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Socio-Natural Processes and Land-Use Modeling in Support of Integrated Water Resource Management Practices

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REAL 18-T-2

May, 2018

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Abstract: This paper argues that a systems thinking and explicit modeling approach is needed to address noted weaknesses (practicality and usefulness) in Integrated Water Resource Management projects. A pioneering effort in coupling land-use, regional economy, and water systems models is demonstrated with a proof of concept applications in 2 cities (Chicago and Stockholm). The analysis is conducted primarily through refining, applying, and integrating existing (stand-alone) models. The approach faces challenges that including data, deep uncertainties, and information constraints. Solutions including uncertainty analysis, mutual learning, and scenario building are discussed and demonstrated. The integrated model results reveal that the physical availability of land for economic activities forecasted via land use change probabilities can vary widely from sectoral regional economic forecasts, suggesting that both human (economic and land-use planning) and natural processes (land-cover evolution) need to be justified in order to reconcile integrated results. Moreover, land-use and water models both need to be adjusted when assessing one system's impact on the other. For example, flood-zone regulations can divert land-use to other locations, while land-cover change affects the amount of impervious surfaces and alter future hydrological outcomes. Our results demonstrate that modeling social and natural processes with the appropriate feedback provides a more comprehensive understanding of both the causal mechanisms and the potential impacts of an Integrated Water Resource Management application.

Key words: Integrated Water Resource Management, land use/cover change modeling, regional economy, storm-water management, hydrological modeling

1. Introduction

Cities are complex and evolving systems. Understanding these systems and their dynamics is becoming critical as our urban areas shift from a relatively static and dependent determinism, toward a more 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 cannot be understood or reliably improved by studying the behavior of its parts in isolation; the system must be viewed 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 socio-economic processes within a sustainability framework is Integrated Water Resource Management (IWRM) framework (Hazbavi & Sadeghi, 2017; Petit, 2016; 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 (Liu *et al.*, 2008). According to the UN 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 Global Water Partnership (GWP) and other prominent water-centric organizations, the framework has not been universally accepted. Some contend that a lack of clarity and an inability to guide implementation inhibit its usefulness (Biswas, 2008; Giordano & Shah, 2014; Jeffrey & Gearey, 2006). For example, Biswas (2008), suggests that IWRM is not implementable; Jeffrey & Gearey (2006) claim that there is no evidence that IWRM has actually worked in practice: and Giordano and Shah (2014) think that IWRM processes are detrimental and can hinder alternative thinking and pragmatic, water management solutions.

The primary aim of this paper is to demonstrate a comprehensive systems modeling approach within a socio-hydrological context to identify difficulties and barriers to IWRM operationalization. Specifically, this research explores how land use, hydrology, and climate interact with social, economic, and political systems to produce unforeseen and unintended consequences; and how exposure to knowledge generated across urban settings using these models can affect socio-hydrological learning at a deeper level than is typical achieved using current best management practices; and how this leads to more sustainable and resilient places. We integrate regional economic, dynamic land-use, and hydro-systems models in an IWRM framework for 2 cities (Chicago and Stockholm) to explore the historic and evolving relationship between social activities and water within a context of changing climatic scenarios. We argue that a systems thinking and explicit modeling approach can help materialize the IWRM conceptual framework into concrete data and information that is more useful for application and can therefore address the noted weaknesses in IWRM practicality and usefulness. Systems models allow the testing of various policies, producing data that can be used to engage a wider constituency, resulting in more informed and consensually inclusive policies (Deal & Pan, 2016). The ability to test various IWRM configurations and policy scenarios can also help alleviate implementation concerns.

We organize the remainder of the paper into 3 sections. **Section 2** introduces our IWRM modeling framework, detailing our integrated socio-hydrological modeling approach and the challenges the approach presents (uncertainty analysis, mutual learning, and scenario building) and some of the ways we address those challenges. **Section 3** presents 2 applications of our integrated modeling approach (at different levels of model integration) in Chicago and Stockholm and how the exposure to the information provides a platform for mutual learning and deeper understanding of both the issues and potential paths forward. **In Section 4** we conclude with a review of the strengths and weaknesses of our IWRM modeling framework, approach and applications along with a discussion of potential improvements and next steps.

2. A Socio-hydrological Systems Model

The importance of integrated systems modeling has been well documented in the literature on water resource management (Hazbavi & Sadeghi, 2017; Liu *et al.*, 2008; Medema *et al.*, 2008; Pires *et al.*, 2017; Yu *et al.*, 2013). Integrated modeling has been noted to help address the complexity of the human/natural interface in a watershed (Hazbavi & Sadeghi, 2017) and generally bolster the integration of useful and relevant scientific information in IWRM problem solving (Liu *et al.*, 2008). Yu et al. (2013) suggest that an IWRM by nature is a complex undertaking and requires an integrated approach. Medema (2008) and Pires et al. (2017) elaborate on the idea, noting that an IWRM approach will be successful only through multi-sector collaboration among water, land, and other resource management stakeholders with different socioeconomic backgrounds. An integrated modeling environment therefore, would have to provide a diverse range of information in order to interface with the diverse stakeholders needed. Such a modeling environment would face challenges in operationalization (Biswas, 2004; Giordano and Shah, 2014), data and information exchange (Liu et al., 2008), and the deep uncertainty inherent in complex integrated modeling endeavors (Liu *et al.*, 2008; Pahl-Wostl *et al.*, 2007).

