

Risk-based zoning for urbanizing floodplains

Erik Porse

ABSTRACT

Urban floodplain development brings economic benefits and enhanced flood risks. Rapidly growing cities must often balance the economic benefits and increased risks of floodplain settlement. Planning can provide multiple flood mitigation and environmental benefits by combining traditional structural measures such as levees, increasingly popular landscape and design features (green infrastructure), and non-structural measures such as zoning. Flexibility in both structural and non-structural options, including zoning procedures, can reduce flood risks. This paper presents a linear programming formulation to assess cost-effective urban floodplain development decisions that consider benefits and costs of development along with expected flood damages. It uses a probabilistic approach to identify combinations of land-use allocations (residential and commercial development, flood channels, distributed runoff management) and zoning regulations (development zones in channel) to maximize benefits. The model is applied to a floodplain planning analysis for an urbanizing region in the Baja Sur peninsula of Mexico. The analysis demonstrates how (1) economic benefits drive floodplain development, (2) flexible zoning can improve economic returns, and (3) cities can use landscapes, enhanced by technology and design, to manage floods. The framework can incorporate additional green infrastructure benefits, and bridges typical disciplinary gaps for planning and engineering.

Key words | optimization, risk, urban development, urban floodplains, zoning

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INTRODUCTION

Urban flood control is an issue of historic and global concern. Floodplain development increases potential economic damages and risks the health and safety of residents (Wisner 2004). Most cities locate near bodies of water for numerous benefits and amenities, including access to resources, energy, and transportation. Development in a region often begins in areas with best access to resources and lowest risk of threats such as flooding. Continued economic and population growth, while bringing benefits, stresses land and water resources. In time, residents often settle in more marginal lands of greater risk from flooding and other hazards.

Historically, poorer urban residents often settled in marginal lands (Engels 1887), although cities with sufficient capital build expensive infrastructure projects such as levees, dredging, and infill to reduce flood risks. In recent decades, however, infrastructure in many industrializing cities has not kept pace with rapid population growth fueled by migration and public health improvements (Davis 1965). Population increases create housing shortages,

which, given corruption, inadequate planning, and lack of capital, force new residents to settle in marginal land, often 'informally' and without publicly supported infrastructure (Neuwirth 2006).

Other factors also shape urban floodplain planning. For instance, geologic conditions and vegetation affect average flood flows in a channel. Additionally, urban regions alter the timing and duration of runoff entering channels (Hollis 1975), which can exacerbate floods. In some areas, flood protection technology and expertise are not readily available. Local topography and geography also drive formal and informal urban settlement patterns based on proximity to urban cores, transit, and access to resources. Finally, benefits and costs of urban development in floodplains may disperse to different groups. These and other constraints all influence the flexibility that engineers and planners have in managing flood risks.

Investment decisions for flood management are complex. Traditionally, flood control infrastructure was

designed to prevent floods by (1) estimating flood events of specified magnitudes, or (2) minimizing expected annual flood damages and construction and maintenance costs (Lind 1967; USWRC 1983). Yet, policies differ throughout the world. In the USA, flood management controversies often ensue over boundaries of protection zones (i.e. the 100-year flood), while countries such as the Netherlands require greater protection in many areas (exceedence frequencies of 1/1,250 to 1/10,000 per year) (Burby 2001; Jonkman *et al.* 2008). Consistent sources of uncertainty in flood protection include (1) estimating the magnitude and likelihood of rainfall events (Klemes 2000) and (2) estimating damages from floods of various sizes (Grigg & Helweg 1975; USACE 1988). Optimization can evaluate efficient sizing of structural flood control measures by identifying low-cost flood prevention actions (James 1967; Jacoby & Loucks 1972; Davis 1974) with structural and non-structural options (Lund 2002). Risk-based approaches optimize flood protection using probability-weighted storm events (Davis *et al.* 1972; USACE 1996; Stedinger 1997; Lund 2002; Zhu *et al.* 2007).

