

# Sea Level Rise and Urban Adaptation in Jakarta

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Sea level rise poses an existential threat to Jakarta, which faces frequent and worsening flooding. The government has responded with a proposed sea wall. In this setting, I study how government intervention complicates long-run adaptation to climate change. I show that government intervention creates coastal moral hazard, and I quantify this force with a dynamic spatial model in which developers and residents act with flood risk in mind. I find that moral hazard generates severe lock-in and limits migration inland, even over the long run.

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# 1 Introduction

Sea level rise is a major threat to economic development. Globally, 680 million people currently live in low-elevation coastal zones, with more than one billion expected by 2050 as sea levels continue to rise ([IPCC 2019](#)). The situation is especially severe in Southeast Asia, where land subsidence contributes to inundation rates that exceed those elsewhere by up to an order of magnitude.<sup>1</sup> Particularly vulnerable are the 31 million residents of the Jakarta metropolitan area, which is on pace to overtake Tokyo as the world’s most populous megacity by 2030 ([Euromonitor 2018](#)).

Jakarta faces severe and frequent flooding, with damages exceeding \$300 million annually ([Budiyono et al. 2015](#)), and sea level rise brings substantial additional risk in the years to come. In response, the Indonesian government has proposed up to \$40 billion in flood infrastructure investments, including in a protective sea wall. I study how this government intervention complicates long-run adaptation by inducing moral hazard among coastal developers. The government tends to protect development ex post despite not wanting to ex ante, and developers over-invest at the coast in anticipation of this protection. The government thus faces a commitment problem, and indeed the seminal work of [Kydland and Prescott \(1977\)](#) mentions flood protection as a supporting example.<sup>2</sup> I formalize the commitment problem in the context of sea level rise, and I show how it compounds over time to limit adaptation.

I begin by documenting how developers responded to historical government intervention. The West Flood Canal is a key part of Jakarta’s existing flood infrastructure, as it diverts a major river around city center. In doing so, the canal protects areas to its north but not to its south. I measure northern and southern land development before and after the completion of the canal in 1918 by digitizing Dutch colonial maps

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<sup>1</sup> In Southeast Asia, population-weighted rates of relative sea level rise are 3.2 times as large as those in South Asia, 11.2 times those in Russia, and 3.9 times those elsewhere ([Nicholls et al. 2021](#)). Relative sea level rise combines absolute sea level rise and land subsidence.

<sup>2</sup> [Kydland and Prescott \(1977\)](#), page 477. “For example, suppose the socially desirable outcome is not to have houses built in a particular flood plain but, given that they are there, to take certain costly flood-control measures. If the government’s policy were not to build the dams and levees needed for flood protection and agents knew this was the case, even if houses were built there, rational agents would not live in the flood plains. But the rational agent knows that, if he and others build houses there, the government will take the necessary flood-control measures. Consequently, in the absence of a law prohibiting the construction of houses in the flood plain, houses are built there, and the army corps of engineers subsequently builds the dams and levees.”

from 1887 to 1945. I then apply a spatial regression discontinuity design at the canal boundary in the spirit of [Almond et al. \(2009\)](#), who study the Huai River in China.<sup>3</sup> I show that the north and south are similar before the canal, but that the north experiences less flooding and more land development after the completion of the canal. That is, developers responded to government intervention by increasing investment.

I study how this response creates a commitment problem for future government intervention. I do so quantitatively with a dynamic spatial model of urban development and a focus on Jakarta's planned sea wall. In the model, developers and residents make investment and location decisions with flooding in mind. Residential demand is spatial, as individuals make location decisions based on rents, flooding, amenities, and migration costs. Moving inland abandons high-amenity areas and incurs migration costs. Developer supply is dynamic, as forward-looking developers make sunk investment decisions in immobile buildings. They do so trading off a stream of future rents against the upfront costs of construction. Moving inland abandons high-rent areas and incurs construction costs. Total supply arises as a dynamic competitive equilibrium among atomistic developers, as in [Hopenhayn \(1992\)](#), and rents clear markets for development, equalizing residential demand and developer supply in each period. The government intervenes with a sea wall, as informed by a hydrological model of how sea wall construction affects flooding across locations.

Estimation leverages granular data on developers, residents, and flooding. I estimate residential demand by matching changes in the spatial distribution of population between 2015 and 2020. Estimation mirrors [Berry et al. \(1995\)](#), integrating over origins and addressing the endogeneity of rents with instruments. I estimate developer supply by matching the spatial distribution of new construction between 2015 and 2020. Estimation reads continuation values from data on market prices, in the style of [Kalouptsidi \(2014\)](#), and again addresses the endogeneity of rents with instruments. If markets are efficient, then property prices capture the stream of rents from completed development, and land prices capture the option value of undeveloped land. Prices thus offer a direct measure of expectations, which I accommodate flexibly, including over government intervention. Finally, I follow the frontier of the hydrological literature in training a machine-learning model with monthly, tract-level data on flooding

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<sup>3</sup> [Almond et al. \(2009\)](#), along with subsequent work by [Chen et al. \(2013\)](#) and [Ebenstein et al. \(2017\)](#), compare air quality in Chinese cities to the north and south of the Huai River. Northern cities receive free coal for winter heating, while southern cities do not.

from 2013 to 2020. A histogram gradient boosting decision tree fits the data well and offers sensible predictions for how sea wall construction decreases flooding over space.

In simulations, I quantify the effects of commitment on long-run adaptation and social welfare. I consider both forward-looking and politically myopic governments, as well as the impact of reducing coastal demand. I find that non-commitment increases coastal development, slowing adaptation and reducing welfare by 78% relative to the first best achieved under full commitment. Limited commitment raises welfare, particularly when forward-looking governments internalize costs to future administrations. Reducing coastal demand, including moving of the political capital from Jakarta, lessens both moral hazard and welfare losses under non-commitment. This move also requires commitment, but may be more politically feasible than commitment not to intervene at the coast. Full counterfactuals are in progress.

I highlight several implications for policy. First, political economy is crucial. Long-run commitment eliminates moral hazard in theory but is difficult in practice. Indeed, political incentives often push governments to prioritize short-run gains. I quantify how political forces hinder adaptation and worsen damages from climate change. Second, political constraints may be less binding for policies that encourage rather than punish. Subsidizing inland migration, for example, lessens coastal demand and thus moral hazard, but is less efficient than directly restricting coastal development. Governments should consider politically feasible policy whether or not it achieves the theoretical first best. Third, policy has dynamic effects. Persistence amplifies the effects of policy, adding to the case for good, feasible policy even if it can only be implemented temporarily. At the same time, current politicians may not fully internalize future costs, generating moral hazard across administrations and reinforcing the importance of political economy.

My main contribution is to quantify how endogenous government intervention limits adaptation to sea level rise. Adaptation blunts the consequences of sea level rise ([Balboni 2021](#), [Desmet et al. 2021](#), [Castro-Vincenzi 2022](#), [Jia et al. 2022](#)) and of climate change more broadly ([Barreca et al. 2016](#), [Costinot et al. 2016](#), [Cruz and Rossi-Hansberg 2021](#), [Nath 2022](#)). In particular, [Desmet et al. \(2021\)](#) show that inland migration can greatly reduce damages from coastal flooding. Government intervention complicates this narrative by displacing private investment in self-protection ([Peltzman 1975](#), [Kousky et al. 2006](#), [Boustan et al. 2012](#), [Annan and Schlenker 2015](#),

Kousky et al. 2018, Baylis and Boomhower 2022, Fried 2022), creating moral hazard that mirrors distortions in insurance markets (Coate 1995, Mulder 2022, Ostriker and Russo 2022, Wagner 2022). Endogenizing government intervention exacerbates moral hazard, as intervention induces continued coastal investment, which in turn forces further intervention. The result is severe coastal lock-in with high social costs, in contrast to the smooth inland transition of Desmet et al. (2021). The same force rationalizes the incomplete capitalization of flood risk into property prices (Hino and Burke 2021, Bakkensen and Barrage 2022, Gourevitch et al. 2023) and the persistence of coastal concentration (Vigdor 2008, Kocornik-Mina et al. 2020, Lin et al. 2022), even in the absence of biased beliefs.

Methodologically, I estimate a model of industry dynamics in the tradition of Hopenhayn (1992) and Ericson and Pakes (1995), drawing on dynamic discrete choice methods from Hotz and Miller (1993) and Arcidiacono and Miller (2011). I build on Kalouptsidi (2014), who shows how to avoid computing continuation values, at least in estimation, by reading them from data. I show how this insight greatly simplifies estimation of dynamic land use models with data generally available in urban settings, where dynamics are important given the durability of development (Glaeser and Gyourko 2005). This approach accommodates developer expectations with significantly more flexibility than full-solution approaches that must specify long-run expectations, and even two-step approaches that require only rational expectations, as in the Euler conditional choice probability approach of Scott (2013). In incorporating geography, I also complement a growing literature that brings dynamics to spatial models (Desmet et al. 2018, Caliendo et al. 2019, Kleinman et al. 2022).

Finally, I provide quantitative estimates and recommendations for Jakarta, drawing on work in environmental studies that assesses current and future flood risk (Budiyono et al. 2015, Takagi et al. 2016, Wijayanti et al. 2017, Andreas et al. 2018). Land subsidence in Jakarta effectively accelerates sea level rise, bringing questions of adaptation to the fore. Jakarta thus foreshadows the future that most coastal cities will face by century's end, including as sea walls enter policy discussions worldwide.<sup>4</sup> Jakarta's challenges are the world's challenges.

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<sup>4</sup> China plans 15,000km of coastline sea wall, and Japan has built 400km along the Tohoku coastline. The Northern European Enclosure Dam project proposes dams from France to England and Scotland to Norway. Miami has proposed 10km of coastline sea wall, and New York has proposed the BIG U project covering Lower Manhattan.

## 2 Background

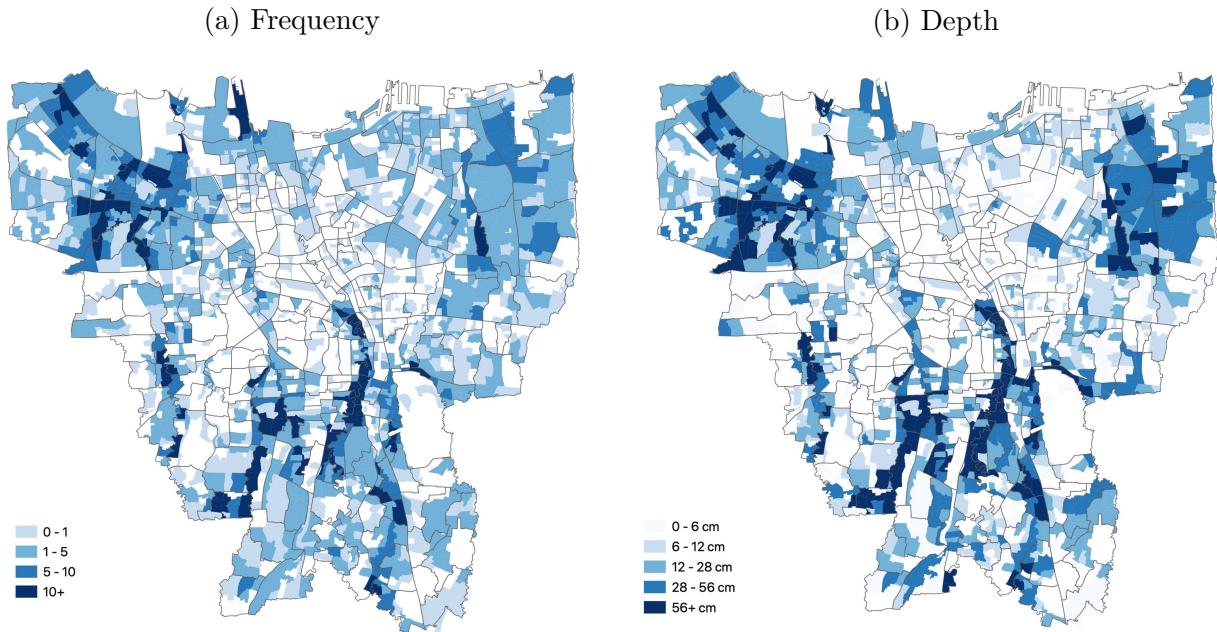
Flooding has long plagued Jakarta. Historical records capture flooding as early as 1621, shortly after the Dutch East India Company established its capital of Batavia at the north of the present-day city ([Abeysekere 1987](#)). Figure 1 shows that widespread flooding persists today, with major incidents in 1996, 2002, 2007, 2013, and 2020. Geography makes flooding inescapable, as Jakarta occupies a delta where thirteen rivers meet the ocean. This nexus of waters both nurtures and menaces the city.

Fluvial (river) flooding in times of extreme rainfall has been the key challenge to date. Historical flood policy thus focused on infrastructure aimed at managing river water, including a westward canal (*Westerse Vaart*) in 1725, the West Flood Canal (*Banjir Kanal Barat*) in 1918, and the East Flood Canal (*Banjir Kanal Timur*) in 2002 ([Caljouw et al. 2005](#), [Ward et al. 2011](#), [Octavianti and Charles 2019](#)). Each operates within a broader system of dams, reservoirs, drainage systems, pumping stations, and flood gates. Figure 2 maps this infrastructure.

Coastal flooding adds significant additional risk in the coming decades. North Jakarta faces near total submersion by 2050, as sea level rise combines with rapid land subsidence. Projected subsidence in some coastal neighborhoods exceeds 5m by 2050, compared to projected sea level rise of 25cm ([Andreas et al. 2018](#), [Kulp and Strauss 2019](#)). Groundwater extraction drives subsidence. Piped surface water accounts for only half of total water consumption, with the shortfall met by groundwater extraction that is largely unregistered and unregulated ([Taftazani et al. 2022](#)). Indeed, water demand continues to rise with Jakarta's growing population, but surface water reserves remain fixed and undermined by high pollution levels, poor treatment systems, and limited piping infrastructure ([Luo et al. 2019](#)). Efforts to quell subsidence thus face fundamental difficulties.

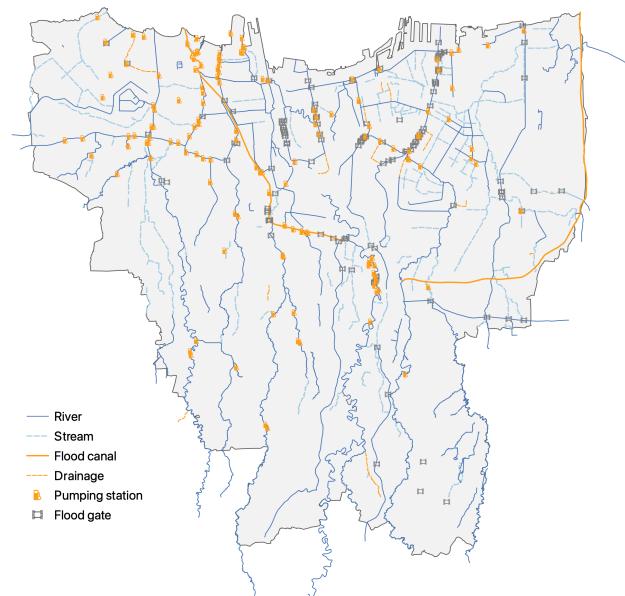
These existential threats to the nation's capital have prompted two major government initiatives. The stakes are high in this context, as public funds involve forgone investment in areas like education with known aggregate benefits ([Hsiao 2022b](#)). First, a sea wall has been in discussion since 2011, with costs of up to \$40 billion ([Garscha-gen et al. 2018](#), [Colven 2020](#)). Proposals have varied in scope and ambition, but each has prioritized onshore walls for short-term protection. The Jakarta Coastal Defense

Figure 1: Flooding (2013-2020)



Source: Regional Disaster Management Agency (*BPBD* via [data.jakarta.go.id](http://data.jakarta.go.id)). The left plots the average number of months per year with flood incidents, and the right plots average monthly flood depth. Each displays flooding by tract and boundaries by neighborhood.

