Policy Research Working Paper 11178

Assessing Secondary Benefits of Urban Flood Protection Projects

The Case of Wroclaw, Poland

Winston Yu
Ran Goldblatt
Tess Doeffinger
Ross Eisenberg
Steven Rubinyi

WORLD BANK GROUP
Water Global Department &
Urban, Disaster Risk Management, Resilience and Land Global Department
July 2025

Policy Research Working Paper 11178

Abstract

With global climate change impacting cities around the world, local and national governments need to plan for and invest in solutions that mitigate the climate and disaster risks their populations and economies face. Urban flooding poses an acute threat to sustainable and equitable urban growth and wellbeing. While the primary benefit of investments in urban flood protection is the avoidance of future damages and losses, such investments can also provide secondary benefits that can help unlock localized economic potential and contribute toward green growth. Although secondary benefits of investments in urban flood protection can be difficult to assess and quantify, the growing availability of locally sourced and remotely sensed data opens new possibilities. This study presents a spatially focused methodology that employs proxies to provide further evidence of secondary benefits linked to large-scale investments in urban flood protection in Wroclaw, Poland. Within newly protected areas, the study finds increases in land and residential real estate values, and an increase in economic development in parallel to on an increase in nighttime light intensity and built-up area. The study also finds that the relative rate of change for land and residential real estate values, nighttime light intensity, and built-up area within areas newly protected from flooding outstripped that of other areas of the city.

This paper is a product of the Water Global Department and the Urban, Disaster Risk Management, Resilience and Land Global Department. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/prwp. The authors may be contacted at wyu@worldbank.org, reisenberg1@worldbank.org, and srubinyi@worldbank.org.

Assessing Secondary Benefits of Urban Flood Protection Projects: The Case of Wroclaw, Poland

Winston Yu, Ran Goldblatt, Tess Doeffinger, Ross Eisenberg, Steven Rubinyi

Keywords: secondary benefits, cost benefit analysis, urban flood protection

JEL Classification Codes: C21 (Spatial Models)**; Q54** (Natural Disasters and Their Management)**; P25** (Urban, Rural, and Regional Economics); **O44** (Environment and Growth); **R11** (Regional Economic Activity: Growth, Development, Environmental Issues, and Changes)

1. Introduction

1.1. The global challenge of urban flooding

In this century's first 20 years, floods and storms have caused nearly 166,000 deaths and accounted for 69% of global natural disaster financial damages (Amarasinghe et al., 2020). Flood events with 100 deaths and more occur globally on average 10 times a year (Jonkman et al., 2024). Between 1980 and 2011, hydrological phenomena caused more than €140 billion ($165 billion) in damage in Europe alone (Erdlenbruch & Grelot, 2017). Beyond the direct destruction they cause, floods have other significant short-, medium-, and long-term impacts on society, such as changes in peoples' means of subsistence, migratory processes, psychosocial health, relationships within and between communities, and regional development (WHO, 2017). Over the next century, climate change will amplify both the frequency and severity of flooding and other hydrometeorological hazards (WHO, 2008; Peterson et al., 2013; Steffen et al., 2014).

In parallel to the effects of climate change, the world has seen a dramatic increase in the number of people living in cities—particularly in rapidly developing countries. Between 1950 and 2014, the share of the global population living in urban areas increased from 30% to 54% (UN, 2015). By 2050, an additional 2.5 billion people are expected to live in urban areas (UN, 2015). This intensifying urbanization concentrates the exposure of populations and assets to flooding hazards. Other factors, including socioeconomic (i.e. location within cities, poor access to information, little resources and ability to prepare, respond, and recover from flooding), environmental (i.e. poor floodplain management, natural resources conservation), and physical (i.e. land cover and land use) circumstances, heighten the vulnerability of populations and assets in cities to flooding (Kaźmierczak & Cavan, 2011). In particular, the increase in artificial surfaces, poor water infiltration, and reduction of water flow resistance that urban built environments typically entail (Huong & Pathirana, 2011) make the effects of flooding on urban residents more severe.

Climate change and urbanization are thus fundamental factors contributing to a trend of increasing urban flood risk worldwide. This reality has led to a growing recognition of the need for urban flood mitigation plans and physical adaptation measures, such as concrete channels and floodwalls, compacted earthen levees, channel improvements, and more, in order to reduce future risks and the exposure of people and assets while increasing resilience to floods (Tschakert & Dietrich, 2010). Such mitigation and adaptation actions may all be considered *flood protection*. Vulnerable cities must balance and prioritize a multitude of competing infrastructure needs, including flood protection investments, within their often limited budgets, while delivering services to their residents in the short term and accounting for longer term, compounding risks such as rising heat waves and pandemics. Thus, financing for expensive flood protection investments presents an acute challenge in urban areas.

1.2. Economic analysis of flood protection infrastructure

Decisions as to whether and what types of urban flood protection efforts and investments are needed for a particular city and situation are complex. They require comprehensive cost-benefit assessments that consider a wide range of detailed factors, such as available levels of protection, prevailing risk aversion, different means of providing protection, and uncertainties in cost, socioeconomic trends, and climatological scenarios (Rozenberg & Fay, 2019). In order to identify and compare the costs incurred by prospective flood mitigation measures and the benefits that would result from them, an economic assessment of disaster risk reduction interventions is often performed. Generally, the underlying assumption of such a cost-benefit analysis (CBA) is that if benefits exceed costs, the investment would be justifiable (Genovese et al., 2020).

But the potential *indirect* effects of public flood infrastructure investments on urban development – such as development of tourism, land, real estate, and enterprises of all sizes – are rarely accounted for in traditional economic analyses of such investments. Often, these investments unlock private development of waterfront areas and generate tremendous value for the local economy (e.g., New York's Battery Park, London's Docklands, Boston's Charlestown Navy Yard, Toronto's Harbourfront) (Gordon, 1997). Therefore, to attract investors to potential flood mitigation infrastructure projects, it is important to capture the full added value associated with past and future investments in flood control.

In a CBA, *costs* are typically defined as the costs of construction and necessary maintenance (NOAA, 2015). However, assessing the potential *benefits* of an investment (e.g. environmental, social and economic) is more difficult and has been a challenge since CBA became a standard decision making tool (Hufschmidt, 2000). One key problem is determining what benefits to include in a CBA. In this study, we separate benefits into two categories: *primary* and *secondary*. We define primary benefits of flood protection infrastructure as the damages averted (loss of life or economic losses) (NOAA, 2015). Secondary benefits, meanwhile, are the additional benefits that may arise from investment in flood protection, including increases in tourism, land and property value, economic growth, and environmental protection.

1.3. Measuring secondary benefits of flood protection infrastructure

Here, we focus on the secondary benefits of flood protection infrastructure. If these secondary benefits of investments in urban flood protection can be quantified, they could then be monetized to help meet infrastructure financing needs. Two key types of secondary benefits are *changes in real estate values* and *changes in economic development*. Measuring such secondary benefits, however, is difficult. If these secondary benefits are included in a project's CBA *ex ante*, they might be mentioned and not quantified (World Bank, 2001), or otherwise estimated with an economic model. For example, a report by the Bay Area Council Economic Institute (2020) used an input-output model to show that every $1 million that would be spent on flood control and recreation

investments would create between 13.2 and 13.9 new jobs. Assessing an infrastructure investment's secondary benefits after it has been made, *ex post*, can offer more precise evidence for its economic value.

Studies that assess changes in land value *ex post* traditionally rely on transactional or economic data over the investment's lifetime. For example, Kahn et al. (2020) found a 13% increase in home values in a community in Connecticut, USA after an investment in the creation of a park that doubled as a retention area. Separately, hedonic pricing models have been used to determine the effects of flood events on housing prices (Bin & Polasky, 2004; Daniel et al., 2009; Donnelly, 1989). In addition, these models can be used to study changes in land and property value following investments in flood protection. A recent study combined a hedonic pricing model with a geospatial model to analyze the effect of increased flood protection on property values in Venice, Italy (Rosato et al., 2017), finding that property value increases coincide with flood protection infrastructure investments. The analysis also illustrated the benefits of incorporating geospatial data into a value generation model. While such a combination of data types may not be new, higher-quality and more granular data sources offer a promising pathway for further economic quantification of flood infrastructure protection benefits.

Assessing economic development *ex post* and quantifying the economic impacts of human interventions, meanwhile, can be achieved with remotely sensed measurements (measurements collected, for example, through sensors aboard satellites) and analysis of spatial and temporal trends (Kumar et al., 2021). This is especially true in developing countries where reliable socioeconomic data may not be consistently available. Remotely sensed observations of nighttime lights, in particular, can capture the signature of many aspects of human activity. Previous studies have shown that the amount of light emitted from Earth at night corresponds to the distribution of the population (Amaral et al., 2006), electricity consumption (Proville et al., 2017; Wu et al., 2013), gross domestic product (Doll et al., 2006; Elvidge et al., 2014), true income growth (Henderson et al., 2012), poverty and wealth (Weidmann & Schutte, 2017; Xie et al., 2016), and the distribution of economic activity (Ghosh et al., 2010) at global (J. V. Henderson et al., 2012) and local (Bruederle & Hodler, 2018) scales. Because nighttime lights are associated with human activity, remotely sensed measurements of nighttime lights also provide a proxy for urban form (Duque et al., 2019), the density of urban establishments (Mellander et al., 2015; Zhuo et al., 2005), the distribution and patterns of human settlements (Elvidge et al., 1999; Imhoff, Lawrence, Elvidge, et al., 1997), and urban growth and expansion (Liu et al., 2012; Ma et al., 2012; Zhang & Seto, 2011; Zhou et al., 2014).

Elvidge et al. (1997) demonstrate a relationship between the intensity of nighttime light emission and various indicators of human activity, such as population distribution, GDP, and electricity usage. Additional studies suggest that data fusion – the incorporation and analysis of different types of measurements and datasets, such as the distribution of land cover and land use along with nighttime light data – can improve predictions of socioeconomic indicators such as GDP

(Sun et al., 2020) and economic growth (Keola et al., 2015). Because land is an indispensable production factor for economic development, the characteristics of land may be tightly linked to economic growth (Chen et al., 2020). Henderson et al. (2018), for example, showed that a combination of several physical geography attributes explain around 47% of the worldwide variation and 35% of within-country variation in nighttime light emissions and the spatial distribution of economic activity. Nighttime and daytime remotely sensed measurements can also complement one another; Baragwanath et al., (2019) showed that while remotely sensed daytime imagery is well suited for defining the spatial expanse of urban infrastructure and asset types such as markets, the polycentricity of urban areas and the urban development gaps that exist even within densely populated cities make nighttime imagery better suited for measuring urban economic activity. Thus, a combination of multiple sources of spatial data is needed to capture the wide range and variation of human economic activity in cities.

1.4. Study objectives

In this study, we assess and quantify the secondary benefits of investments in flood protection infrastructure in the city of Wroclaw, Poland. We use granular data and recent advancements in geospatial analysis methods to evaluate the infrastructure investments according to the land value changes and economic development they delivered. First, we evaluate transaction data to assess changes in land and property value. The assessment of property transactions did not establish direct causality between flood protection and increased transaction values. We thus advance the strength of that relationship by demonstrating the relative effectiveness of three spatial measurements—nighttime lights, built-up land cover, and population counts—to serve as proxy indicators for the secondary benefits of urban flood protection infrastructure based on localized, temporal changes in economic development.

2. Study Area

2.1. Wroclaw, Poland

Wroclaw is Poland's fourth largest city by population, with 642,869 residents in 2020 (Główny Urząd Statystyczny, 2020) in an area of 292.8 km^2 . The city is situated in the southwest of the country on the banks of the River Odra (or Oder) in Central Europe's Silesian Lowlands (Figure 1). In recent years, Wroclaw has transformed itself from a declining industrial city into the economic engine of Lower Silesia (*Higher Education in Regional and City Development - OECD*, n.d.). The city's total annual precipitation averages 590 mm, with heavy precipitation occurring especially during its mild winters.

