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Tsunami Propagation in Tidal Rivers

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Foreword

Flooding from the sea took thousands of lives in northeast Japan in December 1611. News of the disaster reached the first Tokugawa shogun. One of his aides wrote of the flooding as a “so-called tsunami”—an early conjoining of characters for harbor (*tsu*) and wave or waves (*nami*).

It is unlikely that the 1611 tsunami was confined to harbors. In northeast Japan it reached heights of 5 m or more. So did the disastrous 2011 Tohoku tsunami—and its waves, in addition to flooding coastal plains, ran into and out of rivers.

Coastal rivers have also been invaded by tsunamis from the eastern Pacific. The main Chilean tsunami of 1960 swept away riverside villages near its source. Near-field tsunamis in North America’s Cascadia region are evidenced by sheets of sand beside tidal streams that successive waves ascended. Documented far-field effects of the 1700 Cascadia tsunami include anomalous river-mouth waves, in northeast Japan, that occasioned the loss of a rice freighter and two of its crew.

In this book, twenty-first century measurements provide starting points for exploring how tsunamis interact with rivers. The measurements were made in rivers on both sides of the Pacific and beside the Indian Ocean as well. They inform analyses of how a riverine tsunami increases average water levels, why it intensifies during rising tides, and how it behaves after transforming into bores. The findings shed light on the fluvial expressions of the so-called harbor waves.

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October 2017

Preface

"One cannot step into the same river twice, for other waters are continually flowing on" (Heraclitus of Ephesus, 535 BC – 475 BC).

People have settled around rivers for probably as long as they have inhabited the planet Earth. To most, the rivers are one-way systems, where the waters make their way toward the ocean. The river water is like time: it is always moving in one direction, from past to the future, from mountains to the ocean. Closer to the ocean, though, the river's philosophy changes. The ocean continuously invades rivers with tides, and occasionally—with storm surges and tsunamis. The amount of water entering the river with rising tide and leaving it with falling (ebb) tide—a so-called tidal prism—can exceed the freshwater inflow from the upstream by several times. The amount of water brought into a river by a large tsunami can exceed the tidal prism by several times. Next to the mouth, currents flow in both directions, whereas tides and tsunamis make their way upstream and away from the ocean.

Unlike the riverine current, ocean waves carry not only the fluid, but the state of motion itself, and thus typically travel much faster and penetrate much farther than the fluid particles which they move. Tides penetrate in rivers from several or a few tens of kilometers (in relatively small, steep rivers) to a few hundred kilometers (in large low-land rivers). Estuarine tidal scientists have long been studying propagation of tides into rivers. Over many years, tides have been observed in river estuaries, assigned a number of specific parameters in the process, and analyzed for how these parameters depend on the distance from the river mouth, on the shape of the channel (exponentially narrowing channels are commonly considered), sometimes—on the riverine current, and on some other conditions. A tsunami is just a "short tide," and therefore behavior of well-studied river tides can be extrapolated to tsunamis. Or can it be? Tsunami observations in rivers sometimes display features not known in relation to river tides, nor fully explicable in terms of harmonic constituents employed by tidal hydrodynamics.

This book reflects on recently collected evidence of tsunami penetration in rivers. It will focus on three of the observed phenomena. Firstly, in rivers on the east coast of Japan invaded by the Tohoku tsunami of March 11, 2011, average water levels rose with the tsunami arrival and remained elevated for many hours, even during the tsunami withdrawal phases. Secondly, after crossing the Pacific and losing much of its destructive power, this tsunami propagated into the Columbia River in the USA and clearly showed tsunami's modulation by tide, progressing upriver. Records of earlier tsunamis imply that propagation of relatively small tsunamis in rivers is controlled by tidal phase in a typical manner: receding tide obstructs the intrusion, while high tide facilitates it. And lastly, the 2011 Tohoku tsunami occasioned a set of detailed water level records of a train of bores propagating in a river.

Analysis of these observed phenomena can be a step for improving predictions of the upriver impacts of a tsunami. Modern tsunami forecasts provide, in real time, accurate estimates of when far-traveled tsunami waves will reach a coast, and how high they will be. One of the purposes of this book is to lay a basis for predicting tsunami upriver impacts with the tsunami forecast near the mouth, and a few parameters defining a river's response. Which river parameters quantify tsunami dynamics in a river, how these parameters can be computed knowing a river's morphology, how these parameters can be found using everyday tidal observations—these are some of the questions which this book attempts to answer.

This book employs three methods of investigation, which rely on three different information sources: field data analysis, numerical experiment, and analytical analysis. Field observations, such as water level measurements or the high water marks, are meant to sample ground truth. Thereby wave patterns, which emerge from field observations, presumably convey the ground truth as well. However, finding the physics behind those patterns might be challenging: there are too many factors affecting wave dynamics in a natural river, and there are never enough observations to fully describe the spatial and temporal evolution of the wave. By contrast, numerical experiments supply unlimited observations in a simplified, fully regulated river model with no unknowns. Numerical experiments can greatly aid deducing the wave patterns, but leave the question of whether the simplified numerical river provided adequate representation of real-world conditions. Field data and numerical simulations can be used in the same manner and for the same purpose: to deduce which river conditions, and in which way, affect tsunami intrusion. Differently, an analytical solution provides immediate answers to these questions but often requires further simplification of reality. The three methods aid, guide, verify, and sometimes duplicate each other in our attempts to understand tsunami penetration in a river.

Moreover, the three methods allow the observed wave phenomena to be explained both in layman's terms and in equations of the non-linear shallow-water theory. So, a reader wishing to bypass the extensive use of differential equations can skip analytical chapters. The author tried to compose this book so that the two analytical chapters were complementary rather than mandatory for understanding the rest of the material. This book is not a textbook but can be used as supplemental reading for a course on water gravity waves. The book is intended for specialists in the hydrodynamics of tsunamis and tides, as well as—after omitting the differential equations—for nonspecialized readers interested in natural phenomena.

The author found her determination for writing this book at NorthWest Research Associates, Inc.—a small institute owned and operated by its scientists, brought together by a passion for science and, with occasional luck, by funds to do it. This book grows from a series of four articles published in *Pure and Applied Geophysics* in 2013–2016. Some of the articles are written jointly with Professor Hitoshi Tanaka of Tohoku University, Japan, who has been collecting tsunami observations in rivers, and to whom the author is thankful for sharing these unique datasets. The Preface and Chap. 1 were improved by reviews from Brian Atwater of the U.S. Geological Survey and University of Washington. The author deeply thanks Irina Tolkova and Igor Tolkov for improving English of the original manuscript, and Valeriy Tolkov for troubleshooting all computer-related issues. Water level measurements in rivers in Japan, displayed in this book, came from stations operated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan. Gage records in the Columbia River, USA, and at the offshore buoys were provided by the National Oceanic and Atmospheric Administration (NOAA), USA.

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