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An integrated modeling approach coupling stakeholders' values and policy trade-offs in Oklahoma, USA

Gehendra Kharel Dr.
Oklahoma State University - Main Campus, gehendra.kharel@okstate.edu

Ronald Miller Dr.
Oklahoma State University, ron.miller@okstate.edu

Chris Zou Dr.
Oklahoma State University - Main Campus, chris.zou@okstate.edu

Jennifer Koch Dr.
University of Oklahoma Norman Campus, jakoch@ou.edu

Tracy Boyer Dr.
University of Wisconsin - Milwaukee, taboyer@uwm.edu

See next page for additional authors

Presenter/Author Information

Gehendra Kharel Dr., Ronald Miller Dr., Chris Zou Dr., Jennifer Koch Dr., Tracy Boyer Dr., Heather McCarthy Dr., Naci Dilekli Dr., and Raymond Huhnke Dr.

An Integrated Modeling Approach Coupling Stakeholders' Values and Policy Trade-offs in Oklahoma, USA

Gehendra Kharel[a], Ronald Miller[b], Chris Zou[a], Jennifer Koch[c], Tracy Boyer[d], Heather McCarthy[e], Naci Dilekli[c,f], Raymond Huhnke[b]
Affiliations (provide email addresses)
[a] Department of Natural Resource Ecology and Management, Oklahoma State University, Email: gehendra.kharel@okstate.edu (Kharel); chris.zou@okstate.edu (Zou)
[b] Department of Biosystems and Agricultural Engineering, Oklahoma State, Email: ron.miller@okstate.edu (Miller); Raymond.huhnke@okstate.edu (Huhnke)
[c]Department of Geography and Environmental Sustainability, University of Oklahoma, Email: jakoch@ou.edu
[d] School of Freshwater Sciences, University of Wisconsin-Milwaukee, Email: taboyer@uwm.edu
[e] Department of Microbiology and Plant Biology, University of Oklahoma, Email: <heather.mccarthy@ou.edu
[f]Center for Spatial Analysis, University of Oklahoma, Email: ndilekli@ou.edu

Abstract: Oklahoma watersheds and urban areas are subject to increased water shortages, woody plant encroachment, and other socio-environmental issues. To investigate these issues in an integrative manner, we are using agent-based modeling approaches within the ENVISION modeling framework. Our three study areas represent the diversity within Oklahoma: Oklahoma City (urban), Kiamichi watershed (timber, reservoir), and Cimarron watershed (agriculture, grassland). An important environmental issue in the Oklahoma City (OKC) study area is the residential water consumption for irrigation during the dry summer months and the sustainable use of scarce water resources in the context of future urban growth and climate change. To analyse this issue, the OKC model simulates the relationship among climate change, population growth, urban expansion, and residential water consumption. Kiamichi stakeholders are concerned about the local economic impacts of lowered levels of a major reservoir, and the integrated model simulates reservoir water levels under various withdrawal policies and future climate scenarios. Cimarron stakeholders are concerned about eastern redcedar encroachment in the watershed, and the model evaluates changes in water flows due to changes in climatic conditions and woody plant encroachment into the existing agriculture and grassland. Important linkages exist between the models which can help explore potential resource conflicts between these areas. For example, the Kiamichi reservoir also supplies water for OKC, and thus water use in OKC directly affects the economic base of Kiamichi residents. Similarly, redcedar encroachment is an emerging issue throughout Oklahoma with impacts upon water supply and land productivity, and policies that effectively encourage redcedar control can be applied throughout the state with a positive impact on water resources.

***Keywords**:* ENVISION; integrated modeling; climate change; Oklahoma EPSCoR; reservoir

1 INTRODUCTION

Increasing climate variability and anthropogenic alterations including changes in land use, and urbanization have complicated the management of natural resources and social welfare globally (Rosenzweig et al., 2007). This is particularly evident in many rural and urban watersheds in Oklahoma located in the southern Great Plains of the United States (Dale et al., 2015; O'Driscoll et al., 2010; Steiner et al., 2018). Oklahoma ranks among the top ten states in producing food and energy in the US. At first glance water might not seem a limiting issue in Oklahoma since several major river systems pass through the state, reservoirs have been constructed on major and minor streams, and some regions of the state receive more than 1,300 mm annual average rainfall. However, a recent increase in the number and intensity of extreme drought and floods events have been observed in Oklahoma (Mesonet 2018a; Mesonet 2018b) with negative impacts on environments, local economies and society (US EPA, 2016). Understanding the effect of those stressors on the state's socio-environmental systems and the potential effects of future changes in regional climate can help create resilient socio-environmental systems.