Our objective here is to better understand urban systems resilience in an IWRM framework in 2 global cities, Chicago and Stockholm. Our proposed framework is the result of a multi-disciplinary collaboration that includes complex systems models of hydrology, urban planning, land-use, and economics. The work also lends itself toward the 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 land use model, and a regional economic model in each of the study cities. These integrated models are 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.

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

2.1 Models

The models utilized in this analysis are existing models that have been applied to the study areas in some form.

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 that simulates future land-use change and its consequences. LEAM uses a modified cellular automata approach where 30x30m cells evolve over a surface defined by biophysical factors such as hydrology, soil, geology and landforms; and socio-economic factors such as administrative boundaries, census districts, and planning areas. LEAM uses the factors to establish a probability of change for each 30m cell in the study region. Fundamentally, the LEAM model is defined by two major parts: 1) A dynamic land-use change model (at a 30x30m resolution) which is driven by a set of sub-models that describe the local causality of land use changes and allow for the creation of what-if scenarios. 2) Impact assessment models that use these 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 a different spatial scale (Deal *et al.*, 2018) and backcasting and other multi-directional analysis (Deal *et al.*, 2017b). LEAM has been loosely coupled with economic forecasting models (CREIM) (Pallathucheril & Deal, 2012), bi-directional travel demand models (Deal *et al.*, 2013); water quality models (Choi & Deal, 2008); water quantity models (Kalantari *et al.*, 2014b); and social cost models (Pallathucheril & Deal, 2012). Demographic output and future demands for space are inputs to the model derived from the CREIM econometric model described below.

Economic and Policy Analysis Models. The Regional Economics Applications Laboratory (REAL) at UIUC 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 *et al.* (1997), and its application to Chicago (the Chicago Regional Econometric Input-Output Model—CREIM) in Kim *et al.* (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.

The CREIM model will be synthesized with LEAM to understand the impact of land-use availability on economic development, as well as socioeconomic factors' impacts on land-use change. This feedback between models is important for water systems because human activities impact water systems in significant ways, through human-induced land-use change and an increase in impervious surface area. First, we will synthesize the model by providing LEAM with population and employment growth from the CREIM baseline scenario for each scenario tested. Second, we will use LEAM to identify areas of future growth for each economic sector. Third, we compare the growth in each sector and adjust and justify the forecasts in each model until each is in equilibrium. For example, if LEAM estimates higher retail growth in one geographic area, CREIM model analysis can be adjusted to reflect this higher retail demand. Or if the CRIEM mode indicates lower growth in another sector, LEAM results are adjusted to reflect that limitation. The structure of the coupled models is shown in **figure 1**.

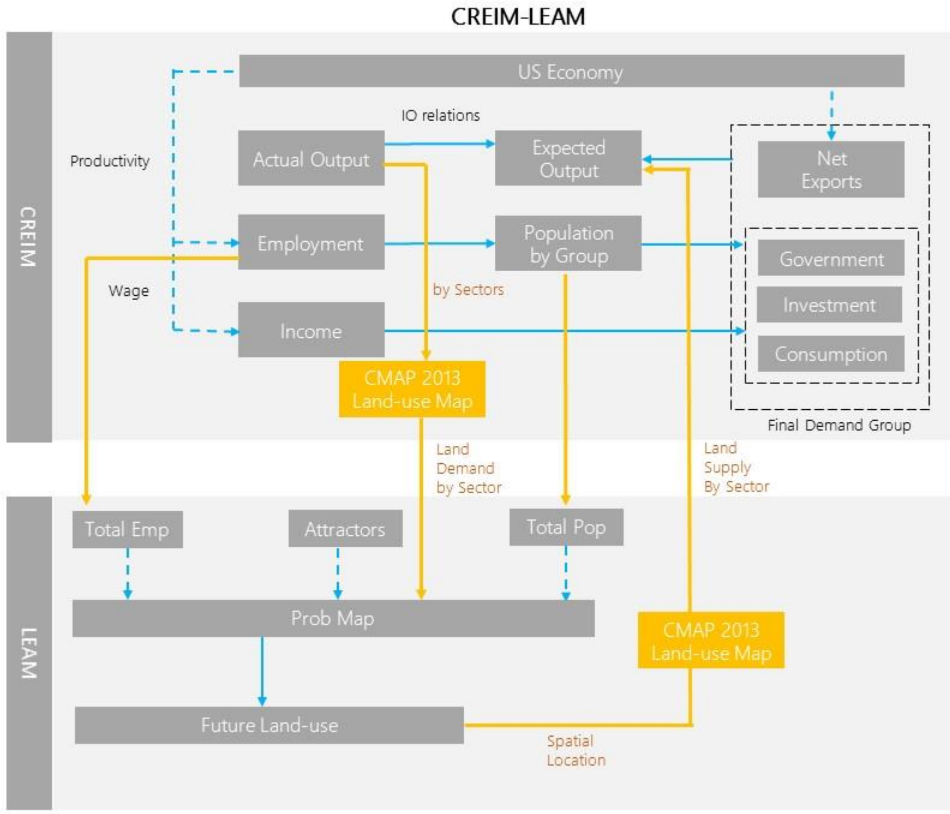

Figure 1. Integration framework of LEAM and CREIM. The grey boxes are the model mechanisms of standalone LEAM and CREIM summarized in (Deal *et al.*, 2017b) and Israilevich *et al.* (1997). The yellow boxes and lines show the input/output flow for a synthesized LEAM and CREIM model.