While traditional flood management sought protection, evolving notions of flood risk management advocate land-use planning and accept some potentially inevitable inundation. Risk assessment can include flood threats, vulnerability assessments, and mitigation actions (Wisner 2004; White 2010). Urban flood risk management is moving beyond levees and flood walls to include land-use policies and landscape actions, along with non-structural measures such as emergency planning (Clark *et al.* 2002; Vis *et al.* 2003; Hayes 2004; Brouwer & van Ek 2004; Rauch *et al.* 2005; Miguez *et al.* 2007; Price & Vojinovic 2008; Ashley *et al.* 2010). For instance, the 2007 European flood risk directive emphasizes prevention and non-structural measures for member states (EC 2007). While some arid-climate cities have long incorporated both surface and underground infrastructure as part of flood management, more recent surface-based approaches emphasize localized retention, infiltration, and pollutant removal through 'green infrastructure' (Orsi 2004; Fratini *et al.* 2012). Targeted land-use planning can reduce potential flood damages (Medina *et al.* 2011; Kousky *et al.* 2013). In rapidly-industrializing countries, research advocates more rigorous zoning and multi-functional landscapes (Tucci 2007; Miguez *et al.* 2011). The links between flood risk management, urban planning, and water resources engineering are still evolving in both theory and practice (Herk *et al.* 2011; Fratini *et al.* 2012).

The economic benefits of urban growth will likely drive continued floodplain development. This paper presents an illustrative, risk-based modeling framework to assess integrated land-use and zoning decisions for urban floodplain planning. It uses a probabilistic optimization to identify cost-effective combinations of land-use allocations (flood channels, buffer zones, retention basins, and residential and commercial development) and zoning decisions (width of land-use development zones) in a flood channel that maximize benefits of urban expansion given infrastructure costs and flood damage risks. The methodology assesses expected annual flood damages in channel zones of a downstream urban floodplain based on estimated flows from a basin-wide rainfall-runoff model. The methodology is applied to a case study basin in Baja California Sur region of Mexico, and can be adapted to other regions. The analysis addresses a theoretical and applied void between urban planning, flood risk management, and water resources engineering, while demonstrating application of new conceptions of risk for cities.

MODEL DEVELOPMENT

Development in an urban floodplain has benefits for economic development, costs for construction of various types of infrastructure, and potential risks of flood damages. A linear programming model, presented below, identifies cost-effective decisions for flood channel zoning and associated development using a risk-based optimization, where risk mitigation favors situating development in areas of low risk. The model maximizes total benefits of development in the flood channel given net benefits of development (economic benefits minus construction costs) and potential damages from probabilistic assessment of expected flooding.

Land-use planning and zoning are powerful tools for urban planners to manage flood risks. The model considers a flood channel near an expanding urban region, which is divided into zones of development with different associated flood risks. Land area in each zone can be dedicated to one or more land uses, which include residential and commercial buildings, dedicated flood channels, agriculture, and green infrastructure such as linear parks, retention basins, filtration strips, and flood buffer zones. In the model, a flood channel of width w was divided into zones of width, w_z , where each zone has a mix of potential land uses. The channel is designed for particular zones to have higher flood risk, which can then be allocated land uses with

lower associated damages. Figure 1 illustrates the configuration of the modeled channel, where zones on the right (Zones 1 and 2) have higher flood risks than zones on the left (Zones 4 and 5).

Dividing the flood channel into zones simulates different opportunities to incorporate multiple planning goals. For instance, some zones may have a majority of land dedicated to parks, while others are slated for development of residential and commercial properties. Such zoning requirements model many real-world situations, including local regulations, environmental constraints, and prior settlements. Additionally, while traditional urban flood control typically focused on fast and efficient conveyance in channels, more recent approaches use landscape designs to slow or retain runoff, which can alter peak flow timings and reduce the requirements to manage and treat runoff.