Researchers in Oklahoma have begun to address these water-related issues by building integrative computer simulation models for three discrete areas. The focus of the Cimarron model is the mesic grassland that dominates the landscape of Oklahoma, which is being encroached in many areas by juniper woodland (Zou et al., 2014). The eastern redcedar encroachment has altered the hydrological balance and reduced streamflow in the region because the redcedar stands intercept up to 33% of annual rainfall, which is considerably more interception than the native warm-season grassland (Qiao et al., 2015; Starks and Moriasi, 2017). The OKC model addresses urban water use by Oklahoma City (OKC), the largest urban area in Oklahoma. Simplistically, water use by OKC can be divided into the daily needs of residents and industrial users, and the 'discretionary' use for private and public landscaping, which affects the 'greenness' of the urban landscape. The greenness of an urban area reduces energy use and increases human wellbeing, but the water required to maintain greenness peaks during times of highest water stress such as the summertime and especially during droughts (Bijoor et al., 2012). Finally, across Oklahoma there are wide variations in both water abundance and water use rates: the Kiamichi model concerns a watershed in southeast Oklahoma with locally abundant water including a reservoir, but limited local water use because of the very low population. The water stored in the reservoir is controlled from outside the watershed, but local residents have come to depend economically on the reservoir as a tourist destination, setting up stakeholder conflict over reservoir management between the local and outside groups.

Each of these models can contribute to the understanding of and finding sustainable solutions to local socio-environmental issues. Furthermore, there are very strong direct and indirect linkages between all of the models. Therefore, together they can help to address the more complex regional and state-wide issues of understanding the effects of climate change, woody plant encroachment and urbanization in Oklahoma. The main objective of this study is to model varieties of socio-ecological issues in select watersheds and an urban area in Oklahoma as an integrated system. This study will provide successful and effective stakeholder contact techniques, integrated modeling, and decision support tools that can form the basis of conflict resolution.

2 METHODOLOGY AND DATA

2.1 Study Area

We are studying three areas in Oklahoma as representatives of rural forested watershed (Kiamichi River watershed), agricultural-grassland watershed (Cimarron River watershed) and urban region (Oklahoma City area) (Figure 1). The Cimarron Watershed within Oklahoma (18,240 km^2) is an agriculture-grassland intensive watershed with the Cimarron River flowing from northwest to central Oklahoma (Figure 1). The watershed is predominantly grassland (~50%) and agriculture (~33%) with a population of more than 200,000. The watershed has a steep precipitation gradient with an average annual precipitation of 500 mm in the north-western region to 1,000 mm in the east-central region. Since 1950, there has been a shift in land use. Between 1950 and 2011, nearly 6,000 km^2 of cropland was lost to other land uses, mostly grassland, rangeland and urban land. Since 1999, the watershed has witnessed an encroachment of eastern redcedar, an evergreen juniper species (*Juniperus virginiana*) with known and unknown consequences to value and quality of land, water resources, wildlife, and wildfire in the region (Coppedge et al., 2001; Weir and Scasta, 2014; Zou et al., 2014).

The Kiamichi River is located in southeast Oklahoma with its headwaters near the Arkansas-Oklahoma border in the upper Ouachita Mountains and its terminus at the confluence with the Red River. The watershed covers 4,720 km^2, and is predominantly forest (~66%) and grassland/pasture (~25%) with average annual precipitation ranging from 1,200 mm to over 1,400 mm. The combination of steep topography and thin soils in the watershed contributes to both high runoff and drought conditions in the watershed. In addition to timber and cattle contributions to local economy, Sardis Lake Reservoir located in this watershed, generates revenue from recreational and tourism activities while serving as a domestic water supply. Recently, the number of second-home sales has grown in the area near Sardis Lake, with purchasers citing the scenic lake and the uncrowded environment as desirable features (D. Faulkner, February 2018, private conversation). Additionally, a recent agreement between the City of Oklahoma City, the State of Oklahoma, and the Choctaw and Chickasaw Nations allows transfer of a portion of up to 40% of the stored Sardis Lake to users outside of the watershed (OK Water, 2016). These two important developments – growth in local economy, and water transfer – have put pressure on the management of Sardis Lake Reservoir and the Kiamichi Watershed.