Hydrodynamic Modeling. Hydrodynamic models have many application areas: land-use analysis (Kalantari *et al.*, 2014b), climate change analysis (Kalantari *et al.*, 2014b, 2014a), flood prediction and rainfall-runoff modelling (Kalantari *et al.*, 2015, 2017). There are several different software packages that can be used for hydrodynamic modelling. MIKE FLOOD floodplain model (Teng *et al.*, 2017) is a tool that integrates 1-D MIKE 11 channel flows with the 2-D MIKE 21 overland flows into a single, dynamically coupled modelling system, enabling the modelling of flood problems. These models were coupled with LEAM and applied in a case study in Stockholm, Sweden.

Model integration. Integrating models of varying spatial and temporal specification requires careful consideration—both from a top-down and bottom-up perspective. Top-down analysis using a cascading model approach from large-scale natural systems dynamics to small-scale discrete choices of human activities and the related infrastructure needed to support them is important for understanding the implications of a changing climate on human activities. Bottom up feedback is equally important for understanding how human systems and human decision making affect these larger scaled systems and ultimately how they impact climate changes. Our proposed model integration uses the hierarchical incorporation of models to integrate the diverse spatial and temporal scaled models noted. Larger-scaled models will provide the constraints from which smaller-scaled model results will operate, and smaller-scaled models will provide the dynamic changes that will feed back up into the larger-scaled models. This simple but important concept will help to frame the aggregation of our smaller-scaled human interaction and decision models back up to the larger-scaled models. In this research we begin the process by loosely coupling our systems models (**figure 2**).

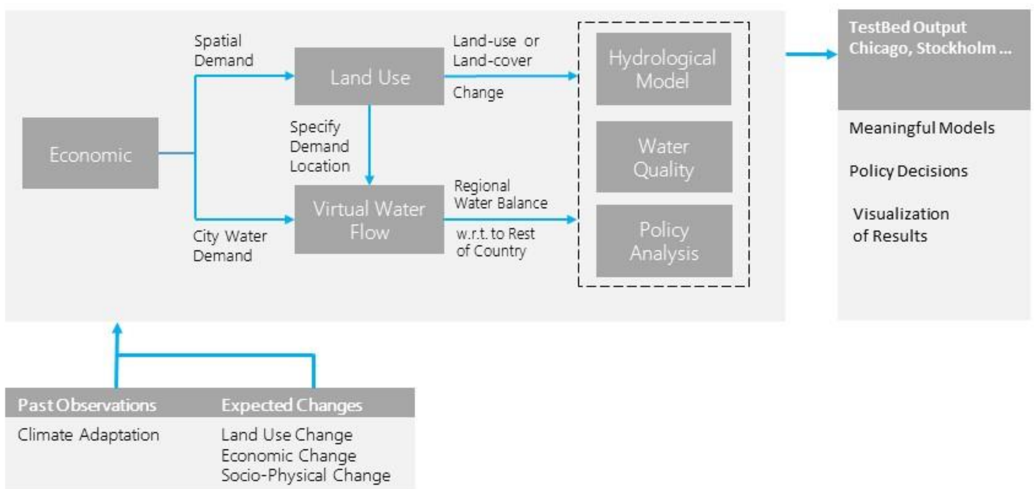

Figure 2. Integrated modeling framework for land-use, economic and hydrological systems

Planning Support Systems (PSS) Approach. The evolution of PSS technology could provide some parallels for developing an integrated socio-natural systems modeling approach. Current PSS research has produced models that can understand 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 Land-use Evolution and Impact Assessment Modeling (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-base, 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 the water system-oriented modeling, modelers can define a water system model as a core model (such as a land-use change model in LEAM), and then give it flexibility, allowing it to couple with other models that either provide inputs or use outputs of the water system model.

2.2 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:

Deep Uncertainty. Our integrated approach is subject to the limits of data, models and long-term forecasts; therefore, handling uncertainty is critically important (Kabat *et al.*, 2005). However, traditional predict-then-act approaches (such as global sensitivity analysis) characterize the future and then rank order the desirability of alternative options using static criteria. It is difficult to address the deep uncertainty associated with 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.

Scenario Analysis. Systems modeling approaches are generally more useful for guiding policy decision-making when multiple policy scenarios are included in the model (Deal *et al.*, 2017b). 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 option rather than a predict-then-act decision framework. Utilizing multiple future states rejects the view that a single probability distribution represents the best description of a deeply uncertain future (Deal *et al.*, 2017b). The approach has cognitive benefits for decision making, by uncovering the key assumptions and uncertainties that underlie each alternative future. Compared to the traditional predict-then-act approaches, our approach considers all potential futures as viable; it's the uncertainty in each that separates them.

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 socio-natural system models (Biswas, 2008; Liu *et al.*, 2008). The challenge is not only whether certain data exists; it is also whether the data is 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 by IWRM may not be available in developing countries. In the US, required data are often available through public sources such as Census, NOAA or USGS database. However, those sources may not be publicly available in 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 inputting them into 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 from the US, and will require significant re-calibration when using data from other places.

Practical Difficulties. An integrated socio-natural systems model is difficult to coordinate among the necessary disciplines. One successful run of the full model requires coordination from a large team of experts. 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 run quick quality checks on model outputs. This is particularly challenging since experts with local knowledge may not exist in some locations that need IWRM. An integrated system model project is also likely to be large-scale, requiring extensive funding to build and run a full version of the systems model.