Figure 2: Flood infrastructure



Source: Regional Disaster Management Agency (*BPBD* via [data.jakarta.go.id](http://data.jakarta.go.id)).

Strategy (JCDS) in 2011 became the National Capital Integrated Coastal Development Masterplan (NCICD) in 2014 – the so-called “Great Garuda Project” – and was further revised in 2016. Progress then slowed with a 2016 moratorium and the 2017 election of Anies Baswedan, whose gubernatorial campaign called for halting construction. Work resumed in 2019 with the Integrated Flood Safety Plan (IFSP).

Second, the government plans to establish a new political capital called Nusantara, at once hedging against flood risk and relieving congestion in Jakarta. The move to what is currently East Kalimantan province comes at a proposed cost of \$32 billion, with inauguration slated for Indonesia’s national day on August 17, 2024. The government envisions a planned, modern city nestled in the forests of Borneo, named in tribute to the ancestral word for the archipelago. Official goals include employment of nearly five million and net-zero emissions by 2045 ([IKN 2022](#)).

## 3 Theory

I show how coastal development forces government intervention both today and tomorrow, thereby delaying adaptation away from the coast.

### 3.1 Development and defense

I model flood-prone coastal development and the government investment aimed at defending it. In each period  $t$ , atomistic developers undertake development  $d_t$  at cost  $c(d_t)$ , then the government undertakes defense  $g_t$  at cost  $e(g_t)$ . Development increases total  $D_t = D_{t-1} + d_t$ , and costs are increasing and weakly convex. Development and defense create residential value  $r_t = r(D_t, g_t)$ , which is increasing and concave in each with complementarity  $\kappa = \frac{\partial^2 r}{\partial d \partial g} > 0$ .<sup>5</sup> I model defense with physical infrastructure in mind, but it encompasses any costly government intervention that raises residential value, including flood insurance programs.<sup>6</sup> The complementarity is

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<sup>5</sup> For costs,  $\frac{dc}{dd}, \frac{de}{dg} > 0$  and  $\frac{d^2 c}{dd^2}, \frac{d^2 e}{dg^2} \geq 0$ . For  $r(D, g)$ ,  $\frac{\partial r}{\partial d}, \frac{\partial r}{\partial g} > 0$  and  $\frac{\partial^2 r}{\partial d^2}, \frac{\partial^2 r}{\partial g^2} < 0$  given  $\frac{\partial}{\partial d} = \frac{\partial}{\partial D}$ . Fixing  $g_t$ ,  $r(D_t; g_t)$  captures downward-sloping residential demand. It measures the area under the demand curve for development  $[0, D_t]$ . The demand curve itself is  $r'(D_t; g_t)$ . Higher  $g_t$  shifts demand upward, subject to diminishing marginal returns to  $g_t$ .

<sup>6</sup> Coastal flooding presents recurring aggregate risk, limiting the role of risk aversion or sharing. As such, flood insurance programs raise residential value only if they underprice and thus subsidize risk. Like infrastructure, such subsidies are coastal transfers.

that development is only valuable if there is defense to protect it. Similarly, defense is only valuable if there is development to protect. Dynamics arise from durable development that demands both current and future defense. Defense is nondurable for simplicity, capturing that maintenance costs and continued sea level rise both require repeated intervention over time. The empirics will relax this simplification.

The government chooses defense to maximize social welfare, while developers choose development with private profits in mind. Welfare and profits are

$$W_t = \sum_{t'=0}^{T-t} \beta^{t'} w_{t+t'}, \quad w_t = r(D_t, g_t) - c(d_t) - e(g_t),$$

$$\Pi_t = \sum_{t'=0}^{T-t} \beta^{t'} \pi_{t+t'}, \quad \pi_t = r(D_t, g_t) - c(d_t)$$

for net present values ( $W_t, \Pi_t$ ) and current terms ( $w_t, \pi_t$ ). Developers do not internalize costs  $e(g_t)$  of defense, and so the first best requires correcting this uninternalized externality. However, the government faces a commitment problem in doing so: it tends to defend development ex post despite not wanting to ex ante, and developers take advantage to force defense at suboptimally high levels. Too much protection then leads to too little adaptation. Coastal defense offers short-term protection, but it slows long-term adaptation by delaying the move inland.

### 3.2 Commitment

Over-development arises when the government lacks commitment power. Consider the one-period case with a single round of interaction between the government and developers. Setting  $D_0 = 0$  for simplicity, social welfare and private profits are

$$W = r(d, g) - c(d) - e(g), \quad \Pi = r(d, g) - c(d).$$

In the first best, the government chooses development and defense jointly to maximize social welfare. The resulting first order conditions are

$$[d^*] \quad r'(d) = c'(d), \quad [g^*] \quad r'(g) = e'(g) \tag{1}$$

for  $r'(x) = \frac{\partial}{\partial x} r(d, g)$ . Each equalizes marginal benefits and costs.

Without commitment, the government revises its choice of defense after development is sunk, and developers act anticipating this response. That is, the government gives in to static incentives, and developers exploit this tendency. Developers enter until profits are driven to zero, where profits for the marginal developer are

$$\Pi'(d) = r'(d) + r'(g) g'(d) - c'(d)$$

for defense that responds to development. The zero-profit condition for the marginal developer and the first order condition for government defense are

$$[d^n] \quad r'(d) + r'(g) g'(d) = c'(d), \quad [g^n] \quad r'(g) = e'(g). \quad (2)$$

The result is over-development  $d^n > d^*$ . First, defense increases with sunk development. Differentiating condition  $2g^n$  with respect to development,

$$\kappa + r''(g) g'(d) = e''(g) g'(d).$$

It follows that  $g'(d) > 0$  given  $\kappa > 0$ ,  $r''(g) < 0$ , and  $e''(g) \geq 0$ . Second, this response creates moral hazard, as over-development anticipates over-defense.<sup>7</sup> Comparing conditions  $1d^*$  and  $2d^n$ ,  $g'(d) > 0$  implies  $d^n > d^*$  given  $r'(g) > 0$ ,  $r''(d) < 0$ , and  $c''(d) \geq 0$ . That is, moral hazard raises developer returns and thus development. Excessive coastal development then leads to insufficient inland adaptation.

Commitment avoids over-development but faces political economy challenges. Committing to first-best defense  $g^*$  eliminates moral hazard, as it implies  $g'(d) = 0$ . However, the government finds it optimal to protect over-development ex post, particularly if lobbying or upcoming elections increase its returns to doing so. Targeting first-best development  $d^*$  also eliminates moral hazard. Tax  $e(g)$  on development forces developers to internalize the costs of defense, implying profit condition

$$r'(d) + r'(g) g'(d) - e'(g) g'(d) = c'(d),$$

which coincides with condition  $1d^*$  given  $2g^n$ . Restricting permits or zoning achieves

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<sup>7</sup> Note that atomistic marginal developer  $d$  does not itself affect residential values or defense, but that its revenues  $r'(d) + r'(g) g'(d)$  are set by mass  $[0, d]$  of inframarginal developers. The typical zero-profit condition features the same intuition for prices, with entrants that act as price-takers individually but face downward-sloping demand collectively.

similar outcomes by regulating quantities instead of prices. However, taxes and restrictions still require commitment of enforcement. Indeed, developers will lobby against these policies, particularly if lobbying is facilitated by corruption.

That is, the government tends to bail out developers. The commitment problem is mitigated if developers faces the costs of defense in other forms. For example, a budget-constrained local government might reduce other services or increase future taxes. But funding can also come from external sources. Internationally, the World Bank administers the Adaptation Fund, which supports climate-adaptation projects worldwide, and the International Monetary Fund has proposed the Resilience and Sustainability Trust with similar aims. Domestically, national and regional governments fund local adaptation. In Jakarta, national government agencies manage the sea wall project. Elsewhere, sea wall plans for New York City propose 65% federal funding and 35% state funding ([USACE 2022](#)). Even locally, inland residents help fund coastal defense despite not benefiting directly. The commitment problem holds as long as coastal defense is not funded solely by coastal developers.

The commitment problem yields over-development  $d^n > d^*$  with strict inequality if the solutions are interior. If defense beyond a threshold can guarantee safety, then developers gain little from forcing additional defense. But sea walls do not guarantee safety, as storm surges generate risks of overtopping. Similarly, if defense beyond a threshold is infeasible, then developers cannot force additional defense. At the extreme, an ineffective government constrained to  $g = 0$  yields  $g'(d) = 0$ , which eliminates moral hazard (although zero defense will be suboptimally low). But such constraints are likely soft, as international climate aid allows defense even where domestic capacity is weak. Indeed, governments face considerable pressure to act defensively. Flood damages are salient to voters, and post-disaster inaction has political consequences. In Indonesia, government plans state that “abandoning” Jakarta is “not considered . . . a viable option,” citing its large population and economic value ([NCICD 2014](#)). Furthermore, public works projects are politically popular and opportunities for corruption ([Olken 2007](#)). These forces push toward action.

For Jakarta today, which is already built up, the model directly explains new areas of development. Land reclamation for the *Pantai Indah Kapuk II* neighborhood is a recent case that demonstrates the interdependence of development and defense in practice, as discussed in appendix A. The model also directly explains rebuilding after

destruction, as is common worldwide (Kocornik-Mina et al. 2020). On other margins, developer moral hazard is mitigated by existing development  $D_0 > 0$ . If defense largely responds to existing rather than new development, then new developers have limited ability to force additional defense. But first, existing development was itself once new, and today's static incentive to defend it remains consistent with yesterday's commitment problem. Even if past developers did not expect future sea level rise, they might still seek defense against baseline flooding that has long been salient in Jakarta. Second, depreciation of existing development gives added weight to new development. Third, political bias can do the same, making new development more salient as developers lobby for permits and politicians claim credit for growth. Finally, even if small individually, these distortions will compound over time.

### 3.3 Commitment over time

The commitment problem features rich dynamics with additional sources of moral hazard over time. Consider the two-period case with multiple interactions between the government and developers. In the first best, the government chooses development and defense across periods to maximize social welfare  $W_1 = w_1 + \beta w_2$ . The resulting first order conditions are

$$\begin{aligned} [d_1^*] \quad r'_1(d_1) + \beta r'_2(d_1) &= c'(d_1), & [g_1^*] \quad r'_1(g_1) &= e'(g_1), \\ [d_2^*] \quad r'_2(d_2) &= c'(d_2), & [g_2^*] \quad r'_2(g_2) &= e'(g_2) \end{aligned}$$

for  $r'_t(x) = \frac{\partial}{\partial x} r(D_t, g_t)$ . Each equalizes marginal benefits and costs.<sup>8</sup>

Without commitment in period two, the government chooses  $g_2$  to maximize welfare  $W_2$ , and developers choose  $d_2$  considering profits  $\pi_2$ . The resulting equilibrium conditions mirror equations 2.

$$[d_2^n] \quad r'_2(d_2) + r'_2(g_2)g'_2(d_2) = c'(d_2), \quad [g_2^n] \quad r'_2(g_2) = e'(g_2) \quad (3)$$

Period one depends on government commitment. Under limited commitment, the government chooses  $(d_1, g_1)$  in period one. Under no commitment, the government

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<sup>8</sup> I can accommodate flood risk uncertainty with a shock realized between periods one and two. Period-one conditions would be in expectation of the shock, with direct commitment to specific actions. Period-two conditions would be conditional on the shock, with commitment to a contingency plan specifying actions under each possible realization of the shock.

chooses  $g_1$  while developers set  $d_1$  with  $\pi_1$  in mind. Each anticipates no commitment in period two. Limited commitment further depends on government horizon. A forward-looking government ( $f$ ) maximizes  $w_1 + \beta w_2$ , while a politically myopic government ( $m$ ) instead maximizes  $w_1 + \beta r_2$ . The latter government weighs future benefits, for which it claims political credit today, but it ignores future costs, which fall to the next administration. For development, the equilibrium conditions vary by case.

$$\begin{aligned} [d_1^f] \quad & r'_1(d_1) + \beta r'_2(d_1) = c'(d_1) + \beta r'_2(g_2)g'_2(d_1), \\ [d_1^m] \quad & r'_1(d_1) + \beta r'_2(d_1) + \beta r'_2(d_2)d'_2(d_1) + \beta r'_2(g_2)g'_2(d_1) = c'(d_1), \\ [d_1^n] \quad & r'_1(d_1) + \beta r'_2(d_1) + \beta r'_2(d_2)d'_2(d_1) + \beta r'_2(g_2)g'_2(d_1) + r'_1(g_1)g'_1(d_1) = c'(d_1) \end{aligned} \quad (4d)$$

For defense, the same first order condition holds across cases.<sup>9</sup>

$$[g_1] \quad r'_1(g_1) = e'(g_1) \quad (4g)$$

Moral hazard arises for both developers and the government. Within periods, developers exploit the government. Over-development forces contemporaneous over-defense, as captured by  $r'_2(g_2)g'_2(d_2) > 0$  in period two (condition  $3d^n$ ) and  $r'_1(g_1)g'_1(d_1) > 0$  in period one (condition  $4d^n$ ). Across periods, current developers exploit the future government. Durable development both benefits from and forces future defense given  $r'_2(g_2)g'_2(d_1) > 0$  in condition  $4d^n$ . Similarly, the current government may exploit the future government. A politically myopic government pursues current gains despite future costs, raising current defense given  $r'_2(g_2)g'_2(d_1) > 0$  in condition  $4d^m$ . In doing so, it encourages current development and forces future defense.<sup>10</sup> At the same time, the current government may help the future government. A forward-looking government incurs current costs for future gains, reducing current defense given  $r'_2(g_2)g'_2(d_1) > 0$  in condition  $4d^f$ . In doing so, it undercuts future developers and lessens future moral hazard.

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<sup>9</sup> Although  $d'_2(d_1), g'_2(d_1) > 0$ ,  $d'_1(g_1) = 0$  and the chain rule imply  $d'_2(g_1) = g'_2(g_1) = 0$ . With commitment,  $d'_1(g_1) = 0$  given joint optimization over  $(d_1, g_1)$ . Without commitment,  $d'_1(g_1) = 0$  because developers set  $d_1$  before the government chooses  $g_1$ .

<sup>10</sup> Current development also affects future development. Conditions  $4d^m$  and  $4d^n$  contain  $d'_2(d_1) = \frac{dd_2}{dd_1} = \frac{\partial d_2}{\partial d_1} + \frac{\partial d_2}{\partial g_2} \frac{dg_2}{dd_1}$ , where  $d'_2(d_1) > 0$  if current development increases future defense and thus development, but  $d'_2(d_1) < 0$  if current development decreases future prices, defense, and thus development. The former dominates unless demand is very elastic, such that  $d'_2(d_1) > 0$ . This force worsens over-development in forcing future defense.

Commitment avoids over-development, but only if maintained over the long run. First, development is persistent: current non-commitment leads to future over-development, even under future commitment. High current defense raises current development, which prompts future defense that raises future development. Second, development is forward-looking: future non-commitment leads to current over-development, even under current commitment. High future defense directly raises current development. Thus, the government avoids over-development only by resisting its static incentives for many periods. But doing so is challenging in practice, as political pressures can be significant – even for one period and especially for many.

For Jakarta today, which is already built up, long-run peril necessitates an eventual move inland. Even ignoring land subsidence, sea level rise projections reach 1m in 2100, 3m in 2200, and 10m in 2300 for RCP8.5 ([Kopp et al. 2014](#), [van de Wal et al. 2022](#)). Moral hazard impedes adaptation, creating coastal lock-in and delaying the transition inland, while persistence in development exacerbates these consequences. Delayed adaptation has high social cost, as continued coastal development involves costly defense and large damages when defense becomes infeasible. The first best involves gradual coastal retreat, weighing existing development against future doom. Costs today bring benefits tomorrow, but politics are present-biased.