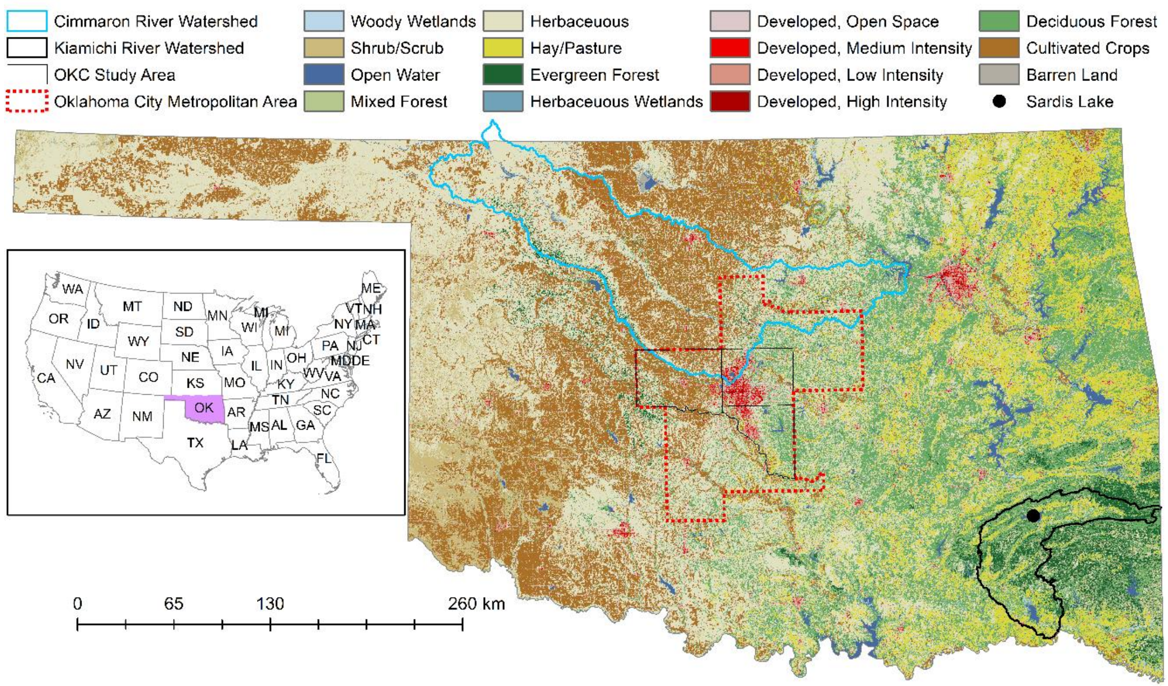

Figure 1. Three study areas (Cimarron, Kiamichi and Oklahoma City) located in the State of Oklahoma.

The Oklahoma City (OKC) model application covers Canadian County, Oklahoma County and Cleveland County, with a total land area of 5,554 km^2. According to the U.S Census, the estimated population for this area in 2016 was about 1.198 million. Due to the prolonged drought during 2011–2015, Oklahoma's municipal water supply has come under stress due to increased demand caused by population growth on the one hand and climate variability on the other hand. The Oklahoma City metropolitan area experienced considerable sprawl in the past. While this trend has levelled off in recent years (Lopez, 2014), continued population growth is expected throughout the study area. In Oklahoma, water consumption and especially residential water demand, including activities for outdoor use such as landscape irrigation are typically high during the relatively hot summer months (Ghimire et al., 2015). The OKC model application will increase the understanding of the relationship among changing climate, urban development, and changes in residential water demand with the latter two driven by continued population growth.

