L-113-01-63

臺日「河川預警與模擬技術」交流講席會

Taiwan-Japan River Flood Warning and Simulation Technology Workshop

Hosting:

Sinotech Foundation for R&D of Engineering Sciences & Technologies
Hydrotech Research Institute, NTU
Ecological Engineering Research Center, NTU
Sinotech Engineering Consultants, Ltd.

Taiwan-Japan River Flood Warning and Simulation Technology Workshop

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Audio-Visual Classroom 406 Hydrotech Research Institute, NTU Apr-26-2024

Time	Agenda	Host
09:20~09:30	Registration	
09:30~09:40	Taiwan-Japan River Flood Warning and Simulation Technology Workshop Opening Ceremony	Chairman Sheng-Bao Tseng Professor Tsang-Jung Chang
09:40~09:50	Announcement of New Publication	Chairman Sheng-Bao Tseng
09:50~10:40	Topic: Lessons learned from recent heavy rain disasters in Japan and building a flood-resilient society that adapts to climate change Speaker: Koji Ikeuchi (President, Foundation of River & Basin Integrated Communications ; Emeritus Professor, University of Tokyo)	Professor Tsang-Jung Chang
10:40~11:00	Tea break	
11:00~11:50	Topic: Computational Challenges in River Morphodynamics by iRIC Speaker: Yasuyuki Shimizu (Senior Fellow Professor, Hokkai-Gakuen University; Emeritus Professor, Hokkaido University)	Professor Gene Jiing-Yun You
11:50~12:10	Comprehensive Discussion	Chairman Sheng-Bao Tseng Professor Tsang-Jung Chang
12:10~13:30	Lunch	
13:30~14:00	Topic: A case study on River Flood Prevention Measures in Jhuoshuei River Speaker: Yueh-Yang Li (Project Manager, SINOTECH Engineering Consultants, Ltd.)	Deputy General Manager Wen-Hao Tsai
14:00~14:30	Topic: The development and application of an efficient river flood modeling based on Cellular Automata framework Speaker: Hsiang-Lin Yu (Postdoctoral Research Fellow, Department of Bioenvironmental Systems Engineering, National Taiwan University)	Deputy General Manager Wen-Hao Tsai
14:30~14:50	Tea break	
14:50~15:20	Topic: The meshless SPH method applied to open channel flows Speaker: Kao-Hua Chang (Assistant Prof., Department of Soil and Water Conservation, National Chung Hsing University)	Dr. Jihn-Sung Lai
15:20~15:50	Topic: Hydraulic and sediment transport simulation of rivers and cross-river structures using the SRH2D model. Speaker: Fong-Zuo Lee (Assistant Prof., Department of Civil Engineering, National Chung Hsing University)	Dr. Jihn-Sung Lai
15:50~16:10	Comprehensive Discussion	CEO Chi-Bin Chen Professor Tsang-Jung Chang

Hosting:
Sinotech Foundation for R&D of Engineering Sciences & Technologies
Hydrotech Research Institute, NTU
Ecological Engineering Research Center, NTU
Sinotech Engineering Consultants, Ltd.

Co-sponsor:
Water Resources Committee, / Sustainable Development Committee of the Chinese Institute of Civil and Hydraulic Engineering

Co-organizer:
Dept. of Bioenvironmental Systems Engineering, NTU
Dept. of Civil Engineering, NTU
Dept. of Civil Engineering, NCHU
Sinotech Engineering Consultants, Inc.

臺日「河川預警與模擬技術」交流講席會

Taiwan-Japan River Flood Warning and Simulation Technology Workshop

In today's world, water resource management and disaster prevention have become crucial issues that countries worldwide must collectively face. This is especially true in the context of research and application of river flood warning and simulation technologies, which are indispensable. Taiwan and Japan are two island nations that are prone to frequent earthquakes and often affected by typhoons. The river systems in Taiwan and Japan play vital roles, impacting various aspects such as agriculture, urban development, and ecological conservation. Thus, through the “Taiwan-Japan River Flood Warning and Simulation Technology Workshop", we explore and strengthen collaboration and communication between the two countries in this field.

Rivers are not only vital sources of water resources but also significant areas for human life and production. However, rivers also serve as important pathways for natural disasters, including disasters like floods and landslides, which frequently cause severe losses and disruptions. Consequently, the development of effective river flood warning systems and simulation technologies is crucial for ensuring the safety of people's lives and properties. Taiwan and Japan, being countries prone to earthquakes and typhoons, have profound needs and experiences in river flood warning and simulation technologies. While both countries have relatively well-developed hydraulic engineering and disaster prevention systems, they must continuously innovate and improve to confront new challenges like climate change. Through this workshop, we hope to collectively discuss the latest developments, research findings, and application cases of river flood warning and simulation technologies, seeking better ways to address future challenges. Furthermore, both countries possess abundant resources and advantages in technology and talent. Taiwan is home to many outstanding tech professionals and research institutions, while Japan has numerous globally recognized universities and research organizations. Through this workshop, we can promote technological exchange and cooperation between the two countries, jointly promoting innovation and application in river flood warning and simulation technologies. Therefore, this workshop is organized by the Sinotech Foundation for Research & Development of Engineering Sciences & Technologies, the Ecological Engineering Research Center of National Taiwan University, the Hydrotech Research Institute of National Taiwan University, and Sinotech Engineering Consultants, Ltd. Also co-sponsored by the Sustainable Development Committee of the Chinese Institute of Civil and Hydraulic Engineering and the Water Resources Committee of the Chinese Institute of Civil and Hydraulic Engineering. and The Department of Bioenvironmental Systems Engineering of National Taiwan University, the Department of Civil Engineering of National Taiwan University, and the Department of Civil Engineering of National Chung Hsing University , Sinotech Engineering Consultants, Inc. co-organizes the event.

The Sinotech Foundation for Research & Development of Engineering Sciences & Technologies is dedicated to elevating the domestic standards of hydraulic and civil engineering technology. In addition to actively gathering relevant domestic literature on hydraulic and civil engineering, the Foundation actively introduces advanced technologies from abroad. Hence, through this workshop, we invite academic institutions with substantial experience and expertise, such as Hokkai-Gakuen University in Japan, National

Taiwan University, and National Chung Hsing University, to participate. Particularly in the fields of hydrology, water resource management, and geographic information systems, their participation will facilitate technical exchange and knowledge sharing, driving continuous innovation and improvement in river simulation technology. Additionally, the Foundation has invited the Japan River Information Center to participate in the workshop, facilitating the exchange of river hydrological data, meteorological information, and hydrological observation data. This is crucial for Taiwan's research and development of river flood warning systems. This workshop can promote cooperation between Taiwan and the Center, fully utilizing its rich data resources to ensure the reliability and accuracy of river flood warning systems.

We also hope that this workshop will provide an opportunity to promote cultural exchange and deepen friendship. Despite the geographical distance between Taiwan and Japan, there are many commonalities in culture, history, and values. Through the Taiwan-Japan River Flood Warning and Simulation Technology Workshop, we can deepen mutual understanding and friendship, collectively contributing more to global water resource management and disaster prevention. It will also strengthen cooperation and communication between the two countries in the field of water resource management and disaster prevention, promoting technological innovation and talent development, and making positive contributions to the sustainable development of the region and the world.

CONTENTS

Lessons learned from recent heavy rain disasters in Japan and building a flood-resilient society that adapts to climate change

池內　幸司

Koji Ikeuchi

一般財團法人河川情報中心　理事長

（東京大學名譽教授）

President , Foundation of River & Basin Integrated Communications

（Emeritus Professor, University of Tokyo）

RFWST

Lessons learned from recent heavy rain disasters in Japan and building a flood-resilient society that adapts to climate change

April 2024

President, Foundation of River & Basin Integrated Communications (FRICS)
Emeritus Professor, The University of Tokyo

Koji IKEUCHI, Ph.D.

Computational Challenges in River Morphodynamics by iRIC

清水　康行

Yasuyuki Shimizu

北海學園大學工學部　特任教授

Senior Fellow Professor, Hokkai-Gakuen University; Emeritus Professor, Hokkaido University

Computational Challenges in River Morphodynamics by iRIC

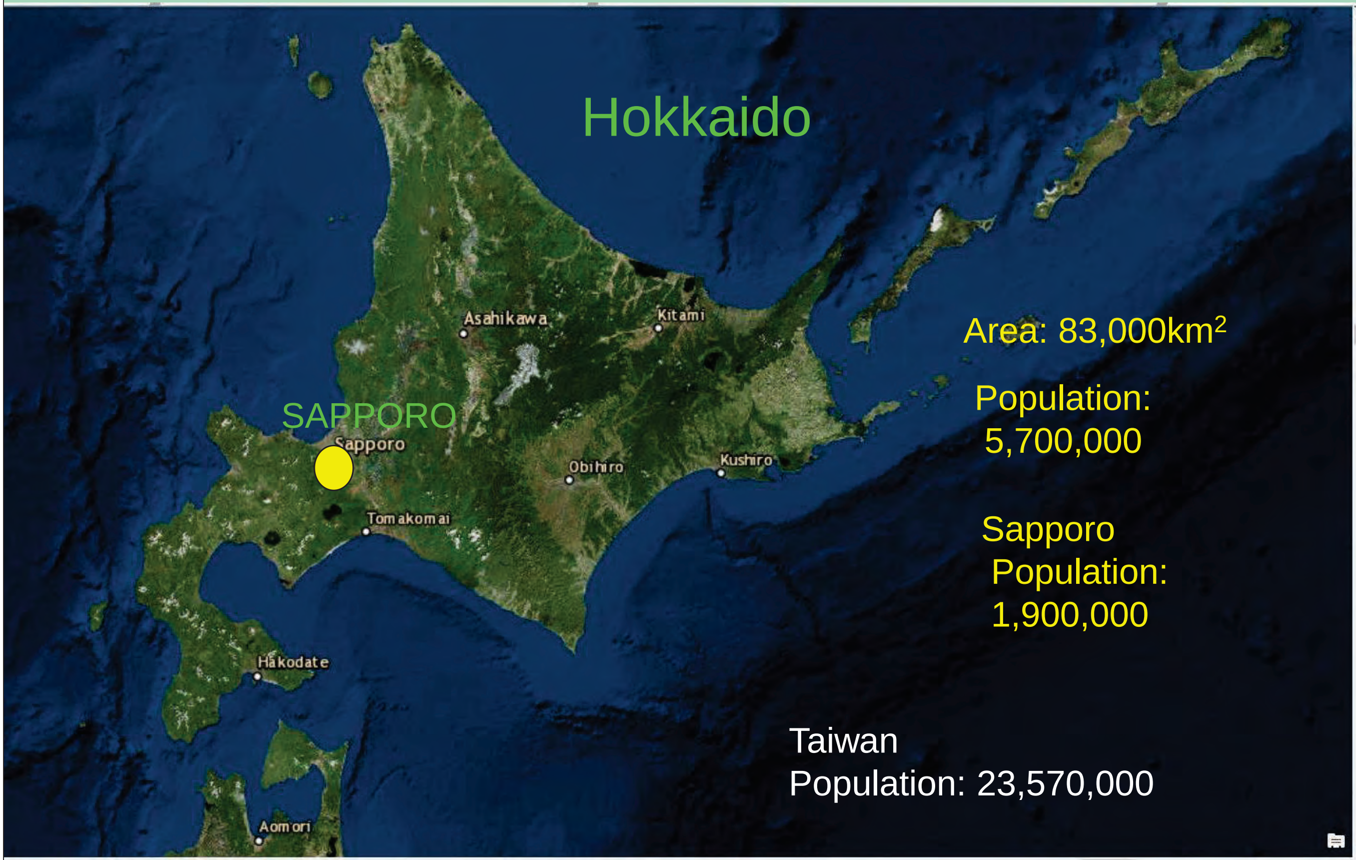
Yasuyuki Shimizu, Hokkai-Gakuen University

Yasuyuki Shimizu

Senior Fellow Professor,
Faculty of Engineering
Civil and Environmental Engineering
Hokkai-Gakuen University

Professor Emeritus, Hokkaido University

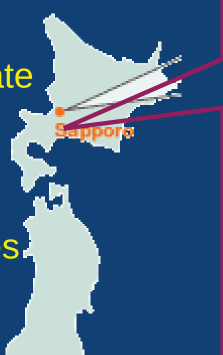
Field of Interest:
Water Related Disaster Prevention Research
Hydraulic Engineering
Water Resources Engineering
Computational Fluid Dynamics, and Computational Models
like iRIC



Where Hokkaido University is

<u>Working for Hokkai Gakuen University since April 2023</u>

- Main campus located in Sapporo, Hokkaido
- Another campus in Hakodate (Grad. School of Fisheries Sciences)
- Several off-campus facilities mostly in Hokkaido



Established in 1876
11,000 Under Graduate Students
6,000 Graduate Students
2,000 Teaching Staff
1,800 Non-Teaching Staff
12 Faculties + 10 Institutes


25

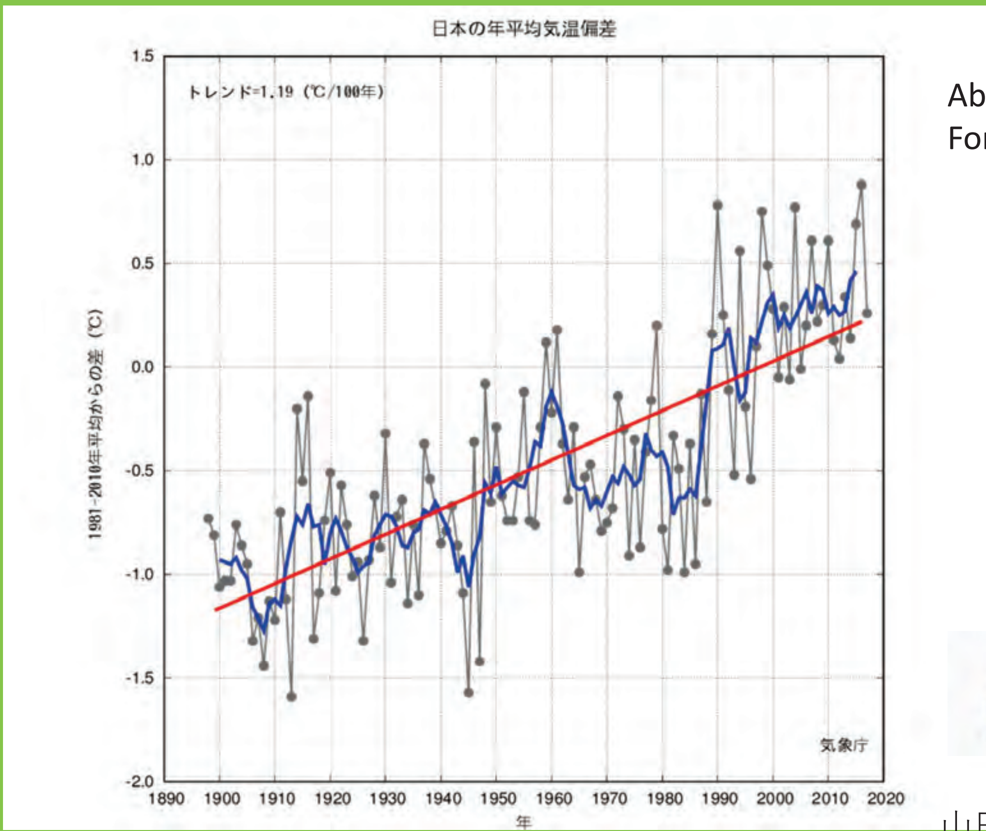
iRIC Software
Changing River Science

Introduction to iRIC Project

International
River Interface Corporative
iRIC

International River Interface Cooperative

Temperature changes of main 15 points in Japan from 1981 to 2010 (deviation from average temperature).

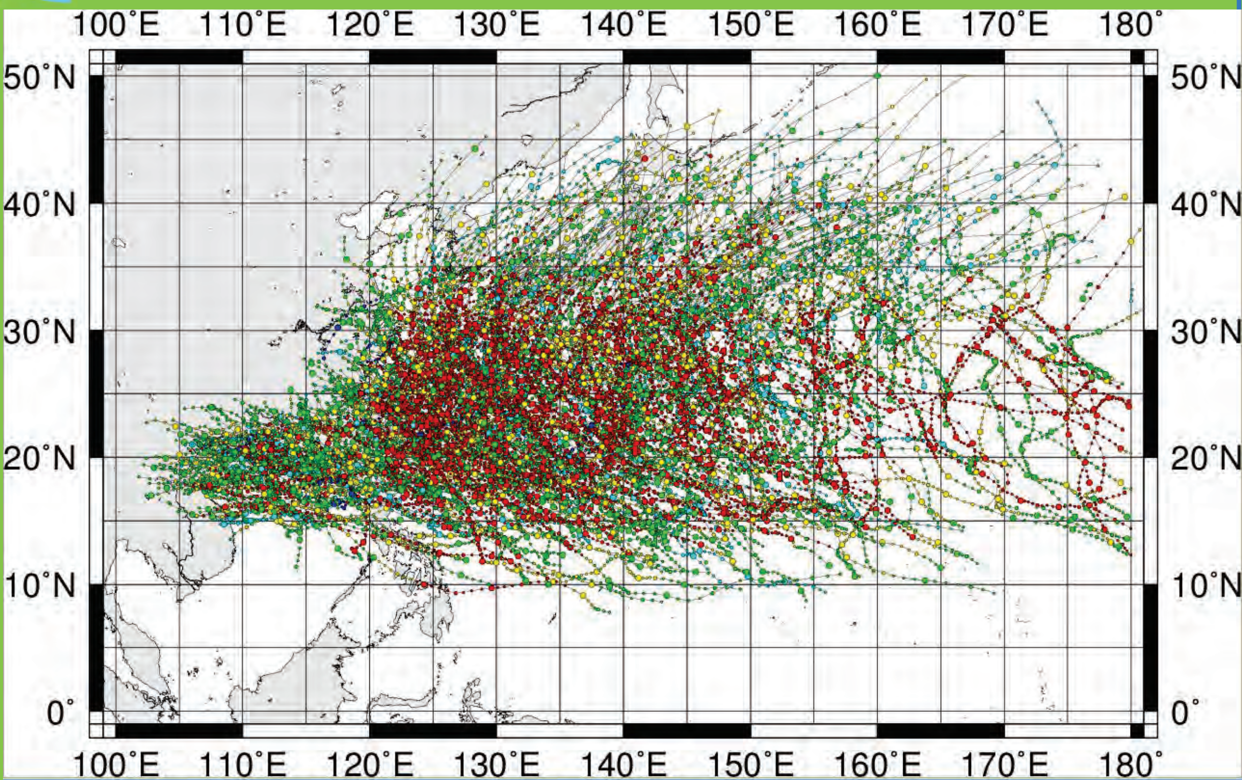


About 2.7 degree increase
Form 1900 to 2018

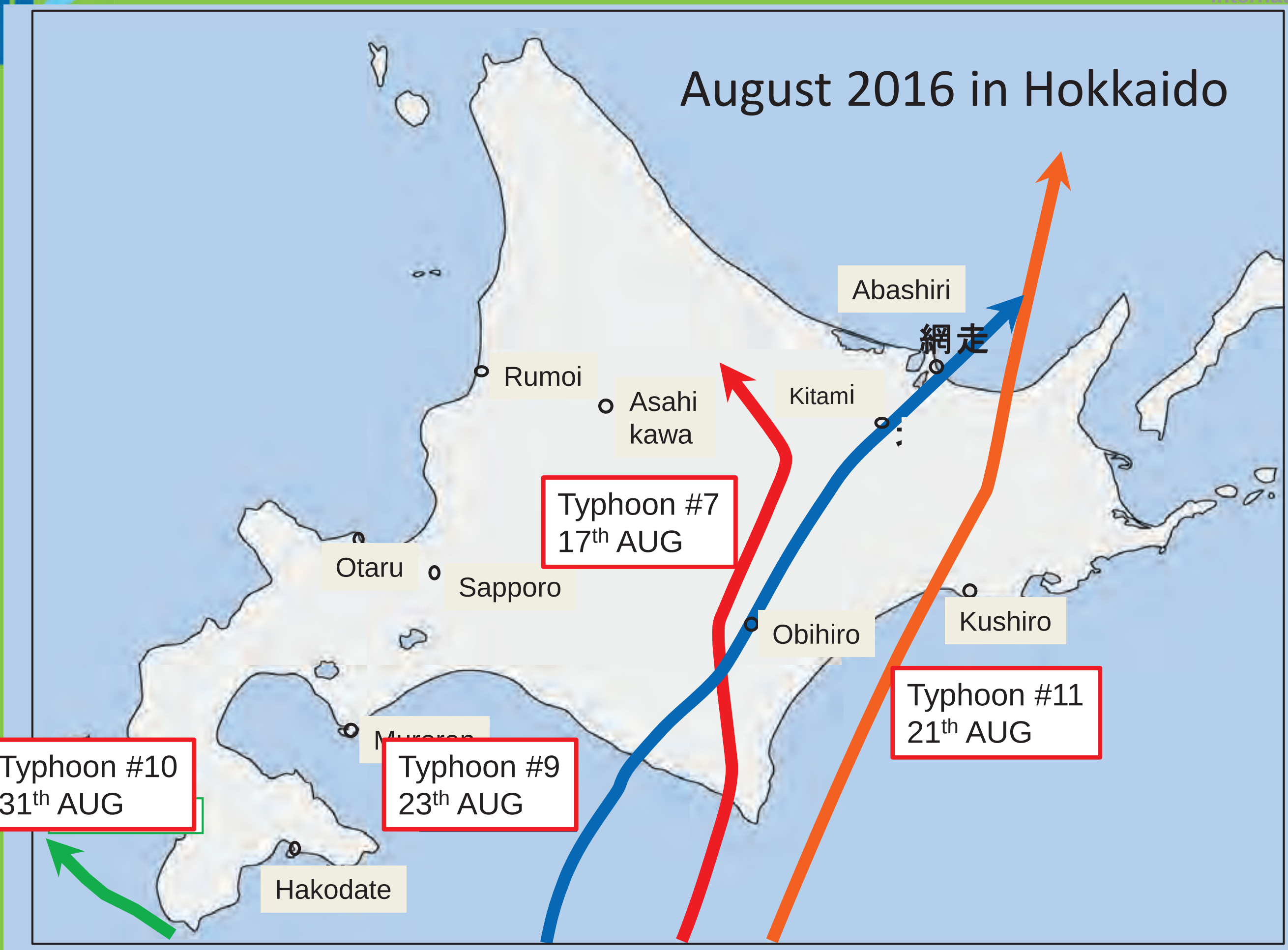
国土交通省 気象庁 Japan Meteorological Agency

Websiteより
山田朋人(2018)

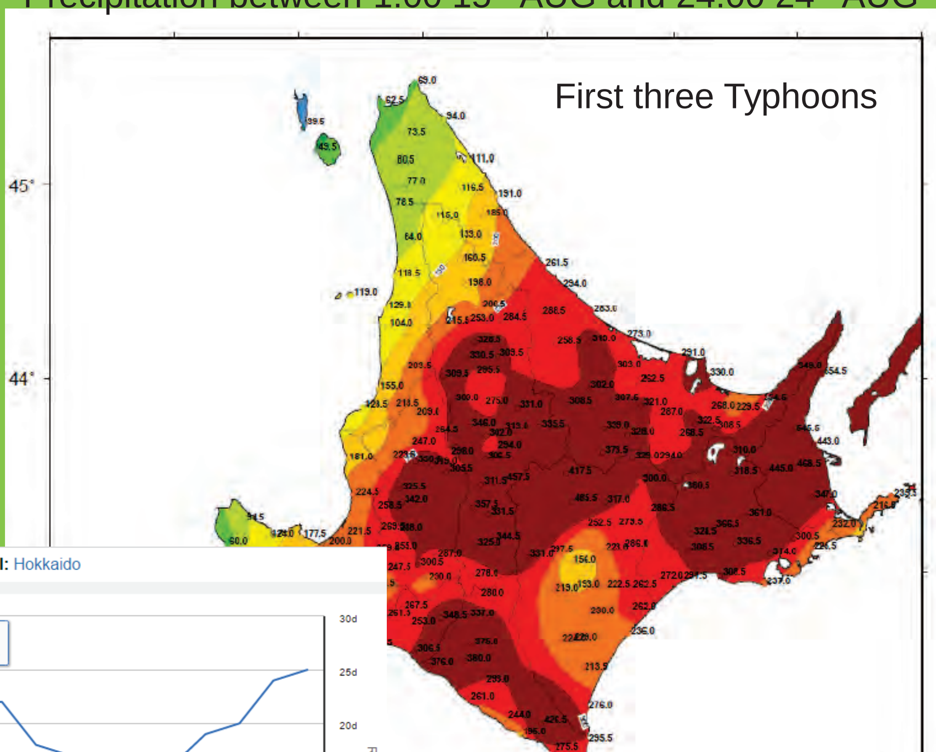
1970年～2018年，7～9月の北太平洋で発生したすべての台風の経路

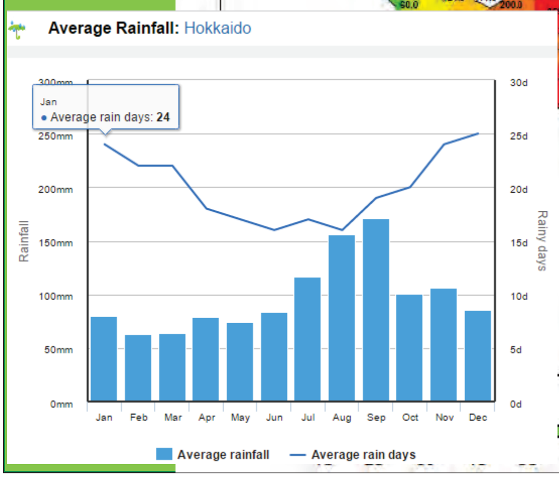


北本 朝展 @ 国立情報学研究所(NII)
デジタル台風(http://agora.ex.nii.ac.jp/)より引用



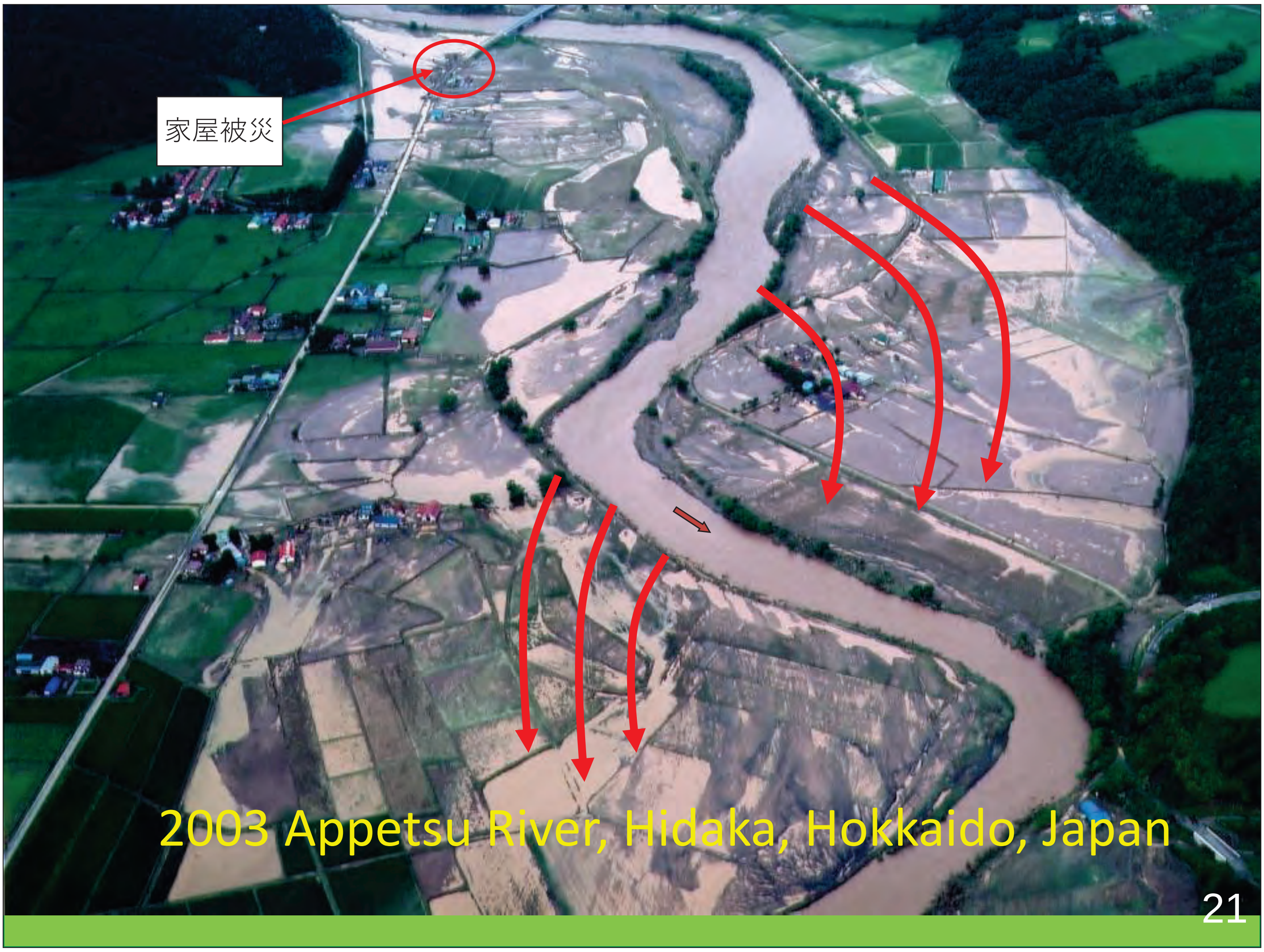
Precipitation between 1:00 15th AUG and 24:00 24th AUG





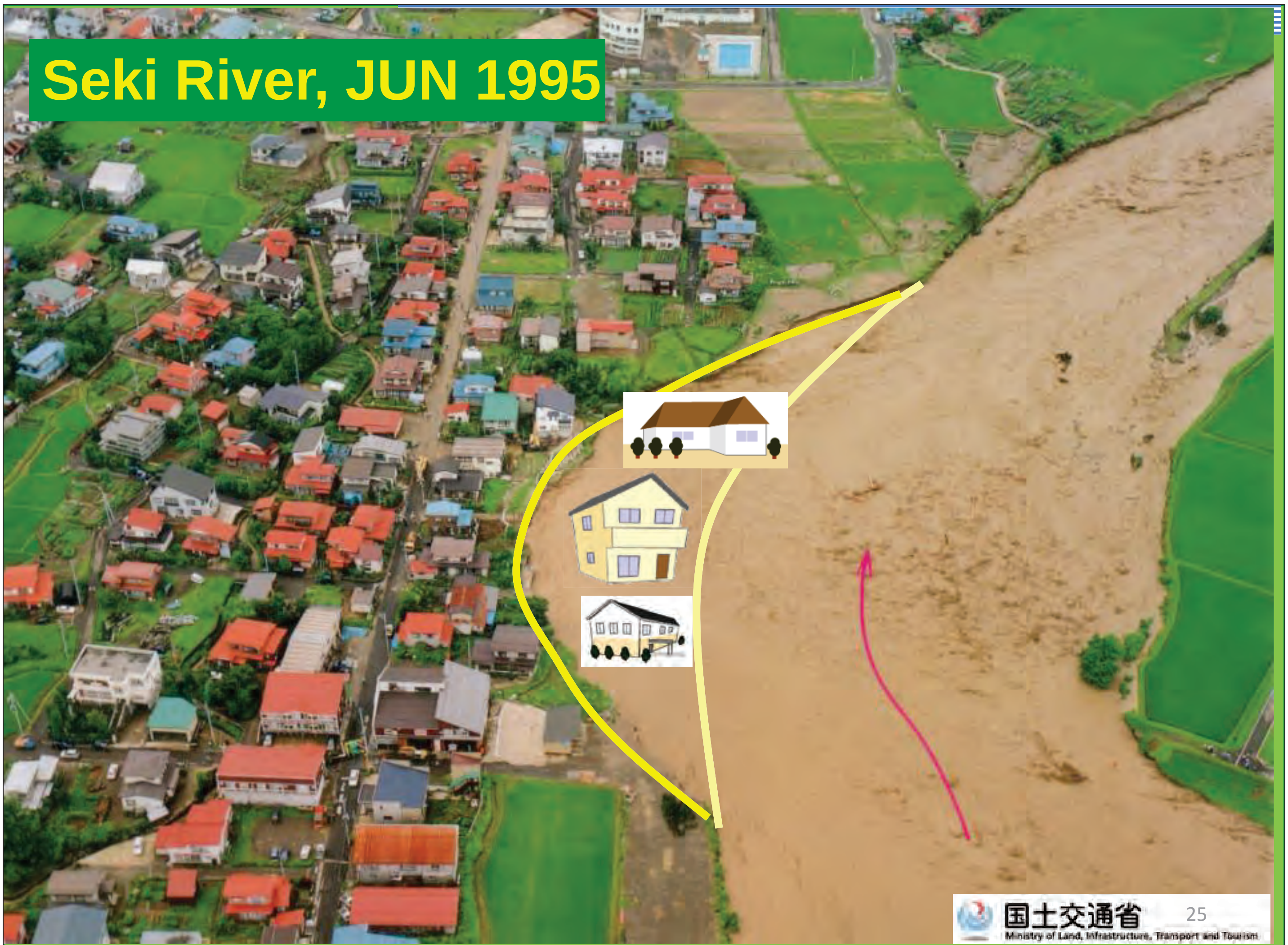
Sorachi River, AUG 2016
Hokkaido, Japan

Akatani River in Kyushu, 2017


家屋被災
2003 Appetsu River, Hidaka, Hokkaido, Japan
21


22

2011, Levee Beach Otofuke, Hokkaido



International
River Interface Corporative
iRIC

Pekerebetsu River, 2016 Hokkaido

写真提供:(株)パスコ

International
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- In order to predict, plan counter measures, estimate the efficiency of the projects, constriction works, and for the environmental assessments, we need models to reproduce and analyze these kind of natural disasters.
- Large numbers of models have been developed for these purpose, but most of them are only for limited researchers' use and using them are usually very expensive.

➢ We need free models for anybody.

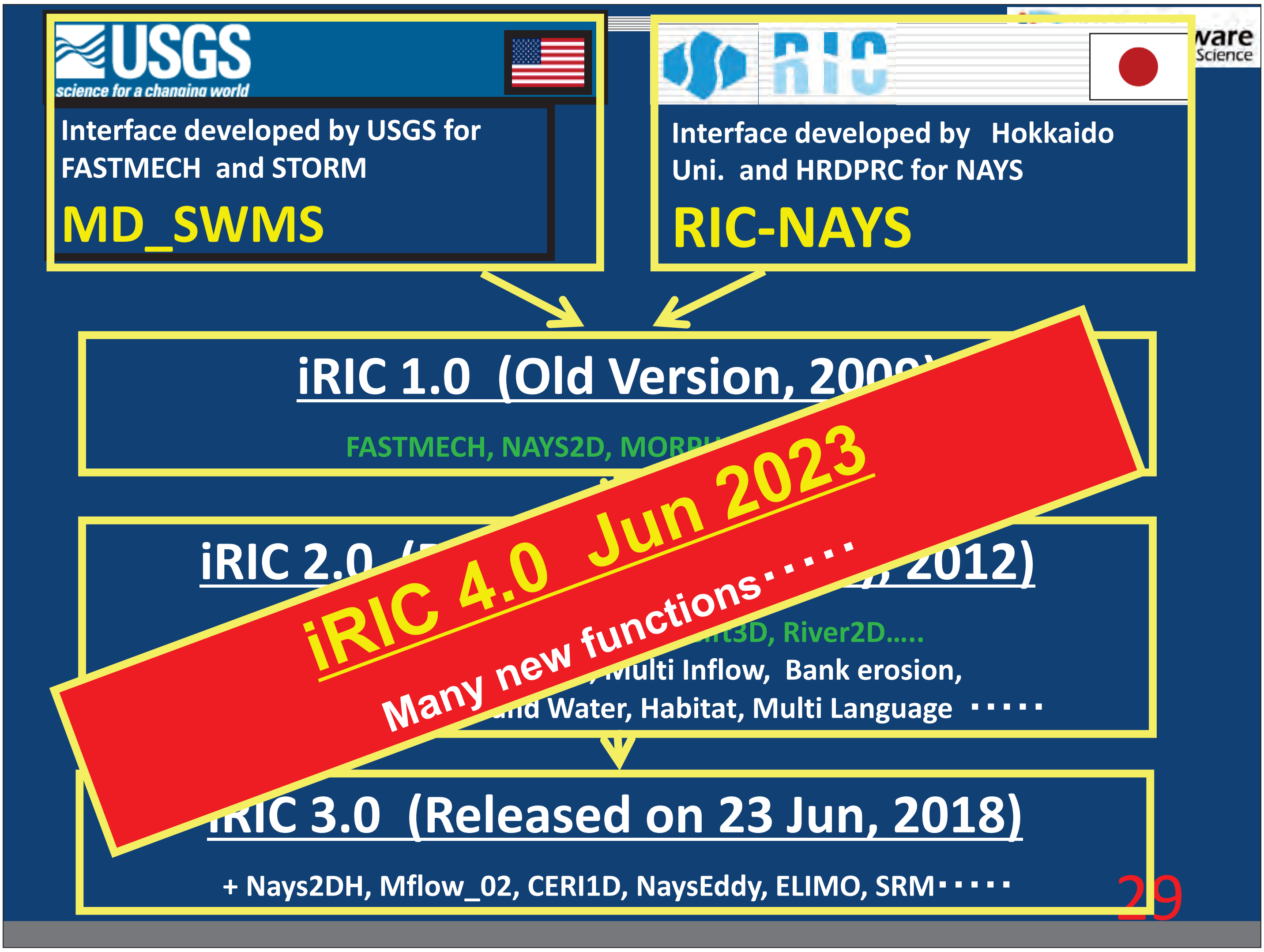
iRIC Software
Changing River Science

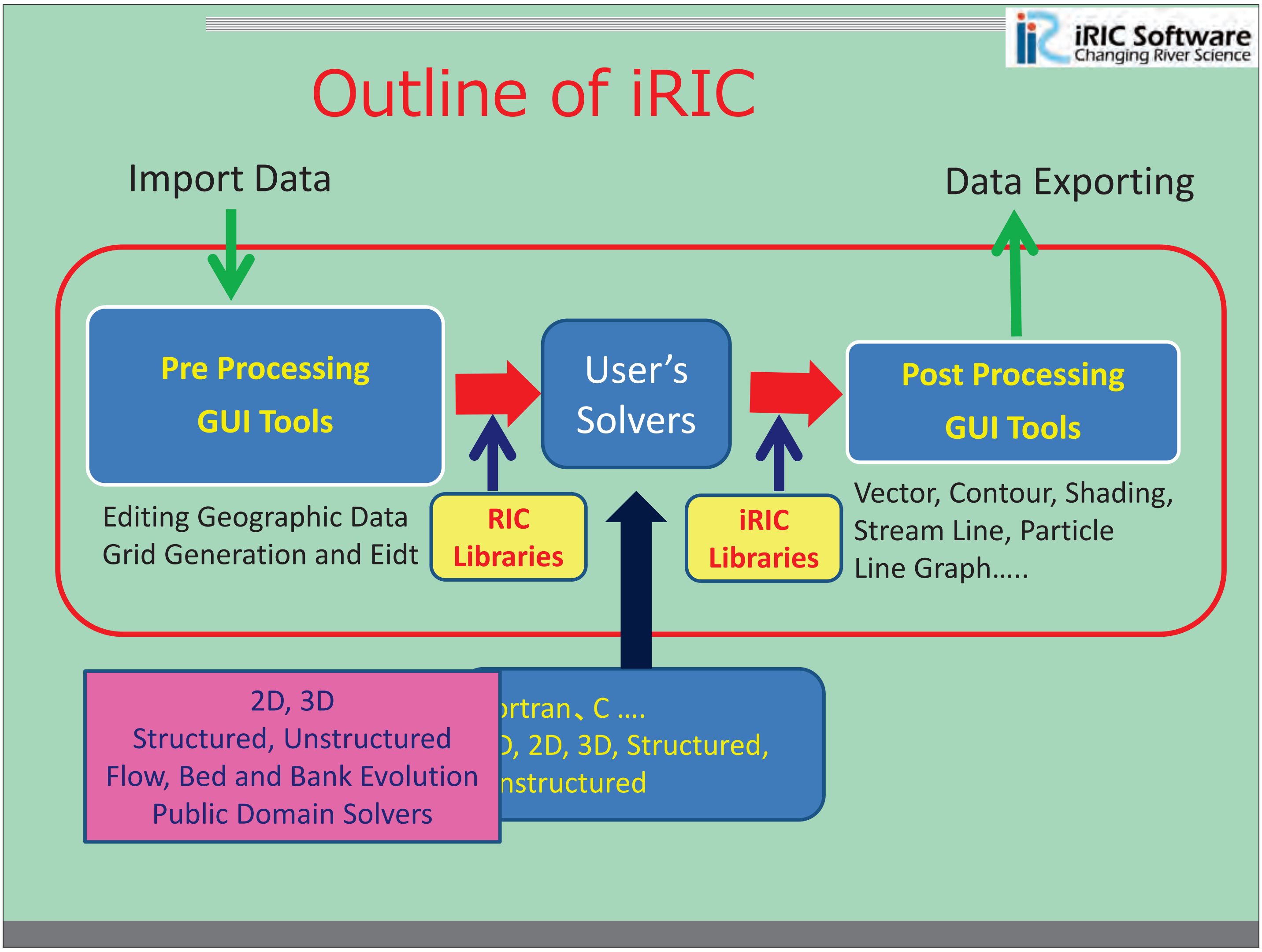
What is iRIC?

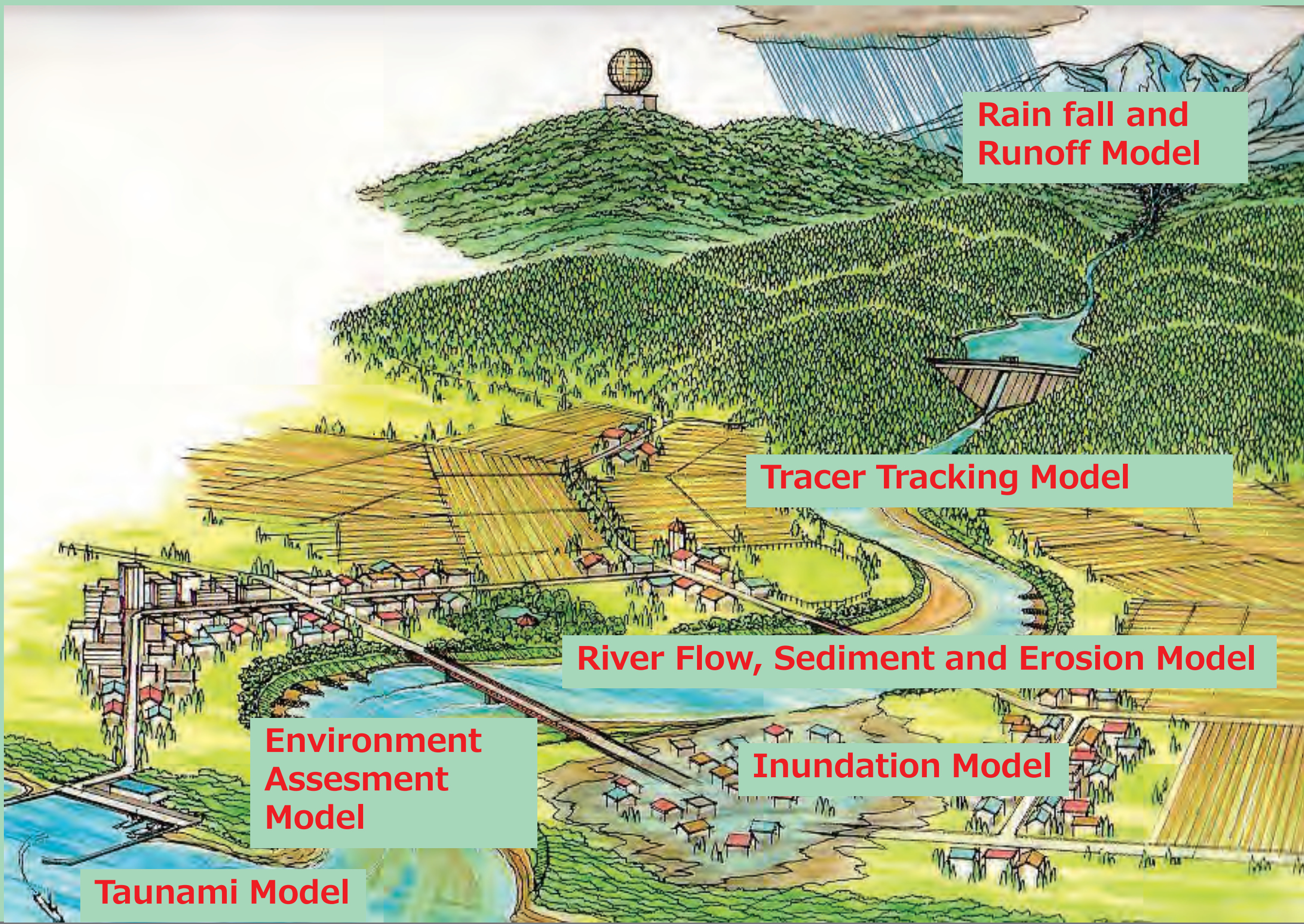
International River Interface Cooperative

iRIC is a public-domain modeling interface and an associated group of open-source models that can be used to simulate flow, sediment transport, channel and bank evolution and habitat in riverine environments across a wide range of temporal and spatial scales

Using iRIC does not mean you need to use the models we present!


USGS
science for a changing world
Interface developed by USGS for FASTMECH and STORM
MD_SWMS
RIC
Interface developed by Hokkaido Uni. and HRDPRC for NAYS
RIC-NAYS
iRIC 1.0 (Old Version, 2009)
FASTMECH, NAYS2D, MORPH
iRIC 2.0
2012)
River2D.....
Multi Inflow, Bank erosion,
Water, Habitat, Multi Language ・・・・・
iRIC 3.0 (Released on 23 Jun, 2018)
+ Nays2DH, Mflow_02, CERI1D, NaysEddy, ELIMO, SRM・・・・・
iRIC 4.0 Jun 2023
Many new functions・・・・・
29


iRIC Software
Changing River Science
Outline of iRIC
Import Data
Data Exporting
Pre Processing
GUI Tools
User's Solvers
Post Processing
GUI Tools
Editing Geographic Data
Grid Generation and Eidt
RIC Libraries
iRIC Libraries
Vector, Contour, Shading,
Stream Line, Particle
Line Graph.....
2D, 3D
Structured, Unstructured
Flow, Bed and Bank Evolution
Public Domain Solvers
rtran、C ....
D, 2D, 3D, Structured,
nstructured



iRIC Solvers Line up

(1)Runoff Model → SRM(Lumped Model), RRI(Distributed Model)

(2)River Model → Nays1D+, CERI1D, Nays2DH, NaysMini, Nays2d+
FaSTMECH, SToRM, River2D, Mflow_02
Morpho2DH, Nays2DV, Nays3DV, NaysCube

(3)Inundation Model → Nays2dFlood

(4)Taunami Model → ELIMO

Open Sourse

(5)Environmental Assessment Model → DHABSIM, EvaTrip_Pro

Solver Coupling

(6) Mass Transport Model → GELATO(General Lagrangian Tracer Tracking)
Nays2DW(Drift Wood)

http://i-ric.org/

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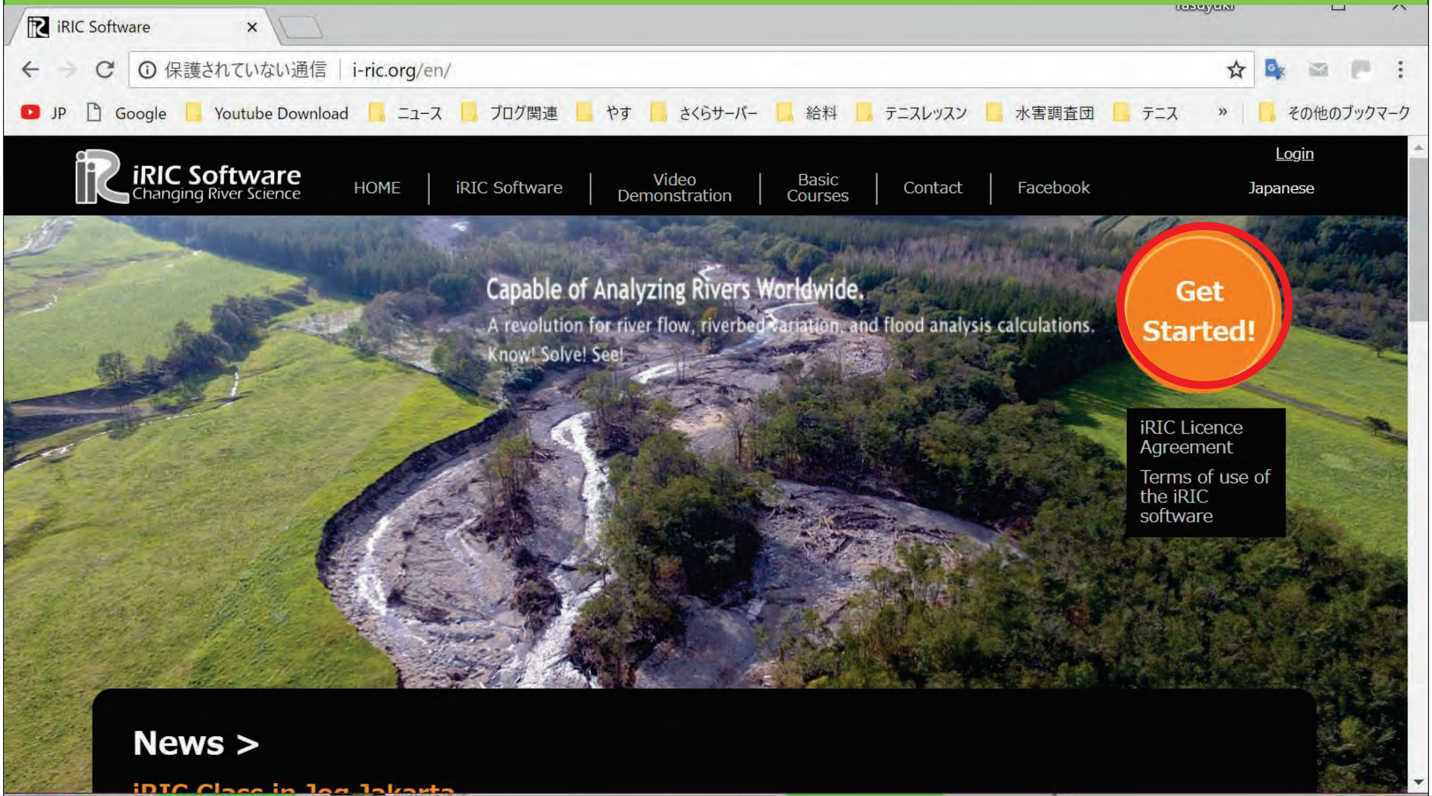

iRIC Seminar in Feng-Chia University Taichung, Taiwan1-2, April 2017

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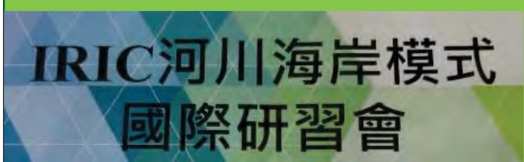
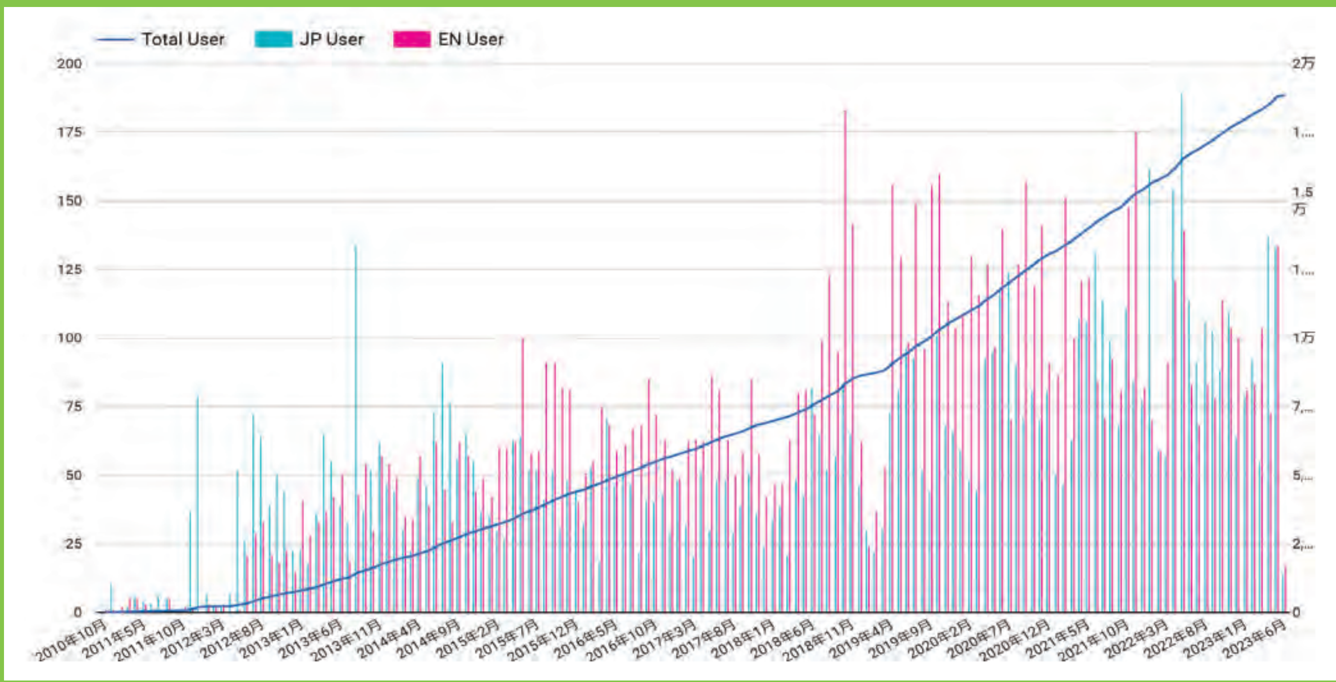


iRIC version2.0
www.i-ric.org

International
River Interface Corporative
iRIC

Numbers of registered users 18,000
Half English users and half Japanese users

More than 50 times seminars in 20 countries



Demonstration of iRIC

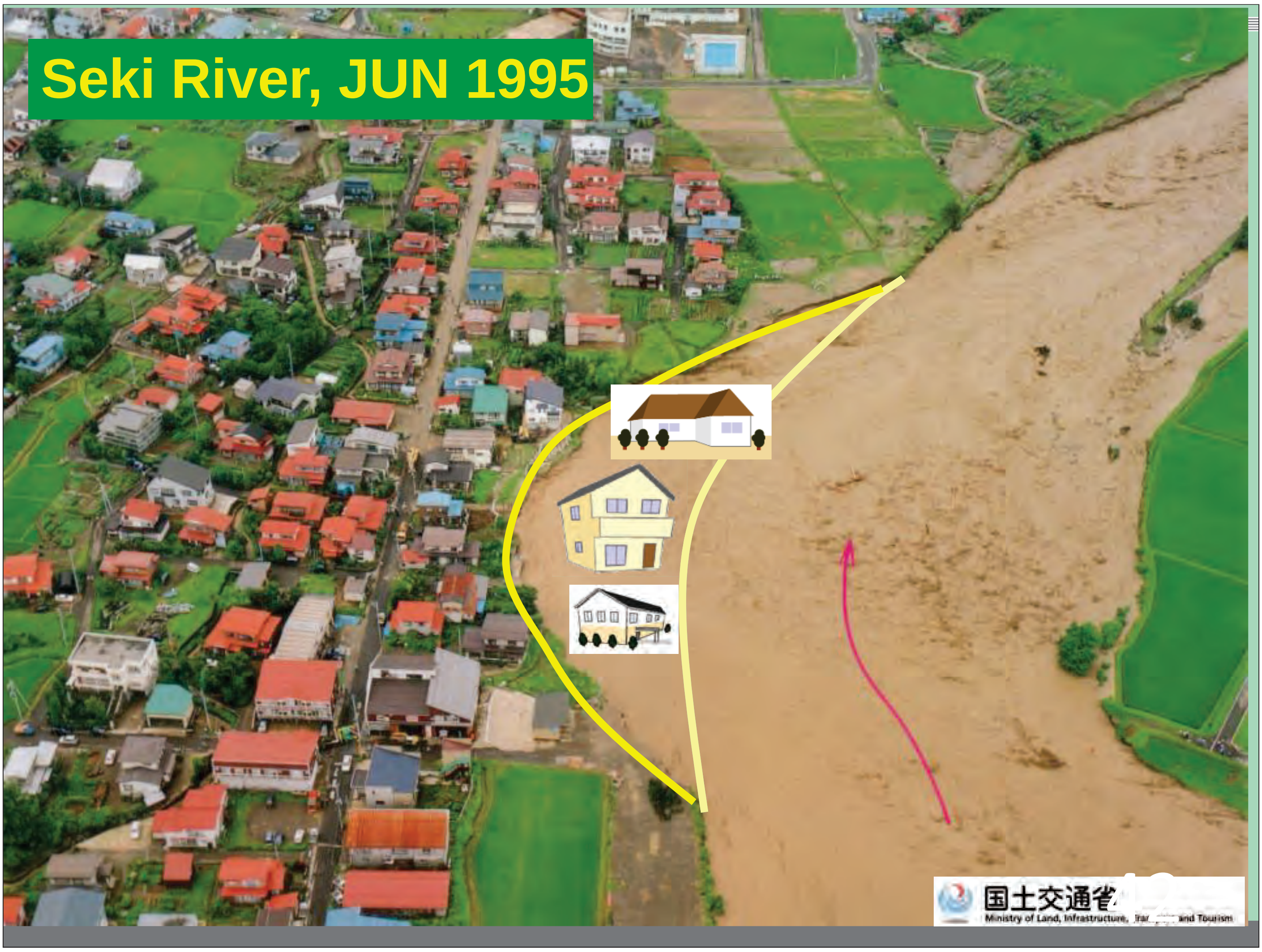
Levee Breach and Inundation in Sorachi River, 2018

