, Pooyandeh, et al. (2017). The study notes that proximity to water is highly valued and generally favorable for residential and commercial location choices, but that flooding risks and controls limiting impervious surfaces help regulate proximity to urban water bodies.

### 1.2 Past implementations of IWRM projects

A review of the literature finds a limited record of successful IWRM implementations. The main issues reported include difficulties in setting up integrated models and problems with inferring policy from the IWRM processes (Hazbavi & Sadeghi, 2017; Liu et al., 2008; Medema, McIntosh, & Jeffrey, 2008; Pires et al., 2017; Yu et al., 2013). Although examples exist of implemented policy support systems models that account for, link, and operationalize complex socioeconomic and physical processes (Van Delden, Luja, & Engelen, 2007), there is a gap in addressing the practical difficulties in the entire process of establishing and delivering comprehensive coupled human–water systems models and their implications for socioeconomic systems in support of practical projects.

The research presented in this paper explores how hydrology interacts with regional economic systems through land use changes and the potential unforeseen and unintended consequences these interactions can produce. It also helps reveal how exposure to knowledge generated across urban settings using these models can affect sociohydrological learning at a deeper level, facilitating policy application and leading to more sustainable and resilient urban developments. We integrate regional economic, dynamic land use, and hydro-systems
models in an IWRM framework to explore the historical and evolving relationships between social activities and water within a context of changing climatic scenarios. We apply our framework to two cities, Chicago and Stockholm. Both Chicago and Stockholm are major economic hubs and have large metropolitan areas with diverse activities and critical connections to water systems.

This paper has two major contributions to sociohydrology modeling literature and IWRM practices. First, in our coupled systems model, land use scenarios are not static assumptions but are instead based on a complex urban systems model of linked socioeconomic and land use. The physical availability of land for economic activities is forecasted via bottom-up land use change probabilities that may differ from top-down, separate sectoral economic forecasts for a region. This modeling requires integration and justification of both human (economic and land use planning) and natural processes. Second, our approach allows for testing of various policies, produces data that can be used to engage a wider constituency, and can lead to more informed and consensually inclusive policies (Deal & Pan, 2016) and also facilitates testing of various IWRM configurations and policy scenarios, through a Planning Support System (PSS) interface that helps alleviate implementation concerns.

The primary aim of this paper is to demonstrate a comprehensive approach to systems modeling within a sociohydrological context that can be used to identify drivers for and barriers to IWRM operationalization. Specifically, this paper presents a coupled systems model (of regional economics, land use, and water system interactions); a path to transfer modeling expertise and local knowledge into useful policy practices through comprehensive modeling accounting for feedbacks (Figure 1); and a discussion on the practicality of our modeling approach (presenting challenges in uncertainty analysis, mutual learning, and scenario building). We organize the remainder of the paper into three sections. Section 2 introduces our IWRM modeling framework and details our integrated sociohydrological modeling approach. Section 3 presents two applications of the integrated modeling approach (at different levels of model integration) for Chicago and Stockholm and how exposure to information from the modeling can provide a platform for mutual learning and deeper understanding of both critical issues and potential paths forward. In Section 4, we conclude with a review of the strengths and weaknesses of our IWRM framework, modeling approach, and applications along with a discussion of potential improvements and next steps.

2 | A SOCIOHYDROLOGICAL SYSTEMS MODEL

The importance of integrated systems modeling has been well documented in the literature on water resource management (GWP, 2017; Liu et al., 2008; Mitchell, 2005). Although we propose an integrated modeling framework, our main objective here is to better understand urban systems resilience from an IWRM modeling perspective. Our proposed framework is the result of a multidisciplinary collaboration that includes complex systems models of hydrology, land use, and economics. The work also lends itself to inclusion of hydro-climate, water quality, and virtual flow models that are not currently a part of this work but will be explored in future research. Our main focus is the coupling of an existing hydrological model, a dynamic land use model, and a regional economic model in each of the study cities. The integrated model is used to analyze the transition from a traditional urban water management approach to one that enhances urban water system resilience in a changing world. We use scenario analysis to study various urban development policies and their impacts on hydrological systems at different scales. We use the systems models to help determine and incorporate feedbacks. For example, the relationship between economic efficiency, land use, and water, with economics driving land use demand through allocation of control variables, such as employment by sector and households by cohort group; associated land use model results imposing land restrictions on economic sector growth and also affecting spatial externality of production; and land use growth increasing surface areas impervious to water infiltration, thus increasing risks of hydrological
flooding, and in turn leading to flood-related zoning that affects land use scenarios (Figure 1).

