Longitudinal Assessment of Development Composition and Spatial Patterns of Green Infrastructure for Effective Flood Control in Growing and Shrinking US Metropolitan Areas

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Abstract

This study empirically assesses the longitudinal impacts of the development composition and spatial patterns of green infrastructure on urban runoff in two Midwestern metropolitan areas: Greater Chicago and Detroit. It is hypothesized that the contrasting trends in demographic transition have distinctively shaped the trajectory of flood risk over time.

Research Problem Statement

Total impervious area (TIA) is a common development indicator that predicts local flooding magnitude. Another measure, directly connected impervious area, is a subset of TIA by which hydraulic connectivity to downstream channels contributes to the rapid discharge of stormwater. Which development measure to control to best moderate urban flooding has long been debated. The longitudinal effects remain unclear for cities where different trajectories of population shift have either driven infill development or the recovery of greenspace in underutilized/abandoned properties. A lack of long-term monitoring of regional green infrastructure can even hinder the securing and maintenance of local flood storage capacity.

Background and Significance

Greater Chicago and Detroit (also known as Chicago-Naperville-Joliet and Detroit–Warren–Dearborn metropolitan statistical areas), two of the largest metropolitans in the Midwest, have experienced contrasting trends in demographic transition in the last several decades. Greater Chicago is a budding region, recording more than a 15% population growth from 1990 to 2010 and forecasting an additional 25% by 2040 (CMAP, 2010; Fee & Hartley, 2011). Conversely, Greater Detroit is a rapidly shrinking area. Its population declined by approximately 14% from 1990 to 2010 (Fee & Hartley, 2011; Harpel, 2011). These contradictory population changes have led to divergent land use approaches. Greater Chicago has invested substantially in infill housing construction to accommodate the population growth, ranking seventh among all US metropolitan regions from 2000 to 2009 (Ramsey, 2012). The increasing demand for housing has also encouraged sprawling residential development at the urban fringe (Sööt et al., 2013). Meanwhile, Greater Detroit has suffered from limited municipal resources resulting from tax base losses attributable to the population decline. The vacancy rate in the region peaked at 12.9% in 2008 and continued to hover above 9% through 2018 (U.S. Census Bureau, 2020). Recent efforts have been made to demolish vacant houses and integrate green infrastructure (GI) into abandoned lots, revitalizing the green economy in economically deprived neighborhoods (Detroit Works Long Term Planning Steering Team, 2012; Kirkpatrick, 2015).

Given the conditions, it is unclear how different land use approaches, in association with population gain or loss, shape the resilience of cities to current and future natural disasters. Climate projections suggest that both Chicago and Detroit metropolitan areas will suffer increasingly severe flooding by the end of this century, due to growing storm intensities over extended dry periods (Kling et al., 2017). To develop a comprehensive understanding of development's effects on local flooding in relation to demographic changes, compositional variations in impervious surfaces must be cross-sectionally and longitudinally examined in both growing and shrinking communities.

Two compositional factors of impervious surfaces have commonly been examined in recent hazard-related research: total impervious area (TIA) and directly connected impervious area (DCIA). TIA is an integrative development measure used to indirectly quantify urbanization's impacts on local flooding and stream health (Shuster et al., 2005). Studies have shown that TIA contributes to flooding by limiting the water storage capacity of natural landscapes and elevating the amount and speed of stormwater discharge in the shortened lag time between rainfall and runoff (Guan et al., 2016; McGrane, 2016; Olivera & DeFee, 2007; Sohn et al., 2019). Local planners and water resource managers have often emphasized the importance of parcel-scale TIA regulations for flood control purposes. For example, stormwater fees are charged to landowners based on the proportional ratio of TIA on a property lot. Local ordinances often limit the maximum coverage of parcel-scale impervious surfaces in new development (Moglen & Kim, 2007; Sung et al., 2013). Yet some studies have argued that TIA approximates the complexity of the urban hydrology system and cannot fully explain the causal effects of development on urban flooding (Sohn et al., 2017; Yao et al., 2016).