Akatani River in Kyushu, 2017

Kinu River Flood of 2015

Movie

Kinu River Flood of 2015

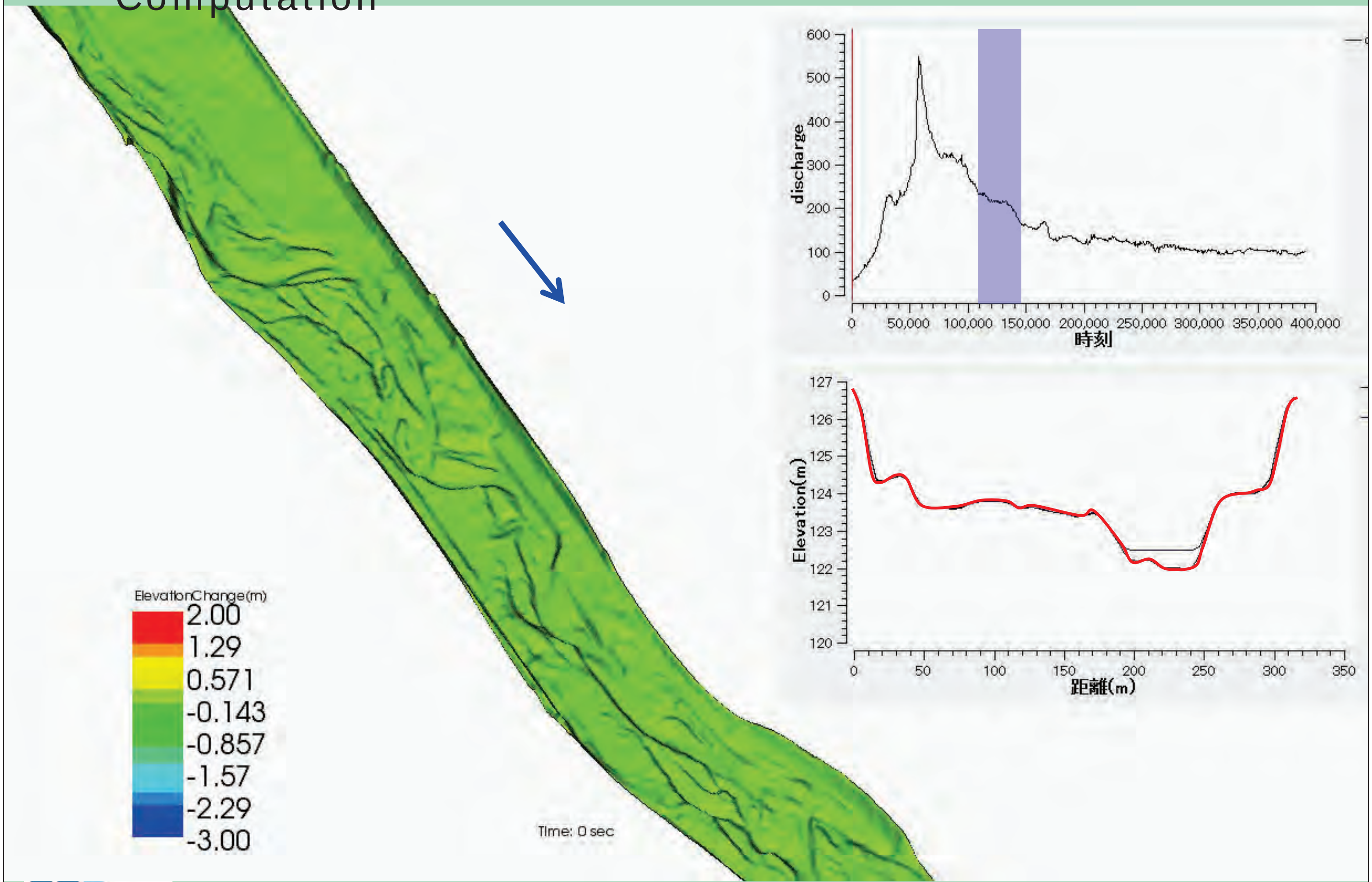


2011, Levee Beach Otofuke, Hokkaido

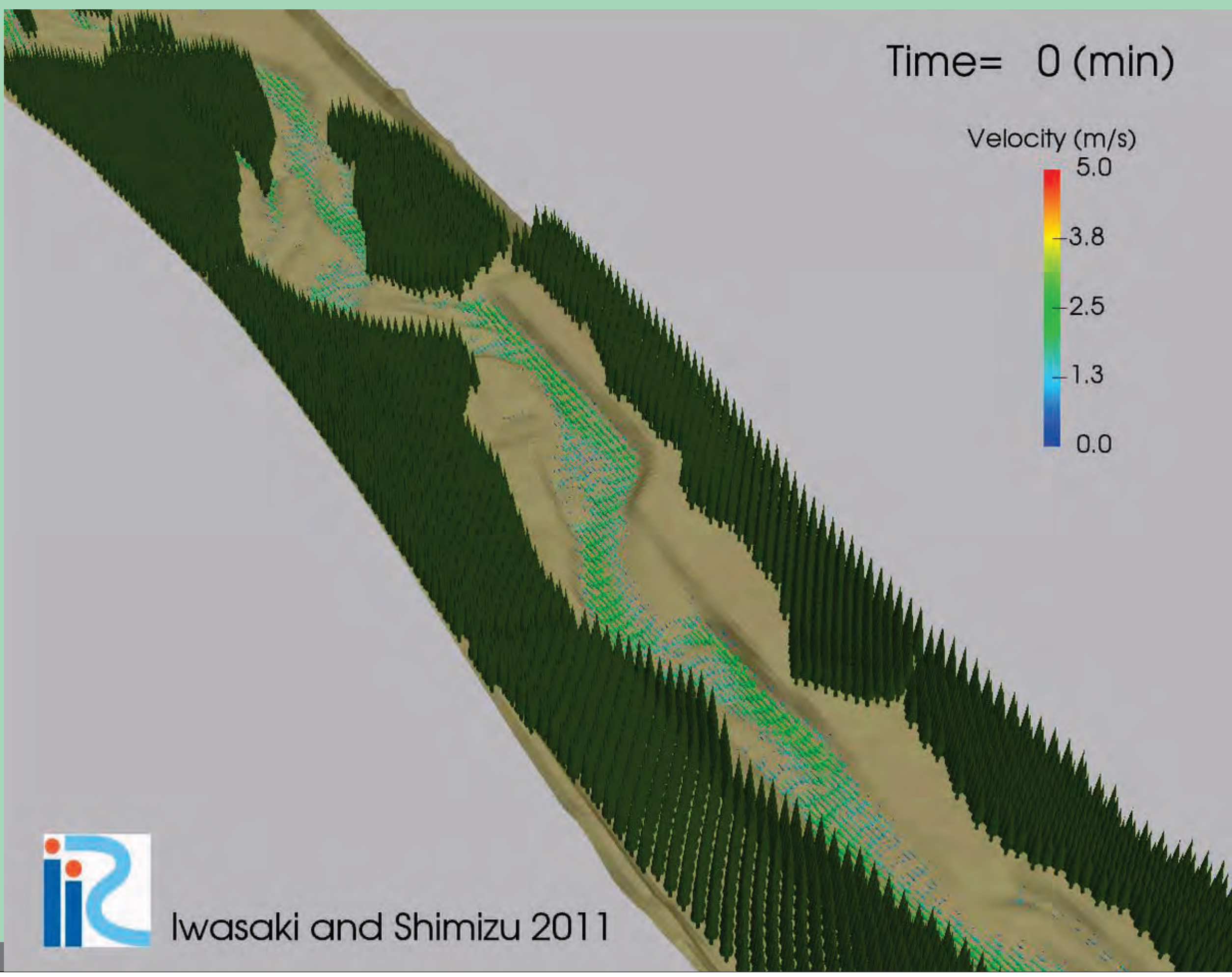
北海道大学

2011.9.6 The Otofuke River, Hokkaido, Japan

Nasy2DH Computation

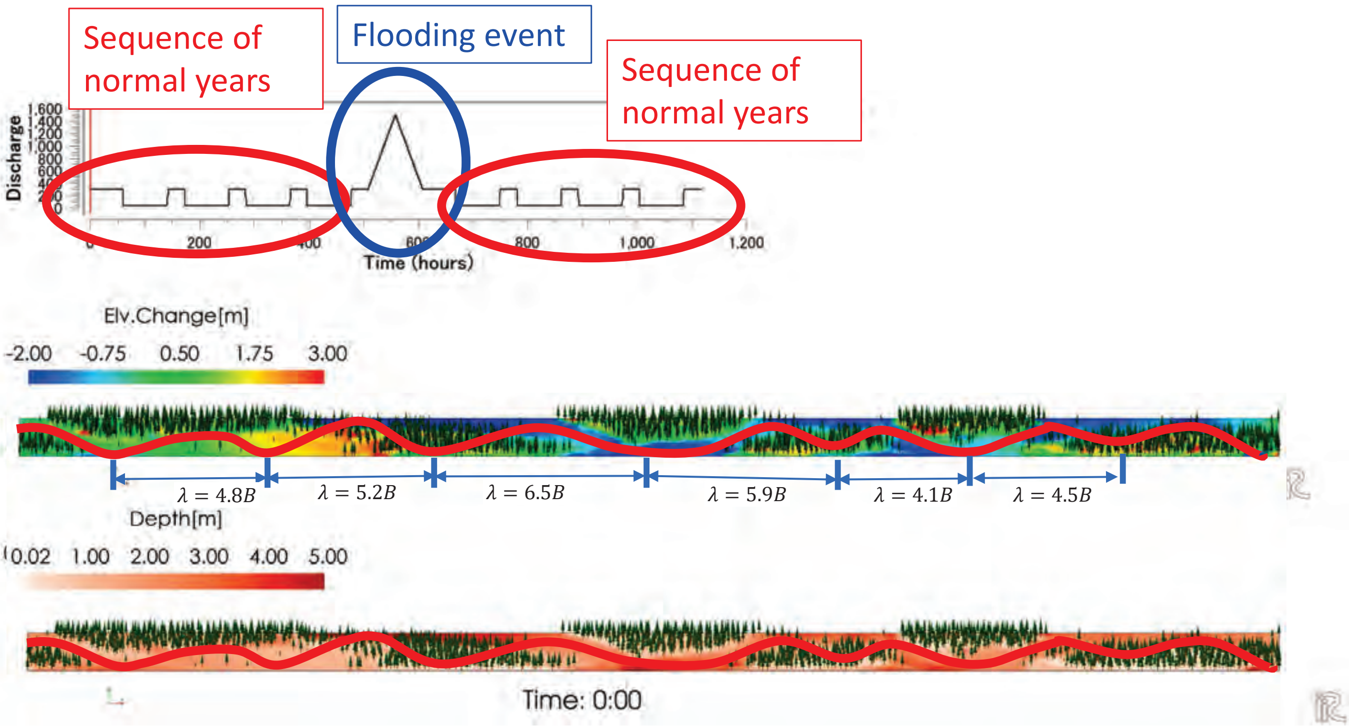


Flow, bed and bank evolution by Nays2D



Bisei River, Hokkaido, Japan
2022/8/11 Drone Photo

Numerical Modelling of Flow and Bed Deformation Considering the Effects of Channel Vegetation

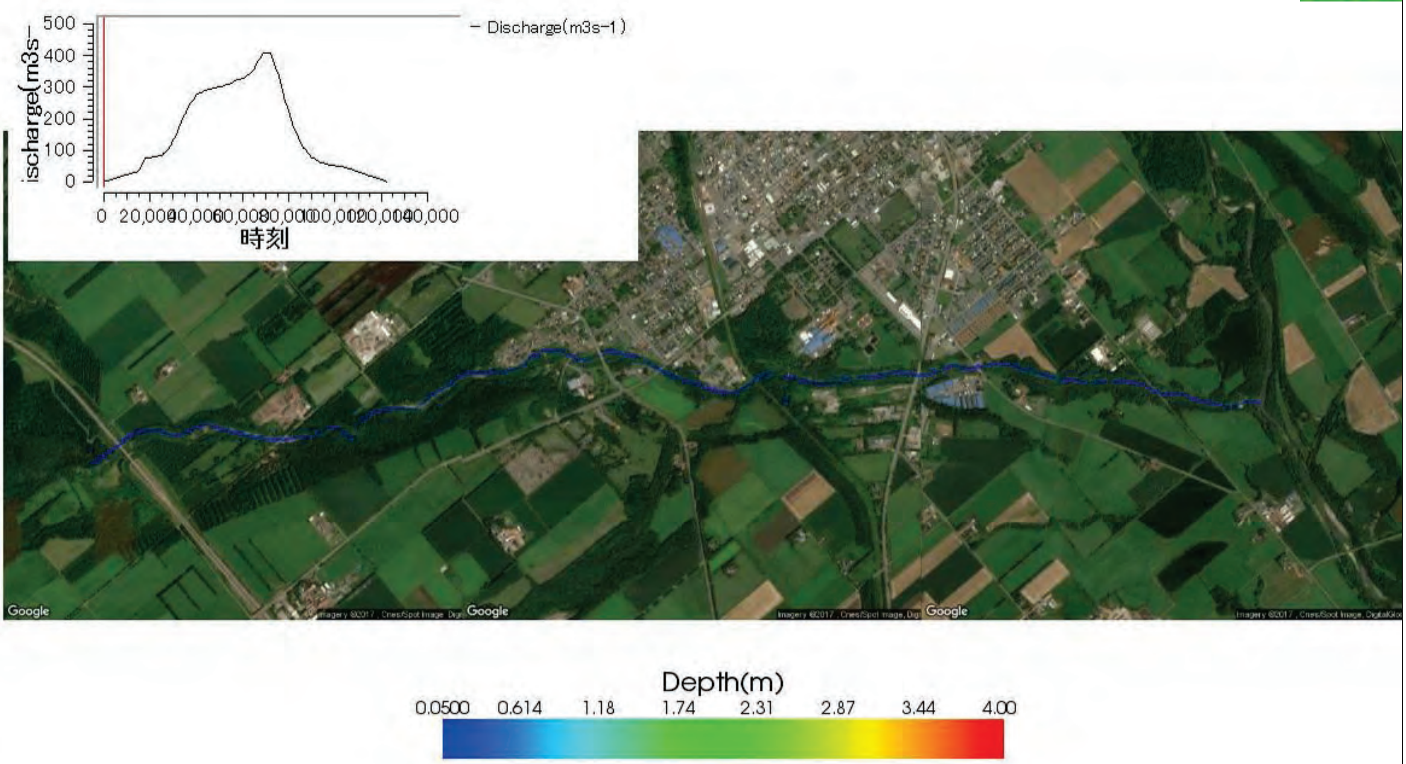


Pekerebetsu River, 2016 Hokkaido

写真提供：(株)パスコ

Large-scale riverbed changes in the 2016 Hokkaido rainfall disaster (Memuro River)

Flood simulation without sediment transport

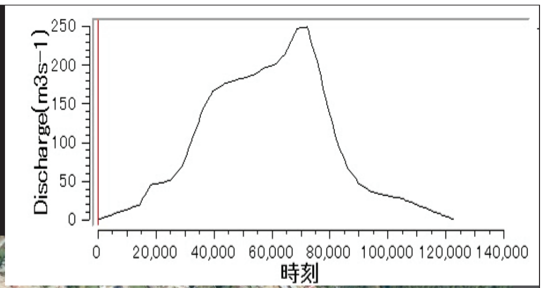


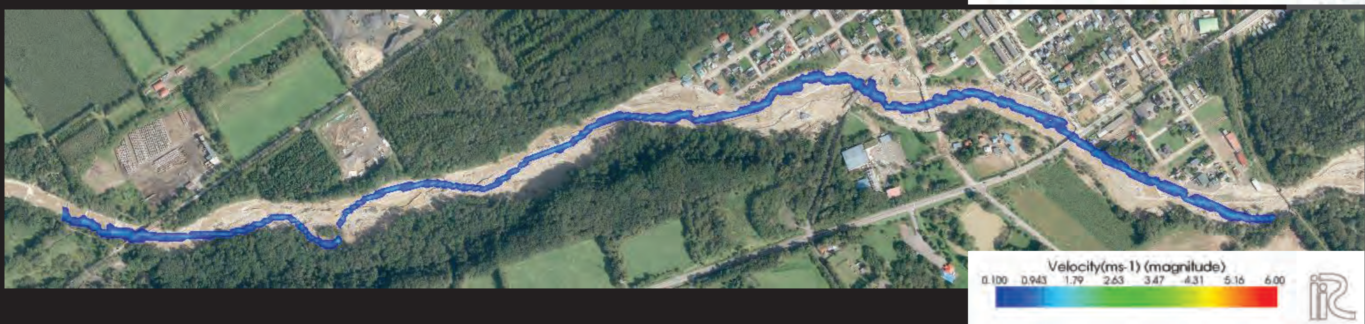
数値計算: by

・When sediment movement is not considered, there was almost no flooding near the urban area, and the scale of damage was underestimated.

Numerical calculations: by Tomoko Kuka

・When sediment movement is considered, The inundation range becomes closer to the actually flooded area.





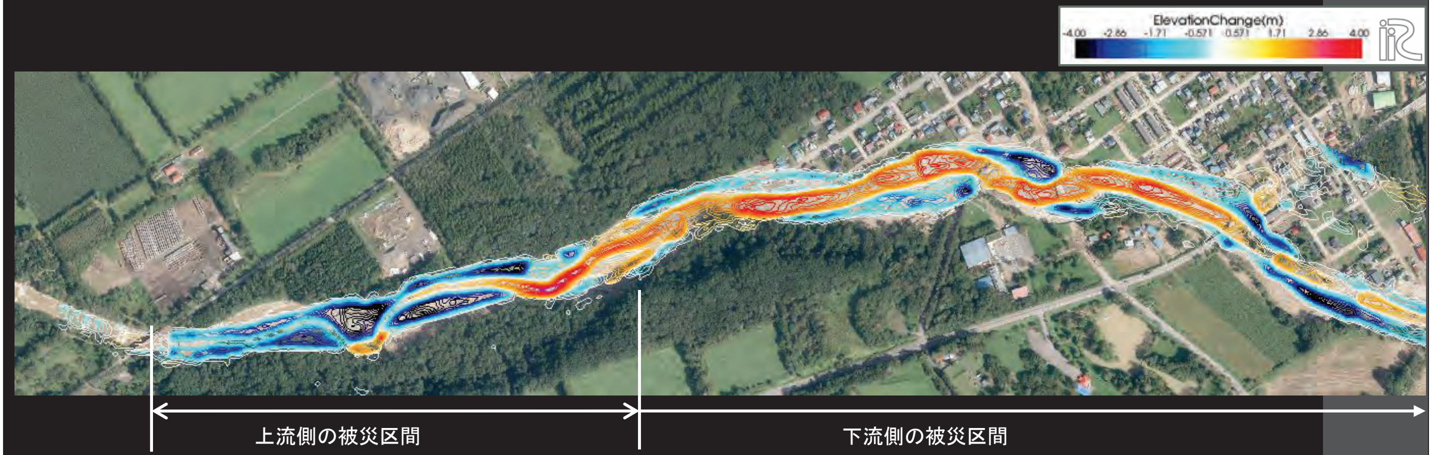
図：Case2：上) 河床変動量コンター図，下) 流速コンター図

Simulation: by T.Kyuka

Simulation with sediment transport

数値計算

Case2 ：再現計算



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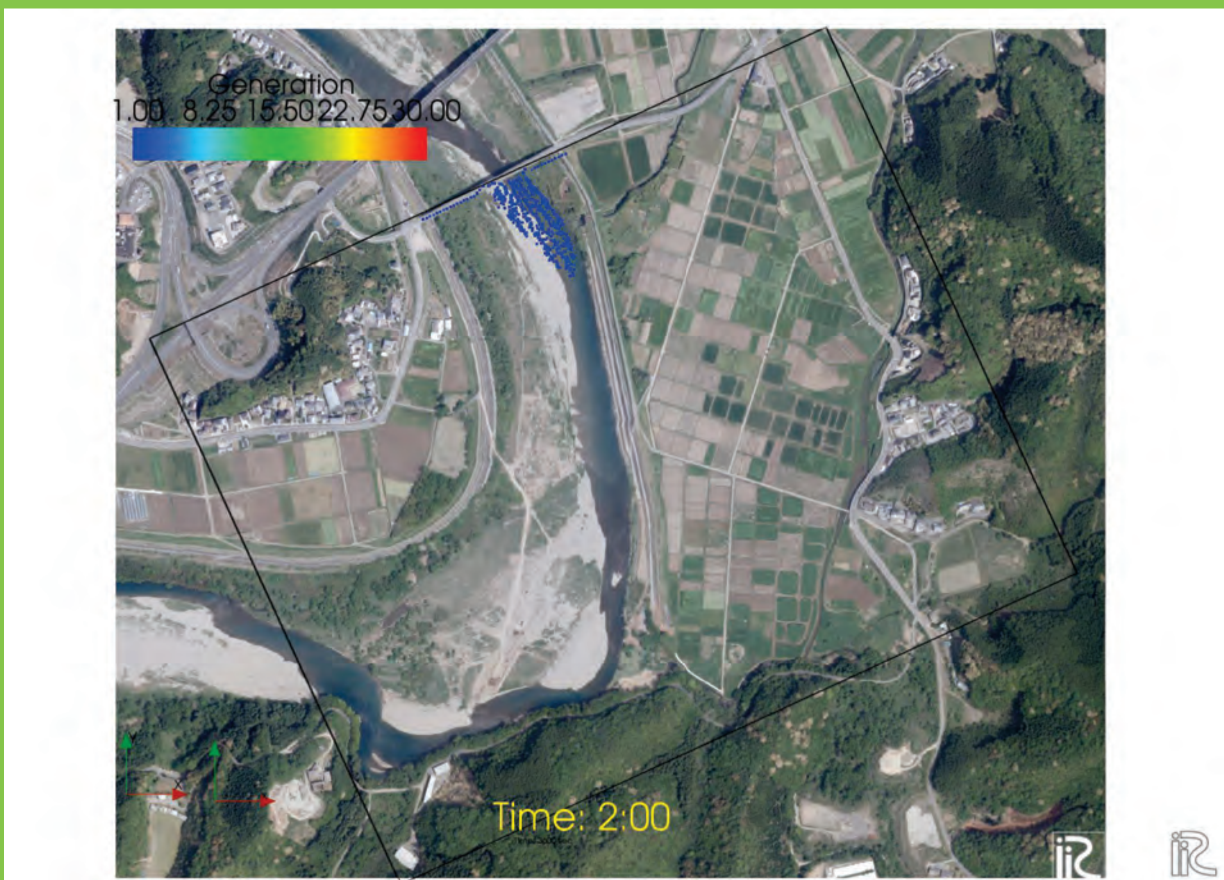
Kita River in Miyazaki, Kyushuu



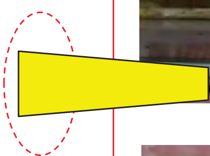
Kimura and Kang(2018)

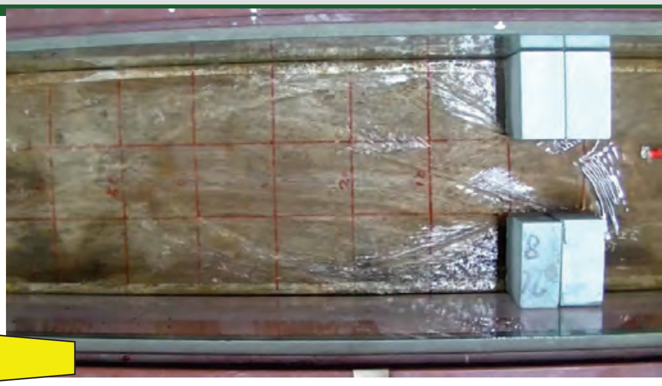
Result of driftwood deposition with root effect in simulation

Large discharge / Low slope

S=0.0045, Q=0.00100 m^3/s

Root part





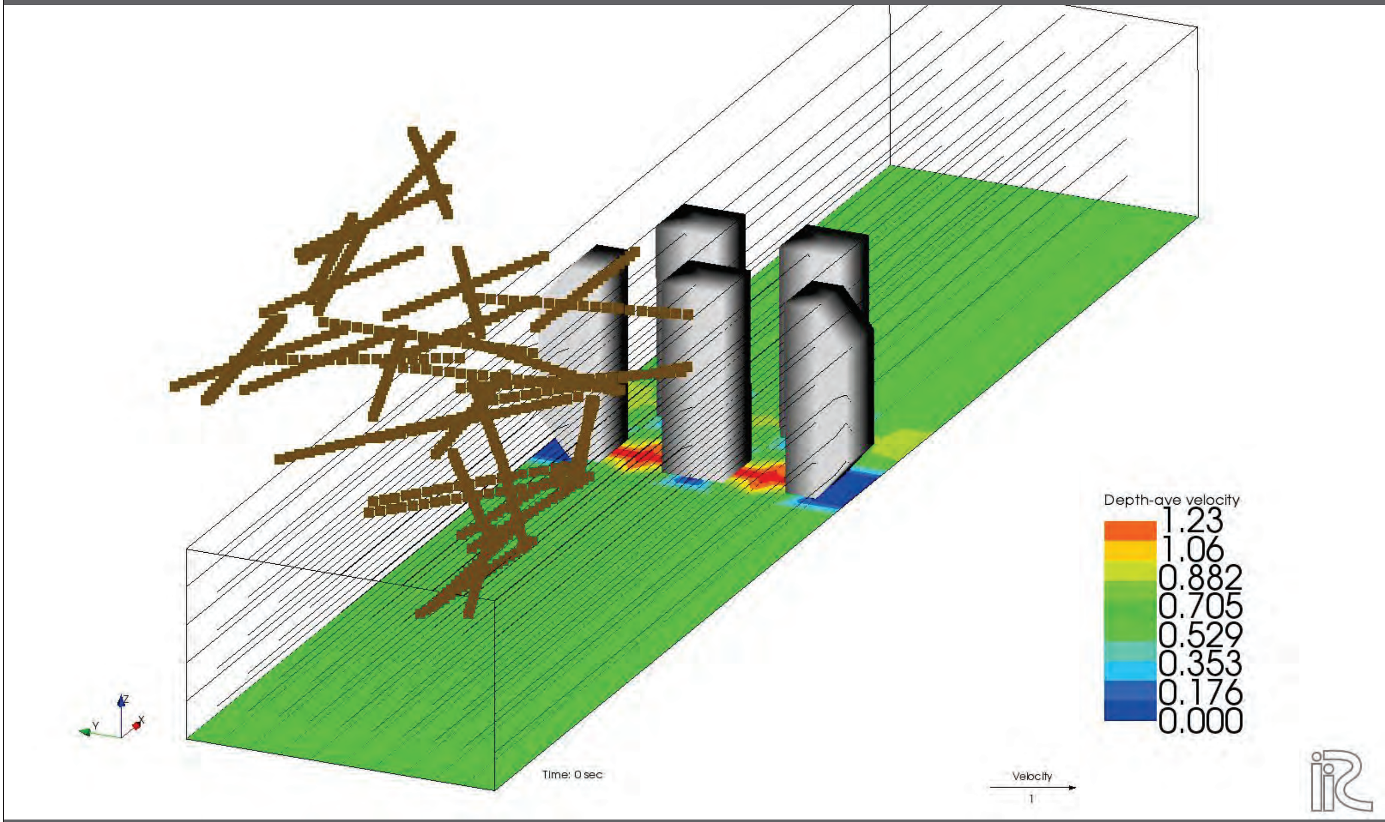
S=0.0045, Q=0.0010m^3/s

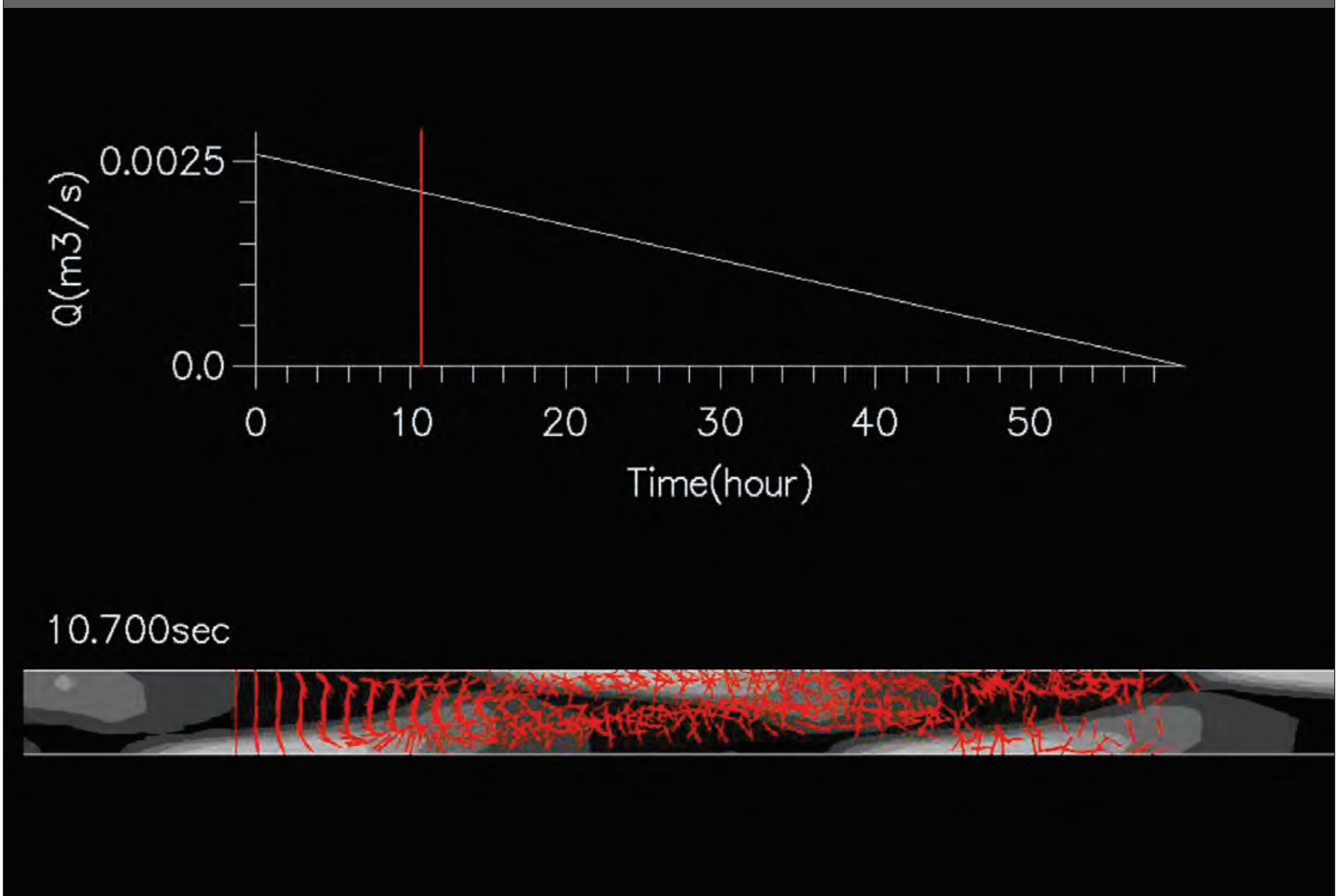
Large discharge / High slope

S=0.0070, Q=0.00110 m^3/s

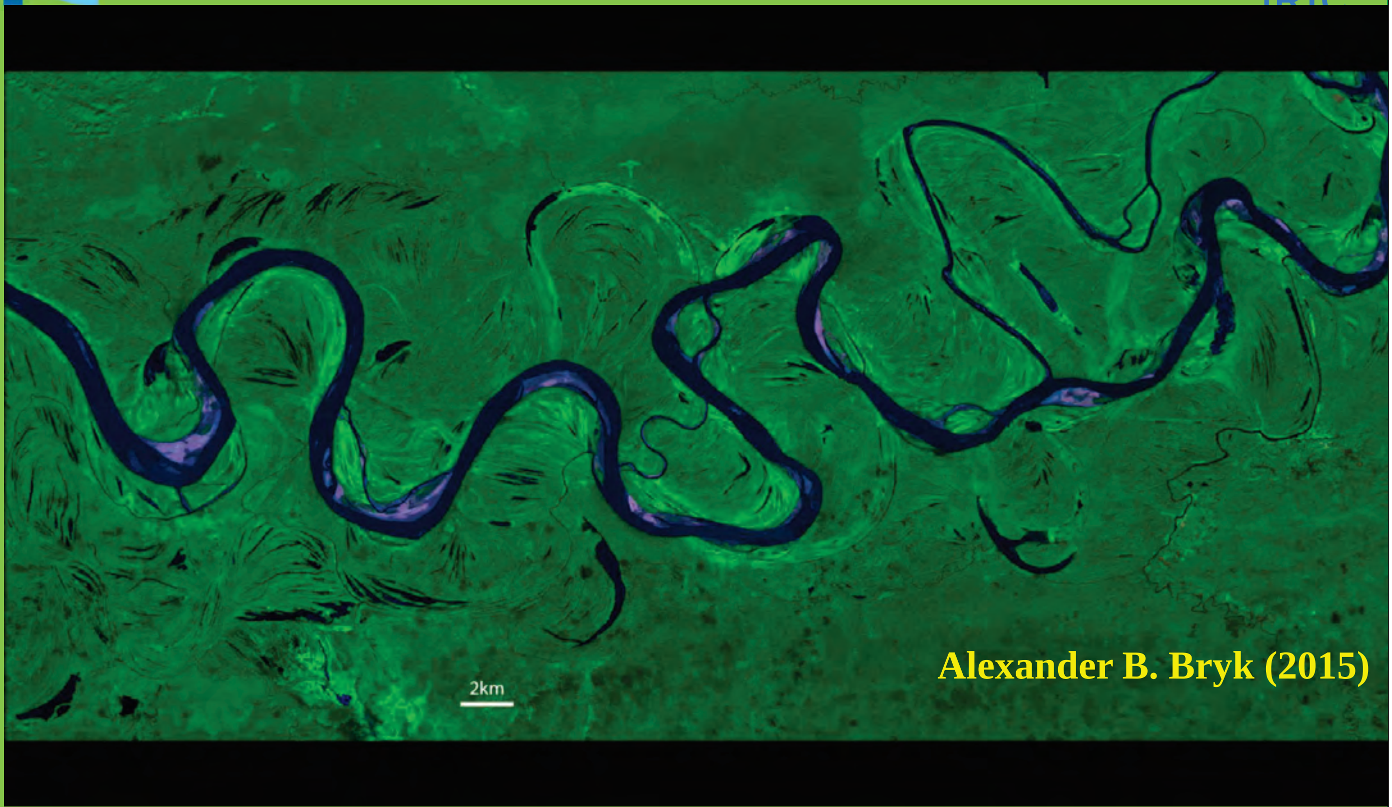
S=0.0070, Q=0.0011m^3/s

Drift Wood Simulation by I. Kimura(2018)





Río Ucayali, Peru
-32 years (1982-2015) Landsat Image



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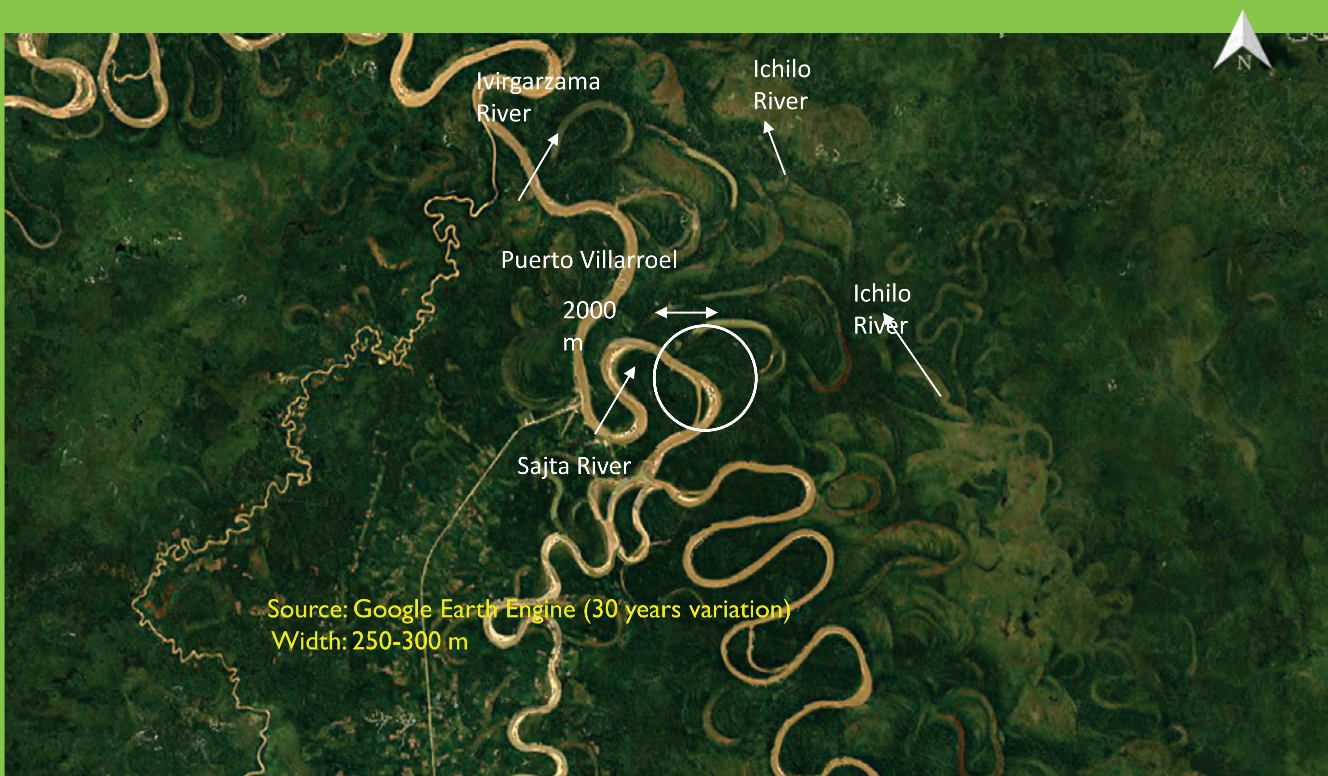
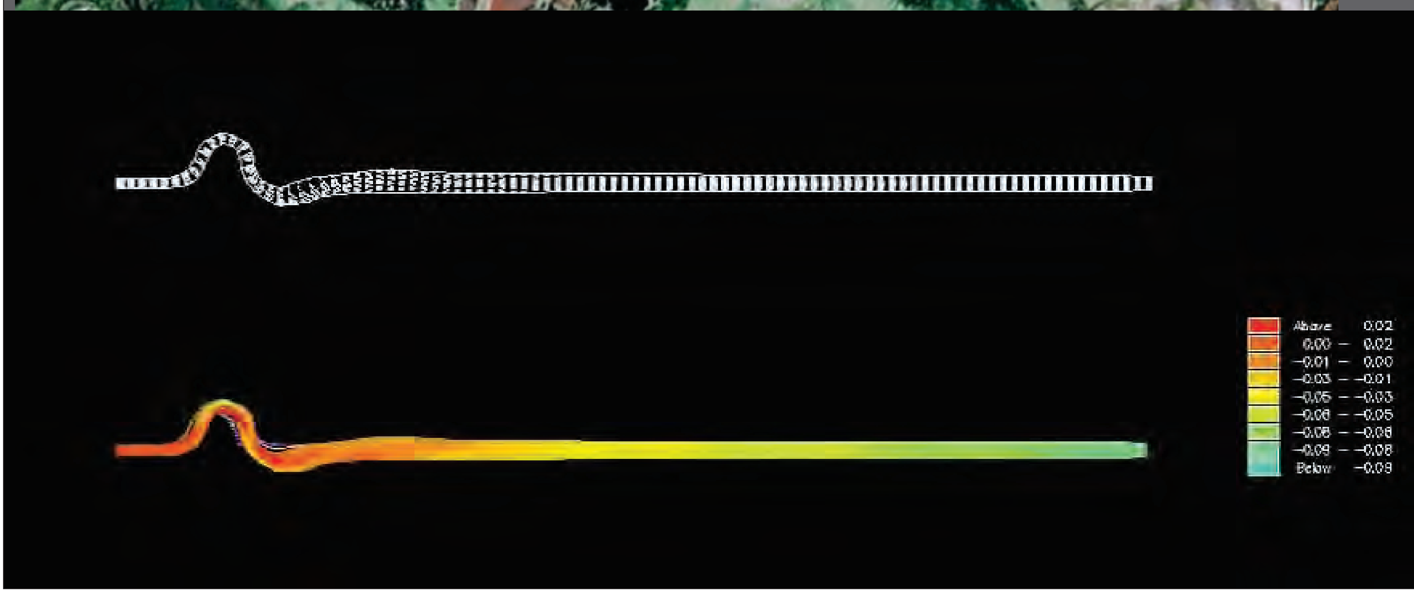
Meander migration of Ichilo River and Sajta River, Bolivia



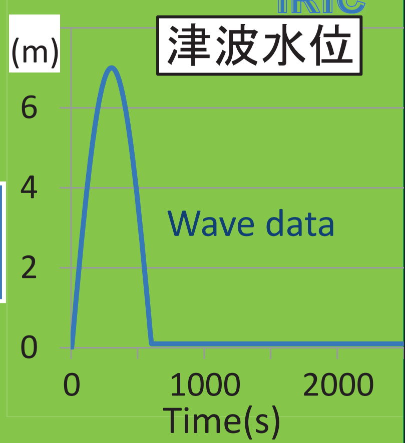
International
er Interface Corporative
iRIC

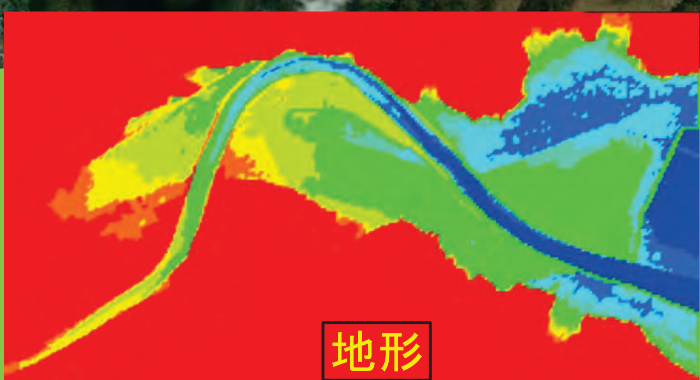



Rikuzen Takada City
Before
Pine Tree Foresets
66
資料：東北開発建設部

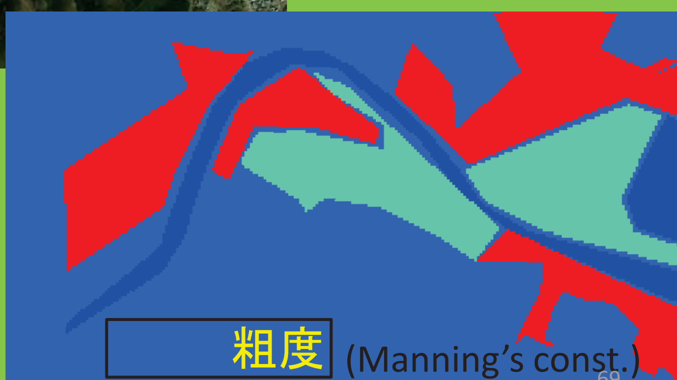

After
2,000 people, 10% of the total population is killed or missing
in this city.
67
資料：東北開発建設部

津波遡上の計算





0 10(m)



(Manning's const.)

0.020 0.070

The simulation of flooding caused by Tsunami runup

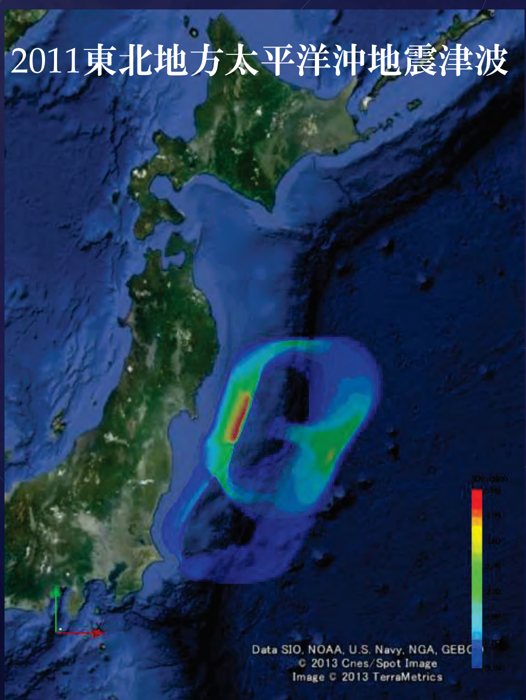
by S. Kawamura

Water Depth 0.0 – 7.0(m)

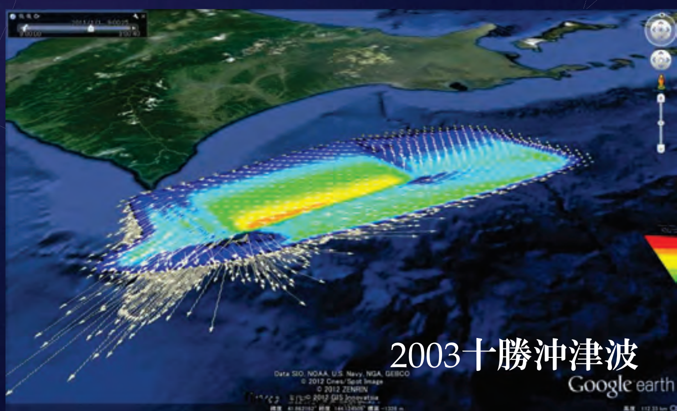
iRIC-ELIMO

Easy-performable Long-wave Inundation Model

By Yasunori Watanabe (Hokkaido Univ.)