Alternative policies constrain coastal development more indirectly. Migration subsidies, improving inland amenities, and coordinating on new cities can each lower coastal demand, reducing developers' returns from over-defense and thus lessening moral hazard. Each still requires long-run commitment, but these policies that encourage rather than punish are arguably more politically feasible than regulating development directly. Indeed, moving the political capital to East Kalimantan is consistent with such an approach. Policymakers should consider such policies even if they fall short of the theoretical first best, which may not be politically feasible. Persistence allows for lasting benefits, even if interventions are implemented temporarily, although failures too have lasting consequences. Appendix A considers extensions.

## 4 Empirics

I outline a framework for the empirics, describe the data, and show how developers responded to historical government intervention.

## 4.1 Framework

The theory of section 3 frames the empirical analysis. Consider components  $r(d, g)$ ,  $c(d)$ , and  $e(g)$  of social welfare for development  $d$  and defense  $g$ , and let  $r(d, g)$  be  $r(d, f(g))$  given defense that increases residential value by reducing flooding  $f(g)$ . The sections that follow construct empirical analogues for each term. I obtain  $r(d, f(g))$  by estimating a spatial model of residential demand, and costs  $c(d)$  of development by estimating a dynamic model of developer supply. Sections 5 and 6 describe these economic models that characterize how flooding affects urban development in equilibrium. A hydrological model specifies how defense reduces flooding  $f(g)$ , and engineering estimates yield the costs  $e(g)$  of defense. Section 7 describes these benefits and costs of government intervention.

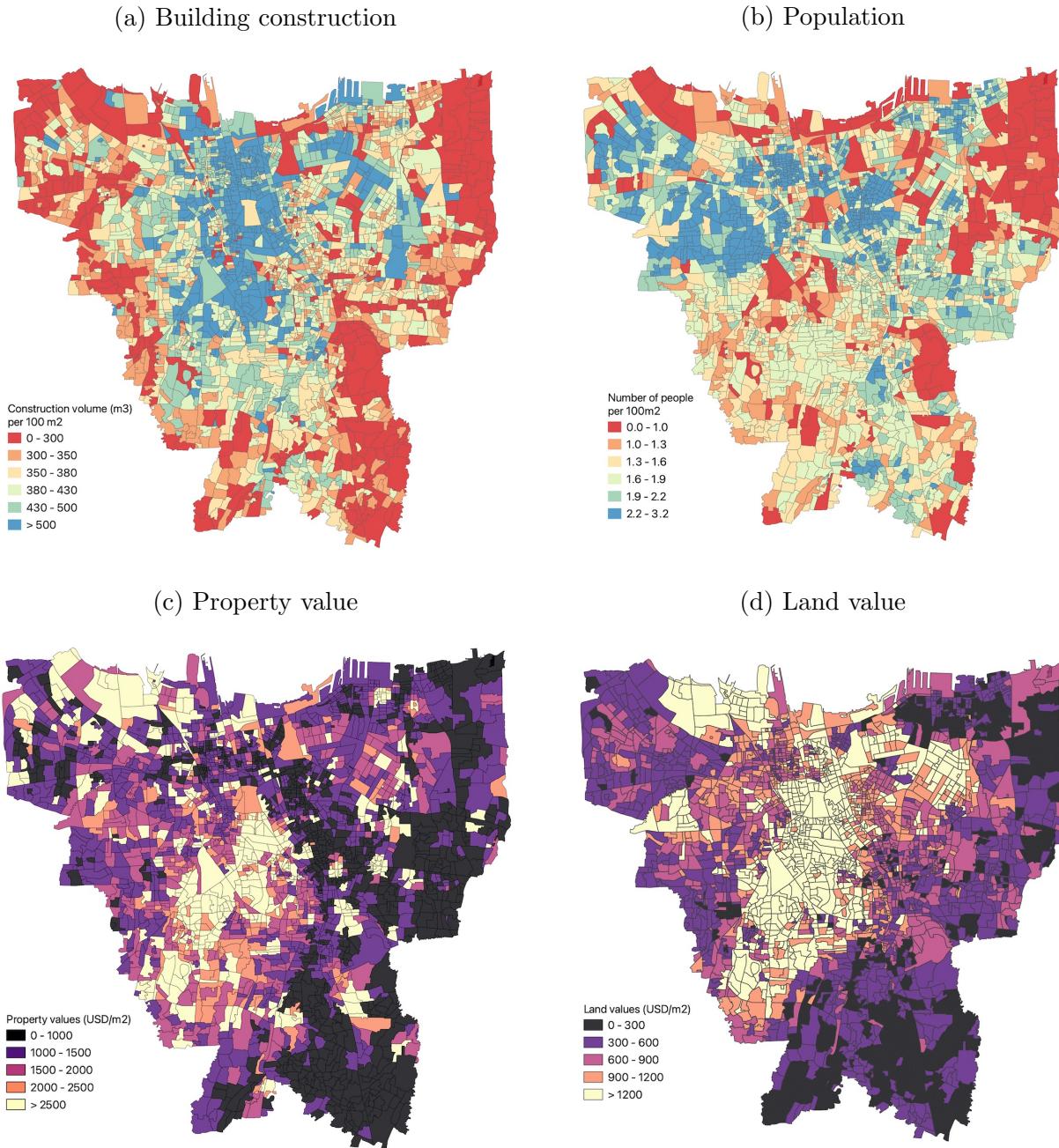
## 4.2 Data

I compile high-resolution spatial data on building construction, populations, real estate values, and flooding across Jakarta at the tract level and below. Jakarta consists of five districts (*kota*), 44 sub-districts (*kecamatan*), 267 neighborhoods (*kelurahan*), and 2,722 tracts (*rukun warga*). Each tract contains around 4,000 people. I focus on Jakarta proper, but the empirical analysis will allow for movement across the broader metropolitan area. I exclude the islands of *Kepulauan Seribu* district. Figure 3 illustrates the data, and appendix B provides additional detail.

The Global Human Settlement Layer measures building construction and populations across Jakarta (GHS 2022). It does so at the 100m grid cell level every five years from 1975 to 2020. The construction data record built-up surface areas and volumes, separating residential from non-residential construction. I verify the 2015 measures by comparing them to 2015 data from Visicom, a provider of satellite-derived 3D maps that capture building heights at the 1m pixel level. When aggregated by tract, the correlation between the datasets exceeds 0.90. The population data are downsampled from regional administrative data based on the distribution and density of residential buildings, as measured in the construction data. This approach assumes that residents occupy development, consistent with my empirical model in which rents clear markets for development in equilibrium.

Real estate values include property and land values, where property values in-

Figure 3: Data (2015)



Building construction and populations come from the Global Human Settlement Layer. I construct property values with transactions and listings data from 99.co and brickz.id. Land values come from the Smart City initiative of the Jakarta city government.

clude constructed buildings. I construct property values for 2015 by combining data on property transactions and listings from two major real estate websites, 99.co and brickz.id, covering both residential and non-residential properties. From 99.co, I scrape and geocode 56,222 listings with prices and floor spaces for October 2022. I compute property values as prices per square meter of floor space, then I aggregate to the tract level. From brickz.id, I obtain 6,929 property transactions for 2015. I use these data to backcast the 2022 property values and to adjust for differences between listed and transacted prices. I thus obtain transacted property prices for 2015.

Land values for 2015 come from the Jakarta Smart City initiative, through which the city government and the National Land Agency (*Badan Pertanahan Nasional*) sought to update property tax appraisals and improve collections. They did so by computing land values at a granular level, drawing on administrative data from transactions, market data from brokers and online platforms, and property characteristics from field visits. The data include 20,892 observations at the sub-block level, with land values measured as prices per square meter. I aggregate to the tract level. [Harari and Wong \(2019\)](#) describe these data in further detail and take additional steps to verify the quality of the data, including in informal areas.

Flooding data from 2013 to 2020 come from the Regional Disaster Management Agency. For each month, I observe the tracts that experienced flooding, the depth and duration of flooding, and the number of people affected. I use these data to compute measures of flood frequency and depth. I do so by tract as follows. For flood frequency, I count the number of months each year with flooding, then I average across years. For flood depth, I measure monthly flood depths, then I average across months. Figure 1 maps these frequencies and depths.

I capture other dimensions of spatial heterogeneity with ruggedness, residential amenities, and distances to city center, the coast, and major roads, as observed with city government data ([Jakarta 2022](#)). Ruggedness is the topographic ruggedness index of [Riley et al. \(1999\)](#). I use digital elevation model data at the 30m level to compute the mean difference in elevation between a cell and its surrounding cells. Residential amenities is an index variable that measures proximity to schools, healthcare clinics, and passenger railway stations. I compute Euclidean distances to the closest point in each category, sum with equal weighting, and take the negative to reflect proximity. Ruggedness provides a supply shifter in estimating demand, and residential amenities

provide a demand shifter in estimating supply. I also compute Euclidean distances to city center, the coast, and major roads. I define city center as the National Monument, the coast as the Jakarta Bay coast, and major roads as those designed for long-distance travel, including primary highways, trunk roads, and motorways.

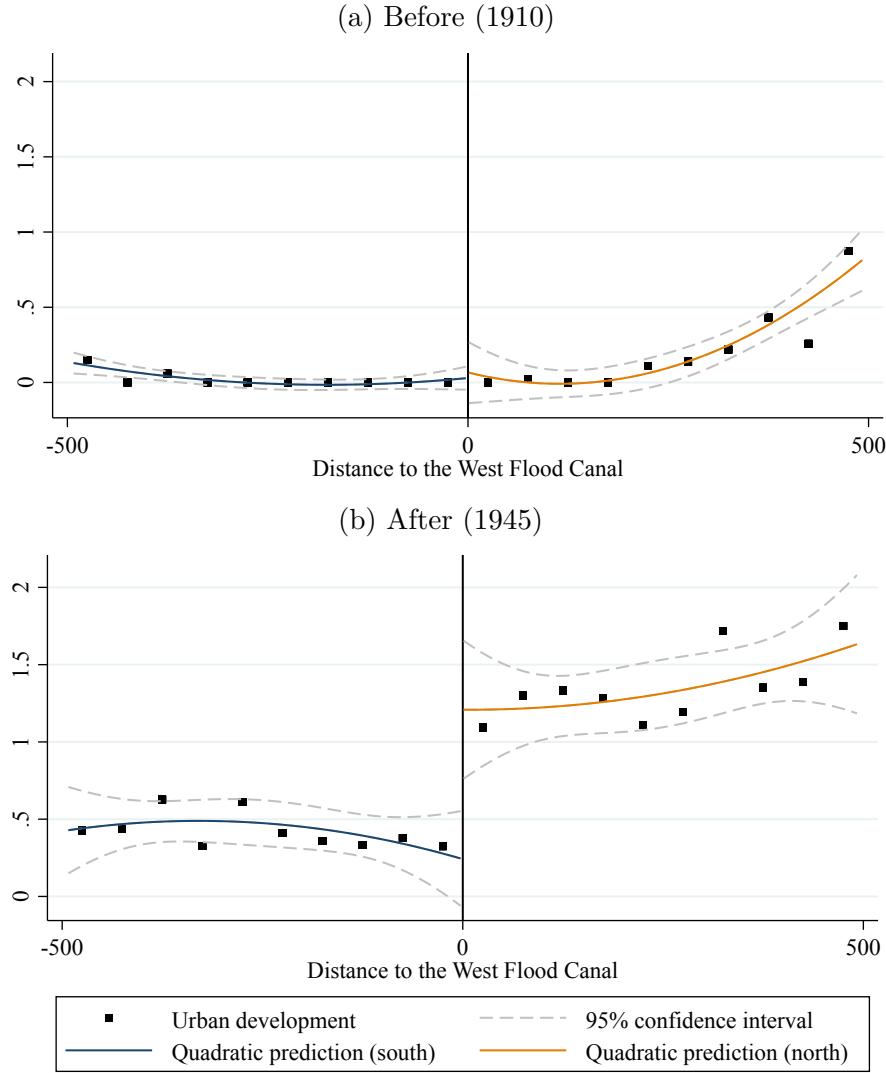
### 4.3 Historical government intervention

I consider whether historical investments in flood protection led to higher levels of land development. The opening of the West Flood Canal in 1918 allows me to study this dynamic over the last century, with historical maps from the Dutch colonial era providing measures of land development both before and after the construction of the canal. I georeference eight maps that cover the period from 1887 to 1845 in six- to eight-year intervals. I digitize them to construct a panel that records, over time, whether each 50m cell contains developed or undeveloped land. I then aggregate to the 100m cell by counting the developed 50m cells within each 100m cell. This aggregation allows me to accommodate misalignment over time, which otherwise introduces conflicting measures of development from year to year.

The West Flood Canal diverts floodwaters that flow from the higher-elevation south to the lower-elevation north, protecting neighborhoods north of the canal but not those south of the canal. I leverage this spatial discontinuity to study how land development responds to flood protection. I restrict attention to cells in the vicinity of the canal, and I plot land development relative to distance to the canal. Figure 4 shows the results: land development jumps at the boundary after the opening of the canal, but not before, as development responds positively to increased flood protection. Appendix B shows the associated regression table and documents decreased flooding north of the boundary, smoothness in elevation across the boundary, and smoothness in land development across the boundary throughout the pre-canal period.

This spatial discontinuity approach is subject to several potential concerns. First, the government may have anticipated future land development when placing the canal. But it seems difficult to target development 30 years in the future, and also to target finely enough to distinguish among 100m cells. Second, flooding may not be the only driver of post-canal differences in northern and southern land development. The north is closer to city center, which grows more quickly than the periphery, but differences in proximity are minimal when restricting attention around the boundary. I also show

Figure 4: Land development and the West Flood Canal



Data on historical land development come from Dutch colonial maps. The West Flood Canal was completed in 1918 and protected neighborhoods to its north (positive distances), but not to its south (negative distances). Each observation is a 100m grid cell. The  $x$ -axis measures distance to the West Flood Canal in meters, and 500m is the optimal bandwidth.

the absence of pre-canal differences in growth. The canal may itself impose a physical barrier between north and south, but 15 crossings minimize the separation between north and south over the 10km stretch of canal that I study. Finally, the canal may facilitate other forms of government intervention by establishing clear boundaries for favored neighborhoods.<sup>11</sup> Such effects remain consistent with the theory, which only

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<sup>11</sup> The prime example of such favoritism is the once-European neighborhood of Menteng, which

requires that government intervention increase residential value. Absent exhaustive data on non-flood intervention, the empirical model focuses on flooding and abstracts from this dimension. Adding it would worsen moral hazard.

## 5 Demand

Residents determine the demand for development, choosing locations with flooding in mind. Estimation matches changes in populations.

### 5.1 Model

Residents are renters that make static location choices over space. For an individual  $i$  in origin  $j$  considering destination  $k$ , utility is

$$U_{ijk} = \underbrace{\alpha r_k + \phi f_k + x_k \gamma + \varepsilon_k}_{\delta_k} + \tau m_{jk} + \epsilon_{ijk} \quad (5)$$

for rent  $r_k$ , flooding  $f_k$ , observed characteristics  $x_k$ , unobserved amenity  $\varepsilon_k$ , migration distance  $m_{jk}$ , logit shock  $\epsilon_{ijk}$ , and destination-specific utility  $\delta_k$ . Residents seek low rents, low flooding, high amenities, and short distances. Observed  $x_k$  include district fixed effects that help capture unobserved heterogeneity. Distance introduces spatial dependence.<sup>12</sup> Residential demand sums over origins given populations  $n_j$  and choice probabilities  $p_{jk}^{\text{res}}$ . Development demanded in each location is thus

$$D_k^{\text{res}} = \sum_j n_j p_{jk}^{\text{res}} \varphi, \quad p_{jk}^{\text{res}} = \frac{\exp(\delta_k - \tau m_{jk})}{\sum_{\hat{k}} \exp(\delta_{\hat{k}} - \tau m_{j\hat{k}})} \quad (6)$$

given floor space  $\varphi$  per resident. Moving inland is costly because it abandons high-amenity tracts and incurs migration costs. Price endogeneity arises because rents are correlated with unobserved amenities.

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canal construction explicitly sought to protect. While I do see increased land development in Menteng, I see the same in other northern neighborhoods as well.