DCIA is a subset of TIA that distinguishes the contribution of sewer flow to stream discharge from the lumped effects of surface and underground flow (Ali Ebrahimian et al., 2015; Ebrahimian et al., 2018). DCIA is hydraulically connected to downstream channels through closed sewer systems, while runoff from non-DCIA drains into adjacent greenspace, mainly being infiltrated or evapotranspirated during small storm events. Which development measure (either TIA and DCIA) better predicts urban flooding impacts has long been debated (Sohn et al., 2020). Recent studies have argued that DCIA is a better measure for preventing the overestimation of development impacts and quantifying the benefits of GI (Brabec et al., 2002; Sohn et al., 2017). Implementation of GI helps disconnect impervious surfaces from stream networks and reroute surface runoff to water storage systems such as detention basins, mitigating the level of DCIA. For effective flood control, understanding the compositional impacts of impervious surfaces is critical to prioritizing the importance of regulating either TIA or DCIA. It is expected that the hydrological performance of TIA and DCIA are subject to demographic conditions and land use approaches. By determining which measure to reduce the most, landscape architects, property developers, land use managers, and planners will be better able to strategize respective mitigation goals in growing and shrinking cities and integrate long-term resilient designs at both site and regional scales to protect against the future risk of flooding.

In addition to the development composition, the spatial patterning of GI is another contributing factor that affects the regional capacity for water storage during flood events. Many cross-sectional studies have assessed the relationship between GI configuration and flooding. Larger, more connected, and less fragmented GI has been found to benefit runoff reduction (Kim & Park, 2016; Li et al., 2020; Su et al., 2018). However, the results are often inconsistent, with disaggregated wetlands and fragmented urban forests enhancing flood regulation (McDonough et al., 2020; Zhang et al., 2013). Nonetheless, how changes in GI configuration longitudinally affect the flooding response of a city remains unknown. In association with demographic changes, growing and shrinking metropolitan areas may experience varying patterns of land use change over time. Without long-term monitoring, the maintenance of well-shaped GI for effective flood regulation can be threatened by increasing land use pressure and flood risk.

Research Objectives

The purpose of this research is to empirically examine the longitudinal impacts of development composition and GI patterns on urban runoff through years-long monitoring of two Midwestern metropolitan areas: Greater Chicago and Detroit. By tracking the contributions of TIA and DCIA to runoff yield, the research team will identify: 1) how impervious composition has distinctively changed over time in growing and depopulating regions, and 2) the control of which measure of impervious surfaces (TIA and DCIA) better moderates the runoff depth and peak flow of watersheds in response to long-term storm events. In this research, practical, quantitative goals of TIA and DCIA reduction for effective flood control will be formulated for the respective metropolitan areas, based on the outcomes of predictive models.

In addition, we will monitor the longitudinal performance of GI patterns to explore: 1) the spatial and temporal trends in GI distribution in association with gains or losses of demographic power, and 2) the specific features of GI's various forms (e.g., size, edge, shape, isolation, and connectivity) that help mitigate urban runoff. Regional goals for building resilient GI will be recommended for future design and planning efforts.

Work Plan

The proposed study includes four major tasks: watershed delineation, variables measurement, data analysis, and documentation/information dissemination (see Figure 1). The first task will be to delineate watersheds located within the Chicago and Detroit metropolitan areas using Arc Hydro, a hydrologic model in ArcGIS. The second task will focus on collecting data and measuring a set of independent and dependent variables, including impervious composition, GI configuration, and climatic, geophysical, and hydrological attributes. Ordinary least squares (OLS) regression and spatial panel data models will then be developed to predict runoff yields, comprising the third task. Finally, the research team will document and disseminate the prediction results and practical implications of the findings via diverse academic channels.