Mutual Learning. It is difficult to create a team with the experts needed to implement a systems model. To address this, researchers should learn from other researchers who have knowledge in these modeling systems. This idea of mutual and global learning is an important goal of IWRM and other multi-disciplinary systems modeling approaches (Liu *et al.*, 2008). For example, scholars in “Region A” might know how to implement one model, while another scholar team in “Region B” may have no modeling expertise, but does have localized knowledge of the region. Working together allows scholars in Region B to learn how to implement the model, while scholars in “Region A” are provided the localized knowledge they need from the Region B scholars.

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 socio-economic policy makers.

It is therefore critical that the modeling team gain credibility and work to make their systems models understandable. Work in PSSs has shown that some approaches are needed to restore system legitimacy to engineering system models and effectively convey information, which include tailoring analysis to context, interact with stakeholders via participatory workshops, and seek both status-based and consent-based sources for building models.

3. Results in Progress for Chicago and Stockholm

3.1 Economic and Land-use Model for Chicago

To understand how urban land-use evolves from human socio-economic activities in Chicago, we applied a coupled regional economy (CREIM) and a land-use change (LEAM) model.

Figure 3 presents the results of the economic forecast to 2040 from different economic sectors by CREIM, based on sectoral input-output relations in 2013. We obtained aggregate population and employment output as by-products of the sectoral forecast and used those as inputs for the LEAM model. LEAM allocates newly generated population and employment data into residential and commercial land-use growth based on existing density. For LEAM, we ran 2 scenarios. The first is a scenario that all development is new development; the second scenario assumes as much redevelopment occurs as new development in the Cook County Watershed. The subsequent analysis proves that the second scenario serves much better for storm-water management purposes, which is intuitive because redevelopment does not add new hard surface.

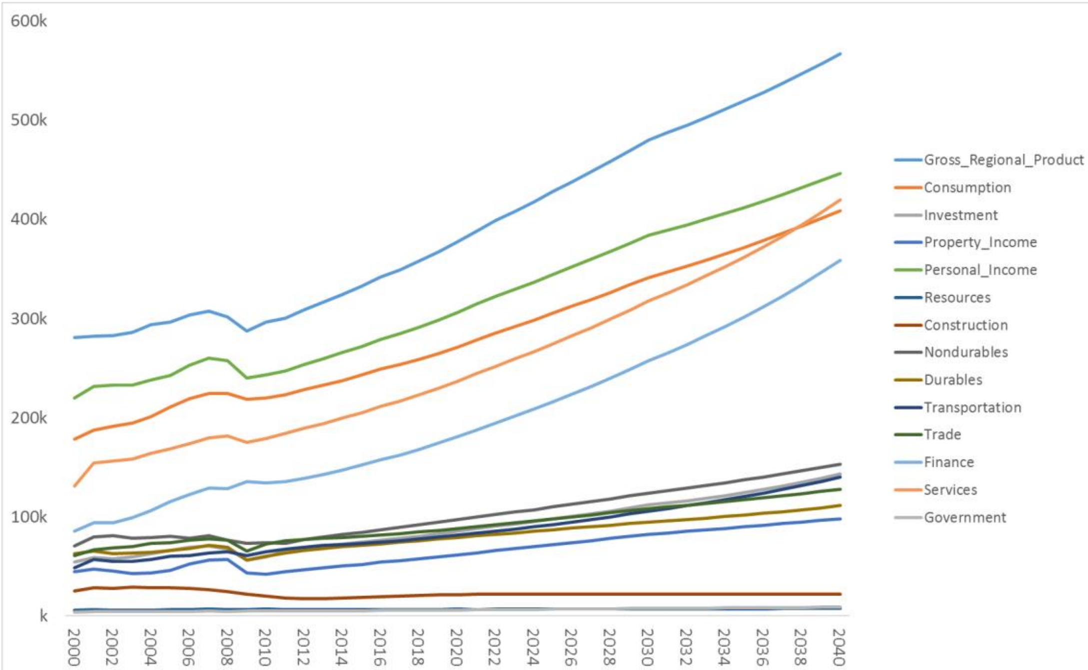

Figure 3 presents the results for the economic forecast to 2040 from different economic sectors by CREIM, based on sectoral input-output relations in 2013. We obtained aggregate population and employment output as a by-product of the sectoral forecast and used those as inputs for the LEAM model. LEAM allocates newly generated population and employment data into residential and commercial land-use growth based on existing density.

Based on this observation, we chose the second scenario (redevelopment) as the preferred scenario and proceeded with our model (**figure 4**). Using 2013 CMAP 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 compared LEAM and CREIM sectoral forecasts and identified 6 outstanding sectors: 3 that were underestimated and another 3 sectors that were overestimated by CREIM compared to LEAM (**table 1**). Then, we applied ±10%, ±5%, ±2% output shocks to the outstanding sectors (respectively) in CREIM, depending on if they were over- or underestimated. We also applied ±10%, ±5%, ±2% changes to LEAM probability maps for the 6 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 is shown in table 2. The modified land-use forecast was then coupled with a watershed model to explore its impact on storm-water management.