In this section, we address the following: Can coupled systems models effectively capture the essence of changes to stormwater management and associated strategies? How do local choices impact water systems—and how do local policy choices (e.g., of land uses and best management practices) lead to system output (failure or resilience)? How are socioeconomic and sociophysical systems linked? At what point do they diverge and lead to goal conflicts?

2.1 | Models

This section explains each standalone part of the integrated systems model. The detailed calibration, validation, variable specifications of each model can be found in Data S1. Results of models are presented in Data S2 through S5 with legends specified in Data S1.

2.1.1 | Land use modeling

The Land Use Evolution and Impact Assessment Model (LEAM) is a dynamic spatial model, developed at the University of Illinois at Urbana–Champaign, and simulating future land use changes and their consequences. LEAM uses a modified cellular automata approach where 30 × 30-m cells evolve over a surface defined by biophysical factors, such as hydrology, soil, geology, and landforms, and socioeconomic factors, such as administrative boundaries, census districts, and planning areas. LEAM uses these factors to establish a probability of change for each 30-m cell in the study region. Fundamentally, the LEAM is defined by two major parts: (a) a dynamic land use change model (at a 30 × 30-m resolution), which is driven by a set of submodels that describe local causality of land use changes and allow for creation of what-if scenarios, and (b) impact assessment models that use the land use change scenarios to analyze the impacts generated by these changes. The approach enables loose and tightly coupled links with other models that might operate at different spatial scale (Deal, Pan, & Zhuang, 2018) and backcasting and other multidirectional analysis (Deal, Pan, Timm, & Pallathucheril, 2017). LEAM has been loosely coupled with economic forecasting models (Chicago Regional Econometric Input–Output Model [CREIM]; Deal, Kim, Hewings, & Kim, 2013), bidirectional travel demand models (Deal, Kim, Hewings, & Kim, 2013), water quality models (Choi & Deal, 2008), water quantity models (Kalantari, Lyon, et al., 2014), and social cost models (Deal & Pan, 2016). Demographic output and future demands for space are inputs to the model derived from the CREIM econometric model described below.

2.1.2 | Economic and policy analysis models

The Regional Economics Applications Laboratory at University of Illinois at Urbana–Champaign integrates an input–output modeling framework with a demographic component that helps make up a regional econometric model used for impact analysis and forecasting. Details of the system can be found in Israilevich, Hewings, Sonis, and Schindler (1997) and its application to Chicago (the CREIM) in Kim, Hewings, and Kratena (2015). The model provides information on production, income, and employment for 45 sectors, population cohorts, migration, and ultimately water demand data for use in subsequent models. This annual model, with a current forecasting horizon through 2040, will be complemented by shorter term indices that mimic leading indicators and business cycles, thus providing the opportunity to integrate analysis over shorter and longer terms.

2.1.3 | Hydrological/hydrodynamical modeling

Hydrodynamical models have many application areas: land use analysis (Kalantari, Lyon, et al., 2014), climate change analysis (Kalantari, Lyon, et al., 2014; Kalantari, Briel, et al., 2014), and flood prediction and rainfall–runoff modeling (Kalantari et al., 2015; Kalantari, Ferreira, Walsh, Ferreira, & Destouni, 2017). There are several different software packages that can be used for hydrodynamical modeling. Among these, the MIKE FLOOD floodplain model (Teng et al., 2017) is a tool that integrates the model one-dimensional (1D) MIKE 11 of channel flows with the model two-dimensional (2D) MIKE 21 of overland flows into a single, dynamically coupled modeling system, enabling modeling of flood problems.