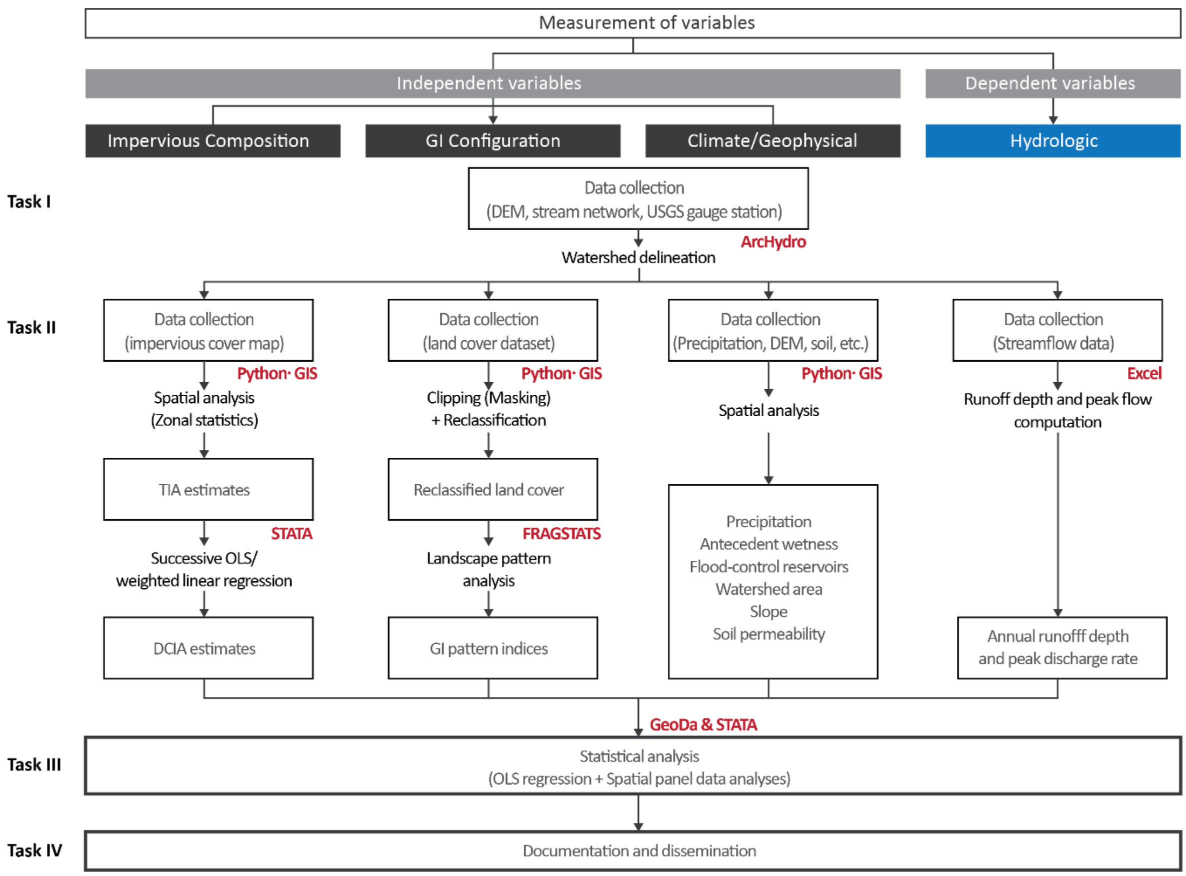

Figure 1. Conceptual framework for data analysis.

Task 1: Watershed Delineation

Using Arc Hydro, we will delineate watersheds based on the National Elevation Dataset and 2001 to 2016 streamflow data obtained from USGS gauging stations. To ensure measurement validity, the simulated stream network will be verified using measured data obtained from the National Hydrography Dataset (NHD Plus). The research team has already confirmed that 99 USGS gauging stations within the study area possess continuous streamflow data for the study period.