2.2 Methods

The sustainability of these three representative systems depends on important variables such as changes in climate, land cover and land use, policies and stakeholder perceptions. In order to integrate these variables, we selected the integrated modeling platform ENVISION (Bolte et al., 2007) to model each of these systems. ENVISION is a GIS-based multi-paradigm modelling platform for integrative analyses of human-natural systems, which can be adjusted and parameterized for different research foci and landscapes. It is designed to examine alternative landscape futures, based on different scenarios, allowing management decisions to be tested within the context of different stakeholder concerns (Guzy et al., 2008). This platform can connect sub-models, called plug-ins, to achieve specific modeling goals (e.g., implementation of forest succession or hydrologic processes). By hard-coupling those plug-ins and integrating them with an agent-based component, ENVISION provides a way to model the interactions between human and natural landscape processes over space and time. This allows us to analyse the properties of a coupled human-natural systems as a whole. The choice of plug-ins allows the platform to be 'customized' to portray and evaluate a large variety of stakeholder concerns and environmental or landscape issues.

The basic unit of an ENVISION application is the landscape representation through polygons, called integrated decision units (IDUs). Each IDU is associated with an actor capable of decision-making (in form of policy and management strategy selection and implementation). Furthermore, an IDU stores spatial and non-spatial attributes of the landscape related to the modeling purpose. The spatial configuration of IDUs is polygon-based and flexible, and should be determined according to the modeling goals. Multiple IDUs can have the same actor but not a vice-versa (Figure 2).

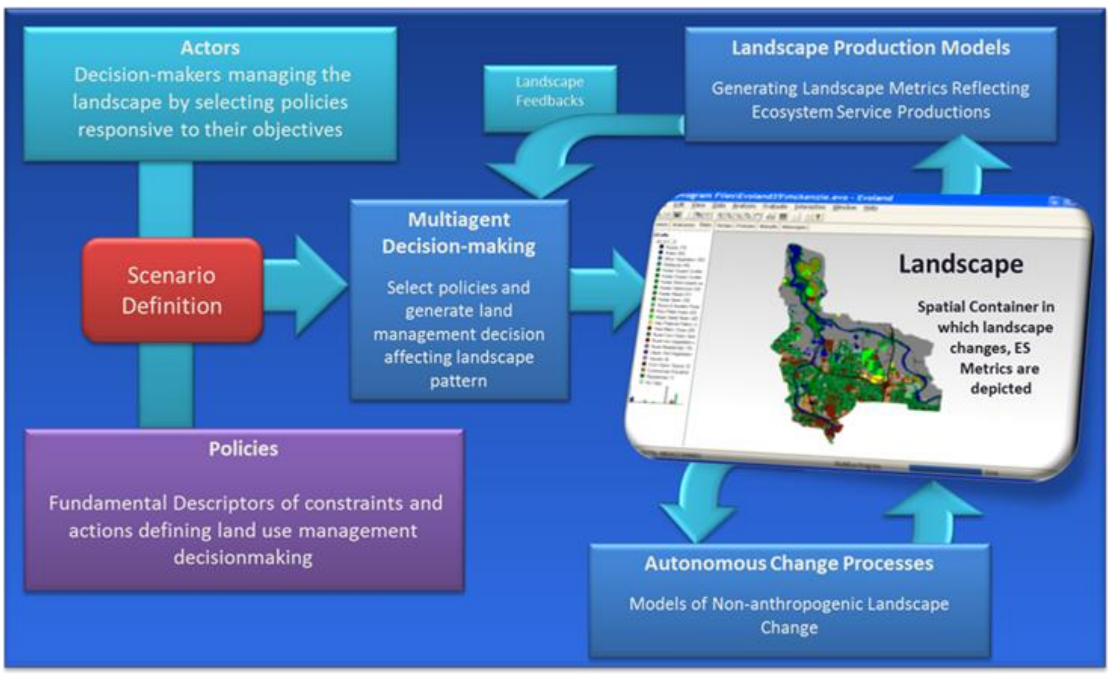

Figure 2. Conceptual framework of Envision model showing the landscape as the central component of autonomous (e.g. climate, hydrology) and human agent-based (e.g. development, timber harvest) influences, with feedback occurring between model iterations. (Source: http://envision.bioe.orst.edu/)