2.1.4 | Planning support systems approach

The evolution of PSS technology provides some parallels for developing an integrated approach to socionatural systems modeling. Current PSS research has produced models that can account for feedback loops between land use development and other social and physical dynamics and forecast how future land use evolves and impacts natural systems (Deal & Pan, 2016). For example, the LEAM platform has an online interface that can read input data in different regions of the world and forecast future land use change scenarios (Deal & Pan, 2016). It can also be loosely or tightly coupled with other models, including economic, water, and transportation models (Choi & Deal, 2008; Deal et al., 2013). Many of the proposed components of LEAM, such as context-based simulations and a cloud-based platform (Deal et al., 2018), are similar to the components described in our conceptualization of an integrated water system. In water system-oriented modeling, models can define a water system model as a core model (such as a land use change model in LEAM) and give it flexibility that allows its coupling with other models that either provide inputs or output of the water system model.

2.2 | Model integration framework and feedbacks

Our regional economic model is synthesized with LEAM to help understand the socioeconomic drivers of land use changes and the feedback of land use availability on economic development. This feedback between regional economy and land use is important for determining changes in impervious surface areas and associated impacts on regional water systems. The model integration process starts with population and employment projections produced by coupling the regional economic input–output model with regional econometric projections for each scenario tested. We use these projections to feed mathematical probabilities of land use change using LEAM. We use feedbacks of LEAM outcomes to identify areas of future growth for each economic sector. We then compare the growth in each sector and adjust and justify the forecasts in each model until each is in equilibrium. For example, if the land use model estimates higher retail growth in one geographical area, the regional economic input–output model analysis can be adjusted to reflect this higher retail demand. Or if the regional economic
input–output model indicates lower growth in another sector, the land use model results are adjusted to reflect that decrease.

The LEAM is further coupled with hydrological/hydrodynamical models to assess scenario impacts on hydrological systems in the study region. The resulting hydrological output information is fed back into the LEAM land use model in an iterative process. Land use change probabilities are then recalculated using the hydrodynamical results in terms of flood and flood zone changes. Flood zone changes affect transportation routes, land use decisions, and economic efficiency. A detailed feedback loop between economic, land use, and hydrodynamical models is shown in Figure 2. It is noteworthy to note that climate variables are included for our hydrological model, but we have not yet explored possible dynamics in human–climate–water systems. Human-induced climate change has deep implications on water systems and in turn has impacts on human systems in terms of long-term land use change and socioeconomic activities (Farjad, Gupta, et al., 2017; Gain, Rouillard, & Benson, 2013; Ludwig, van Slobbe, & Cofino, 2014). Future work is aimed at expanding this framework.

3 RESULTS IN APPLICATIONS TO CHICAGO AND STOCKHOLM

We apply our integrated framework to the cases of Chicago and Stockholm. Both Chicago and Stockholm have large metropolitan areas (Chicago 5,498 km² and Stockholm 6,519 km²); both have diverse economic activities; and both have critical relationships to water systems. The base data are collected for periods from 2006 to 2010, and the coupled models simulate scenarios up to 2040 for both cities. In the Chicago case, we demonstrate how long-term (to 2040) top-down economic forecast drives land use models and how spatial configuration from land use models in turn adjust economic forecasts. In the Stockholm case, we show how land use growth increase impervious surfaces and result in higher flooding risks on higher spatial extent and how growth regulations based on flooding risks in turn affect land use growth. The concept of a full feedback loop from human activities to/from water systems is proposed and will be the next step of this research.

3.1 Chicago, IL, USA

To understand how urban land use evolves from human socioeconomic activities in Chicago, we applied the coupled regional economy (CREIM) and land use change (LEAM) models.

Figure 3 presents the results of the economic forecast to 2040 from different economic sectors by CREIM, on the basis of sectoral input–output relations in 2013. We obtained aggregate population and employment outputs as by-products of the sectoral forecasts and used those as inputs for the LEAM. LEAM allocates newly generated population and employment data into residential and commercial land use growth based on existing density. For LEAM, we ran two scenarios. The first is a scenario that all development is new
development; the second scenario assumes that much redevelopment occurs as new development in the Cook County Watershed. The subsequent analysis proves that the second scenario serves much better for stormwater management purposes, which is intuitive because redevelopment does not add new impervious surfaces.