Task 2: Variables Measurement

Hydrologic variables: Two hydrologic parameters, annual runoff depth per unit watershed area and peak flow, will be computed as dependent variables for each watershed, based on USGS streamflow data collected every 15 minutes from 2001 to 2016. Out of the total 99 watersheds, only head watersheds in which streams of the highest order are positioned will be selected for peak flow computation. The peak flow of downstream watersheds will be excluded from the sampling, considering that the duration of runoff and time to peak are not consistent across watersheds.

Impervious composition variables: Two compositional variables of impervious surfaces, TIA and DCIA, will be measured as independent variables. First, the research team will extract TIA values from the USGS National Land Cover Dataset at a 30-meter level of resolution. Second, we will employ a statistical approach initially suggested by Boyd et al. (1993) and further developed by Ebrahimian et al. (2016) for the DCIA estimation. By applying a successive weighted least squares method, the fraction of DCIA for each watershed will be computed from historical rainfall and runoff data. To complete this task, the monthly rainfall and runoff data from 2000 to 2017 will be plotted for each watershed.

GI pattern variables: To quantify the spatial arrangement of GI, the research team will use the FRAGSTATS software developed by McGarigal (2014) to compute spatial landscape indices that measure the size, edge, shape, isolation, fragmentation, and connectivity of GI patches. We first will obtain the 30-meter resolution land cover map for a series of years between 2001 and 2016 from the USGS National Land Cover Dataset. The research team will then reclassify the land use codes into GI and non-GI. The reclassified maps will be masked for each watershed and imported into FRAGSTATS for index computation.

Climate/geophysical variables: To quantify climatic factors, we will retrieve time-series spatial rainfall data from the Parameter-Elevation Regressions on Independent Slopes Model Climate Group at a 4-km level of resolution. The total precipitation depth that correlates with annual runoff depth, as well as the 24-hour precipitation on the day that peak flow takes place, will be computed for each watershed. We will also assess the one-year and five-day prior rainfall depths as measures of antecedent wetness. Additionally, geophysical variables such as the number/size of flood control reservoirs, slope, and soil permeability will be obtained from the US Army Corps of Engineers, USGS National Elevation Dataset, and Natural Resources Conservation Service's Soil Survey Geographic Database.

Task 3: Data Analysis

With the sets of independent and dependent variables measured, the research team will develop pooled OLS and panel data models to predict individual runoff depth and peak flow. The interaction effects of geographic locations (i.e., Greater Chicago and Detroit) will be specified in the models to predict the competing effects of GI and development on urban flooding by location. Depending on the correlation between watershed-specific effects and independent variables, either a fixed or random effects method will be adopted for panel data modeling. In addition, we will perform a Moran’s I analysis to detect spatial autocorrelation in the dependent variables. If we identify any significant spatial dependence in runoff yields across watersheds for each time panel, spatial econometric models will be developed using geostatistical tools. We will also conduct a series of model selection tests (e.g., Lagrange multiplier test) to identify the most suitable spatial panel data model (e.g., spatial lag, error, Durbin, autoregressive with spatially autocorrelated errors, etc.). Considering the potential overflow effects from adjacent watersheds during major storm events, we will employ the contiguity weight method to specify spatial weight matrices.

Task 4: Documentation and Dissemination

The study results and practical recommendations for site development and regional GI interventions will be documented in a report and presented at prominent national and international conferences (e.g., Council of Educators in Landscape Architecture (CELA), Association of Collegiate Schools of Planning, American Geophysical Union, International Conference on Flood Recovery, Innovation and Response, etc.). The research team will also publish the manuscript in a peer-reviewed journal.

List of Deliverables

The deliverables for this project include: 1) a final report that contains the study findings, directions for future research, and practical applications in landscape design and planning fields; 2) codebook of analysis scripts; 3) conference abstract that will be presented at the annual CELA conference in March; and 4) manuscript submitted to a peer-reviewed journal. The study findings can potentially be included as pilot test results for external grant applications.

Three quarterly interim reports will also be delivered as the project proceeds.