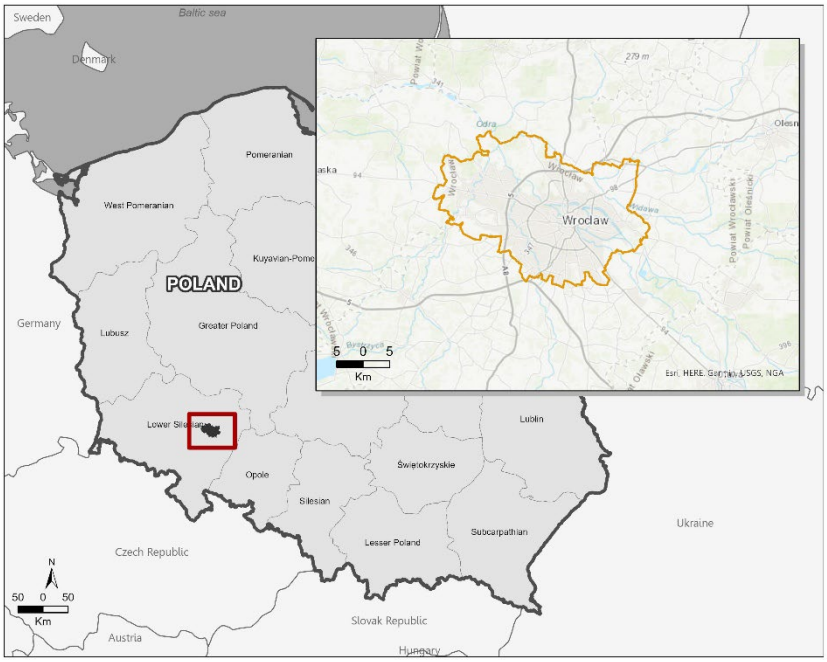


Figure 1: *Study Area*

2.2. The 1997 flood

The flood that occurred in Wroclaw in July 1997 was the worst flood event on record in Poland, in both hydrological terms (peak stage, flow, inundated area in the Odra drainage basin) and economic terms (material losses) (Kundzewicz et al., 1999). The disaster resulted from a combination of intense and long-lasting rainfall on the region's water catchments, exposing the weaknesses of the flood protection system in the Odra River Basin and the connected Vistula River basin. The rainfall occurred in two periods in early and mid-July, with exceptional intensity, duration, and areal coverage, leading to a rapid rise in the flow of the Odra River and overlapping flood waves in its tributaries (Butts et al., 2007). Twenty-five percent of the area in seven of Poland's 16 voivodeships (provinces) in the upper and middle Odra and upper Vistula River

basins were flooded, including Wroclaw (Figure 2). Fifty-four people were killed, 110,000 people required evacuation, and over 700,000 houses were impacted. The floods damaged private residences and apartment buildings, public buildings, roads and bridges, railroad infrastructure, hydro-technical structures, sewage treatment plants, natural gas distribution lines, telecommunication systems, and other facilities. Approximately 3,000 km of roads and 2,000 km of railways were damaged (Kundzewicz et al., 1999). The floods also destroyed crops and caused financial losses to agricultural and non-agricultural enterprises, with material damages totaling between $2 billion and $4 billion (Zaleski and Krochmal, 1997).

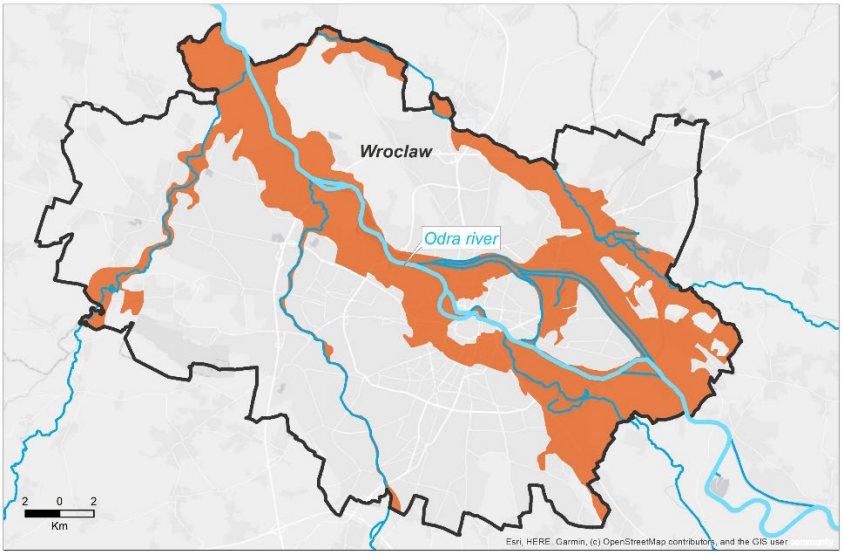


Figure 2: *Extent of 1997 flooded area*

At the time of the flood, the flood protection system in the Odra River basin consisted of embankments, weirs, reservoirs, and relief channels. Small polders upstream from Wroclaw provided temporary flood storage to reduce flood peaks entering the city. But Wroclaw`s flood forecasting, monitoring, and warning systems performed poorly during the flood event, resulting in suboptimal operation of upstream retention reservoirs. The floods overpowered the local emergency management systems, as the operation of hydraulic structures in Wroclaw was based on engineering manuals that did not consider the maximum flows observed during this disaster. At the time, the Wroclaw Floodway System (WFS) was designed for a maximum flow of 2,400 m^3/sec. Yet the peak flow rate in July 1997 was nearly 50% greater, at up to 3,640 m^3/sec. About one-third of the city of Wroclaw was inundated because of the system's insufficient capacity to handle flows of this magnitude. Water levels in both the main Odra river and its Nysa Klodzka tributary peaked just upstream of the city.

2.3. Rescue operation and the improved flood protection system

The rescue operation was a massive effort, involving 80,000 Polish soldiers, firemen, and policemen, and 100,000 civilian volunteers. Poland quickly established the Anti-Crisis Committee

for Fighting and Mitigation of Flood to coordinate the response. Internationally, the European Union (EU), several individual countries, the World Bank, the European Investment Bank, and other actors provided emergency financial assistance (Kundzewicz et al., 1999). This included emergency repairs to municipal and rural waterflow and social infrastructure in about 185 of the most damaged *gminas* (municipalities), improvements to the flood forecasting and early warning system, and the development of policy frameworks and institutional capacity for flood preparedness. Poland provided victims with financial aid, loan interest payments, preferential credits, and assistance with fees and taxes. The country also increased its long-term budget reserve earmarked for flood-related expenditures by nearly 600%.

In 2001, Poland developed the *Oder 2006 Program*, establishing a long-term plan for modernizing the Odra River system to ensure protection against major floods. The Program includes improved land use planning, regional ecosystems restoration and afforestation, and passive and active infrastructure investments. When Poland joined the EU in 2004, it was required to comply with the second cycle of the EU Floods Directive (World Bank, 2021). To continue to carry out the *Oder 2006 Program* and adhere to the EU Floods Directive, several projects were financed under the Odra River Basin Flood Protection Project (ORFPP). These include the construction of the Racibórz Dolny flood prevention dry polder and the upgrading and modernization of the WFS infrastructure. The ORFPP was funded by the World Bank, the Council of Europe Development Bank, EU Cohesion Funds, and other donors.

The dry polder, 150 km upstream from Wroclaw and 185 cubic megameters in size, was designed to improve the operational capacity of the WFS to handle a flow rate up to 3,100 m^3/sec (defined at Brzeg, a town just upstream of the city). During normal flow periods, the outlet gates on the Racibórz Dolny polder upstream remain open and the reservoir is "dry." During flooding, the gates are used to limit outflow to the minimum possible, subject to the water level in the reservoir not exceeding a pre-determined maximum storage level. Thus, the polder serves to reduce peak flows downstream. The objective of the second component, improving the WFS, was to extend and enhance existing flood defense mechanisms within the city of Wroclaw and adjacent settlements to provide effective flood protection (*Odra River Basin Flood Protection, n.d.*). Infrastructure upgrades were made along the Odra River channels passing through the city to both 1,000-year and 333-year return periods, depending on the hydraulic object. This effort included improvements to the Odra dikes and embankments, improvements to the Odra channels (including both deepening and widening), and the building of the Widawa tributary water bypass transfer.

The World Bank began project development in 2004, with the initial funds of the ORFPP committed in 2007 and investment spending continuing through 2020, though the WFS has been operational since 2016. Table 1 outlines the timing, source, and size of flood investments in the WFS (investments complementing the ORFPP were made by the city, the Regional Water Management Authority in Wroclaw, and the Lower Silesian Board of Amelioration and Water

Facilities in Wroclaw). Changes in Wroclaw's land and property values and economic development resulting from flood investments to upgrade the Wroclaw Floodway System are the subject of this study. We analyze all investments toward the improvement of the Wroclaw Floodway System in the period between 1997 and 2020, including by the Regional Water Management Authority of Wroclaw, the World Bank, and DZMiUW.

Table 1: *Flood Investments in the Wroclaw Floodway System (WFS)*

Year	RZGW Wrocław[1]	POPDO/ORFPP[2]	DZMiUW[3]	City of Wrocław	Total
1997					0
1998	13,100,000		2,365,000		15,465,000
1999	13,100,000		2,365,000		15,465,000
2000	13,100,000		2,365,000		15,465,000
2001	13,100,000		2,365,000		15,465,000
2002	13,100,000		2,365,000		15,465,000
2003	5,700,000		2,365,000		8,065,000
2004	12,964,630		2,365,000		15,329,630
2005	6,697,320		2,365,000		9,062,320
2006	3,896,651		9,795,000		13,691,651
2007			234,000		234,000
2008		9,249	188,000		197,249
2009		10,211,599			10,211,599
2010	3,962,274	9,348,323			13,310,597
2011		13,596,459		4,807,000	18,403,459
2012	3,800,019	131,035,115		4,807,000	139,642,134
2013	527,416	148,648,565		4,807,000	153,982,981
2014	200,201	414,023,309			414,223,510
2015	24,115,136	361,156,079			385,271,215
2016		218,093,295			218,093,295
2017		163,131,150		285,000	163,416,150
2018		28,903,000			28,903,000
Total	127,363,647	1,624,190,000	29,137,000	14,706,000	1,795,396,647
				USD[4]	**471,232,716**

Data presented in PLN, in nominal terms

[1] Regional Water Management Authority of Wroclaw – This is a regional branch of the Polish national water agency (now Polish Waters); The total spending from 1998-2002 was provided by RZGW. This was distributed equally over the time period.

[2] Investments related to the World Bank projects

[3] Former local amelioration unit which was dissolved and functionally absorbed during the establishment of Polish Waters in 2016; The total spending from 1998-2005 was provided by RZGW. This was distributed equally over the period.

[4] 1USD = 3.8 PLN (as of April 2019)

3. Data and Methods

We study two sets of data and the urban developments they signal in order to analyze the secondary benefits of the ORFPP investments made in the Wroclaw Floodway System: value generated from increases in land and residential property values, and spatiotemporally disaggregated increases in economic activity. We assess changes in land and residential property values by evaluating local transaction data. To evaluate spatial and temporal economic development, we examine three indicators in relation to the physical location of the infrastructure investments and in comparison to one another: economic activity (measured according to nighttime lights), built-up area, and population. Accordingly, we rely on three corresponding datasets to estimate changes and trends in these indicators across Wroclaw over time owing to the ORFPP's implementation: nighttime light emission measured by means of remotely sensed data, built-up land cover, and population count estimates. We also compare these datasets to available data related to the amounts invested in the WFS and to changes in local real estate transaction prices over time.

3.1. Data

Data to assess the presences of secondary benefits is split into two main categories: transaction data and data indicative of economic growth. Transaction data is used to assess changes in real estate values, specifically focusing on land and residential property sales, and remote sensing data is used to evaluate economic development captured by means of physical attributes. A list of data utilized in this study and their sources is found in Table 2.

Table 2: *Data used in the analysis*

Variable	Unit/Data Type	Resolution	Timeframe	Source
Transaction Data				
Land sales	PLN	-	2000 – 2018	RCiWN, 2019
Residential property sales	PLN	-	2000 – 2018	RCiWN, 2019
Property tax collection	PLN	-	1997 – 2018	City of Wroclaw, Poland
WFS investments	PLN/USD	-	1998-2020	RZGW[1]
Remote Sensing Data				
Nighttime lights	DMSP-OLS	2.7km	1992 – 2013	DMSP-OLS[2] (Elvidge et al., 2009)
Built-up land cover – World Settlement Footprint - Evolution	Raster	30 m	1985 – 2015	(Marconcini et al., 2020)
Population	Raster	100 m	2000 – 2020	WorldPop, 2015

[1] The total spending from 1998-2002 was provided by the Regional Water Management Board (RZGW).

3.1.1. Transaction data

Transaction data analysis is based on an 18-year record of transaction price data from 2000-2018. Data includes all records of land sales,[1] a selection set of residential sales,[2] and all real estate investment records available.[3] These data are from the Geodesy and Cadaster Office of the City of Wroclaw. Because these data are geocoded, each transaction location can be identified as to whether it was previously flooded in 1997 or not. Data are segmented into two time periods, pre- and post-2004, when Poland joined the European Union. Investments in the Odra River flood protection began during disaster recovery after the 1997 flood. These included "upgrading the flood forecasting, monitoring, and warning system … and improving flood management at the local level" (World Bank, 2004). These upgrades had been made by 2004, which was also when the World Bank began project planning for the ORFPP. With Poland's EU accession then as well, 2004 marks a significant change in the country's economic and political landscape, which also coincided with a distinct growth difference in land sales and prices in Wroclaw, particularly in areas that had been previously flooded. This study analyzed 6,331 residential transactions. These are secondary market data, i.e. houses which were sold one or more times. The study analyzed 2,019 land transactions.