On the basis of this observation, we chose the second scenario (redevelopment) as the preferred scenario and proceeded with our modeling (Figure 4). Using 2013 Chicago Metropolitan Agency for Planning land use data that can pinpoint locations of each economic sector in CREIM for both existing and newly developed commercial land uses (Figure 5), we compare LEAM and CREIM sectoral forecasts and identified six outstanding sectors: three that were underestimated and another three sectors that were overestimated by CREIM compared with LEAM (Table 1). We limit the growth ‘shock’ for each sector in economic and land use models to no more than 10% to control uncertainties. Then, we apply ±10%, ±5%, and ±2% output shocks to the outstanding sectors (respectively) in CREIM, depending on if they were overestimated or underestimated. We also apply ±10%, ±5%, and ±2% changes to LEAM probability maps for the six outstanding sectors. After modifying those model assumptions, we recast CREIM and LEAM from 2013 to 2040. The impacts of those adjustment on each CREIM sector by 2040 are shown in Table 2. The modified land use forecast is then coupled with a watershed model to explore its impacts on stormwater management.

3.2 Stockholm, Sweden

The first land use projection efforts are calibrated to fit past land use change patterns and project future growth. We define this as a ‘business-as-usual’ scenario. This is the baseline scenario onto which all future scenarios were compared. Scenarios are determined through local engagement and local planning processes. In this urban case, they are ongoing processes, being determined by the regional planning organization in Stockholm.

After calibration, Stockholm LEAM is coupled with a hydrological model (r.sim.water, described further below) to assess the impacts of land use change on the local hydrological system (Level 1) and also with a hydrodynamical model (MIKE FLOOD) in Level 2.

3.2.1 Level 1

At this level, we consider how water moves and is channelized and collected in topographical depressions, the potential impact of flooding, and the location of potential flood areas. The analysis represents a 50-mm storm event (approximately 2 in.) over an hour, which is equivalent to a 100-year storm for the region. The hydrological model uses, r.sim.water, is an open-source, cell-based dynamic simulation tool, developed as r.hydro by the U.S. Army Corps of Engineers for the Geographic Resources Analysis Support System geographical information systems tool. We use the hydro model to calculate flood risks as a feedback mechanism to the land use model. In Stockholm, we assign 100-year flood risk areas as no-growth zones for future development.

The r.sim.water model and the actual data for low areas and ponding match at percentage of 66.7% by cell-by-cell overlay. Catchment areas indicated as streams, rivers, and ponds match the model exactly. In this analysis, we are concerned with other topographical depressions and how water collection in these might prohibit future development or green infrastructure-based solutions. These areas are designated as floodplain areas. This information is extracted and matched with the existing no-growth map that acts as a driver in the model. No growth is a term used in this model to represent areas that are protected, waterways, steep areas, wildlife or forest
FIGURE 4 Results of the land use change forecast to 2040 for new residential and commercial land use based on the National Land Cover Database base year 2011. These results assume that as much redevelopment will happen in the Cook County subwatersheds as new development [Colour figure can be viewed at wileyonlinelibrary.com]
preserves, government or public lands, and so forth. The floodplain map is added to this, and the model is rerun. The results indicate little change. This is largely because the floodplain areas were mostly considered in the existing no-growth map. The change only impacts several geographically small areas, which had little influence on urban growth to begin with.
Model results indicate that the no-growth zones generated from the impact analysis model do not have significant effects on updating the land use model—less than 5% of the flooding areas (proposed modified no-growth zones) overlay with the projected growth, so a modified no-growth zone does not lead to visible difference in future land use pattern. When we brought that result to local experts (university scholars and Stockholm city planners), they were surprised and suggested that critical mechanisms might be missing. This is one reason for a more detailed, Level 2 modeling exercise, described further below.