Schedule of Activities

Task	Major Activities	2021										2022	
		Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Task 1: Watershed delineation	Activity 1 – Watershed delineation	■											
	Activity 2 – Verification	■	■										
Task 2: Variables measurement	Activity 3 – Measurement of hydrologic variables			■	■								
	Activity 4 – Measurement of imperviousness variables				■	■	■						
	Activity 5 – Measurement of GI pattern variables						■	■					
	Activity 6 – Measurement of climate and geophysical variables							■					
Task 3: Data analysis	Activity 7 – Statistical modeling								■	■	■		
Task 4: Documentation and dissemination	Activity 8 – Report writing, manuscript publication, and conference presentation											■	■

Budget plan

Category	Amount	Justification
Personnel	**$18,050.70**	**Sub-Total**
Faculty Salary	$1,999.40	Summer (SU) salary support requested for the PI is $1,999.40. Responsible for most of the work of the project, including its overall scientific, administrative, and fiscal direction. Directly involved in the preparation of all phases of the project, including data collection, data analysis, interpretation of results, and documentation.
Student Assistants	$15,600	Two graduate students will be recruited for the research project, under the supervision of the PI. Salary for each student is hourly-based ($15/hour) for 10 hours per week. Each graduate student will work for 39 weeks during the regular semesters in the academic year (totaling $5,850 per person). Support over the summer months is budgeted as an hourly wage ($15/hour) for 10 hours during the 13-week summer period (totaling $1,950 per person). The students will assist with the literature review, data collection, statistical analysis, and documentation throughout the entire project period. They will be exposed to advanced quantitative measurement techniques and reasoning sequences, expanding their knowledge in landscape analysis and nurturing empirical research skills.
Fringe Benefits	$451.30	Benefits for PI = $1,999.40 × 7.65% = 152.95 Benefits for student assistants = $1,950 × 7.65% × 2 persons = 298.35
Non-Personnel	**$4,270.72**	**Sub-Total**
Software and Equipment	$1,470.72	Software annual licensing costs (e.g., ArcGIS and STATA) and equipment (e.g., external hard drive, etc.).
Office Supplies and Printing	$1,000	Project-specific supplies (e.g., paper, pens, binders, etc.) and printing/publication costs.
Travel	$1,800	Travel funds are requested in support of domestic travel to attend annual professional conferences (to publish and disseminate research results).
Total Direct Costs	**$22,321.42**	Total direct costs
Indirect Costs	**$2,678.58**	Total direct costs × 12% = 2,678.58
Total Budget Requested	**$25,000**	

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Education

Ph.D.	Urban and Regional Sciences, Department of Landscape Architecture and Urban Planning, Texas A&M University, College Station, TX, 2019
MLA	Department of Landscape Architecture and Urban Planning, Texas A&M University, College Station, TX, 2015
Certificate	Sustainable Urbanism Certificate, Texas A&M University, College Station, TX, 2015
BS	Department of Landscape Architecture and Rural Systems Engineering, Seoul National University, Seoul, South Korea, 2011

Academic Appointment

2019 – Present	Assistant Professor, School of Planning, Design & Construction, Michigan State University, East Lansing, MI
2016 – 2019	Instructor, Dept. of Landscape Architecture and Urban Planning, Texas A&M University, College Station, TX
2014 – 2019	Research Assistant, Landscape Architecture and Urban Planning, Texas A&M University, College Station, TX
2010 – 2012	Research Assistant, Landscape Ecology and Climate Change Adaptation Laboratory (previously Landscape Ecology and Geographic Information System Laboratory), Seoul National University, Seoul, South Korea

Affiliation

2020 – Present	Affiliated Faculty, Environmental Science & Policy Program, Michigan State University

Selected Peer-Reviewed Journal Articles

Bae, J., **Sohn, W.**, Newman, G., Gu, D., Woodruff, S., Van Zandt, S., Ndubisi, F., Wilkins, C., Lee, J., and Tran, T. (Under review). A Longitudinal Assessment of Green Infrastructure Quantity and Quality in Coastal Texan Cities. *Urban Forestry and Urban Greening*.