<sup>12</sup> Although all origins respond proportionally to changes in destination characteristics given IIA substitution, migration from faraway origins is low at baseline because the disutility of distance dominates. Random coefficients would strengthen spatial dependence, as coefficients  $(\alpha_j, \phi_j)$  that depend on distance would relax IIA and allow nearby origins to respond disproportionately to changes in destination characteristics.

## 5.2 Estimation

I estimate demand by matching changes in the spatial distribution of population between 2015 and 2020, and I address price endogeneity by instrumenting for rents with ruggedness as a cost shifter. I focus on residential choice within the core of Jakarta, but I include the option of a location that aggregates over the periphery.<sup>13</sup> Total metropolitan population, which includes both core and periphery, evolves exogenously. I take rents to be mortgage payments on observed property values.

Estimation follows Berry (1994) and Berry et al. (1995), except that I integrate over origins instead of over a broader set of demographics. I estimate  $\theta = (\theta_1, \theta_2)$  for  $\theta_1 = (\alpha, \phi, \gamma)$  and  $\theta_2 = \tau$ . First, fixing  $\theta_2$ , I match observed and model-implied populations by computing  $\delta = \{\delta_k\}$  by contraction mapping.<sup>14</sup> Suppressing dependence on data  $(n, m)$ , equation 6 implies destination populations

$$n_k = \frac{\lambda}{\varphi} D_k^{\text{res}}(\delta, \theta_2),$$

where computing the right-hand side requires integrating over origin populations  $n_j$ . I read destination populations from the 2020 data and origin populations from the 2015 data. Uniform population growth rate  $\lambda = (\sum_k n_k^{2020}) / (\sum_j n_j^{2015})$  augments 2015 populations, such that origin and destination populations balance. Second, I regress  $\hat{\delta}$  on data  $(r, f, x)$  to obtain estimates  $\hat{\theta}_1$  and residuals  $\hat{\varepsilon}$ .

$$\varepsilon_k = \delta_k - \alpha r_k - \phi f_k - x_k \gamma$$

Third, I compute the GMM objective function with instruments  $Z$ , weighting matrix  $W$ , and sample analog  $g(\varepsilon(\theta)) = \sum_k Z_k \varepsilon_k(\theta)$  of moment condition  $\mathbb{E}[Z \varepsilon(\theta)] = 0$ .

$$Q(\theta) = g(\varepsilon(\theta))' W g(\varepsilon(\theta))$$

Fourth, I search over  $\theta_2$  to minimize  $Q(\theta)$ .

$$\hat{\theta}_2 = \arg \min_{\theta_2} Q(\theta_1(\theta_2), \theta_2)$$

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<sup>13</sup> I take this periphery to be free of flooding and to have rents set at the minimum observed within the core. Individuals originating at the periphery face distance  $m_{0k}$  to destination  $k$  defined as the minimum distance from  $k$  to the core-periphery border.

<sup>14</sup> Intuitively,  $\text{population}_k > D_k^h(\delta_k^h)$  at iteration  $h$  is remedied by  $\delta_k^{h+1} > \delta_k^h$  at  $h + 1$ .

Table 1: Residential demand estimates

	IV		First stage		
	Estimate	SE	Estimate	SE	Mean
Rents (USD/m <sup>2</sup> /year)	-0.032***	(0.004)			144
Ruggedness (index)			12.20***	(1.176)	1.43
Flooding (m/month)	-0.490***	(0.097)	-15.53***	(2.485)	0.15
Residential amenities (km)	0.110***	(0.018)	1.540***	(0.469)	2.91
Distance to city center (km)	-0.141***	(0.018)	-3.878***	(0.245)	10.8
Distance to coast (km)	0.024***	(0.006)	-0.091	(0.154)	10.8
Distance to major road (km)	-0.060***	(0.020)	1.344**	(0.546)	1.85
District FE		x		x	
Observations		5,780		5,780	
F-statistic				108	

Each observation is a 300m grid cell. IV estimation matches population shares, and the first stage is a regression with rents as the dependent variable. Rents are yearly mortgage payments, which I compute from property prices with a discount factor of 0.9. Flooding is as observed from 2013 to 2020. Residential amenities is an index variable that measures proximity to schools, clinics, and passenger rail stations. City center is the National Monument. By 2020 rates, 1M IDR = 70 USD.  
 \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

### 5.3 Estimates

Table 1 presents demand estimates, defining locations as 300m cells. I address rent endogeneity by instrumenting with ruggedness as a supply shifter, where ruggedness raises rents with a large  $F$ -statistic in the first stage. I find that demand is decreasing in rents and in flooding. The flooding coefficient captures the welfare benefits of decreasing flooding with a sea wall, and the rent coefficient monetizes these benefits. Demand is increasing in residential amenities, as measured by an index of proximity to schools, clinics, and passenger rail stations. I take these observed amenities as exogenous, but future work can apply an optimal placement instrument given potential correlation with unobserved amenities. Endogenizing residential amenities will also allow them to adjust in counterfactuals. Demand is decreasing in distance to city center, while distances to the coast and major roads have smaller effects. I take these distances as exogenous, noting that major roads largely date back to colonial times and are less likely than minor roads to target specific grid cells.

I consider magnitudes by comparing coefficients. The rent and flooding coefficients suggest that mean flood levels require a \$2.30 decrease in yearly rents per square meter as compensation variation. Annual construction of 7M square meters of floor space from 1999 to 2013 ([BPS 2022](#)), combined with a 5% depreciation rate, suggests 140M square meters of total floor space. Multiplying this total by \$2.30 implies yearly damages of \$320M, consistent with \$300M in accounting damages estimated by [Budiyono et al. \(2015\)](#). Flooding has a standard deviation of 0.26 meters per month. Considering variation within the data, increasing flooding by one and two standard deviations implies further yearly damages of \$560M and \$1.1B. Considering variation beyond the data, flooding at four standard deviations corresponds to one-meter inundation, as is well within the range of projected scenarios for sea level rise by 2100 ([IPCC 2019](#)). This level of flooding implies yearly damages of \$2.2B and total damages of \$22B (at 10% discounting). Comparing other coefficients, increasing flooding by one standard deviation has roughly the same impact as increasing distance to residential amenities or city center by one kilometer.

One concern is that ruggedness may violate the exclusion restriction by affecting demand directly. I argue that ruggedness is not especially salient to residents of Jakarta, where many live above ground floor in multi-story buildings and where walking activity is quite limited ([Althoff et al. 2017](#), [Cochrane 2017](#)). Jakarta is also relatively flat, unlike cities like San Francisco where large hills affect daily life. At the same time, developers remain sensitive to even mild ruggedness because structural integrity requires laying flat foundations. Where residents do view ruggedness as a disamenity, the exclusion restriction remains satisfied if the resulting costs are borne by developers. If ruggedness affects earthquake safety, for example, then developers will either invest in earthquake-safe construction or be penalized with lower sales prices. Perfect competition among atomistic developers – as I assume in the supply model to follow – will be consistent with such behavior.

Another concern is that flooding may be correlated with unobserved amenities, as coastal proximity can bring both positive amenity value and increased flooding. Not controlling for this proximity thus attenuates the estimated effect of flooding on residential demand. I address this concern by controlling for neighborhood fixed effects and coastal distance. However, I find coastal distance to have a small, positive effect on demand, such that coastal amenities seem not to weigh heavily. Additional

controls would further reduce the bias from uncaptured amenities, but also reduce the remaining variation in flooding. Another approach is to focus on discontinuities in flood risk maps (Bakkensen and Ma 2020), but I rely on observed flooding that varies smoothly over space rather than flood risk measures from government maps.

This focus on flooding rather than flood risk mitigates bias from misperception of risk. Risk is challenging to assess, even for experts, and disentangling perceptions from preferences is difficult in general. I isolate preferences by considering how residents respond to eight years of observed flooding history. In this sense, I infer the welfare impacts of future flooding from residents' reactions to past flooding. The implicit assumption that the past flooding, which is largely pluvial and fluvial, is informative of future coastal flooding. Indeed, flooding is flooding. Even so, the nature of climate change makes some extrapolation unavoidable, as sea level rise brings future flooding at unprecedented levels. And while past flooding does capture tail risk, including 30- and 50-year floods in 2013 and 2020, it does not capture permanent inundation. If the past is mild relative to the future, then my demand estimates will be biased toward understating the moral hazard problem.

## 6 Supply

Developers determine the supply of development, investing with current and future rents in mind. Estimation matches changes in construction.

### 6.1 Model

Developers are atomistic landlords that make forward-looking investments in durable, immobile development. In each location  $k$  and period  $t$ , individual developers  $i$  begin with holdings of completed development  $D_{ikt}$  and undeveloped land  $L_{ikt}$ , with development measured in floor space. Next, they realize idiosyncratic development draws and undertake new development  $d_{ikt}$  on land  $\ell_{ikt}$ . Development incurs construction costs but generates rental revenues once complete. Costs and revenues depend on individual actions  $(d_{ikt}, \ell_{ikt})$  and states  $(D_{ikt}, L_{ikt})$ , as well as aggregate state  $w_{kt} = (x_{kt}, \varepsilon_{kt}, D_{kt}, \{D_{-kt}\}, L_{kt}, \{L_{-kt}\}, G_t)$ , which includes observed cost factors  $x_{kt}$ , unobserved costs  $\varepsilon_{kt}$ , completed development  $(D_{kt}, \{D_{-kt}\})$  across locations,

undeveloped land ( $L_{kt}, \{L_{-kt}\}$ ) across locations, and defense  $G_t$ . Time to build is one period, such that development and land follow laws of motion

$$D_{ikt+1} = D_{ikt} + d_{ikt}, \quad L_{ikt+1} = L_{ikt} - \ell_{ikt}.$$

I explicitly model the extensive-margin choice to develop or not, which lumpiness makes a key margin of variation in the data.<sup>15</sup> The ex-ante value function is

$$V(D_{ikt}, L_{ikt}, w_{kt}) = r(D_{ikt}, w_{kt}) + \mathbb{E}[\max_{d \in \{0,1\}} \{v^d(D_{ikt}, L_{ikt}, w_{kt}) + \epsilon_{ikt}^d\}]. \quad (7)$$

Developers collect rental revenues from completed development, then consider new development subject to logit shocks  $\epsilon_{ikt}^d$ . Expectations are over these shocks. Denoting dependence on state  $w_{kt}$  with  $kt$  subscripts, such that  $v_{kt}^1(\cdot) \equiv v^1(\cdot, w_{kt})$ ,  $V_{kt+1}(\cdot) \equiv V(\cdot, w_{kt+1})$ , and  $\mathbb{E}_{kt}[\cdot] \equiv \mathbb{E}[\cdot | w_{kt}]$ , the choice-specific conditional value functions are

$$v_{kt}^1(D_{ikt}, L_{ikt}) = \max_{d, \ell} \{ -c_{kt}(d, \ell) + \beta \mathbb{E}_{kt}[V_{kt+1}(D_{ikt} + d, L_{ikt} - \ell)] \}, \quad (8a)$$

$$v_{kt}^0(D_{ikt}, L_{ikt}) = \beta \mathbb{E}_{kt}[V_{kt+1}(D_{ikt}, L_{ikt})], \quad (8b)$$

Developers incur construction costs if they develop, then in the next period face the same choice to develop or not. Expectations are over next-period state  $w_{kt+1}$ .

The intensive-margin choice of how much to develop trades off higher rental revenues against higher construction costs. Revenues are linear and costs are convex.

$$r_{kt}(D) = \alpha r_{kt} D, \quad c_{kt}(d, \ell) = \left( \frac{1}{2} \psi d + \phi f_{kt} + x_{kt} \gamma \right) d + \frac{1}{2} \omega \left( \frac{d}{\ell} \right)^2 + \varepsilon_{kt} \quad (9)$$

Revenues depend on completed development  $D$  and rents  $r_{kt}$ , abusing notation slightly in distinguishing  $r_{kt}$  from  $r_{kt}(\cdot)$ . Costs depend on new development floor space  $d$  and land use  $\ell$ , which together determine height  $h = \frac{d}{\ell}$ . Convexities  $(\psi, \omega)$  reflect increasing marginal costs of space and height. Observed  $x_{kt}$  capture spatial heterogeneity, including in flooding  $f_{kt}$  if flood protection involves private costs. Observed  $x_k$  also include district fixed effects that help capture unobserved heterogeneity. Unobserved  $\varepsilon_{kt}$  and idiosyncratic  $\epsilon_{ikt} = \epsilon_{ikt}^1 - \epsilon_{ikt}^0$  are fixed costs that influence neither floor space

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<sup>15</sup> In the data, most cells in a given period contain zero development. Larger cells would contain fewer zeros, but also obscure spatial heterogeneity.

nor land use. Flow costs are passed onto residents and thus subsumed into rents. Developers seek high rents and low construction costs. Where needed, superscripts explicitly mark demand and supply parameters as  $(\alpha^d, \phi^d, \gamma^d, \varepsilon^d)$  and  $(\alpha^s, \phi^s, \gamma^s, \varepsilon^s)$ .

I abstract from the intensive-margin choice of quality given inherent difficulties in measuring quality and computing quality-adjusted rents. However, I still capture quality that is correlated with floor space and height. If large, tall construction serves high-income residents that are sensitive to quality, then it must be of high quality. The costs of floor space and height capture the cost of this quality, which adjusts in counterfactuals alongside floor space and height. Furthermore, unobserved costs capture quality that is uncorrelated with floor space and height. If some locations have specific demand for high quality, then unobserved costs capture the cost of providing it. But counterfactuals hold fixed this component of quality.

Developer supply sums over new and old development given floor space  $d_{kt}$  and probability  $p_{kt}^{\text{dev}}$  of new development. Development supplied in each location is thus

$$D_{kt+1}^{\text{dev}} = D_{kt} + d_{kt} p_{kt}^{\text{dev}}, \quad p_{kt}^{\text{dev}} = \frac{\exp\{v_{kt}^1(D_{ikt}, L_{ikt})\}}{\exp\{v_{kt}^1(D_{ikt}, L_{ikt})\} + \exp\{v_{kt}^0(D_{ikt}, L_{ikt})\}}. \quad (10)$$

Moving inland is costly because it abandons high-rent areas and incurs construction costs. Price endogeneity arises because rents are correlated with unobserved construction costs. Development is determined in dynamic competitive equilibrium, with rents  $r_{kt}$  that equalize demand  $D_{kt}^{\text{res}}$  and supply  $D_{kt}^{\text{dev}}$  of development in each location  $k$  and period  $t$ . Excessively high rents lead to a shortage of residential demand, while excessively low rents lead to a shortage of developer supply.