3.1.2. Remote sensing and measurements of the physical environment

3.1.2.1. Nighttime lights

We rely on nighttime light data collected by the Operational Linescan System (OLS) sensors on the Defense Meteorological Satellite Program (DMSP) to indicate economic activity. With 14 orbits per day, each OLS satellite captured every location on Earth every 24 hours from 1992-2013,[4] with a swath width of about 3,000 km and a spatial resolution of 30 arc seconds (approximately 1 km). OLS detected visible and near-infrared light emissions at nighttime from human and natural activities (Croft, 1973), including city lights, gas flares, fires, and auroras. The digital number (DN) of the calibrated light intensity of each OLS pixel ranges from 0 to 63. The underlying assumption is that because persistent light emitted at night is associated with manmade structures, if the DN value of a pixel exceeds a given threshold, this pixel represents a populated location and an associated level of economic activity. OLS data have been used for

[1] Land transaction data comes from the Price and Property Value Register. 2019 transactions were recorded over the 1998-2018 period. These data contain information about sales of land. Each sale may include several plots.

[2] Residential transaction data comes from the Price and Property Value Register. Over the 1998-2018 period, 6,331 transactions were recorded. These are secondary market data i.e. houses which were sold one or more times.

[3] Real estate investments come from a database of Polish construction projects. In the 1998-2018 period, 751 completed and 151 ongoing projects were recorded.

[4] Other contemporary studies on the relationship between human activity and remotely sensed nighttime lights rely on more recent data from the Visible Infrared Radiometer Suite (VIIRS) satellite instrument, currently flying on the Suomi NPP satellite mission. VIIRS has produced global nighttime light data from 2012 to the near-present. As DMSP-OLS provides nightlight data before and after the 1997 flood and before and after the 2007 investment, whereas VIIRS data only exist later on, DMSP-OLS is relied on in this study.

many purposes, such as monitoring human settlements, population growth, socioeconomic activity, energy consumption, and the ecological footprint of human activity (Huang et al., 2014; Small et al., 2005).

From the DMSP-OLS data, we utilize an annual average Sum of Light (SOL) measurement. Each pixel is denoted by the sum of all measured DN values averaged over the number of measurements over the course of each year.

3.1.2.2. Built-up land cover

We estimate spatial and temporal patterns of built-up land cover using the World Settlement Footprint (WSF) data suite. Created by the German Aerospace Center (DLR), WSF is a global raster dataset of the world's human settlements. We rely on the WSF-Evolution dataset, created using open and free data from the Landsat 5 and Landsat 7 satellites, which identifies annual human settlement extents every year from 1985 to 2015 at a spatial resolution of 30 m (Esch et al., 2018).

Further, in order to assess the *intensity* of urban expansion, we utilize the WSF-Evolution data to calculate an Annual Urban Growth Rate (AGR) indicator, which measures the urbanization *rate* of a given unit area (Xiao et al., 2006). AGR is calculated for each unit of analysis (hex-cell) as:

$$\mathrm{AGR} = \frac{\mathrm{BUA}_{n+i} - \mathrm{BUA}_i}{n\mathrm{TA}_{n+i}} \times 100\%$$

where:

TA_{n+i} = the total unit area at time $n + i$

BUA_{n+i} = the built-up area in the target spatial unit at time $n + i$ (note: we calculate the built-up area in hex-cells)

BUA_i = the built-up area in the target unit at time i

n = the interval of the period over which the calculation is performed (in years)

The result of this procedure is an AGR measure *per unit of analysis* that can be used to describe spatial patterns of urban expansion.

3.1.2.3. Distribution of population

We estimate spatial and temporal patterns in the distribution of the population since 2000 using WorldPop data, an open-access archive of spatial demographic data throughout the world. Population distribution estimates are derived at a spatial resolution of approximately 100 m through a model that incorporates a flexible, random forest estimation technique with a wide variety of input data (Stevens et al., 2015). In addition to land cover and associated raster datasets, the model is based on detailed census and geospatial data that correlates with human population

presence such as networks of roads and waterways, large water bodies, settled or populated places, protected areas, and various "facility" locations (such as clinics, hospitals, and schools). Compared to other global population datasets, the WorldPop dataset was selected considering its high temporal resolution in addition to its good spatial resolution and advanced derivation techniques.

3.2. Methods

This study is split into three analyses: value generation, economic development, and comparison between transaction and spatially derived data. The value generation analysis assesses the differences in real estate and land sales transition from 2000-2004 and 2004-2018. The transition year for this analysis is 2004 as it was the year that Poland entered the European Union. Similarly, the spatial analysis compares changes in nighttime lights from 2000 to 2004, and then from 2004 forward (we note that the processed DMSP-OLS nighttime light data used in this study is available up to 2013). Finally, all transaction data are compared to the spatially derived data to determine how closely they are correlated throughout the years of analysis.

3.2.1 Land and residential property value generation

3.2.1.1 Value generation for land

To estimate the potential land value created from the flood investments, the difference in average land prices is calculated over two time periods – 2000-2004 and 2004-2018 – for both the flooded and non-flooded areas. These differences are then multiplied by the average size (in square meters) of the transaction and the volume of transactions observed to derive an overall change in transaction value.

3.2.1.2 Value generation for residential property

Given the enormous number of residential transactions, three residential areas (A1-3) that were flooded in 1997 and one non-flooded area (Ref) of comparable market characteristics from 1997 were selected for analysis. These areas were selected in consultation with city officials and were identified as being representative of the changes observed in both flooded and non-flooded neighborhoods. These areas are shown in Figure 3. Area 1 is perhaps one of the most attractive residential neighborhoods in Wroclaw due to its proximity to the Old Town/City Center and other amenities such as schools and shopping centers. Area 2 is another important residential neighborhood with several large apartment blocks and proximity to the Wroclaw Main Station and several museums and art galleries. Area 3 extends along the banks of the Odra River and has seen rapid development of residential apartments. This area is attractive due to its proximity to the Nadodrze Railway Station. All three areas were flooded in 1997. In contrast to these three areas, the reference neighborhood, situated on the northern part of the city along the Odra River

(denoted as REF 3 in Figure 3) was not flooded in 1997. This area is similar in its residential density and access to amenities and has seen significant real estate investment since the 1990s.

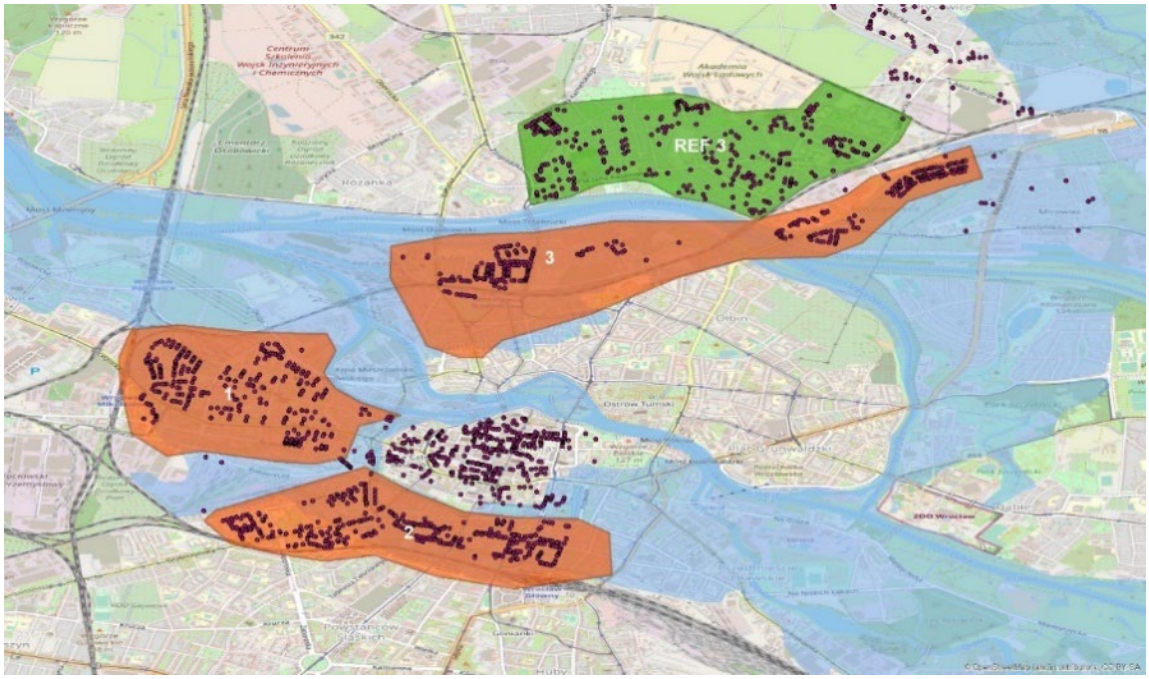


Figure 3: *Residential transaction data points in areas of interest (blue represents 1997 flooded area)*

3.2.2. Spatiotemporally disaggregated economic development

3.2.2.1. Hexagonal tessellation

Mapping the physical characteristics of large, heterogeneous geographical areas using satellite data often demands working with a wide variety of spectral gradients within remotely sensed datasets. This variability can be analytically problematic, as it can make spatial characteristics and trends difficult to isolate. A "zone mapping" procedure (Homer & Gallant, 2001) is therefore often used to partition an area of interest being studied with satellite data into homogenously-sized tessellated sub-regions of relatively similar physical characteristics (Homer et al., 2004). Generally, the plane of an area of interest can be divided into four types of regular tessellations: hexagons, squares, diamonds, and triangles (Carr et al., 1992). For the unit of analysis in this study, we divide the study area (the city of Wroclaw`s administrative area) into equal-area hexagon cells (hex-cells) with a distance of 1km between hex-cells centers. We choose a distance of 1 km between hexagon centers to roughly correspond to the spatial resolution of DMSP-OLS, which has the lowest spatial resolution among the examined datasets. Partial hex-cells which were "cut off" by Wroclaw's border were excluded. This operation resulted in 761 complete hex-cells in Wroclaw for analysis.

3.2.2.2. Treatment and control

As a proxy for the theoretical boundaries of all areas city-wide that are and are not protected from flooding following the completion of the WFS, we consider all hex-cells that are entirely or partially overlapped by the area that was flooded in 1997 as the treatment group—as these were the key areas the ORFPP was designed to protect—and the remaining hex-cells (outside the 1997 flooded area) as the control group. With the upgraded WFS becoming fully operational in 2016, the areas of Wroclaw that were flooded in 1997 are no longer exposed to the risk of flooding from the extreme water flow rates observed then. Therefore, a hex-cell within the flooded area of 1997 is considered to "benefit" from the new flood protection works (the "treatment") whereas a hex-cell that lies outside this area is considered not directly affected by the new flood protection (the "control"). We note that any hex-cell in the vicinity of the new WFS works (even if not located in the 1997 flooded area) might receive indirect economic benefits from the investments; though this is certainly a positive consequence, it is not the specific effect we seek to measure, i.e. the secondary economic development benefits of flood protection in *areas exposed to flooding*. Of the city's 761 hex-cells, 363 are considered "treatment" and 398 "control" (Figure 4).

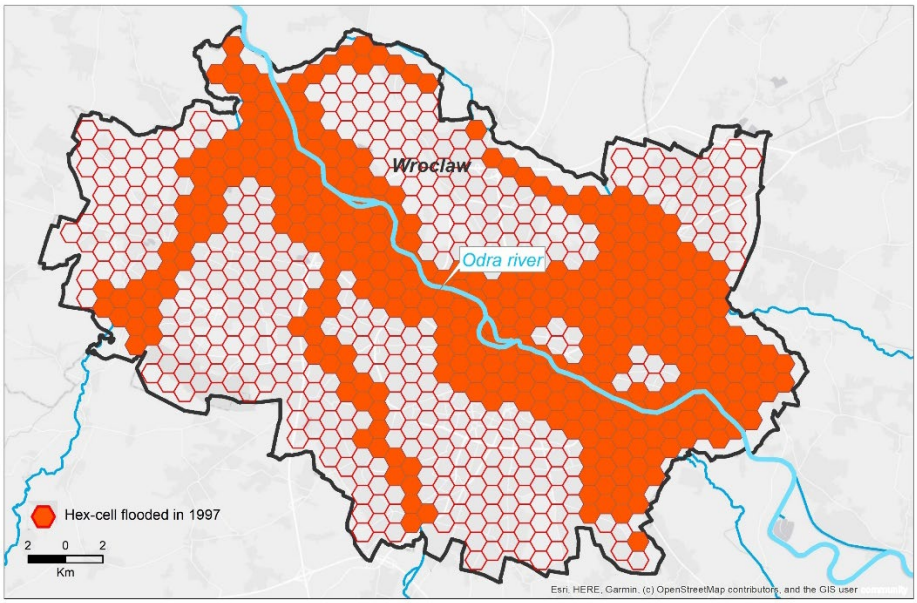


Figure 4: *Analyzed hex-cells (in orange: 1997 flooded hex-cells)*

3.2.2.3. Economic development assessment

We compare the values of each of the three remotely-sensed spatial datasets across the treatment and control groups before and after the "flood event year," 1997, and 2004, the transition year. Each indicator is evaluated for its suitability as a proxy measure of economic development. We develop our analysis by assessing trends in each indicator's growth, growth rates, and year over year (YOY) changes. For the calculation of YOY, values are calculated for each individual hex-cell and then averaged to create the YOY flooded versus non-flooded values.