Park, J., Kim, J.-H., **Sohn, W.**, and Li, M.-H. (Under review). Cooling Ranges for Urban Heat Mitigation: Continuous Cooling Effects along the Edges of Small Greenspaces. *Landscape and Ecological Engineering*.

Sohn, W., Brody, S., Kim, J.-H., Li, and M.-H. (In Press). How Effective Are Drainage Systems in Mitigating Flood Losses? *Cities*. 107.

Sohn, W., Kim, J.-H., Li, M.-H., Brown, R., and Jaber, F. (In Press). How Does Increasing Impervious Surfaces Affect Urban Flooding in Response to Climate Variability? *Ecological Indicators*. 118.

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Kim, J.-H., Gu, D., **Sohn, W**., Kil, S.-H., Kim, H., and Lee, D.-K. (2016). Neighborhood Landscape Spatial Patterns and Land Surface Temperature: An Empirical Study on Single-Family Residential Areas in Austin, Texas. *International Journal of Environmental Research and Public Health*. 13, 880.

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Manuscripts in Preparation

Sohn, W., Kim, J.-H., Li, M.-H. (In preparation). The Effect of Land Use Configuration on Surface Runoff under Varying Climate Conditions.

Sohn, W., Bae, J., and Newman, G. (In preparation). The Longitudinal Impact of Green Infrastructure Configuration on Flood Losses.

Lee, E., **Sohn, W.**, Kim, J.-H., and Park, J. (In preparation). Climate Change Vulnerability Assessment for Predicting Future Urban Resilience.

Kim, J.-H., Li, W., and **Sohn, W.** (In preparation). Neighborhood Landscape Spatial Patterns and Housing Market Values in Urban and Suburban Regions.

Peer-reviewed Papers in Conference Proceedings

Sohn, W., Kim, J.-H., and Li, M.-H. (2015). Low Impact Development Applications in Urban Watersheds: Efficacy Evaluation by Imperviousness Connectivity Estimations. True Smart and Green City? Proceedings of the 8th International Conference of the International Forum on Urbanism (IFoU).

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Peer-reviewed Published Abstracts

*(*Note: 16 poster and oral presentations delivered in national/international conferences since 2014)*

Sohn, W., Brody, S., Kim, J.-H., Li, and M.-H. (Accepted). How Effective Are Drainage Systems in Mitigating Flood Losses? Council of Educators in Landscape Architecture (CELA).

Park, J., Kim, J.-H., **Sohn, W.**, and Lee, D. (Accepted). Do small green spaces cool down urban air temperature more than building-shaded spaces in summer? Council of Educators in Landscape Architecture (CELA).

Sohn, W., Kim, J.-H., and Li, M.-H. (Accepted). Hydraulic Connectivity of Impervious Surfaces as a Key Indicator of Urban Flood Control. American Geophysical Union (AGU).

Sohn, W., Kim, J.-H., Li, M.-H., Brown, R., and Jaber, F. (2020). The Effect of Imperviousness on Surface Runoff under Varying Climate Conditions. Council of Educators in Landscape Architecture (CELA), March 18-21, Louisville, KY (Physical conference cancelled).

Sohn, W., Kim, H.-W., Kim, J.-H., and Li, M.-H. (2019). Assessing the Capitalization Effects of Retention and Detention Ponds on Single-Family Housing Values. Council of Educators in Landscape Architecture (CELA), March 6-9, Sacramento, CA.

Sohn, W., Kim, J.-H., and Li, M.-H. (2018). The Impact of Climatic Factors on the Efficiency of Low Impact Development: A Systematical Review of Empirical and Methodological Research. Council of Educators in Landscape Architecture (CELA), March 21-24, Blacksburg, VA.

Sohn, W., Kim, J.-H., and Li, M.-H. (2017). What Factors Determine the Effectiveness of Low Impact Development Practices?: A Review of Current Literature. Council of Educators in Landscape Architecture (CELA), May 26-29, Beijing, China.