### 3.2.2 Level 2

At this level, the main focus of the modeling work was to study the impact of land use change on flood extent and flood depth corresponding to a 100-year flood in the specific Igelbäcken stream catchment within the Stockholm region (Figure 6). We use integrated 1D/2D hydrodynamical MIKE FLOOD modeling package that consists of the two components described above: a 1D hydrodynamical model with MIKE11 and a 2D hydrodynamical model with MIKE 21. In this study, the Igelbäcken stream network in MIKE 11 is coupled with the MIKE 21 for the catchment overland flows to form the MIKE FLOOD modeling platform. The MIKE FLOOD model is run with two different land use scenarios reflecting current land use conditions and land use change for year 2030 as predicted by LEAM.

Figure 7 shows how the flooding extent and flood depth were altered under changed land use. Results also provide a good representation of where water will accumulate in the residential area, to what extent flooding can be expected, and how the flooding will be forced to move due to changes in land use. Furthermore, hydrological responses of land use changes were evident in terms of stream flow and stream water level in Igelbäcken.

### 3.3 Interregional mutual learning

We have in the above demonstrated how to build a coupled land use and regional economy model for the Chicago case and a coupled land use/hydrology model for the Stockholm case. We have not shown integrated economy–land-use–hydrology models for both cases due to lack of local experts and data. To investigate ways to overcome such issues across regions, we have also built alternative scenarios to complete models, for example, using official population/employment projections for socioeconomic data. In this context, we also develop a mutual learning process. For example, the regional economic model for Chicago was applied to Stockholm with sectoral

### TABLE 1 Sectoral growth by ratio for each CREIM and LEAM sector

| CREIM sector growth (2040 total/2013 total) | LEAM sector growth (2040 total/2013 total) | Disagreement between LEAM and CREIM |
|----------------------------------------|----------------------------------------|-------------------------------------|
| Sector Whole trade Retail trade Commercial Entertainment Accommodation Health care | Sector Whole trade Retail trade Commercial Entertainment Accommodation Health care | Sector Whole trade Retail trade Commercial Entertainment Accommodation Health care |
| Value 1.7 1.54 2.36 1.54 2.08 1.77 | Value 1.04 1.3 1.09 1.03 1.2 1.1 | Rankdiff -5 11 -6 |
| Rank 7-T 13-T 2 13-T 3 | Rank 12-T 2 8 14-T 3 |
| Sector Education Government Membership Mining Manufacturing Warehousing | Sector Education Government Membership Mining Manufacturing Warehousing | Rankdiff 5 -6 -38 |
| Value 1.64 1.74 1.66 0.9 1.7 0.97 | Value 1.12 1.06 1.36 1.05 1.04 1.11 |
| Rank 10 6 9 16 7-T 15 | Rank 5 9 1 |
| Sector Railroad Transit Air Personal Information Utilities | Sector Railroad Transit Air Personal Information Utilities | Rankdiff -10 -10 |
| Value 1.83 1.06 1.57 1.63 2.37 0.47 | Value 1.03 1.02 1.01 1.01 1.05 1.13 | Rankdiff -10 -15 -4 |
| Rank 4 12 11 11 1 17 | Rank 14-T 15 16-T 16-T 10-T 4 |

Note. We calculate the rank of the growth ratio for each sector in CREIM and LEAM and calculate the rank difference. The three sectors that CREIM underestimated the most are marked in red. The three sectors that CREIM overestimated the most are marked in yellow. CREIM: Chicago Regional Economic Input–Output Model; LEAM: Land Use Evolution and Impact Assessment Model.
economy data from Stockholm and some recalibration, whereas the Stockholm hydrological model is applied to Chicago along with associated LEAM land use change forecast. We compare forecast and current results, using relevant official forecast scenarios to see whether the integrated model-generated results would fall within reasonable confidence intervals of existing data-driven models.

We also use the mutual learning process to build LEAM land use models for multiple regions. To deploy LEAM for different regions, we set up an online, cloud-based modeling platform. Data from different regions were sent to the same computing server to generate model results. For each region, a similar site was set up to allow for data input, parameter tuning, and calibration. An explanation of how this cloud-based platform works can be found in other publications (Deal, Pan, Pallathucheril, & Fulton, 2017; Deal & Pan, 2016). The Chicago and Stockholm models are both constructed and shared using a computing server for this purpose. An example of LEAM interface visualization is shown in Figure 8.