4. Results

4.1. Real estate value generation

4.1.1. Land values

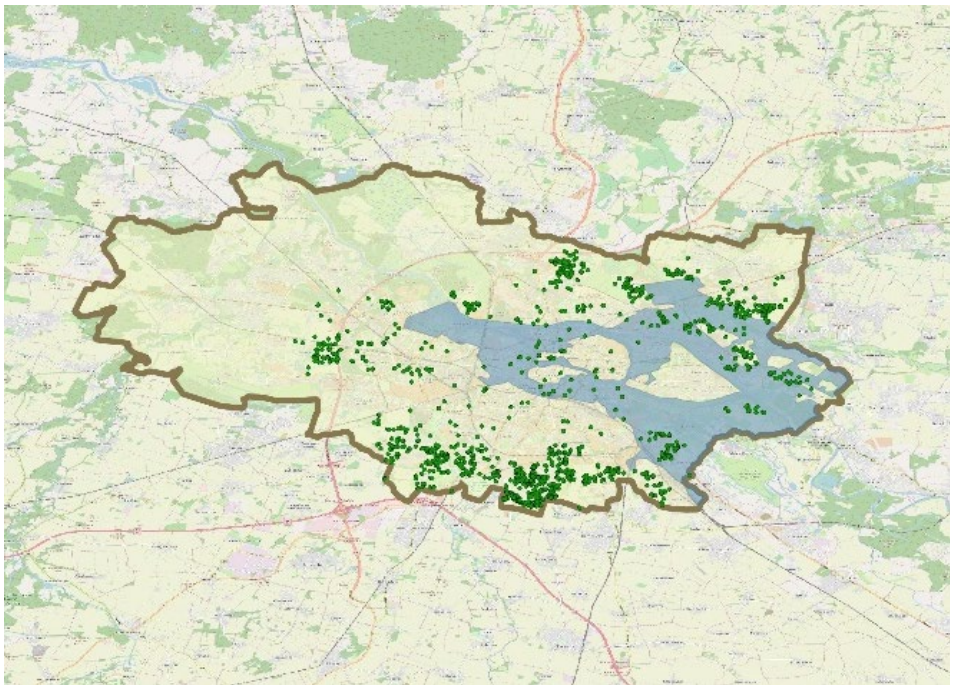


Figure 5: *All land transactions data points within Wroclaw*

The locations of all the land transaction data are shown in Figure 5 (as green dots). In the period 2000-2018 there was a growth in average prices for land, in areas both previously flooded and non-flooded (Figure 6). In addition, the volume of land sales also increased over this period (with more sales observed in non-flooded areas). This general increase in land sales and prices is consistent with those observed for the overall land market across the country. Although the differences in average values for flooded and non-flooded areas in these time periods are not statistically significant, a distinct growth difference is observed between the 2000-2004 and 2004-2018 time periods (Figure 7a). Comparing these two periods, the Compound Annual Growth Rate (CAGR) for land sales across the flooded areas (which received public investment in flood protection) outpaces non-flooded areas. The price growth rate changed from -9% to +15% in the flooded areas in contrast to 17% to 8% in non-flooded areas (Figure 7b), indicating a "faster" growth in land prices within the flooded areas. If we assume that the non-flooded areas represent the "market" in Wroclaw, these results suggest that the previously flooded areas "caught up" to the overall market. This general observation of significant growth in previously flooded neighborhoods has also been confirmed in discussions with city officials.

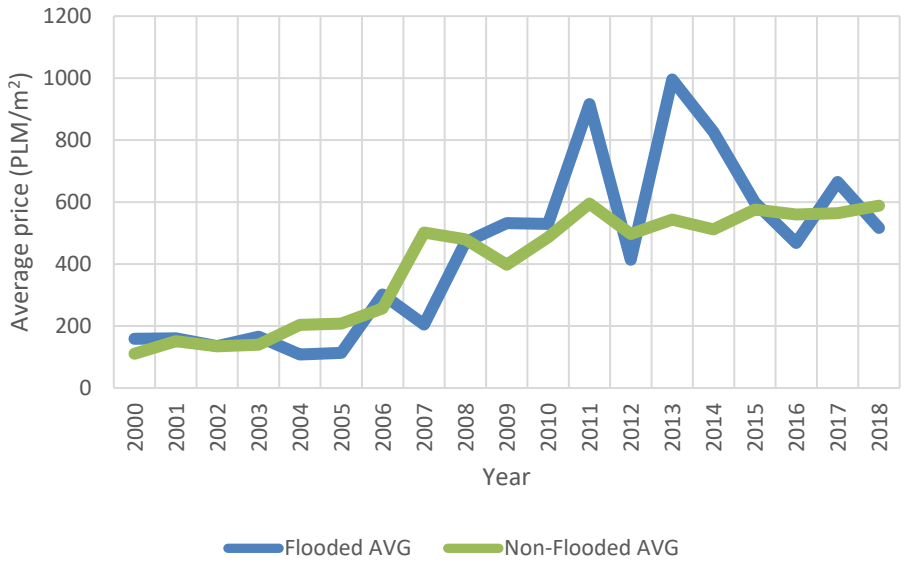


Figure 6: *Average price per m² in flooded and non-flooded areas (PLN/m²)*

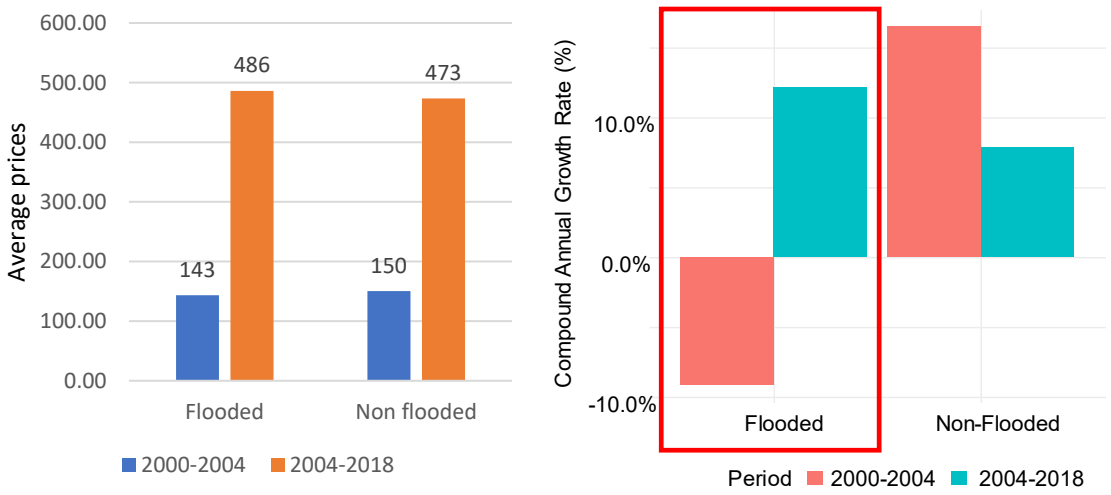


Figure 7 (a) *Average price per m² by time period* ***(b)*** *Growth dynamics of average prices per m² over two time periods*

More variability in land prices is also observed in transactions within the previously flooded lands (standard deviation of 717 PLN/m²) compared to non-flooded lands (454 PLN/m²) between 2004 and 2018. Similarly, changes in the maximum land prices observed are more pronounced across the flooded areas. Though the minimum prices are virtually the same across locations and time periods (Table 3), the maximum observed prices in the flooded locations in the 2000-2004 period is about half of that observed in the non-flooded areas, but "catches up" to and surpasses the maximum observed in the non-flooded areas. Again, this data reveals greater dynamics in land prices for areas that were previously flooded.

Table 3: *Maximum and Minimum Land price per m² (PLN/m²)*

		2000-2004	2005-2018
Flooded	*Min*	27	25
	Max	822	3972
Non-flooded	*Min*	20	20
	Max	1780	3851

4.1.2. Residential values

Like the trends observed with land prices, the average residential prices (per square meter on the secondary market) increased steadily in the period between 2000 and 2018 across flooded and non-flooded areas (Figure 8). This increase is consistent with that observed for the overall market in Wroclaw and other major cities across Poland (e.g. Warsaw, Krakow). However, relying on the three selected residential areas to generalize to the broader market is difficult. In some cases (e.g., transactions within areas A1 and A2), 2018 average prices in previously flooded locations are significantly higher in comparison to the average market in Wroclaw, while in others they are significantly lower (e.g., in area A3). The pattern of growth with respect to average prices is also not clear. However, the number of residential transactions in the flooded areas shows a statistically significant marked increase in comparison to the reference non-flooded area (Figure 9). That is, like in the land sales data, more opportunities became possible on previously flooded lands. This finding was confirmed in discussions with city officials and interviews with developers.