Sohn, W., Kim, J.-H., and Newman, G. (2016). Design Assessment for Sustainable Hydrologic System Development using a Systematic Framework. Council of Educators in Landscape Architecture (CELA), March 23-26, Logan, UT.

Sohn, W., Guo, R., and Kim, J.-H. (2015). Multi-functional Infiltration: WaterSmart Management for Campus Landscape. Environmental Design Research Association (EDRA), May 27-30, Los Angeles, CA.

Sohn, W., Kim, J.-H., and Newman, G. (2015). Groundwater Infiltration as a WaterSmart Use Strategy: Performance Evaluation of Low Impact Development in Conroe, Texas. Council of Educators in Landscape Architecture (CELA), March 24-28, Manhattan, KS.

Sohn, W., Kim, J.-H., and Newman, G. (2015). An Efficacy Assessment Model for Integrated LID Designs: Application to Three LID Based Projects in Texas. International LID Conference of the American Society of Civil Engineers (ASCE), January 19-21, Houston, TX.

Sohn, W., Kim, J.-H., and Newman, G. (2014). A BLUEprint for Stormwater Infrastructure Design: Implementation and Efficacy of LID. Council of Educators in Landscape Architecture (CELA), March 26-30, Baltimore, MD.

Selected Funded Research

2020	Co-Principal Investigator, "A Case Study of Community Resilience Planning and Design Guideline for Vulnerable Urban Areas" funded by the Architecture and Urban Research Institute (AURI), South Korea (PI: Kim, Co-PIs: Sohn, Lee, and Park/ $25,000)
2018 – 2019	Research Assistant, "Green Infrastructure Plans for Flood and Storm Water Hazards Reduction in the Texas Coastal Region" funded by the Texas Sea Grant and National Oceanic and Atmospheric Administration (PI: Van Zandt, Co-PIs: Newman, Woodruff/ $222,516)
2016 – 2019	Research Assistant, "Aggie B.L.U.E.print Laboratories: Building Lasting University Environments" funded by the Tier One Program (TOP) Interdisciplinary Education Grant, Texas A&M University (PIs: Newman, Kim, Li, Arnold, and Chu/ $300,000)
2018	Principal Investigator, "The Impact of Climate Conditions on The Urbanization-Runoff Process and Implications for Low Impact Development" funded by the Texas Water Resources Institute (TWRI) (Co-PI: Li/ $5,000)
2017	Research Assistant, "Ecological Impact Assessment of Land Development" funded by the Korea Forest Service (PI: Dr. Lee/ $402,600)
2012	Research Assistant, "Development of Ecological Indicators for Forest Ecosystem Management" funded by the Korea Forest Conservation Association (PI: Dr. Lee/ $53,680)

Selected Honors and Awards

*(*Note: More than 20 honors and awards received in academia since 2007)*

2017	CELA Outstanding Poster Award (Honorable Mention) with "A system-oriented design approach for urban revitalization: Transit hub and mixed-use development in the Energy Corridor District, Houston, Texas, USA", Sohn, W., Kim, J.-H., Ning, S., and Kim, Y.
2016	CELA Best Poster Award with "Design Assessment for Sustainable Hydrologic System Development Using a Systematic Framework", Sohn, W., Kim, J.-H., and Newman, G.
2015	University Top-Off Scholarship, Texas A&M University, College Station, TX.
2015	ASLA Student Merit Award, American Society of Landscape Architects.
2014	Department Head Award, Dept. of Landscape Architecture and Urban Planning, Texas A&M University, College Station, TX.
2014	University Olmsted Scholar, Landscape Architecture Foundation.
2014	Texas ASLA Student Design Competition Merit Awards (2 Awards), Texas Chapter of the American Society of Landscape Architects.
2011	Summa Cum Laude College of Agriculture and Life Science, Seoul National University, Seoul, South Korea.