MATHEMATICAL FORMULATION

The model maximizes total benefits, Z , of developing land for different uses, u , within each of z zones in a

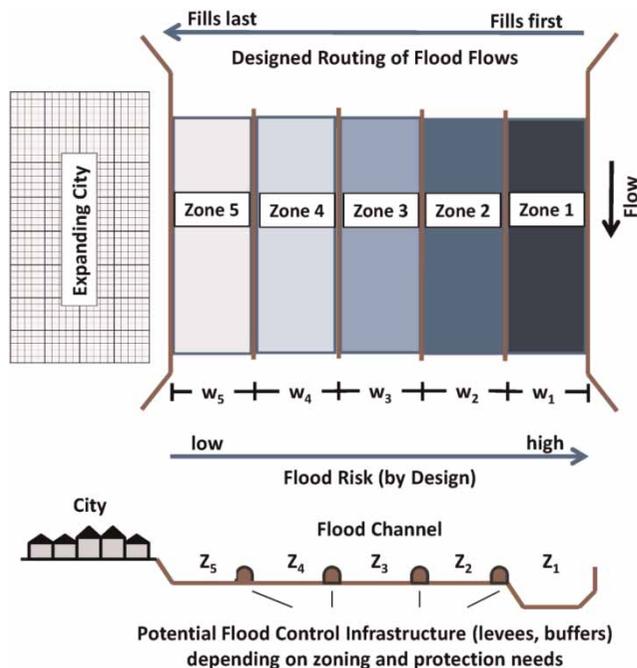


Figure 1 | Flood channel schematic as depicted in model, with view from above (top) and channel cross-section (bottom). The flood channel is divided into zones, which are inundated from right to left as runoff based on flood control structures and design. The highest flood risk is in the main flood channel, Zone 1, on the right side. Other zones may have a variety of protective or green infrastructure measures, depending on design.

flood channel:

$$\text{Max } Z = \sum_{u=1}^i \sum_{z=1}^j \left[X_{uz}(B_{uz} - C_{uz}) - \sum_{s=1}^k p_s X_{uz} D_{uz,s} \right] \quad (1)$$

where $u \in \{\text{possible land uses}\}$, $z \in \{\text{zones in the flood channel}\}$, $s \in \{\text{flood events}\}$.

Total benefits are the difference between the net benefits of developing land in the river channel and expected annual damages of land development in the flood channel. The decision variable in the model, X_{uz} , is the number of units (hectares) of land use, u , developed in zone z . The channel length is assumed to be the same for all zones within the channel, since a section of the riverbed would be developed all at once. The model calculates total benefits as the net benefits minus expected damages. The net benefits of development are calculated by multiplying the number of units (hectares) allocated for a given land use in each zone by the difference of (1) annualized unit benefits of development in the zone (B_{uz}) and (2) annualized unit construction costs of development in the zone (C_{uz}). The expected annual damages are calculated by multiplying the number of hectares of a given land use in each zone, the unit damages ($D_{uz,s}$) occurring from a flood event (s), and the event probability (p_s).

In many applications of economic analysis for flood protection, potential actions are compared to a 'no action' case. The sum of costs and expected annual damages for a set of actions would be compared to the sum of costs and expected annual damages for the no action case. In this framework, however, expected annual damages are compared to net benefits of development.

Channel flow capacity can be determined using any number of approaches appropriate to available data and expertise for a region. Here, the conveyance capacity of a zone is calculated using Manning's equation for velocity in an open channel and a standard estimation of flow rate. The velocity requires parameter estimates for the hydraulic radius (R), bottom roughness (Manning's n), and the channel slope (S):

$$V_z = \left(\frac{k}{n_z} \right) \left(\frac{A_z}{P_z} \right)^{2/3} S_z^{1/2} \quad (2)$$

The cross-sectional area (A_z) and perimeter (P_z) for each channel are based on the zoning and design of the flood control system. During floods, flows successively fill each zone

Table 1 | Description of fixed-width and variable-width cases used in the model

Case	Objective	Decision variables	Description
Fixed width zones in flood channel	Maximize total benefits of floodplain development (net benefits minus expected damages)	Number of acres developed for a land use in each zone in a flood channel (X_{uz})	Simulates a case where regulations, planning, ecology, or existing infrastructure establishes zoning restrictions within the flood channel
Variable width zones in flood channel		Number of acres developed for a land use in each zone in a flood channel (X_{uz}) Width of each zone in the flood channel (w_z)	Simulates a case where no restrictions exist for zone widths in channel, providing more flexibility to size channel zones according to benefits and risks

based on the design, starting with Zone 1. For each zone, the flow capacity (m^3/s) is the product of velocity and cross-sectional area in the channel:

$$Q_z = V_z A_z \quad (3)$$

Flood flows successively inundate each zone of the floodplain based on designed flood control measures and channel geometry. The main flood control channel (Zone 1), which fills first, is a trapezoidal configuration. With larger floods, additional zones become inundated. The flow capacity in the entire channel is equal to the sum of the flow capacities in each channel:

$$Q_T = \sum_{z=1}^j Q_z \quad (4)$$

Decision variables identify the mix of land uses in each zone of the floodplain that provide benefits of development while minimizing damages from flooding. The total land area (L_T) in the entire channel is equal to the sum of areas dedicated to each land use across all zones:

$$L_T = \sum_{z=1}^j L_z = \sum_{z=1}^j w_z * l = \sum_{u=1}^i \sum_{z=1}^j X_{uz} \quad (5)$$

Finally, non-negativity constraints require the number of acres of a land use in each zone to be equal to or greater than zero.

Land-use and channel width restrictions

The model incorporated two cases. In the first case, the objective function optimized one decision variable of the

number of acres per land use in each zone (X_{uz}). The widths of the zones within the flood channels were fixed. The second case included two decision variables: the number of acres per land use in each zone (X_{uz}) and the width of each zone (w_z) (Table 1).

Application: case study for Baja California Sur, Mexico

The model was applied in a case study for a dry, rapidly urbanizing coastal watershed in Baja California Sur, Mexico. Throughout the region, runoff collects from inland and drains through channels (arroyos) towards the ocean. Long periods of no rain are typical, but intense hurricanes can bring the equivalent of the annual average of rainfall during short periods. Dedicated flood channels, carved over years of runoff from such storms, cover the landscape.

The San Jose watershed at the tip of the peninsula spans over 127,000 hectares. During large storms, typically dry riverbeds (arroyos) quickly fill. At the outlet of the watershed's drainage network along the coast lies the city of San Jose del Cabo, which covers 4.2 hectares and has a population of approximately 87,000 people. Several arroyos cut through the city, while the large Arroyo de Santa Rosa is located directly beside the city and is the last reach of the drainage network for the entire basin, as shown in the Appendix (available online at <http://www.iwaponline.com/wst/070/256.pdf>) (IMPLAN Los Cabos 2012b). Rapid urban growth pushes development into arroyos with areas of higher flood risk. A mixture of agriculture, sporadic buildings, conservation areas, and informal housing settlements lie in the large arroyo near the city. Municipal, private sector, and other public agencies (the Municipal Institute of Urban Planning, or IMPLAN) undertake collaborative planning to try to keep pace with urban growth (IMPLAN Los Cabos 2012a).

Benefits, costs and damages

Annualized unit values (per hectare) were assigned for benefits and flood damages for each land use, annualized over a sufficiently long time using a discount rate of 5% (see Appendix). Present values of unit construction costs were based on previous studies of infrastructure development for the region (IMPLAN Los Cabos 2012a). Annualized unit costs of benefits for floodplain development were calculated based on property values for improved land and estimates of yearly economic returns.

Expected annual damages linked land use with flood effects. The runoff from an event was compared to the capacity of zones in the channel. Starting with Zone 1, if the zone capacity exceeded runoff from a given storm event, no damages were assessed. If runoff exceeded zone capacity, damages were assessed in that zone using Equation (1). The extent of flood damages were based on land-use types (see Appendix).

Estimating rainfall and runoff

Probabilities of flooding were based on an intensity–duration–frequency (IDF) curve for the region. Historic rainfall parameters were used to model IDF curves for the basin using the Chen (1983) method and reported values for the region (Campos-Aranda 2010). The analysis calculated peak runoff from a given return period using the US Soil Conservation Service method (NRCS 2010). A unit hydrograph was developed based on estimation of the time of concentration in sub-watersheds, with peak runoff calculated for the identified reach of concern in Arroyo de Santa Rosa.

Estimating event probabilities

The probability of a flood can be continuous, such as a flood frequency distribution, or discretized into intervals with a probability of occurrence or non-exceedence. With limited historical data, flood probabilities were discretized to intervals corresponding to return periods of 5, 10, 25, 50, and 1,000-year storms of 2-hours duration. The probability, p_s , of event, s , in the interval between two return periods, T_a and T_b , is the difference of the probabilities of events that do not exceed the return periods:

$$p_s = \left(1 - \frac{1}{T_b}\right) - \left(1 - \frac{1}{T_a}\right) \quad (6)$$

The probability for storm events was categorized for selected intervals of flood control targets. Based on regional

practices, the 10-year and 1,000-year events were of particular interest to guide zoning decisions in the flood channel.

