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Short communication

Predicting tidal flooding of urbanized embayments: A modeling framework and data requirements

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ABSTRACT

Numerous urbanized embayments in California are at risk of flooding during extreme high tides caused by a combination of astronomical, meteorologic and climatic factors (e.g., El Niño), and the risk will increase as sea levels rise and storminess intensifies. Across California, the potential exists for billions of dollars in losses by 2100 and predictive inundation models will be relied upon at the local level to plan adaptation strategies and forecast localized flood impacts to support emergency management. However, the predictive skill of urban inundation models for extreme tide events has not been critically examined particularly in relation to data quality and flood mapping methodologies. With a case study of Newport Beach, California, we show that tidal flooding can be resolved along streets and at individual parcels using a 2D hydraulic inundation model that captures embayment amplification of the tide, overtopping of flood defenses, and overland flow along streets and into parcels. Furthermore, hydraulic models outperform equilibrium flood mapping methodologies which ignore hydraulic connectivity and are strongly biased towards over-prediction of flood extent. However, infrastructure geometry data including flood barriers, street and parcel elevations are crucial to accurate flood prediction. A real time kinematic (RTK) survey instrument with an error of approximately 1 cm (RMSE) is found to be suitable for barrier height measurement, but an error of approximately15 cm (RMSE) typical of aerial laser scanning or LiDAR is found to be inadequate. Finally, we note that the harbor waterfront in Newport Beach is lined by a patchwork of public and private parcels and flood barriers of varied designs and integrity. Careful attention to hydraulic connectivity (e.g., low points and gaps in barriers) is needed for successful flood prediction.

1. Introduction

Absolute sea levels are projected to rise 1–1.4 m along the California coast in the next century (Cayan et al., 2009). A statewide impact assessment indicates a wide range of critical infrastructure including 5600 km of roadways, 450 km of railways, 29 wastewater treatment facilities and countless buildings and contents valued at over $100 billion dollars are at risk (Heberger et al., 2009), and there have been calls for statewide adaptation planning and action at the local level. A California Assembly Bill, introduced in the 2009–2010 legislative session, would require local entities to develop "sea level action plans" that estimate the financial costs of sea level rise and develop plans to prevent or mitigate damage to development, infrastructure and habitats. Local, regional and global planning efforts of a similar nature are underway in many parts of the world, particularly in the UK (Defra, 2005; Hall et al., 2005, 2006). A recent investigation of coastal flooding and erosion scenarios demonstrates natural coastal erosion yields significant flood risk benefits and urges managed retreat as a necessary adaptation strategy (Dawson et al., 2009). Another study urges a dynamic approach to flood risk management and suggests managed retreat as a tool to facilitate estuary migration (Pethick, 2001). Broad actions to reduce future flood impacts are also encouraged: the reduction of greenhouse gas emissions, avoidance of anthropogenic subsidence enhancement, upgrading flood defense infrastructure and control of coastal floodplain development (Nicholls, 2002). Globally, four major impacts have been identified from sea level rise analyses: wetland and lowland inundation and displacement, shoreline erosion, enhanced storm flooding and increased salinity effecting estuaries and potentially, fresh water aquifers (Nicholls, 2002, 2007).

This study is focused on coastal flooding, and the manifestation of "sea level rise" as an increase in the frequency and severity of extreme events. From a California flooding perspective, the greatest threat is posed by the coincidence of high tides and winter storms that cause a surge in ocean height and excite wave activity. A strong winter storm can yield a surge of 0.2–0.3 m over a period of hours (Flick, 1998), in contrast to the Gulf and Atlantic Coasts where storm surges on the order of meters are possible and have been the focus of coastal

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flooding studies (e.g. Bunya et al., 2010; Sheng et al., 2010). The El Niño Southern Oscillation (ENSO) is also important. During its warm phase, the jet stream intensifies, splits and redirects cyclonic systems across California and this can lead to 0.1–0.3 m higher water ocean levels over a period of days or weeks (Flick, 1986; Storlazzi & Griggs, 2000). Tides in California are a mixture of diurnal and semi-diurnal constituents and exhibit a fortnightly spring–neap cycle in the diurnal range with a spring range of 2–3 m (Flick, 1998; Zetler & Flick, 1985). Consequently, the risk of flooding is heightened under spring tide and El Niño conditions. Indeed, extensive flooding and damage has occurred during past El Niño winters with coincident spring tides and storms, while only minor flooding has resulted from spring tides in the absence of storm activity or from strong storms coincident with neap tides (Flick, 1998).

The preceding history highlights the sensitivity of California flood impacts to relatively small (10–30 cm) increases in ocean heights beyond astronomical high tide predictions, as well as the importance of wave-driven flooding. This also focuses attention on factors that, in a warmer climate, could further raise high water levels: higher mean sea levels, larger tidal amplitudes, and increased storminess characterized by greater winds and waves and lower atmospheric pressure (Bromirski et al., 2003; Flick et al., 2003; Graham & Diaz, 2001).