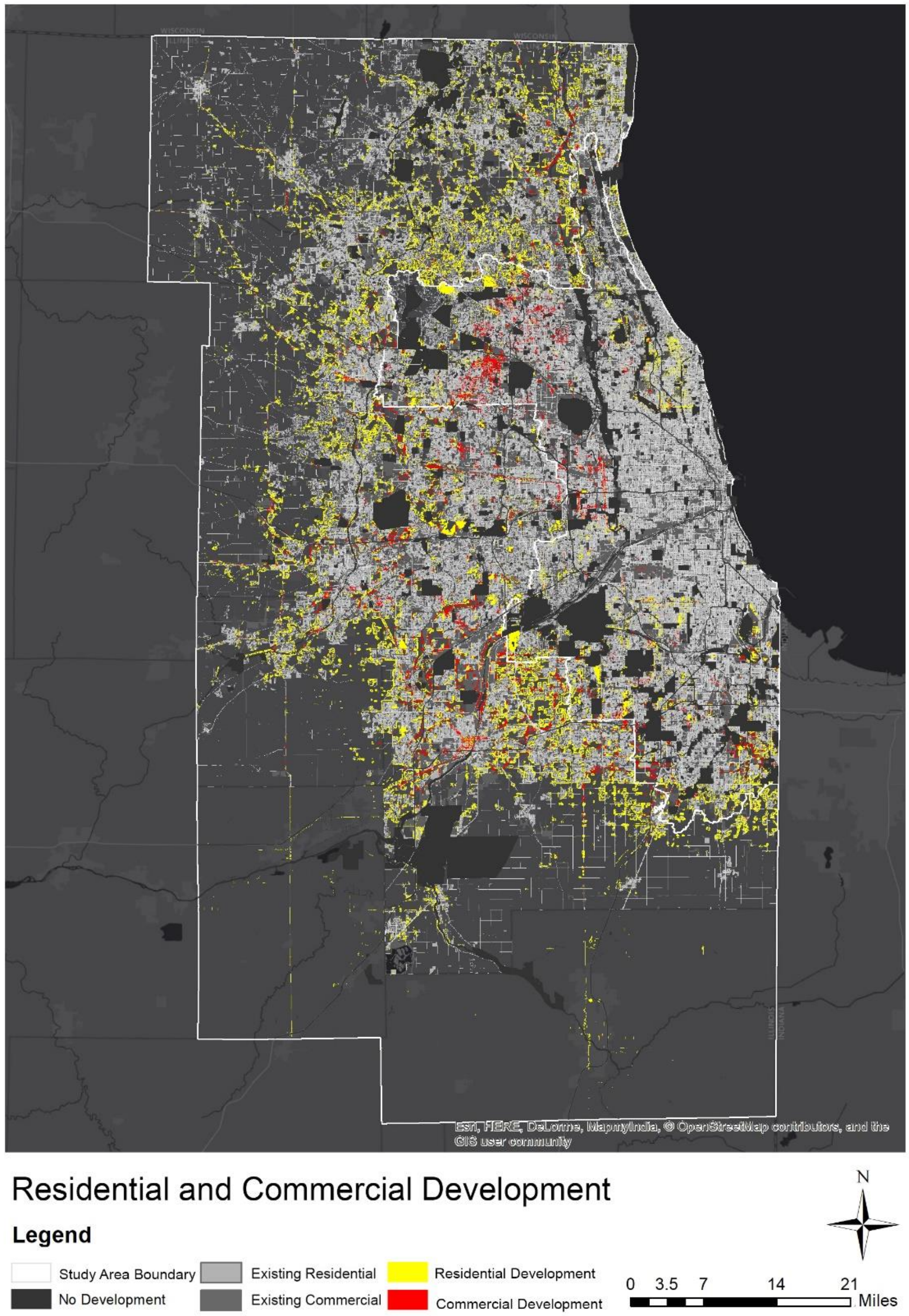

Figure 4. Results of the land-use change forecast to 2040 for new residential and commercial land-use based on NLCD base year 2011. These results assume that as much redevelopment will happen in the Cook County sub-watersheds as new development.