Assumptions

The following assumptions are included in applying the model to the Los Cabos region.

- (1) Damage assessments are simplified. Typical flood protection projects assess damages using a variety of empirical approaches. Although the modeling framework generally assumes that data exist to assess damages from flood stage, s , for the case study, insufficient damage data exist. Damages are instead related to property values based on logical assumptions.
- (2) The model assumes a linear relationship between land area and unit costs. Yet, this may not always hold true. Convex costs may be applied using a piece-wise linear relationship and integer programming.
- (3) The model treats the Arroyo de Santa Rosa as an open channel with a specified length (3 m) and slope (0.003). Flows in Zone 1, the designated channel for small and medium storms, are based on trapezoidal channel geometry with a total depth of 2 m. For other zones, channel geometry is assumed to be rectangular based on flood control infrastructure. The simplification mimics channel geometry in some dry riverbeds of Baja California Sur, but is illustrative, and designs incorporate existing slope, landscape features, earthworks, and other measures to delineate zones. The model can accommodate varied land uses with different values of Manning's n but it ignores potential non-uniform flows.

RESULTS AND DISCUSSION

Flood protection analysis often compares flood protection actions with the 'no action' case, where actions seek to retroactively protect areas at flood risk. With an empty floodplain, the low-cost solution to a minimization problem (sum of costs and expected annual damages) would be no development. Yet, development still occurs. This framework incorporates both net benefits of development and expected damages from that development to better capture drivers of urban growth. Using a maximization formulation also allows economic analysis to incorporate other benefits from green infrastructure actions, such as pollution reduction or aquifer recharge.

Results from the case study in Baja California Sur, Mexico, identified a cost-effective combination of flood zone development decisions for two cases.

- (1) Fixed-width zones case, which optimized land-use allocations in each zone in the flood channel to determine maximum benefits. In this case, zoning or other restrictions are assumed to dictate widths for five zones of development in the flood channel.
- (2) Variable-width zones case, which optimized both the width of each zone in the flood channel *and* land-use allocations in each zone. In this case, no restrictions exist for the widths of the five zones.

In both cases, net benefits of the identified cost-effective combination of development options outweighed the expected flood damages. Total benefits were greater for the case of variable channel widths (\$6.19 billion; all monetary values given in US dollars) than the case of fixed widths (\$5.04 billion). While incentives for residential and commercial development are high for both cases, the case of variable width zones achieves higher benefits by resizing zone widths to minimize expected flood damages. The potential benefits of urban development (assumed to be 25% of development costs annualized over a long period) are strong. Although development zones in the floodplain are at significant risk from even small floods, the benefits of developing a large amount of land in the floodplain outweigh expected flood damages. For case 2, when optimizing both the land-use allocation in the zones and the width of the zones, the flood-prone zone is reduced further. Periphery zones in the flood channel (Zones 4 and 5) become larger while channels farther from the urban center handle runoff from smaller storms (Zone 1). [Figure 2](#) illustrates the width of each zone in the channel and the associated land-use allocation for each case in the analysis.

In both cases, land allocated to residential and commercial development was the dominant land use (60% of all land in the case of fixed width zones and 95% of all land in the case of variable width zones). The high damage costs associated with developed land are overshadowed by long-term revenue prospects. Model results also indicated benefits for maintaining the existing flood channels in both cases, with 40% of the land in the case with fixed widths and 5% of the land for the case of variable widths. Other allocations, including green infrastructure and agriculture, were not selected. As modeled, the long-term benefits accruing from these land uses were small compared to revenues from urban development. This reflects the case of many green infrastructure advocates, who seek to demonstrate

the varied benefits of such actions across sectors. Tables in the Appendix (available online at <http://www.iwaponline.com/wst/070/256.pdf>) detail the cost-effective land-use allocations.