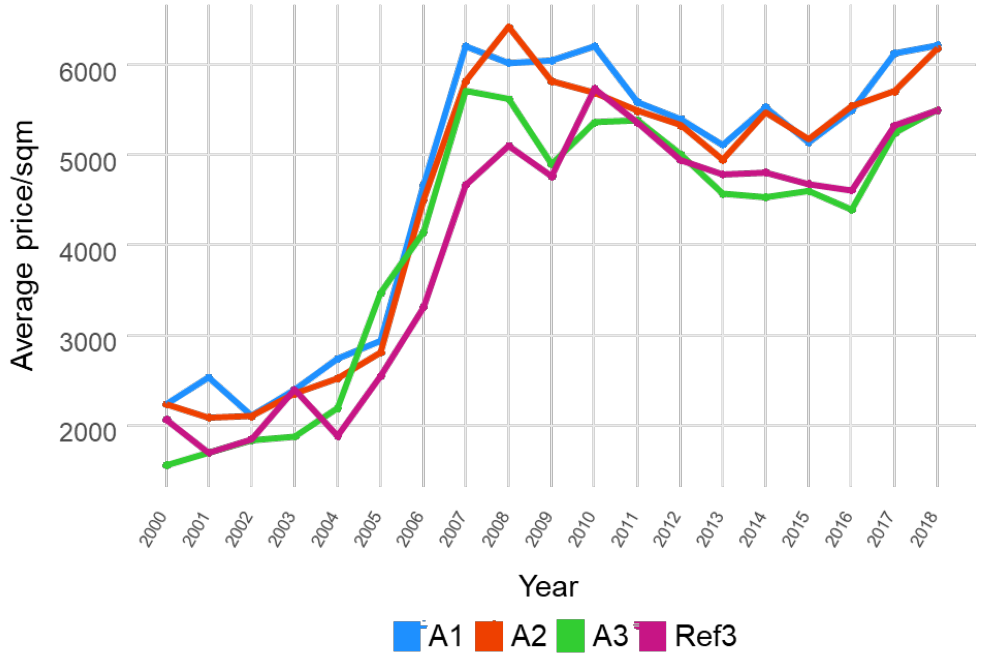


Figure 8: *Average price per m2 in flooded and non-flooded areas*

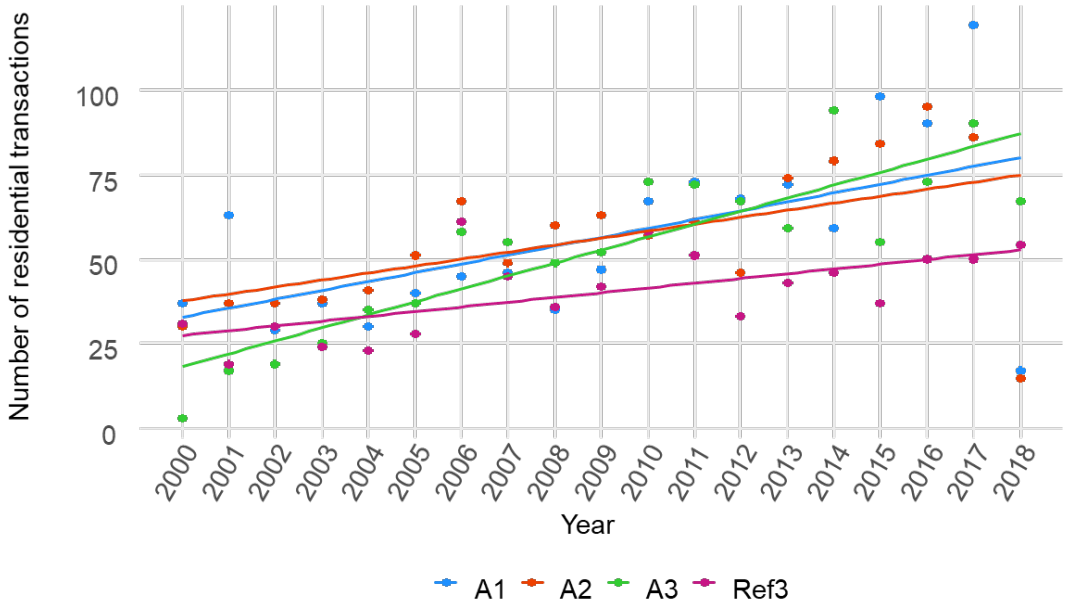
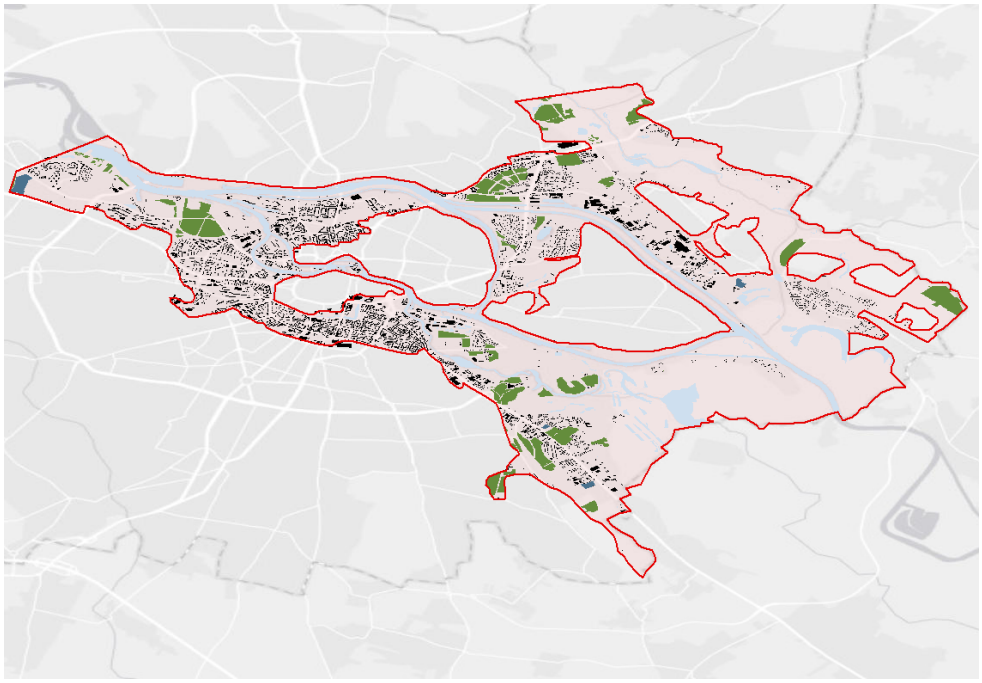


Figure 9: *Number of residential transactions in flooded and non-flooded areas*

4.1.3 Overall value

To estimate the potential land value being created from these flood investments, the difference in average land prices is calculated over the two time periods 2000-2004 and 2004-2018 for both the flooded and non-flooded areas (see Table 4). These differences are then multiplied by the average size (in square meters) of the transaction and the volume of transactions observed to derive an overall change in transaction value (last column in Table 4). The results show that land values have increased between 2000 and 2018 by about USD 100 million and USD 500 million on flooded and non-flooded lands respectively. The *incremental* price change above the market (i.e., flooded average price difference minus the non-flooded average price difference) was also extrapolated over the land area in Wroclaw that was previously flooded, where flood risks have been minimized due to public infrastructure investments. This area is estimated to be on the order of 4,000-7,000 ha.[5] This is a conservative estimate given that the flooded areas from 1997 (Figure 10) do not fully capture the entire extent of now flood protected areas and are based on ortho-photomaps from 2015 (i.e., Wroclaw experienced substantial growth over the last two decades and as such the undeveloped areas were greater back then). Nonetheless, considering the incremental price of about 20 PLN/m^2 (USD 5.2/m^2) between the flooded and non-flooded areas (Tables 4a and 4b) and the estimated area size, around 800 million to 1,400 million PLN (USD 210 million to USD 370 million) in incremental value creation remain. This additional value (net of the market) is made possible with the investments in flood protection.



[5] The upper bound of 7,000 ha is based on an estimated 75% of the flooded area from 1997 that is undeveloped.

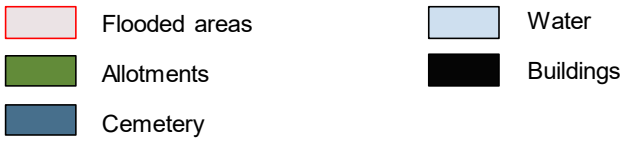


Figure 10: *Undeveloped Areas within Flooded Lands in Wroclaw*

Table 4*: Change in Land Transaction Prices for 1997 (a) Flooded Areas and (b) Non-Flooded areas*

(a)

Flooded areas	**Avg. Price (PLN/m²)**	**Sqm**	**St. Dev.**	**No. of trans.**	**Estimated value of lands**
2000-2004	143.3	2117.1	149.3	36	10,919,916
2004-2018	486.2	3739.5	716.3	195	354,505,864
Difference	**342.9**				**343,585,947**

(b)

Non-Flooded areas	**Avg. Price (PLN/m²)**	**Sqm**	**St. Dev.**	**No. of trans.**	**Estimated value of lands**
2000-2004	150.4	2175.8	136.9	314	102,742,519
2004-2018	473.5	4126.4	454.6	990	1,934,189,051
Difference	**323.1**				**1,831,446,532**

4.2. Economic development

4.2.1. Nighttime lights

From 1992 to 2013 (the period for which DMSP-OLS nighttime light data is available), the intensity of nighttime light emission throughout Wroclaw increased by approximately 45%, from an annual average Digital Number (DN) of 24 to 35.[6] While the average SOL across the city increased during that time (Figure 11), the rate (or slope) of change is more moderate in the time between 1997 and 2004 compared to the period after 2004 (Figure 12). The question is whether this trend varies between flooded and non-flooded areas in the city.

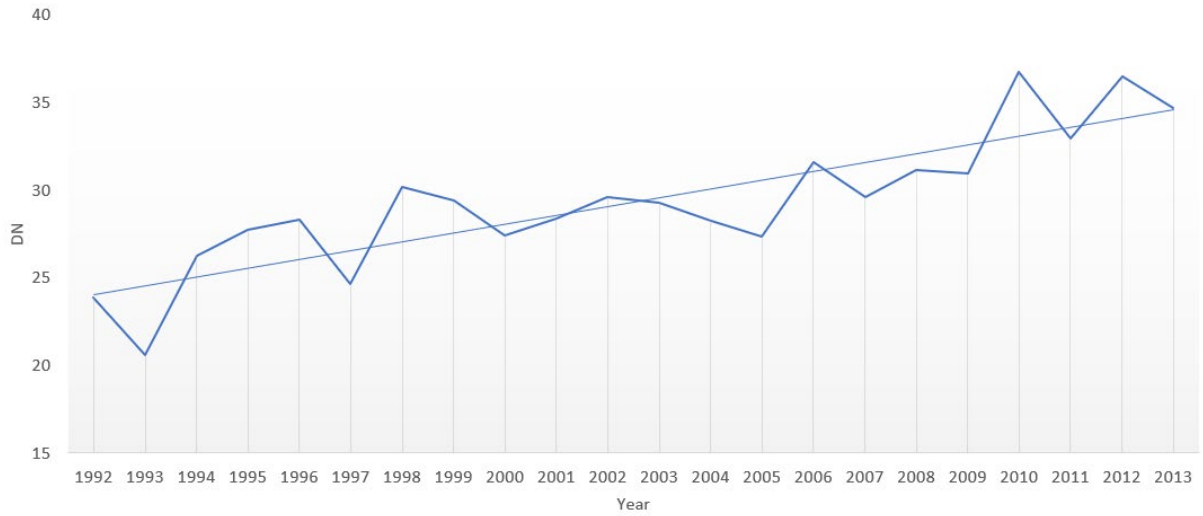


Figure 11: *Average per-hex-cell SOL, Wroclaw*

[6] DN values range from 0 to 63.

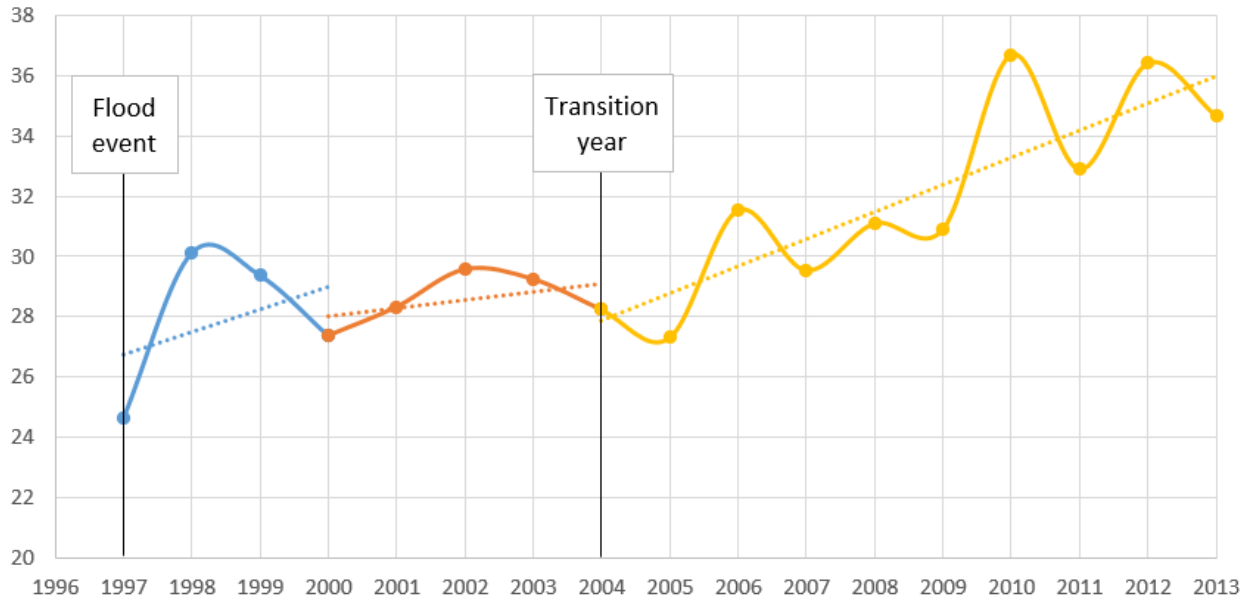


Figure 12: *Mean SOL across all hexagons in the city in the periods between 1997-2004 and 2004-2013*

We therefore examine SOL trends across the flooded and non-flooded hex-cells. The results suggest that from 1992 to 2004, SOL remained consistently higher across the flooded compared to the non-flooded hex-cells (Figure 13). During this period, the average difference in SOL value between the flooded and the non-flooded hex-cells is 1.93; a two-sample t-test ($t(24) = -1.79$, $p=0.04$) indicates that this result is statistically significant. This trend can be explained by the fact that large portions of the flooded area in 1997 are located in Wroclaw's city center, by the Odra river, where we would expect to observe more intense economic activity and thus more intense emission of nighttime lights compared to more peripheral, less flooded areas of the city. After 2004, however, the intensity of nighttime light emission across the non-flooded hex-cells outpaced that of the flooded hex-cells (Figure 13). A two-sample t-test shows that the difference in average SOL between the flooded and the non-flooded hex-cells is significantly larger in the period from 1992-to 2004 compared to 2004-2013 ($M=1.93$, $SD=0.51$ and $M=0.14$, $SD=0.74$, respectively; $t(14) = -6.99$, $p=0.000$). Hence, the growth of nighttime lights in 1997's non-flooded areas "caught up" to the nighttime light growth in the flooded areas around 2004.