## 6.2 Estimation

I estimate supply by matching the spatial distribution of new construction between 2015 and 2020. I address the endogeneity of rents by instrumenting with residential amenities, which shift local demand for development. Inverting equation 10 and substituting equations 8,

$$\ln p_{kt}^{\text{dev}} - \ln(1 - p_{kt}^{\text{dev}}) = -c_{kt}(d_{kt}, \ell_{kt}) + \beta \mathbb{E}_{kt}[V_{kt+1}(D_{ikt} + d_{kt}, L_{ikt} - \ell_{kt}) - V_{kt+1}(D_{ikt}, L_{ikt})].$$

I avoid computing continuation values by reading them from the data in the spirit of [Kalouptsidi \(2014\)](#). If real estate markets are efficient, then real estate prices capture

market expectations over the value of development and land holdings.

$$\frac{1}{\alpha} \left( \beta \mathbb{E}_{kt} [V_{kt+1}(D_{kt+1}, L_{kt+1})] \right) = P_{kt}^D D_{kt+1} + P_{kt}^L L_{kt+1} \quad (11)$$

for property prices  $P_{kt}^D$  per unit of floor space and land prices  $P_{kt}^L$  per unit of land. Market value is priced after new development and land use  $(d_{kt}, \ell_{kt})$ . It thus depends on current-period prices  $(P_{kt}^D, P_{kt}^L)$ , which capture current-period expectations, and next-period holdings  $(D_{kt+1}, L_{kt+1})$ , which condition on development in progress. Rent coefficient  $\alpha$  monetizes utility. I substitute to eliminate continuation values, greatly simplifying estimation and yielding estimating equation

$$\ln p_{kt}^{\text{dev}} - \ln(1 - p_{kt}^{\text{dev}}) = \alpha P_{kt}^D d_{kt} - \alpha P_{kt}^L \ell_{kt} - c_{kt}(d_{kt}, \ell_{kt}). \quad (12)$$

Identification is clearest in the simplified case that follows. Here, I focus on the extensive-margin choice to develop or not, imposing uniform, exogenous floor space, land use, and height across locations.

$$d_{kt} = d_t, \quad \ell_{kt} = \ell_t, \quad h_{kt} = h_t \quad \forall k$$

For  $P_{kt} \equiv P_{kt}^D - \frac{P_{kt}^L}{h_t}$  and  $v_t \equiv \frac{1}{2}\psi d_t^2 + \frac{1}{2}\omega h_t^2$ , equation 12 simplifies to

$$\ln p_{kt}^{\text{dev}} - \ln(1 - p_{kt}^{\text{dev}}) = \alpha P_{kt} d_t - \phi f_{kt} d_t - d_t x_{kt} \gamma - v_t - \varepsilon_{kt}.$$

Estimation reduces to simple linear IV regression. The endogeneity problem is that unobserved costs  $\varepsilon_{kt}$  affect development supply, which influences the property and land prices  $(P_{kt}^D, P_{kt}^L)$  that determine  $P_{kt}$ .<sup>16</sup> The main data requirements are measures of building construction, property prices, and land prices. Indeed, such measures are available in many urban settings, although perhaps not in rural settings. Building construction data give probabilities  $\hat{p}_{kt}^{\text{dev}}$  of new development, which I compute from the data in a first stage. I do so by applying a frequency estimator and smoothing nonparametrically across bins. The  $d_t$  term depends on how individual developer

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<sup>16</sup> Consider decomposed costs  $\varepsilon_{kt} = \mu_k + \tilde{\varepsilon}_{kt}$ . Permanent  $\mu_k$  induce strong responses from forward-looking real estate prices, even if transient  $\tilde{\varepsilon}_{kt}$  do not. Estimation relies on cross-sectional data, which precludes capturing  $\mu_k$  with fixed effects. Even with panel data, fixed effects do not fully capture potential persistence in  $\tilde{\varepsilon}_{kt}$ . Furthermore, spatial residential demand implies that location-specific shocks affect location-specific prices, even if shocks average to zero in aggregate.

boundaries are defined, but it scales all regressors equally and thus affects neither estimates nor counterfactuals.<sup>17</sup> Prices act as numeraire.

I reintroduce and endogenize intensive-margin decisions as follows. By equation 8a, floor space and land use satisfy conditions

$$[d_{kt}] \quad \frac{\partial}{\partial d} c_{kt} = \frac{\partial}{\partial d} \beta \mathbb{E}_{kt}[V_{kt+1}], \quad [\ell_{kt}] \quad \frac{\partial}{\partial \ell} c_{kt} = \frac{\partial}{\partial \ell} \beta \mathbb{E}_{kt}[V_{kt+1}]. \quad (13)$$

It follows that equation 12 simplifies to

$$\ln p_{kt}^{\text{dev}} - \ln(1 - p_{kt}^{\text{dev}}) = \frac{1}{2} \psi d_{kt}^2 - \frac{1}{2} \omega h_{kt}^2 - \varepsilon_{kt} \quad (14)$$

for floor space, height, and land use given by

$$d_{kt} = \frac{1}{\psi} \left( \alpha P_{kt}^D - \frac{\alpha P_{kt}^L}{h_{kt}} - \phi f_{kt} - x_{kt} \gamma \right), \quad h_{kt} = \left( \frac{\alpha P_{kt}^L d_{kt}}{\omega} \right)^{\frac{1}{3}}, \quad \ell_{kt} = \frac{d_{kt}}{h_{kt}}. \quad (15)$$

Estimation applies nonlinear instrumental variables, with instruments  $Z$  and moment condition  $\mathbb{E}[Z\varepsilon(\theta)]$ . For parameters  $\theta = (\alpha, \phi, \gamma, \psi, \omega)$ , data  $X_{kt} = (P_{kt}^D, P_{kt}^L, f_{kt}, x_{kt})$ , and computed  $\hat{p}_{kt}^{\text{dev}}$ , I solve equations 15 – three equations in three unknowns – to obtain  $d_{kt}(\theta)$ ,  $h_{kt}(\theta)$ , and  $\ell_{kt}(\theta)$ , then I solve equation 14 to obtain  $\varepsilon_{kt}(\theta)$ .<sup>18</sup> Estimation thus accommodates intensive-margin variation, but avoids exploiting it directly. Indeed, this variation is noisily measured and only observed on a selected sample. Appendix C shows that identification holds as in the simplified case.

### 6.3 Estimates

Table 2 presents supply estimates, defining locations as 300m grid cells. I address price endogeneity by instrumenting with residential amenities as a demand shifter, where residential amenities raise prices with a large  $F$ -statistic in the first stage. I find that supply is increasing in prices. The price coefficient captures how strongly developers respond to higher prices when sea wall construction reduces flooding and raises demand. Supply is unresponsive to flooding beyond this demand-side effect

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<sup>17</sup> For  $\tilde{d}_t = sd_t$  and scalar  $s$ ,  $s$  affects estimates  $(\hat{\alpha}, \hat{\phi}, \hat{\gamma})$  but not  $(\frac{\hat{\phi}}{\hat{\alpha}}, \frac{\hat{\gamma}}{\hat{\alpha}})$ . Predicted actions and welfare are also unaffected. For example,  $s$  amplifies  $P_{kt}$  but reduces  $\hat{\alpha}$ , such that  $\frac{\hat{\alpha}}{s} P_{kt} s d_t = \alpha P_{kt} d_t$ .

<sup>18</sup> Prices  $(P_{kt}^D, P_{kt}^L)$  are bundled in the simplified case, such that a single instrument is sufficient. Here, they appear separately and thus require separate instruments.

Table 2: Developer supply estimates

	IV		First stage		
	Estimate	SE	Estimate	SE	Mean
Prices (100 USD/m <sup>2</sup> )	0.171***	(0.041)			11.8
Residential amenities (km)			0.182***	(0.043)	2.91
Flooding (m/month)	0.064	(0.044)	-0.842***	(0.216)	0.15
Ruggedness (index)	-0.143***	(0.054)	1.268***	(0.103)	1.43
Distance to city center (km)	0.084***	(0.011)	-0.224***	(0.023)	10.8
Distance to coast (km)	-0.028***	(0.003)	0.012	(0.014)	10.8
Distance to major road (km)	-0.005	(0.008)	0.101**	(0.050)	1.85
District FE		x		x	
Observations		5,780		5,780	
F-statistic				18.14	

Each observation is a 300m grid cell. IV estimation matches development probabilities, and the first stage is a regression with prices as the dependent variable. Prices are property prices net of land prices. Flooding is as observed from 2013 to 2020. Residential amenities is an index variable that measures proximity to schools, clinics, and passenger rail stations. City center is the National Monument. By 2020 rates, 1M IDR = 70 USD. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

on prices. Conditional on prices, flooding may even encourage development. The mean level of flooding decreases costs by a small and statistically insignificant \$5 per square meter, perhaps reflecting government intervention. Supply is decreasing in ruggedness, consistent with its role as a supply shifter in estimating demand. Increasing the ruggedness index by one, given a mean of 1.43, increases costs by \$83 per square meter. Supply is increasing in distance from city center, while distances to the coast and major roads have smaller effects. Each kilometer to city center reduces costs by \$49 per square meter, as developers avoid congestion and land fragmentation in central neighborhoods. Each kilometer to the coast and major roads increases costs by \$16 and \$3 per square meter, capturing added transportation costs.

The exclusion restriction requires that residential amenities do not affect supply directly, as is reasonable if construction does not itself rely on schools and clinics. However, these residential amenities may be correlated with unobserved developer amenities do affect supply. Warehouse access and building regulations are two such examples. While imperfect, controlling for distances to city center, the coast, and major roads helps to reduce bias. And if anything, the bias that remains will attenu-

ate the price elasticity and understate the moral hazard problem. The reason is that residential and developer amenities are likely negatively correlated. Warehouses locate away from schools and clinics, which bid up real estate prices by occupying land and increasing demand. And building regulations may be more loosely enforced away from residential clusters. Thus, high instrumented prices imply low developer amenities that mute the extent to which high prices encourage high supply. In assuming exclusion and ignoring this effect, the bias is toward less elastic supply.

Equation 11 is the key assumption for estimation. If market prices capture expected future profits, then estimation is computationally simple, accommodates expectations flexibly, and allows discussion of endogeneity and instruments in the usual way. In particular, I require efficient markets that push prices toward expectations. This force is straightforward if expectations are homogeneous across developers in each location. In this case, developers eagerly develop if prices exceed expectations, leading to high supply that pushes prices down toward expectations. Similarly, developers reluctantly develop if expectations exceed prices, leading to low supply that pushes prices up toward expectations.

Now consider heterogeneous expectations. Pessimism does not introduce bias, as individual developers with low expectations tomorrow will develop if market prices are high today. Rather than collecting rents themselves, they can develop and sell to the market. Optimism does introduce bias, as developers with high expectations tomorrow may still develop if market prices are low today. Rather than selling to the market, they can develop and collect rents themselves. Even so, several factors mitigate this bias. Optimistic developers must collect low rents until market prices rise to meet their optimism, as competitors undercut high rents. This reality tempers optimism. Furthermore, development financing is difficult if lending follows market prices, and market prices provide coordinating information that challenges optimism and unifies expectations. At the same time, inefficiencies like thin markets and transaction costs may persist. Estimation accommodates these inefficiencies by attributing them to unobserved costs, but counterfactuals will hold them fixed.

My approach remains flexible on expectations themselves. In particular, I can accommodate expectations consistent with empirical findings that flood risk does not fully capitalize into real estate prices ([Hino and Burke 2021](#), [Bakkensen and Barrage 2022](#)). I begin by noting that such findings do not necessarily imply irrational

expectations. If developers accurately anticipate government intervention, then risk does not fully capitalize into prices – even with perfect foresight over future flooding. Indeed, allowing for expectations over government intervention is crucial in my context. At the same time, I can also accommodate irrational expectations, such as those arising from behavioral biases and hysteresis. My dynamic model is one in which prices reveal expectations of future rents, which forward-looking developers anticipate collecting. An isomorphic model casts prices as revenues from selling development outright, with developers making static decisions to construct and sell immediately. Market expectations may be irrational, but developers take the resulting prices as given and develop accordingly.

For equation 11 to hold, I also require atomistic developers. If individual developers do not affect prices, then observed prices capture continuation values. But if large developers depress prices, then observed prices do not. Continuation values must be computed directly, and I lose the benefit of appealing to price data. However, I argue that developers are approximately atomistic in this setting. Indeed, the Jakarta city government registered 14,505 construction companies in 2021 ([BPS 2022](#)). Market segmentation may create opportunities for non-atomistic behavior, but the same registration data include 1,024 large-scale companies with annual revenues exceeding \$3M (50B IDR). Competitive pressure exists even at the top end.

## 6.4 Alternative approaches

I compare alternative approaches for dynamic discrete choice estimation. The full-solution approach is computationally intensive and must specify expectations. It computes continuation values repeatedly, applying nested fixed point methods from [Rust \(1987\)](#), and it imposes assumed expectations, including into the distant future. Two-step approaches simplify computation but still specify expectations. They estimate continuation values from data, applying conditional choice probability methods from [Hotz and Miller \(1993\)](#). Estimation then depends on expectations, as in the forward simulation of [Bajari et al. \(2007\)](#).<sup>19</sup> More recently, the Euler conditional choice probability approach simplifies computation and affords flexibility over expec-

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<sup>19</sup> [Ackerberg et al. \(2007\)](#) review this literature. [Hotz and Miller \(1993\)](#) and [Hotz et al. \(1994\)](#) develop these methods in the single-agent setting. [Rust \(1994\)](#) suggests expanding to multi-agent games, and [Jofre-Benet and Pesendorfer \(2003\)](#), [Aguirregabiria and Mira \(2007\)](#), [Bajari et al. \(2007\)](#), [Pakes et al. \(2007\)](#), and [Pesendorfer and Schmidt-Dengler \(2008\)](#) show how to do so.

tations ([Scott 2013](#)). It analyzes short-run perturbations, applying finite dependence as in [Arcidiacono and Miller \(2011\)](#) such that continuation values difference out. Expectations must be rational but can be left unspecified. My approach simplifies computation and allows full flexibility over expectations. I read continuation values from data, drawing on price data that also provide a measure of expectations. I need not impose rational expectations because expectations are no longer unobserved.

Beyond expectations, I highlight additional differences between the Euler approach and my approach. I extend the Euler approach in previous work ([Hsiao 2022a](#)), and I apply the same methods in appendix C to derive an Euler equation for Jakarta. It requires long-lived developers that control land for multiple periods and choose the timing of development, while I accommodate short-lived entrants that buy land, develop, and sell immediately. It cannot accommodate depreciating development, while I allow for depreciation through its capitalization into prices. It requires at least two periods of data on new development, while I need only one. More generally, it emphasizes differences between periods  $t$  and  $t + 1$ , while I emphasize differences between property and land values.

Relative to prior approaches, the Euler approach and my approach make progress with straightforward estimation and transparent identification. However, they cannot avoid specifying expectations when solving the model for counterfactuals, as with prior approaches that specify expectations throughout. Furthermore, they require atomistic agents, whereas prior approaches do not. For the Euler approach, large developers influence the evolution of the economy, causing finite dependence to fail. For my approach, large developers change prices from those observed in the data. I abstract from market power given a lack of concentration in my setting, but I also note that offsetting mechanisms may limit bias. Under-development arises from typical price-setting incentives, while over-development arises as market power increases developers' influence on government intervention.

## 7 Government

Government commitment, as well as the benefits and costs of defense, determine the extent of government intervention. A hydrological flood model captures benefits, and engineering estimates describe costs.

## 7.1 Commitment

Commitment dictates the government’s ability to resist static incentives and stick to dynamically optimal strategies. I consider a range of scenarios. Under full commitment, the government makes an upfront plan for defense over time by maximizing jointly over defense in each period. It then adheres to this plan in subsequent periods. Under no commitment, the government instead pursues sequential static optimization, choosing defense in each period while taking prior development and defense as given. Limited commitment lies between these extremes: the government plans defense upfront and acts accordingly during the commitment period, after which it acts with no commitment.

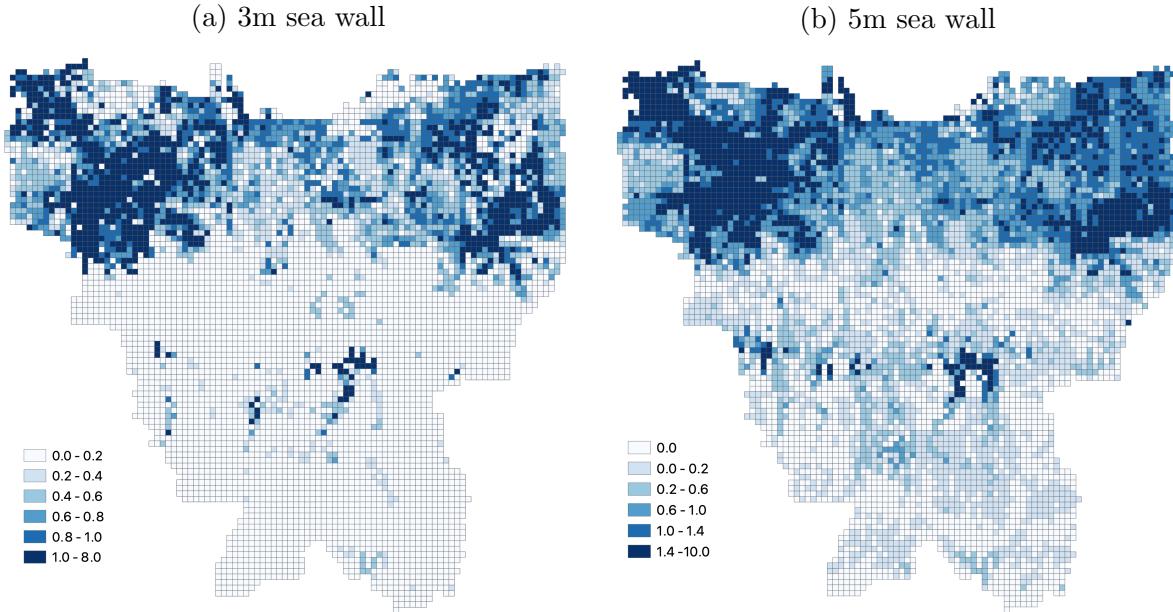
Politics affect the government’s objective function under limited commitment. A forward-looking government chooses defense to maximize social welfare from the current period to the terminal period. By contrast, a politically myopic government maximizes social welfare during its administration. It also considers future social benefits, which it claims credit for providing, but it ignores future social costs, which instead fall to future administrations. I abstract from politics for full commitment, which demands forward-lookingness, and also for no commitment, which involves its own form of myopia.