Each study area in Oklahoma is modeled as a landscape divided into multiple IDUs; 24,147 for Kiamichi, 29,751 for Cimarron and around 500,000 for OKC. Then, the plug-ins specific to human-natural processes related to study objectives are connected to the landscape or, if no suitable plug-in is available, a new one is developed (Table 1). The FLOW plug-in is used to simulate the watershed hydrology for the Kiamichi and Cimarron models. FLOW is based on the HBV semi-distributed hydrologic model (Bergström, 1992), and provides basic hydrologic connectivity, geometric representation of riverine features including stream segments, and other processes such as, reservoir operations and evapotranspiration. The Simple State Transition Model (SSTM) plug-in is used to define land cover changes such as forest aging during model simulation based on defined transition probabilities and time periods. The TARGET plug-in is used in the OKC application to project future urban development. Furthermore, we developed a new module for the OKC study area. It is based on a panel regression model and evaluates the relationship between greenness of the landscape as given by enhanced vegetation index (EVI), climate factors (temperature, precipitation, wind speed, humidity), parcel characteristics (building area and age, land value, number of residential units), and residential water consumption.

Table 1. Data sets and ENVISION plug-ins used in the Oklahoma study areas.

Data and Plug-ins	Source	Description
Land use land cover	USGS National Land Cover database & USDA crop layer	Assigned to each IDU
Vegetation type and red cedar encroachment	Oklahoma Department of Wildlife Conservation	Oklahoma Ecological System Mapping
Land parcels	Oklahoma Office of Geographic Information (*https://okmaps.org/OGI/*)	Used to find the urban development trend
Soil	USDA	Assigned to each IDU
Historical climate	Global Weather Database (*https://globalweather.tamu.edu/*) , Oklahoma MesoNet (*https://www.mesonet.org/*)	Daily data (1979–2017 for precipitation, temperature, relative humidity, solar radiation, wind speed
Future climate	Multivariate Adaptive Constructed Analogs (MACA) datasets	Future climate scenarios are based on the IPCC-CMIP5 projections downscaled to study areas
Lake/reservoir	US Army Corps of Engineers (USCAE)	Water levels and pumping schedule
Streamflow	USGS	Daily records at different stations within the watersheds
Actors	Stakeholder meetings, focus group, literature review, personal communications *http://water.okstate.edu/watersheds*	Identification of stakeholders in each watershed and their assignment as actors within the models; stakeholder input through meetings with the OKC city planners
FLOW	ENVISION (*http://envision.bioe.orst.edu/*)	Used in Kiamichi and Cimarron models
SSTM	ENVISION *http://envision.bioe.orst.edu/*	Used in Kiamichi and Cimarron models
TARGET	ENVISION *http://envision.bioe.orst.edu/*	Used in OKC model
GREENNESS	Oklahoma Established Program to Stimulate Competitive Research, EPSCoR	Used in OKC model

One way to include local knowledge in the modelling process and model parameterization is inclusion of stakeholders and their perceptions and opinions about important issues in the watershed/region into the modeling study (Voinov and Bousquet, 2010). Stakeholders for two of the study areas (Kiamichi and Cimarron) were invited to participate in a day-long symposium held separately for each watershed. During the symposia, stakeholders gave oral and poster presentations related to the important environmental issues in their watersheds, followed by discussions. Afterwards, the participants selected several important factors related to the strengths, weaknesses, opportunities and threats (SWOT) in the overall management of the watershed in the context of a changing environment. For the OKC model, the research team held several meetings with the representatives from cities to learn about their needs and priorities for managing urban development and resource use.

3 PRELIMINARY RESULTS AND DISCUSSION

3.1 Stakeholder Insights

There were three meetings with Kiamichi watershed stakeholders. At the first in June 2016, a total of 35 individuals from 13 different institutions and organizations participated in the meeting. These individuals represent state and federal governments, tribal nations, academic institutions, for-profit and non-profit organizations with varied interests in the watershed. The participants identified the three most important factors for research in the watershed (Table 2). At a subsequent meeting in October of 2017, a group of 11 Kiamichi stakeholders voiced concerns about the local economic and water supply impacts of lowered levels of Sardis Lake resulting from a recent agreement that allowed OKC to build a pipeline to withdraw water, and a final meeting in March 2018 with two stakeholders helped to refine the focus on potential economic impacts of reduced lake levels due to water withdrawals (Table 2). All of these meetings helped to focus model development on issues that were important to the stakeholders.

Table 2. Participation, top three stakeholder concerns, and operational outcome for the Kiamichi ENVISION model from the three Kiamichi stakeholder meetings.