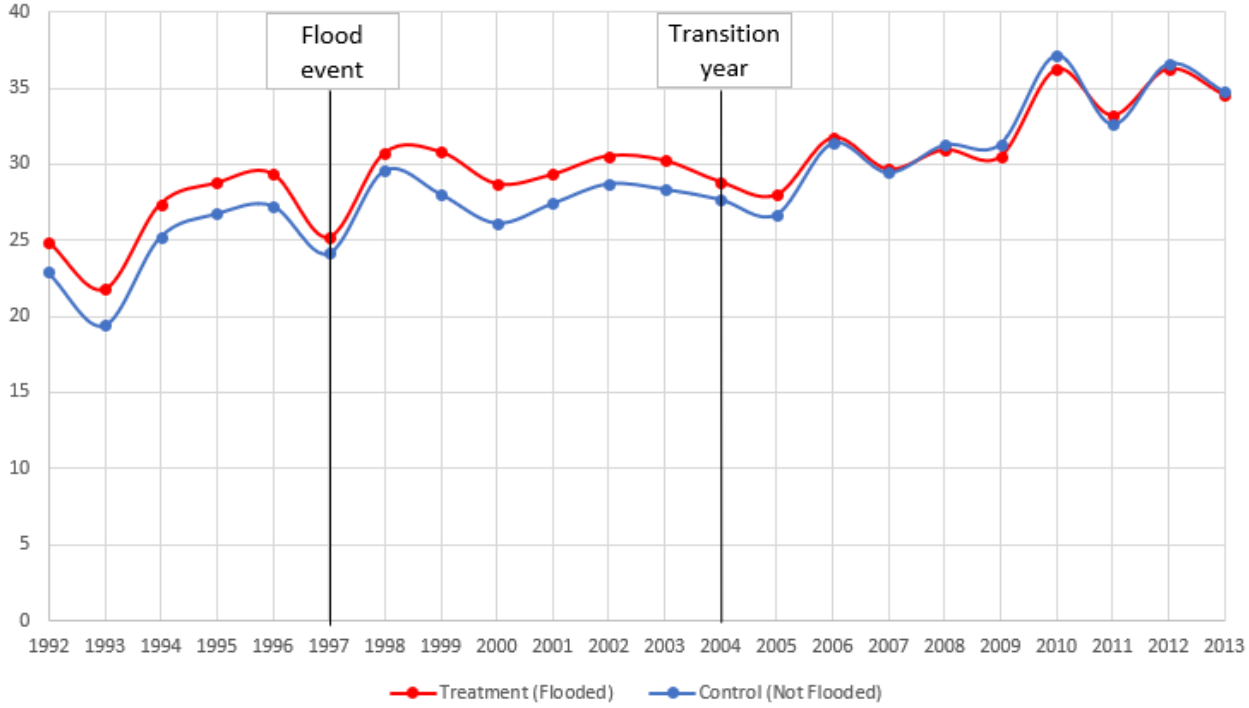


***Figure 13**: Change in average SOL across flooded and non-flooded hexagons*

4.2.2 Built-up land cover (WSF) and annual urban growth rate (AGR)

We also evaluate temporal changes in built-up land cover as an additional proxy for changes in economic activity and development. First, the results show a strong and significant correlation between SOL and built-up land cover across all hex-cells in Wroclaw from 1992 to 2013 ($r=0.87$, $p<0.05$); namely, as expected, the increase in built-up land cover coincides with an increase in nighttime light emissions. As Figure 14 shows, the increase in built-up land cover across the city remains relatively constant since 1997. However, a more nuanced examination of built-up land cover AGR (Figure 15) shows that prior to 2004 there is a general decrease in the AGR, a trend that shifts post-2004, when an increase in built-up land cover AGR is observed across flooded and non-flooded hex-cells, with a slightly steeper increase across flooded hex-cells.

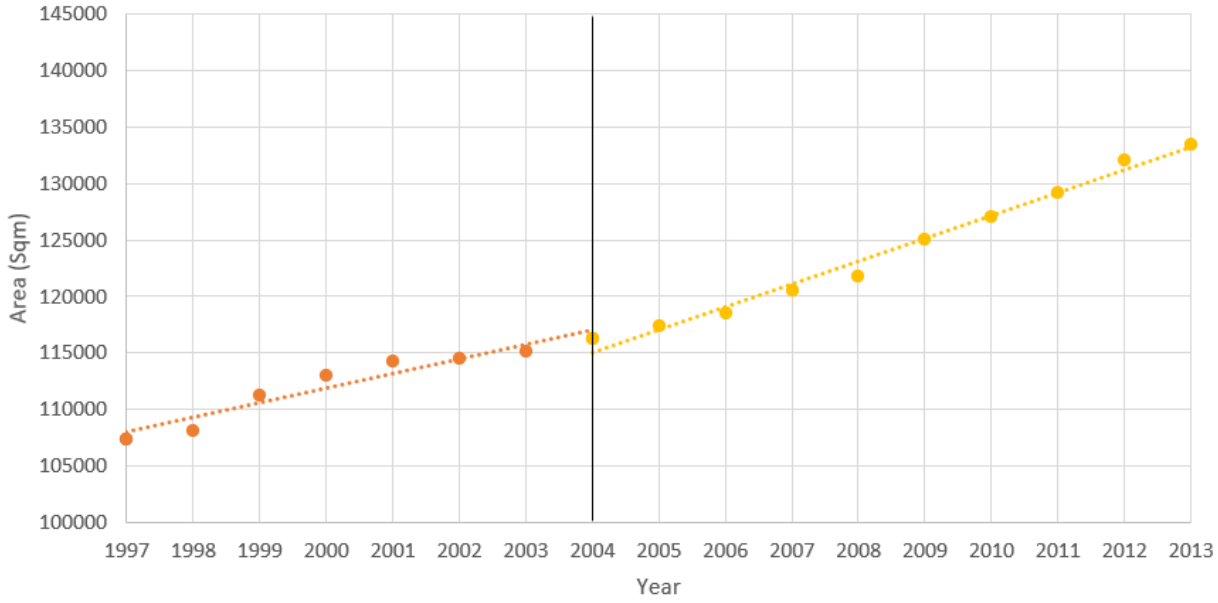


Figure 14: Average area of built-up land cover (Sqm) per hex-cell (all hex-cells).

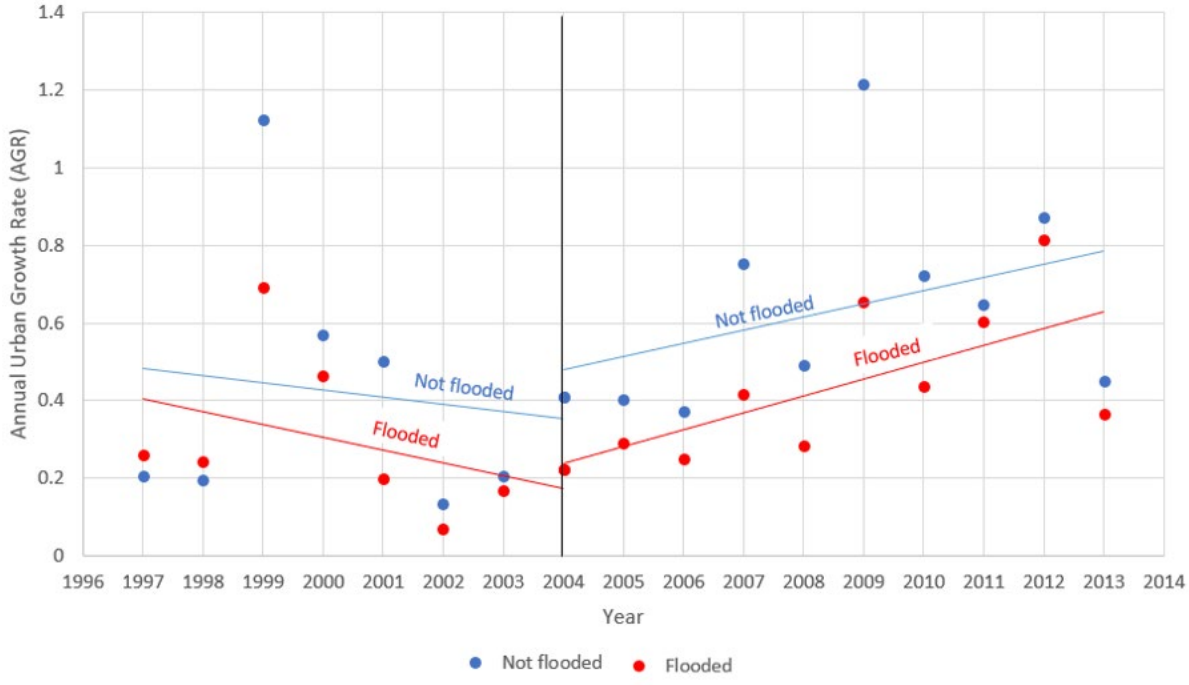


Figure 15: Trends in built-up land cover AGR before and after 2004, across flooded and non-flooded hex-cells

4.2.3 Distribution of the population

While nighttime light emissions and built-up land cover measurements provide an indication of economic development that is independent of specific human activities on land, changes in population counts offer valuable insights into the spatial distribution of people, including migration patterns. Analyzing Wroclaw's population spatially over time reveals a steady decrease in the number of people from 2000 to 2020 within areas flooded during the 1997 event, accompanied by an increase in population in non-flooded areas (Figure 16). Within the flooded areas, there is a significant negative correlation between population and the two other variables: nighttime light emissions ($r = -0.76$, $p < 0.05$) and built-up land cover ($r = -0.85$, $p < 0.05$). Conversely, in non-flooded areas, these correlations are positive and significant ($r = 0.61$ and $r = 0.56$, respectively, $p < 0.05$ for both). This finding suggests that although economic activity steadily increased in the flooded areas, as indicated by the observed rise in nighttime light emissions and built-up land cover, this trend coincides with a decline in population within these areas and a corresponding rise in population in non-flooded areas. Previous studies, such as (Długosz & Szmytkie, 2021) suggest a general trend of migration from the city to its immediate vicinity. Suburbanization processes have intensified in recent years, which is evidenced by the increasing number of people moving outside the city. Our result suggests that these migration trends are not uniform across the city, and that some areas, particularly those that were flooded and situated in the city center, exhibit a steeper decrease in population than other areas. Outmigration continues to be observed from high-risk areas to unflooded zones to avoid future disasters.

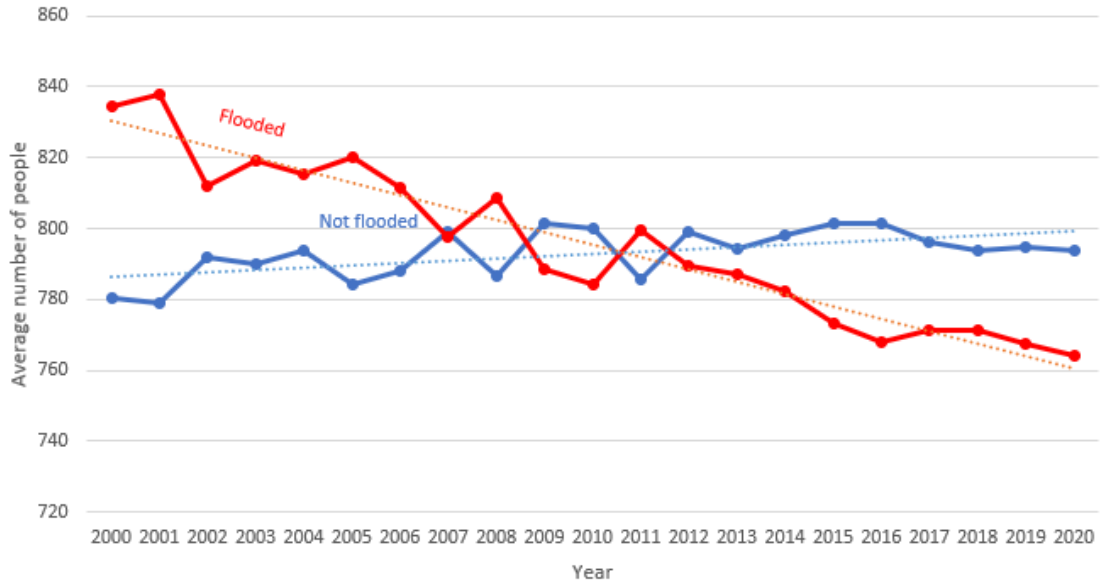


Figure 16: *Average number of people per hex-cell (WorldPop)*

5 Discussion

5.1. Results

5.1.1. Value generation

The spatiotemporal analyses conducted above demonstrate that the development of flood protection infrastructure in Wroclaw has resulted in strong residential property and land value growth for the areas formerly at risk of flooding, similar to findings from a recent study (Rosato et al., 2017) that found an increase in property values after investments in flood protection. As the residential and land transaction data show, prices observed in 2018 after the completion of the majority of the flood protection infrastructure resemble those in areas previously unaffected by the flood. That is, prices (as well as the volume of transactions) have grown faster in flooded areas than in previously non-flooded areas and "caught up" with the market.