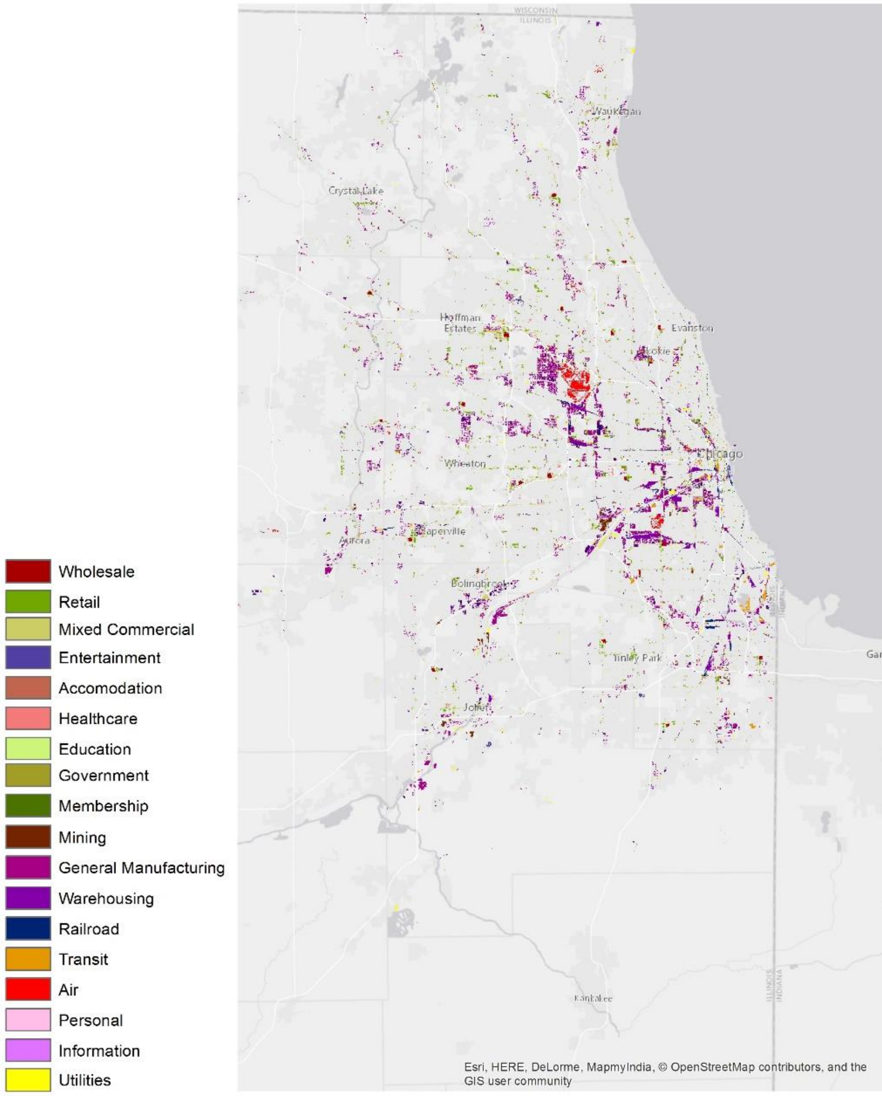

Figure 5. The disaggregated existing and new commercial land-uses (from LEAM) by CREIM sectors.

3.2 Land-use and Water Model for Stockholm

The first land-use projection effort calibrates to past land-use change patterns to 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 were determined through local engagement and local planning processes. In this case they are on-going and being determined by the regional planning organization in Stockholm.

After calibration, Stockholm LEAM was coupled with a hydrological model (r.sim.water) to assess the impacts of land-use change on the local hydrological system (level 1) and also with a hydrodynamic model (MIKE FLOOD) in level 2.

Level 1. At this level we considered how water moves and collects, the potential impact of flooding, and the location of potential flood areas. The analysis represents a 50mm storm event (approximately 2 inches) over an hour, which is equivalent to a 100-year storm for the region. The hydrologic model used is r.sim.water, an open source, cell-based dynamic simulation tool, developed as r.hydro by the US Army Corps of engineers for the GRASS geographic information systems tool. We used the hydro model to calculate flood risks as a feedback mechanism to the land-use model. In Stockholm, we assigned 100-year flood risk areas as no-growth zones for future development.

Visually, the r.sim.water model and the actual data for low areas and ponding match quite well. Catchment areas indicated as streams, rivers, and ponds match the model exactly. In this analysis we are concerned with other depressions and how water collection might prohibit future development or green infrastructure-based solutions. These areas are designated as floodplain areas. This information was 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 preserves, government or public lands, etc. The floodplain map was added to this and the model 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 five percent of the flooding areas (proposed modified no-growth zones) overlay with the projected growth, so a modified no-growth zone does not make produce a visible difference in the 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 below.

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

Figure 7 shows how flooding extent and flood depth were altered to change 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, the hydrological response of land-use changes on the stream flow and stream water level in Igelbäcken was evident.

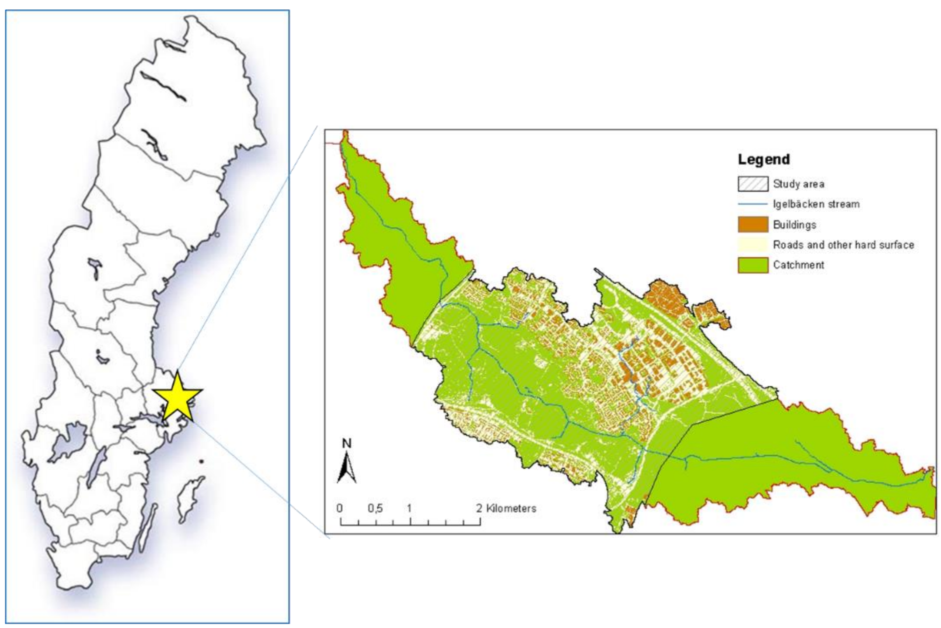

Figure 6. Location of the study area, Igelbäcken stream catchment, Stockholm region, Sweden.