Meeting	**Participants**	**Stakeholder Concerns**			**Model Implementation**	
		1	**2**	**3**		
2016	35	In-stream flows	Surface-GW Interactions	Climate LULC change interactions	3: Integrated pine plantation and pine/deciduous forest harvest components	
2017	11	Water Quantity	Economic Opportunity	Water Quality	1: Sardis reservoir operations	1: Water release scenarios
2018	2	Sardis level effects on Tourism	Sardis level effects on 2nd home development		1: Adapt Daniels-Melstrom visitation model (Daniels and Melstrom, 2017)	2: Scenarios based on historic 2nd home development trends, dependence on lake levels

For the Cimarron watershed, a total of 33 individuals from 12 different institutions and organizations participated in the symposium meeting. These individuals represent state and federal governments, academic institutions, for-profit and non-profit organizations with their varied interests in the watershed. The participants identified 16 important factors pertaining to strengths, weaknesses, opportunities, and threats in the overall management of the watershed (Table 3). The participants indicated that stronger collaborations among various stakeholders including water users (farmers, industries), water use management through new regulations and incentive programs, and development of decision support tools leveraging already available data and information would potentially help them address the internal weaknesses and external threats to effectively manage the watershed. In addition to the symposium meeting, two online surveys were administered between January 2017 to March 2017 using the Qualtrics platform (https://www.qualtrics.com/). The surveys were approved by the Oklahoma State University Institutional Review Board. These surveys were designed to elicit opinions of experts on the 16 identified factors and rank these factors in terms of their importance based on their knowledge. Additionally, the participants were asked to identify particular issues in the watershed if any that they believed need to be addressed for the sustainable management of the watershed. Issues of woody plant encroachment, drought, reduced streamflow, increased salinity and sedimentation in streams, and increased water use for oil and gas extraction were identified to be the most critical in the watershed. These perceptions of stakeholders and experts about issues related to the sustainable management of the watershed formed the basis for developing different policy scenarios to be used during model simulations.

Table 3. Important factors related to the Cimarron River Watershed management as identified by stakeholders.

Strengths	**Weaknesses**
S1: Willingness to work together	W1: No platform to share data
S2: Amount of historical data	W2: Social perception is unknown
S3: Informing policy based on science	W3: Inability to track water use
S4: Stream & biological monitoring activities	W4: Underutilization of data
Opportunities	**Threats**
O1: Incentives for water & wetlands conservation	T1: Uncertainty with regulations and policies
O2: Enforcement of water uses	T2: Increased water use for energy and irrigation
O3: Stronger stakeholder collaborations	T3: Lower funding priority
O4: Data use in decision support system	T4: Climate change/drought

For the OKC metropolitan area, a different approach was used. As seen during the recent drought – and reflected in the Sardis Lake agreement – water is a scarce resource in the OKC metropolitan area. Still, large amounts of this scarce resource is used during the dry summer months for outdoor activities such as irrigation. Since the focus in this study area is on the combined effects of population growth and change in climate on water consumption, we facilitated the already established connection to the OKC city planners to retrieve detailed data on spatio-temporal parcel dynamics and held meetings to understand the planners' interest in scenarios and suitability factors for the spatial simulation of potential future developed area. The suggested components for spatial allocation include infrastructure and distance to fire stations (spatial data available through OKC Data Portal: https://data.okc.gov/)

3.2 Model Implementation

Hydrological modeling was carried out for both Kiamichi and Cimarron watersheds using the FLOW plug-in. Output from FLOW was calibrated with the daily streamflow observations obtained at the USGS gauge stations located within the watershed.