## 7.2 Benefits

A hydrological model of flooding captures how government defense affects flood safety across Jakarta. I adopt a machine-learning approach to modeling flooding, following the frontier in hydrology as reviewed by [Mosavi et al. \(2018\)](#). I train and validate the model on observed flooding from 2013 to 2020, which I measure monthly and at the tract level. As input data, I use rainfall, elevation, slope, and distances to major rivers, minor rivers, and the coast. I train a range of machine learning models and find that a histogram gradient boosting decision tree performs best. I impose monotonicity constraints on distance to major rivers and elevation, which help to reduce overfitting by applying basic physical properties without the complexity of modeling the full physical system. Appendix C describes this procedure in detail.

The trained model allows me to simulate how a sea wall would affect flooding across Jakarta. Figure 5 shows the impact of a 5m sea wall, which I simulate by raising

Figure 5: Reductions in flood frequency



I map reductions in flood frequency, as measured in months per year, following the construction of a sea wall. I use the trained hydrological model to simulate the sea wall, raising elevation by 3m and 5m in the figures above, then I compute predicted changes in flood frequency over space.

the elevation of the city relative to sea level. The predictions align with intuition. The coastal north benefits most from the sea wall, with especially large reductions in flooding in low-elevation areas. Some parts of the high-elevation south also benefit, as greater drainage in the north alleviates flooding near river banks in the south. Indeed, the machine learning model captures this interaction without an explicit model of the complex physical processes that determine river drainage. I ignore existing sea wall protections, which a 2020 government report calls “very poor” ([NCICD 2020](#)).<sup>20</sup>

I quantify the benefits of decreased flooding with the equilibrium model of sections 5 and 6, which describe spatial demand by residents and dynamic supply by developers. Intervention decreases flooding, which raises resident demand and consumer surplus as given by the demand model. Higher demand increases rents, which raise developer supply and producer surplus as given by the supply model. Higher supply decreases rents, which in equilibrium balance demand and supply responses.

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<sup>20</sup> “Currently, the level of flood protection on existing coastal and river embankments is very low.” (“Saat ini, tingkat perlindungan banjir pada tanggul pantai dan sungai eksisting sangat rendah.”)

### 7.3 Costs

I focus on direct costs of Jakarta's planned sea wall, omitting opportunity costs of public funds that are more difficult to quantify. I thus view these direct costs as a lower bound, noting that larger costs would amplify the moral hazard problem. I obtain engineering cost estimates from government reports on the planned wall, which runs onshore along the coast and offshore through Jakarta Bay ([NCICD 2014, 2020](#)). Onshore length is 60km with a height of 4m, while offshore length is 32km with a height of 24m, of which 8m is above water. Estimated costs are \$11B in 2014 USD: construction costs of \$2B onshore and \$6B offshore, plus maintenance costs that add another 35% in net-present-value terms.<sup>21</sup> In making this investment, the government seeks protection against sea levels of up to 4m above street level, with a range of 3m to 5m expected by 2050 as land subsidence accelerates the impacts of sea level rise.

I use these estimates to project costs for sea walls of alternative heights. I assume that 1m of sea level rise requires walls with 1m of height onshore and 2m of above-water height offshore, following the ratios of the current plan. For example, relative to the planned 4m sea wall, the 3m wall of figure 5 would require 3m of height onshore and 6m offshore. I compute costs following [Lenk et al. \(2017\)](#), who analyze cost estimates for sea walls in Canada and the Netherlands. They find costs to be roughly linear in height and length, with little gained from computing fixed costs or higher-order terms. Indeed, I find this linearity to hold for Jakarta, where both onshore and offshore estimates imply costs of roughly \$11M per meter of height and kilometer of length. For a sea wall of height  $g$  in meters, total costs  $e(g)$  combine onshore and offshore unit costs of \$10.67M and \$10.78M per meter-kilometer, heights of  $g$  and  $2g + 16$  meters, and lengths of 60 and 32 kilometers.

$$e(g) = 10.67 * 60 * g + 10.78 * 32 * (2g + 16) \quad (\$1M)$$

For 3m and 5m sea walls, total costs are thus \$9.5B and \$12B.<sup>22</sup> I can also consider

<sup>21</sup> The 2014 plan includes 25km of offshore wall with a cost estimate of \$4.8B, while the updated 2020 plan includes 32km but no cost estimate. I consider the 32km length and scale the 2014 estimate accordingly. Costs include associated flood investments in pumping stations, jetties, and mangrove restoration. I exclude non-flood investments in transport, land reclamation, and port development, which in early plans brought the total to \$40B.

<sup>22</sup> For a 3m wall, offshore above-water and total heights are 6m and 22m. For a 5m wall, these heights are 10m and 26m. Each is relative to 8m and 24m for the planned 4m wall.

cost uncertainty, which Lenk et al. (2017) find is well captured by a factor of three.

## 8 Counterfactuals

I simulate how coastal development and defense vary with government commitment, and I show how relocating demand affects the commitment problem.

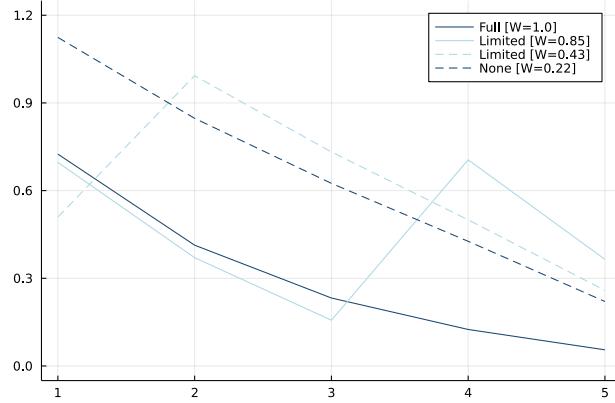
### 8.1 Simulations

I simulate coastal development and defense over five periods, noting that prolonged coastal activity corresponds to delayed inland investment and thus delayed long-run adaptation. Figure 6a considers a forward-looking government. Full commitment gives the first best, while no commitment induces moral hazard and over-development in each period. Limited commitment involves under-development during the commitment period, lessening moral hazard in the periods that follow and reducing the resulting over-development. Figure 6b considers a politically myopic government. Limited commitment does less to reduce over-development, as the benefits of commitment are undercut by the failure to internalize future costs. The earlier government over-defends relative to full commitment, as it benefits from exploiting the later government. But it under-defends relative to no commitment, as it seeks to avoid being exploited itself. Figure 6c considers relocated demand that reduces coastal residential value by 25%. Moving the political capital from Jakarta might lead to such a reduction, as could other policies like inland investments or migration subsidies. Lower demand reduces developers' gains from exploiting the government, lessening moral hazard and reducing over-development under non-commitment. Appendix D presents the corresponding patterns of government defense.

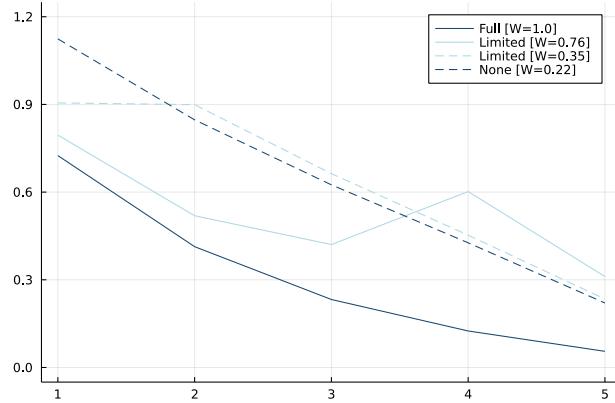
Table 3 computes welfare effects. The baseline analysis characterizes the commitment problem, normalizing first-best welfare to one. Full commitment achieves the first best. Non-commitment has severe consequences, resulting in only 22% of first-best welfare. Limited commitment leads to large gains. Under a forward-looking government, one-period commitment brings 43% of first-best welfare, and three-period commitment 85%. Political myopia undercuts these gains, but they remain substantial relative to no-commitment outcomes. I then relocate demand and repeat the

Figure 6: New coastal development over time ( $d_t$ )

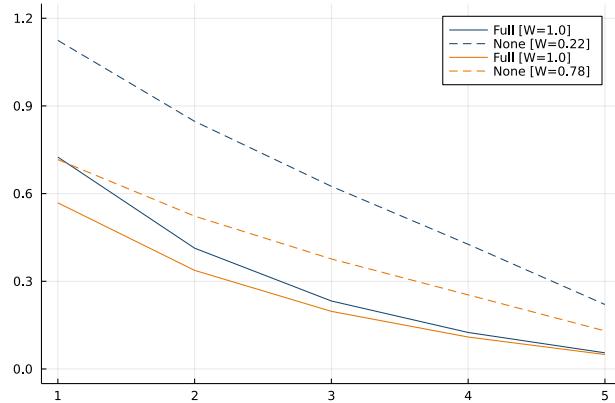
(a) Forward-looking government



(b) Political myopia



(c) Relocating demand



In the first two figures, limited commitment is for one and three periods (dashed and solid, respectively). Social welfare is denoted by “W” and normalized to one under full commitment. In the third figure, orange marks a moved capital that reduces residential value by 25%.

Table 3: Welfare effects

	$L$	$W$	
		Baseline	Relocating demand
Full commitment	5	1.00	1.00
Limited commitment			
Forward looking	3	0.85	0.94
Political myopia	3	0.76	0.92
Limited commitment			
Forward looking	1	0.43	0.82
Political myopia	1	0.35	0.81
No commitment	0	0.22	0.78

I simulate over five periods, with  $L$  denoting periods of commitment. For limited commitment, a forward-looking government considers social welfare  $W$  until the terminal period, while a politically myopic government ignores future costs. Welfare columns each normalize full-commitment values to one, and relocating demand reduces residential values by 25%.

commitment simulations, again normalizing first-best welfare to one. Relocating demand greatly reduces the commitment problem, raising no-commitment welfare to 78% of first-best welfare and scaling limited-commitment outcomes proportionally.

## 9 Conclusion

This paper studies adaptation to sea level rise in Jakarta, the second-most populous metropolitan area in the world. I show that adaptation faces major frictions, including over the long run, as government intervention worsens lock-in by creating moral hazard for private developers. Government commitment reduces this friction but is subject to fundamental challenges. Jakarta thus provides an early view into the future for other major coastal cities like Miami, New York, and Shanghai as sea levels continue to rise worldwide.

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# APPENDIX

## A Theory

### Extensions

I consider inland development that does not require flood defense. The typical adaptation narrative is that flood risk prompts a move inland, reestablishing agglomeration forces away from flood zones over the long run. Endogenizing government intervention complicates this narrative by inducing coastal over-defense. The result is significant delay to the move inland, as coastal and inland development are rival. Agglomeration does not take hold inland as long as coastal over-development keeps residents at the coast. Allowing inland development thus increases welfare losses.

To this end, rents may be endogenous and determined in equilibrium. Coastal defense protects against flooding, raising the returns to coastal development. But as development increases at the coast, greater supply places downward pressure on rents. At the same time, a countervailing force is that lower rents encourage individuals and firms to move in, with greater demand placing upward pressure on rents. The quantitative exercise considers these forces in spatial equilibrium by modeling individuals and firms that co-locate across coastal and inland neighborhoods.

Defense may also be durable. In this case, defense investments are largely up-front: if defense is optimal tomorrow, then it is optimal today because it protects development for an additional period. Future defense investments are thus minimal under the baseline assumptions, particularly if defense depreciates slowly. In reality, however, rising sea levels increase flood risk over time and prompt continued investment in defense. Maintenance costs motivate the same even absent increasing flood risk. Similarly, rising rents and falling costs prompt continued development, as do convex costs that force development to be spread over time. This continued development prompts continued defense. Nondurable defense thus captures the repeated government intervention observed in the richer model, as well as in practice.<sup>23</sup>

Finally, developers may invest in private defense  $\tilde{g}$  alongside public defense  $g$ . If public and private defense are (perfect) substitutes, then residential value is  $r(d, g + \tilde{g})$  with development costs  $c(d, \tilde{g})$  and defense costs  $e(g)$ . Although developers internalize  $\tilde{g}$ , they do not internalize  $g$  and can free-ride on public defense. Public defense thus crowds out private defense, which is inefficiently low. This result mirrors that of the baseline model, in which private efforts  $\tilde{g}$  take the form of moving inland.

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<sup>23</sup> Nondurable defense has another benefit. With durable defense and a finite horizon, earlier defense provides longer protection than later defense. Defense thus falls over time, but only as an artifact of the assumed horizon. Nondurable defense eliminates this mechanical effect.

Figure A1: Co-determination of development and defense

(a) Development given defense



(b) Defense given development

WILL BE A NEW, MODERN PLACE TO LIVE AND FOR JAKARTA RESIDENTS THE PLACE TO ESCAPE  
THE CROWDED CITY WITHOUT TRAVELLING FOR HOURS AND SPEND SOME TIME ON THE WATER  
FRONT WITH CLEAN SEA WATER AND A FRESH BREEZE.



Source: PIK 2 Sedayu Indo City (via <https://www.sedayuindocitypi2.com/lokasi.html>) and National Capital Integrated Coastal Development Masterplan (2014, page 48). The figures show private development plans given proposed government defense, and government defense plans (at early, hand-drafted conception) given proposed private development.

## Anecdotal evidence

The co-determination of development and defense is also salient in practice. In Jakarta, figure A1 shows examples of interdependence. Developers cite government defense in planning for and marketing private development on the flood-prone coast. At the same time, the government cites private development in planning for and marketing proposed investments in coastal defense.

Similar dynamics arise in the United States. In New Orleans, the National Flood Insurance Program (NFIP) has enabled continued development in flood-prone neighborhoods, such as the Lower Ninth Ward. In North Carolina, increased coastal development led business groups to lobby for House Bill 819, which restricts state agencies in applying sea level rise projections to policy. In Florida, developers lobbied for Urban Development Boundary zoning expansions to allow construction in hurricane-prone areas, and the state legislature dismantled the Department for Community Affairs, which managed long-term development risk with initiative like the Flood Mitigation Assistance program. At the national level, NFIP Risk Rating 2.0 adjusted insurance pricing to better reflect risk, but bipartisan resistance delayed implementation. Furthermore, the US Army Corps of Engineers focuses levee spending where economic exposure is high via its Levee Safety Action Classification system.

## B Data

Table B1 lists data sources. This section details data construction and validation.

### Building construction

These data come from the Global Human Settlement Layer, with measurements at the 100m pixel level. Jakarta consists of 65,260 such pixels. For building construction, 1,900 pixels feature an increase in measured built-up volume between 2015 and 2020. I verify these data with 2015 data from Visicom, a company that produces satellite-derived 3D maps that capture building heights at the 1m pixel level. These maps rely on light detection and ranging (lidar) data, which satellites collect by emitting pulsed laser beams and measuring reflection times. Beams that reflect quickly imply taller building heights, with measurements accurate to the meter. When aggregated to the tract level, the correlation between Global Human Settlement Layer and Visicom measures is 0.90 for built-up surface and 0.92 for built-up volume. Figure B1 shows the comparison visually.