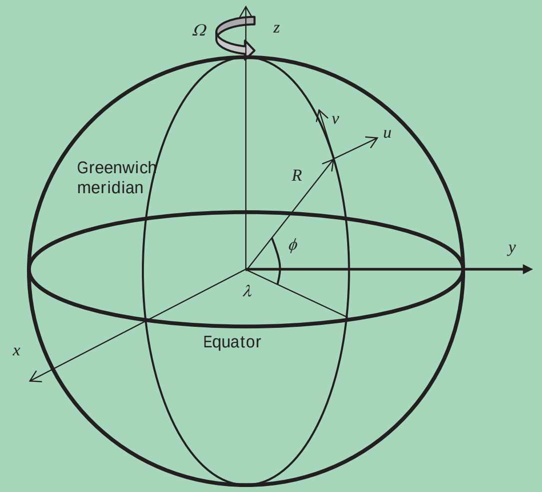


- 手軽に本格的津波計算
- 任意の既往・想定津波を生成
- フリーの海底地形データを使用可能
- さくさく可視化



ERIMO by Dr. Yasuharu Watanabe (Tsunami Model)

- Nonlinear long-wave computation in global spherical coordinates
- Reliable computing methods with high-order accuracy
- Polished open boundary conditions: minimize reflection at the boundary



spherical coordinate

Download Bathymetry data from Japan Oceanographic Data Center

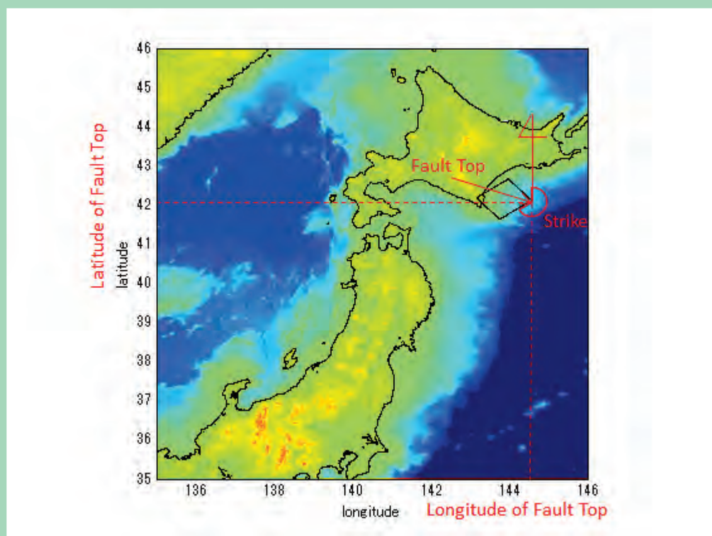
Bathymetry format conversion to iRIC compatible dataset

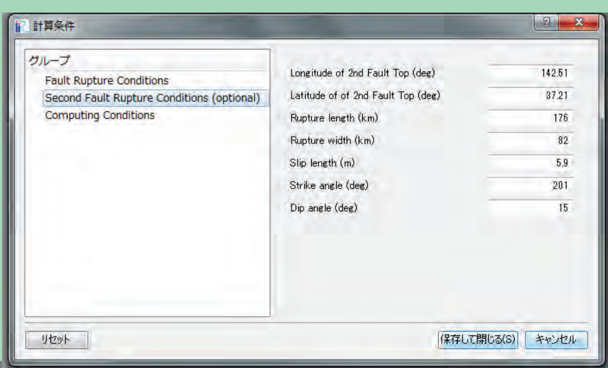
Grid generation on iRIC

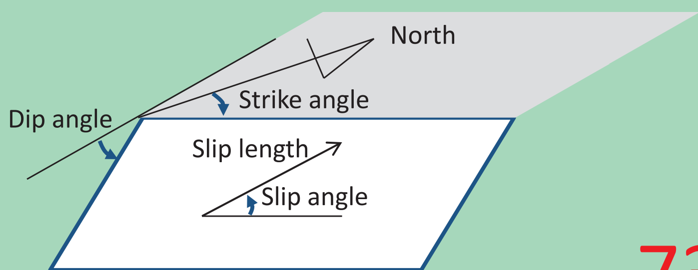
Fault Model Parameters

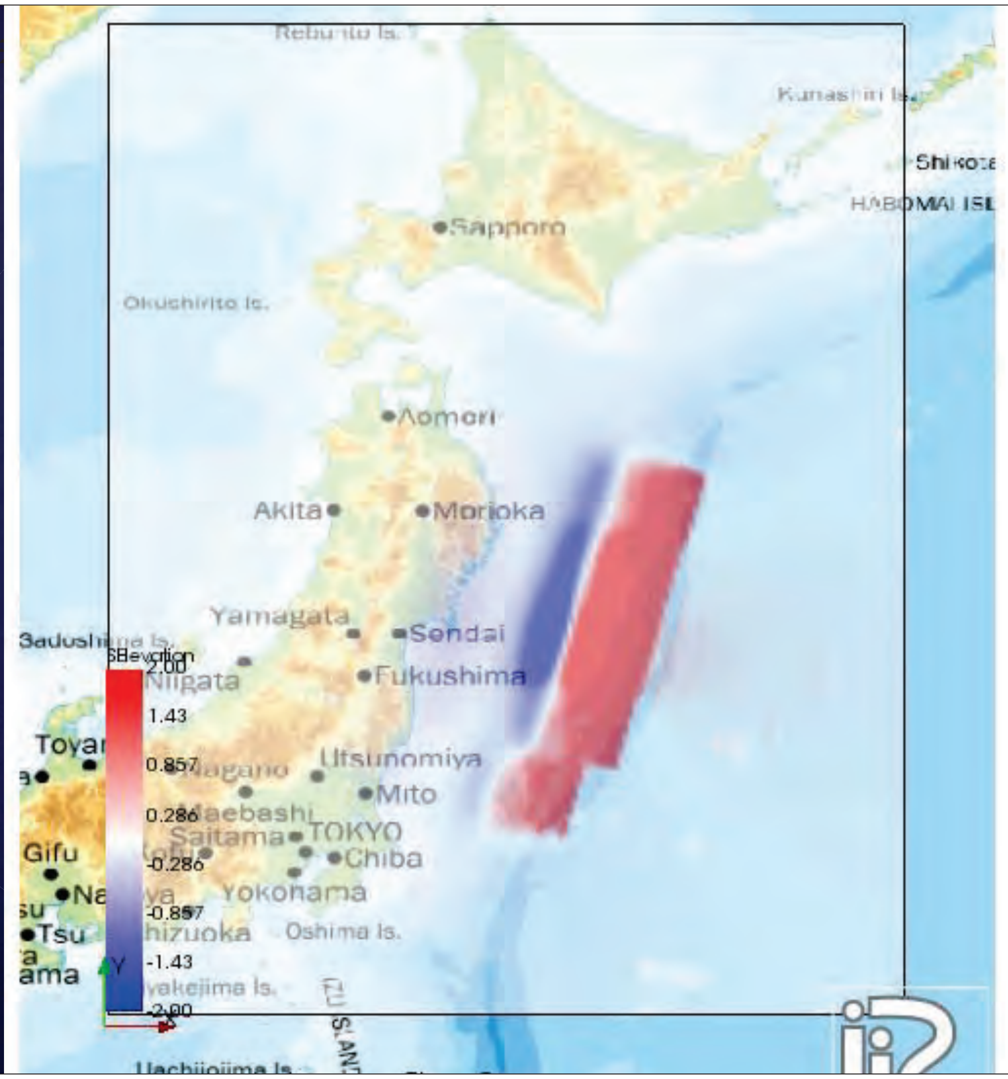
Input fault parameters for a rectangle fault model as an initial condition of tsunami

1. Longitude, latitude of the fault top
2. Rupture length
3. Rupture width
4. Slip length
5. Strike angle
6. Dip angle
7. Slip angle

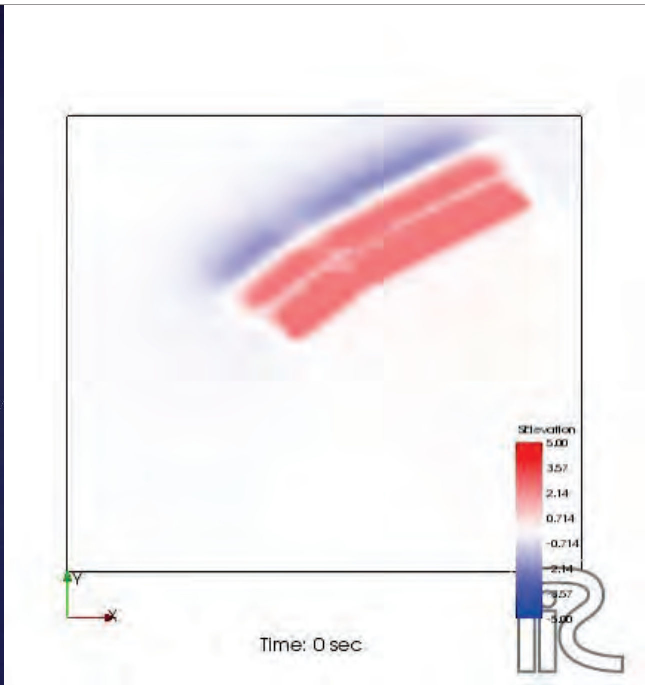




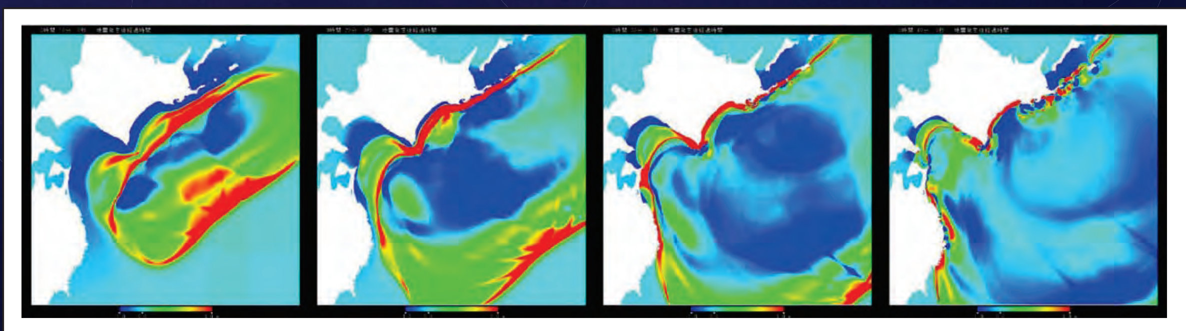




想定津波　（北海道500年間隔津波）



北海道500年間隔津波　入力断層



北海道500年間隔津波　北海道庁計算結果

Oiranbuchi in Toyohira River
(2015/7/29)

Application of Nays2D Computation with multi UAV in a bedrock river

Supported by
Hokkaido Consultant Corporation

Precise survey

Ground Area

Laser survey

Water Area

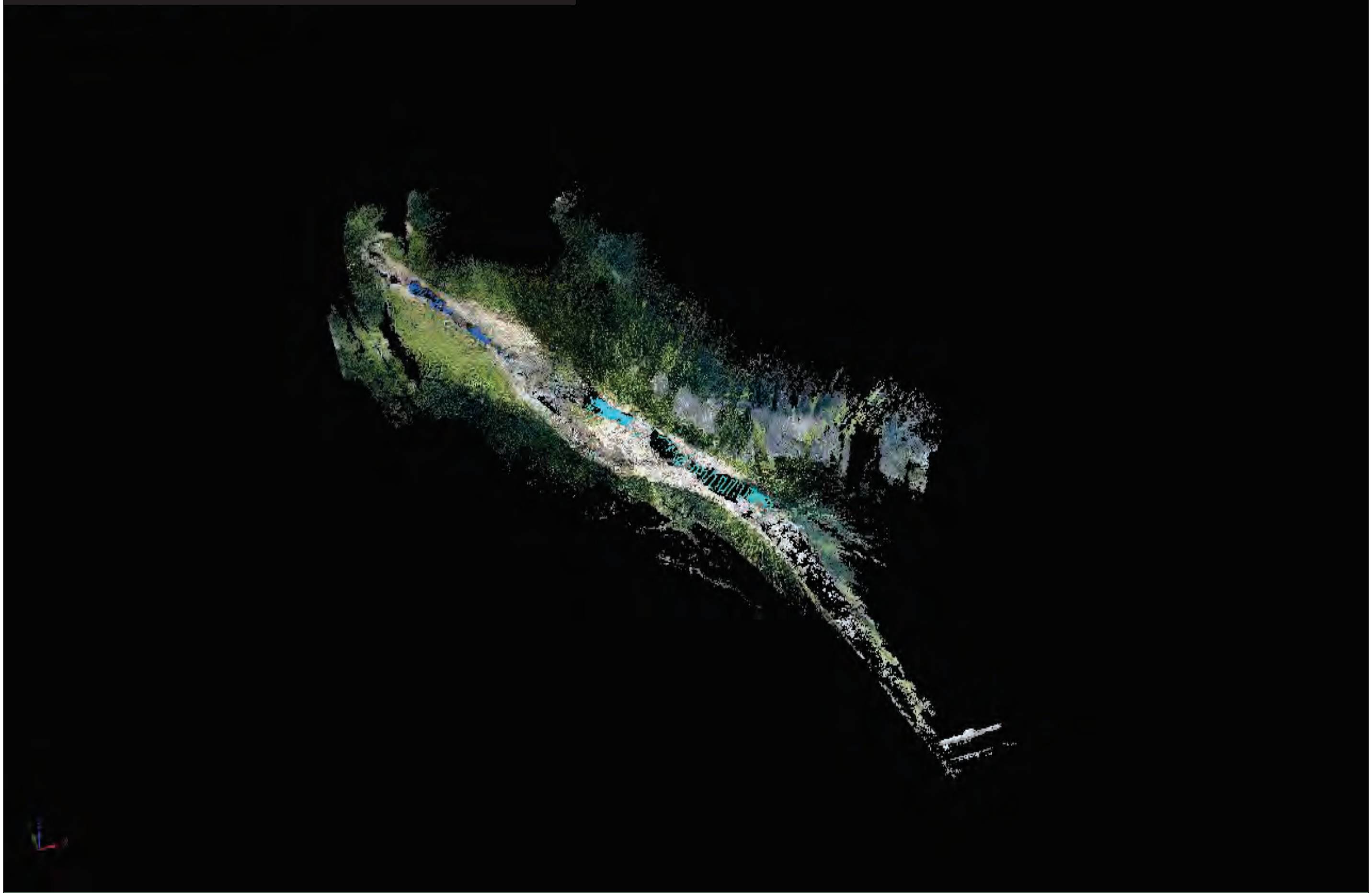
ADCP

Sonar survey

Supplement

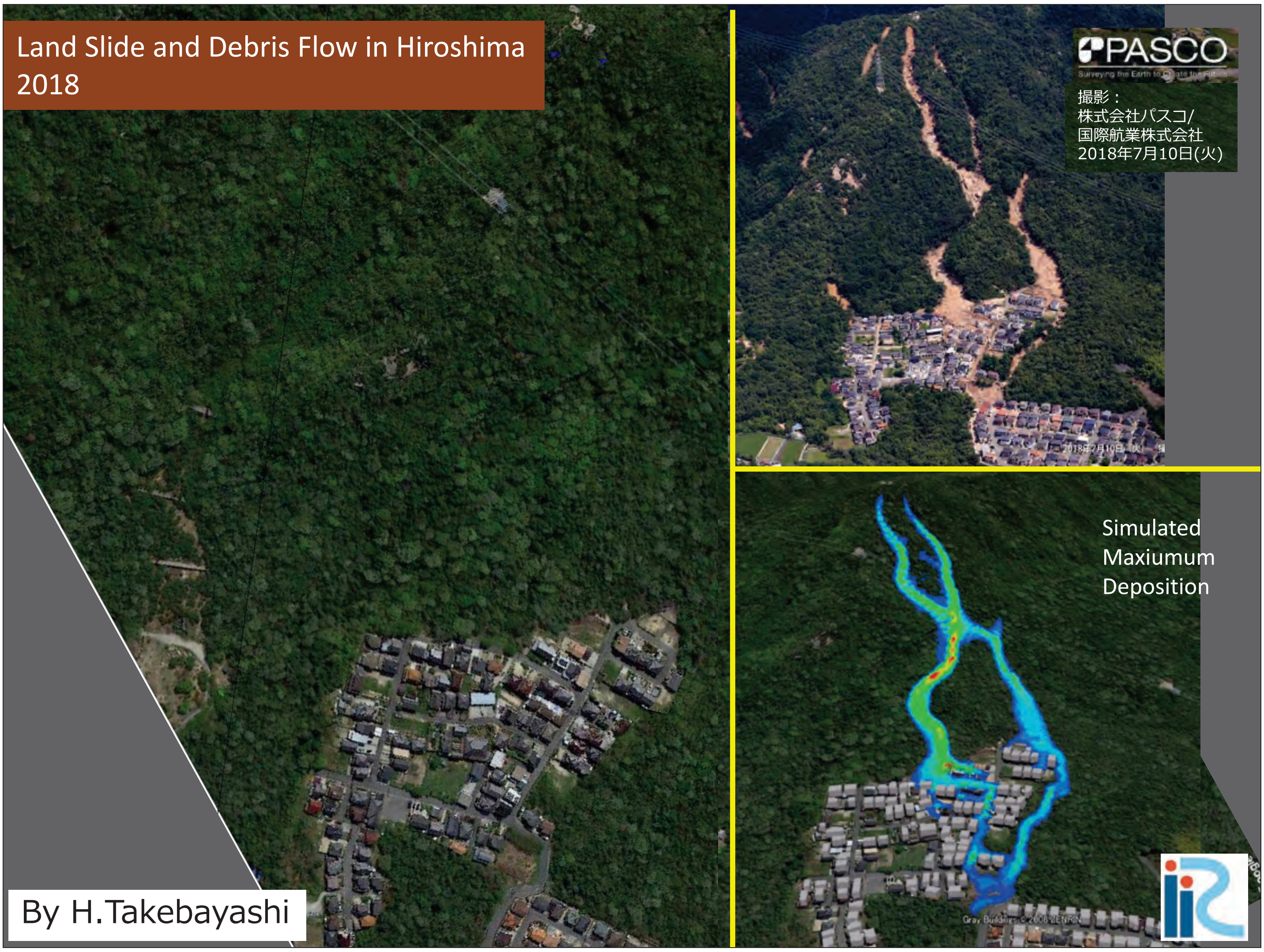
GPS

3D data made by Composing all data

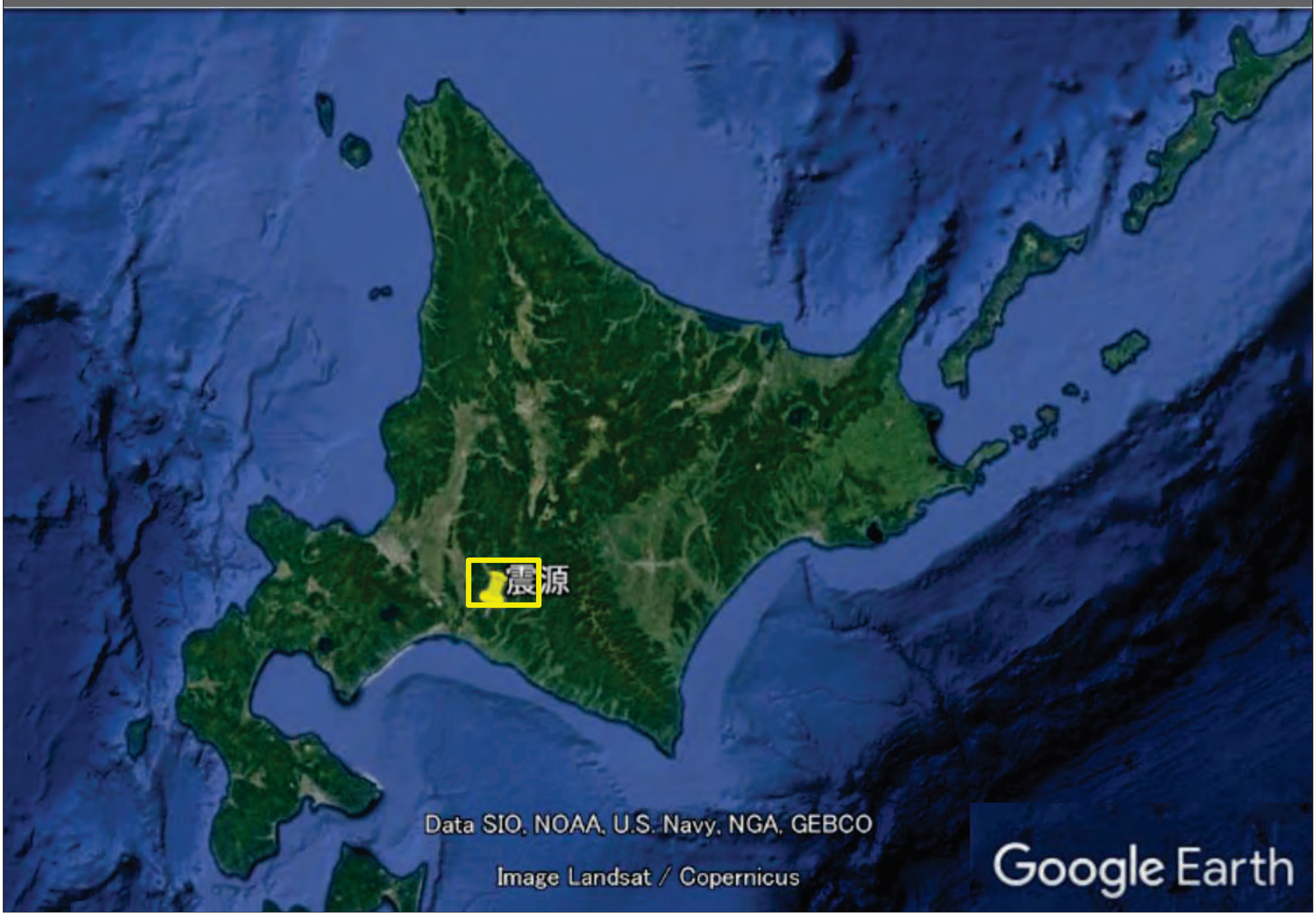


78

79

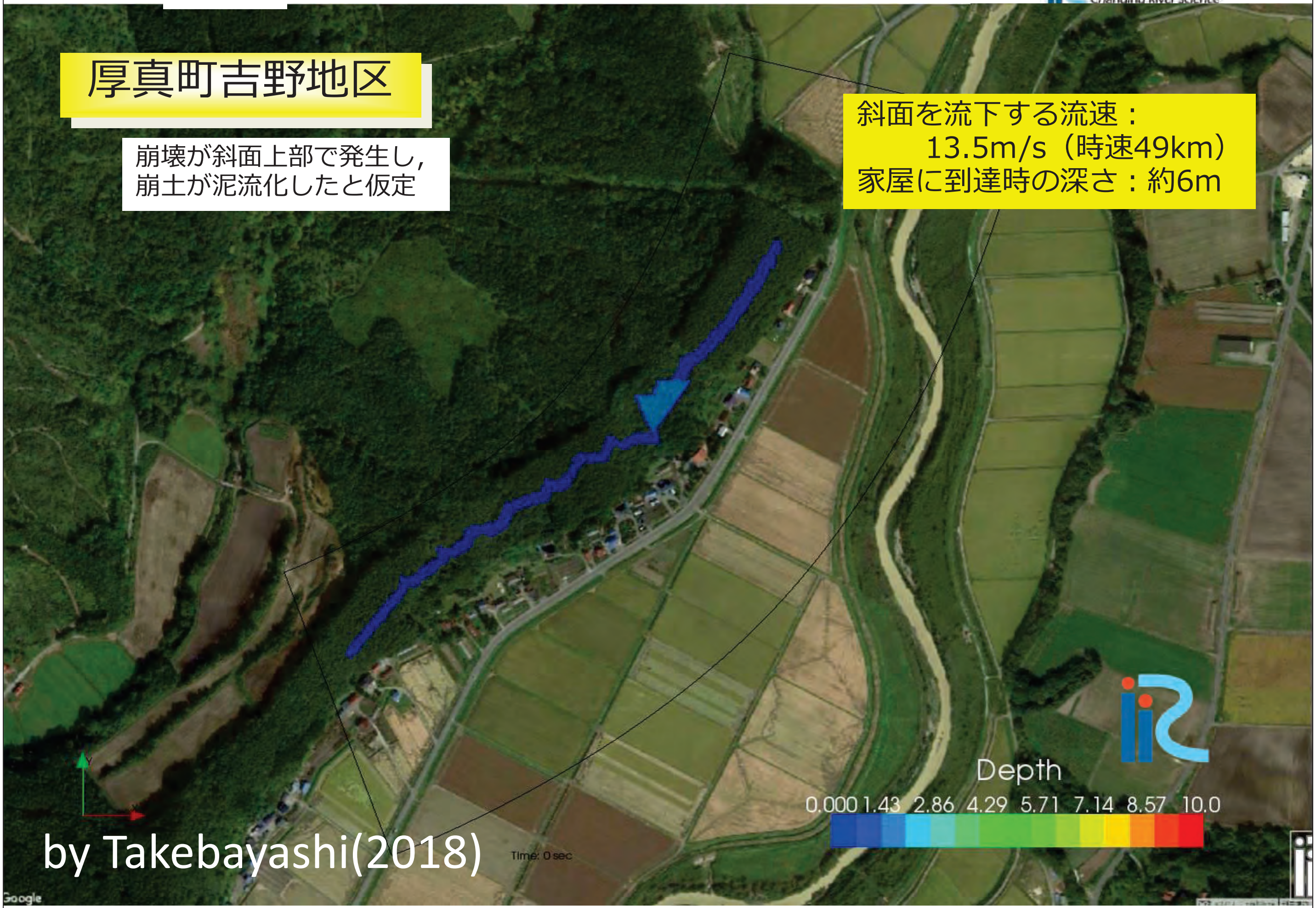


Hokkaido East Iburi Earthquakes, SEP 6 2020



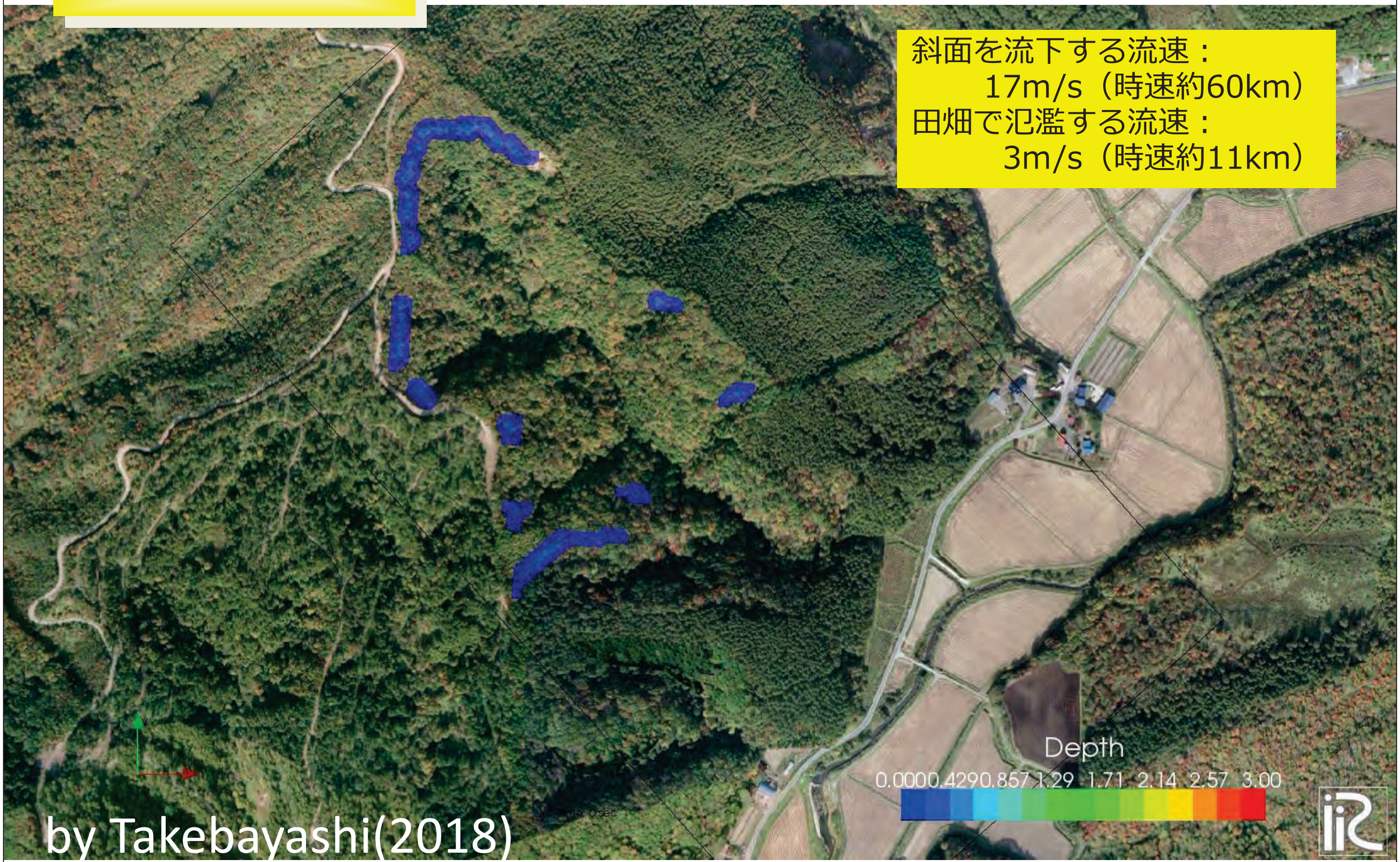
厚真川流域

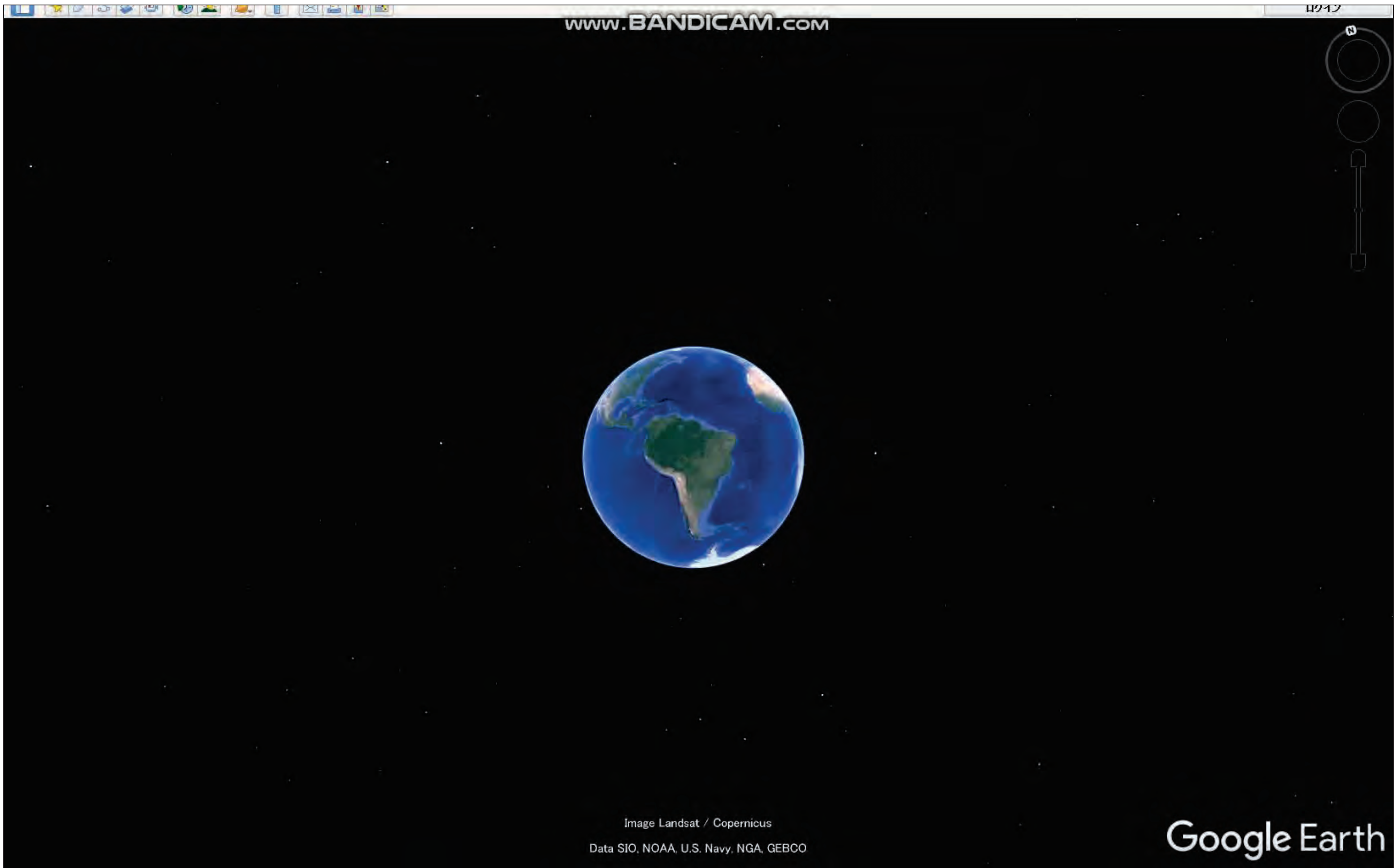
厚真町吉野地区


厚真町吉野地区
崩壊が斜面上部で発生し，
崩土が泥流化したと仮定
斜面を流下する流速：
13.5m/s（時速49km）
家屋に到達時の深さ：約6m
Depth
0.000 1.43 2.86 4.29 5.71 7.14 8.57 10.0
by Takebayashi(2018)
Time: 0 sec

厚真町高丘地区

厚真町高丘地区





Google Street Viewを用いた氾濫解析結果のVR表示
井上，田中(2018)

3D-Hazard Map Application for Smart Phone

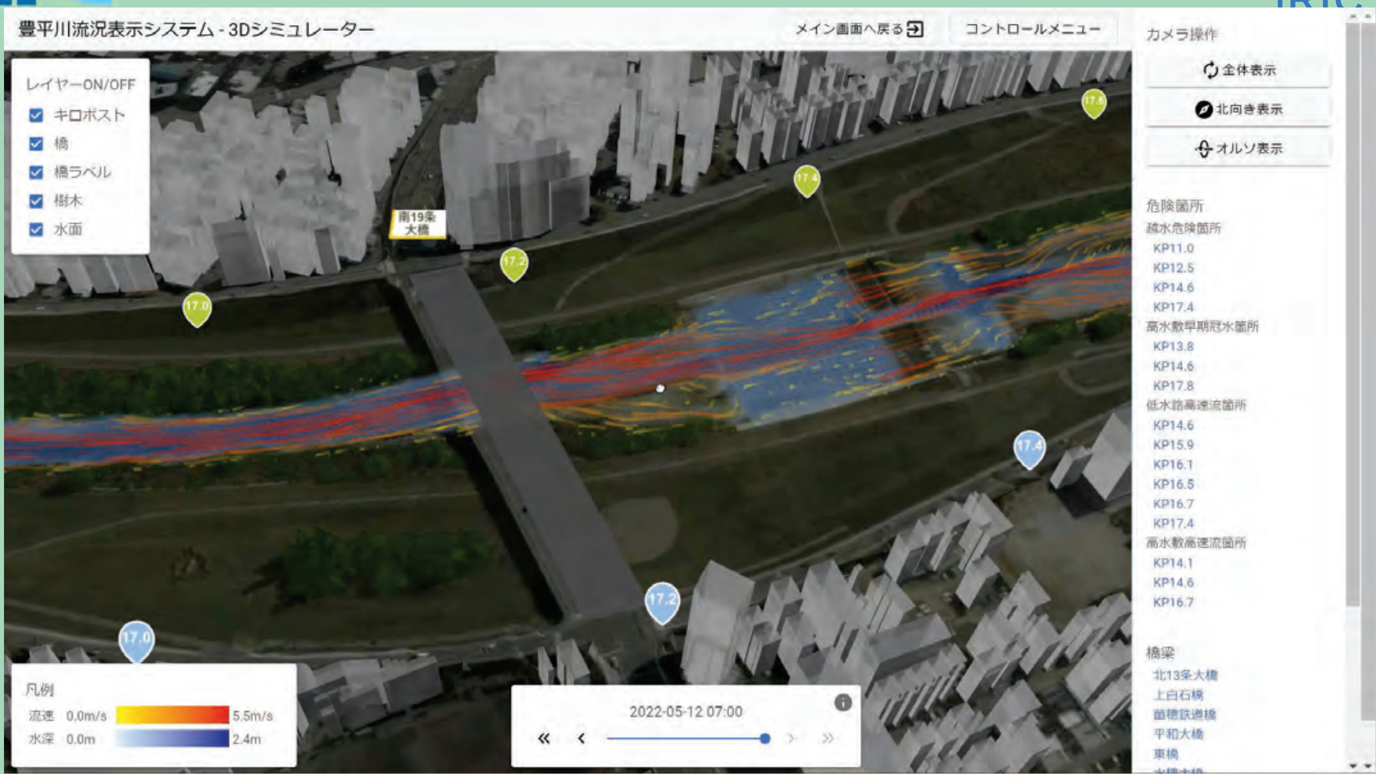
Where are you?

How deep will the inundation become at your place.

Good for educational purpose as well.

Real time flow simulator

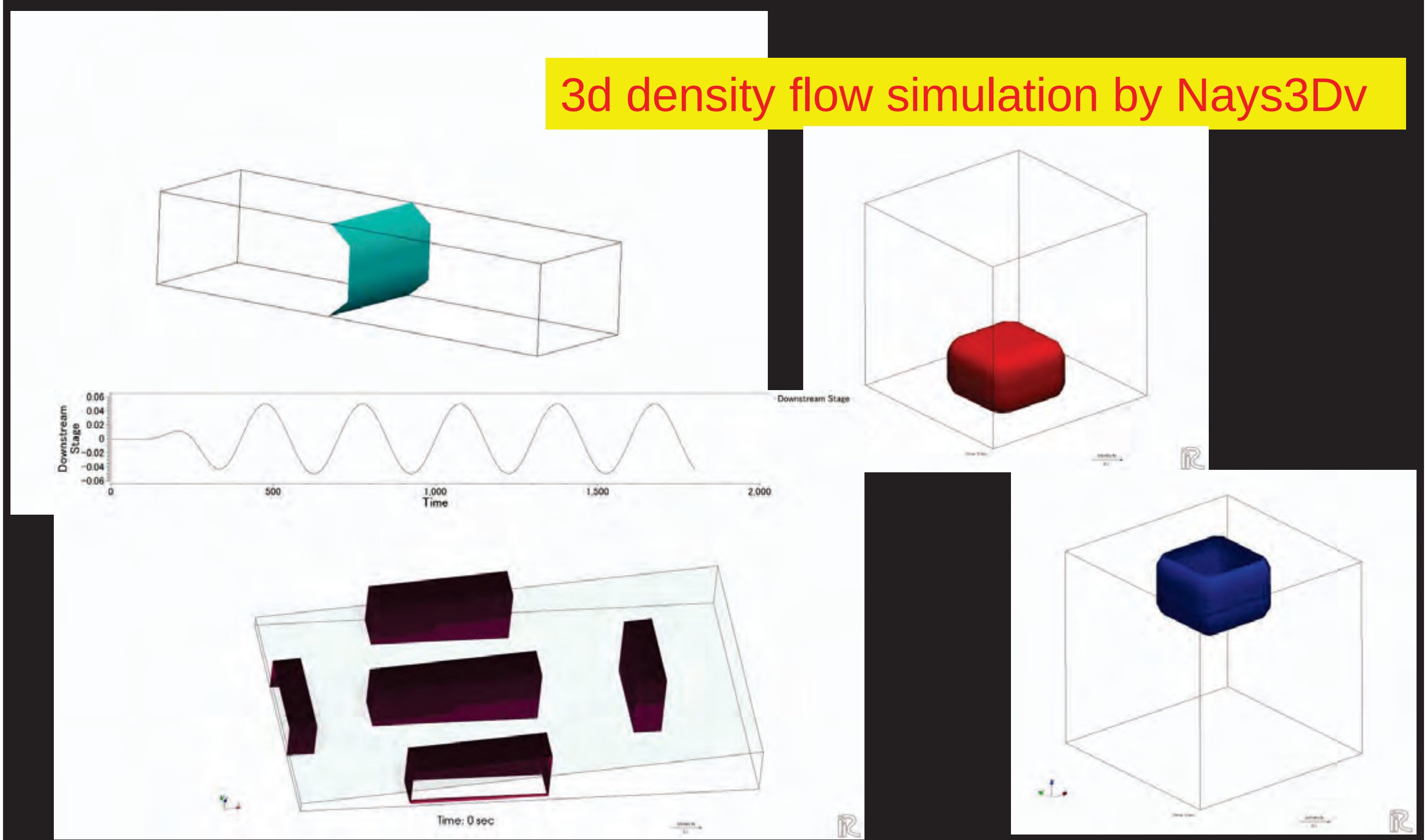
International
River Interface Corporative
iRIC

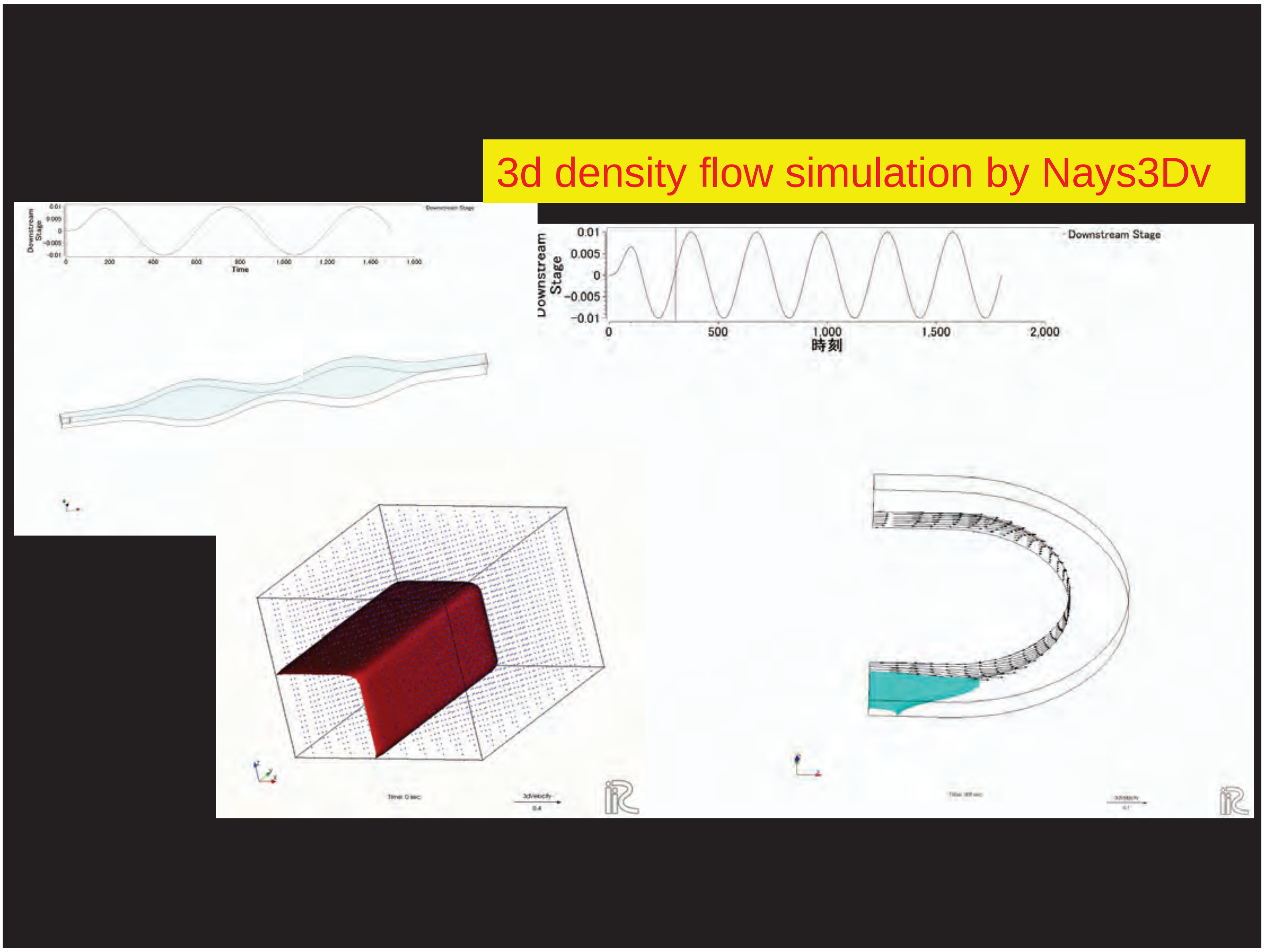


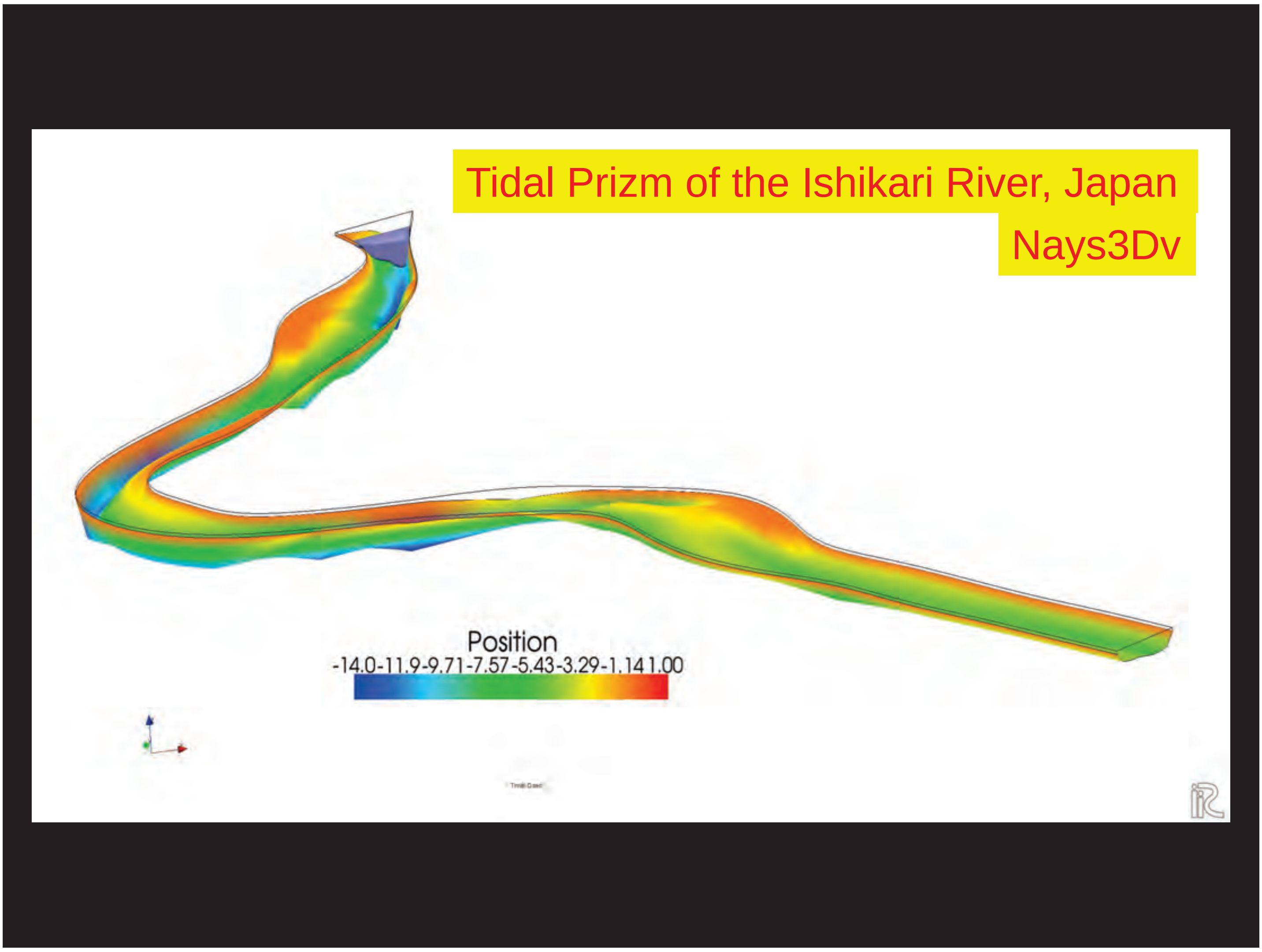
International
River Interface Corporative
iRIC

Exporting to Blender

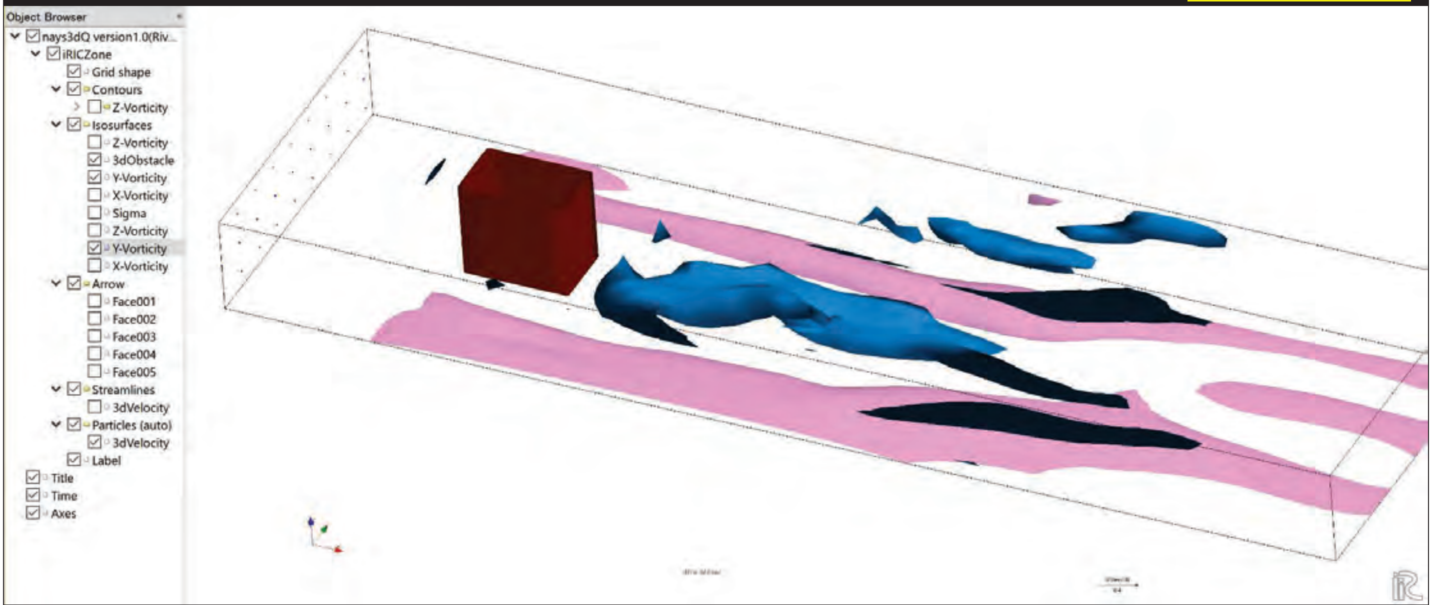
By Toshiyuki Tanaka



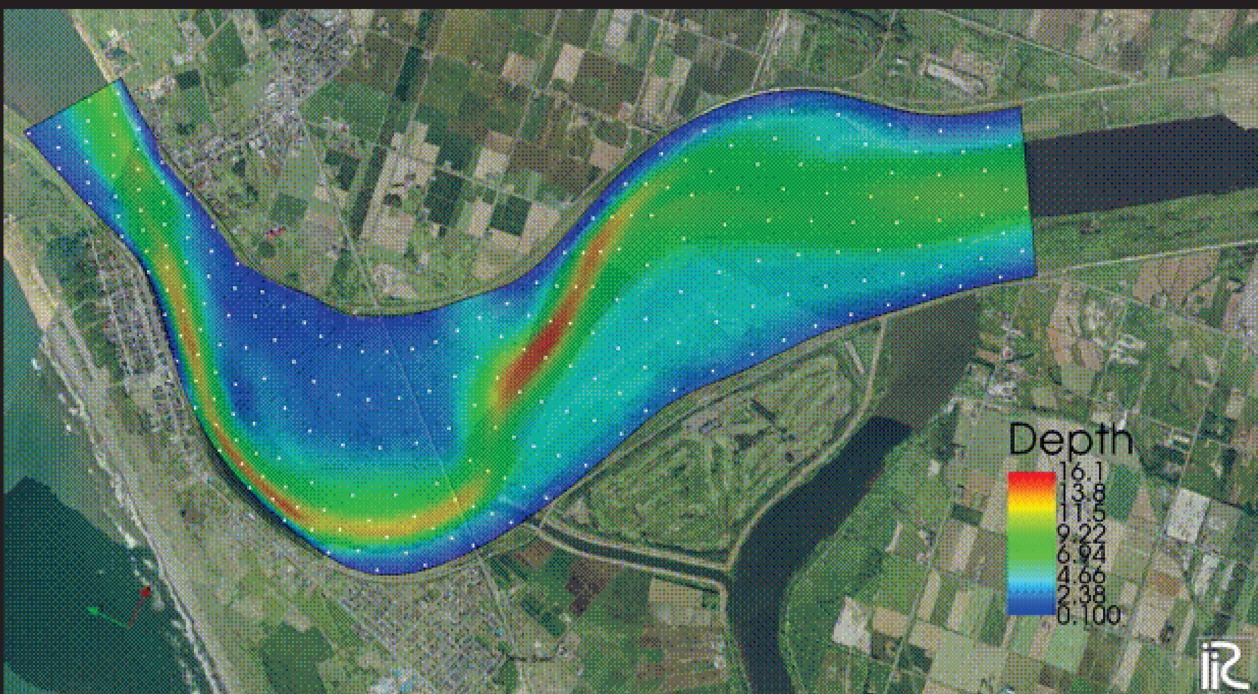

3d density flow simulation by Nays3Dv
Downstream Stage
Downstream Stage
0.01
0.005
0
−0.005
−0.01
0
500
1,000
1,500
2,000
時刻

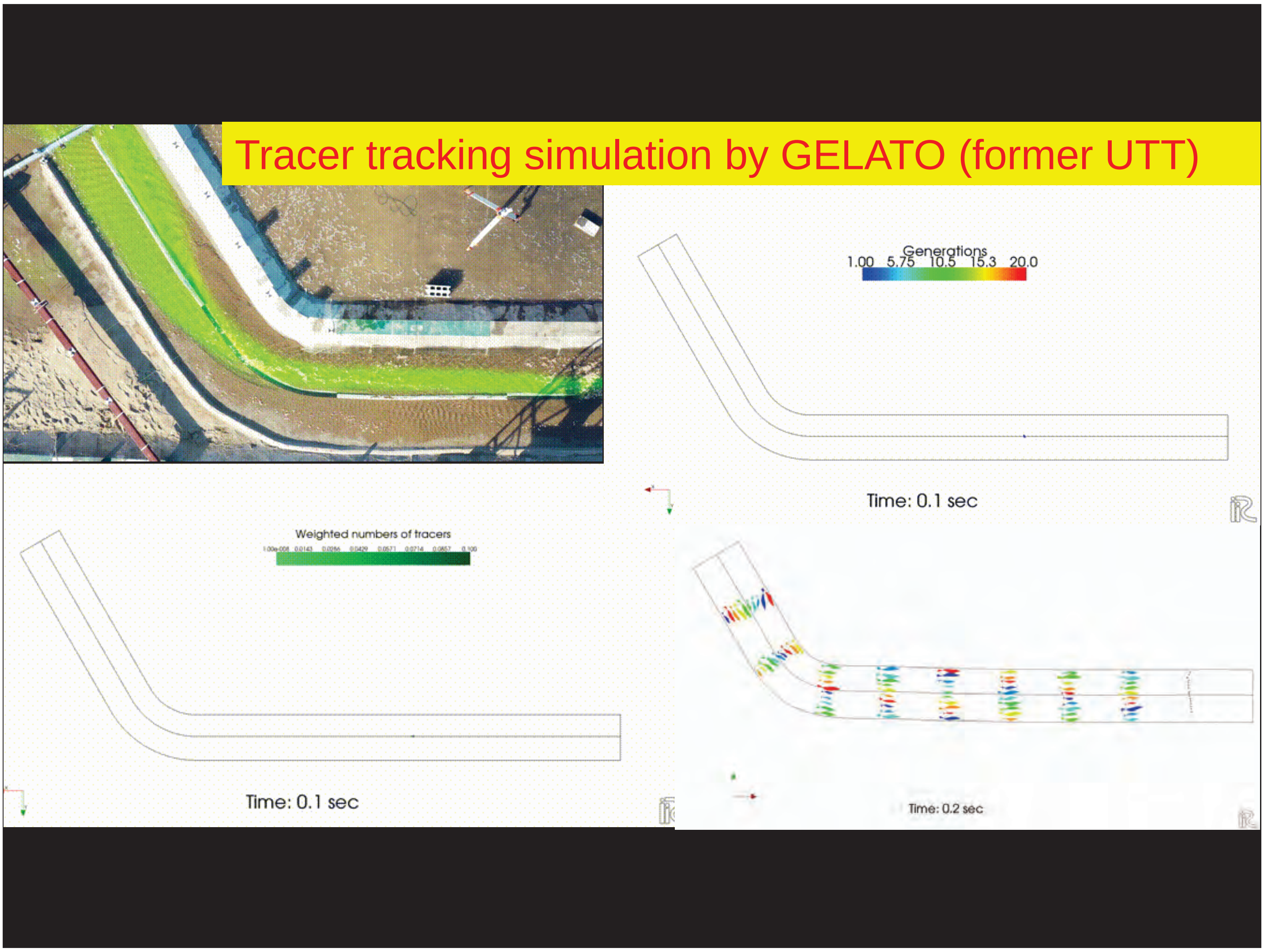

Tidal Prizm of the Ishikari River, Japan
Nays3Dv
Position
-14.0 -11.9 -9.71 -7.57 -5.43 -3.29 -1.14 1.00

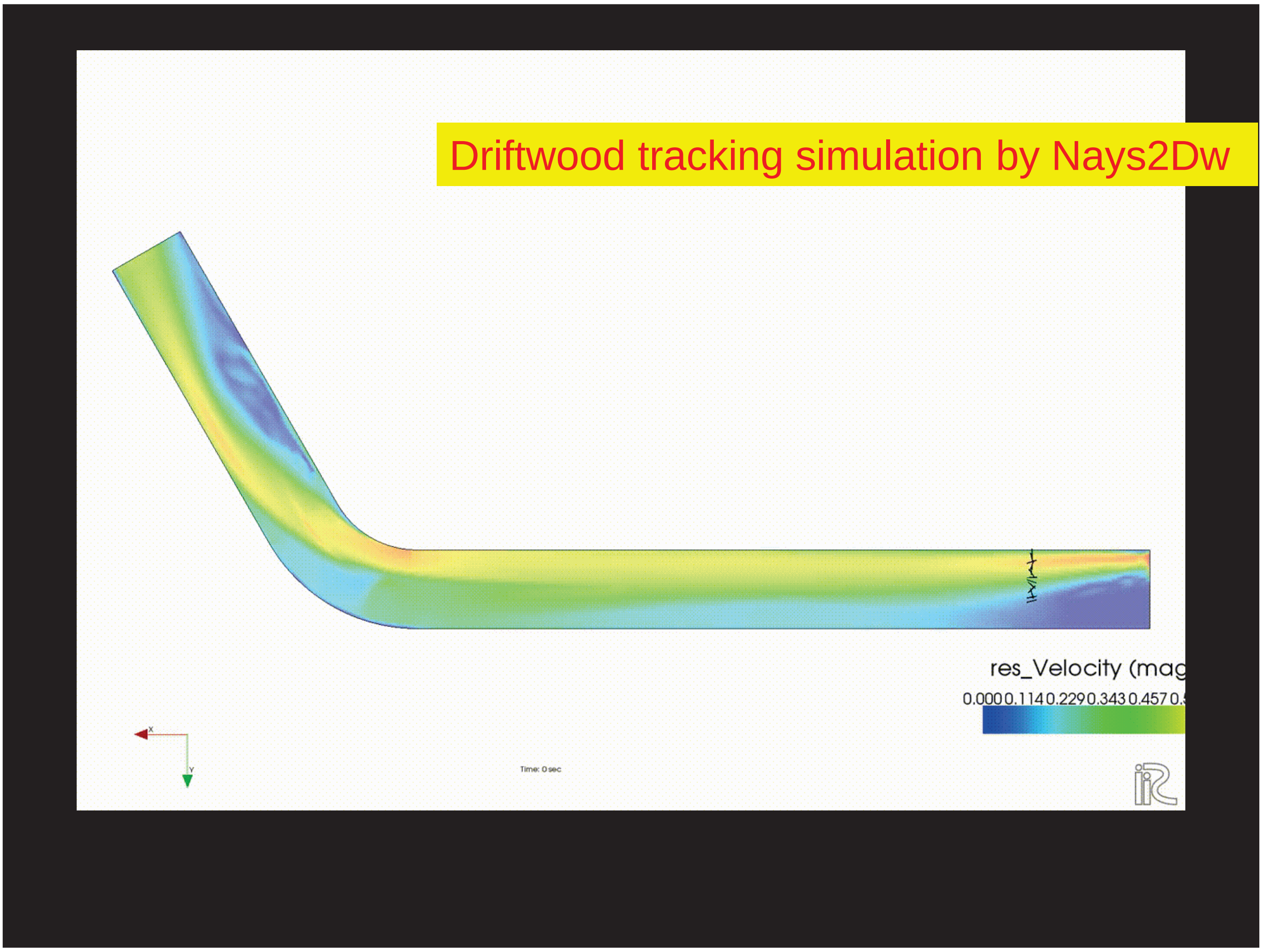
3D flow passing threw an obstacle simulated Nays3Dv



Tracer tracking simulation by GELATO (former UTT)