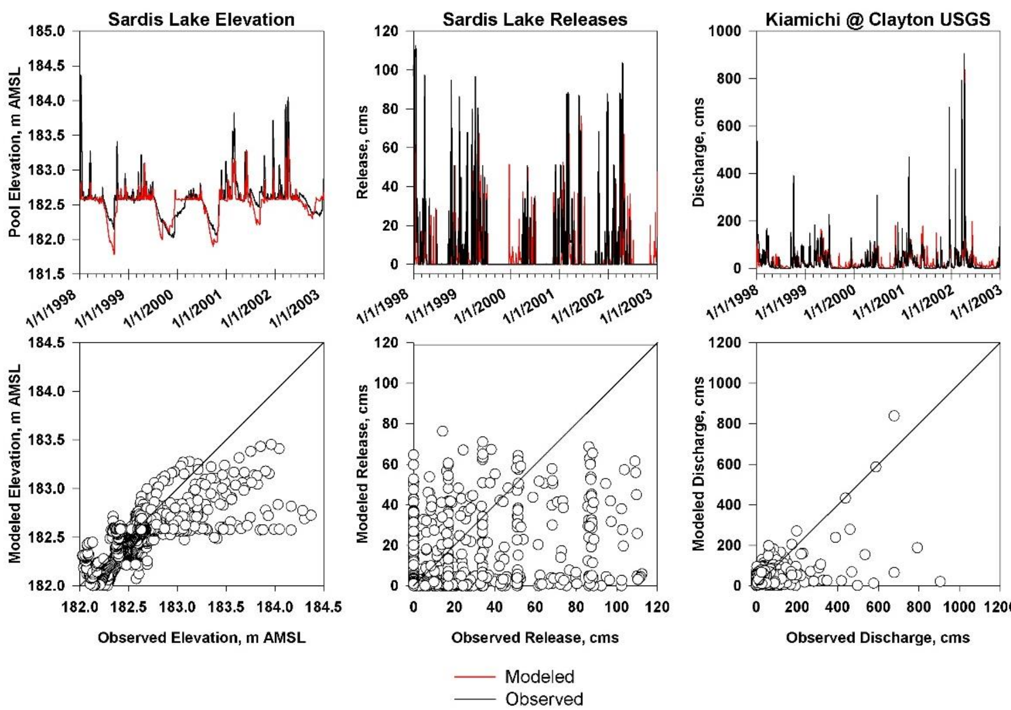

Figure 3. Observed (black lines) vs. modeled (red lines) pool elevations and releases for Sardis Lake, and streamflow at the USGS stream gauge at Clayton (07335790). Nash-Sutcliffe Efficiencies for pool elevations, releases and streamflow are 0.43, 0.17, and 0.36 respectively.

Similarly, the reservoir operation rules for controlling reservoir releases in the Kiamichi model were adapted from the US Army Corps of Engineers Sardis Lake operations manual (USACE, 2010), and the simulated reservoir water levels were then compared to USACE records of pool elevation (USACE, 2016). When adequately calibrated, the FLOW component of the model will be used to estimate pool elevations and Kiamichi River flows under various withdrawal policies and future climate scenarios. The agreement at lower elevations shows good agreement between the modeled rules and the actual reservoir management under normal conditions (Figure 3). Disagreement occurring at higher pool elevations indicates a mismatch between actual and modeled storm runoff, and is due to inadequate hydrologic calibration, a process which is underway at the present time.