Through this mutual learning exercise, we find that to effectively communicate with local stakeholders via our PSS interface, it is essential to build the model with local stakeholders, involving them in tuning model parameters and validating model results. The information shown to nonexpert stakeholders should be easy to digest, such as visual maps of model forecast of some policy scenarios, or some understandable quantitative outcomes (such as goodness-of-fit scores).

### TABLE 2  Aggregated impact of LEAM sectoral adjustment applied on CREIM

| Economic sectors | Cumulative impacts Output ($m) |
|------------------|-------------------------------|
| Resources        | 16.1                          |
| Construction     | 98.8                          |
| Nondurables      | 145.4                         |
| Durables         | 102.8                         |
| TCU              | -1,004.8                      |
| Trade            | 2,627.4                       |
| FIRE             | 392.9                         |
| Services         | 481.3                         |
| Government       | 17.2                          |
| Total            | 2,877.0                       |
| Direct           | 1,541.0                       |
| Indirect         | 1,336.0                       |
| Multiplier       | 1.87                          |

Note. Durables and nondurables are manufacturing; TCU is transportation, communications, and public utilities; trade is wholesale and retail; FIRE is finance, insurance, and real estate; direct impact is the impact we directly assessed from land use availability for each sector; and indirect impact is the impact resulting from direct impact to all economic sectors. Multiplier is calculated by total/direct. CREIM: Chicago Regional Econometric Input–Output Model; LEAM: Land Use Evolution and Impact Assessment Model.
3.4 | Discussions

3.4.1 | Result discussions

Our results show social and natural process interactions. In the Chicago economy and land use model application, we find that physical land use availability for economic activities differs from sectoral forecasts based on regional economic methods, suggesting that both human (economic and land use planning) and natural processes (land cover evolution) need to be modified to reconcile the differences.
Similarly, in the Stockholm land use and stormwater model application, we find that land use and water models both need to be adjusted to realistically assess one system's impact on the other. Flood zone regulations can divert land use to other locations, whereas land cover changes may change impervious surfaces and alter future hydrological processes.

These results show that modeling social and natural processes together provides a more comprehensive understanding of causes and impacts in the coupled dynamics of economic, land use, and hydrological systems. Our model provides theoretical and practical evidence to Mitchell's (2005) argument that land use modeling grants credibility and a more comprehensive and systemic understanding to IWRM practices.

Building large-scale integrated models is understandably complicated and challenging. We apply multiple techniques to address such challenges. For example, we limit growth 'shock' for each sector in economic and land use models to no more than 10% to control uncertainties. The different models are also applied to multiple regions with experts of diverse skills so that mutual and global learning could take place, leading to more complete model understanding and application experience for different parts of the world.

### 3.4.2 Model challenges and solutions

One challenge of this work is adapting models and analytic approaches across cities that differ significantly in terms of data standards. For example, cadastral data are often used to develop land use models, but property ownership regimes are different in the United States and Sweden. Similarly, during the calibration phase, data availability and level of detail will almost certainly vary. Other challenges include

1. **Deep uncertainty.** Previous work demonstrates the use of fuzzy techniques to address uncertainty of coupled modeling framework (Farjad, Pooyandeh, et al., 2017). However, it is difficult to address the deep uncertainty associated with the multiple modeling inputs that evolve with time-steps in our modeling framework. We will employ a robust decision-making framework including scenario analysis to address this issue in future work.

2. **Scenario analysis.** Systems modeling (including modeling of land use systems) approaches are generally more useful for guiding policy decision making when multiple policy scenarios are included in the model (Deal, Pan, Timm, & Pallathucheril, 2017; Parker, Manson, Janssen, Hoffmann, & Deadman, 2003). Scenario analysis in a robust decision-making framework can help us address deep uncertainty. Robust decision making employs three key concepts: multiple views of the future, a robustness criteria, and an iterative process based on a vulnerability and response. Utilizing multiple future states rejects the view that a single probability distribution represents the best description of a deeply uncertain future (Deal, Pan, Timm, & Pallathucheril, 2017). The approach has cognitive benefits for decision making, by uncovering key assumptions and uncertainties that underlie each alternative future.