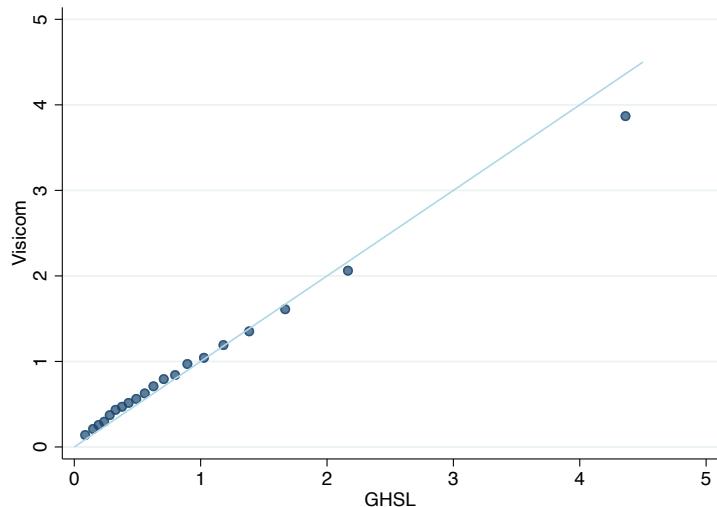
### Property values

I collect property values in four steps. First, I scrape data on property listings in October 2022 from 99.co Indonesia ([www.99.co/id](http://www.99.co/id)), a major real estate website. I

Table B1: Data sources

Period	Source (description)
1975-2020	Global Human Settlement Layer (building construction, populations)
2015	Visicom (building construction)
2022	99.co (property values)
2015	Brickz.id (property values) ( <a href="#">Harari and Wong 2019</a> )
2015	Jakarta Smart City (land values)
2013-2020	Regional Disaster Management Agency (flooding)
2022	Jakarta Satu (schools, clinics, rail stations, roads)
1887-1945	Dutch colonial maps (historical land development)

Figure B1: Building volumes (1M m<sup>3</sup>), GHSL vs. Visicom



Source: Global Human Settlement Layer and Visicom. Each observation of the binned scatterplot measures 2015 built-up volume at the tract level. I plot the 45° line in light blue.

Table B2: Geocoding property listings

Type	All	Apartment	Home	Shop	Office
Geocoded proportion	65.5%	84.0%	52.6%	56.0%	39.8%
Geocoded observations	56,222	29,733	17,182	7,786	1,521

Property listings for sale come from 99.co, and geocoding is with the Google Maps API.

focus on properties for sale, with listings covering both residential and non-residential properties in Jakarta. Residential properties include apartments and homes, and non-residential properties include shops and offices. Listings contain prices, floor spaces, land areas, addresses, and descriptions.

Second, I geolocate listings with the Google Maps API. As inputs, I supply property addresses, types, and districts. Property addresses include street names and sometimes street numbers. I identify street names with the keyword *jalan* where possible. For apartments, I also include apartment complex names given keyword *apartemen*. As outputs, I obtain formatted addresses with geographic coordinates and return types. I keep the following return types: street addresses, routes, establishments, points of interest, premises, and sub-premises. Routes are entire streets and thus require additional processing to geocode. I compute street lengths from geometric bounds, drop long streets, and geocode the short ones that remain by centroid. A cutoff length of 1km avoids dropping data excessively while maintaining accuracy at the tract level. Table B2 shows the high rate of success in geocoding.

Third, I construct property values at the tract level. I compute prices per square meter by dividing prices by floor space, dropping the 1% of listings without information on prices or building areas. I collapse listings with identical addresses – primarily apartment listings within complexes – into single observations by taking means. I then aggregate to the tract level as follows. For the 70% of tracts with more than five observations, I take the mean. For the 30% of tracts with less than five observations, I compute an inverse-distance-weighted mean of nearby observations.<sup>24</sup> I thus obtain property values for 2022.

Fourth, I backcast the 2022 values to 2015. I obtain data on 2015 property transactions from Brickz ([www.brickz.id](http://www.brickz.id)), as scraped and kindly shared by [Harari and Wong \(2019\)](#). The 2015 data contain 6,929 observations that I use to compute 2015-2022 adjustment factors by district. I do so by computing district means in 2015 and 2022, reweighing 2022 values to match the property type composition of the 2015 data. The resulting adjustment factors capture price changes over time, as well as differences between transacted and listed prices. I then apply the adjustment factors to the 2022 data to obtain 2015 values. Relying directly on the 2015 values would be more straightforward, but the relatively small number of geocoded observations – around half of the 6,929 transactions – complicates measurement at the tract level.

## Historical land development

I construct a panel of historical land development by digitizing maps of Batavia from the Dutch colonial era. These maps come from the digital collections of the

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<sup>24</sup> For the inverse distance weighting, I use a weighting power of two, a smoothing parameter of zero, a search circle radius of 1km, a maximum of 20 observations, and a minimum of five observations. I include observations from the periphery of Jakarta.

Table B3: Dutch colonial maps

Year	Source
1887	Visser & Co. ( <a href="#">link</a> )
1897	Topographisch Bureau ( <a href="#">link</a> )
1904	Seyffardt's Boekhandel ( <a href="#">link</a> )
1910	Official Tourist Bureau ( <a href="#">link</a> )
1920	Topografische Dienst ( <a href="#">link</a> )
1930	Official Tourist Bureau ( <a href="#">link</a> )
1937	G. Kolff & Co. ( <a href="#">link</a> )
1945	AFNEI Headquarters Survey Department ( <a href="#">link</a> )

Source: Leiden University Library Digital Collections. Maps are also available for 1890 ([link](#)), 1905 ([link](#)), 1914 ([link](#)), 1938 ([link](#)), and 1942 ([link](#)).

Leiden University Libraries. Table B3 lists years and sources. I select eight maps based on ease of digitization and a desire for consistent coverage throughout the study period, but the table lists all available maps. I georeference and digitize the maps, then overlay them to form a panel. These data capture the extensive margin of built-up land development, but not the intensive margins of density or height.

I georeference each map by overlaying it onto an OpenStreetMap base layer. I do so by selecting and matching five ground control points, as shown in figure B2. I select these points to prioritize accuracy in the vicinity of the National Monument and the West Flood Canal, with a modified set of points before the canal is constructed. I implement the overlay with first-order polynomial (affine) transformation and nearest-neighbor resampling. This affine transformation preserves the collinearity of points by applying only rotation, scaling, and translation, avoiding image distortions but ruling out the exact matching of more than two control points.

I digitize each map with unsupervised machine learning. In each map, red shading denotes built-up areas, while green and white denote undeveloped lands. I divide maps into 50m grid cells, then I take the modal R, G, and B values across pixels in each cell to obtain one RGB code per cell. I apply a  $k$ -means clustering algorithm on these RGB codes to group cells with similar colors. I choose  $k$  to obtain no more than one grouping of red cells, and I code these cells as built-up. This approach reduces noise in the image files, which contain red in many different shades. The 1910 map marks built-up areas with red dots instead of shading, and so I apply shading manually then digitize it as above. Figure B3 overlays the image inputs and the digitization outputs, which together illustrate the accuracy of this procedure.

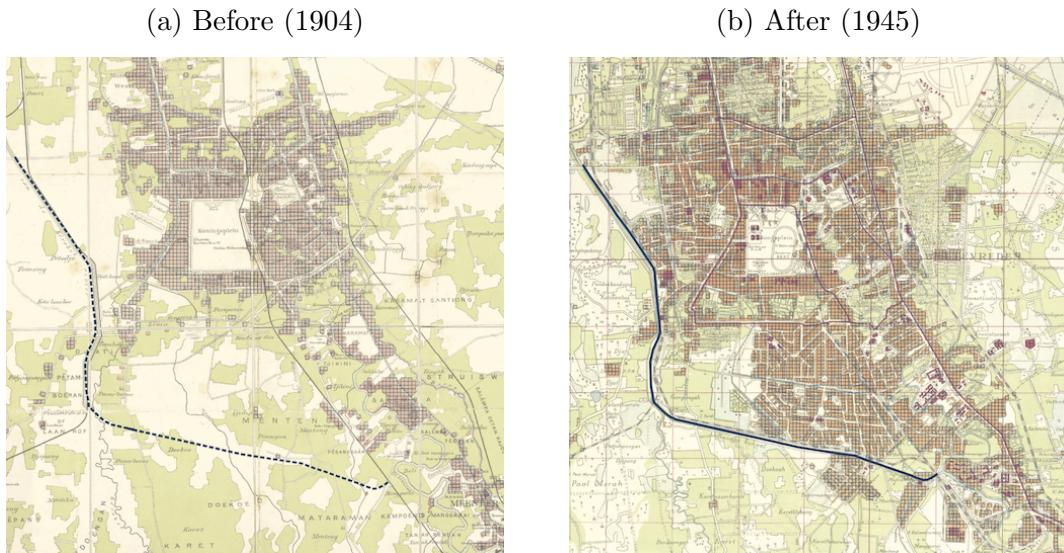
I then ask whether the construction of the West Flood Canal in 1918 led to increased land development in protected areas. I leverage a spatial discontinuity in

Figure B2: Ground control points for georeferencing



Red stars mark the five ground control points used for georeferencing.

Figure B3: Land development and the West Flood Canal



Red shading denotes developed lands, and square boxes mark 50m grid cells that are coded as developed. I mark the West Flood Canal with a black curve – dotted in 1904 before its construction in 1918, and solid in 1945 after its construction.

Table B4: Land development at the canal boundary by year

	300m bandwidth	400m bandwidth	500m bandwidth	600m bandwidth
North of canal $\times$ 1887	-0.06 (0.07)	-0.07 (0.06)	-0.09* (0.06)	-0.11** (0.05)
North of canal $\times$ 1897	-0.03 (0.07)	-0.03 (0.06)	-0.00 (0.06)	-0.02 (0.06)
North of canal $\times$ 1904	-0.06 (0.07)	-0.08 (0.06)	-0.09 (0.06)	-0.09 (0.05)
North of canal $\times$ 1920	0.15* (0.09)	0.23*** (0.08)	0.31*** (0.07)	0.32*** (0.07)
North of canal $\times$ 1930	0.41*** (0.11)	0.41*** (0.09)	0.40*** (0.08)	0.46*** (0.08)
North of canal $\times$ 1937	0.78*** (0.10)	0.76*** (0.09)	0.75*** (0.08)	0.76*** (0.08)
North of canal $\times$ 1945	0.77*** (0.10)	0.76*** (0.08)	0.74*** (0.08)	0.72*** (0.07)
Tract FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	3792	5072	6320	7568

Data on historical land development come from Dutch colonial maps. The West Flood Canal was completed in 1918 and protected neighborhoods to its north, but not to its south. The dependent variable is land development, and each observation is a 100m grid cell. The optimal bandwidth is 500m. Robust standard errors in parentheses. \*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

flooding at the boundary of the canal, which protects areas to its north but not to its south. I plot the discontinuity in land development around the boundary in the main text, alongside the lack of a discontinuity before the canal's opening. In this analysis and what follows, I aggregate the historical land development data to the 100m cell level by counting the number of developed 50m cells within each 100m cell. Misalignment across maps can cause measurements at the 50m cell level to alternate spuriously between developed and undeveloped because of slight differences in how maps are drawn. Aggregation alleviates this concern without the complexity of harmonizing data across years. Year fixed effects in the pooled analysis further account for systematic differences across maps.

Table B4 draws on data from the full panel to measure the discontinuity in each available year. For cell  $c$  and year  $t$ , the specification is

$$Y_{ct} = \alpha + \sum_{t'} \beta_{t'} N_c \mathbb{1}[t' = t] + \delta_c + \delta_t + \varepsilon_{ct}$$

for land development  $Y_{ct}$ , dummy  $N_c$  for being on the protected north of the canal, and year fixed effect  $\delta_t$ . I compute an optimal bandwidth of 500m, and I restrict attention to cells within this distance from the boundary. I also show robustness to this choice. The coefficients of interest are the  $\beta$  terms by year. Cell and year fixed effects account for permanent, cell-specific determinants of land development as well as transitory, common ones. The table shows insignificant effects and thus smoothness across the boundary in all pre-canal years. The discontinuity in land development emerges only after the canal opens in 1918, and it grows in subsequent years. Figure B4 provides further validation checks, showing that elevation is smooth across the boundary and that the canal indeed offers flood protection to its north.

A similar pattern holds in the modern cross-section. Lower flood risk is associated with higher land values and more building construction in 2015. Table B5 presents these results with cross-tract regressions that control for unobservables at the district, sub-district, and neighborhood levels. Increased flood protection can therefore prompt increased construction in areas facing long-term flood risk, as it does in the historical data. The advantage of the modern data is that they capture real estate prices as a mechanism for this relationship, as well as development on the intensive margin.

## C Estimation

### Identification with endogenous intensive-margin decisions

Prices again act as numeraire. Applying equations 15, I express equation 14 in terms of intensive-margin choice  $h_{kt}(X_{kt}; \theta)$  for data  $X_{kt}$  and parameters  $\theta$ .

$$\ln p_{kt}^{\text{dev}} - \ln(1 - p_{kt}^{\text{dev}}) = \psi \left( \alpha P_{kt}^D - \frac{\alpha P_{kt}^L}{h_{kt}} - \phi f_{kt} \right)^2 - \omega \left( \frac{h_{kt}^2}{2} \right) - \varepsilon_{kt},$$

where I drop  $x_{kt}\gamma$  for simplicity. Expanding terms that depend only on  $(X_{kt}, \theta)$ ,

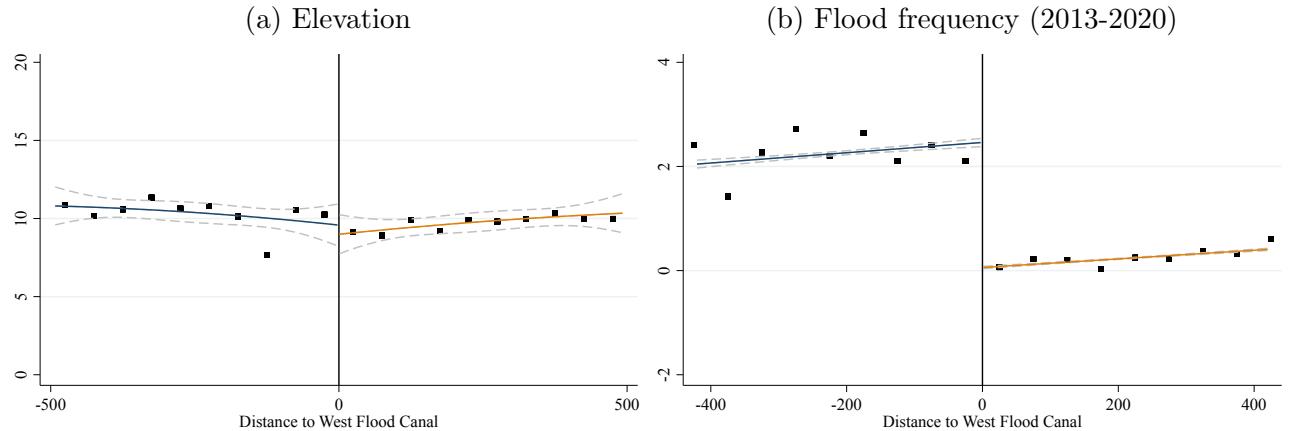
$$\Gamma_1(X_{kt}; \theta) = \psi \alpha^2 (P_{kt}^D)^2 - \psi \alpha \phi (2P_{kt}^D f_{kt}) + \psi \phi^2 (f_{kt}^2),$$

For coefficients  $(\beta_1, \beta_2, \beta_3) = (\psi \alpha^2, \psi \alpha \phi, \psi \phi^2)$ ,  $\frac{\beta_2}{\beta_1}$ ,  $\frac{\beta_3}{\beta_2}$ , and  $\frac{\beta_3}{\beta_1}$  each identify relative parameter  $\frac{\phi}{\alpha}$ , but  $(\psi, \alpha, \phi)$  are not separately identified. Expanding terms that additionally depend on  $h_{kt}$ ,

$$\Gamma_2(h_{kt}, X_{kt}; \theta) = -\psi \alpha^2 \left( \frac{2P_{kt}^D P_{kt}^L}{h_{kt}} \right) + \psi \alpha \phi \left( \frac{2P_{kt}^L f_{kt}}{h_{kt}} \right) + \psi \alpha^2 \left( \frac{P_{kt}^L}{h_{kt}} \right)^2 - \omega \left( \frac{h_{kt}^2}{2} \right).$$

For exogenous  $h_{kt}$ , coefficients  $(\beta_4, \beta_5, \beta_6) = (\psi \alpha^2, \psi \alpha \phi, \phi \alpha^2)$  identify no more than identified previously. But for endogenous  $h_{kt}$ , convexity  $\psi$  has level effects: by equa-

Figure B4: Validating the spatial regression discontinuity design



Data on historical land development come from Dutch colonial maps. The West Flood Canal was completed in 1918 and protected neighborhoods to its north (positive distances), but not to its south (negative distances). Each observation is a 100m grid cell. The  $x$ -axis measures distance to the West Flood Canal in meters, and 500m is the optimal bandwidth.