If the net gain (i.e., removing the market trend – non-flooded area changes) is extrapolated to all the area under improved protection now, the incremental value is estimated around 2019 USD 210 million to USD 370 million. This additional value (net of the market) is made possible in part through the investments in flood protection. Moreover, based on interviews with two developers working in the vicinity of the flood protection interventions, the flood protection investments are valued in the order of hundreds of millions of USD. This provides an indication of the relative (large) magnitude of leveraging that the public investment in flood protection can generate.

5.1.2. Spatial analysis

The results of this study suggest that two remotely sensed indicators — nighttime lights and built-up land cover — can be used not only to assess the temporal and spatial relationships between the 1997 flood event in Wroclaw and the city's economic development, but also to provide insights into how the flood protection project starting in 2004 impacted the city's development. We find that between 1997 and 2004, the rate of change in economic activity across the city – as indicated by nighttime lights emissions – was relatively moderate, but increased following the investment in 2004, in parallel to a rapid increase in the rate of change of built-up land cover, as indicated by the AGR measure. Prior to 2004, we find a gradual decrease in AGR across the flooded sections of the city, while after 2004 the trend changes and we observe a constant and gradual increase in built-up area growth in the places directly "treated" by the investment, paralleling an increase in the YOY percent change in these areas in the number of people.

5.2. Limitations

This study aims to investigate the relationship between flood protection investments and land and property value appreciation using both transaction-based and geospatial analyses. While the method and results have offered various insights, several limitations should be acknowledged.

First, the underlying assumption that differences in transaction values between flooded and non-flooded areas—after adjusting for general market trends—can be attributed primarily to flood protection investments presumes that, absent the investments, the areas would have experienced similar development trajectories. However, a range of confounding factors could challenge this assumption. Locational characteristics such as proximity to amenities, school quality, public transport access, or housing quality can also influence land and property values. While qualitative inputs from government officials suggested comparability between locations, future studies could validate this assumption by accounting for statistical controls.

Further, while we attempt to isolate the effect of flood protection through a difference-in-differences-like approach, we acknowledge other techniques—such as hedonic pricing models that control for micro-level characteristics—could help establish causal inference. Although a potential refinement could involve restricting the analysis to properties transacted both before and after the investments, data limitations and resulting sample size constraints make such an approach difficult to implement robustly.

The selection of 2004 as a dividing year between pre- and post-investment periods also warrants consideration. Risk reduction began during disaster recovery of the 1997 flood (World Bank,2004), with numerous projects conducted over the years making it difficult to define a sole pre- and post-period. 2004 was chosen as a cut-off year because it marks Poland's accession to the EU and the start of project planning for the ORFPP project. Thus, the timing of observed changes in property values may not all align perfectly with the actual reduction in flood risk, potentially scattering the attribution of observed effects to the intervention.

We also acknowledge that flood and non-flood zones may not be fully independent in urban settings. Spatial interdependencies—where improvements in one area affect development and value in others—challenge a perfect distinction between "treatment" and "control" zones. As such, attributing changes solely to local flood protection may overstate the net benefit.

Data limitations are also relevant. There were fewer land transactions than residential transactions, limiting the variation in spatial scale of analysis; DMSP-OLS data is available from 1992-2013 while WSF data is available from 1985-2015 and WorldPop data is available from 2000; and transaction price data is only available in Wroclaw from 2000-2018. The lack of a full temporal overlap between these datasets did not permit a perfect comparison between them. Second, the analysis of nighttime lights may always be impacted by possible noise in the data. For example, DMSP-OLS may exaggerate the extent of urban areas (M. Henderson et al., 2003; Small et al., 2005) while overlooking small or developing settlements. In addition, the extent and intensity of lit areas cannot directly delimit urban regions due to the "blooming" effect (Imhoff, Lawrence, Stutzer, et al., 1997), which can indicate lit areas as larger than the settlements with which they are associated (Small et al., 2005), and the saturation of pixels (Hsu et al., 2015) that can occur when pixels in bright areas like city centers reach DMSP-OLS's highest possible digital value.

These limitations may hinder the differentiation of urban areas, especially between adjacent hex-cells.

Despite these limitations, the complementary nature of the transaction and geospatial analyses provides a degree of triangulation. This mixed-methods approach offers preliminary yet meaningful evidence of the impacts of flood protection investments, while also highlighting the need for more granular, causally robust future research.

5.3. Implications

In a traditional economic analysis for this kind of flood infrastructure investment, the indirect impacts on urban development (e.g. tourism, real estate, land, small enterprises) are oftentimes not accounted. Flood infrastructure will play an important role in better managing these opportunities. However, with the challenges that many governments in developing countries face in securing public funding for flood infrastructure projects, more innovative approaches will be needed to leverage public assets and the concomitant value being generated to gain access to sources of financing, including from the private sector. For example, Popovici (2013) discusses in detail the case of the Pevensey Coastal Defense Project (PCDL) in the UK. Here the private sector is contracted by the UK government to provide a flood protection service. To increase the chance of such partnerships, focusing on the co-benefits of flood protection, such as a potential reduction in carbon emissions, land value capture, and increase in economic activity could be advantageous.

This study provides an ex-post example of the value generated through real estate development that can come from public investments in flood protection. A question for further research is whether land value capture (LVC) techniques (through e.g. targeted taxation and/or various fee structures) can be a viable way of attracting private investment in future flood protection investments. This innovative financing solution can offer a way to finance large infrastructure projects. For example, a 17 million USD investment in riverfront infrastructure in India has resulted in "30 hectares of reclaimed land for sale" with only 15% of the sale proceeds needed to recover the upfront investment cost (City Resilience Program, 2018). Simply put, increasing the land value in the floodplain could be used as a tool to leverage upfront financing for increased flood protection.

A more densified urban core may also lead to reduced carbon emissions. While this may sound counterintuitive, sustainable densification has the potential to lower CO_2 emissions (Muñiz & Dominguez, 2020), especially through the transport sector (Makido et al., 2012). And an increase in population is often associated with an increase in economic activity (Peterson & Wesley, 2017). An attendant rise in tax base could offer up funds for public improvement. If targeted on areas of urban decay and blighted urban cores, this could lead to urban regeneration (World Bank Group, 2015). Similar benefits have been found with urban flood protection in Mexico, showing that residents took more of an initiative in taking care of the local urban environment following public investment in flood defense (Vorhies & Wilkinson, 2016).

6 Conclusions

This study demonstrates that investments in flood control infrastructure are directly linked to increases in nighttime light emissions and built-up area, which serve as proxies for economic development in Wroclaw, Poland. We also find that the three remotely sensed measures we assess have a statistically significant and strongly correlated relationship to both annual investments made in flood protection and annual real estate transaction prices.

This study provides a basis for the further application of alternative ways like remotely sensed data to assess the secondary benefits of investments in flood protection infrastructure as well as other types of infrastructure investments. As CBA is typically performed prior to construction, including secondary benefits in ex-ante analyses is crucial. This conclusion offers an extensive field for future research. While the current study is ex-post in nature, it presents several applications for ex-ante studies as well. For example, remote sensing data could be combined with machine learning techniques to predict changes in nighttime lights, built-up area, and the spatial and temporal dimensions of economic development.

7 References

Amaral, S., Monteiro, A. M. V., Camara, G., & Quintanilha, J. A. (2006). DMSP/OLS night-time light imagery for urban population estimates in the Brazilian Amazon. *International Journal of Remote Sensing*, *27*(5), 855–870. https://doi.org/10.1080/01431160500181861

Amarasinghe, U., Amarnath, G., Alahacoon, N., & Ghosh, S. (2020). How Do Floods and Drought Impact Economic Growth and Human Development at the Sub-National Level in India? *Climate*, *8*(11), Article 11. https://doi.org/10.3390/cli8110123

Amer, M.,Mustafa, A.,Teller, J.,Attia, S., and Reiter, S. (2017). A methodology to determine the potential of urban densification through roof stacking. *Sustainable cities and society, 35*, 677-691. doi:10.1016/j.scs.2017.09.021

Bagan, H., & Yamagata, Y. (2015). Analysis of urban growth and estimating population density using satellite images of nighttime lights and land-use and population data. *GIScience & Remote Sensing*, *52*(6), 765–780. https://doi.org/10.1080/15481603.2015.1072400

Baragwanath, K., Goldblatt, R., Hanson, G., & Khandelwal, A. K. (2019). Detecting urban markets with satellite imagery: An application to India. *Journal of Urban Economics*, 103173.

Bay Area Council Economic Institute. (2020). *Linking the Environment and the Economy An Economic Impact Analysis of California Climate Resilience Bond Proposals*. http://www.bayareaeconomy.org/files/pdf/BACEI_ClimateResilience_FINAL.pdf

Bin, O., & Polasky, S. (2004). Effects of Flood Hazards on Property Values: Evidence Before and After Hurricane Floyd. *Land Economics*, *80*(4), 490–500. https://doi.org/10.2307/3655805

Bruederle, A., & Hodler, R. (2018). Nighttime lights as a proxy for human development at the local level. *PLOS ONE*, *13*(9), e0202231. https://doi.org/10.1371/journal.pone.0202231

Butts, M., Dubicki, A., Stronska, K., JØrgensen, G., Nalberczynski, A., Lewandowski, A., & Kalken, T. van. (2007). Flood Forecasting for the Upper and Middle Odra River Basin. In S. Begum, M. J. F. Stive, & J. W. Hall (Eds.), *Flood Risk Management in Europe: Innovation in Policy and Practice* (pp. 353–384). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4200-3_19

Carr, D. B., Olsen, A. R., & White, D. (1992). Hexagon mosaic maps for display of univariate and bivariate geographical data. *Cartography and Geographic Information Systems*, *19*(4), 228–236.

Chen, C., He, X., Liu, Z., Sun, W., Dong, H., & Chu, Y. (2020). Analysis of regional economic development based on land use and land cover change information derived from Landsat imagery. *Scientific Reports*, *10*(1), Article 1. https://doi.org/10.1038/s41598-020-69716-2

City Resilience Program. (2018). *Land Value Capture*. Retrieved from https://www.gfdrr.org/sites/default/files/publication/Land%20Value%20Capture.pdf

Croft, T. A. (1973). Burning waste gas in oil fields. *Nature*, *245*(5425), 375–376.

Daniel, V. E., Florax, R. J., & Rietveld, P. (2009). Flooding risk and housing values: An economic assessment of environmental hazard. *Ecological Economics*, *69*(2), 355–365.

Długosz, M., & Szmytkie, R. (2021). Migratory Outflow from Wrocław: Directions of Population Flows within the Framework of Internal Migration in the Period 2002–2018. *Quaestiones Geographicae*, *40*(2), 19–33. https://doi.org/10.2478/quageo-2021-0014

Doll, C. N. H., Muller, J.-P., & Morley, J. G. (2006). Mapping regional economic activity from night-time light satellite imagery. *Ecological Economics*, *57*(1), 75–92. https://doi.org/10.1016/j.ecolecon.2005.03.007

Donnelly, W. A. (1989). HEDONIC PRICE ANALYSIS OF THE EFFECT OF A FLOODPLAIN ON PROPERTY VALUES 1. *JAWRA Journal of the American Water Resources Association*, *25*(3), 581–586.

Duque, J. C., Lozano-Gracia, N., Patino, J. E., Restrepo, P., & Velasquez, W. A. (2019). Spatiotemporal dynamics of urban growth in Latin American cities: An analysis using nighttime light imagery. *Landscape and Urban Planning*, *191*, 103640. https://doi.org/10.1016/j.landurbplan.2019.103640

Elvidge, C. D., Baugh, K. E., Dietz, J. B., Bland, T., Sutton, P. C., & Kroehl, H. W. (1999). Radiance calibration of DMSP-OLS low-light imaging data of human settlements. *Remote Sensing of Environment*, *68*(1), 77–88.

Elvidge, C. D., Hsu, F.-C., Baugh, K. E., & Ghosh, T. (2014). National trends in satellite-observed lighting. *Global Urban Monitoring and Assessment through Earth Observation*, *23*, 97–118.

Elvidge, C. D., Ziskin, D., Baugh, K. E., Tuttle, B. T., Ghosh, T., Pack, D. W., Erwin, E. H., & Zhizhin, M. (2009). A Fifteen Year Record of Global Natural Gas Flaring Derived from Satellite Data. *Energies*, *2*(3), Article 3. https://doi.org/10.3390/en20300595

Erdlenbruch, K., & Grelot, F. (2017). 21—Economic Assessment of Flood Prevention Projects. In F. Vinet (Ed.), *Floods* (pp. 321–335). Elsevier. https://doi.org/10.1016/B978-1-78548-269-4.50021-4

Esch, T., Bachofer, F., Heldens, W., Hirner, A., Marconcini, M., Palacios-Lopez, D., Roth, A., Üreyen, S., Zeidler, J., Dech, S., & Gorelick, N. (2018). Where We Live—A Summary of the Achievements and Planned Evolution of the Global Urban Footprint. *Remote Sensing*, *10*(6), 895. https://doi.org/10.3390/rs10060895

Genovese, E., Thaler, T., Genovese, E., & Thaler, T. (2020). The benefits of flood mitigation strategies: Effectiveness of integrated protection measures. *AIMS Geosciences*, *6*(4), Article geosci-06-04-025. https://doi.org/10.3934/geosci.2020025

Ghosh, T., L Powell, R., D Elvidge, C., E Baugh, K., C Sutton, P., & Anderson, S. (2010). Shedding light on the global distribution of economic activity. *The Open Geography Journal*, *3*(1).