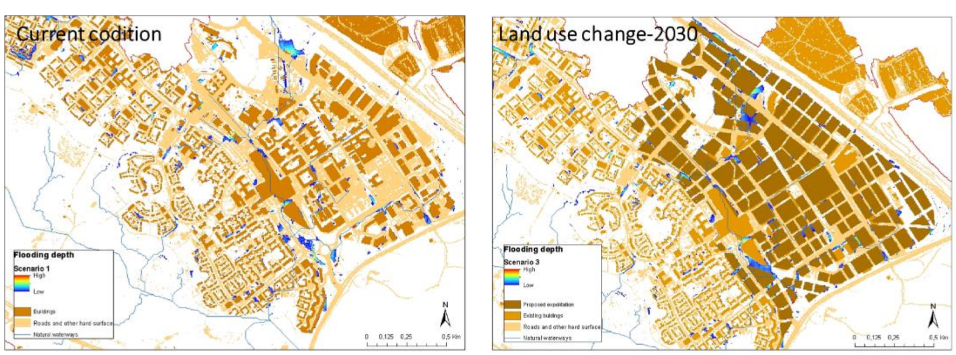

Figure 7. Flooding extent with water depth above surface for current land-use conditions and LEAM land-use change scenario for year 2030, displayed together with natural waterways in the landscape, existing roads and buildings.

3.3 Inter-regional Mutual Learning

In this section, we demonstrate how to build a coupled land-use and regional economy model in Chicago, as well as a coupled land-use/hydrology model in Stockholm. We do not show integrated economy-land-use-hydrology models in both locations due to lack of local experts and data. To overcome this issue, we built alternative scenarios to complete the models (such as using official population/employment projection for socioeconomic data). Next, we used a mutual learning process. The regional economic model for Chicago will be applied to Stockholm with sectoral economy data from Stockholm and some recalibration, while the Stockholm hydrological team will run the hydrological model for Chicago with LEAM land-use change forecast. We compared forecast results to the current results, using official forecasts to see whether the integrated model-generated results fall within a reasonable confidence interval of the existing models.

We used the mutual learning process when we built 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 elsewhere (Deal *et al.*, 2017a; Deal & Pan, 2016). Chicago and Stockholm models were both constructed and shared using a computing server for this purpose. An example of LEAM visualized interface is shown in **figure 8**.

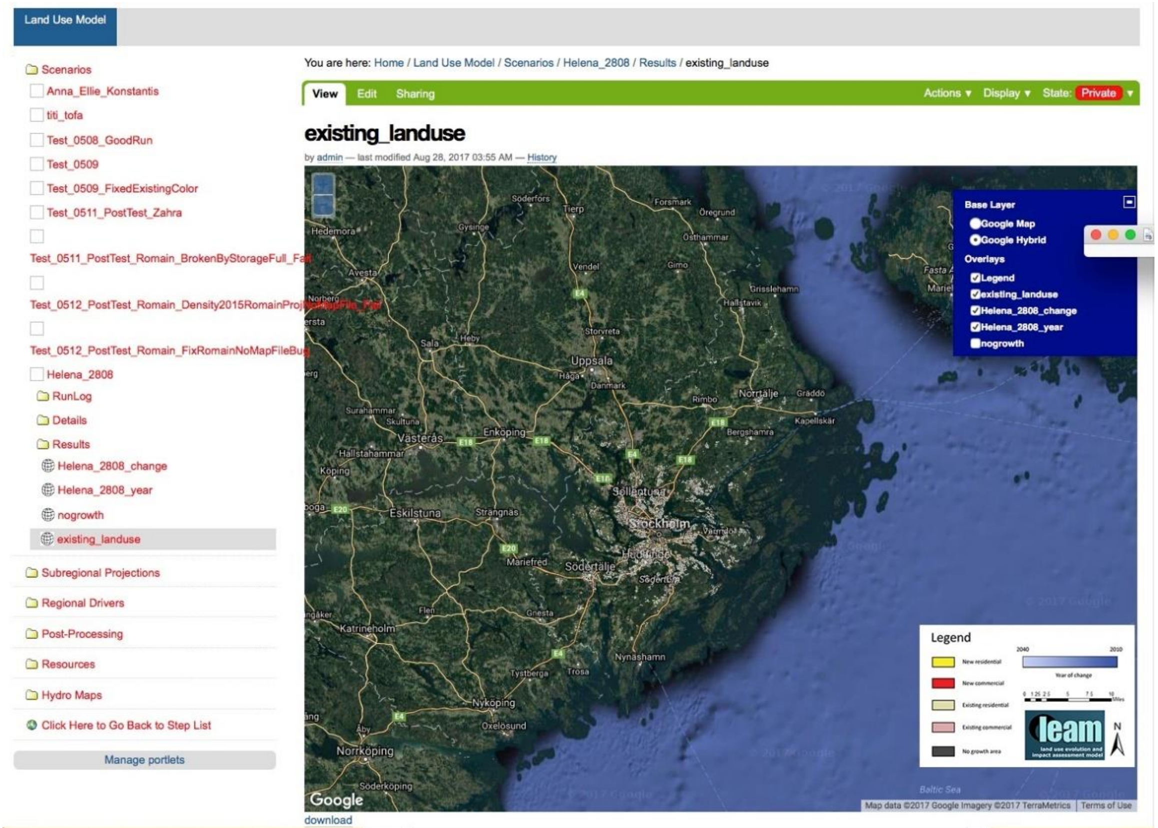

Figure 8. A screenshot of LEAM Stockholm online platform

We figure out that to effectively communicate with local stakeholders via our PSS interface, it is important to build the model with local stakeholders, such as involving stakeholders in tuning model parameters and validating model results. The information shown to non-expert 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).

3.4 Discussion

Our results show potential social and natural process interactions. In the Chicago economy and land-use model application, we found that physical land-use availability for economic activities differs from the sectoral forecast 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, for the Stockholm land-use and storm-water modeling, we found that land-use and water models both need to be adjusted when assessing one system's impact on the other. Flood-zone regulations can divert land-use to other locations, while land-cover change may also change the amount of impervious surfaces and alter future hydrological models.