Resizing channel widths allows for improved allocation of land uses in each zone. For the variable width case, smaller zones with greater flood risk (Zone 1) have no residential and commercial structures. This minimizes damages from small- and medium-sized storms (up to the 10-year storm). Yet, the benefits of developing land for residential and commercial uses dominate any smaller benefits that accrue from parks, buffer strips, or other zoning actions. In both cases, Zones 2 through 5 are entirely dedicated to developed land. Optimizing channel widths (i.e. planning with minimal regulatory, historic, and environmental constraints) allows for larger zones of lower flood risk, which can be allocated to residential and commercial development with reduced expected flood damages.

In summary, the optimization with fixed width zones allocates extensive land in the floodplain for construction, while accepting some level of damages. The variable width optimization, however, designates zones with high flood probabilities to land uses with lower flood damages. The opportunity to optimize zone widths in the flood channel also increases the number of land uses included in the cost-effective mix of land allocations. In the case of variable widths, all zones have more land uses, including land for buffer zones, retention basins, and flood routing. Thus, the analysis indicates that communities can benefit from flexibility in floodplain planning.

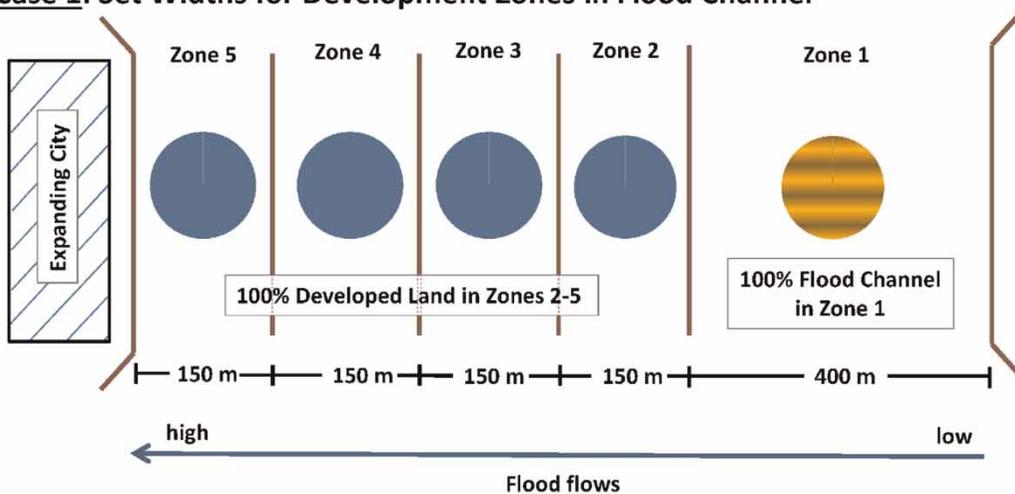
While the approach seeks to improve urban planning processes, optimizing floodplain development increases risks to human lives. The potential for loss of life is significant with such events. Some measures, such as evacuation and warning systems, are typically used to alert residents to coming storms. Yet, in industrializing countries, such measures are less robust and residents may live in sub-standard housing that cannot withstand severe weather. Planners should be very cautious to account for the devastating effects of loss of life.

LIMITATIONS

The modeling framework is subject to a number of limitations. First, reliable rainfall data in many countries are limited. Second, the analysis assumes that the probability of runoff is well-aligned with the probability of rainfall. By correlating these, runoff model assumptions become