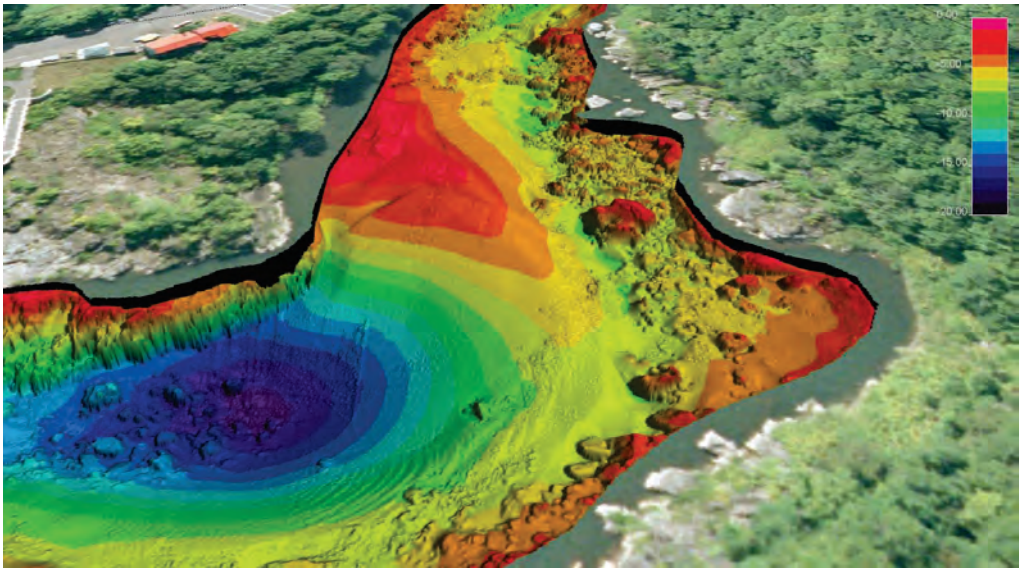



Tracer tracking simulation by GELATO (former UTT)
Generations
1.00 5.75 10.5 15.3 20.0
Time: 0.1 sec
Weighted numbers of tracers
Time: 0.1 sec
Time: 0.2 sec

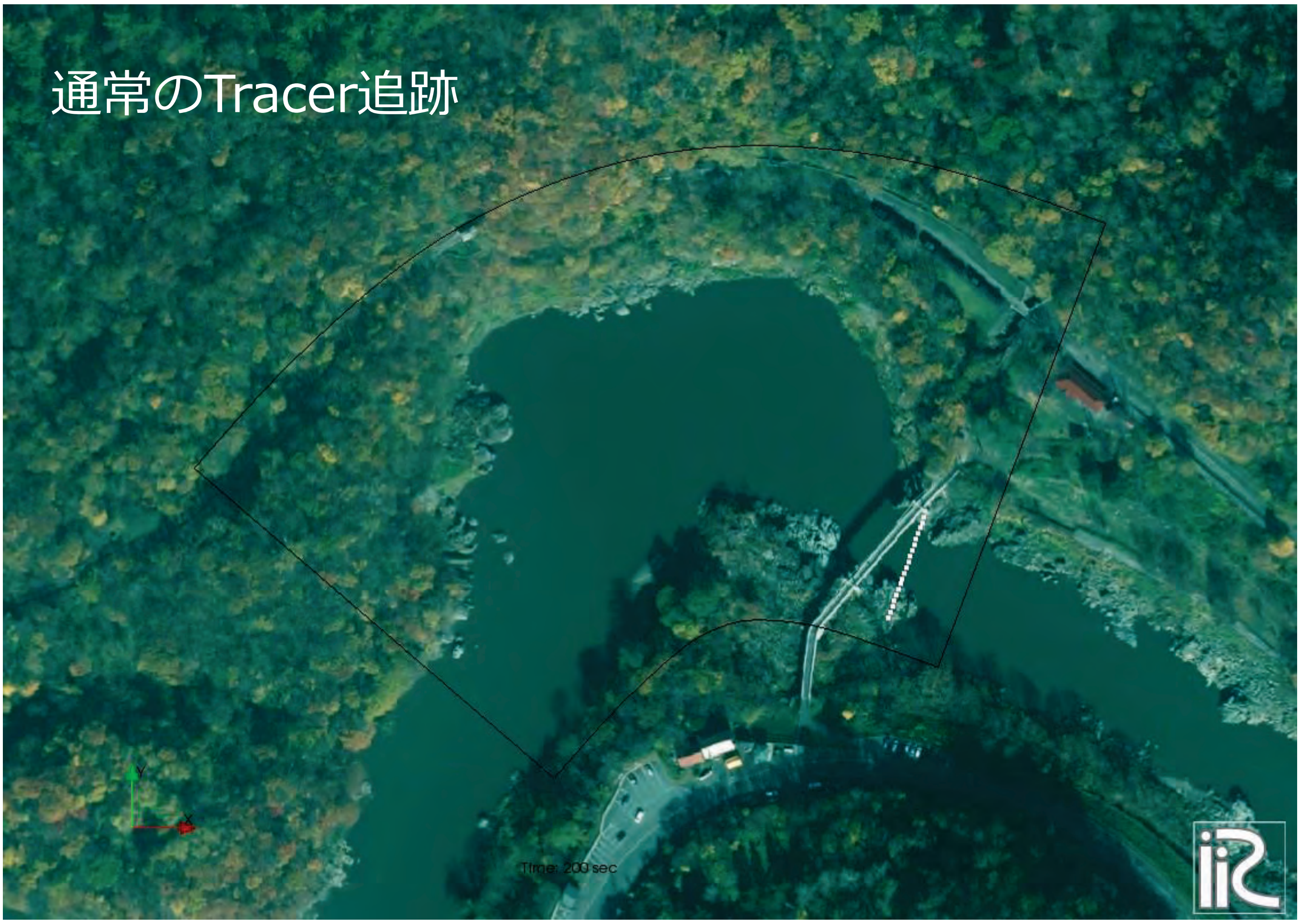

Driftwood tracking simulation by Nays2Dw
res_Velocity (mag
0.000 0.114 0.229 0.343 0.457
Time: 0 sec

Ice circles

石狩川神居古潭にも(2018年3月1日撮影)



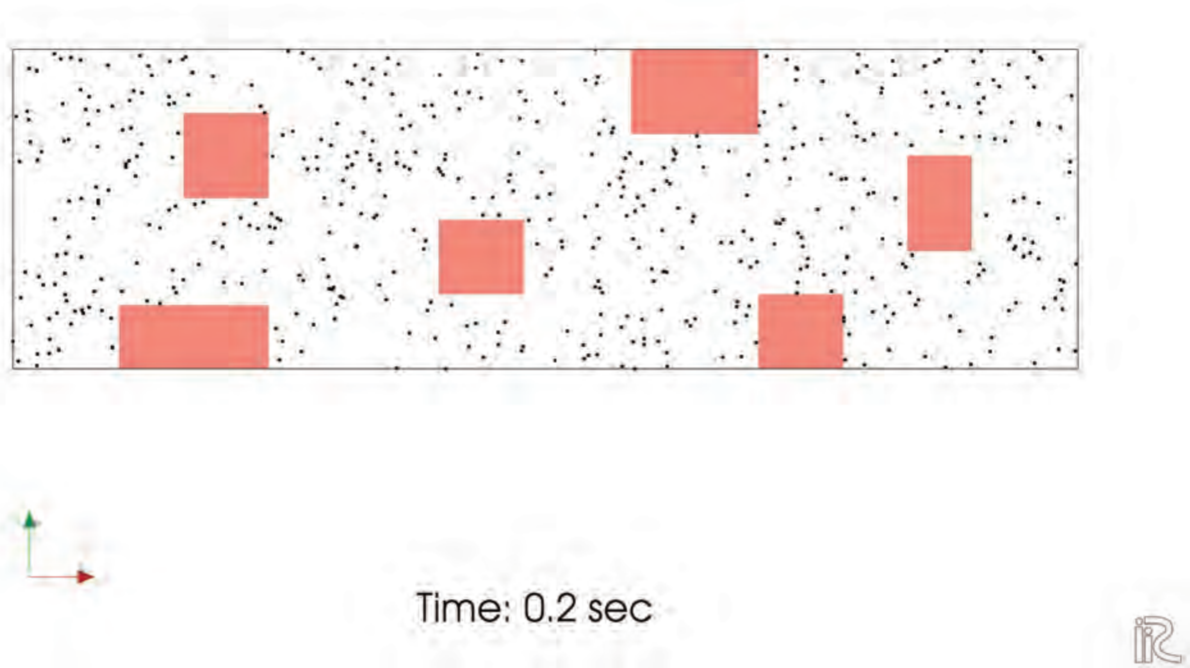
H23年11月　マルチビームによる測量結果(旭川開発建設部)



【Option】空のセルに必ずTracerを発生させる

Wind map like plot

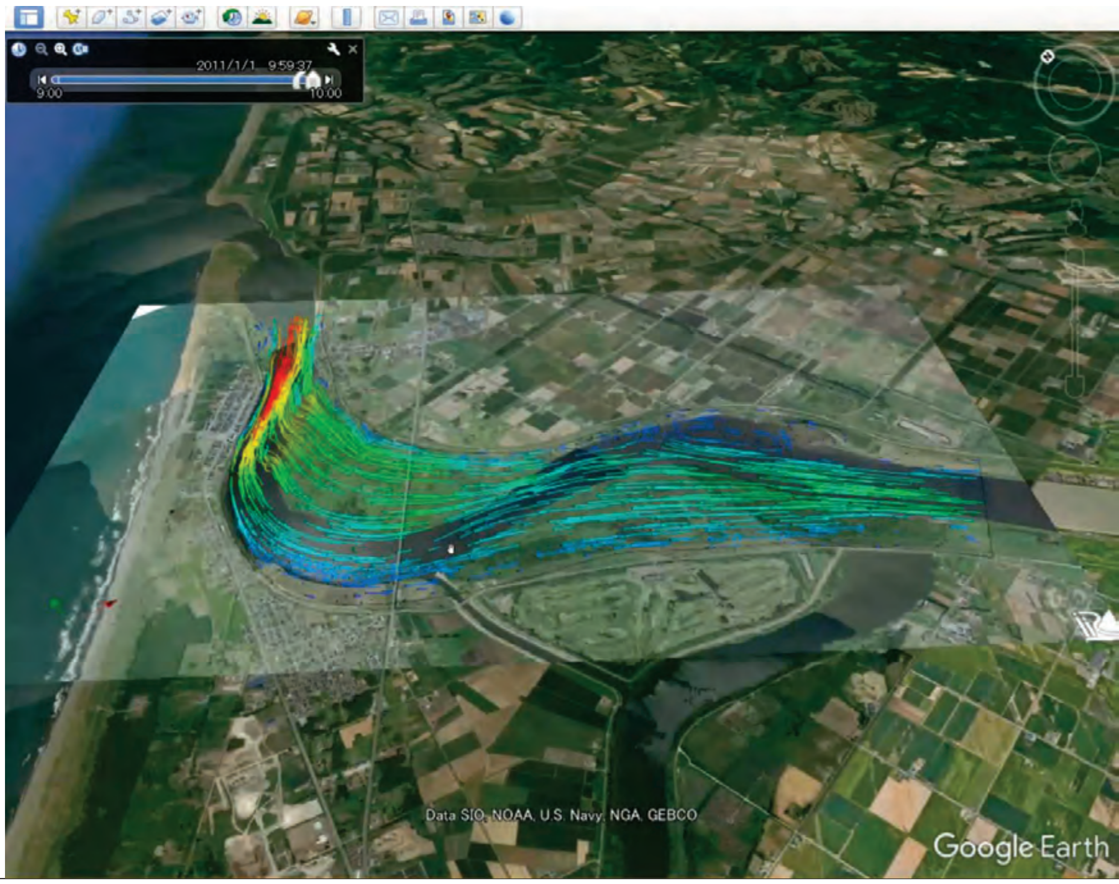
Using Gelato in iRIC



Fish simulation with GELATO in iRIC

Flow in the Ishikari River

Google Earth Output



The iRIC software

Can be downloaded from following url

http://i-ric.org/

iRIC Software
Changing River Science

Thank You

A case study on River Flood Prevention Measures in Jhuoshuei River

李 岳 洋

Yueh-Yang Li

中興工程顧問股份有限公司　計畫主任

Project Manager, SINOTECH Engineering Consultants, Ltd.

中興工程顧問股份有限公司
SINOTECH Engineering Consultants, Ltd.

A case study on River Flood Prevention Measures in Jhuoshuei River

Yueh-Yang Li

Speaker Introduction


(Photoed in 2010)

李岳洋 *Yueh-Yang Li*
Sinotech Engineering Consultants LTD. (2019~Now)
Sinotech Engineering Services LTD. (2010~2018)

- Strategy for enhancing the capacity and resilience of urban drainage systems to rainfall in Taipei City(2022~2024)
- Design of underground detention basin on the north side of the Shilin Official Residence in Taipei City(2023)
- Review and correction management planning for the Qiadongxi River(2021~2024)
- Establishment water resources supply and demand platform in the northern region(2019~2020)
- Construction flood and inundation warning system of Yunlin County(2012~2018)
- Analysis of dam breaches in barrier lakes for Zhuoshui River basin(2016)
- Investigation, analysis, and review of flooding levels and flood protection for the Taipei Metro system(2013~2015)
- Comprehensive inspection of tsunami impacts on nuclear facilities(2011~2012)

Briefing outline

1. Basin Overview
2. Disaster Prevention and Response System
3. Flood warning operations
4. Case Study of Emergency Response
5. Improvement and Development

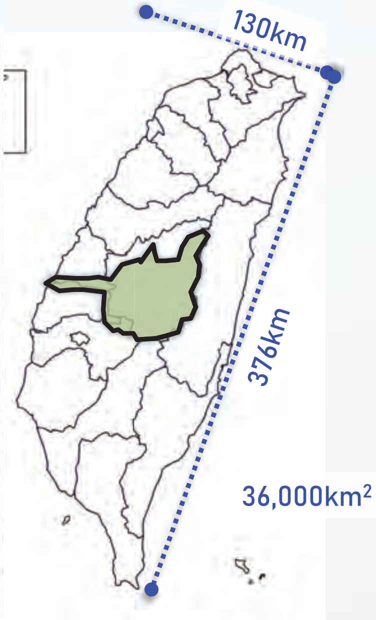
1

Basin Overview

Geographic location

Zhuoshui River Basin (Longest River in Taiwan)

1. Zhuoshui River Basin (186.7km; 3156.9km2)
2. Changhua County Seawall (64km)
3. Changhua County Regional Drainage (1,074km2)

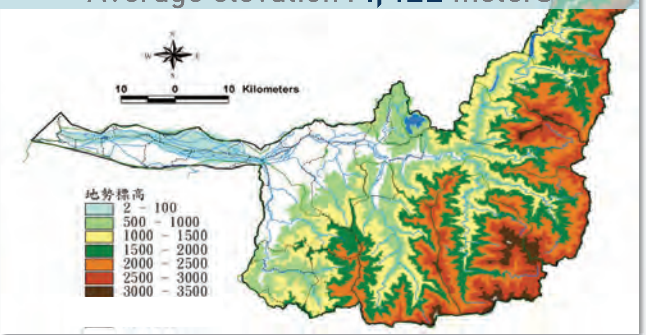


The Zhuoshui River

- runs through 21 townships spanning four counties: Nantou, Chiayi, Changhua, and Yunlin.
- The cultural, social, and economic activities along its basin hold a crucial position in Taiwan.

Geomorphological Characteristics 1

Average elevation : 1,422 meters

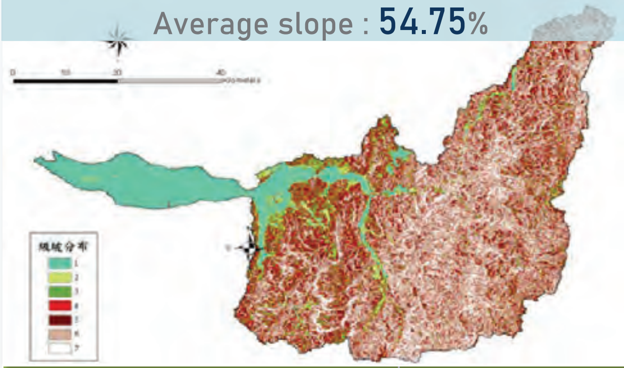


Height(m)	Percentage
<100	7.5%
100-1,000	28.5%
1,000-2,000	34.7%
2,000-3,000	25.3%
3,000以上	4%

64% (1,000 m and above)

- Terrain slopes from east to west, with increasing slope from west to east

Average slope : 54.75%



Slope S	Percentage
S>15% (約8.5°)	88.6%
S>56% (約29.25°)	62.5%
S>74% (約36.5°)	34%

- Upper reaches : rugged mountains and deep valleys
- Lower reaches : gentle terrain and multiple alluvial fans
- Tributaries: steep and towering terrain

Geomorphological Characteristics 2

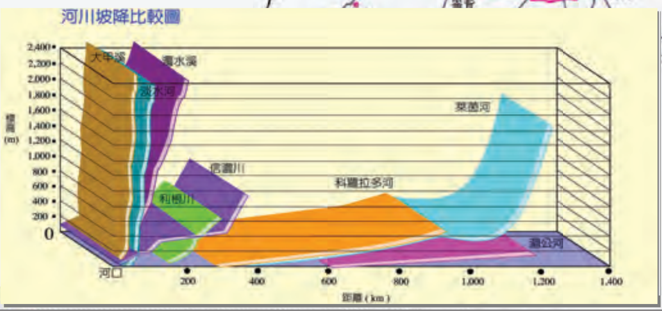
Significant variations in elevation, with short river channels and steep slopes.

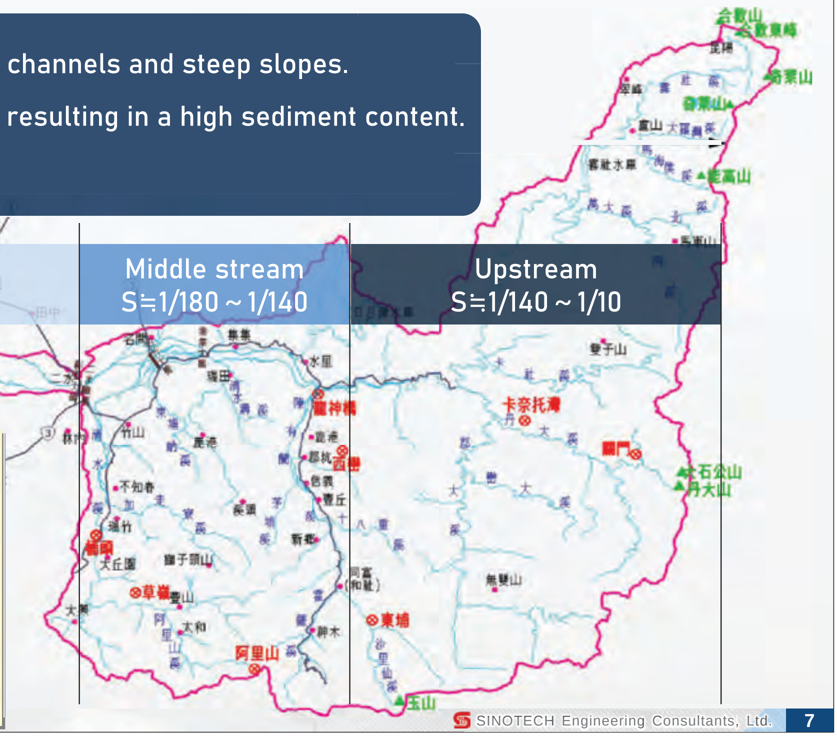
Upstream area are prone to erosion and collapse, resulting in a high sediment content.

The annual sediment yield : 49.52 million tons

$S_{avg.}=1/55$

Downstream	Middle stream	Upstream
S≒1/2600 ~ 1/180	S≒1/180 ~ 1/140	S≒1/140 ~ 1/10





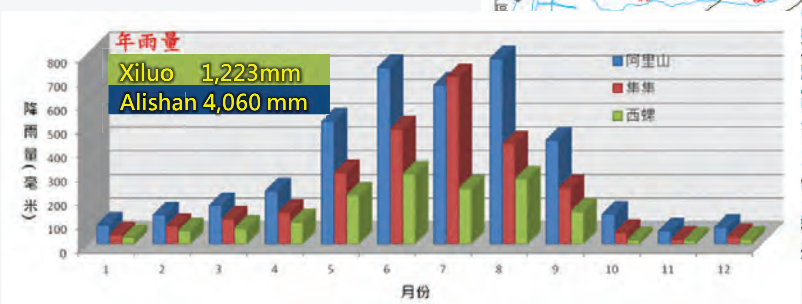
1. Basin Overview | 2.Disaster Prevention and Response System | 3.Flood warning operations | 4.Contingency case study on Disaster Prevention | 5. Future vision

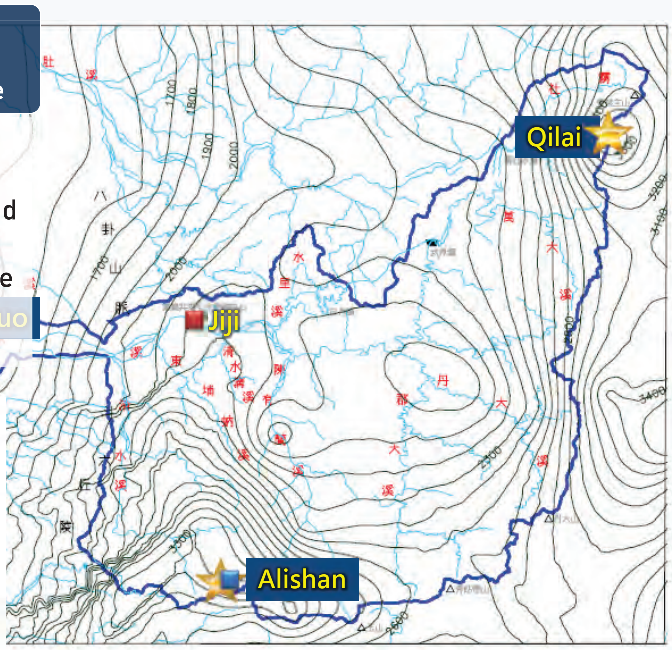
Hydrological Characteristics

Average rainfall in the basin : 2,500 mm/year

Rainfall is concentrated, uneven distribution in time and space

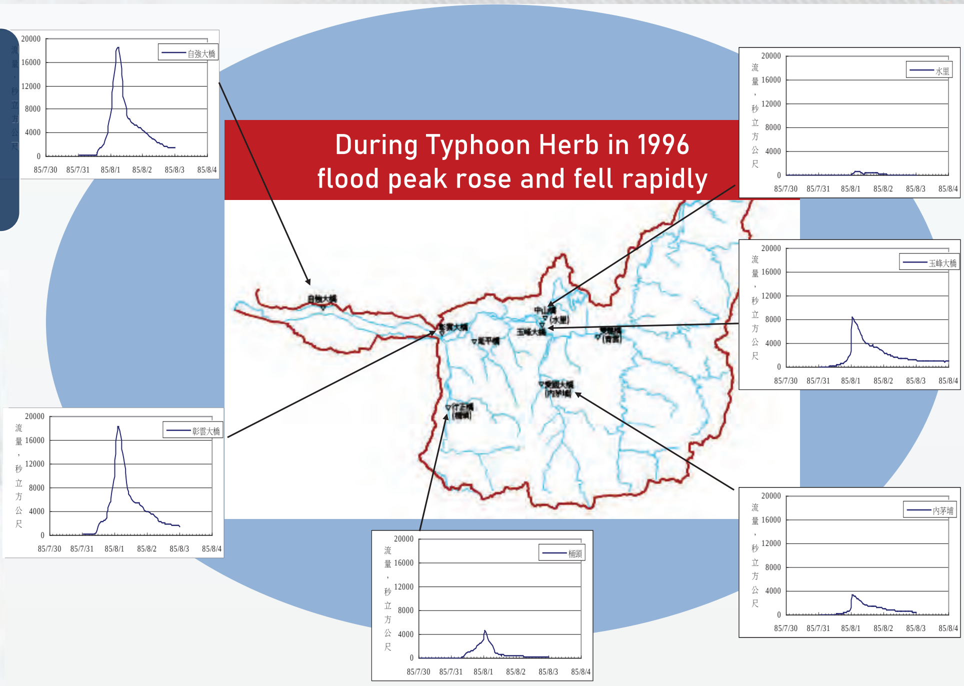
- Rainfall concentrated in wet season (May to October), with an 8:2 ratio of wet to dry periods.
- Main rainfall sources include Mei-Yu front (May to June) and typhoons (July to September)
- Rainfall distribution: increases from west to east, with more rainfall in mountainous areas than plains.
- Rainfall center: Alishan and Qilai Mountains





Flood Characteristics 1

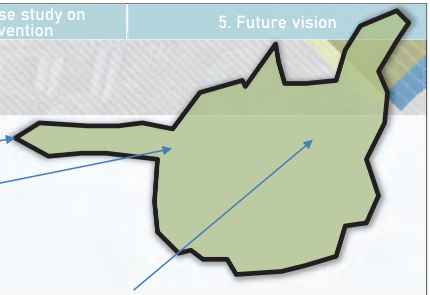
- Steep slopes and rapid flow, with short arrival time of floods.
- Large peak flow and rapid flood propagation.

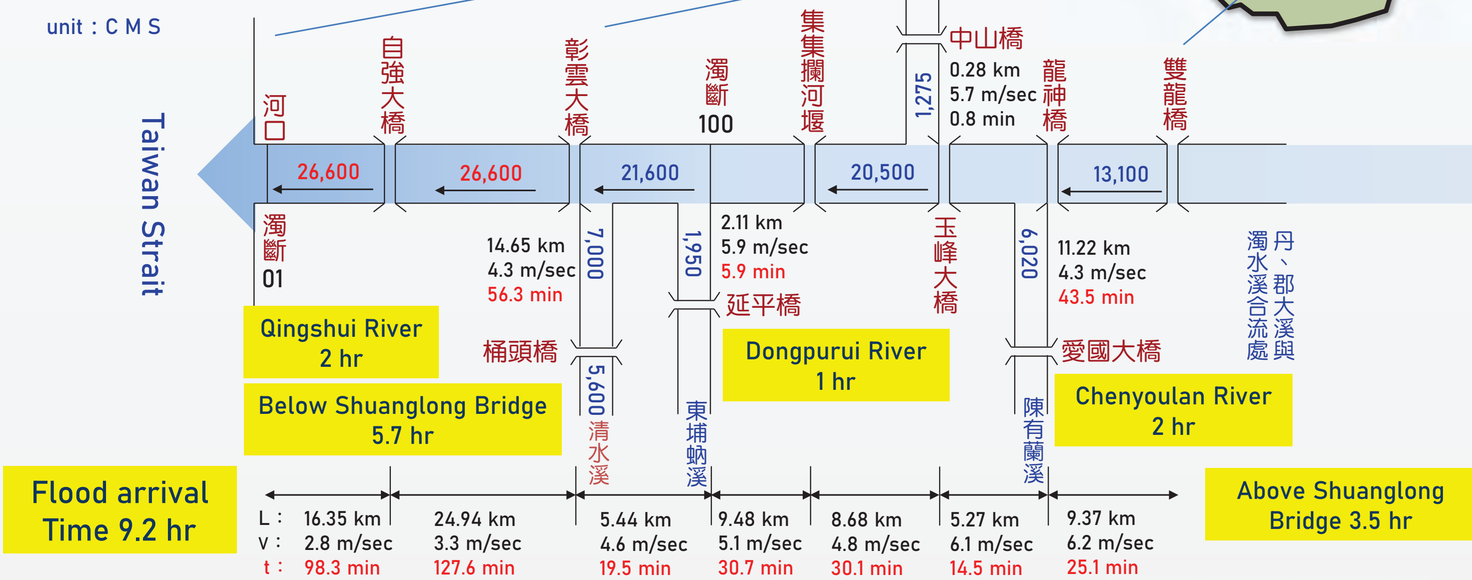


Flood Characteristics 2

Limited time for disaster response

Steep slopes and rapid flow with a short arrival time of floods.





Disaster Potential

Disaster potential:

- Debris flows
- Landslides, dammed lakes
- Riverbank breaches
- Flooding

Riverbank Typhoon Flooding Disaster Distribution Map

Disaster characteristics:

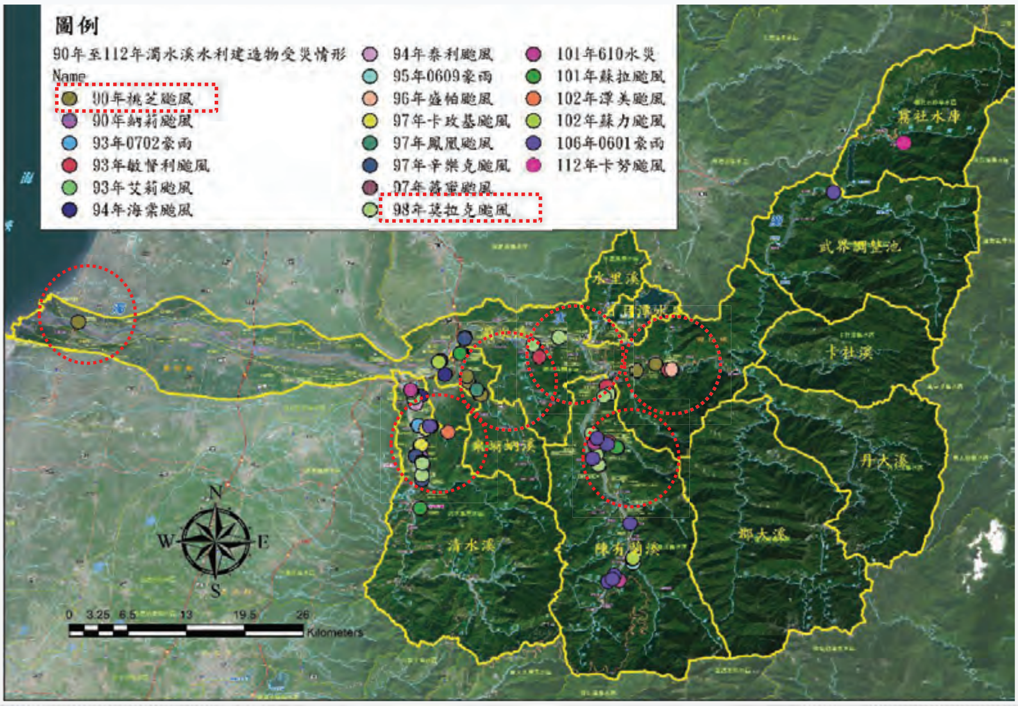
- Concentrated heavy rainfall, high rainfall intensity.
- Meandering effect and excessively high water levels exacerbate the extent of flooding.
- Accumulation of debris and sediment, rising water levels, leading to breaches with boulders and driftwood.

Causes of disasters (in the Changhua area)

- Poor connection of runoff from Bagua Mountain Plateau.
- Subsidence of southwest coastal strata.
- Inadequate drainage capacity of floodways.

Major Flood Events Over the Years 1

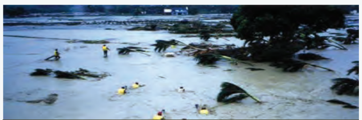
Major Flood Events Over the Years 2

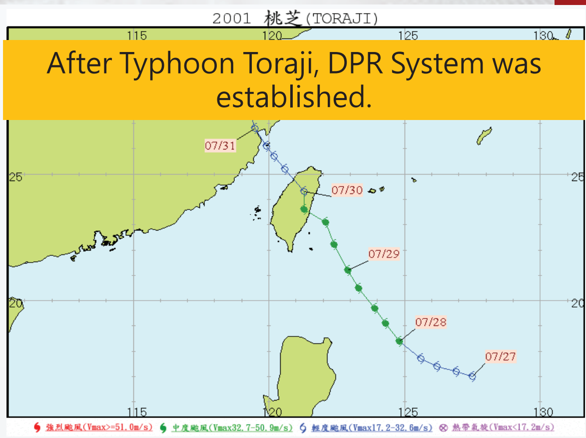


Major Flood Events Over the Years 3

Typhoon Toraji Disaster in 2001


Debris flow (along Gaozouliao Creek estuary)


Embankment breach (Mudiji Liao on Dongpu Rui Creek)



After Typhoon Toraji, DPR System was established.


Downstream Groundsills damage near Xingzheng Bridge on Qing Shui Creek


Damage to Rui Cao Bridge on Qing Shui Creek

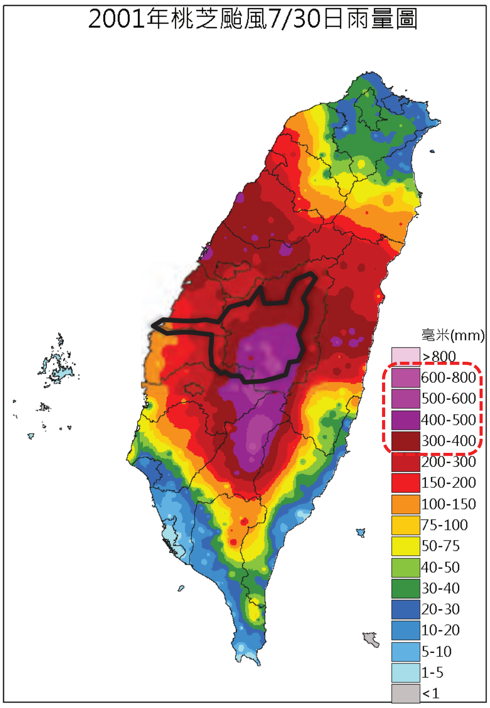

Damage to upstream embankments and residential houses (near Chu Xiang Bridge on Dongpu Rui Creek)


Debris flow in Nanqingshuigou Creek, causing flooding and damage to roads and embankments


Debris flow on Dongpu Rui Creek, damaging embankments near Yanping Bridge

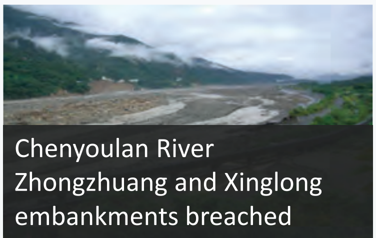
Major Flood Events Over the Years 4

Typhoon Toraji Disaster in 2001

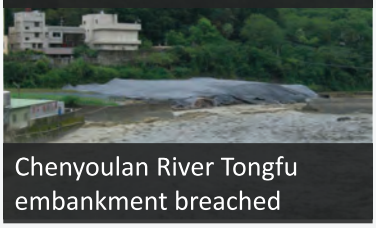


Major Flood Events Over the Years 5

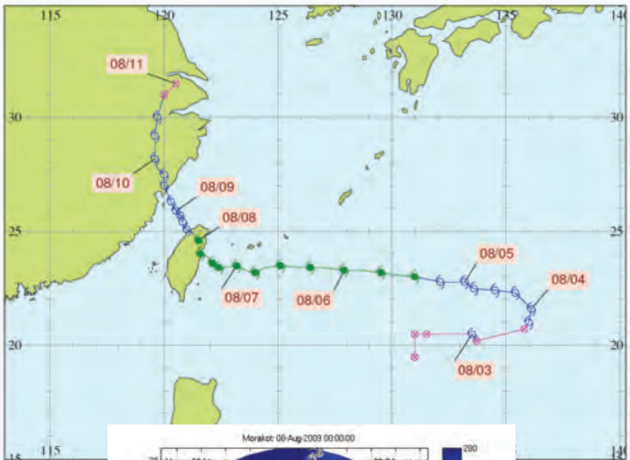
Typhoon Morakot Disaster in 2009



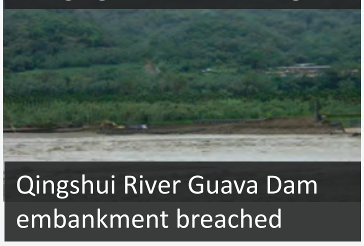
Chenyoulan River Zhongzhuang and Xinglong embankments breached



Chenyoulan River Tongfu embankment breached

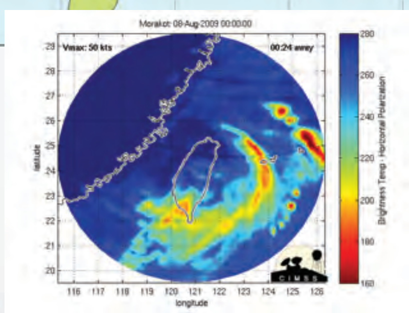


Qingshui River Xingzheng Bridge groundsills damaged



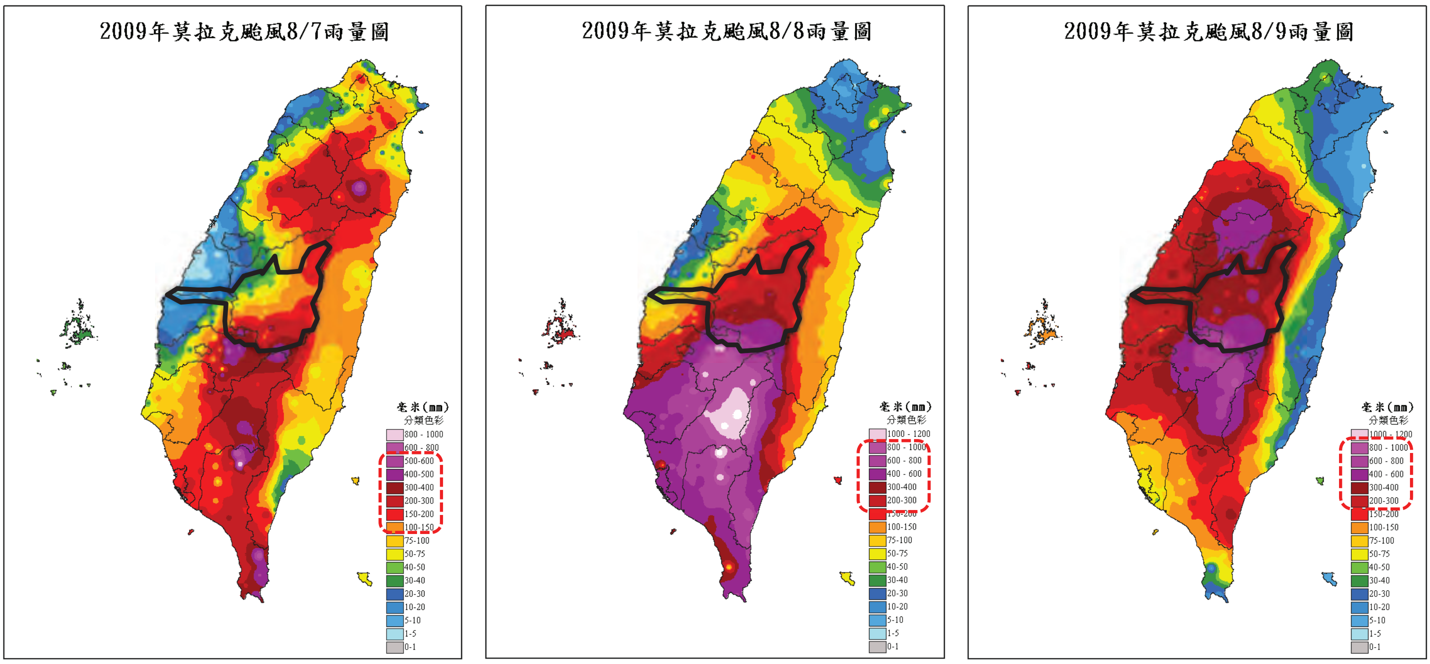
Qingshui River Guava Dam embankment breached

Chenyoulan River Shang'an embankment damaged



Qingshui River Fuxing Canal revetment breached

Major Flood Events Over the Years 6 Typhoon Morakot Disaster in 2009



2

Disaster Prevention and Response System

Flood Forecasting System

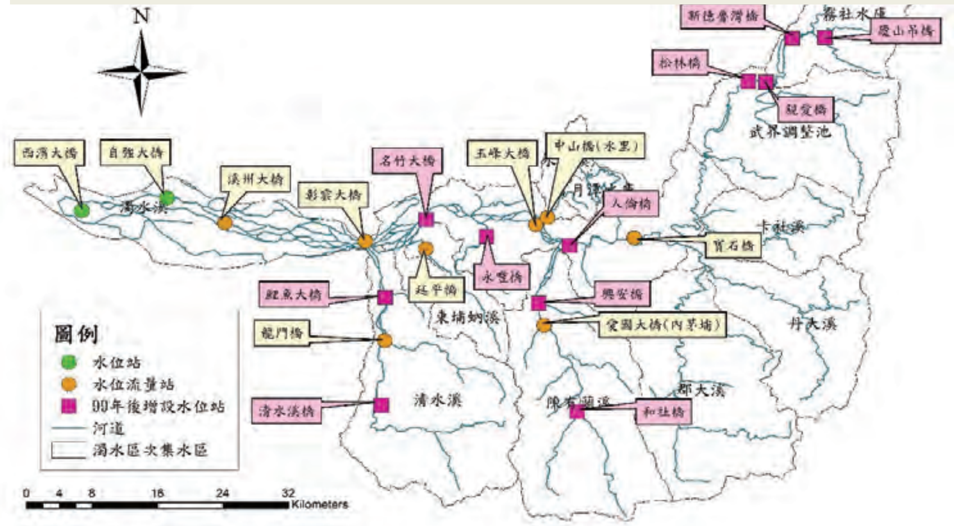
In May 2002, the "Zhuoshui River Basin Direct Runoff Measurement and Forecasting System Construction Project" was completed.

Hardware components:
1 hydrological center
10 water level flow stations
49 rain gauge stations

Software components:
Zhuoshui River Basin flood runoff measurement and forecasting system model

Rain gauge stations:
SFTP interface with the Central Weather Bureau's PDS nationwide rain gauge stations

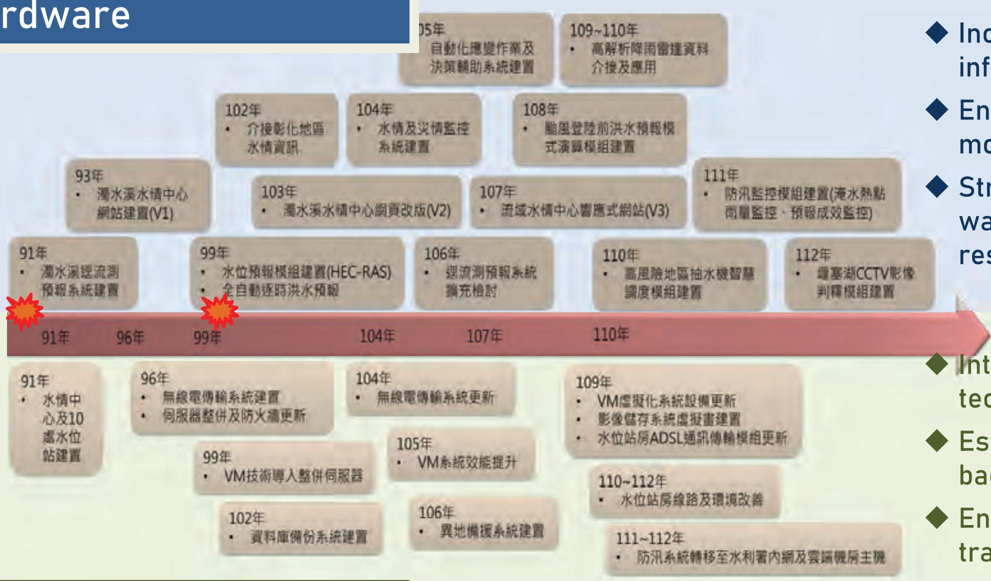
The main purpose of the Zhuoshui River Basin runoff measurement and forecasting system is to improve flood warning time to facilitate subsequent flood control measures.



1. Basin Overview | 2.Disaster Prevention and Response System | 3.Flood warning operations | 4.Contingency case study on Disaster Prevention | 5. Future vision

System Iteration

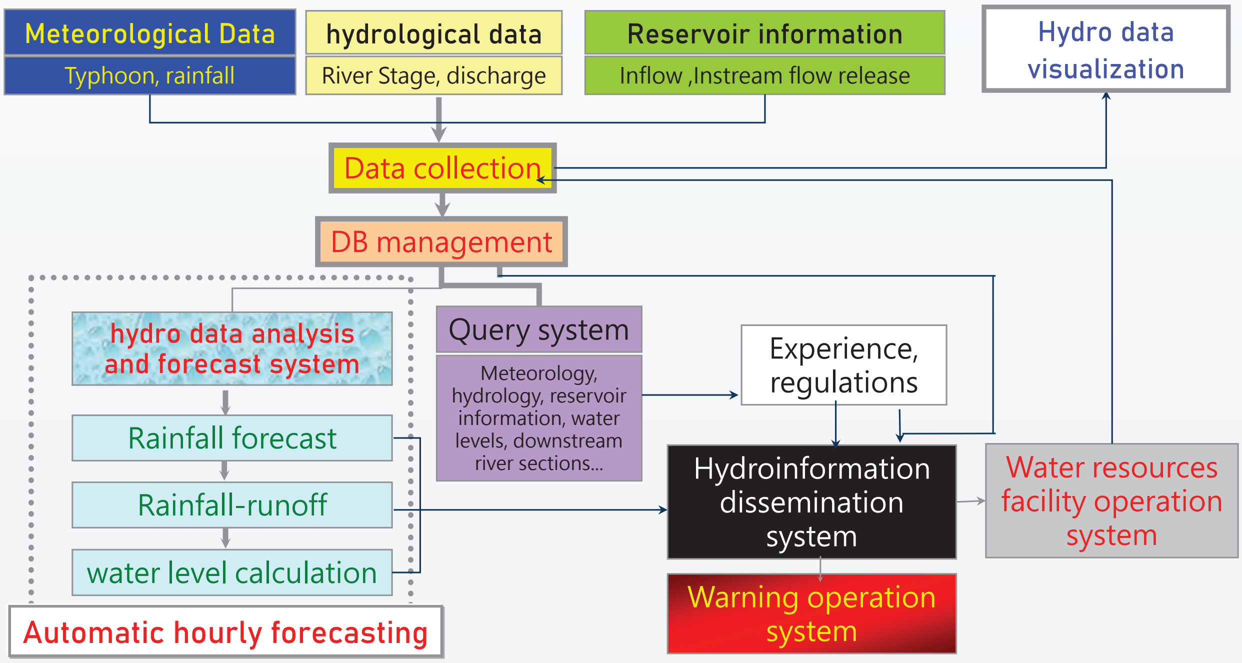
Hardware



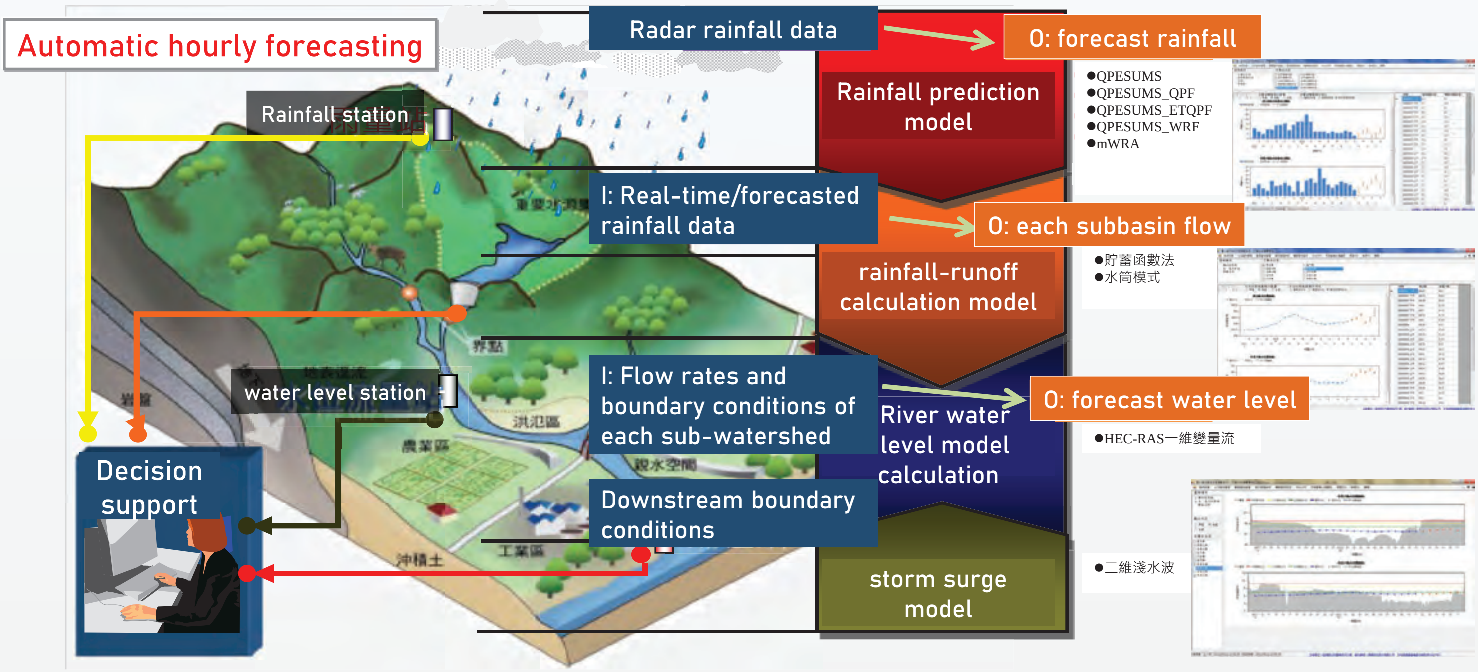
Software

- Incorporation of flood-related information
- Enhancement of flood simulation models
- Strengthening of capabilities in warning, notification, and emergency response operations
- Integration of new hardware technologies
- Establishment of comprehensive backup and contingency mechanisms
- Ensuring stability of data transmission
- Enhancing cybersecurity; centralized management of the system

System Structure

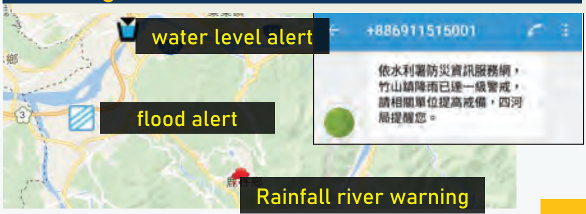


Flood Forecasting System

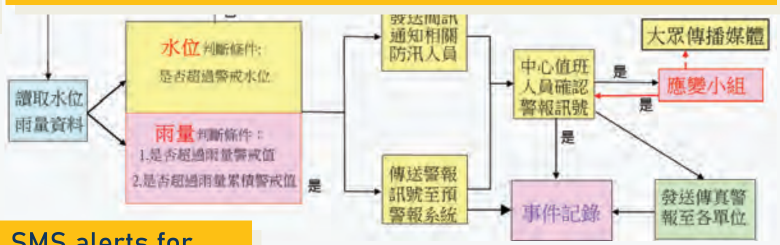


Warning Issuance System

Real-time monitoring and SMS alert for warning information



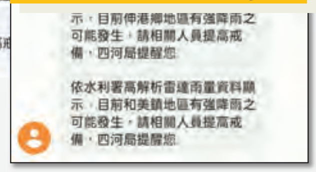
Early warning issuance process



Real-time monitoring of current disaster situation

SMS alerts for flooding

SMS alerts for heavy rainfall warning

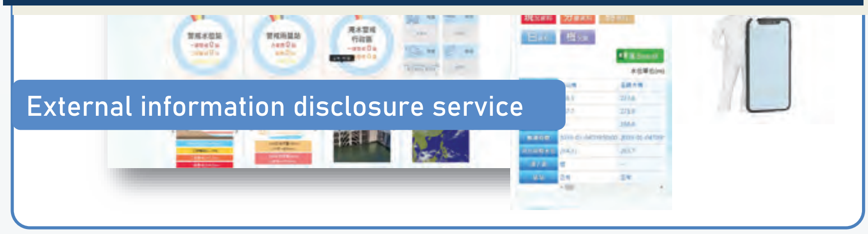


FAX alerts for flood warnings

Hydro data visualization and Flood Control Assistance 1

Zhuoshui River Basin hydro data visualization Center platform

External information disclosure service



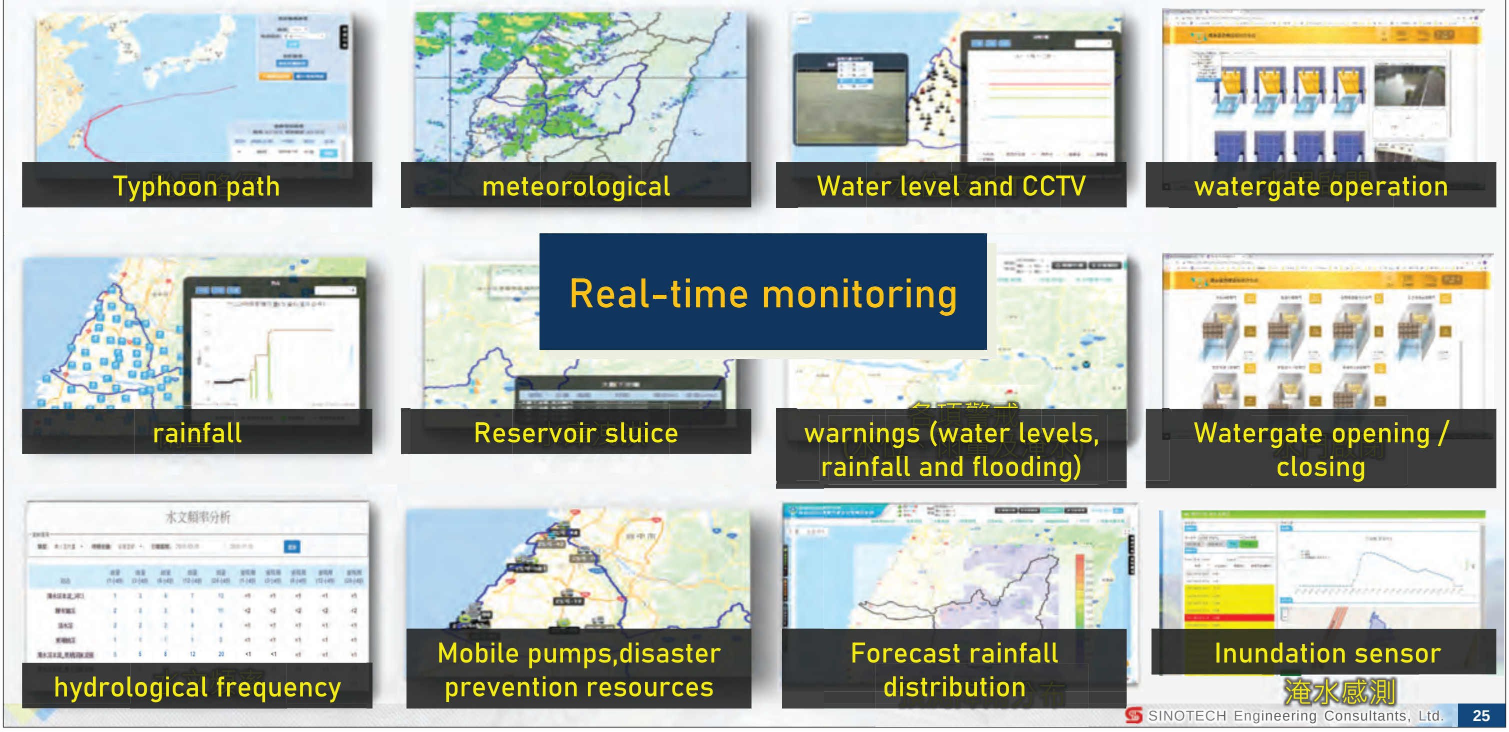
Integrated Smart Management System for the Zhuoshui River Basin

Internal use, river management and flood control operations

Automated and Process-oriented Disaster Prevention Operation Integration Platform

functions including readiness, monitoring, warning, notification, response, and decision-making.