3. **Data constraints.** For complex system models, data availability must be carefully considered. Data availability has been identified as one of the main challenges of IWRM and socionatural system models (Biswas, 2008; Liu et al., 2008). The challenge is not only whether certain data exists, it is also whether the data are available across different parts of the world and whether the data for different disciplines can be retrieved and understood. Biswas (2008) notes that the massive data required for IWRM may not be available in developing countries. In the United States, required data are often available through public sources such as Census, National Oceanic and Atmospheric Administration, or United States Geological Survey databases. However, those sources may not be available or publicly accessible in other, such as developing countries. Researchers may need to contact local authorities or use websites written in local languages to obtain necessary data. Data are also not necessarily comparable across nations, which requires caution when using them in models. This problem is especially important for socioeconomic data: Different nations have different procedures for calculating urban population, unemployment rate, and particular economic sector output. The regional input-output model and land use model proposed in this paper are both related to practices in the United States and will require significant recalibration for using data from other places.

4. **Practical difficulties.** An integrated socionatural systems model is difficult to coordinate among the necessary disciplines. Calder (2005) points out the necessity as well as the difficulties of bringing together academic groups with diverse expertise as well as practical groups with different goals for IWRM and water system modeling. Moreover, at least a few of these experts need to have local knowledge of the modeled region to be able to localize the model and perform quality checks of model outputs. This is particularly challenging because experts with local knowledge may not exist in some locations that need IWRM. An integrated systems model project is also likely to be large scale, requiring extensive funding for a full systems model version.

5. **Mutual learning.** It is difficult to create the wide-ranging team of experts needed to implement a full systems model. To address this, researchers should learn from each other's knowledge in various sectoral models applied to different regions. This idea of mutual and global learning is an important goal of IWRM and other multidisciplinary approaches to systems modeling (Liu et al., 2008). For example, scholars in 'Region A' might know how to implement one model, whereas another scholar team in 'Region B' may have no modeling expertise but does have localized knowledge of the region. Working together allows the scholars in Region B to learn how to implement the model, whereas the scholars in Region A are provided the localized knowledge they need from the Region B scholars.

6. **Complexity in policy formation.** Another question is how to efficiently convey the comprehensive and complex model results to guide policy making. Modelers need to be able to convince policy makers of the credibility of the model. Andrews (2000) points out that systems models developed by engineers are often seen as less credible by socioeconomic policy makers. It is therefore
critical that the modeling team works toward gaining credibility and making their systems models understandable. Work in PSS has shown approaches needed to restore legitimacy to engineering system models and effectively convey information, including tailoring analysis to context, interacting with stakeholders via participatory workshops, and seeking both status-based and consent-based sources for building models.

4 | CONCLUSIONS

The IWRM approach has been criticized as impractical and not clearly defined. Using integrated economy–land-use–water models, this paper develops an IWRM framework for integrating complex systems models in an attempt to understand the sociohydrological implications of urban stormwater dynamics. Water systems are shown to have deep connections to economic systems, human activities, and land use decisions and include both direct effects and indirect feedbacks at urban and regional scales. Our approach calls for collaboration and communication among diverse scientific fields and well-designed (and replicable) processes in model building, problem solving, mutual learning, and knowledge translation. We utilize scenario processes to address uncertainty and to present alternative futures for analysis and engagement purposes.

There are several steps that can be taken to extend this research. First, building process of integrated economy–land-use–hydrological models needs to be continued to incorporate with full feedback loops. Water and economic input–output can also be linked, for example, using a virtual water flow model (Bae & Dall’erba, 2018). Economic, land use, and hydrological modeling may further influence each other (pairwise) such that there is disagreement in some modeling pairs, and an iterative process of adjusting model inputs and assumptions may be required to balance different modeling outcomes. Second, there are also other water-related variables that could be added to the integrated modeling framework, such as water quality and finer scaled water flux and availability measures. Finally, although hydraulic systems are important for understanding urban drainage, supply and sewage, in this study, we focused on surface water flooding, due to our emphasis on nature-based solutions. Future works should include a more comprehensive understanding of urban water systems to include other forms of hydraulic infrastructure.

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