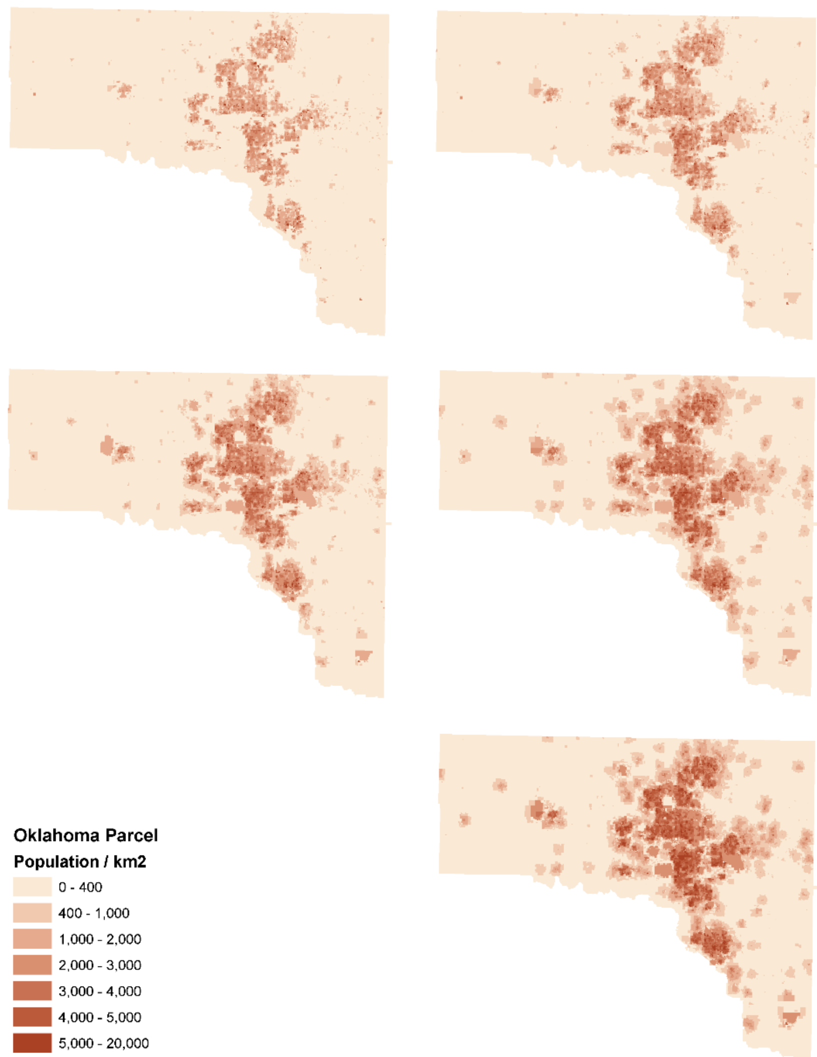

Figure 4. Baseline (2010) and projected population densities of the OKC metropolitan area under infill/increased density scenarios for 2020, 2030, 2040 and 2050.

The OKC ENVISION application was designed to analyse the relationships among climate change, population growth, urban development, vegetation greenness, and residential water use for irrigation. We used greenness of vegetation (as represented by EVI) and evaluated its relationship to climate, landscape, and parcel characteristics through a panel regression model for four parcel size categories. The model showed that vegetation greenness was surprisingly unresponsive to water consumption, but was highly related to mean maximum temperature, building age, and land value. This result may indicate that tree cover may play a larger role for vegetation greenness in OKC than expected. We are currently working on implementing the regression model as a plug-in to ENVISION. The regression model describes the relationship between factors, parcel characteristics, water consumption, and vegetation greenness. By coupling the regression model with climate drivers and a sub-model on change in parcel characteristics, we aim at modeling changes in vegetation greenness. We also used the TARGET plug-in to run an infill (and increased population density) scenario simulation (Figure 4).

3.3 Study Limitations and Next Steps

This is an ongoing project. Therefore, continued development and calibration of each model, developing plausible scenarios based on stakeholder perceptions, existing policies and future climate are still underway. Next steps for the Kiamichi model include fine-tuning the actor-based home-development function. It is suspected by stakeholders that the future draw-down of Sardis Lake by OKC will impact its scenic value and thus adversely affect the rate of development. Because this rate is not a known value, multiple scenarios will need to be constructed to encompass a wide range of possibilities. Importantly, the OKC model is designed to suggest the climate and development circumstances that require the most water to maintain green-ness. Those climate conditions will be used as a Kiamichi model scenario so that watershed conditions in general, and the Sardis Lake levels in particular can be known under greatest export need.

Similar to the Kiamichi model, the Cimarron model features a broad-scale hydrologic model that integrates climate and land cover to streamflow. A spread rate of redcedar will be built into the model based on time-series analysis of satellite imagery (Wang et al., 2017). The agent-based aspect of the Envision platform is used to model various redcedar control scenarios based on research into effective treatments, such as controlled burning, and incentive structures. For the OKC study area, an evapotranspiration module to better represent the relationship between urban development, impervious surface area, residential water consumption, and greenness of vegetation will be implemented.

4 CONCLUSIONS

The three modeled areas represent the landscape and social diversity within Oklahoma: the Kiamichi watershed (timber, reservoir), the Cimarron watershed (agriculture, grassland), and the Oklahoma City Metropolitan Area (low density urban). Each individual model can make important contributions to improving resilience of the local socio-environmental system. However, important linkages exist between those systems (e.g., Lake Sardis as source of municipal water), which can help to explore resource conflicts between these areas and provide context for addressing broader regional or state-wide issues. For example, the Kiamichi reservoir also serves as part of the water supply for OKC, and thus water use in OKC directly affects the economic base of residents in the Kiamichi watershed. Similarly, redcedar encroachment is an emerging issue throughout Oklahoma with unknown effects on fire regimes, water supply, and land productivity. Therefore, the policies that effectively encourage redcedar control in the Cimarron watershed can be applied throughout the state with a positive impact on water resources.

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