Hydro data visualization and Flood Control Assistance 2



Hydro data visualization and Flood Control Assistance 3

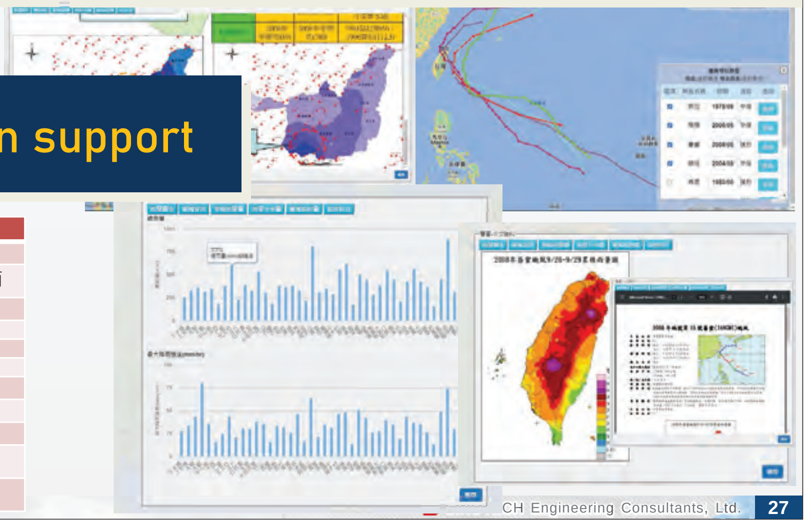
Emergency Repair Assistance
Provide assistance in setting and selecting repair methods based on the scale of the disaster, and conduct relevant decision-making support analysis.

Pump Scheduling Assistance
Integrate real-time : information from mobile pumps and flood sensors, automatically analyze and propose allocation recommendations.

Hydro data visualization and Flood Control Assistance 4

Hydro Briefing material
Automatically collate latest weather information, forecast data, and preparedness information to generate the required briefing materials.

Typhoon Analysis
Conduct searches and information queries on historical typhoon events similar to the current typhoon's path.



Decision support

類型	豪雨事件	颱風事件事件
氣象動態	即時氣象圖資	颱風動態
		歷史相似路徑颱風之降雨
		即時氣象圖資
水文情勢分析	• 降雨資訊(含預報) • 水位資訊(含預報) • 潮位資訊(含預報) • 水庫洩洪資訊	
整備情形	防汛備料數量	
災情資訊	四河局權責災情資訊	
綜合研判	綜合水情研判說明	颱風影響歷程推測
		綜合水情研判說明

Hydro data visualization and Flood Control Assistance 5

Disaster Response Assistance
Guide step-by-step completion of forms through flowcharts, manual or online approval, confirmation of approval, system registration for response, notification (dispatch) of flood response personnel, and checklist for required tasks.

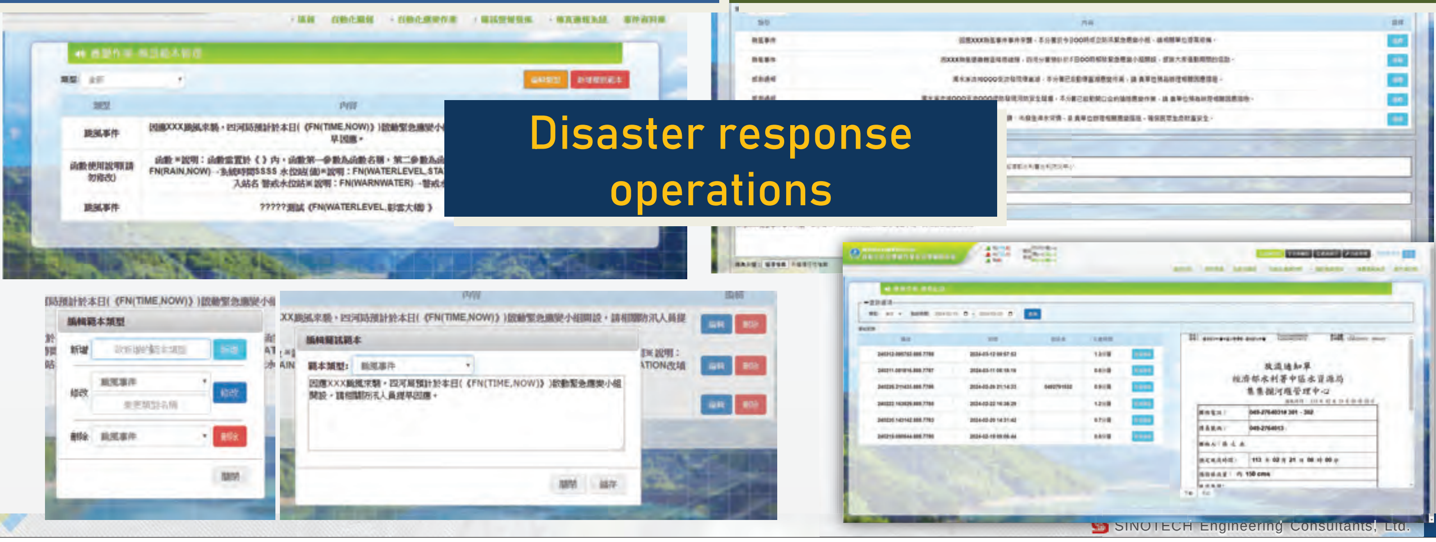
Disaster response operations

Implementation of 18 standardized disaster response procedures to prevent operational oversights.

Hydro data visualization and Flood Control Assistance 6

SMS Alert Distribution
Coordinate with the automated response sub-system to automate the distribution of SMS alerts for each response operation.

Fax Notification
Coordinate with the automated response sub-system to automate the distribution of fax notifications for each response operation.



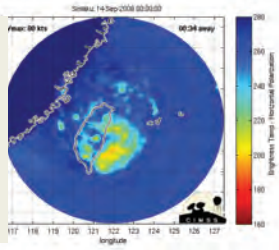
3

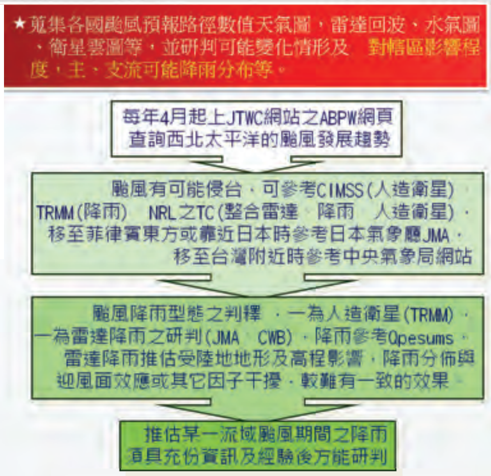
Flood warning operations

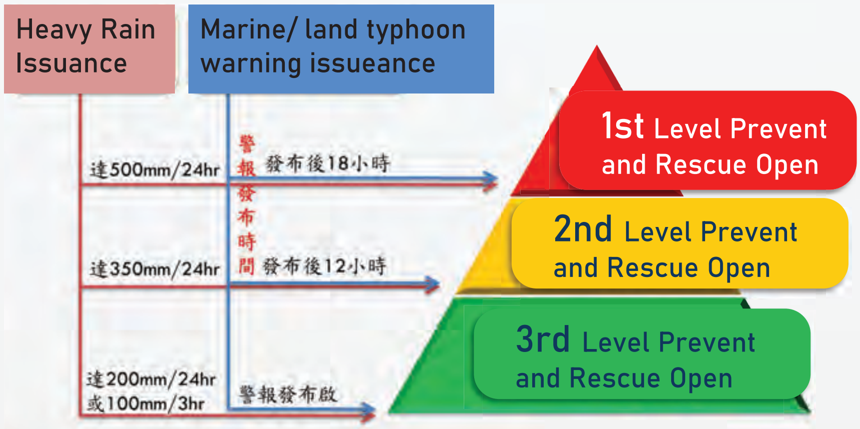
Flood warning operations

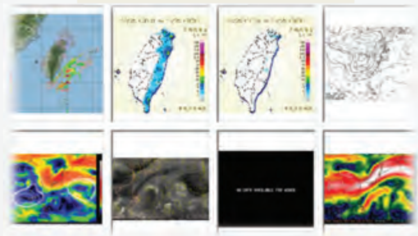
The 4th River Management Branch,WRA disaster response personnel are on duty 24 hours a day.

Sinotech assists in monitoring real-time hydro data and facilitating the dissemination of forecasting information.





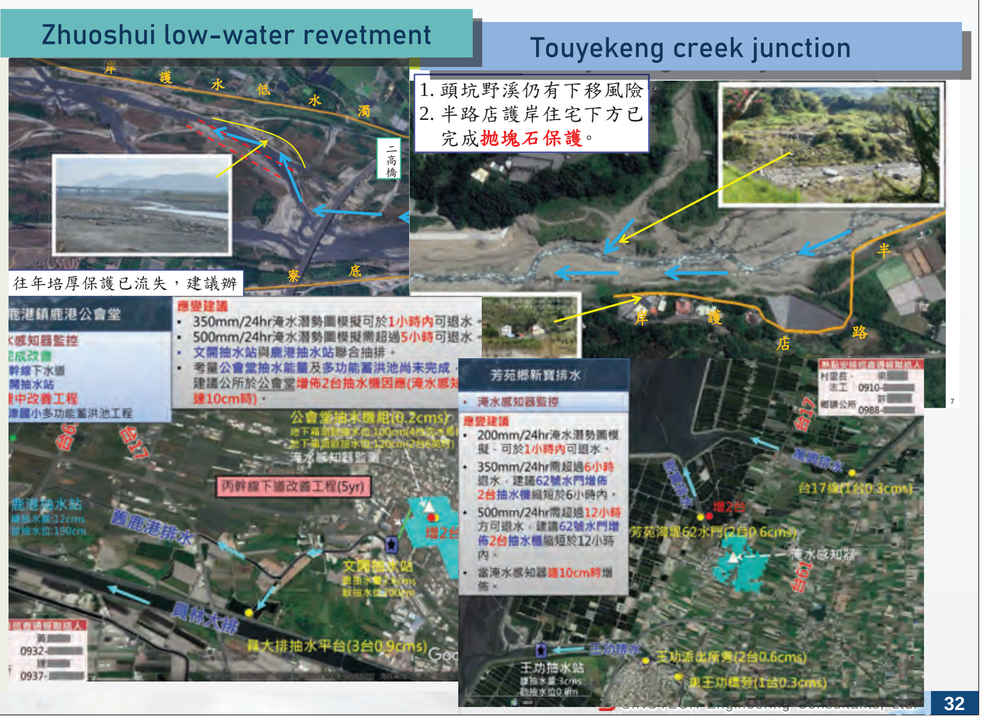




Area Risk Assessment

During typhoon and flood events:

- Analysis of typhoons with similar paths.
- Interpretation of high-risk areas.
- Recommendations for open contracts and preparedness.



1. Basin Overview
2.Disaster Prevention and Response System
3.Flood warning operations
4.Contingency case study on Disaster Prevention
5. Future vision
Prediction and Forecast Announce
Typhoon confirmed to invade Taiwan
Land typhoon warning issued
During typhoon and flood events:
Analysis of typhoons with similar paths.
Interpretation of high-risk areas.
Recommendations for open contracts and preparedness.
交通部中央氣象署
Central Weather Administration
Automatic analysis of typhoons with similar paths
Review and improve key areas
Below Threshold
Preventive rescue decision-making assistance
Find out the location of historical typhoon rainfall distribution
Similar path analysis
Zhuoshui Rivet Runoff Forecasting System
Exceeds Alert value
Open contract entry advice
Match the maximum probability of rain pattern for each path
Flood peak flow forecast
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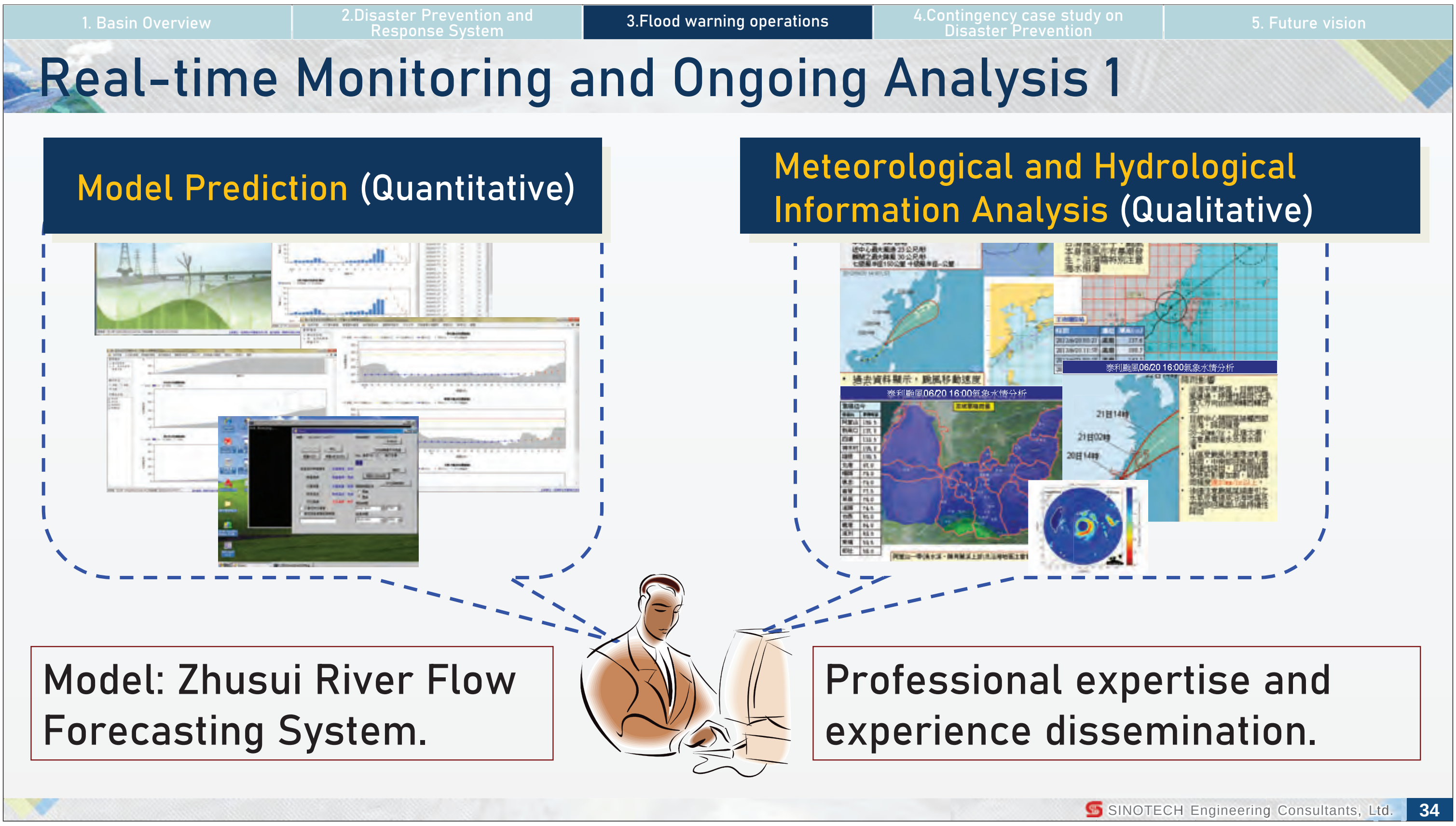
33



1. Basin Overview
2.Disaster Prevention and Response System
3.Flood warning operations
4.Contingency case study on Disaster Prevention
5. Future vision
Real-time Monitoring and Ongoing Analysis 1
Model Prediction (Quantitative)
Meteorological and Hydrological Information Analysis (Qualitative)
Model: Zhusui River Flow Forecasting System.
Professional expertise and experience dissemination.
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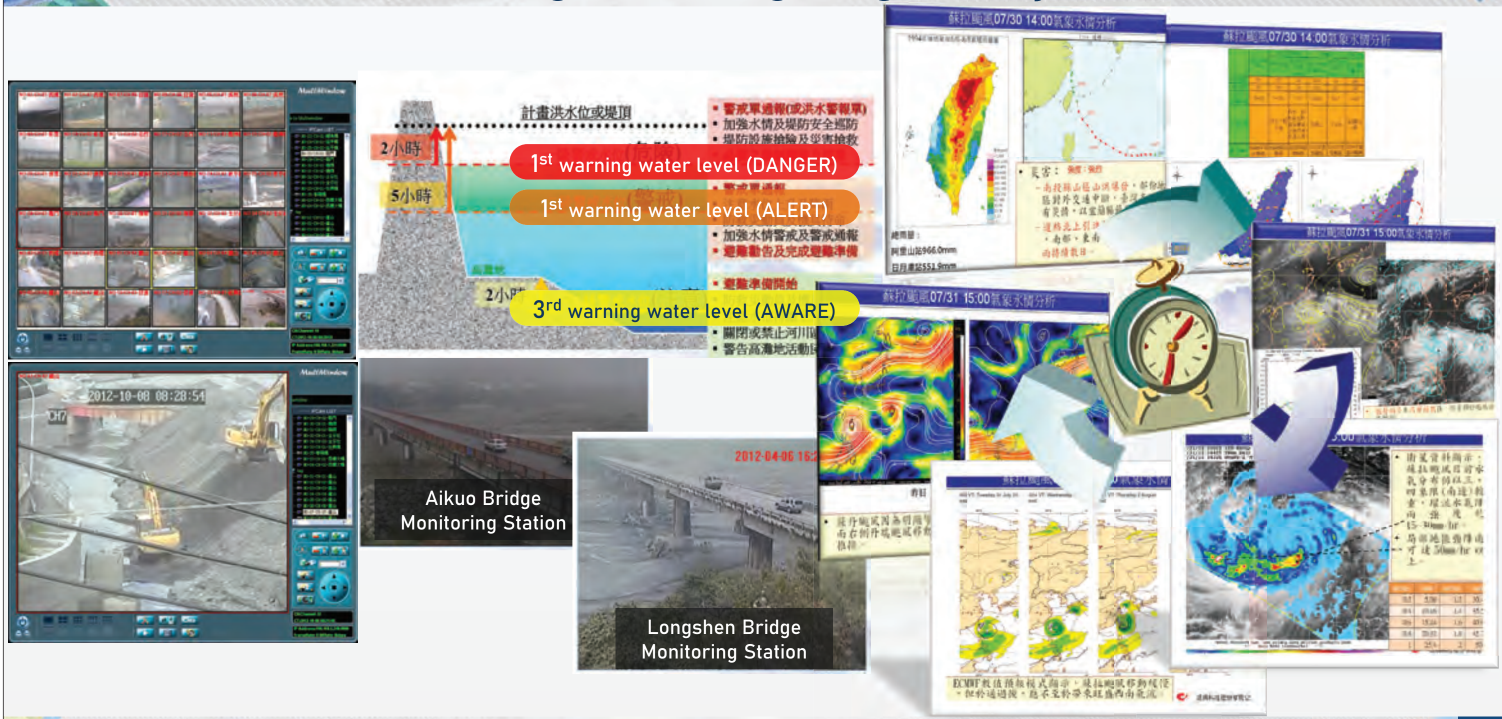
34

Real-time Monitoring and Ongoing Analysis 2



4

Case Study of Emergency Response

2017/06/01 Torrential Rain at Longhua Bridge Disaster 1

Post-disaster (Aerial view on 2017/06/05) | **Pre-disaster** (Aerial view in 2011)

- Longhua Bridge- insufficient flood passage capacity pending bridge reconstruction.
- During heavy rainfall, a torrent of debris flow surged directly into left bank approach of Longhua Bridge.
- The approach of Longhua Bridge collapsed (approximately 100 meters), and Longhua's revetment was damaged and washed away (approximately 200 meters), resulting in the loss of six residential homes.

2017/06/01 Torrential Rain at Longhua Bridge Disaster 2

14PM CWA issued heavy rain warning

0733AM Revetment of Jiulin Village in Tongfu was damaged.

15:39PM Left bank of Longhua Bridge was damaged.

21PM CWA lifted heavy rain warning

6/1 — 2 — 3 — 4 — 5 — 6/8 — 7/10

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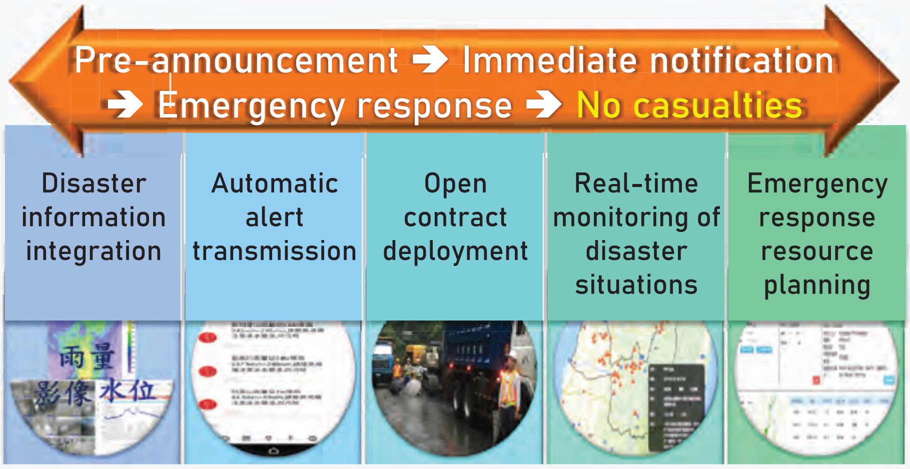
WRA

- 19點三級開設
- 研判晚上及明日豪雨可能致災
- 19點搶險廠商預佈及二級開設
- 降雨警戒簡訊(56)及傳真(4)發布
- 同富九鄰辦理搶險
- 通知地方辦理撤離並調派搶險
- 18點一級開設
- 7點辦理隆華橋搶險作業
- 交通中斷協助規劃調派防汛備料
- 辦理災因調查
- 災情控制5日19點解除開設
- 搶險結束並辦理搶修工程
- 搶修完成

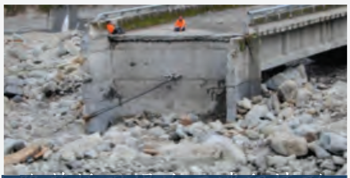
2017/06/01 Torrential Rain at Longhua Bridge Disaster 3

During the disaster response process for the Longhua Bridge in the heavy rain on June 1, 2017, real-time hydrological and forecast data were analyzed to anticipate potential flooding in the jurisdiction. Sinotech promptly advised WRA to prepare for open contract deployment, and disaster alerts were immediately issued through the disaster prevention system.

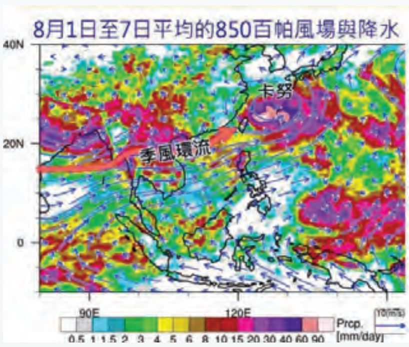


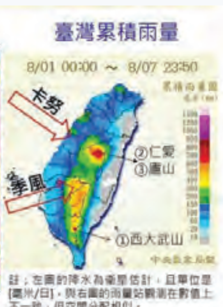

Longhua Bridge Broken Bridge


Longhua revetment (left bank) washed away


Stones left at the site of Longhua Bridge

2023 Typhoon Kanu in Lushan overflow disaster 1





Rainfall exceeding 200-year return period in Ren'ai (885mm/24hr)

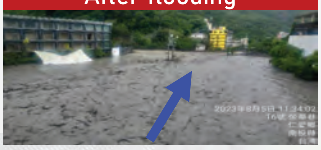
8/1~8/7總雨量的前3名(單位：毫米)

名次	累積值	測站名稱	高度	縣市	2023年8月 1	2	3	4	5	6	7
①	1187.0	西大武山	1828m	屏東縣	14.5	0.5	48.0	326.5	445.0	318.0	34.5
②	1058.5	仁愛	1184m	南投縣	0.0	0.5	243.5	749.0	65.0	0.5	0.0
③	881.0	廬山	1562m	南投縣	0.0	1.5	154.5	667.0	57.5	0.5	0.0

註：仁愛、廬山在8/4分別降下749、667毫米，均為該站單日雨量的最高紀錄。 中央氣象局

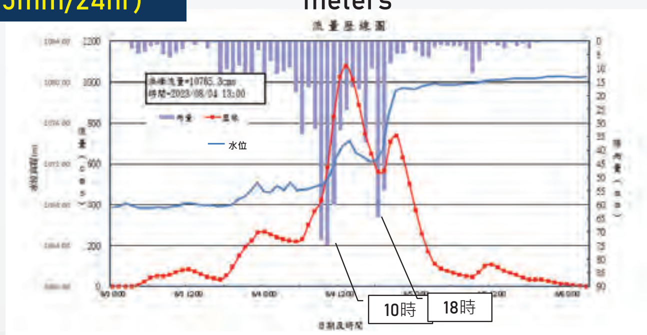
Before flooding

After flooding



Flooding situation (from suspension bridge to downstream hot spring area):

1. Collapse area of upstream Taroko River watershed (MOA data):
   - Before typhoon: 117.4ha
   - After typhoon, increase in Mahai Puxi River: 1.5ha
2. Submerged area: 4.36ha
3. Sediment deposition : 600,000 cubic meters



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2023 Typhoon Khanun in Lushan overflow disaster 2
Marine typhoon warning issued
Land typhoon warning issued
Lushan rainfall station heavy rain level 360mm/24hr
17:36PM Flood Overflow
第一階段搶修
8/1(二) 8/2(三)
8/3(四)
8/4(五)
8/5(六) 8/6(日) 8/7(一)
8/21(一) 10月底
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WRA
17點應變開設
開口合約廠商進駐因應
召開整備會議
09點重點區域水情提醒
4點30分簡訊通知強降雨警訊
4點52分簡訊通知達防汛警戒
5點41分簡訊通知達溢淹警訊
確認仁愛鄉預防性撤離
仁愛鄉強制撤離
18點災情通報
召開應變工作會議
召開後續搶險(修)復建會議
現地搶險作業及現場說明
完成第一階段搶修
完成搶修，接續疏濬
含溫泉業者
水情通報單
災情通報單
應變工作會議
開口合約預佈
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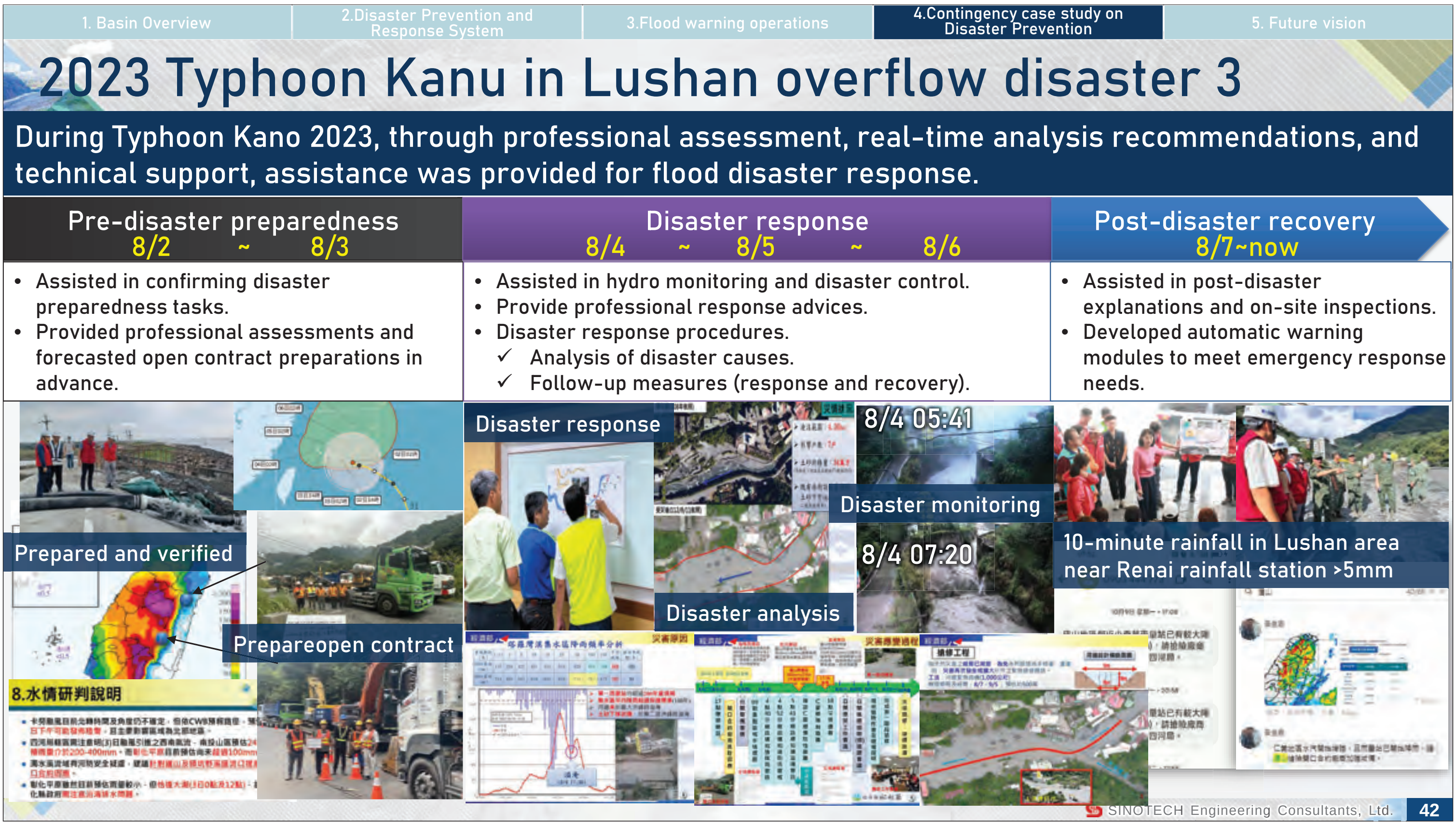
41



1. Basin Overview
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5. Future vision
2023 Typhoon Kanu in Lushan overflow disaster 3
During Typhoon Kano 2023, through professional assessment, real-time analysis recommendations, and technical support, assistance was provided for flood disaster response.
Pre-disaster preparedness 8/2 ~ 8/3
Disaster response 8/4 ~ 8/5 ~ 8/6
Post-disaster recovery 8/7~now
• Assisted in confirming disaster preparedness tasks.
• Provided professional assessments and forecasted open contract preparations in advance.
• Assisted in hydro monitoring and disaster control.
• Provide professional response advices.
• Disaster response procedures.
✓ Analysis of disaster causes.
✓ Follow-up measures (response and recovery).
• Assisted in post-disaster explanations and on-site inspections.
• Developed automatic warning modules to meet emergency response needs.
Prepared and verified
Prepareopen contract
8.水情研判說明
Disaster response
Disaster analysis
8/4 05:41
Disaster monitoring
8/4 07:20
10-minute rainfall in Lushan area near Renai rainfall station >5mm
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42

Flooding in recent years

Integrate high-resolution radar rainfall data for short-latency heavy rainfall warning, and use it with flood sensor device and monitoring systems to proactively grasp the flooding situation in Changhua area, and assist in reporting emergency response and flood investigation operations to relevant units.

Even when flooding lasts for less than an hour, Sinotech could provide advices and respond quickly

Onsite sensor + Disaster analysis module = Disaster info

5

Improvement and Development

Key Issues

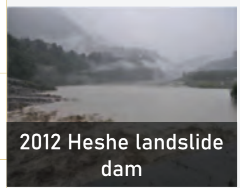
- Through meteorological warnings and forecasts combined with the establishment of dust monitoring stations, we grasped dust conditions and deployed water spraying equipment and water trucks to spray water and implemented ground coverings for bare land, effectively suppressing dust generation.
- In recent years, the number of days with large-scale dust events on both sides of the Dajia River estuary has decreased from nearly 100 days to single digits.


2017 Xiluo Dust


2018 Yuankee flood

Issue	Forecast data	monitoring	Response
Fugitive Dust	meteorological	Dust measuring station	Water suppression
Flood	Rainfall	Flood sensor	Pump allocation in high-risk areas
River defense	Hydrology	embankment observation station	Rescue
Illegal	Automatic image interpretation of hot spots	Monitoring station	Onsite law Enforcement
Sediment	Rainfall	CCTV Image Interpretation	Landslide dam response

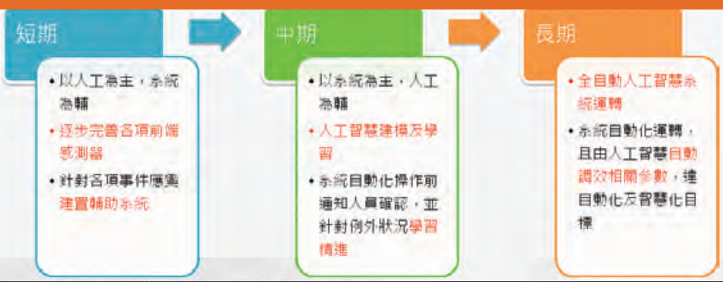

2017 illegal dumping


2012 Heshe landslide dam

Introduction of AI Artificial Intelligence

- Integrate real-time monitoring and forecasting data to automatically warn and monitor related disaster prevention and management events
- Provide the best response operation process
- Gradually introduce AI modules to achieve the goal of intelligent automatic system operation.

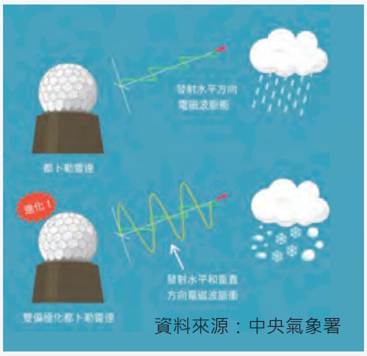
Short-term : Data collection and assistance system establishment
Medium-term: Implementation and learning of AI systems
Long-term : smart automated system operation



2020: High-Resolution Rainfall Radar Data

Heavy rainfall signal warning notice

Through real-time system analysis of high-resolution radar rainfall grid data within the corresponding area, signs of heavy rainfall occurrence can be detected, and automatic SMS alerts and monitoring can be initiated.



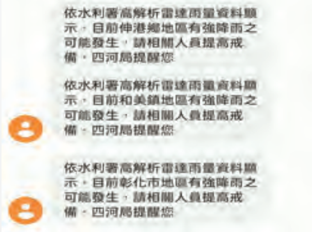
- Data spatial resolution: 250m grid
- Temporal resolution: Updated approx. 2 minutes

Interpretation of heavy rainfall signals:

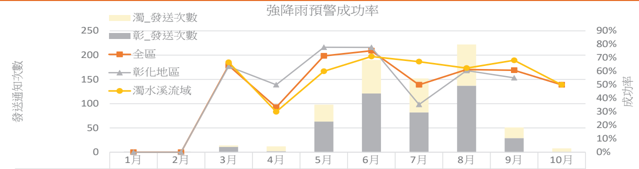
- Changhua districts
- Zhuoshui River basin

SMS recipients:

- Changhua flood alert groups
- Zhuoshui rainfall alert groups



Overall alert success rate is 63% (average)
Over a 45% chance of heavy rainfall occurring WI 30 min

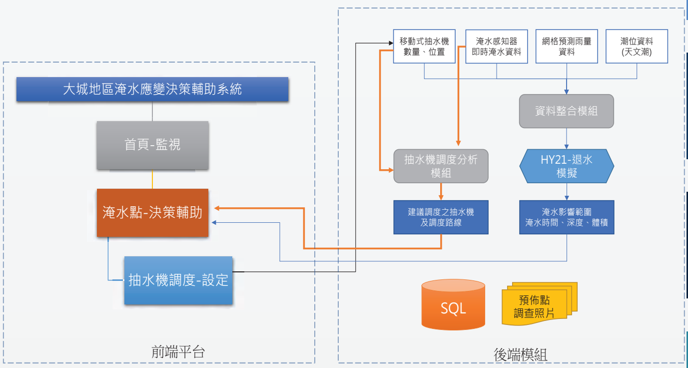


	1月	2月	3月	4月	5月	6月	7月	8月	9月	10月
濁_發送次數	0	0	3	10	35	69	70	85	22	8
彰_發送次數	1	1	11	2	63	121	82	137	29	0
全區	0%	0%	64%	33%	71%	75%	50%	61%	61%	50%
彰化地區	0%	0%	64%	50%	78%	78%	35%	61%	55%	
濁水溪流域			67%	30%	60%	71%	67%	62%	68%	50%

項目	彰化地區		濁水溪流域		轄區合計	
	次數	發生機率	次數	發生機率	次數	發生機率
預警發布	455	-	302	-	757	-
雨量站異常	8	-	0	-	8	-
扣除異常後之預警發布	447	-	302	-	749	-
30分鐘內發生強降雨	209	47%	125	41%	334	45%
30~60分鐘發生強降雨	49	11%	42	14%	91	12%
超過60分鐘後發生強降雨	21	5%	27	9%	48	6%
未發生	168	38%	108	36%	276	37%

2021 : Smart Pump Allocation Module in High-Risk (Urban) Areas

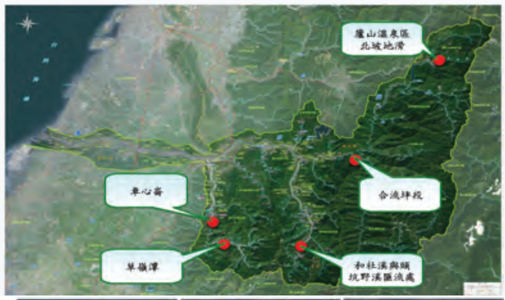
- Integrate real-time information (mobile pumps and flood sensors)
- Automatically analyze and propose allocation suggestions (units, quantities and routes)

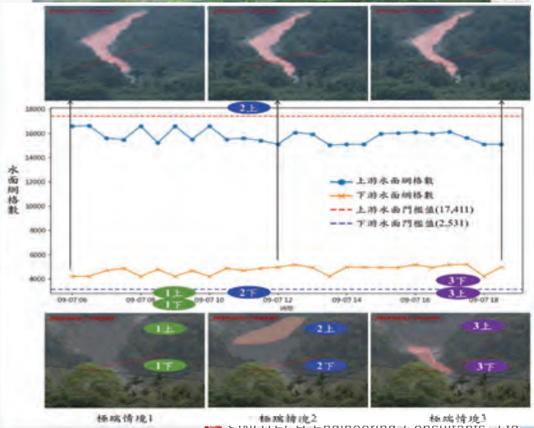


Data collection and inventory
↓
Simulation of flood-prone spots
↓
Assessment of pump layout points
↓
Module development
↓
Finish

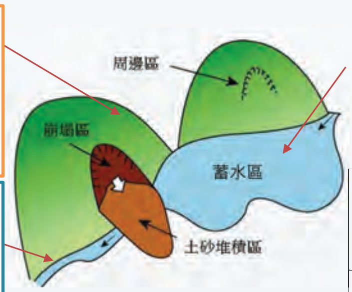
2023: CCTV Image Intepretation Technology for landslide dam Monitoring

- Image interpretation technology is introduced with the characteristics of landslide dam
  (Judged by area changes – the upstream water storage area increases; the downstream river water area decreases)
- Automatically monitor risk information to improve disaster prevention and response effectiveness



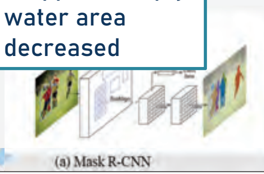


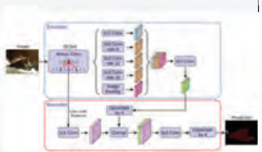
Dam body
- accumulation of sediment
- division of water areas



Upstream forms a lake
- water level rises
- water area increases

Downstream water level
- water level dropped sharply
- water area decreased


(a) Mask R-CNN


(b) DeepLab v3+

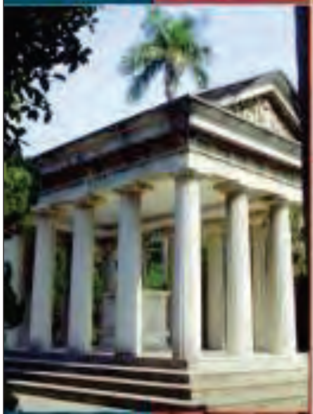
The development and application of an efficient river flood modeling based on Cellular Automata framework

游 翔 麟

Hsiang-Lin Yu

臺灣大學生物環境系統工程學系　博士後研究員

Postdoctoral Research Fellow, Department of Bioenvironmental Systems Engineering, National Taiwan University



國立臺灣大學

細胞自動機快速演算架構於河川洪水模擬之研發與應用

The development and application of an efficient river flood modeling based on Cellular Automata framework

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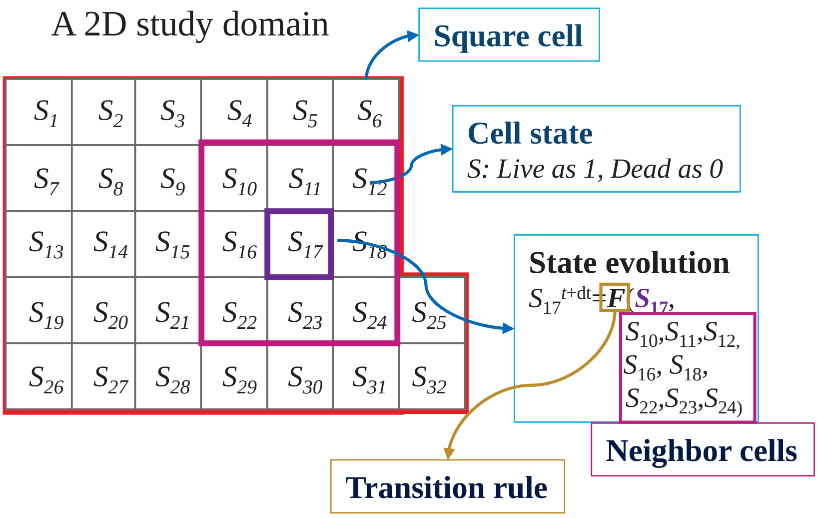
Outline

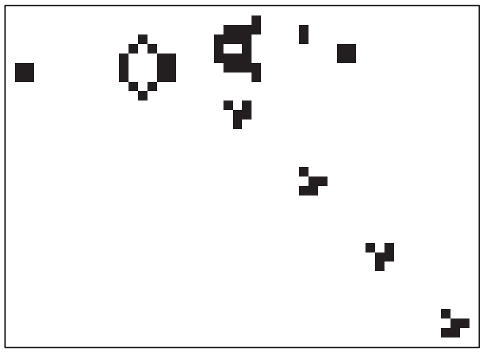
- Introduction
- Methods
- Case studies
- Conclusion

Introduction

- **Cellular Automata framework** sees the study domain as a set of **equal-sized discretized cells** and explicitly evolves the **state of each cell** by the **generic transition rule**.



Example: Game of life



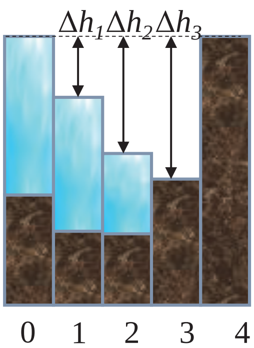
- Characteristic: **explicit, local, generic** → **High performance computing!**

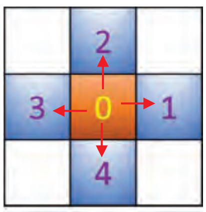
Previously CA studies of our team

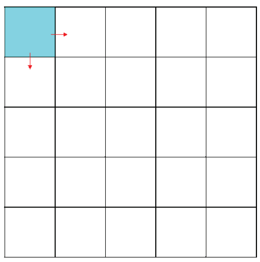
- **Chang et al. (2021)** *Overland-gully-sewer (2D-1D-1D) urban inundation modeling based on cellular automata framework* (*Journal of Hydrology*) for **urban inundation modeling**.

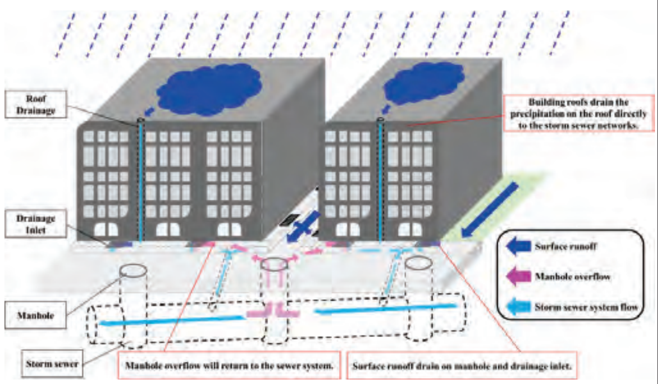
CA-based overland flow model (2D-OFM-CA) + SWMM 5.1 for gully and sewer flows

✓ Use water levels to delineate water movement





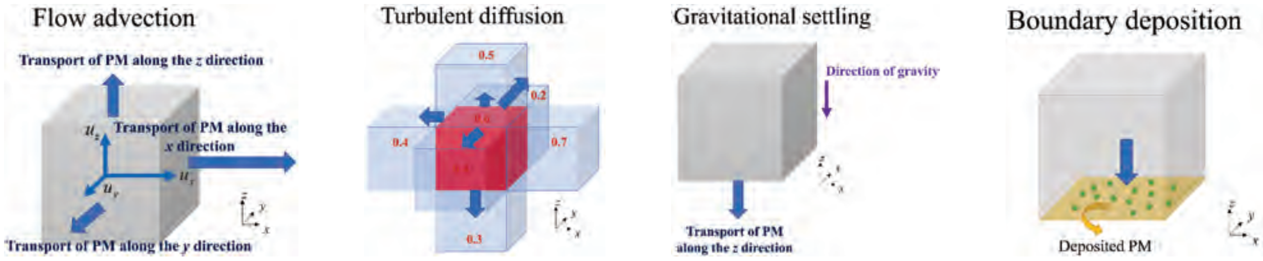




- Used in **real-time flood inundation forecasting** in Taipei city (completing a 2-hour ahead simulation in 10 minutes).

Previously CA studies of our team (Cont.)

- **Yu and Chang (2022)** *Modeling particulate matter concentration in indoor environment with cellular automata framework* (*Building and Environment*) for **3D indoor air quality modeling**.
    a. It simulates four PM transport mechanisms in drift-flux form:



    b. It is faster than the FV model by 4.83-5.65 times.

- **Yu and Chang (2023)** *GPU parallelization of particulate matter concentration modeling in indoor environment with cellular automata framework* (*Building and Environment*) later parallelizes it on **GPU** such that it can accelerate up to 24.27-76.95 times.

Previously CA studies of our team (Cont.)

- **Chang et al. (2022)** *Dynamic-wave cellular automata framework for shallow water flow modeling* (*Journal of Hydrology*) for **dynamic-wave overland and river flow modeling** (**The present study**).
- **Wang et al. (2024)** *A novel cellular automata framework for modeling depth-averaged solute transport during pluvial and fluvial floods* (*Water*) for **2D solute transport modeling**.
    a. The proposed CA solver is as accurate as a finite volume model with the TVD scheme (FV-TVD) but faster by 2.90-3.29 times.
- **Yu and Chang (2024)** *Coupled GPU-based modeling of dynamic-wave flow and solute transport in floods with cellular automata framework* (*Journal of Hydrology, under review*) for **2D dynamic-wave flow and solute transport modeling**.
    a. The novel solute transport solver has higher accuracy than the FV-TVD model but faster by 2.90-3.33 times.
    b. After **GPU parallelization**, the coupled approach reach 56.32-74.15 times acceleration.

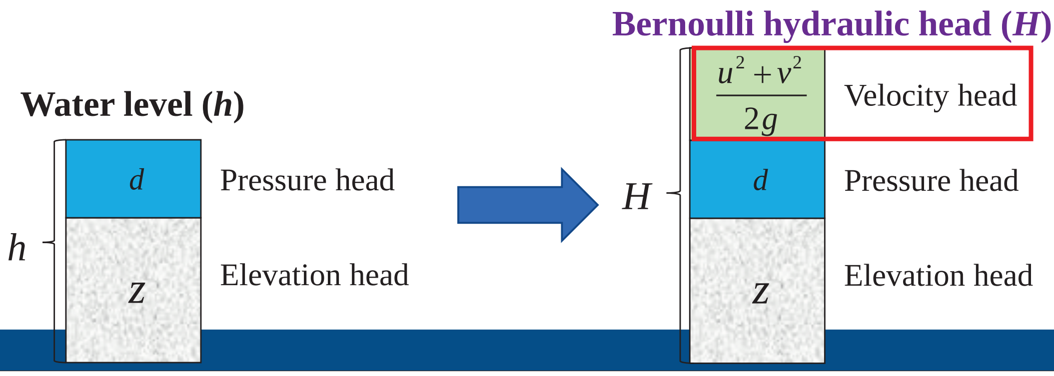
Motivation of the present study

- So far, in fields of **overland/river flood modeling**, CA-based shallow water flow models (*e.g.*, CA2D, WCA2D, 2D-OFM-CA, OFS-CA, CA-ffé models) use **water levels to delineate water movement** so that **they behave like non-inertia waves**.
- They are good for **regular flows** but incapable of handling **strong discontinuous flows**.


Build a new CA-based model behaving like dynamic waves!!

Methods

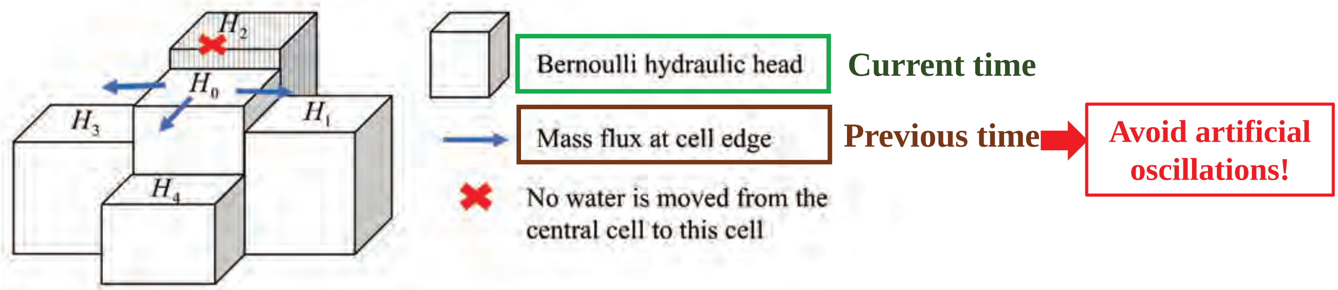
- **How** to make the CA model behave like the dynamic waves?
  - a. **Consideration of water velocity** should be included in deciding the water movement.
  - b. **Coupled relation between water depth and velocity** needs to be handled.
- **What** we have done in the **CA-based shallow water flow (SWFCA)** solver (**Chang et al., 2022**; *Dynamic-wave cellular automata framework for shallow water flow modeling*, *Journal of Hydrology*):
  - a. Use the **Bernoulli hydraulic head** to delineate the water movement to consider water velocity.



b. Establish **five sequential steps** to determine the **transported mass and inertia** to account for the coupled relation between water depth and velocity.

Determine flow direction → Determine transported mass → Determine transported inertia →

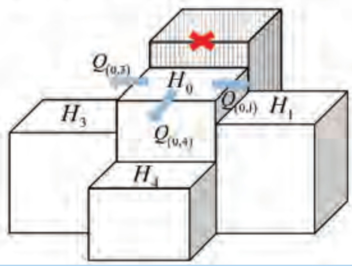
Step 1: Determine the flow direction based on the Bernoulli hydraulic head (H) and mass flux



***Principle:**

Step 2: Update the mass flux at each flow transport route in Step 1

$$Q = \min\left(Q_{Manning}, Q_{Weir}\right)$$



Determine the transported mass!