Table B5: Flood risk, land values, and building construction

(a) Land value (\$/m <sup>2</sup> )				
Flood risk (m/yr)	-2.31*** (3.00)	-1.29*** (3.12)	-0.59** (2.15)	-0.93*** (2.78)
District FE	x			
Sub-district FE		x		
Neighborhood FE			x	
Observations	2,722	2,722	2,722	2,722

(b) Building construction (m <sup>3</sup> )				
Land value (\$/m <sup>2</sup> )	0.21*** (0.03)	0.27*** (0.03)	0.37*** (0.05)	0.30*** (0.05)
District FE	x			
Sub-district FE		x		
Neighborhood FE			x	
Observations	2,722	2,722	2,722	2,722

Each observation is a tract, and each column a regression. Flood risk is realized flooding from 2013 to 2020, land values are from the Jakarta Smart City initiative for 2015, and building construction is from the Global Human Settlement Layer for 2015. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

tions 15, larger convexity implies smaller  $(d_{kt}, h_{kt})$ . Fixing  $(\psi\alpha^2, \psi\alpha\phi, \psi\phi^2)$ , as identified previously, varying  $\psi$  affects  $h_{kt}$  and in turn affects  $\varepsilon_{kt}$  and the moment condition. I thus separately identify  $(\psi, \alpha, \phi)$ , with a similar argument for  $\omega$ . Intuitively, convexity affects intensive-margin choices in levels (monotonically), and these choices affect development profits and probabilities. Inverting development probabilities thus yields convexity in levels. Throughout, overidentification motivates estimating the moment condition by GMM.

### Euler conditional choice probabilities

The Euler approach compares two sequences of actions:  $(d_{kt}, 0)$  and  $(0, d_{kt})$ . The first develops  $d_{kt}$  today and zero tomorrow, while the second develops zero today and  $d_{kt}$  tomorrow. Each involves land use  $\ell_{kt}$ . Intuitively, developing tomorrow reduces upfront costs given discounting, but it also delays the arrival of rental revenue. Choice-specific conditional value functions are

$$v_{kt}^1(D_{ikt}, L_{ikt}) = -c_{kt}(d_{kt}, \ell_{kt}) + \beta \mathbb{E}_{kt}[\alpha r_{kt+1} D_{ikt} + \alpha r_{kt+1} d_{kt} - \ln(1 - p_{kt+1}^{\text{dev}})] + \beta^2 \mathbb{E}_{kt}[V_{kt+2}(D_{ikt} + d_{kt}, L_{ikt} - \ell_{kt})], \quad (16a)$$

$$\begin{aligned} v_{kt}^0(D_{ikt}, L_{ikt}) &= \beta \mathbb{E}_{kt}[\alpha r_{kt+1} D_{ikt} - c_{kt+1}(d_{kt}, \ell_{kt}) - \ln p_{kt+1}^{\text{dev}}] \\ &\quad + \beta^2 \mathbb{E}_{kt}[V_{kt+2}(D_{ikt} + d_{kt}, L_{ikt} - \ell_{kt})] \\ &\quad + \frac{1}{2} \beta \mathbb{E}_{kt}[c''_{kt}(d_{kt})(d_{kt+1} - d_{kt})^2 + c''_{kt}(h_{kt}(\ell_{kt}))(h_{kt+1}(\ell_{kt+1}) - h_{kt}(\ell_{kt}))^2]. \end{aligned} \quad (16b)$$

The first and third lines impose the actions of interest to equations 8. These actions may depart from the optimal actions implied by the choice-specific conditional value functions, and so correction terms in the second and fourth lines account for this potential suboptimality. These correction terms are derived from the following.

$$\begin{aligned} V_{kt}(D_{ikt}, L_{ikt}) - \alpha r_{kt} D_{ikt} &= v_{kt}^1(D_{ikt}, L_{ikt}) - \ln p_{kt}^{\text{dev}} = v_{kt}^0(D_{ikt}, L_{ikt}) - \ln(1 - p_{kt}^{\text{dev}}), \\ v_{kt}^1(D_{ikt}, L_{ikt}, d, \ell) &= v_{kt}^1(D_{ikt}, L_{ikt}) - \frac{1}{2} c''_{kt}(d_{kt})(d_{kt} - d)^2 - \frac{1}{2} c''_{kt}(h_{kt})(h_{kt}(\ell_{kt}) - h(\ell))^2 \end{aligned}$$

for  $v_{kt}^1(D_{ikt}, L_{ikt}) = \max_{d, \ell} \{v_{kt}^1(D_{ikt}, L_{ikt}, d, \ell)\}$ . The first line is a special case of Arcidiacono and Miller (2011) Lemma 1, and the second is as derived in Hsiao (2022a). Inverting equation 10 and substituting equations 16, continuation values  $V_{kt+2}$  cancel under finite dependence. For  $\Delta X_{kt} = X_{kt} - \beta X_{kt+1}$  and  $\tilde{X}_{kt} = X_{kt} - X_{kt+1}$ ,

$$\Delta \ln p_{kt}^{\text{dev}} - \Delta \ln(1 - p_{kt}^{\text{dev}}) = -\Delta c_{kt}(d_{kt}, \ell_{kt}) + \beta \alpha r_{kt+1} d_{kt} - \frac{1}{2} \beta \psi \tilde{d}_{kt}^2 - \frac{1}{2} \beta \omega \tilde{h}_{kt}^2 + \eta_{kt}$$

given expectational errors  $\eta_{kt}$ , which by rational expectations are mean zero (correct on average) and orthogonal (use all in information set  $\mathcal{J}_{kt}$ ). This assumption allows me to proxy for unobserved expectations with observed realizations.

## Hydrological model of flooding

I use a hydrological model to capture flood risk for Jakarta. Flooding models fall in two broad categories: physical and data-driven. The first explicitly models physical processes like rainfall, runoff, hydraulics, and flow dynamics, while the second fits historical data with statistical methods like linear regression, Bayesian models, and machine learning. I take the second approach, which has become increasingly popular among hydrologists. Physical models must specify the complex physical processes that contribute to flooding, while machine-learning methods can detect these complexities directly from the data. [Mosavi et al. \(2018\)](#) reviews the machine-learning approach for hydrology, and [Jati et al. \(2019\)](#) offers an example in the Indonesian setting.

As model inputs, I use rainfall, elevation, slope, distances to major rivers, distance to minor rivers, and distance to the coast. Annual rainfall data at a resolution of 4km come from PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) for the years 2013 to 2020. I compute average annual rainfall. Elevation data at a resolution of 90m come from the Shuttle Radar Topography Mission (SRTM) digital elevation model. I calculate slopes from elevation data using the slope algorithm of the QGIS raster terrain analysis toolkit, which computes slope in degrees as the angle of terrain inclination. I compute river and coastal distances with OpenStreetMap shapefile data, which distinguish major rivers from streams.

As model output, I obtain predicted flood frequency. This flooding includes all sources of flooding – coastal, pluvial, and fluvial – and is net of river water management infrastructure, which I hold fixed in counterfactuals. I train the model and evaluate its performance using monthly data from the Regional Disaster Management Agency on realized flooding from 2013 to 2020. I rasterize these tract-level data to a resolution of 300m for consistency with demand and supply estimation.

I consider a range of models and choose the one with the best fit. Table C1 presents the results. Ensemble methods like random forests, gradient boosting decision trees, and histogram gradient boosting decision trees perform best, as measured by R-squared, mean absolute error, and root mean squared error. As the baseline model, I choose a histogram gradient boosting decision tree with monotonicity constraints on distance to major rivers and elevation. I train this model using the *scikit-learn* package in Python, which yields model parameters of 12 for maximum tree depth, 300 for maximum iterations, and 0.01 for the learning rate. Monotonicity constraints enforce that fluvial flooding is concentrated near rivers and coastal flooding is concentrated in low-lying areas. These constraints help reduce overfitting by imposing physical properties, but without the complexity of a full physical model.

Figure C1 shows visual fit. The model performs reasonably well in capturing the main sources of flood risk in Jakarta. Distance to major rivers and rainfall in upstream watersheds capture fluvial and pluvial flooding historically, while distance

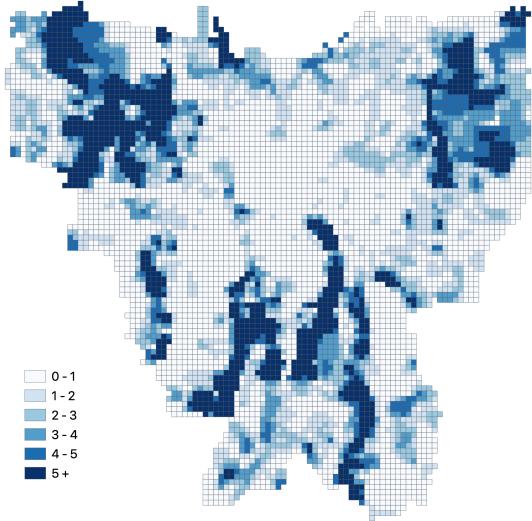
Table C1: Comparing models

	R <sup>2</sup>	MAE	RMSE
Multiple linear regression	0.027	2.467	3.778
Decision tree	0.225	2.035	3.336
Bagging	0.433	1.676	2.959
Random forest	0.458	1.596	2.797
Gradient boosting decision tree	0.467	1.608	2.800
Histogram GBDT	0.466	1.617	2.796
Histogram GBDT with monotonicity	0.471	1.606	2.827

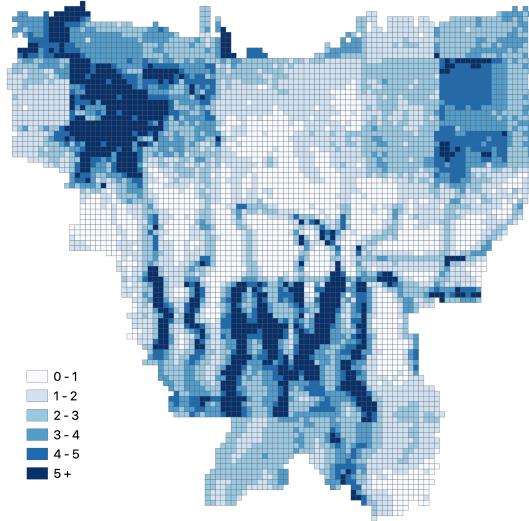
I compute R-squared, mean absolute error (MAE), and root mean squared error (RMSE) with ten-fold cross-validation. Monotonicity constraints apply to distance to major rivers and elevation.

Figure C1: Model fit (flood frequency)

(a) Observed



(b) Predicted



The figures map observed flood frequency, as measured in months per year from 2013 to 2020, against the predictions of a machine learning hydrological model.

Table C2: Feature importance

Feature	Importance
Annual rainfall	0.590
Distance to major rivers	0.586
Distance to the coast	0.487
Elevation	0.418
Distance to minor rivers	0.372
Slope	0.174

Permutation feature importance quantifies the dependence of model fit on a given feature. The table presents this measure for a histogram gradient boosting decision tree with monotonicity constraints on distance to major rivers and elevation.

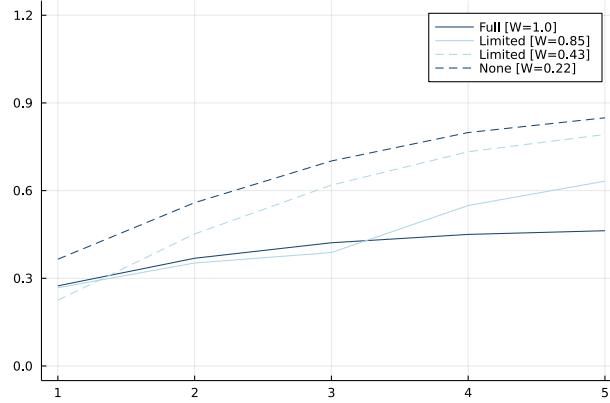
to the coast and elevation capture growing coastal flooding. Table C2 summarizes feature importance as another means of evaluating the model. I compute permutation feature importance for individual features by shuffling them – adding random noise to their values – and measuring the resulting declines in model fit. The results are sensible, with rainfall, distance to major rivers, and distance to the coast being of primary importance, and distance to minor rivers and slope being less pivotal.

## D Counterfactuals

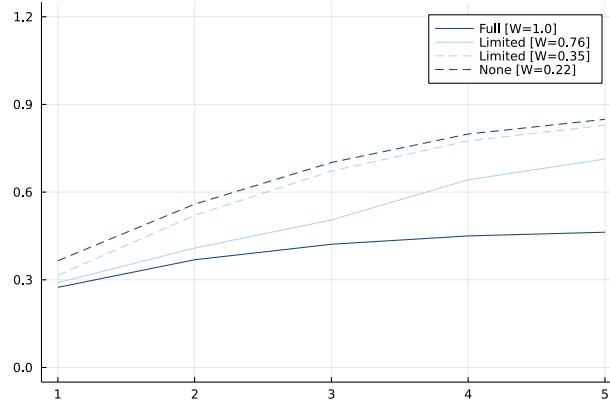
Figure D1 plots simulated government defense over time. Non-commitment leads to higher defense than under full commitment. Limited commitment prompts initial under-defense relative to the first best, which mitigates future moral hazard, but only when the current government is forward-looking. Otherwise political myopia induces over-defense, even during the commitment period, as costs to future administrations remain uninternalized. Relocating demand lessens the commitment problem.

Figure D1: Coastal defense over time ( $g_t$ )

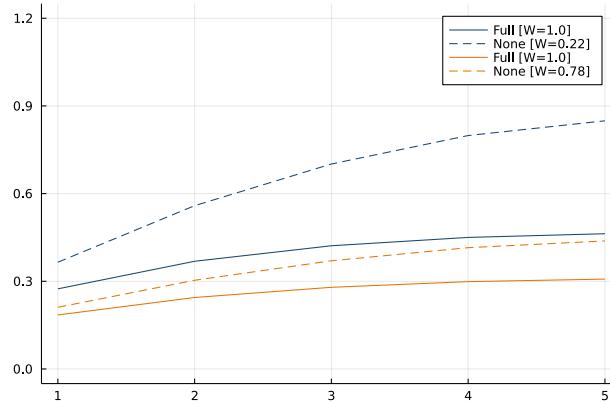
(a) Forward-looking government



(b) Political myopia



(c) Relocating demand



In the first two figures, limited commitment is for one and three periods (dashed and solid, respectively). Social welfare is denoted by “W” and normalized to one under full commitment. In the third figure, orange marks relocated demand that reduces residential value by 25%.