In California, development and infrastructure at risk of coastal flooding is concentrated around urbanized embayments that are sheltered to some extent from ocean swell and large wind waves that impact the open coast (Heberger et al., 2009). San Francisco Bay serves as one example in the northern part of the state, while Marina del Rey, the ports of Los Angeles and Long Beach, Huntington Harbor, Newport Harbor, and San Diego Bay provide examples further south. In sheltered embayments, portions of the bay front are guarded by sea walls and levees and a central issue for development and infrastructure impact assessment is the potential for overtopping and subsequent inundation. Overtopping flows may result in damaging high velocity currents and can be expected to flood low lying terrain first and progressively deepen as overtopping continues. The overtopping flow rate per unit width is scaled by the height difference between the ocean and the barrier, similar to a hydraulic weir. Hence, the flow rate can be expected to rise and fall with the rise and fall of the ocean tide and surge. A key issue becomes the total volume of water that overtops defenses, which corresponds to the integral of the overtopping flow rate per unit width over the length of sea walls and the duration of a flood event.

Concurrently, in the context of flood risk management, there has been a trend towards high-resolution social and economic impact assessment (parcel and street scale) that relies on high-resolution flood intensity data (flood depths and velocity) (Ernts et al., 2010). Aerial laser altimetry or LiDAR is capable of measuring ground elevation with a spatial resolution (~1 m postings) and vertical accuracy (~10–15 cm) that is adequate for many flood mapping applications (Colby & Dobson, 2010; Gesch, 2009; Gallegos et al., 2009; Sanders, 2007; Webster et al., 2004), and the National Research Council (NRC) has called for a National LiDAR terrain modeling effort for flood mapping purposes (National Research Council, 2009) However, multiple studies have noted that low relief areas are especially sensitive to terrain representation (Bates et al., 1997; Colby & Dobson, 2010). A Canadian study conducted at Charlottetown, Prince Edward Island utilized LiDAR to map flood risk and results indicated that LiDAR can provide high resolution data for digital elevation models and flood risk hazard mapping, however abrupt elevation changes such as wharves, sea walls and cliffs are inadequately resolved for inundation modeling (Webster et al., 2004). Néelz et al. (2006) investigated remotely sensed data for flood modeling applications and found significant LiDAR limitations for resolving walls, banks and other hydraulically significant features and emphasizes the need to conduct a high accuracy RTK survey of hydraulically important features. A study on Canvey Island (UK) highlights the complexity and uncertainty inherent to urban flood modeling and urges uncertainties such as flood defense breaching, failure and localized flow sources and sinks to be explicitly incorporated into model predictions (Brown et al., 2007). Cartesian or raster grid modeling of coastal flooding resulting from sea level rise emphasizes the importance of coastal topographic complexity and advocates enforcement of fine scale features such as ditches and dikes within the model (Poulter & Halpin, 2008). In a recent analysis of LiDAR elevation data for delineation of land vulnerable to sea level rise, Gesch (2009) suggests that future assessments will prove more useful and reliable if detailed and infrastructure information included. Additionally, Heberger et al. (2009) calls for the survey, assessment and cataloging of existing flood defenses along with more rigorous local modeling to guide coastal adaptation. Collectively, these studies illuminate the need to incorporate flood defense barriers and associated uncertainties to develop robust local inundation models, and not simply rely on LiDAR data alone. However, the level of accuracy required for the heights of barriers subject to overtopping is not clear, nor is the benefit of hydraulic flood routing methodologies over "bathtub" type models (e.g. Heberger et al., 2009; Knowles, 2009) that determine flood zones by a simple comparison of ocean and land heights.

The objective of this paper is to describe a framework for regional, high resolution mapping of tidal flooding impacts in urbanized embayments and to present a case study of Newport Beach, California that reveals the predictive skill of high-resolution inundation models including a characterization of prediction uncertainties related to data quality and modeling methodologies. This information is essential for meaningful sea level rise impact assessment and effective adaptation planning and emergency management. While wave-driven flooding is also important in California, particularly along the open coast, it is less important in sheltered embayments and is not addressed here in order to focus on tidal flooding.

2. Methods

2.1. Site description

Newport Beach is an economically important, densely populated California coastal community located approximately 70 km southeast of Los Angeles shown in Fig. 1. The City of Newport Beach encompasses one of the largest estuarine embayments in California, Newport Harbor, and is geographically divided into three zones; high relief elevations on the eastern portion of the city, elevated marine terraces on the northwestern portion of the city and urban coastal lowlands which include Balboa Peninsula and Balboa Island, the foci of the investigation. The Peninsula shelters Newport Harbor from swell and large wind waves from the Pacific Ocean, so the outer Peninsula shoreline is exposed to wave-driven flooding while the inner harbor is exposed to tidal flooding. Sand dunes correspond to the highest topography along the Peninsula and therefore constitute its flood defense, while the inner harbor is protected primarily by concrete flood walls. Balboa Island is one of the most densely populated communities in the United States and is fully encircled by a concrete flood wall. Both Balboa Island and Peninsula have experienced several episodes of flooding in the past century including Hurricane Liza generated swell in September 1968 which impacted the outer Peninsula and El Niño Southern Oscillation storm events in 1972–1973, 1982–1983, 1987–1988 and 1997–1998. More recently, on January 10, 2005 the combination of an extreme high tide and a cyclonic low pressure storm system caused tidal flooding of both Balboa Peninsula and Balboa Island. As described in Section 2.3, the January 10 event was thoroughly documented by the City of Newport Beach personnel and therefore serves as a validation dataset for this study.

2.2. Topographic and bathymetric data

The City of Newport Beach provided LiDAR data and orthoimagery from a 2006 city commissioned survey. Original orthoimagery was