Bernoulli hydraulic head

$$Q_{(0,i),Mann} = \frac{1}{n} l \times \left(\frac{d_0 + d_i}{2}\right)^{5/3} \sqrt{\frac{H_0 - H_i}{l}}$$

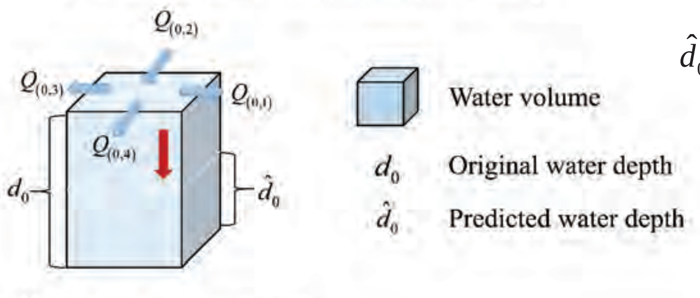
$$Q_{(0,i),Weir} = \frac{2}{3} l \sqrt{2g}\,\psi \left(h_0\right)^{3/2}$$

$$\psi = \left[1 - \left(h_i / h_0\right)^{1.5}\right]^{0.385}$$

$$h_0 = H_0 - \bar{z}_i \quad h_i = \max\left(H_i - \bar{z}_i, 0\right) \quad \bar{z}_i = \max\left(z_0, z_i\right)$$

Bernoulli hydraulic head

Step 3: Calculate the predicted water depth of each cell from the mass fluxes in Step 2

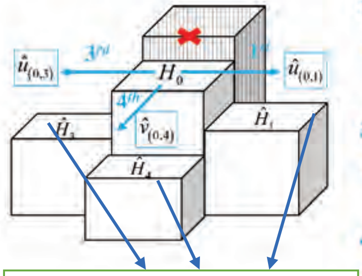


*$Q_{(0,2)}$ is from the 2nd neighbor cell

$$\hat{d}_0 = d_0 + \frac{\Delta t}{l^2}\left[-Q_{(0,1)} - Q_{(0,2)} + Q_{(0,3)} + Q_{(0,4)}\right]$$

Step 4: Predict the downstream water velocity at each route based on updated $\hat{d}_0$ in Step 3

The **Bernoulli principle with friction loss** at each route (by the **standard step method**)



Predicted water velocity at the end of the route

1st route: $\hat{H}_1 = H_0 - l \times S_{f(0,1)}$

Quadratic function $f\left(\hat{u}_{(0,1)}\right) = 0$ with $\hat{u}_{(0,1)} > 0$

$$f\left(\hat{u}_{(0,1)}\right) = \left\{\frac{1}{2g}\right\}\left[\hat{u}_{(0,1)}\right]^2 + \left\{\frac{l}{2}\frac{n_1^2|u_1|}{\hat{d}_1^{4/3}}\right\}\hat{u}_{(0,1)} + \left\{\frac{v_1^2}{2g} + \hat{d}_1 + z_1 + \frac{l}{2}\frac{n_0^2 u_0^2}{d_0^{4/3}} - H_0\right\}$$

3rd route: $\hat{H}_3 = H_0 - l \times S_{f(0,3)}$

Quadratic function $f\left(\hat{u}_{(0,3)}\right) = 0$ with $\hat{u}_{(0,3)} < 0$

$$f\left(\hat{u}_{(0,3)}\right) = \left\{\frac{1}{2g}\right\}\left[\hat{u}_{(0,3)}\right]^2 + \left\{\frac{l}{2}\frac{n_3^2|u_3|}{\hat{d}_3^{4/3}}\right\}\hat{u}_{(0,3)} + \left\{\frac{v_3^2}{2g} + \hat{d}_3 + z_3 + \frac{l}{2}\frac{n_0^2 u_0^2}{d_0^{4/3}} - H_0\right\}$$

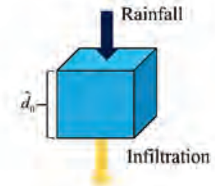
4th route: $\hat{H}_4 = H_0 - l \times S_{f(0,4)}$

Quadratic function $f\left(\hat{v}_{(0,4)}\right) = 0$ with $\hat{v}_{(0,4)} < 0$

$$f\left(\hat{v}_{(0,4)}\right) = \left\{\frac{1}{2g}\right\}\left[\hat{v}_{(0,4)}\right]^2 + \left\{\frac{l}{2}\frac{n_4^2|v_4|}{\hat{d}_4^{4/3}}\right\}\hat{v}_{(0,4)} + \left\{\frac{u_4^2}{2g} + \hat{d}_4 + z_4 + \frac{l}{2}\frac{n_0^2 u_0^2}{d_0^{4/3}} - H_0\right\}$$

Step 5: Update the water depth, velocities and Bernoulli hydraulic head of each cell from Steps 3 and 4

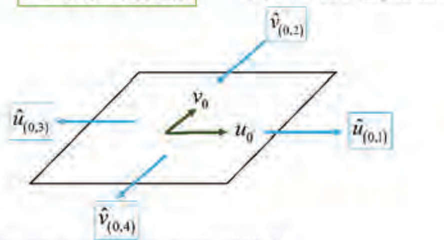
✓ Water depth



$$d_0 = \hat{d}_0 + \frac{\Delta V_{0,in}}{l^2} - \frac{\Delta V_{0,out}}{l^2}$$

✓ Water velocities

* $\hat{v}_{(0,2)}$ is from the 2nd neighbor cell



$$u_0 = \Gamma\left(-\hat{u}_{(0,1)}\right)\hat{u}_{(0,1)} + \Gamma\left(\hat{u}_{(0,3)}\right)\hat{u}_{(0,3)}$$

$$v_0 = \Gamma\left(-\hat{v}_{(0,2)}\right)\hat{v}_{(0,2)} + \Gamma\left(\hat{v}_{(0,4)}\right)\hat{v}_{(0,4)}$$

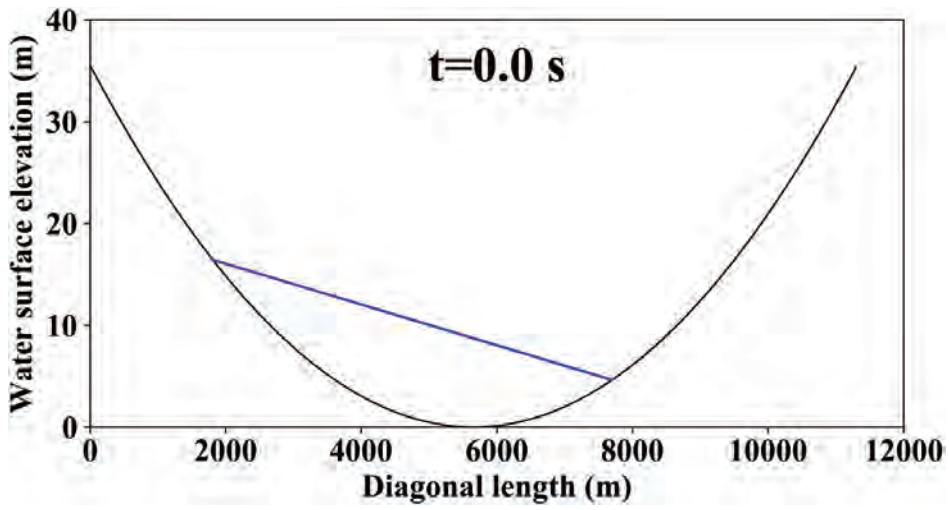
$$\Gamma(u) = \begin{cases} 1 & u > 0 \\ 0 & u \le 0 \end{cases}$$ Toward the central cell

Case Studies

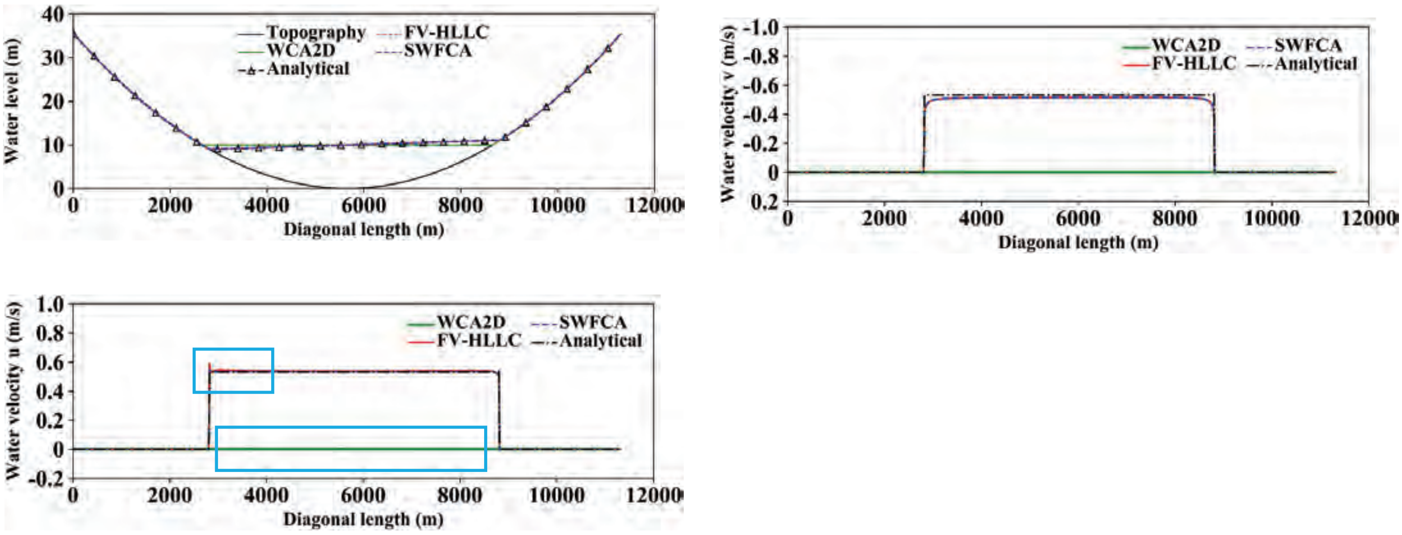
Case study I: Moving shorelines in a 2D frictional parabolic bowl (**moving wet-dry interfaces**)

Accuracy verification

- Used by **Sampson et al., (2006), Hou et al. (2013), and Zhao and Liang (2022)** for verifying the **accuracy of their shallow water flow models on wet-dry interfaces**.
- **Square computational domain** with a size of 8000 m *x* 8000 m. Initially, **inclined the water surface with zero water velocity** is prescribed to drive the periodic water movement.



•Accuracy comparison at *t*=1377.68 s is conducted among the **proposed SWFCA solver**, a finite volume model with the HLLC scheme (**FV-HLLC model**), and the widely-used **WCA2D model** by Guidolin et al. (2016).

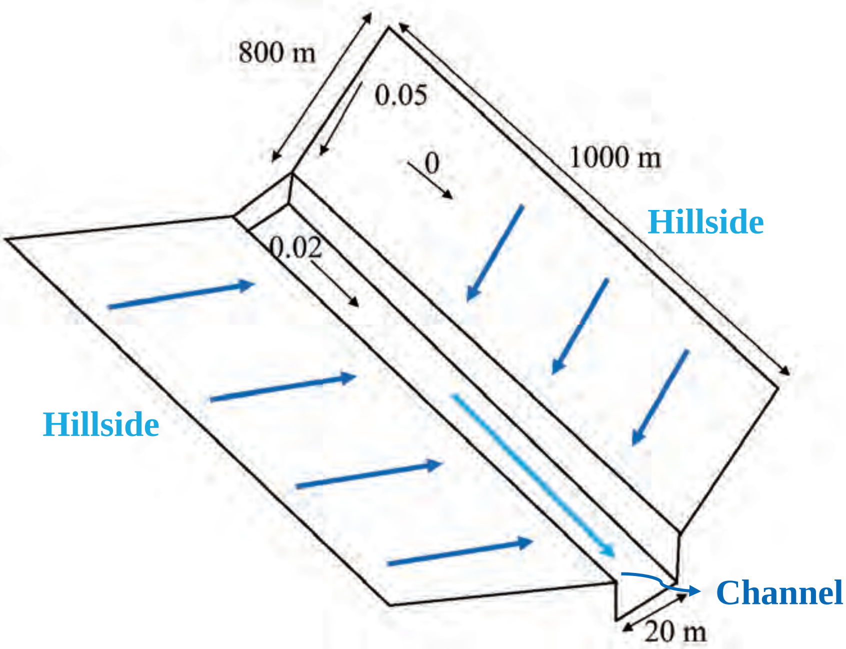


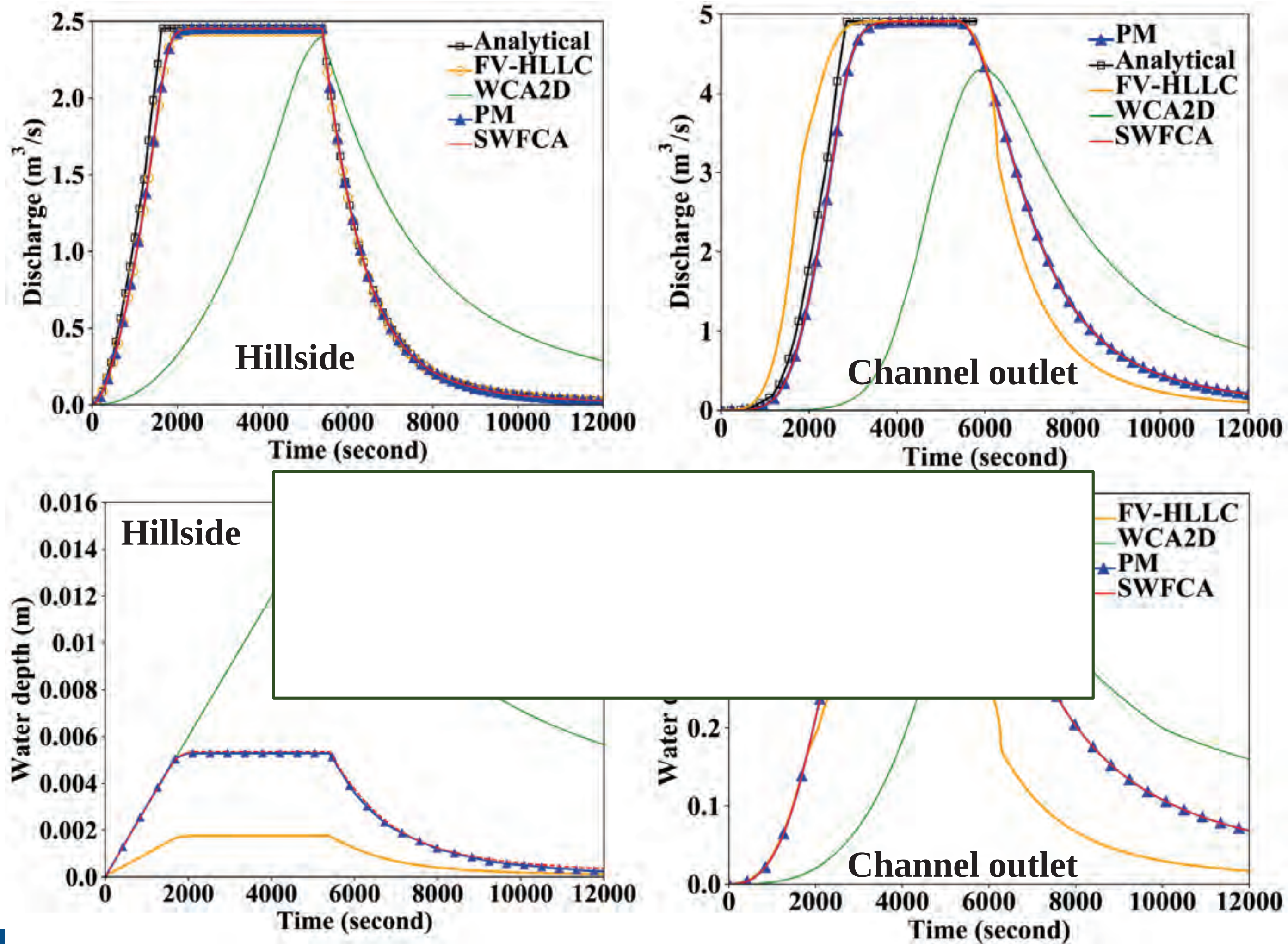
a. The **WCA2D model** predicts a **still water surface**.
b. The **water velocity** of the **FV-HLLC model** increases to **a spurious extent** because of the small water depth.
c. The SWFCA solver predicts satisfactory results.

Case study II: Shallow overland flows in a steep V-shape catchment (**steep shallow flows and channel flows**)

Accuracy verification

•Used by **Xia et al . (2017), and Zhao and Liang (2022)** for verifying the accuracy of their shallow water flow models on **shallow flows on very steep plates**.
•**Uniform rainfall** of a **constant rainfall intensity of 10.8 mm/hr** on the two hillsides for 1.5 hours.

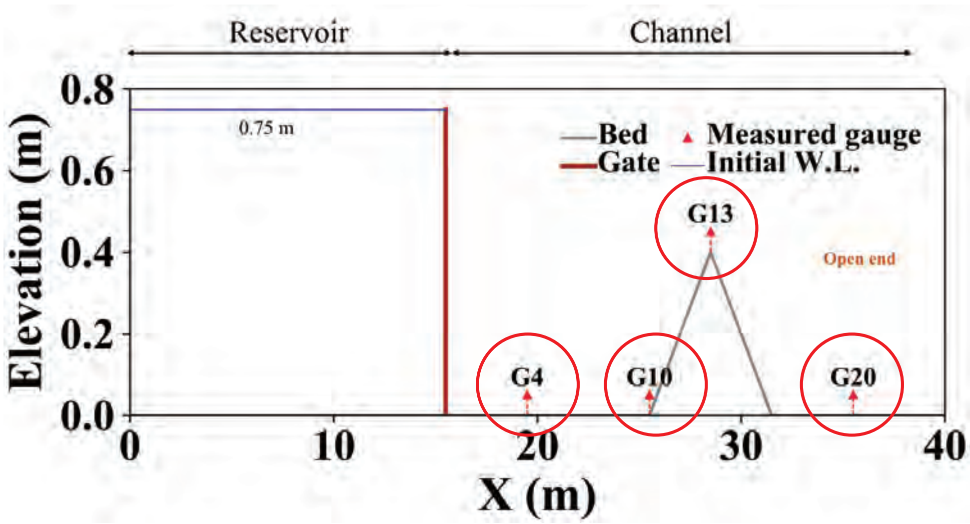


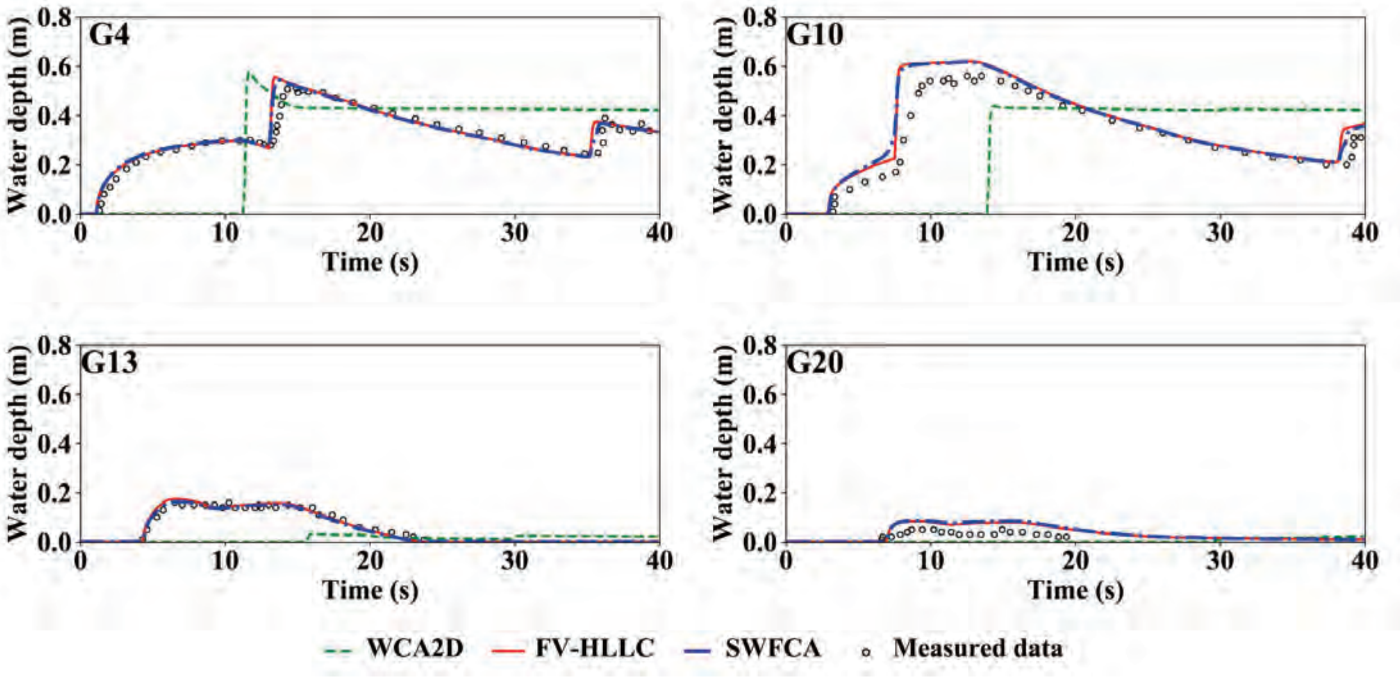


Case study III: Dam-break flows on channel with a symmetric triangular bump and open end (**dam-break flows**)

Accuracy verification

- From a **CADAM test case** used to examine the performance of a shallow water flow model on **simulating dam-break flows on idealized terrain**.
- **Measured water depth hydrographs** can be used for verification.



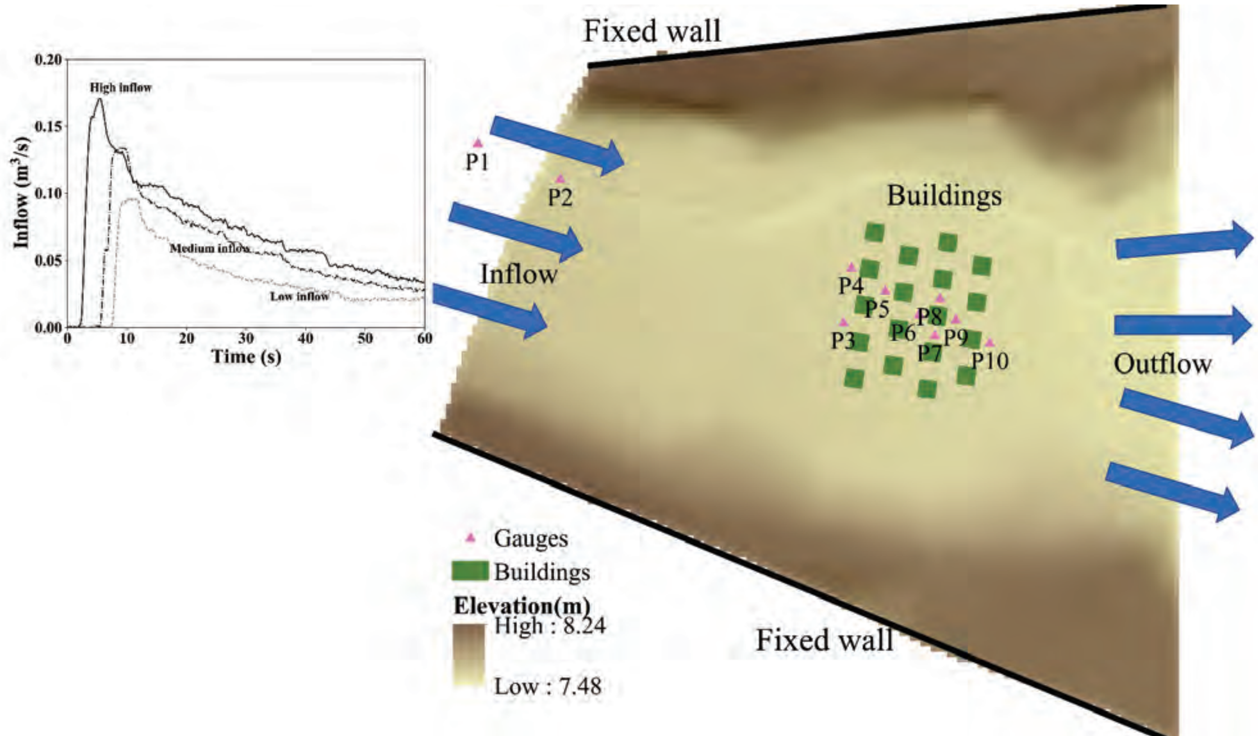


a. The **WCA2D model** is **inappropriate to simulate dam-break flows**.
b. The SWFCA solver predicts almost the same results as the FV-HLLC model.

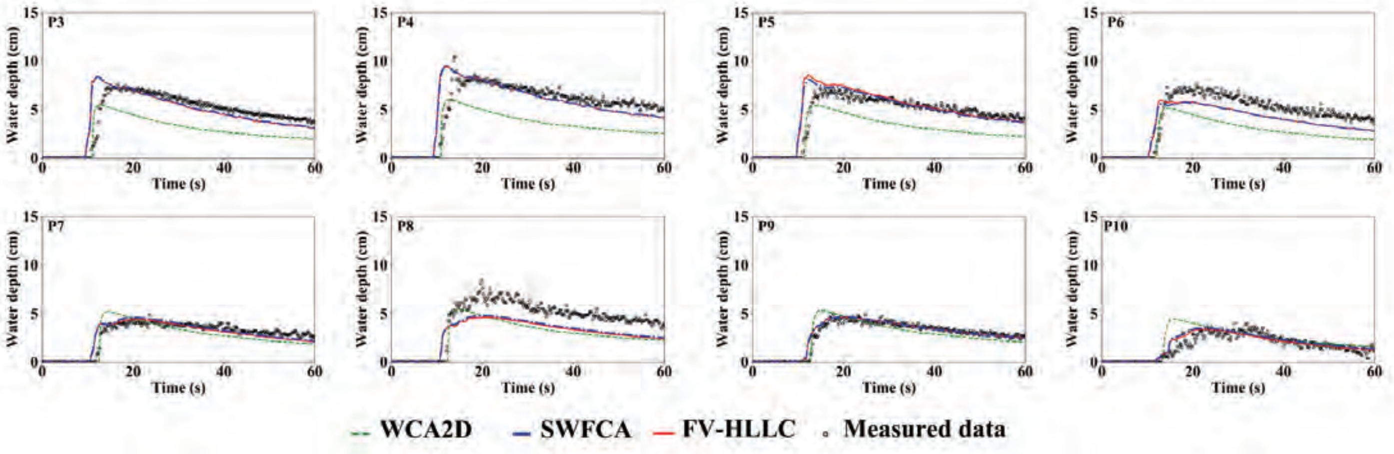
Case study IV: Discharge flows over the Toce floodplain with staggered buildings (**dam-break flows**)

Accuracy verification

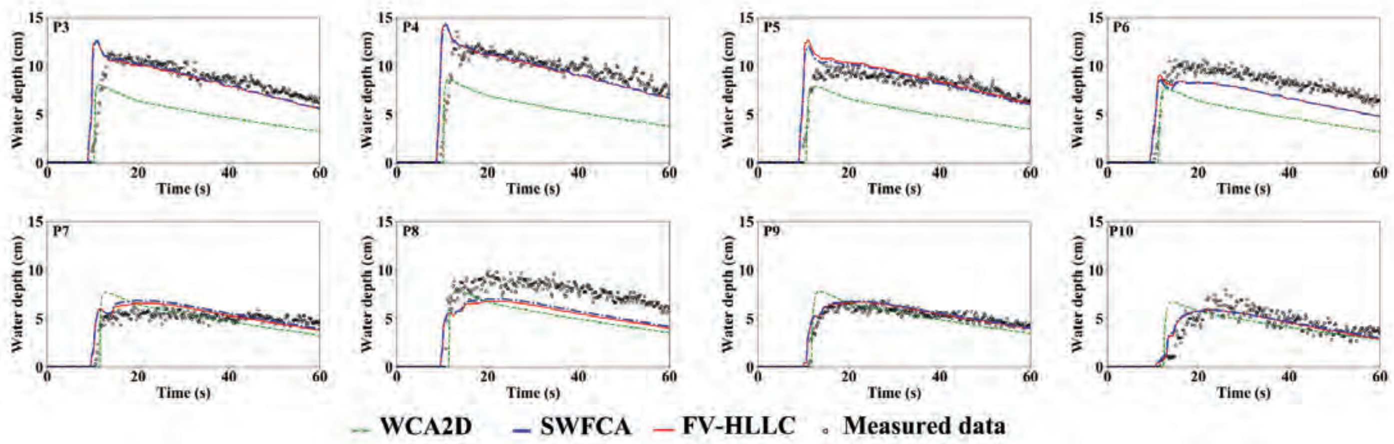
- From a **CADAM test case** used to examine the performance of a shallow water flow model on **simulating dam-break flows on realistic terrain**.
- **Three inflow hydrographs** are prescribed on the left edge.



Low inflow



Medium inflow / High inflow



Case study V: Efficiency assessment based on real-scale Toce valley dam-break events

Efficiency Assessment

- The **involved flow condition** has an impact on the **efficiency** of the WCA2D, FV-HLLC models, and SWFCA solver.

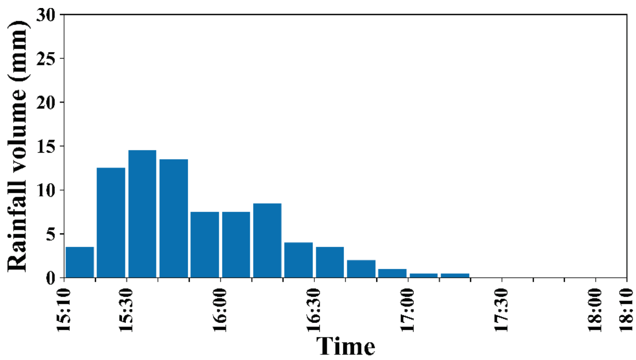
The portion of strong discontinuous flows

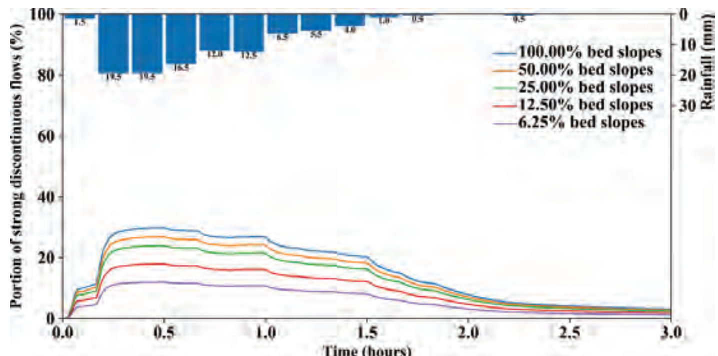
Small ⟷ **Large**

Efficiency comparison

Small	Large
WCA2D>FV-HLLC and SWFCA	**WCA2D<FV-HLLC and SWFCA**

- Using **the original-scale Toce valley** as the study terrain.
- The bed slope is decreased by five factors (**1,1/2, 1/4 1/8, 1/16**), leading to five scenarios (**100.0%, 50.0%, 25.0%, 12.5%,6.3% bed slopes**)
- A **shot-duration heavy rainfall on 21 August 2019** is used as the input rainfall data.





Bed slopes	WCA2D		FV-HLLC		SWFCA	
	(1) The total CPU time (s)	(2) The average time step (s)	(3) The total CPU time (s)	(4) The average time step (s)	(5) The total CPU time (s)	(6) The average time step (s)
100.0%	498.8	0.054	209.4	0.184	163.3	0.162
50.0%	322.7	0.087	154.7	0.246	123.5	0.220
25.0%	136.6	0.210	114.9	0.322	93.0	0.295
12.5%	57.2	0.517	91.4	0.402	75.2	0.380
6.3%	[illegible]	[illegible]	87.0	[illegible]	[illegible]	0.439

Effici

	The ratio of the total CPU time between the WCA2D and SWFCA models (%)	The ratio of the average time steps between the WCA2D and SWFCA models (%)	The ratio of the total CPU time between the FV-HLLC and SWFCA models (%)	The ratio of the average time steps between the FV-HLLC and SWFCA models (%)
	$(7)=\frac{(1)}{(5)}$	$(8)=\frac{(2)}{(6)}$	$(9)=\frac{(3)}{(5)}$	$(10)=\frac{(4)}{(6)}$
100.0%	305.5%	33.3%	128.2%	113.6%
50.0%	261.3%	39.5%	125.3%	111.8%
25.0%	146.9%	71.2%	123.6%	109.2%
12.5%	76.1%	136.1%	121.5%	105.8%
6.3%	68.6%	164.9%	121.0%	104.8%

The WCA2D model can be faster than the SWFCA solver when the portion of strong discontinuous flow is small

The efficiency of the SWFCA solver is higher than the FV-HLLC model by **121.0%-128.2%**

Conclusion

- The present study proposes a new SWFCA solver behaving like dynamic waves.
- The SWFCA solver has the same accuracy as the FV-HLLC model, particularly in simulating strong discontinuous flows occurred in river and urban flooding.
- The SWFCA solver can be 121.0%-128.2% faster than the FV-HLLC model.

Thank you for listening!

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The meshless SPH method applied to open channel flows

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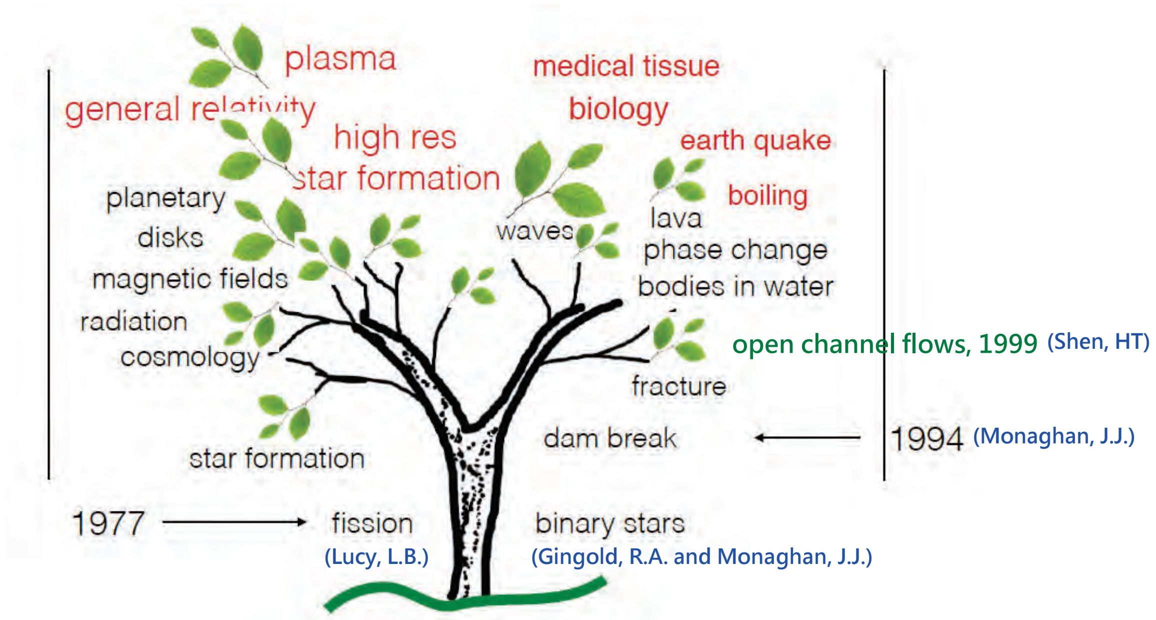
APRIL 26, 2024

Outline

- **Fundamentals of Smoothed Particle Hydrodynamics (SPH)**
- **Lagrangian SPH Shallow Water Models (LSPH-SWM)**
- **Eulerian SPH Shallow Water Models (ESPH-SWM)**
- **Summary**

Fundamentals of Smoothed Particle Hydrodynamics (SPH)



SPH tree of life grows and grows

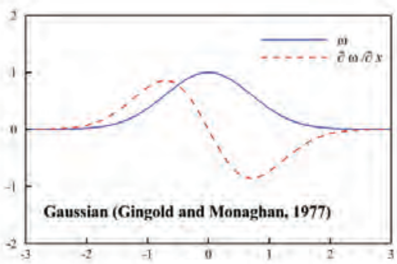
(Monaghan, J.J., 2015. The Evolution of SPH. 10th International SPHERIC Workshop)

The so-called "smoothed particle hydrodynamics" or "SPH" is a explicit meshfree particle method.

Particle: SPH uses a set of particles to approximate a continuum;
Smoothed: a local continuous field is represented by a smoothing interpolation field;
Hydrodynamics: the word can be interpreted as mechanics.

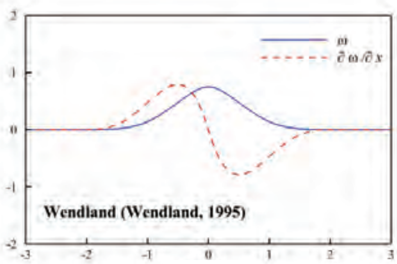
(Li, S., Liu, W.K., 2004. Meshfree and Particle Methods. Springer-Verlag)

Kernel functions (ω) & Smoothing length (l)



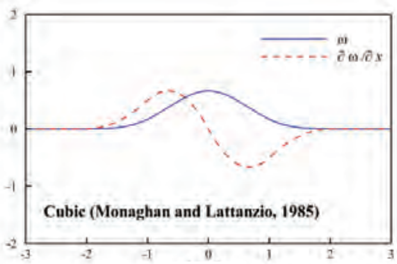
$s = r_{ab}/l$

$$\omega(s,l) = \frac{1}{l\sqrt{\pi}} e^{-s^2}$$



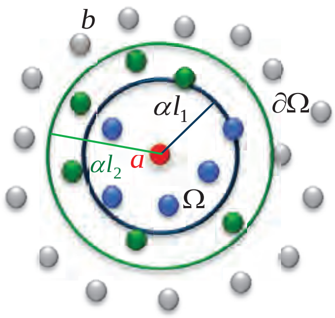
$s = r_{ab}/l$

$$\omega(s,l) = \frac{3}{4l}\begin{cases}(1+2s)(1-\frac{s}{2})^4 & -0 \le s \le 2 \\ 0 & s > 2\end{cases}$$



$s = r_{ab}/l$

$$\omega(s,l) = \frac{1}{l}\begin{cases}\frac{2}{3} - s^2 + \frac{1}{2}s^3 & -0 \le s < 1 \\ \frac{1}{2}(2-s)^3 & -0 \le s < 2 \\ -0 & -s \ge 2\end{cases}$$



Properties of kernel functions

(1) The integral of a kernel function within its compact domain should be equal to one.

$$\int_{\Omega} \omega(r_{ab}, l_a)\,\mathrm{d}V = 1$$

(2) As the smoothing length approaching zero, the kernel function will become a Dirac delta function.

$$\lim_{l \to 0} \omega(r_{ab}, l_a) = \delta(r_{ab})$$

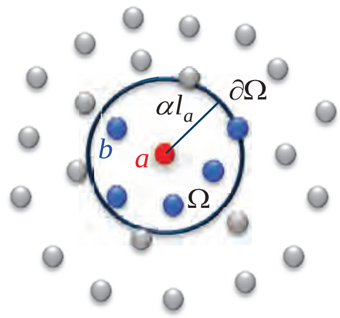
(3) The kernel function should be compactly supported.

$$\omega(r_{ab}, l_a) = 0 \quad \text{when} \;\; r_{ab} > \alpha l_a$$

(4) The kernel function is assumed to be symmetric.

$$\omega(r_{ab}, l_a) = \omega(r_{ba}, l_a)$$

$$\nabla_a \omega(r_{ab}, l_a) = -\nabla_b \omega(r_{ab}, l_a)$$



SPH operators

➢ Summation operator

$$\langle \phi_a \rangle = \sum_{b=1}^{b=N} V_b \phi_b \omega(r_{ab}, l_a)$$

where ϕ is the physical quantities,
V is the volume of particle and
$\boldsymbol{r_{ab}}$ is the distance between two interaction particles.

➢ Differential operator

$$\langle \nabla \phi \rangle_a = \sum_{b=1}^{b=N} V_b \phi_b \nabla_a \omega(r_{ab}, l_a)$$

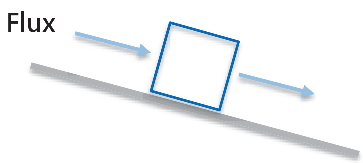
✓ Divergent operator in the symmetric form

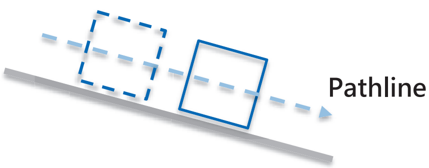
$$\langle \nabla \cdot \vec{\phi} \rangle_a = -\sum_{b=1}^{b=N} V_b (\vec{\phi}_a - \vec{\phi}_b) \cdot \nabla_a \omega(r_{ab}, l_a)$$

✓ Gradient operator in the asymmetric form

$$\langle \nabla \phi \rangle_a = \sum_{b=1}^{b=N} V_b (\phi_a + \phi_b) \nabla_a \omega(r_{ab}, l_a)$$

Lagrangian SPH Shallow Water Models (LSPH-SWM)





Eulerian viewpoint → **Lagrangian viewpoint**

$$\frac{\partial h}{\partial t} + \nabla \cdot (h\mathbf{U}) = 0 \quad \longrightarrow \quad \frac{\mathrm{D}h}{\mathrm{D}t} = -h\nabla \cdot \mathbf{U}$$

$$\underbrace{\frac{\mathrm{D}(\ )}{\mathrm{D}t}}_{\text{Material derivative}} = \underbrace{\frac{\partial(\ )}{\partial t}}_{\text{Local derivative}} + \underbrace{\mathbf{U}\cdot\nabla(\ )}_{\text{Convective derivative}}$$

$$\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U}\cdot\nabla)\mathbf{U} = -g\nabla h + g(\mathbf{S}_0 - \mathbf{S}_f) \quad \longrightarrow \quad \frac{\mathrm{D}\mathbf{U}}{\mathrm{D}t} = -g\nabla h + g(\mathbf{S}_0 - \mathbf{S}_f)$$

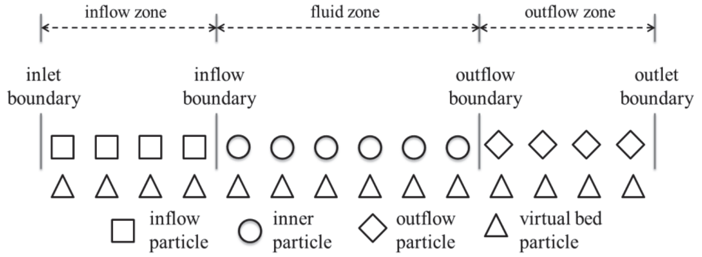
where $\mathbf{U}$ is the velocity vector,
h is the water depth,
$\mathbf{S}_0$ is the bed slope vector, $\mathbf{S}_f$ is the bed friction slope vector,
and g is the gravitational acceleration.

Research Topic 1:
1D Non-rectangular and non-prismatic open channel flows

In/out-flow boundaries

Riemann invariants

$u - 2c = \text{const.}$

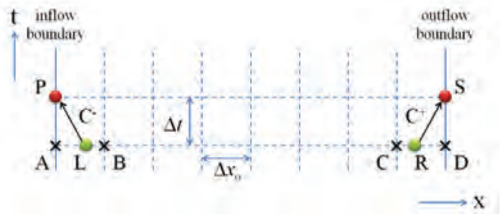


$u + 2c = \text{const.}$

Method of specified time interval

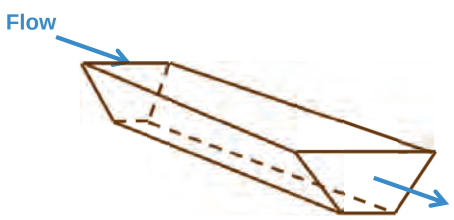
Characteristic equations

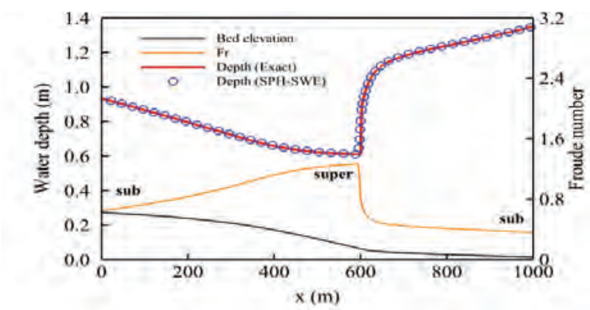
$$C^-: \quad u_P = u_L + \frac{g}{c_L}(h_P - h_L) + g\left(S_{0,L} - S_{f,L}\right)\Delta t, \qquad \frac{x_P - x_L}{\Delta t} = u_L + c_L$$



$$C^+: \quad u_S = u_R - \frac{g}{c_R}(h_S - h_R) + g\left(S_{0,R} - S_{f,R}\right)\Delta t, \qquad \frac{x_S - x_R}{\Delta t} = u_R + c_R$$

◻ **Case study:** Mixed regime flows in a trapezoidal prismatic channel

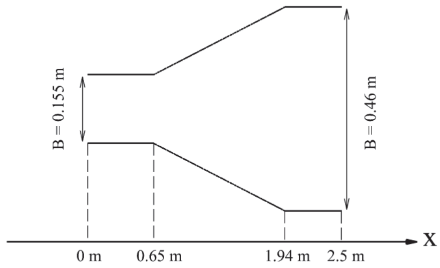


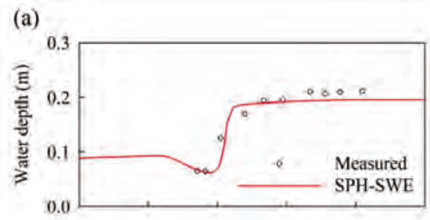


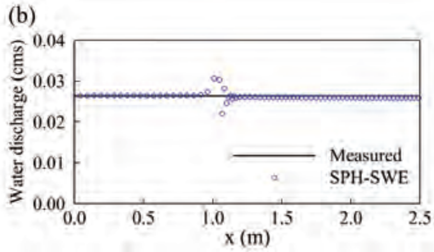
- The trapezoidal channel with n=0.02 s/m$^{1/3}$ is 1000 m long and its width and perimeter equal to $10 + 2h$ m and $10 + 2\sqrt{2}h$ m. The initial particle spacing is 10 m (100 particles).
- B.C.s:

  Inflow boundary condition:
  Discharge Q=20 m^{3}s^{-1}
  Outflow boundary condition:
  Water depth h=1.35 m

Case study: Mixed regime flows in a rectangular non-prismatic channel







- The rectangular channel with n=0.015 s/m$^{1/3}$ is 2.5 m long. The initial particle spacing is 0.01 m (250 particles).
- B.C.s:

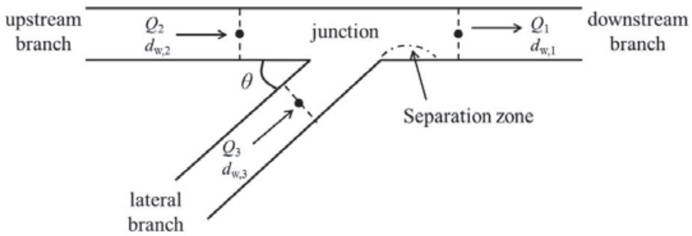
Inflow boundary condition:

Discharge Q=0.0263 m^{3}s^{-1} and water depth h=0.088 m

Outflow boundary condition:

Water depth h=1.35 m

Research Topic 2:
Sub/super-critical flows in an open channel junction

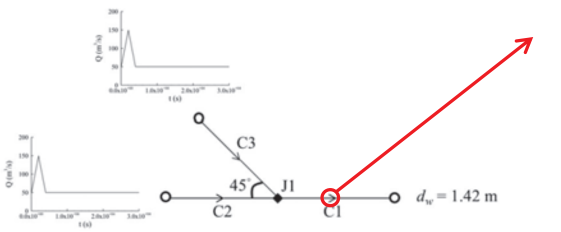


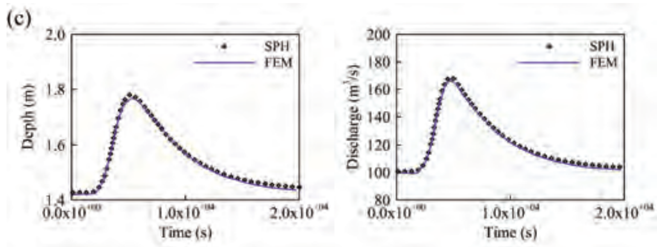
where Q is the discharge,
h is the depth and
B is the channel width.

- ✓ **Equality model:** $\begin{cases} h_2 = h_1 \\ h_3 = h_1 \end{cases}$
- ✓ **Gurram and Hsu models:** $\begin{cases} B_2 = B_3 \\ h_2 = h_3 \end{cases}$
- ✓ **Shabayek model:** Equal depth and width are not assumed at the junction.

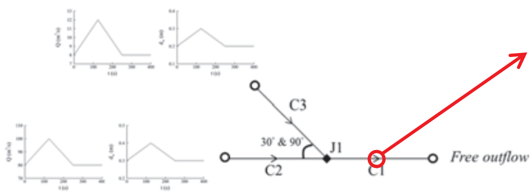
(Kesserwani, Ghostine, G.R., Vazquez, J., Mosé, R., Abdallah, M., Ghenaim, A., 2008. Simulation of subcritical flow at open-channel junction. Advances in Water Resources, 31(2): 287-297.)

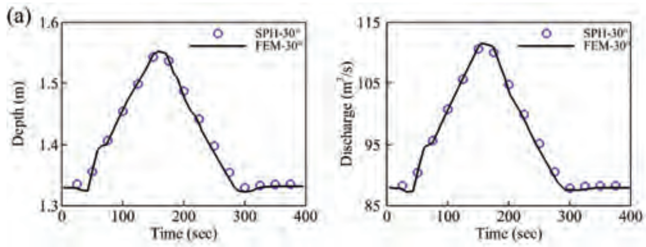
◻ **Case study:** Unsteady subcritical flows at a 45° junction





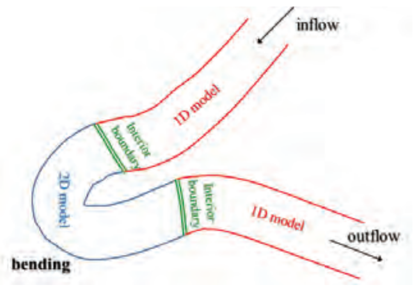
◻ **Case study:** Unsteady supercritical flows at a 30° junction

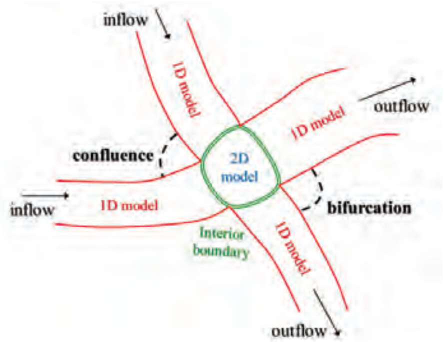


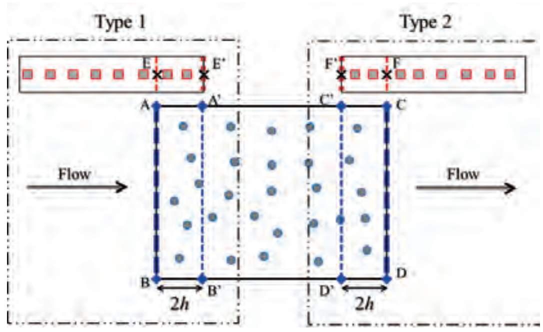


Research Topic 3:

Coupled 1D and 2D LSPH-SW model for open channel flows



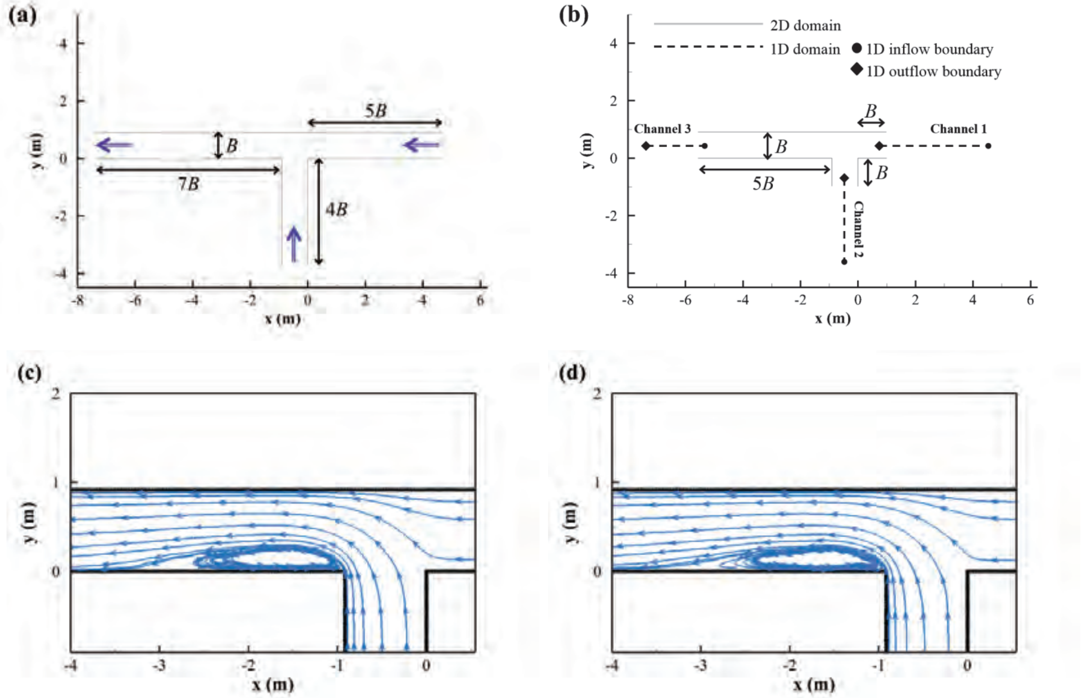


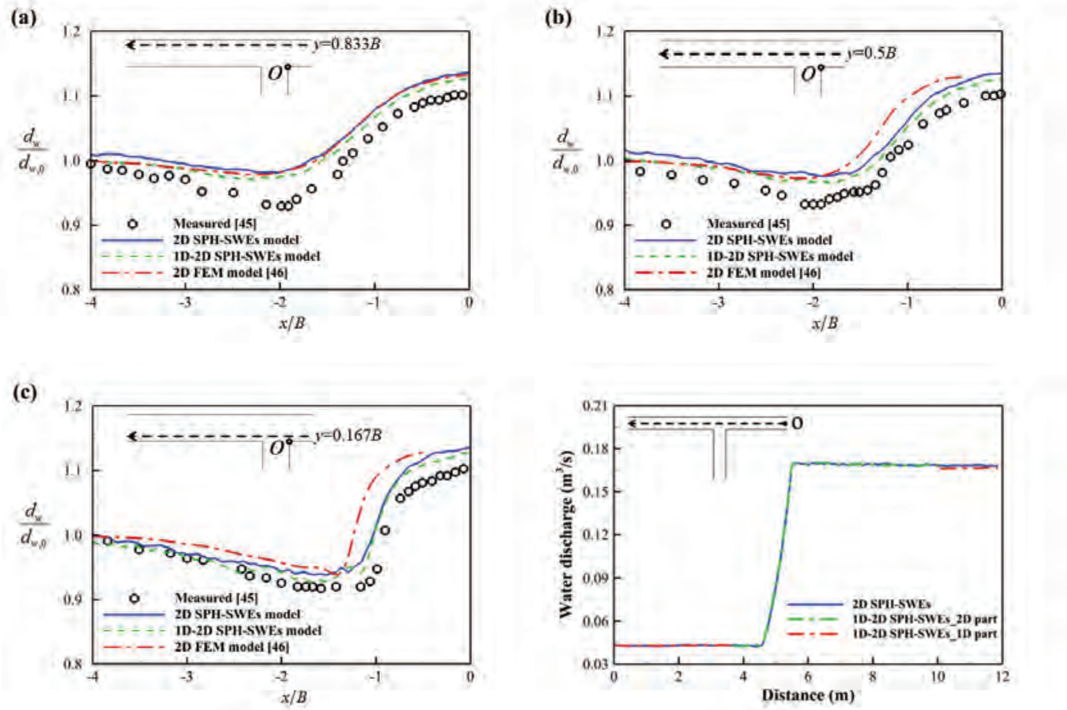


Advantage

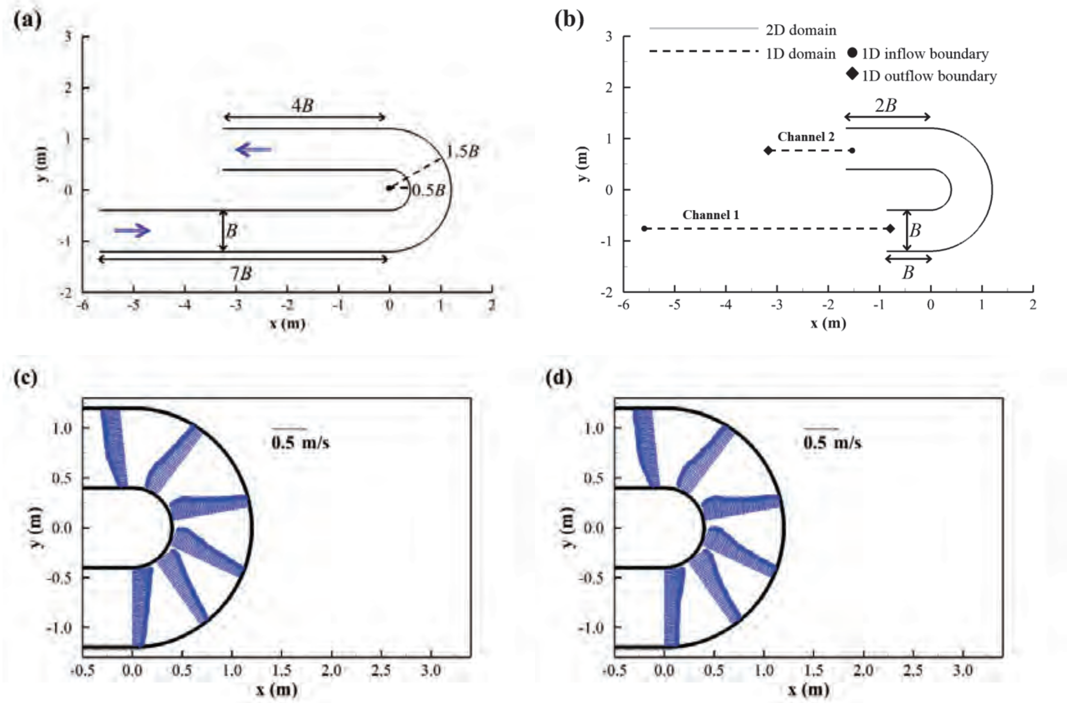
- Combining the efficiency of 1D model and the accuracy of 2D model.