Case 1: Set Widths for Development Zones in Flood Channel



Case 2: Variable Widths (Optimized) for Development Zones in Flood Channel

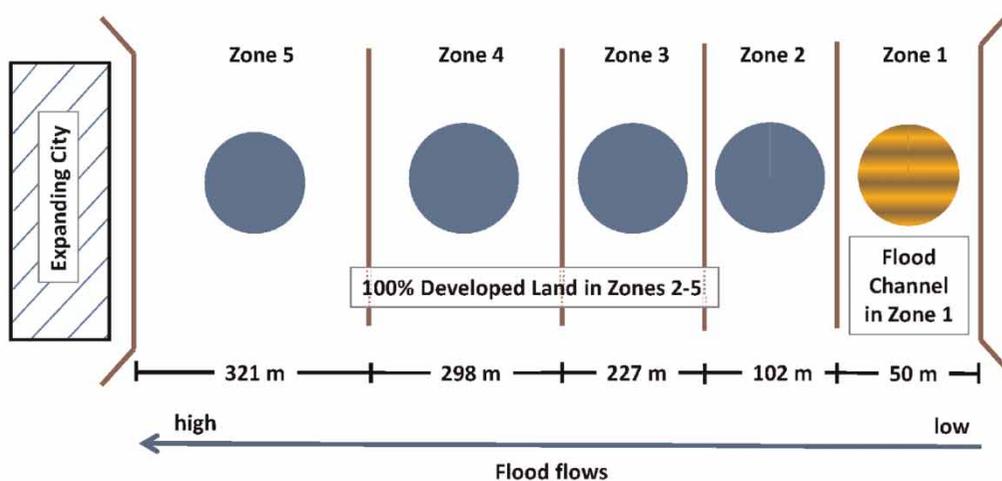


Figure 2 | Illustration of land-use allocations and widths (fixed and optimal) for each development zone in flood channel. The design capacity for each zone (flood return period) increases from right to left. Only flood channels and urban development were identified as land uses in the developing floodplain.

part of the overall uncertainty. Third, the analysis uses simplified channel hydraulic calculations. Many situations would require more precise flow modeling of areas with potential flooding near the city, which may include structural impediments and non-uniform flows. In the case above, the simplifications may make more sense since flows occur in a large, open channel with relatively uniform characteristics in the reach of concern. Fourth, in many situations, existing channel geometry may restrict the available zoning options. Finally, the model assesses

net benefits and damages from development together, which implies that the same parties can accrue both and compare tradeoffs. In many real-world situations, different parties experience benefits, costs, and damages from developing in floodplains. For instance, private citizens may benefit from development while municipalities spend money on flood protection infrastructure that expands available urban areas. National insurance programs can alter risks for some parties to promote urban expansion. Nevertheless, infrastructure development often brings

monetary benefits to many, including public decision-makers, through property acquisitions and even kick-backs (Caro 1974). Thus, urban development in floodplains can yield a variety of monetary and political rewards for all parties.

CONCLUSIONS

A risk-based model was presented to assess cost-effective decisions for land-use allocation and zoning in a flood channel near an expanding urban region. The optimization used a linear programming formulation to maximize total benefits of building in the floodplain, considering net economic benefits of development and potential damages from flood events. The model was applied to a case of an urbanizing region in a dry, coastal, equatorial zone, which is subject to long periods of dryness and large annual tropical storms and hurricanes.

The analysis identified several important points. First, even given significant risk of damages from storms, economic benefits accrue from development in most portions of the flood channel, especially in areas of lower risk that may be flooded only by large storms. As available land in a growing region becomes scarce, the economic benefits of development will likely drive more legal and illegal settlement. Second, dividing the channel into different zones of development can help to efficiently allocate land uses while providing flood control and environmental benefits. Total benefits are greater with fewer zoning restrictions in the channel, primarily due to the opportunity to reduce flood risk for higher-value land uses. Third, zoning may provide opportunities for integrated urban planning using landscape designs that remove runoff contaminants or provide recreation. Buffer zones work in both directions by slowing rising flood waters or filtering urban runoff. Swales, retention ponds, and other designs are increasingly popular to decrease pollutant loading from urbanization. Finally, simple modeling frameworks can provide insights while being adaptable to many situations. The economic, environmental, and spatial parameters included in the model are easily adaptable to other regions facing similar decisions for floodplain development.

The question of floodplain development has consequences for economic prosperity and human health. Many cities locate near water to facilitate commerce and provide resources. More vulnerable land is typically left fallow during early growth, but later built up through formal and informal development. City governments are often unable to effectively enforce the restrictions as informal settlements appear. Such settlements, however, are very unlikely to

benefit from flood protection measures. They also affect water quality via contaminated runoff. Yet, they are vibrant centers of economic activity, especially for new urban migrants. The question of effective management for floodplain development is complex. The analysis identified how risk to economic and human welfare can increase from overall 'beneficial' decisions for floodplain settlement that are not well planned. As urban regions are likely to continue growing through the century, risk-based optimization can improve planning that seeks economic output, environmental preservation, improved human health, and reduced flood risk.

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