We demonstrate that modeling social and natural processes together provides a more comprehensive understanding of causes and impacts of the dynamics and the hydrological systems. This is one of the major benefits of applying IWRM approach in water management practices.

Building large-scale integrated models is understandably complicated and challenging. We applied multiple techniques to address those challenges. For example, we limited the growth "shock" for each sector in economic models and land-use models to no more than 10% to control for uncertainties. Different models are built in multiple regions with experts of diverse skills so that mutual and global learning can take place, leading to more complete models for different places in the world.

4. Conclusion

The IWRM approach has been criticized as impractical and not clearly defined. A systems modeling approach to water management is a first step to extracting well-defined information to guide the practices of an IWRM. This approach calls for collaboration and communication among different scientific fields and well-designed processes in model building, problem solving, mutual learning and knowledge translating.

Using integrated economy-land-use-water models, this paper represents a pioneering attempt to integrate models (that have been successfully deployed as stand-alone models) to develop a comprehensive understanding of how storm-water dynamics will be affected by and affect human activities in cities. We propose a general modeling framework and identify possible challenges that modelers need to address. Regardless of local context, the modeling framework can be implemented with a process of mutual learning, localization, scenario building, and effective communication with local stakeholders.

Our results suggest that integrated modeling generates a different and more comprehensive understanding of land-use, economic, and hydrological systems. Unlike traditional economic models, combined land-use and economic models can show land resource constraints on regional economic development. Industry trends also enhance land-use models by influencing the locations of commercial land-uses. Combined land-use and hydrological modeling offers a dynamic future land cover and can significantly change the extent of flooding zones. The newly-generated flooding zones in turn limit urban land-use growth choices.

Integrated system modeling is fruitful but also very difficult. It requires experts in very diverse fields and a large amount of data. We propose using a replicable process and global learning to develop models in different regions of the world. We also suggest developing scenarios to address uncertainty issues and providing alternative modeling choices if some of the original models do not apply to certain regions.

There are several steps that can be taken to extend this research. First, we can continue to build an integrated economy-land-use-hydrological model with full feedback loops. Water and economic input-output can be linked using the virtual water flow model (Bae & Dall'erba, 2018). Economic, land-use, and hydro-logical modeling can influence each other (pairwise). There will likely be disagreement in some modeling pairs, so an iterative process of adjusting model inputs and assumptions will be required to balance different modeling outcomes. Second, there are also other water-related variables that we could add to the current integrated modeling framework, such as water quantity and quality.

Finally, we demonstrate a LEAM modeling and PSS platform that can easily replicate land-use models for worldwide regions and couple land-use models with impact assessment models. A cloud-based user-interface allows customized model inputs and defining scenarios. This research an example of how integrated modeling systems can be deployed and accessed to guide IWRM practices.

Acknowledgement

The work used the ROGER supercomputer, which is supported by NSF under grant number: 1429699. We thank Shaowen Wang and Anand Padmanabhan for their assistance with high performance computing jobs, which was made possible through the CyberGIS Center Help Desk. We also thanks Linda Larsen for language edits of the paper.

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Tables

Table 1. Sectoral growth by ratio for each CREIM and LEAM sector. We calculate the rank of the growth ratio for each sector in CREIM and LEAM and calculate the rank difference. The 3 sectors that CREIM underestimated the most are marked in red. The 3 sectors that CREIM overestimated the most are marked in yellow.

CREIM Sector Growth (2040 total/2013 total)

Sector	Whole Trade	Retail Trade	Commercial	Entertainment	Accommodation	Healthcare
Value	1.70	1.54	2.36	1.54	2.08	1.77
Rank	7-T	13-T	2	13-T	3	5
Sector	**Education**	**Government**	**Membership**	**Mining**	**Manufacturing**	**Warehousing**
Value	1.64	1.74	1.66	0.90	1.70	0.97
Rank	10	6	9	16	7-T	15
Sector	**Railroad**	**Transit**	**Air**	**Personal**	**Information**	**Utilities**
Value	1.83	1.06	1.57	1.63	2.37	0.47
Rank	4		12	11	1	17

LEAM Sector Growth (2040 total/2013 total)

Sector	Whole Trade	Retail Trade	Commercial	Entertainment	Accomodation	Healthcare
Value	1.04	1.30	1.09	1.03	1.20	1.10
Rank	12-T	2	8	14-T	3	7
Sector	**Education**	**Government**	**Membership**	**Mining**	**Manufacturing**	**Warehousing**
Value	1.12	1.06	1.36	1.05	1.04	1.11
Rank	5	9	1	10-T	12-T	6
Sector	**Railroad**	**Transit**	**Air**	**Personal**	**Information**	**Utilities**
Value	1.03	1.02	1.01	1.01	1.05	1.13
Rank	14-T	15	16-T	16-T	10-T	4

Sector	Whole Trade	Retail Trade	Commercial	Entertainment	Accomodation	Healthcare
Rankdiff	-5	11	-6	-1	0	-2
Sector	**Education**	**Government**	**Membership**	**Mining**	**Manufacturing**	**Warehousing**
Rankdiff	5	-3	8	6	-5	9

Sector	Railroad	Transit	Air	Personal	Information	Utilities
Rankdiff	-10	-15	-4	-5	-9	13

Table 2. Aggregated impact of LEAM sectoral adjustment applied on CREIM. 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; indirect impact is the impact resulting from direct impact to all economic sectors. Multiplier is calculated by Total/Direct.

	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