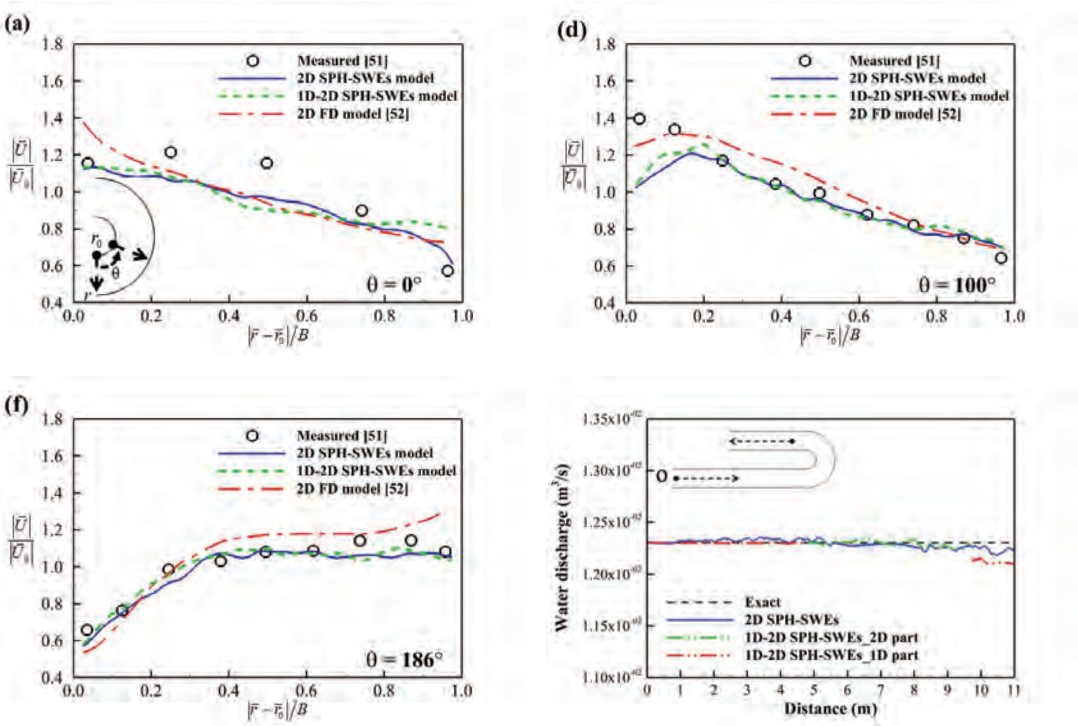
Case study: Converging channel





◻ Case study: Curved channel



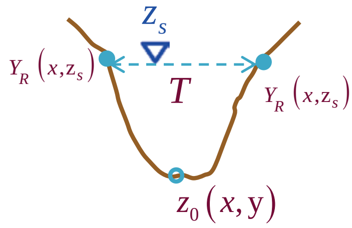


Research Topic 4:
1D and 2D well-balanced and positivity-preserving LSPH-SW models

$$\left(\frac{Dz_s}{Dt}\right)_a = \frac{A_a}{T_a}\sum_{b=1}^{b=N} V_b\left(u_a - u_b\right)\frac{\tilde{\partial}\omega_{ab}}{\partial x} - u\bar{S}_{0,a} + \beta h_0 c_0 D_a$$

$$\left(\frac{Du}{Dt}\right)_a = g\sum_{b=1}^{b=N} V_b\left(z_{s,a} - z_{s,b}\right)\frac{\tilde{\partial}\omega_{ab}}{\partial x} - gS_{f,a} + F_a$$

→ well-balanced



where $\overline{S_0}$ is the averaged bed slope and D and *F* are the dampings associated with the water surface level and the water velocity.

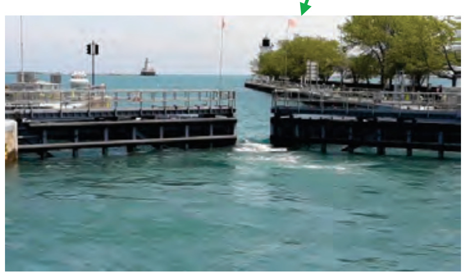
$$\Delta t_c \le CFL \cdot \min_a\left(\frac{\Delta x_0}{\left|u_a\right| + c_a}\right)$$

→ CFL condition

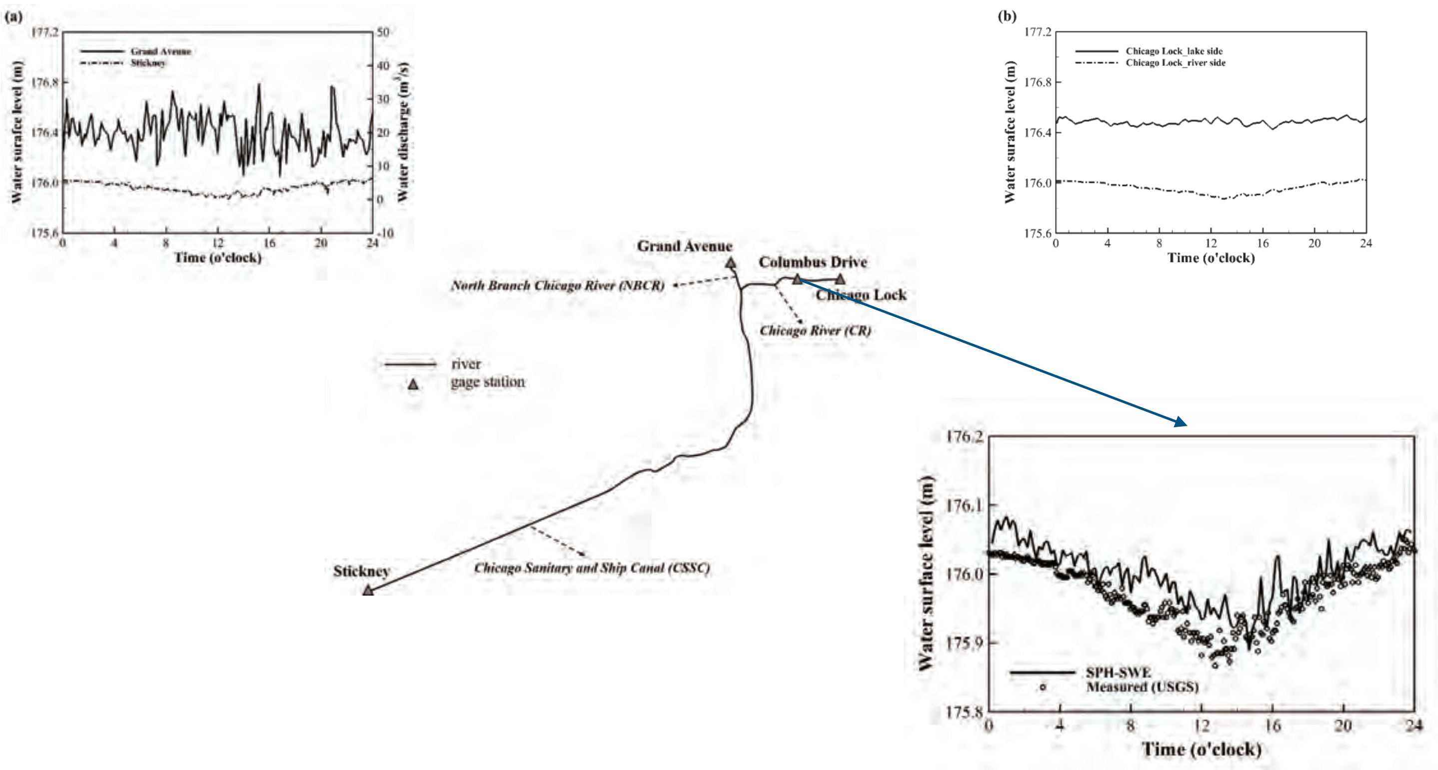
$$\Delta t_p \le \alpha \frac{1}{\left(-\sum_{b=1}^{b=N,b\neq a} V_b^n\left(u_{ab}^n + \beta\frac{h_0}{x_{ab}^n + \varepsilon^2}c_0^n\right)\left(\frac{\partial\omega_{ab}}{\partial x}\right)^n\right)}$$

→ positivity-preserving

- **Case study:** Chicago Area Waterways System



Simulation duration = 24 hours (Sep 10, 2008)



Publications of LSPH-SWM

1. Chang, K.H.*, Chang, T.J., Garcia, M.H. **(2021)**. A well-balanced and positivity-preserving SPH method for shallow water flows in open channels. *Journal of Hydraulic Research*, 59(6): 903–916.
2. Chang, K.H., Sheu, T.W.H.*, Chang, T.J. **(2018)**. A 1D-2D coupled SPH-SWEs model applied to open channel flow simulations in complicated geometries." *Advances in Water Resources*, 15: 185-197.
3. Chang, Y.S., Chang, T.J. **(2017)**. SPH Simulations of Solute Transport in Flows with Steep Velocity and Concentration Gradients. *Water*, 9(2): 132.
4. Chang, K.H., Chang, T.J.*, Sheu, T.W.H. **(2017)**. Development of an upwinding kernel in SPH-SWEs model to capture sharp surface in open channel flow. *Journal of Hydro-environment Research*, 15: 13-26.
5. Chang, K.H., Chang, T.J.*, Chiang, Y.M. **(2016)**. A novel SPH-SWE approach for modelling subcritical and supercritical flows at open channel junctions. *Journal of Hydro-environment Research*, 13: 76-88.
6. Chang, T.J., Chang, Y.S.*, Chang, K.H. **(2016)**. Modeling rainfall-runoff processes using smoothed particle hydrodynamics with mass-varied particles. *Journal of Hydrology*, 543(B): 749-758.
7. Chang, T.J., Chang, K.H., Kao, H.M.* **(2014)**. A new approach to model weakly nonhydrostatic shallow water flows in open channels with smoothed particle hydrodynamics. *Journal of Hydrology*, 519(A): 1010-1019.
8. Chang, T.J., Chang, K.H.* **(2013)**. SPH modeling of one-dimensional non-rectangular and non-prismatic channel flows with open boundaries. *Journal of Hydraulic Engineering*, 139(11): 1142-1149.
9. Kao, H.M., Chang, T.J.* **(2012)**. Numerical modeling of dambreak-induced flood and inundation. *Journal of Hydrology*, 448-449: 232-244.
10. Chang, T.J., Kao, H.M.*, Chang, K.H., Hsu, M.H. **(2011)**. Numerical simulation of shallow-water dam break flows in open channels using smoothed particle hydrodynamics. *Journal of Hydrology*, 408(1-2): 78-90.

Eulerian SPH Shallow Water Models (ESPH-SWM)

Journal of Fluids and Structures 84 (2019) 263–282

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ELSEVIER

Eulerian weakly compressible smoothed particle hydrodynamics (SPH) with the immersed boundary method for thin slender bodies

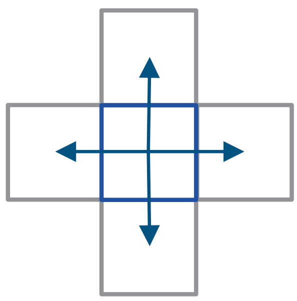
A.M.A. Nasar *, B.D. Rogers, A. Revell, P.K. Stansby, S.J. Lind

School of Mechanical Aerospace and Civil Engineering, The University of Manchester, Manchester, M13 9PL, UK

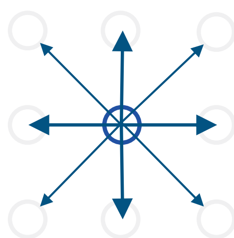
HIGHLIGHTS

- Lagrangian and Eulerian weakly compressible SPH are tested for FSI.
- Immersed boundary method used to model FSI with rigid thin body.
- Well-known treatments used to improve accuracy/stability of Lagrangian SPH.
- Results show Lagrangian SPH fails to accurately capture flow features.
- Eulerian SPH accurately captures flow highlighting advantages for FSI problems.

(a) Neighboring meshes



(b) Neighboring particles



$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}=\mathbf{S}_0(\mathbf{U})+\mathbf{S}_f(\mathbf{U})$$

where

$$\mathbf{U}=\begin{bmatrix} h \\ hu \\ hv \\ z_b \end{bmatrix} \quad \mathbf{G}=\begin{bmatrix} vh \\ uvh \\ v^2h+\frac{1}{2}gh^2 \\ \frac{1}{1-\varphi}q_{b,y} \end{bmatrix} \quad \mathbf{F}=\begin{bmatrix} uh \\ u^2h+\frac{1}{2}gh^2 \\ uvh \\ \frac{1}{1-\varphi}q_{b,x} \end{bmatrix} \quad \mathbf{S}_0=\begin{bmatrix} 0 \\ ghS_{0,x} \\ ghS_{0,y} \\ 0 \end{bmatrix} \quad \mathbf{S}_f=\begin{bmatrix} 0 \\ -ghS_{f,x} \\ -ghS_{f,y} \\ 0 \end{bmatrix}$$

SW Eqs.

Exner Eq.

1. HLLC Riemann solver (nonlinearity, discontinuity)
2. Hydrostatic reconstruction method (well-balanced and positivity-preserving)
3. Weakly coupled approach (SW eqs. and Exner Eq.)

Journal of Hydrology 623 (2023) 129581

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Research papers

A novel Eulerian SPH shallow water model for 2D overland flow simulations

Kao-Hua Chang

Department of Soil & Water Conservation, National Chung Hsing University, Taichung 40227, Taiwan

Journal of Hydrology 634 (2024) 131002

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Research papers

A new 2D ESPH bedload sediment transport model for rapidly varied flows over mobile beds

Kao-Hua Chang [a], Yu-Ting Wu [b], Chia-Ho Wang [c], Tsang-Jung Chang [d,*]

[a] Department of Soil & Water Conservation, National Chung Hsing University, Taichung, Taiwan
[b] Department of Engineering Science, National Cheng Kung University, Tainan, Taiwan
[c] Center for Weather and Climate Disaster Research, National Taiwan University, Taipei, Taiwan
[d] Department of Bioenvironmental Systems Engineering, National Taiwan University, Taipei, Taiwan

Case study: 2D uniform flow in a straight channel

- The rectangular channel with S_0=0.0308 and n=0.001 s/m$^{1/3}$ is 1000 m long and 400 m wide. The initial particle spacing is 20 m (1000 particles).
- B.C.s:

  Inflow boundary condition:

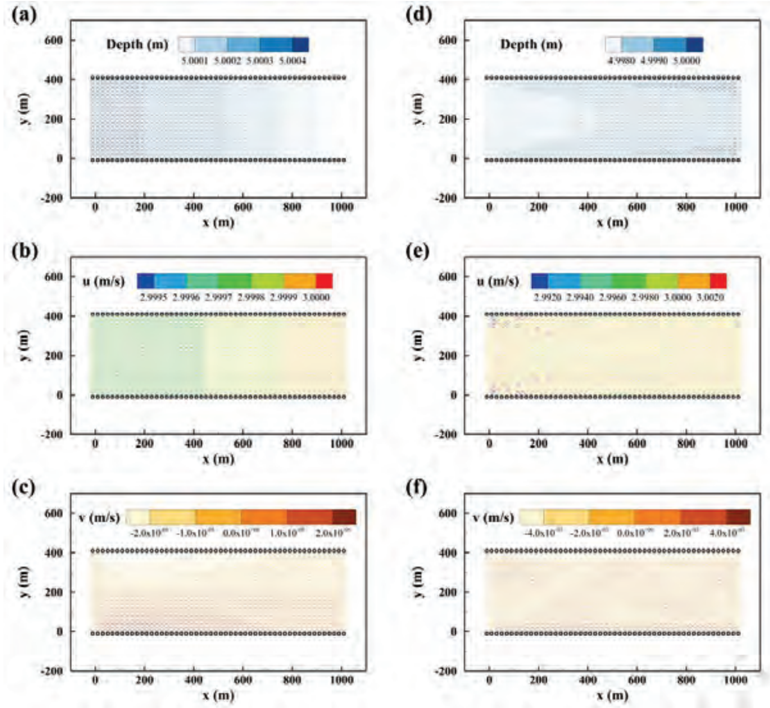
  Unit discharge q=15 m^{2}s^{-1}

  Outflow boundary condition:

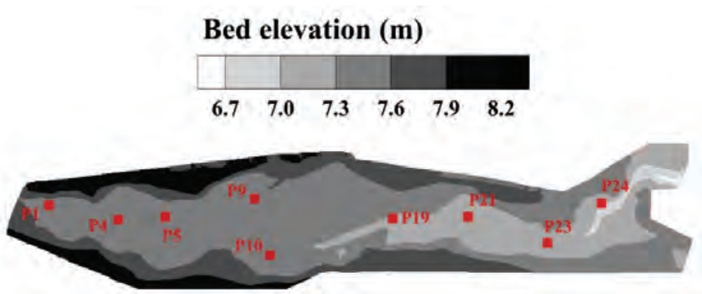
  Water depth h=5 m

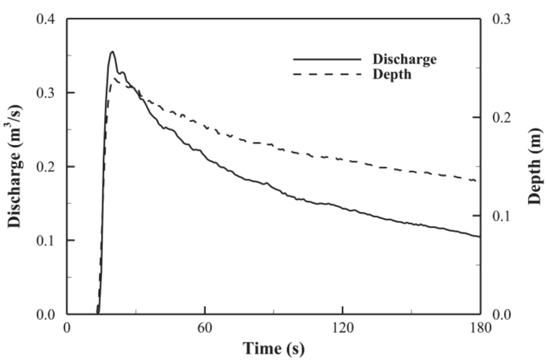
	ESPH	LSPH
Required CPU time (sec)	10.3	420.3
depth	6.19×10^{-5}	1.57×10^{-4}
u velocity	2.72×10^{-5}	1.26×10^{-4}
v velocity	1.47×10^{-9}	1.91×10^{-4}

RRMSE

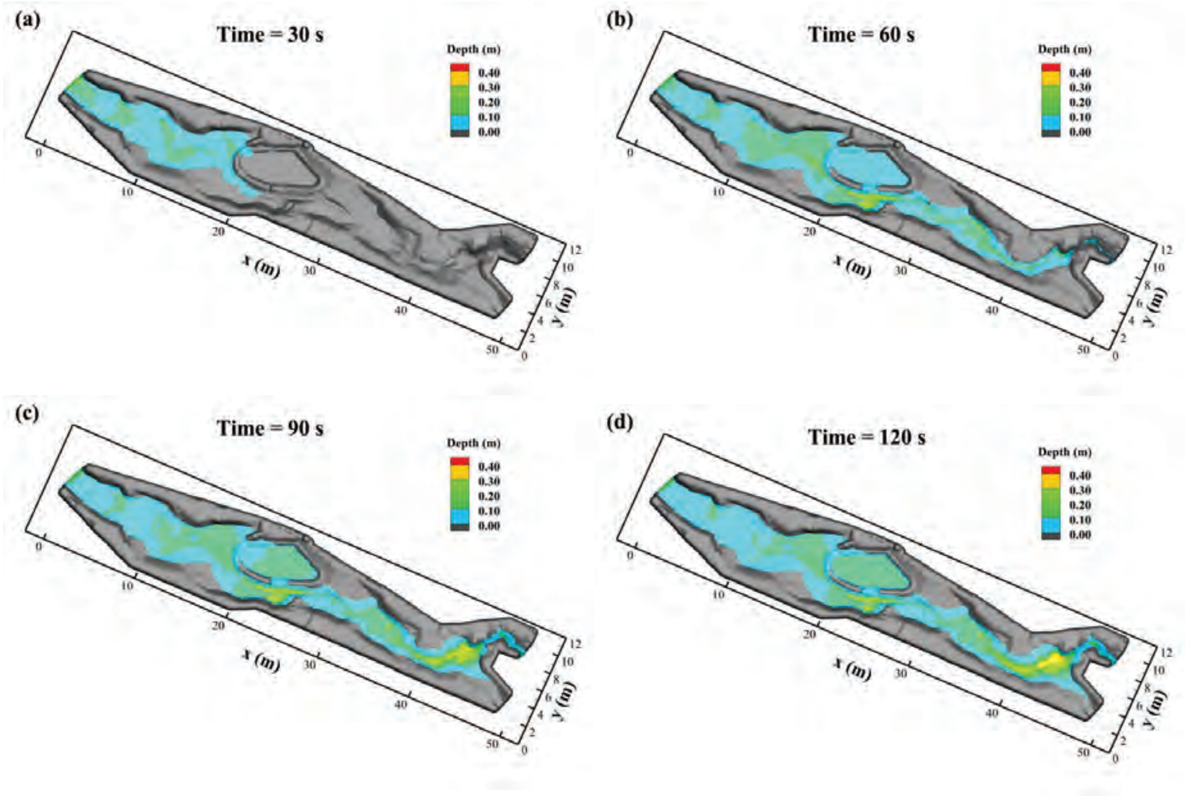


Case study: Dam break flow in a scaled model of the Toce river

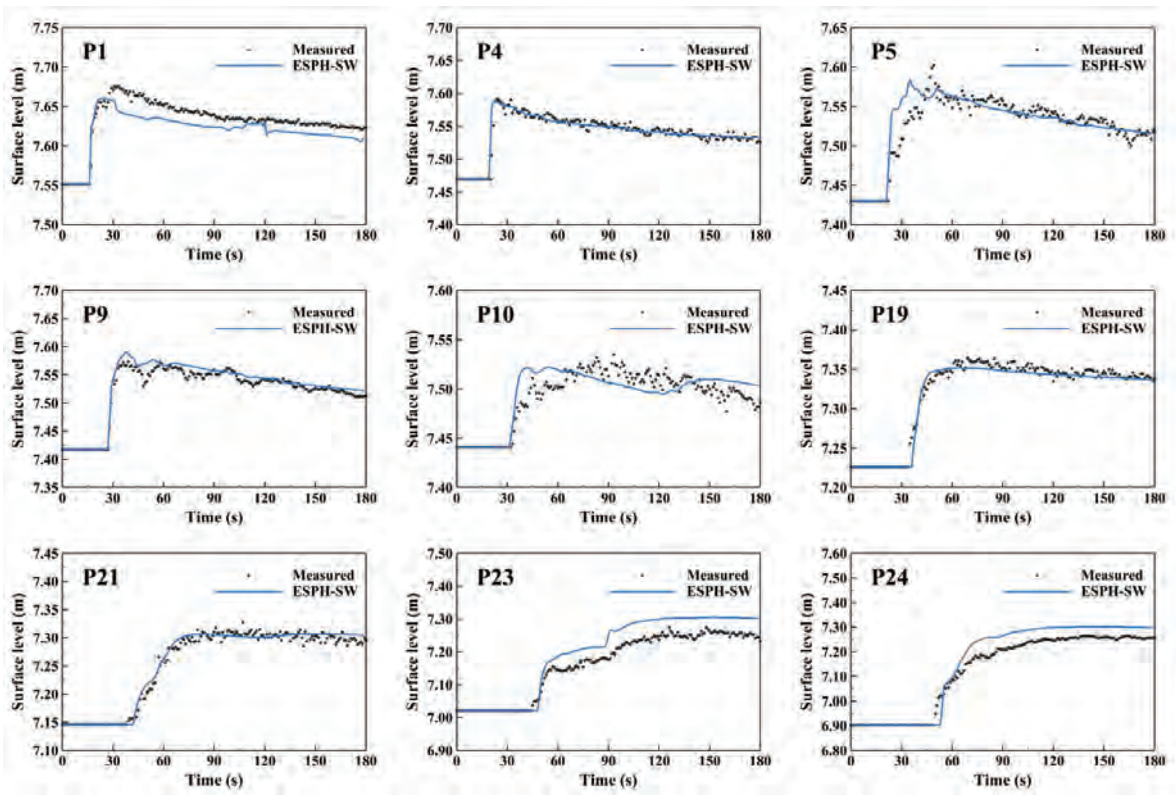




- n=0.0162 s/m$^{1/3}$
- The initial particle spacing is 0.05 m (140985 particles).

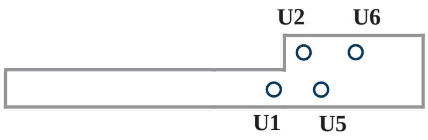

(a)
Time = 30 s
(b)
Time = 60 s
(c)
Time = 90 s
(d)
Time = 120 s
Depth (m)
x (m)
y (m)

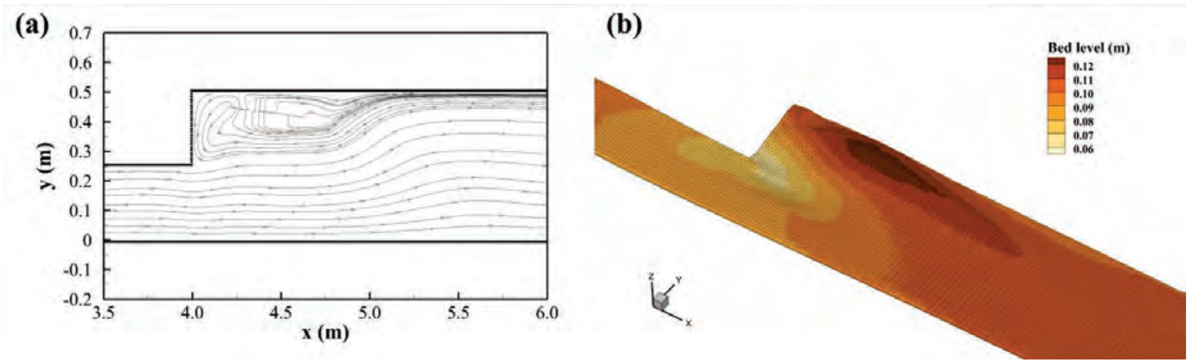
30

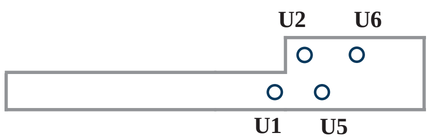

P1
P4
P5
P9
P10
P19
P21
P23
P24
Measured
ESPH-SW
Surface level (m)
Time (s)

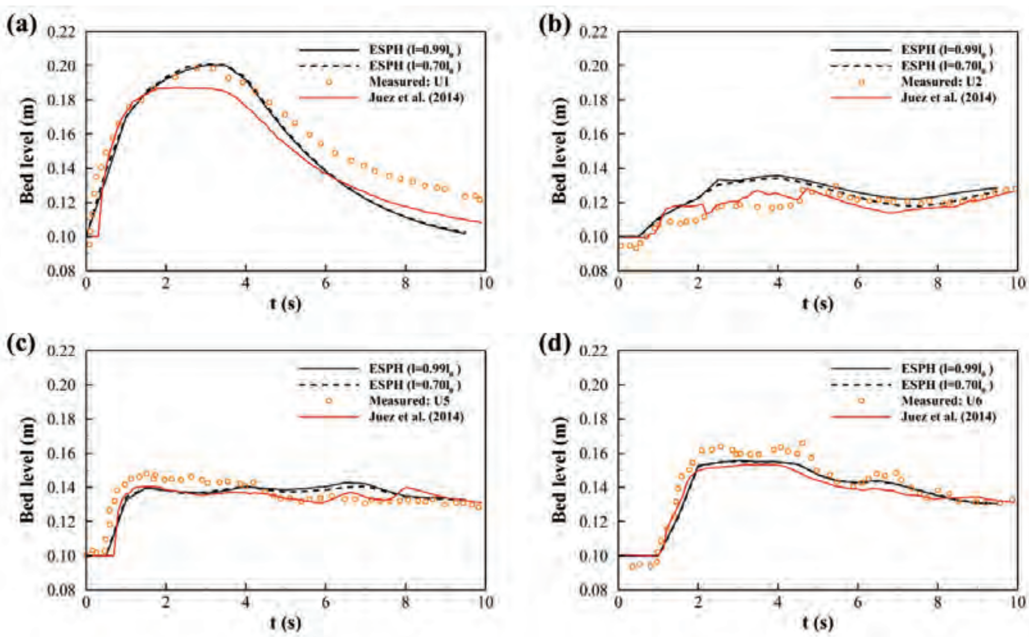
31

Case study: Dam-break flow in an erodible channel with an abrupt expansion



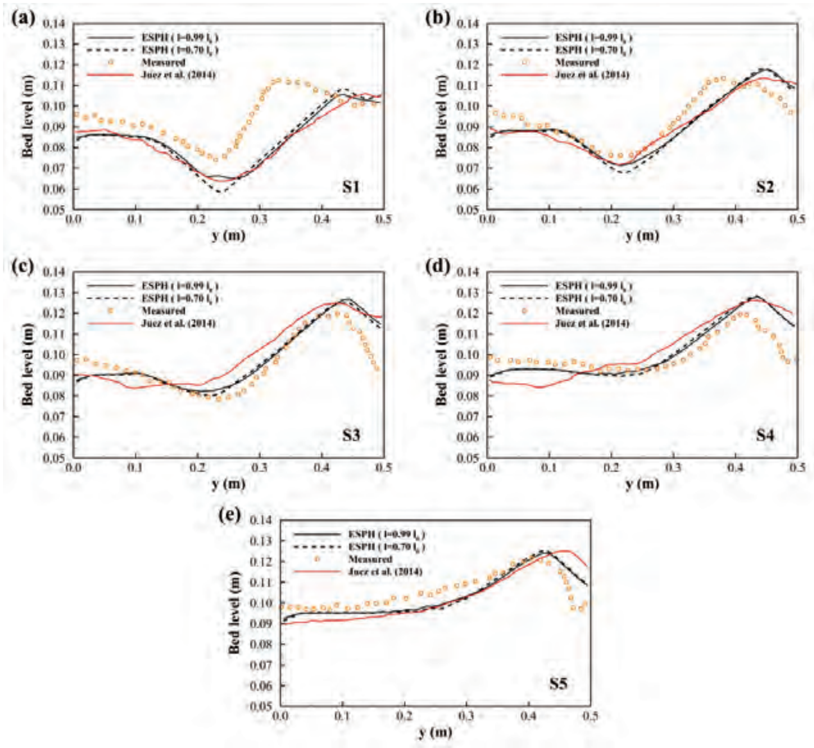






RRMSE

	$I=0.99I_0$	Juez et al. (2014)
S1	1.9%	2.0%
S2	1.4%	0.8%
S3	1.4%	1.2%
S4	1.3%	1.8%
S5	0.6%	1.0%



Summary

	ESPH-SWM	LSPH-SWM
Features	• Extra interacting particles enhancing more accuracy for some special cases • Easily describing rainfall and infiltration • Much more efficient	• Without the numerical errors caused by the nonlinear convective terms • No special treatment for wet-dry bed transitions • Easily tracking interfaces

Thanks for Listening

Hydraulic and sediment transport simulation of rivers and cross-river structures using the SRH2D model

李 豐 佐

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臺日「河川預警與模擬技術」研討會 (Apr. 26th 2024)
River Flood Warning and Simulation Technology Workshop (RFWST)

Hydraulic and sediment transport simulation of rivers and cross-river structures using the SRH2D model

Fong-Zuo Lee (李豐佐)

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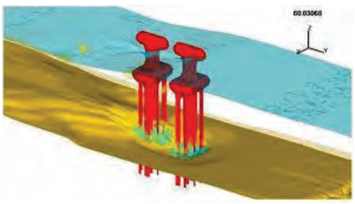
國立臺灣大學 水工試驗所 HRI Hydrotech Research Institute National Taiwan University

Outline

- Introduction
- Methodology 1&2
- Study Area 1&2
- Results 1&2
- Conclusion 1&2



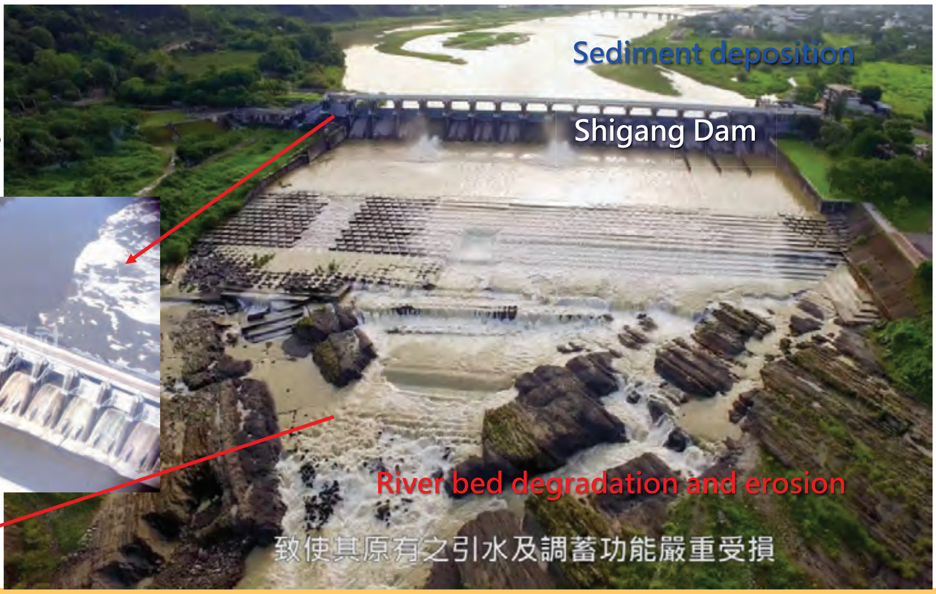
Introduction

- Due to the extreme weather, earthquake, floods occur and sediment sedimentation issues are frequently happened in recent years…

0403 earthquake in 2024

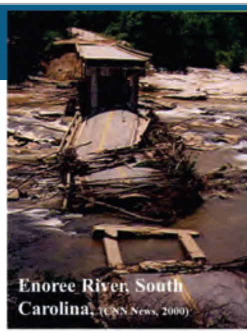
After Chi-Chi earthquake in 1999

No sediment supply
➔Soft rock exposed

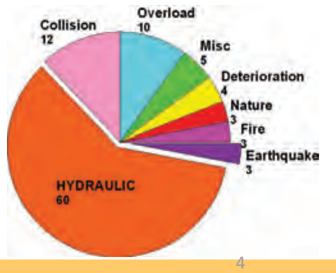


Introduction

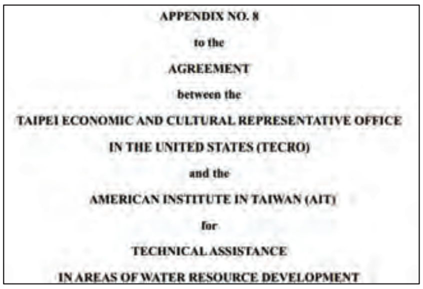
26 bridges collapsed, Chi-Chi Earthquake, 09, 1999
More than 150 bridges collapsed, Morakot Typhoon, 09, 2009



- Scour is one of the major causes for bridge failure.
- More than 1000 bridges have collapsed over the past 30 years in the U.S.,with 60% of the failures due to scour.



Introduction


APPENDIX NO. 8

to the

AGREEMENT

between the

TAIPEI ECONOMIC AND CULTURAL REPRESENTATIVE OFFICE

IN THE UNITED STATES (TECRO)

and the

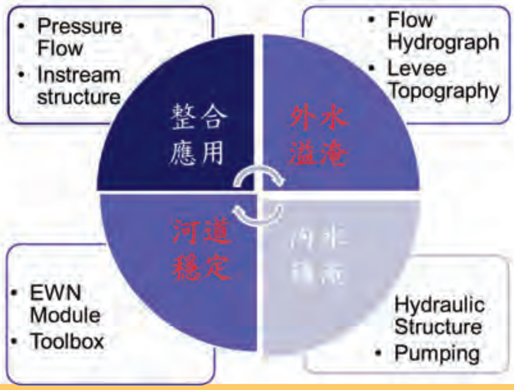
AMERICAN INSTITUTE IN TAIWAN (AIT)

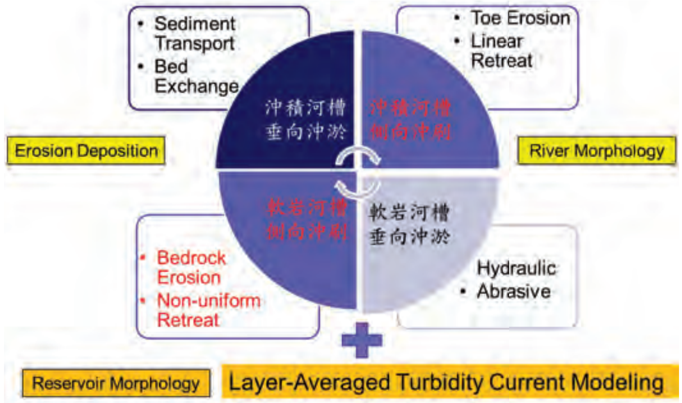
for

TECHNICAL ASSISTANCE

IN AREAS OF WATER RESOURCE DEVELOPMENT

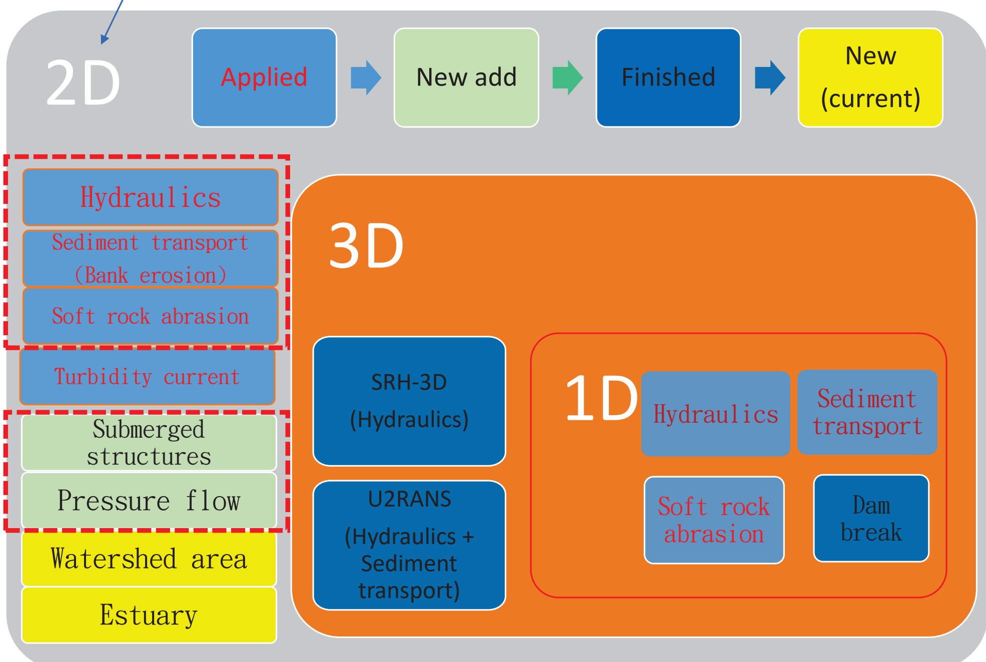
2005～2008 Appendix NO.8 to the Agreement between TECRO and the AIT
2009～2012 Amendment NO.1
2013～2017 Amendment NO.2
2018～2023 Amendment NO.3
2024~continue….





Introduction

SRH-2D, Sedimentation and River Hydraulics – Two-Dimension



Changes supporting the use of 2D modeling

AQUAVEO®

Surface-water Modeling System

SMS provides a custom interface to the SRH model offering a simple way to set model parameters and a graphical user interface to run the model and visualize the results. Gather background data from a variety of sources from GIS to CAD and access online data from numerous databases of maps, images, and elevation data. SMS allows you to interact with models in true 3D taking advantage of optimized OpenGL graphics and to create photo-realistic renderings and animations for PowerPoint, print, and web presentations.

The custom SRH Interface in SMS 12.1 and later supports running the model in multiple simulations and also supports hydraulic structures such as weirs, culverts, pressure zones, gates and obstructions.

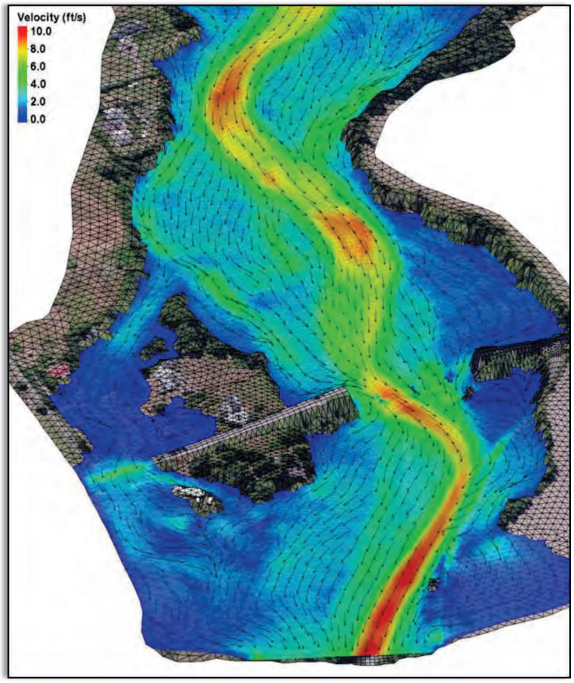
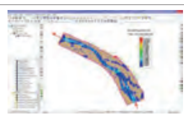


Image Source: FHWA

資料來源：*Scott Hogan, Federal Highway Administration, DOT,USA*



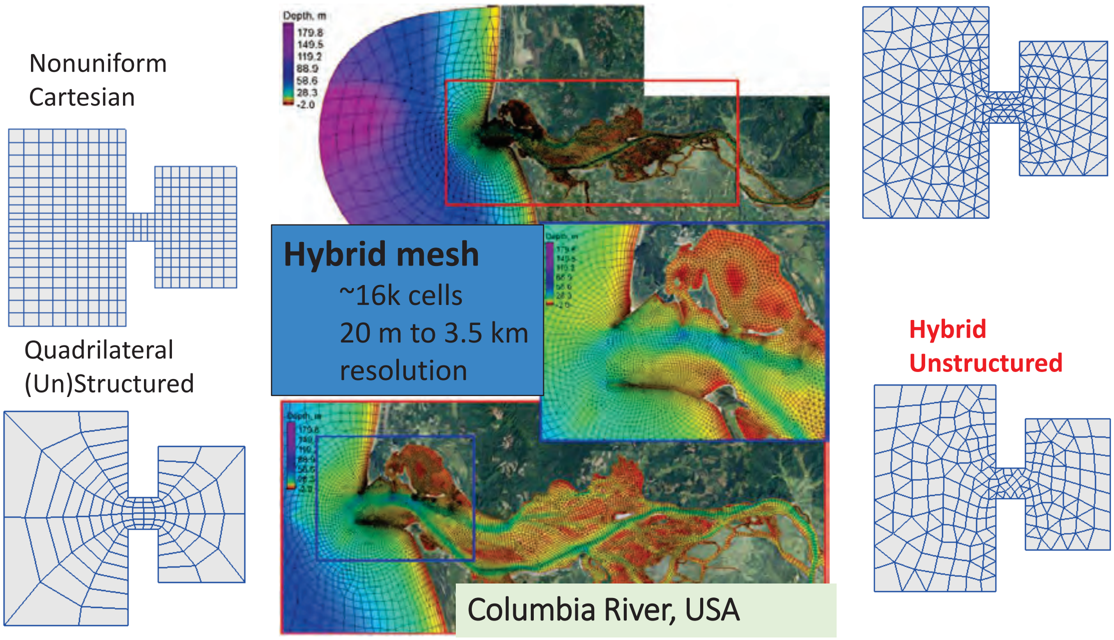
SRH-2D Description

SRH-2D is a hydraulic model developed by the U.S. Bureau of Reclamation that incorporates very robust and stable numerical schemes with a seamless wetting-drying algorithm. The model uses a flexible mesh that may contain arbitrarily shaped cells, both quadrilateral and triangular elements, which promotes solution accuracy while minimizing computing demand. SRH-2D modeling applications include flows with in-stream structures, through bends, with perched rivers, with side channel and agricultural returns, and with braided channel systems. SRH-2D is well suited for modeling local flow velocities, eddy patterns, flow recirculation, lateral velocity variation, and flow over banks and levees.

Features and capabilities of SRH-2D include:

- 2D depth-averaged dynamic wave equations (the standard St. Venant equations) are solved with the **finite-volume** numerical method.
- Steady state and unsteady flows may be simulated.
- **An implicit scheme** used for time integration to achieve solution robustness and efficiency
- An **unstructured** arbitrarily-shaped **mesh** is used which includes the structured quadrilateral mesh, the purely triangular mesh, or a combination of the two.
- **All flow regimes**, i.e., subcritical, transcritical, and supercritical flows, may be simulated simultaneously without the need for special treatments.
- Model incorporates **a robust and seamless wetting-drying algorithm**.
- Output solutions include water surface elevation, water depth, depth averaged velocity, Froude number, and bed shear stress.

More Grids Developed



Yong G. Lai (2010). Two-Dimensional Depth-Averaged Flow Modeling with an Unstructured Hybrid Mesh. J. Hydraulic Eng. 2010.136:12-23.

Introduction

Sedimentation and River Hydraulics

◆Multi-Agency Adoption

- Federal Highway Administration (FHWA)、WRA、USBR
- Project Collaboration (USGS and Army Corp. etc.)

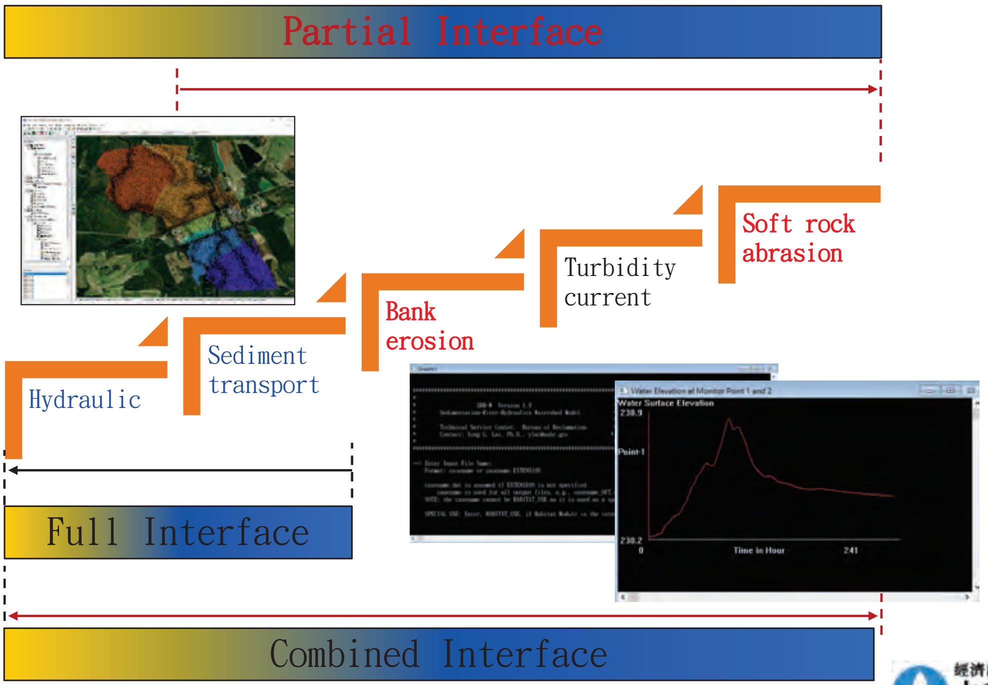
◆One model development

- ■SRH1D、SRH2D、SRH3D、U2RANS、SRH-Watersheld、SRH-Coast
- ■Continued Advancement

◆SRH-2D Advantaged

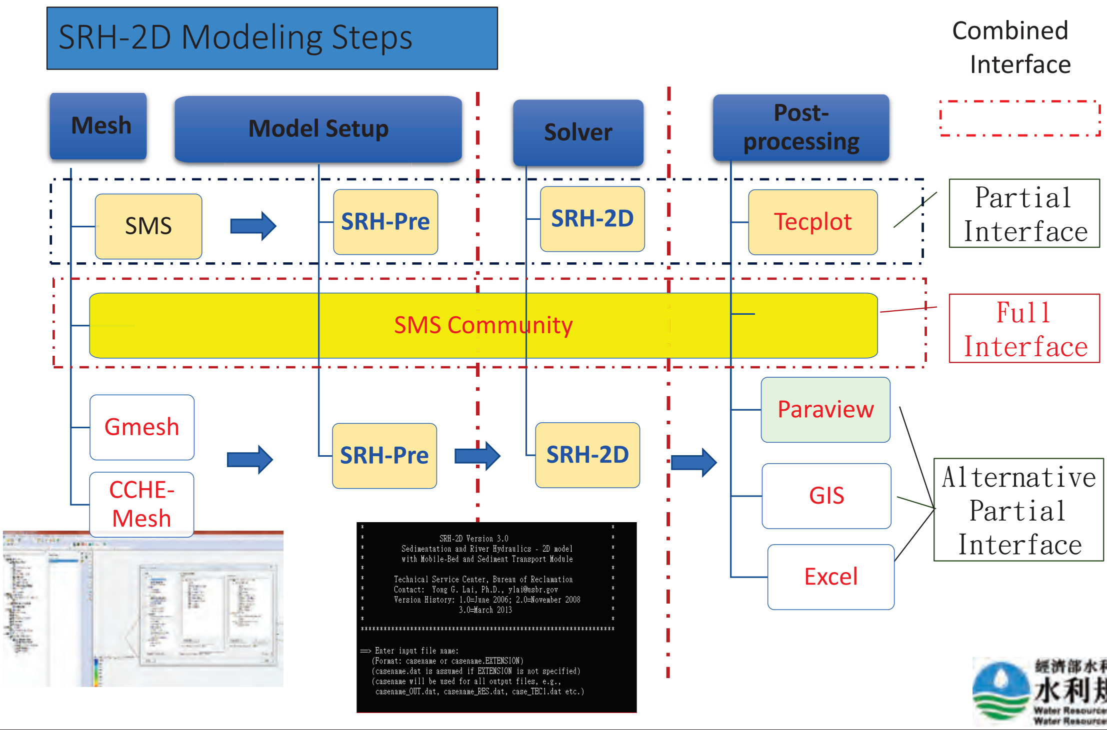
- ■Flexible Mesh
- ■Stable, Accurate, Ease-of-Use
- ■Freely Available

Analysis framework



經濟部水利署
水利規劃分署
Water Resources Planning Branch,
Water Resources Agency, Ministry of Economic Affairs

Analysis framework



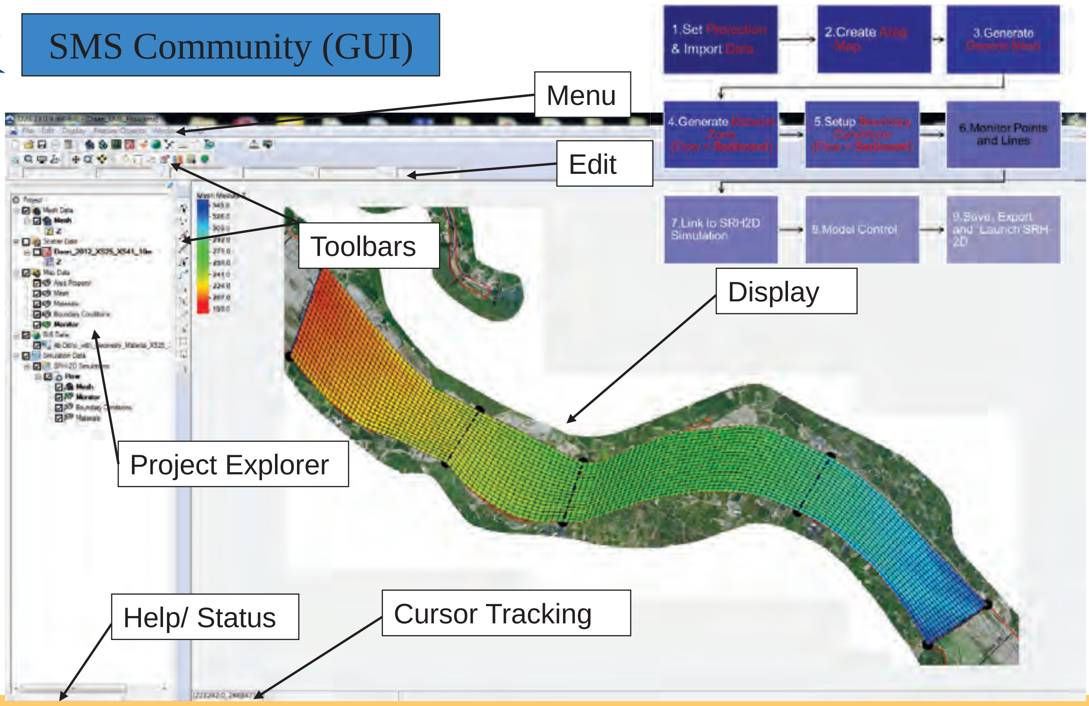
經濟部水利署
水利規劃分署
Water Resources Planning Branch,
Water Resources Agency, Ministry of Economic Affairs

Full Interface

Introduction

Free

SMS Community (GUI)



Methodology

- Sedimentation and River Hydraulics – One Dimension (SRH-1D)
  - Unsteady flow solution of one-dimensional river flows
  - conservation of mass equation:

$$\frac{\partial(A+A_d)}{\partial t}+\frac{\partial Q_s}{\partial x}=q_s$$

A = cross section area;
A_d = volume of bed sediment per unit length;
Q_s = volumetric sediment discharge;
q_s = lateral inflow sediment per unit length of channel;
t = time; ***x*** = distance along the river.

  - conservation of momentum equation

$$\frac{\partial Q_s}{\partial t}+\frac{\partial(\beta Q_s^{\,2}/A)}{\partial x}+gA\frac{\partial Z}{\partial x}=-gAS_f$$

β = velocity distribution coefficients,
Z = water surface elevation
S_f = energy slope = $(Q_s|Q_s|)/K^2$;
K = conveyance.

  - Simulates the physical processes of sediment transport.
  - Sediment transport equation:

$$\frac{\partial Q_s}{\partial x}+(1-P_0)\frac{\partial A_d}{\partial t}-q_s=0$$

P_0 = porosity.

Methodology

- **Sedimentation and River Hydraulics – Two Dimension (SRH-2D)**
  - Depth-averaged two-dimensional equations (2D St. Venant equations)
  - Flow Equations:

$$\frac{\partial h}{\partial t}+\frac{\partial hU}{\partial x}+\frac{\partial hV}{\partial y}=0$$

$$\frac{\partial hU}{\partial t}+\frac{\partial hUU}{\partial x}+\frac{\partial hVU}{\partial y}=\frac{\partial hT_{xx}}{\partial x}+\frac{\partial hT_{xy}}{\partial y}-gh\frac{\partial z}{\partial x}-\frac{\tau_{bx}}{\rho}+D_{xx}+D_{xy}$$

$$\frac{\partial hV}{\partial t}+\frac{\partial hUV}{\partial x}+\frac{\partial hVV}{\partial y}=\frac{\partial hT_{xy}}{\partial x}+\frac{\partial hT_{yy}}{\partial y}-gh\frac{\partial z}{\partial y}-\frac{\tau_{by}}{\rho}+D_{yx}+D_{yy}$$

t = time; x, y = horizontal Cartesian coordinates;
h = water depth; U, V = depth-averaged velocity components in x, y directions, respectively;
g = gravitational acceleration;
T_{xx}, T_{xy}, T_{yy} = depth-averaged turbulent stresses;
D_{xx}, D_{xy}, D_{yx}, D_{yy} = dispersion terms due to depth averaging;
$z = z_b + h$ = water surface elevation (z_b = bed elevation);
ρ = water density;
τ_{bx}, τ_{by} = bed shear stresses.