Główny Urząd Statystyczny. (2020). *Rocznik Demograczny: Demographic Yearbook of Poland*. https://stat.gov.pl/en/topics/statistical-yearbooks/statistical-yearbooks/demographic-yearbook-of-poland-2020,3,14.html

Gordon, D. L. (1997). Financing urban waterfront redevelopment. *American Planning Association. Journal of the American Planning Association*, *63*(2), 244.

Henderson, J. V., Squires, T., Storeygard, A., & Weil, D. (2018). The Global Distribution of Economic Activity: Nature, History, and the Role of Trade1. *The Quarterly Journal of Economics*, *133*(1), 357–406. https://doi.org/10.1093/qje/qjx030

Henderson, J. V., Storeygard, A., & Weil, D. N. (2012). Measuring economic growth from outer space. *American Economic Review*, *102*(2), 994–1028.

Henderson, M., Yeh, E. T., Gong, P., Elvidge, C., & Baugh, K. (2003). Validation of urban boundaries derived from global night-time satellite imagery. *International Journal of Remote Sensing*, *24*(3), 595–609.

Higher education in regional and city development—OECD. (n.d.). Retrieved June 29, 2021, from https://www.oecd.org/education/imhe/highereducationinregionalandcitydevelopment.htm

Homer, C. G., & Gallant, A. (2001). Partitioning the conterminous United States into mapping zones for Landsat TM land cover mapping. *Unpublished US Geologic Survey Report. Http://Landcover. Usgs. Gov/Pdf/Homer. Pdf.(1 August 2008)*.

Homer, C., Huang, C., Yang, L., Wylie, B., & Coan, M. (2004). Development of a 2001 national land-cover database for the United States. *Photogrammetric Engineering & Remote Sensing*, *70*(7), 829–840.

Hsu, F.-C., Baugh, K. E., Ghosh, T., Zhizhin, M., & Elvidge, C. D. (2015). DMSP-OLS radiance calibrated nighttime lights time series with intercalibration. *Remote Sensing*, *7*(2), 1855–1876.

Huang, Q., Yang, X., Gao, B., Yang, Y., & Zhao, Y. (2014). Application of DMSP/OLS Nighttime Light Images: A Meta-Analysis and a Systematic Literature Review. *Remote Sensing*, *6*(8), Article 8. https://doi.org/10.3390/rs6086844

Hufschmidt, M. M. (2000). Benefit-cost analysis: 1933-1985. *Journal of Contemporary Water Research and Education*, *116*(1), 11.

Huong, H. T. L., & Pathirana, A. (2011). Urbanization and climate change impacts on future urban flood risk in Can Tho city, Vietnam. *Hydrology & Earth System Sciences Discussions*, *8*(6).

Imhoff, M. L., Lawrence, W. T., Elvidge, C. D., Paul, T., Levine, E., Privalsky, M. V., & Brown, V. (1997). Using nighttime DMSP/OLS images of city lights to estimate the impact of urban land use on soil resources in the United States. *Remote Sensing of Environment*, *59*(1), 105–117. https://doi.org/10.1016/S0034-4257(96)00110-1

Imhoff, M. L., Lawrence, W. T., Stutzer, D. C., & Elvidge, C. D. (1997). A technique for using composite DMSP/OLS "city lights" satellite data to map urban area. *Remote Sensing of Environment*, *61*(3), 361–370.

Jonkman, S. N., Curran, A., & Bouwer, L. M. (2024). Floods have become less deadly: An analysis of global flood fatalities 1975–2022. *Natural Hazards*, *120*(7), 6327–6342. https://doi.org/10.1007/s11069-024-06444-0

Kaźmierczak, A., & Cavan, G. (2011). Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure. *Landscape and Urban Planning*, *103*(2), 185–197. https://doi.org/10.1016/j.landurbplan.2011.07.008

Keola, S., Andersson, M., & Hall, O. (2015). Monitoring Economic Development from Space: Using Nighttime Light and Land Cover Data to Measure Economic Growth. *World Development*, *66*, 322–334. https://doi.org/10.1016/j.worlddev.2014.08.017

Kumar, P., Debele, S. E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S. M., Basu, B., Basu, A. S., Bowyer, P., Charizopoulos, N., Jaakko, J., Loupis, M., Menenti, M., Mickovski, S. B., Pfeiffer, J., Pilla, F., Pröll, J., Pulvirenti, B., Rutzinger, M., … Zieher, T. (2021). An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. *Earth-Science Reviews*, *217*, 103603. https://doi.org/10.1016/j.earscirev.2021.103603

KUNDZEWICZ, Z. W., SZAMALEK, K., & KOWALCZAK, P. (1999). The Great Flood of 1997 in Poland. *Hydrological Sciences Journal*, *44*(6), 855–870. https://doi.org/10.1080/02626669909492285

Liu, Z., He, C., Zhang, Q., Huang, Q., & Yang, Y. (2012). Extracting the dynamics of urban expansion in China using DMSP-OLS nighttime light data from 1992 to 2008. *Landscape and Urban Planning*, *106*(1), 62–72. https://doi.org/10.1016/j.landurbplan.2012.02.013

Ma, T., Zhou, C., Pei, T., Haynie, S., & Fan, J. (2012). Quantitative estimation of urbanization dynamics using time series of DMSP/OLS nighttime light data: A comparative case study from China's cities. *Remote Sensing of Environment*, *124*, 99–107.

Makido, Y.,Dhakal, S., and Yamagata, Y. (2012). Relationship between urban form and CO2 emissions: Evidence from fifty Japanese cities. *Urban climate, 2*, 55-67. doi:10.1016/j.uclim.2012.10.006

Marconcini, M., Metz-Marconcini, A., Üreyen, S., Palacios-Lopez, D., Hanke, W., Bachofer, F., Zeidler, J., Esch, T., Gorelick, N., Kakarla, A., Paganini, M., & Strano, E. (2020).

Outlining where humans live, the World Settlement Footprint 2015. *Scientific Data*, *7*(1), 242. https://doi.org/10.1038/s41597-020-00580-5

Mellander, C., Lobo, J., Stolarick, K., & Matheson, Z. (2015). Night-Time Light Data: A Good Proxy Measure for Economic Activity? *PLOS ONE*, *10*(10), e0139779. https://doi.org/10.1371/journal.pone.0139779

Muñiz, I. and Dominguez, A. (2020). The Impact of Urban Form and Spatial Structure on per Capita Carbon Footprint in U.S. Larger Metropolitan Areas. *Sustainability, 12*(1), 389. doi:10.3390/su12010389

NOAA. (2015). *A Guide to Assessing Green Infrastructure Costs and Benefits for Flood Reduction*. National Oceanic and Atmospheric Administration (NOAA). https://coast.noaa.gov/data/docs/digitalcoast/gi-cost-benefit.pdf

Odra River Basin Flood Protection. (n.d.). AECOM. Retrieved June 29, 2021, from https://aecom.com/projects/odra-river-basin-flood-protection/

Peterson, E. and Wesley, F. (2017). The Role of Population in Economic Growth. *SAGE open, 7*(4). doi:10.1177/2158244017736094

Peterson, T. C., Heim Jr, R. R., Hirsch, R., Kaiser, D. P., Brooks, H., Diffenbaugh, N. S., Dole, R. M., Giovannettone, J. P., Guirguis, K., & Karl, T. R. (2013). Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge. *Bulletin of the American Meteorological Society*, *94*(6), 821–834.

Popovici, O.P. (2013). *Financing flood protection measures in developing countries*. TU Delft. https://repository.tudelft.nl/record/uuid:5118292f-a35c-4f1b-8c15-c5a5596c05eb

Proville, J., Zavala-Araiza, D., & Wagner, G. (2017). Night-time lights: A global, long term look at links to socio-economic trends. *PLOS ONE*, *12*(3), e0174610. https://doi.org/10.1371/journal.pone.0174610

Rode, P. and Floater, G. (2014). *Accessibility in cities: transport and urban form*, NCE Cities - Paper 03: London School of Economics and Political Science. Retrieved from https://lsecities.net/wp-content/uploads/2014/11/LSE-Cities-2014-Transport-and-Urban-Form-03.pdf

Rosato, P., Breil, M., Giupponi, C., & Berto, R. (2017). Assessing the impact of urban improvement on housing values: A hedonic pricing and multi-attribute analysis model for the historic centre of venice. *Buildings*, *7*(4), 112.

Rozenberg, J., & Fay, M. (2019). *Flood Protection*.

Small, C., Pozzi, F., & Elvidge, C. D. (2005). Spatial analysis of global urban extent from DMSP-OLS night lights. *Remote Sensing of Environment*, *96*(3–4), 277–291.

Steffen, W., Hughes, L., & Perkins, S. (2014). *Heatwaves: Hotter, longer, more often*.

Stevens, F. R., Gaughan, A. E., Linard, C., & Tatem, A. J. (2015). Disaggregating census data for population mapping using random forests with remotely-sensed and ancillary data. *PloS One*, *10*(2), e0107042.

Sun, J., Di, L., Sun, Z., Wang, J., & Wu, Y. (2020). Estimation of GDP Using Deep Learning With NPP-VIIRS Imagery and Land Cover Data at the County Level in CONUS. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 1400–1415.

Tschakert, P., & Dietrich, K. A. (2010). Anticipatory learning for climate change adaptation and resilience. *Ecology and Society*, *15*(2).

UN. (2015). *World Urbanization Prospects: The 2014 Revision*. Department of Economic and Social Affairs, Population Division, United Nations.

Vorhies, F. and Wilkinson, E. (2016). *Co-Benefits of Disaster Risk Management [working paper]*. The World Bank. Retrieved from

Weidmann, N. B., & Schutte, S. (2017). Using night light emissions for the prediction of local wealth. *Journal of Peace Research*, *54*(2), 125–140.

WHO. (2008). *Climate change and health*.

WHO. (2017). *Flooding: Managing health risks in the WHO European Region*. https://apps.who.int/iris/handle/10665/329518

The World Bank Group. (2004). Project Information Document for Odra River Basin Flood Protection. http://documents.worldbank.org/curated/en/776781468776353545

The World Bank Group. (2015). Tools for Urban Regeneration. Retrieved from https://urban-regeneration.worldbank.org/

The World Bank Group. (2021). Implementation Compleition Report for Odra River Basin Flood Protection. Retrieved http://documents.worldbank.org/curated/en/740991623350668337

Wu, J., Wang, Z., Li, W., & Peng, J. (2013). Exploring factors affecting the relationship between light consumption and GDP based on DMSP/OLS nighttime satellite imagery. *Remote Sensing of Environment*, *134*, 111–119. https://doi.org/10.1016/j.rse.2013.03.001

Xiao, J., Shen, Y., Ge, J., Tateishi, R., Tang, C., Liang, Y., & Huang, Z. (2006). Evaluating urban expansion and land use change in Shijiazhuang, China, by using GIS and remote

sensing. *Landscape and Urban Planning*, *75*(1), 69–80. https://doi.org/10.1016/j.landurbplan.2004.12.005

Xie, M., Jean, N., Burke, M., Lobell, D., & Ermon, S. (2016). Transfer learning from deep features for remote sensing and poverty mapping. *Proceedings of the AAAI Conference on Artificial Intelligence*, *30*(1).

Zhang, Q., & Seto, K. C. (2011). Mapping urbanization dynamics at regional and global scales using multi-temporal DMSP/OLS nighttime light data. *Remote Sensing of Environment*, *115*(9), 2320–2329. https://doi.org/10.1016/j.rse.2011.04.032

Zhou, Y., Smith, S. J., Elvidge, C. D., Zhao, K., Thomson, A., & Imhoff, M. (2014). A cluster-based method to map urban area from DMSP/OLS nightlights. *Remote Sensing of Environment*, *147*, 173–185. https://doi.org/10.1016/j.rse.2014.03.004

Zhuo, L., Chen, J., Shi, P. J., Gu, Z., Fan, Y., & Ichinose, T. (2005). Modeling population density of China in 1998 based on DMSP/OLS nighttime light image. *Acta Geographica Sinica*, *60*(2), 266–276.