  - Boussinesq equations:

$$T_{xx}=2(\upsilon+\upsilon_t)\frac{\partial U}{\partial x}-\frac{2}{3}k$$

$$T_{xy}=(\upsilon+\upsilon_t)\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right)$$

$$T_{yy}=2(\upsilon+\upsilon_t)\frac{\partial V}{\partial y}-\frac{2}{3}k$$

υ = kinematic viscosity of water;
υ_t = turbulent eddy viscosity;
k = turbulent kinetic energy.

Methodology

- **Sedimentation and River Hydraulics – Two Dimension (SRH-2D)**
  - Two turbulence models: depth-averaged parabolic model & k-ε model.
  - Equation of depth-averaged parabolic model:

$$\upsilon_t = C_t U_* h$$

υ_t = turbulent eddy viscosity;
C_t = ranges from 0.3 to 1.0 (default value=0.7);
U_* = bed frictional velocity; h = water depth.

  - Equation of k-ε model:

$$\frac{\partial hk}{\partial t}+\frac{\partial hUk}{\partial x}+\frac{\partial hVk}{\partial y}=\frac{\partial}{\partial x}\left(\frac{h\upsilon_t}{\sigma_k}\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{h\upsilon_t}{\sigma_k}\frac{\partial k}{\partial y}\right)+P_h+P_{kb}-h\varepsilon$$

$$\frac{\partial h\varepsilon}{\partial t}+\frac{\partial hU\varepsilon}{\partial x}+\frac{\partial hV\varepsilon}{\partial y}=\frac{\partial}{\partial x}\left(\frac{h\upsilon_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{h\upsilon_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right)+C_{\varepsilon 1}\frac{\varepsilon}{k}P_h+P_{\varepsilon b}-C_{\varepsilon 2}h\frac{\varepsilon^2}{k}$$

k = turbulent kinetic energy;
$\upsilon_t = C_\mu k^2/\varepsilon$ = turbulent eddy viscosity.

  - The following definitions and coefficients are used (Rodi 1993):

$$P_h = h\upsilon_t\left[2\left(\frac{\partial U}{\partial x}\right)^2+2\left(\frac{\partial V}{\partial y}\right)^2+\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right)^2\right]$$

$$P_{kb}=C_f^{-1/2}U_*^3; \qquad P_{\varepsilon b}=C_{\varepsilon\Gamma}C_{\varepsilon 2}C_\mu^{1/2}C_f^{-3/4}U_*^4/h$$

$$C_\mu=0.09,\ C_{\varepsilon 1}=1.44,\ C_{\varepsilon 2}=1.92,\ \sigma_k=1.3,\ C_{\varepsilon\Gamma}=1.8\sim 3.6$$

P_{kb}, $P_{\varepsilon b}$ = added to account for the generation of turbulent energy and dissipation due to bed friction for the case of uniform flows.

Methodology

- **Sedimentation and River Hydraulics – Two Dimension (SRH-2D)**
  - Sediment transport equation (Parker, 1990):

$$\frac{q^{*}_{t,k}\,g(s-1)}{(\tau_b/\rho)^{1.5}} = \frac{Y_g\left[4\pi\left(d_k/2\right)^3/3\right]/\rho_o g(s\text{-}1)}{(\tau_b/\rho)^{1.5}} = P_{ak}G(\phi_k)\ ; \qquad \phi_i = \frac{\theta_k}{\theta_r}\left(\frac{d_k}{d_{50}}\right)^{\alpha}$$

$$G = \begin{cases} 11.933(1-0.853/\phi_i)^{4.5} & \phi > 1.59 \\ 0.00218\exp[14.2(\phi_i-1)-9.28(\phi_i-1)^2]\ , & 1.0 \le \phi \le 1.59 \\ 0.00218\phi_i^{14.2} & \phi < 1.0 \end{cases}$$

$q^{*}_{t,k}$ = volumetric sediment transport rate per unit width;
P_{ak} = volumetric fraction of the kth sediment size class in the bed;
τ_b = bed shear stress;
$\theta_k = \tau_b/[\rho g(s\text{-}1)d_k]$ = Shield's parameter of sediment size class k;
θ_r = reference Shield's parameter;
d_k = diameter of sediment size class k,
d_{50} = median diameter of the sediment mixture in bed

- **Bridge Pier Scouring**
  - Pier scour = General Scour (Y_g) + Constriction scour (Y_c) + Local Scour (Y_s)

Code	Sediment transport Eqs..	Code	Sediment transport Eqs..
EH	Engelund-Hansen (1972)	AW	Ackers and White (1973)
MPM	Meyer-Peter and Muller (1948)	RIJN	van Rijn (1984)
PARKER	Paker (1990)	BAGNLOD	Bagnold (1980)
WILCOCK	Wilcock and Crowe (2003)	TRINITY	Gaeuman et al. (2009)
WU	Wu et al. (2000)	KUO	Kuo et al. (1984)
YANG73	Yang (1973)	GARCIA	Garcia and Parker (1993)
YANG79	Yang (1979)	WRIGHT	Wright and Parker (2004)

Pier Scour Depth	Formula
General Scour (Y_g)	Parker (1990)
Constriction scour (Y_c)	Laursen (1958)
Local Scour (Y_s)	Neill (1964), Shen et al. (1966), Jianmin Wu (1967), Jain and Fischer (1980)Inglis (1949), Froehlich (1991)

Methodology

- **Bridge Pier Scouring**
  - Estimation of constriction scour (Y_c)

$$Y_c = Y_1\left[\left(\frac{Q_2}{Q_1}\right)^{7/6}\cdot\left(\frac{B_1}{B_2}\right)^{k_1}\cdot\left(\frac{n_2}{n_1}\right)^{k_2}-1\right]$$

Q_1 = incoming flow; Q_2 = flow through the piers;
B_1 = width of incoming water; B_2 = width of water between piers;
n_1 = Manning roughness value of the flowing channel;
n_2 = Manning roughness value between bridge piers;
k_1, k_2 = ratio of shear velocity to particle settlement velocity

  - Estimation of local scour (Y_s)

Neill (1964) $\quad Y_s = 1.5D\cdot(Y/D)^{0.3}$

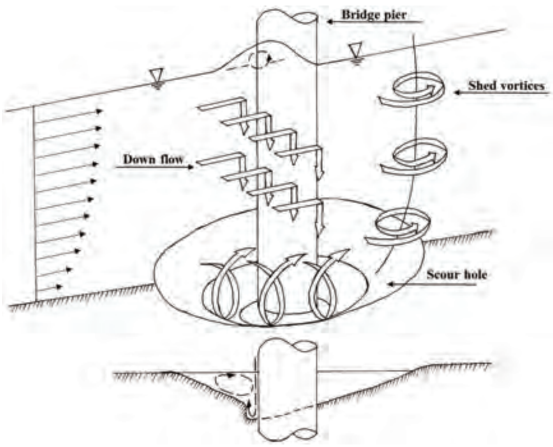
Shen et al. (1966) $\quad Y_s = 2.5Y\cdot F_r^{0.4}(D/Y_1)^{0.6}$

Jianmin Wu (1967) $\quad 1+0.116\left(\frac{Y_S}{Y_1}\right) = \frac{1}{1.02}\left[1+\frac{(b/2Y_1)}{1.3(Y_S/Y_1)}\right]$

Jain and Fischer (1980) $\quad Y_s = 1.86D\cdot(Y/D)^{0.5}\cdot(F_{rc}-F_r)^{0.25}$

Froehlich(1991) $\quad Y_s = 0.32\phi(D)^{0.62}Y^{0.47}F_r^{0.22}d_{50}^{-0.09}$

D = diameter of pier; Y_1 = incoming water depth; φ = 1.3 (rectangular nose point); φ = 1.0 (circular nose point); φ = 0.7 (triangular nose point); point); b = bridge slope; F_r = Froude number; F_{rc} = critical Froude number



Study Area

- Cho-Shui River is the longest river in west-central Taiwan.
- The Study Area is located in the middle of Cho-Shui River , 56km upstream from the estuary.
- A 16 km long reach from Ji-Lu Bridge to junction of tributary of Chin-Sui River.

Study Area

Agents impacted the River Stability

Earthquake

- Sep. 21 , 1999
- Change channel slope 、Increase sediments supply

In stream and cross stream Structures

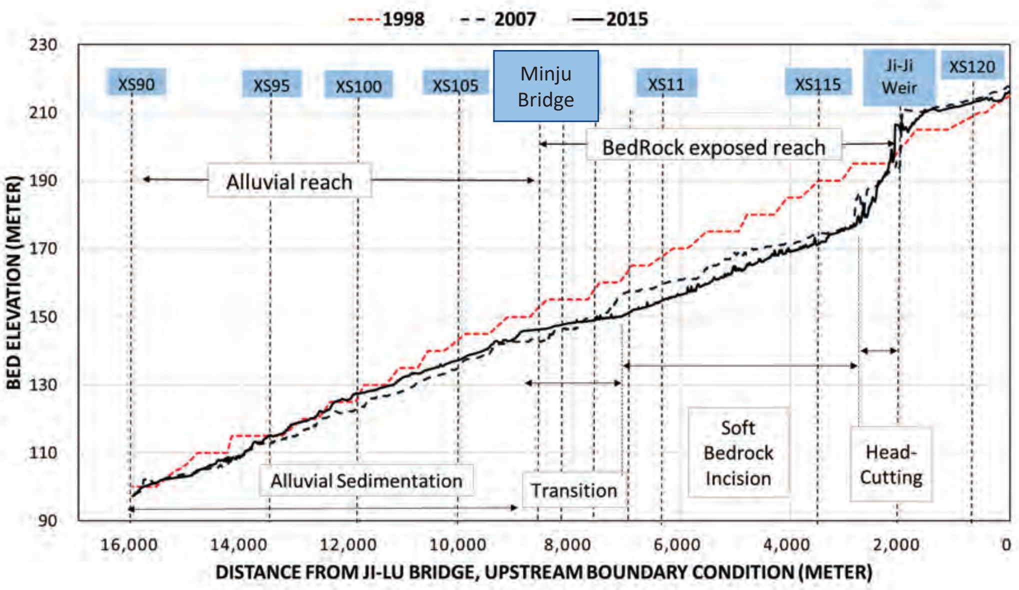
- 1978～2001
- Slope Discontinuity 、Limit lateral migration

Sand Mining

- 1968～1995
- Reduce local sediments 、Bed elevation

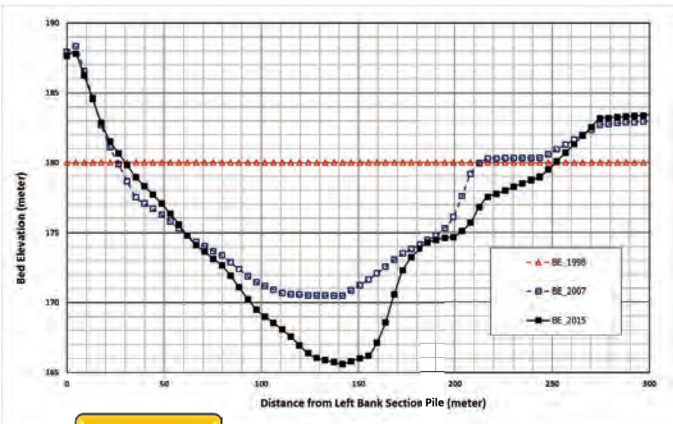
Study Area

Longitudinal Thalweg Evolution



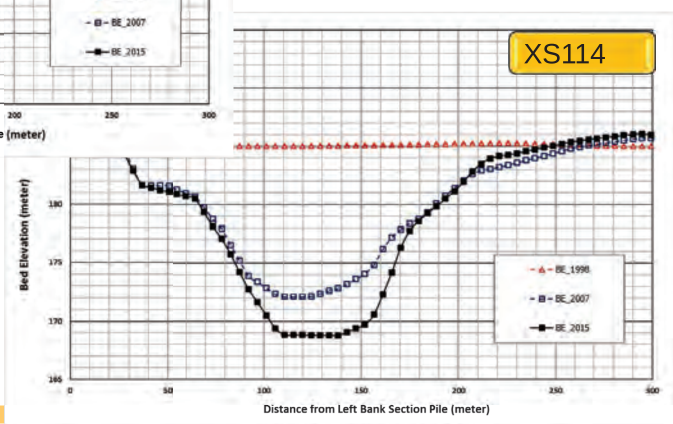
Study Area

XS Soft Bedrock Channel Evolution



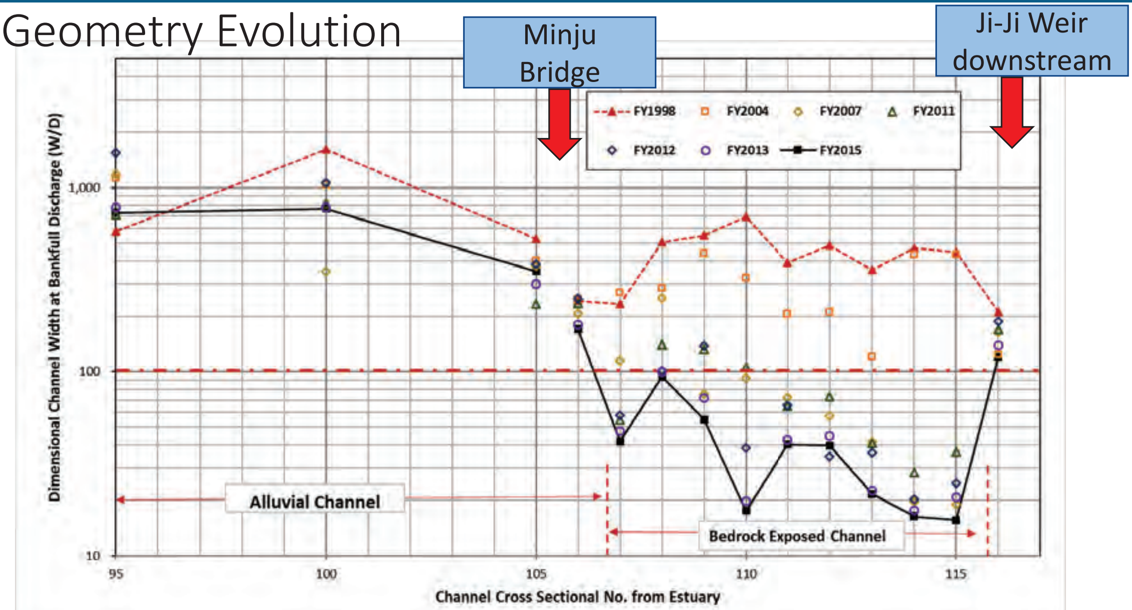
Ji-Ji Weir downstream

XS113



Study Area

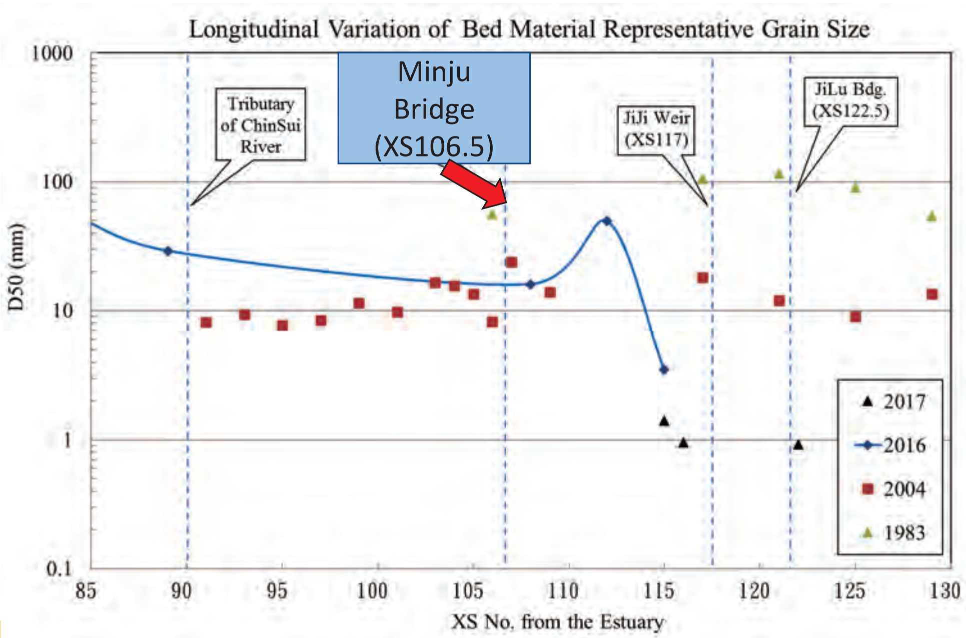
Hydraulic Geometry Evolution



Study Area

Longitudinal Variation of Bed Material

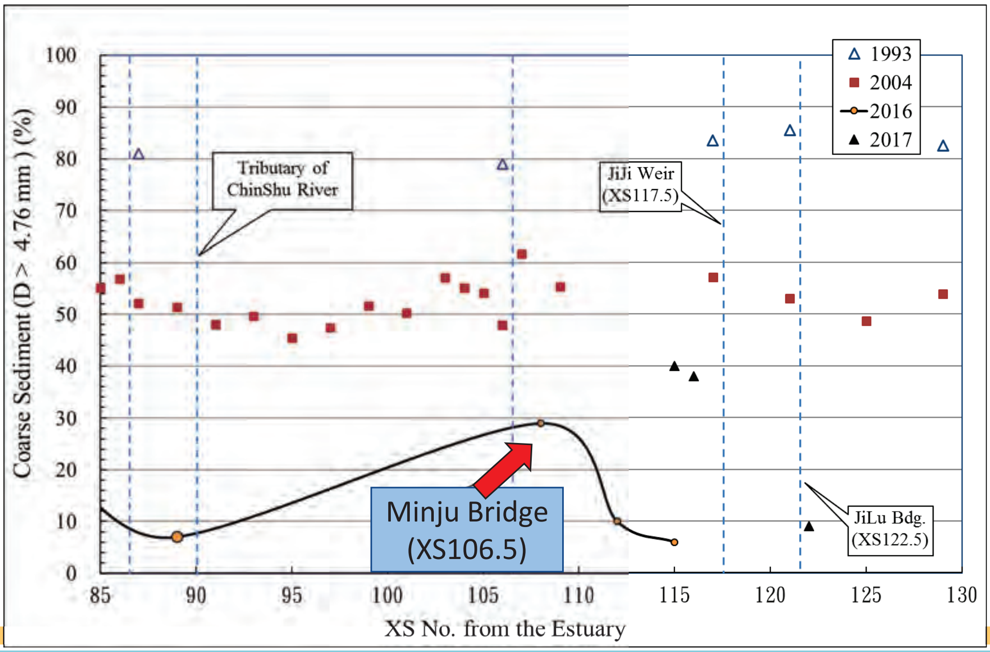
1.Representative Grain Size



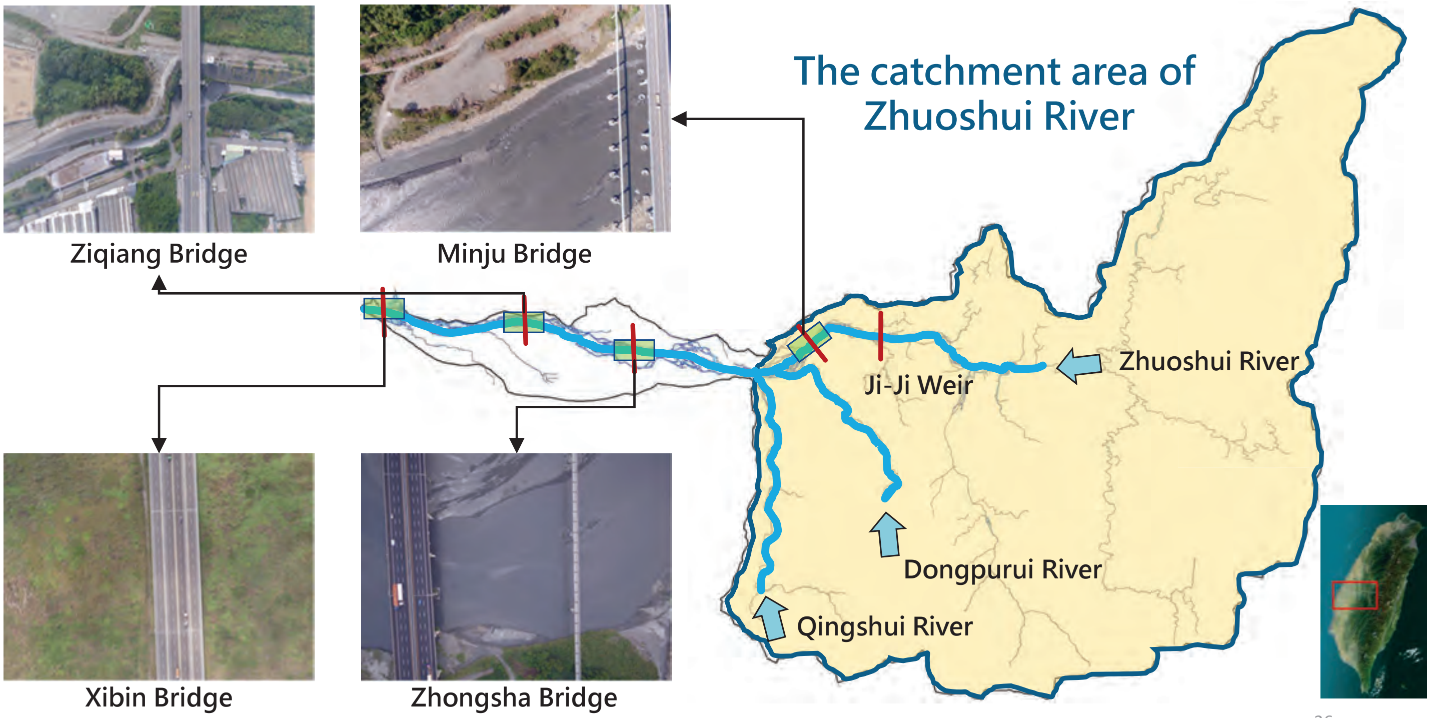
Study Area

2.Coarse Sediment Proportion

Longitudinal Variation of Bed Material

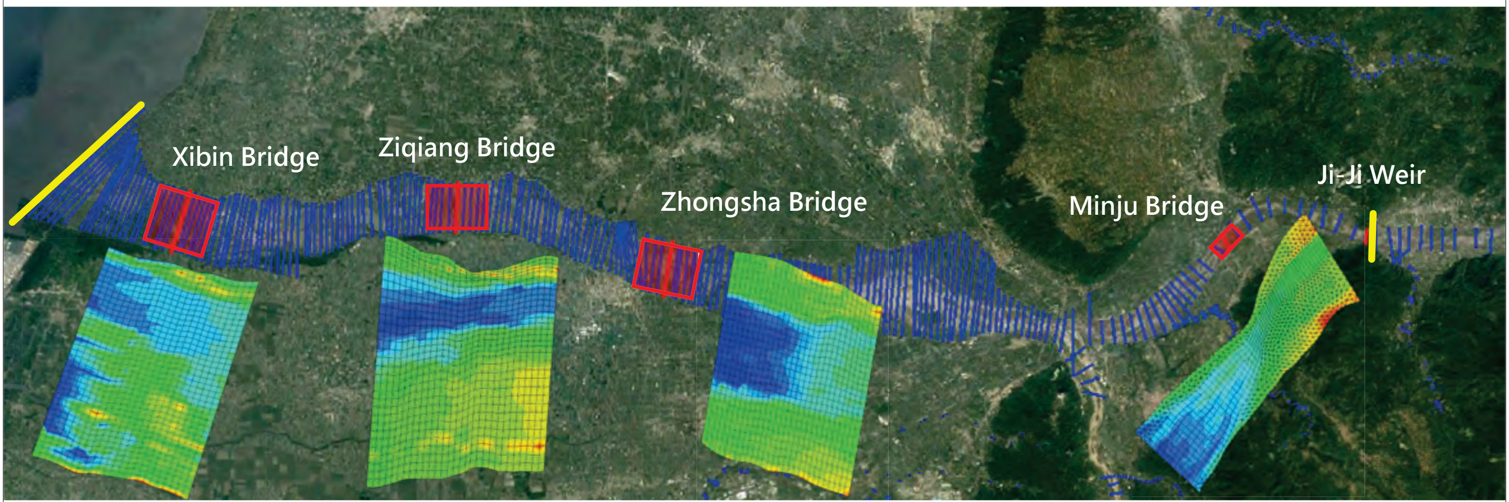


Study Area : Topic 1



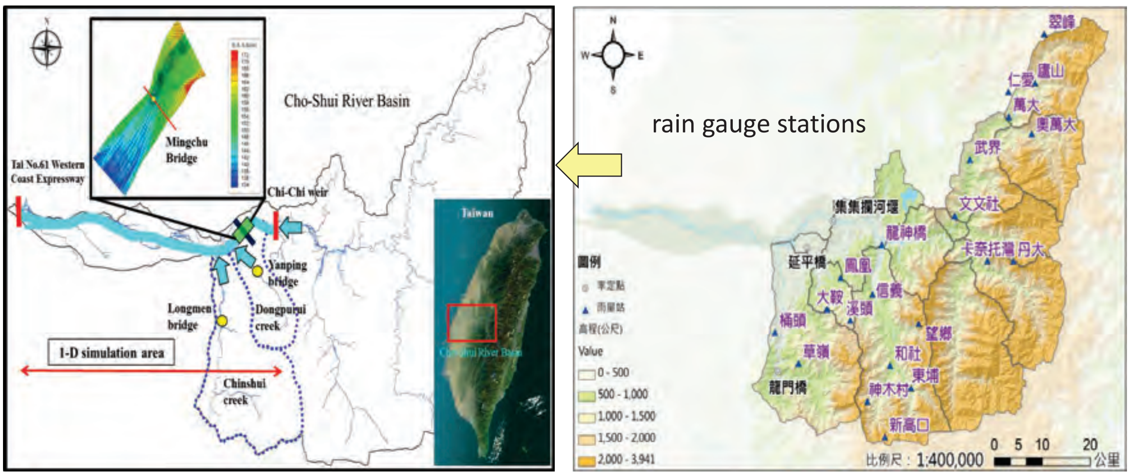
Study Area

- SRH-1D & SRH-2D model building
  - Modeling range of SRH-1D: from Chi-Chi Weir to the estuary
  - Modeling range of SRH-2D: the area of Minju, Zhongsha, Ziqiang and Xibin Bridges



Results

Zhuo-shui River basin



The adapted rainfall data in the watershed is provided by the Central Weather Bureau and upstream hydrological conditions are provided by Water Resources Agency. The downstream boundary condition of water level is set at Tai No.61 Western Coast Expressway. We also applied the rainfall runoff model (Hsieh, 1999) for the upstream boundary condition combining with downstream tidal prediction for bridge pier scour depth forecasting.

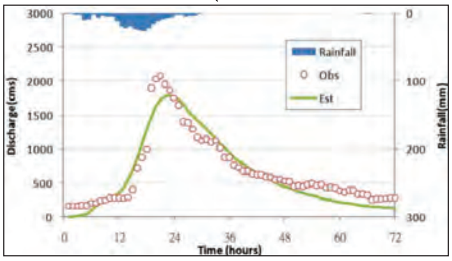
Results

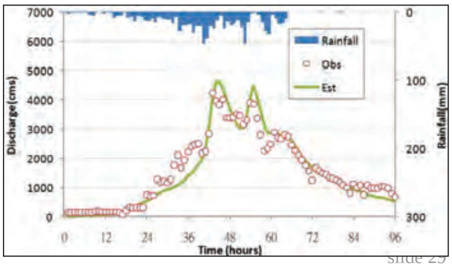
Now ➔SRH-W is developed

flood discharge forecasting

- Flood Early Warning System (FEWS) is currently be used during flood duration by Water Resources Agency. The function of FEWS provides real time hydrological information and platform for hydrological information prediction [Taiwan Freeway Bureau, 2012].
- FEWS is developed by Jave language and its operation interaction could be set up by XML internet language. This system provides more friendly and feasibility to integrate different hydraulic modes. The integrated problem between different models during model establishment, investigation and data exchange are not needed to worry about.

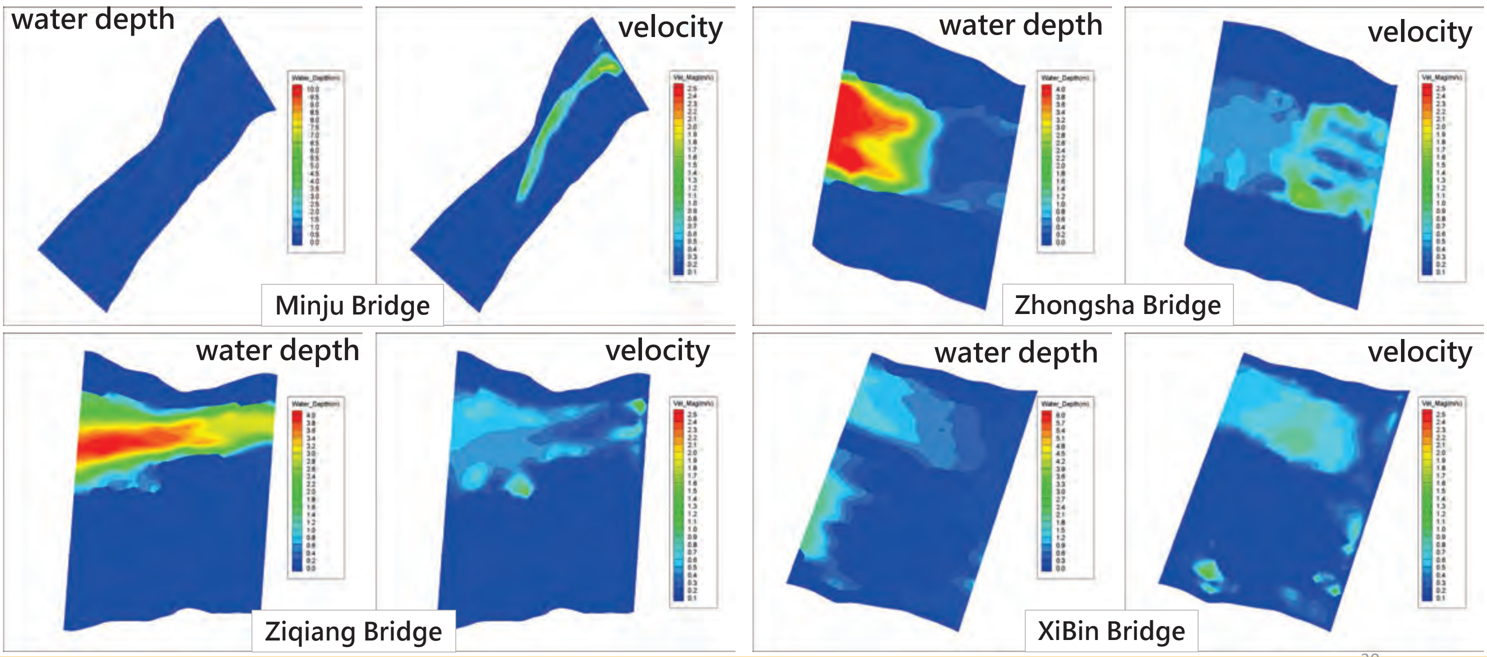
calibration ⬅ 2018 Typhoon Sinlaku at Chi-Chi weir ➡ verification





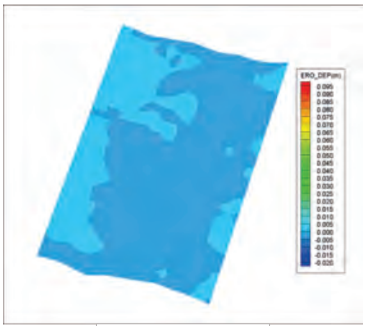
Results

- SRH-2D modeling (Heavy rain event in June 2016) – water depth & velocity

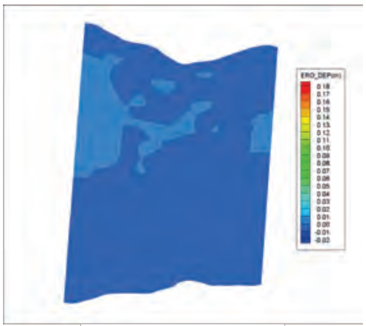


Results

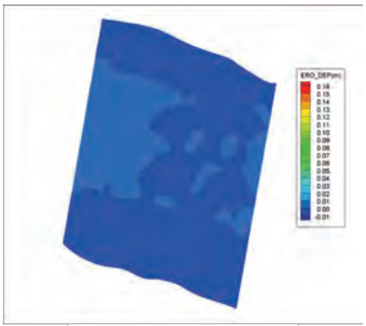
- SRH-2D modeling (Heavy rain event in June 2016)
- results of erosion & deposition



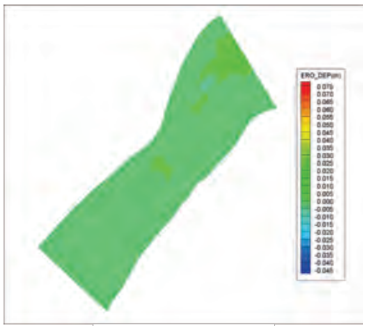
XiBin Bridge



Ziqiang Bridge



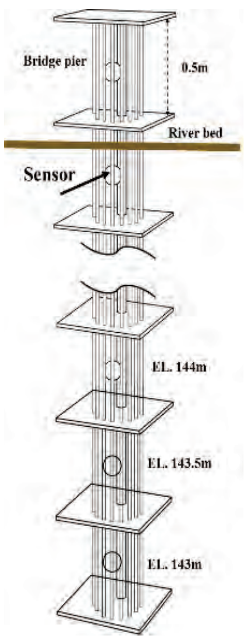
Zhongsha Bridge



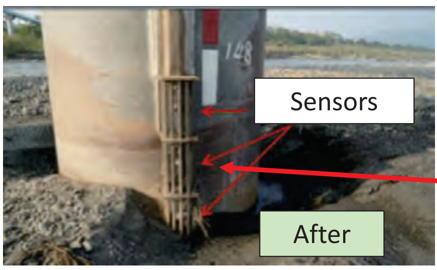
Minju Bridge

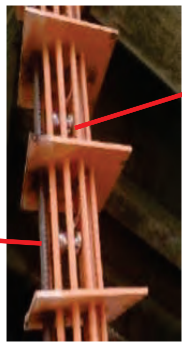
Results

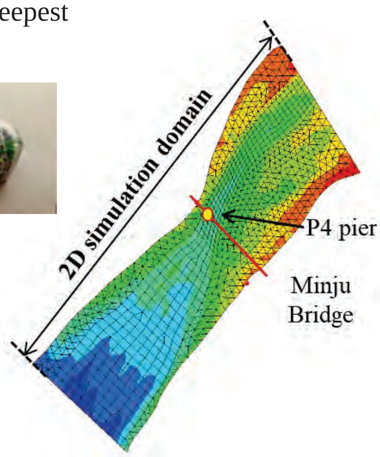
Before



The monitoring sensor of bridge pier scour and numerical model are implemented to study the prediction of bridge pier scour depth. As a result, in this study, the development principle is that a Micro-Electro-Mechanical System (MEMS)-based vibration sensor by the turbulent flow vibrates at significantly higher amplitudes surrounded by bridge piers up and down the river bed (Lee et al., 2014, 2017). The sensor setup located at the P4 bridge pier of Mingchu Bridge and setup depth ranged from river bed to the elevation level (EL.) 143m, the deepest monitoring depth is constrained at EL. 143m.

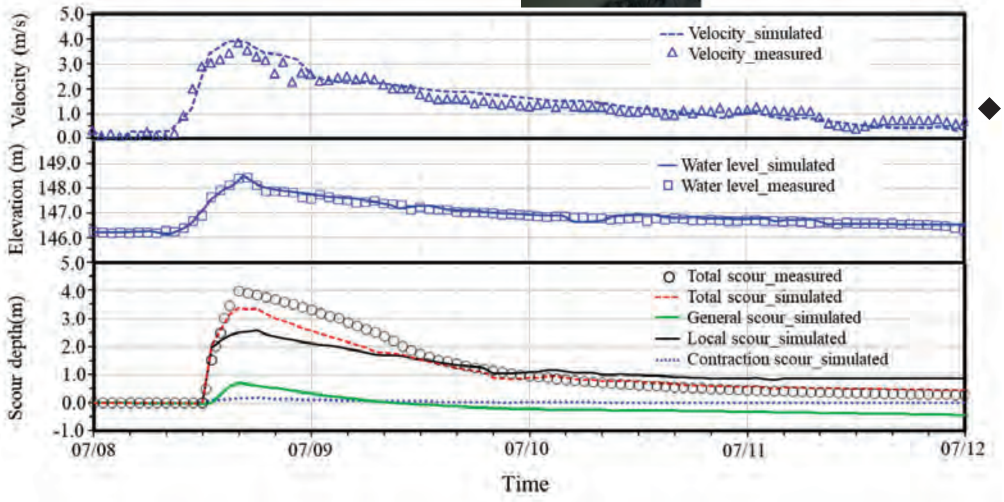






Results

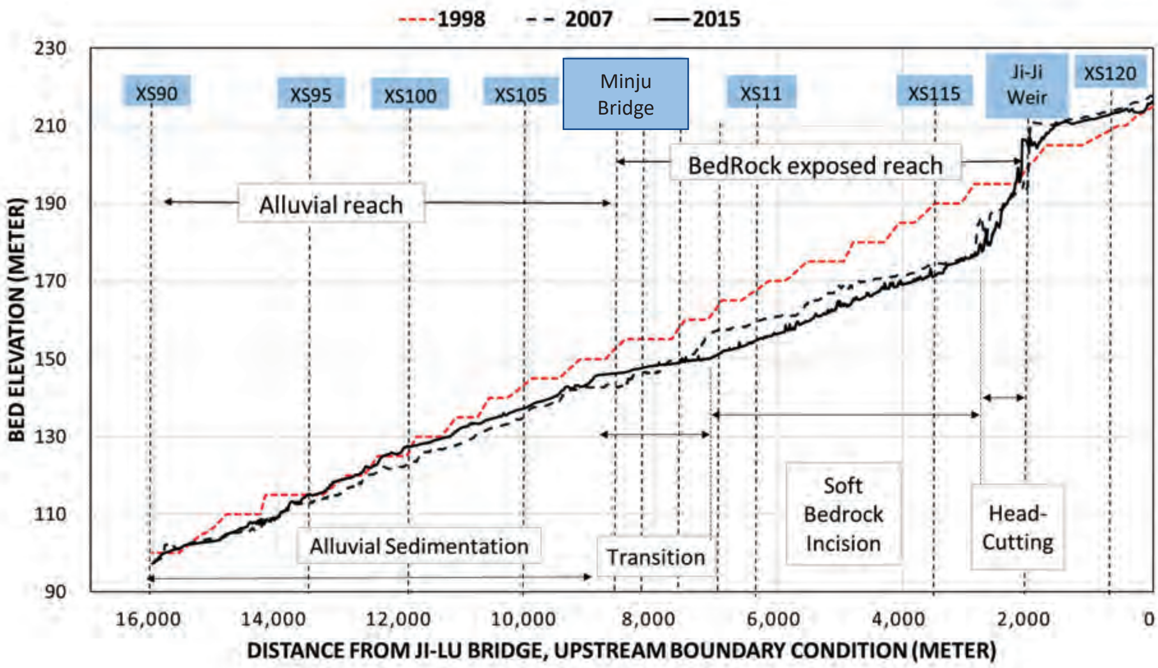
- Results display



- It seems that the depth of bridge pier scour is accompanied with hydrological patterns. It presents the hydrograph of field scour depth monitoring data and consists of the scour and deposition process during typhoon events.
- Based on the simulation results, Shen et al. (1966) is over estimated on the bridge pier scour depth and Forehlich (1991) is lower estimated on the bridge pier scour depth. Inglis(1949) and Jain and Fisher(1980) are relatively agree with the maximum scour depth estimation. However, the mechanism of deposition process cannot be simulated well by all equations.

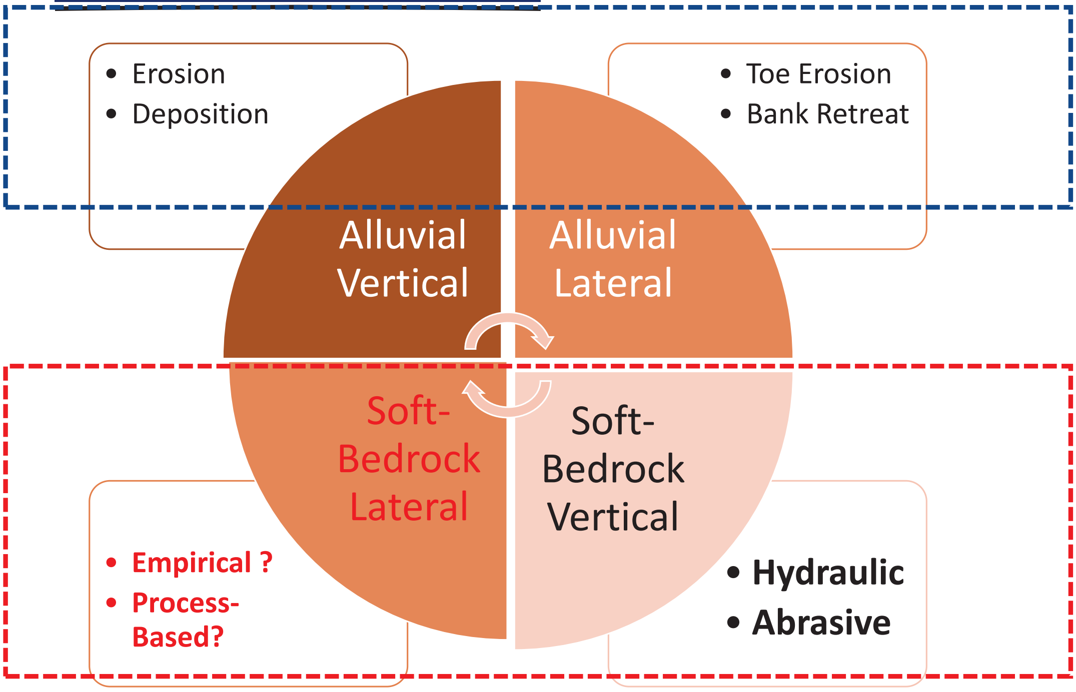
Study Area: Topic 2

Longitudinal Thalweg Evolution



Numerical Model

Model Capability



Modeling of soft bedrock channel evolution with a coupled modified bank stability and toe erosion model

Adopted Numerical Model

SRH-2D Governing Equations (Lai, et.al, 2010)

2D Depth-Averaged	St. Venant Equations

$$\frac{\partial h}{\partial t}+\frac{\partial hU}{\partial x}+\frac{\partial hV}{\partial y}=0$$

$$\frac{\partial hU}{\partial t}+\frac{\partial hUU}{\partial x}+\frac{\partial hVU}{\partial y}=\frac{\partial hT_{xx}}{\partial x}+\frac{\partial hT_{xy}}{\partial y}-gh\frac{\partial z}{\partial x}-\frac{\tau_{bx}}{\rho}$$

Total-Load Approach (Greimann, et. al, 2008)

Direction angle of sediment transport	*Transport mode parameter*	*Velocity ratio*	*Angle of the bed-shear stress*

$$\frac{\partial hC_k}{\partial t}+\frac{\partial \cos(\alpha_k)\beta_k V_t hC_k}{\partial x}+\frac{\partial \sin(\alpha_k)\beta_k V_t hC_k}{\partial y}=\frac{\partial}{\partial x}\left(hf_k D_x\frac{\partial C_k}{\partial x}\right)+\frac{\partial}{\partial y}\left(hf_k D_y\frac{\partial C_k}{\partial y}\right)+S_{e,k}$$

Bedrock Erosion Module (Lai, et.al, 2011)

Hydraulic scour	Abrasive scour

$$E=k_h V_t\left(\frac{\tau_b}{\tau_{ch}}-1\right)F_e+E_a$$

$$E_a=0.08k_a(\gamma-1)gq_s\left(\frac{\tau_b}{\tau_{ci}}-1\right)^{-0.5}\left[1-\left(\frac{u_*}{\omega_f}\right)^2\right]^{1.5}F_e$$

Kuowei Wu, K.C. Yeh and Yong Lai

Methodology

Bank Erosion Model

Alluvial Bank Erosion

- SRH-2D Prediction

Vertical Erosion

Basal Erosion

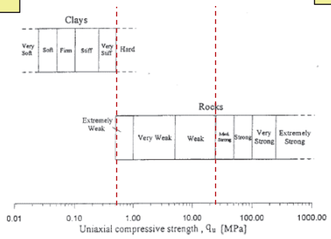
- Wetted Bank Face Lateral Erosion

- Linear Retreat Model

Bank Retreat

Bank Stability and Toe Erosion Model

(Johnston, 1993)



0.5-25 Mpa

Modified
Bank Stability and Toe Erosion Model

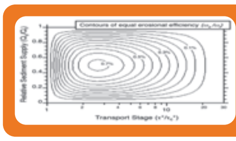
Methodology

Soft Bank Lateral Mechanism

Bank Erosion Model

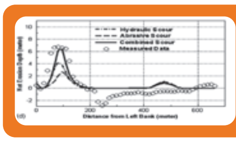
Soft Bedrock Stratum Orientation

- Strike and Dip Direction
- Flow Direction



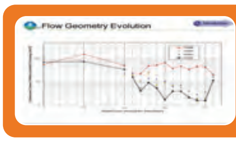
Sediment Supply and Sediment Transport Stage

- Maximum incision rates occur at moderate sediment supply rates



Abrasive Scour to Combined Scour Ratio

- Abrasive Scour dominate the uniform rock erosion zone
- Hydraulic Scour control the Head-Cutting Zone



Dimensionless Channel Width Limitation

- Bank-full Discharge
- Critical Dimensionless Channel Width

Methodology

Bank Erosion Model

Proposed Soft-Bedrock Lateral Erosion Model

$$\omega_v = \int E_c dt \qquad \omega_L = \int \varepsilon_L dt$$

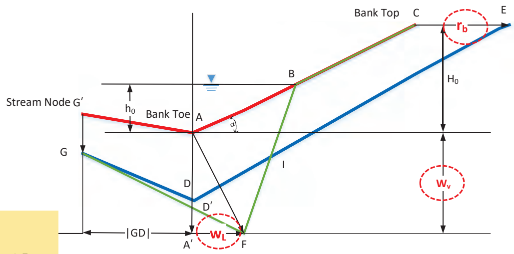
$$E_C = E_h + E_a$$

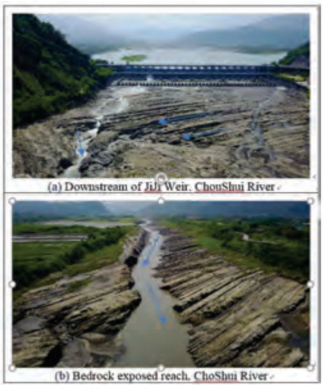
$$= k_h V_t \left(\frac{\tau_b}{\tau_{ch}} - 1\right) F_e + 0.08 k_a (\gamma - 1) g q_s \left(\frac{\tau_b}{\tau_{ci}} - 1\right)^{-0.5} \left[1 - \left(\frac{u_*}{\omega_f}\right)^2\right]^{1.5} F_e$$

$$\varepsilon_L = k_b(\tau / \tau_c - 1)$$

Where k_b = erodibility coefficient

$$r_B = 0.5 \frac{(h_0 + \omega_V)(\omega_L + \frac{\omega_V}{\tan\alpha}) + |GD|\omega_V}{(H_0 + \omega_V) + 0.5|GD|\tan\alpha}$$





(a) Downstream of JiJi Weir, ChouShui River

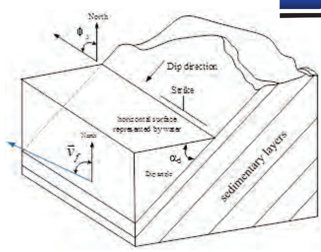
(b) Bedrock exposed reach, ChoShui River

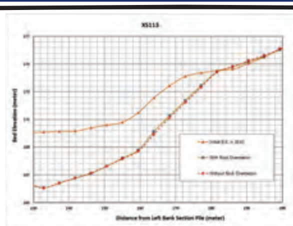
Methodology

Bank Erosion Model

Proposed Soft Bedrock Lateral Erosion Model

$$\varepsilon_L = k_b(\tau / \tau_c - 1)$$





Erodibility coefficient

Rock Stratum Orientation

Sediment Transport Stage

Dimensionless Channel width

$$k_b = A k_c \left[\left(\phi_s \bullet \vec{v}_f\right) \sin\alpha_d\right] [q_s / q_c]^\alpha \left[\tau^* / \tau_c^*\right]^\beta [E_a / E_c]^\gamma \phi_w$$

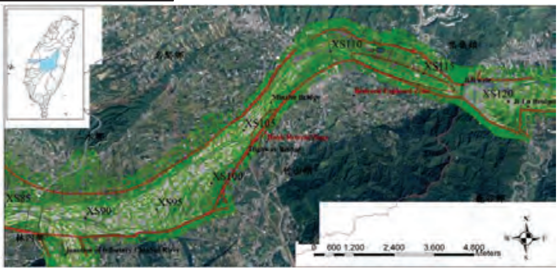
Sediment Supply Rate

Abrasive Scour to Combined Scour Ration

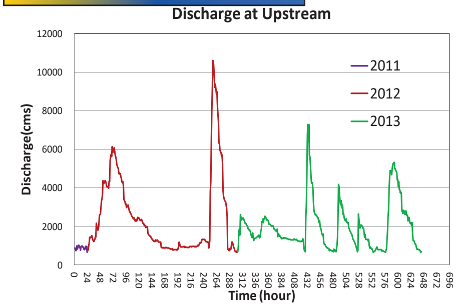
$$k_b = k_c A[E_a / E_c]^\gamma$$

Model Setup

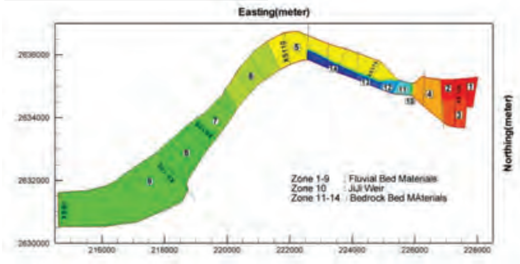
Topography



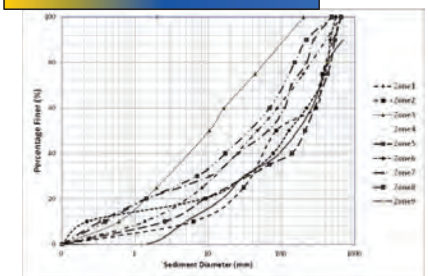
Boundary Condition



Bed Material Zone



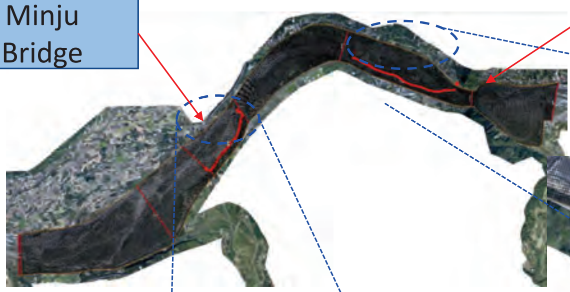
Grain Size Gradation



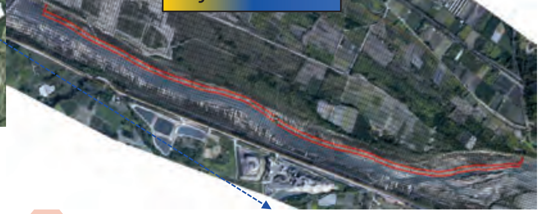
Bank Representation

Minju Bridge

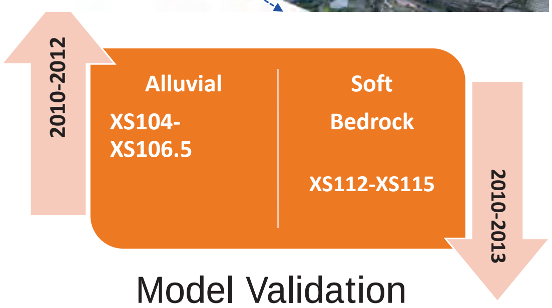
Ji-Ji Weir



Soft Bedrock



Alluvial



Model Validation

Model Parameters

III Model Application

Model Parameters (*1)	Sediment Transport Equation	Reference Shield No.	Manning Roughness	Adaptation Length(m)	Mixing Layer Thickness (m)
	WU (2000)	0.03	0.030～0.040	500	0.25
Alluvial Bank Parameters (*2)	Critical shear stress (Pa)	Erodibility coefficient (m s-1)	Angle of repose	Porosity	Saturated_ Weight (N/m3)
	2.0	5.0E-06	45	0.3	22,000
Soft Bedrock Bank Parameters (*3)	Critical shear stress (Pa)	Erodibility coefficient (m s-1)	Effective Cohesive (Pa)	Porosity	Saturated_ Weight (N/m3)
	450	1.6E-07	2000	0.3	2,2500
Bedrock Erosion Parameters (*1)	Nondimensional hydraulic erodibility	Abrasive erodibility parameter (ms^2/kg)	Critical shear stress for Hydraulic scour (Pa)	Young Modulus	Tensile Strength
	$k_h = 5.0\times10^{-7}$	225～900	$\tau_{cr} = 200$	$Y = 5.0\times10^{-4}$	$\sigma_t = 26.0$

◆**(*1)Model and Bedrock Properties**： Lai, Y.G., Greimann, B.P. and Wu, K. (2011)

◆**(*2) Alluvial Bank Properties**： Yong G. Lai and Kuowei Wu (2014)

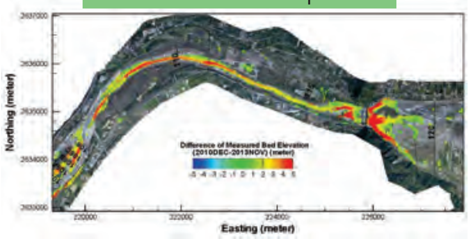
◆**(*3) Soft Bedrock Bank Properties**：Test and Validated in this study

Results

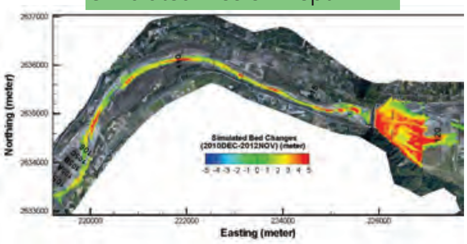
III Model Application

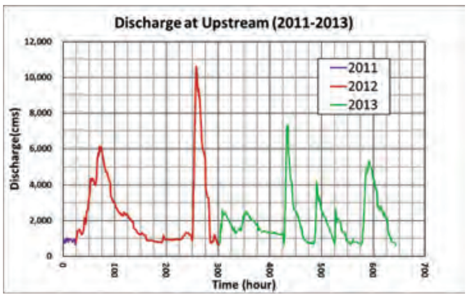
1. Erosion Depth in 2013

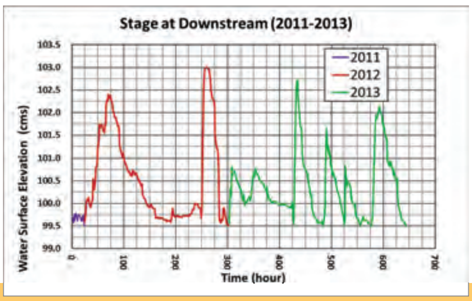
Measured Erosion Depth



Simulated Erosion Depth



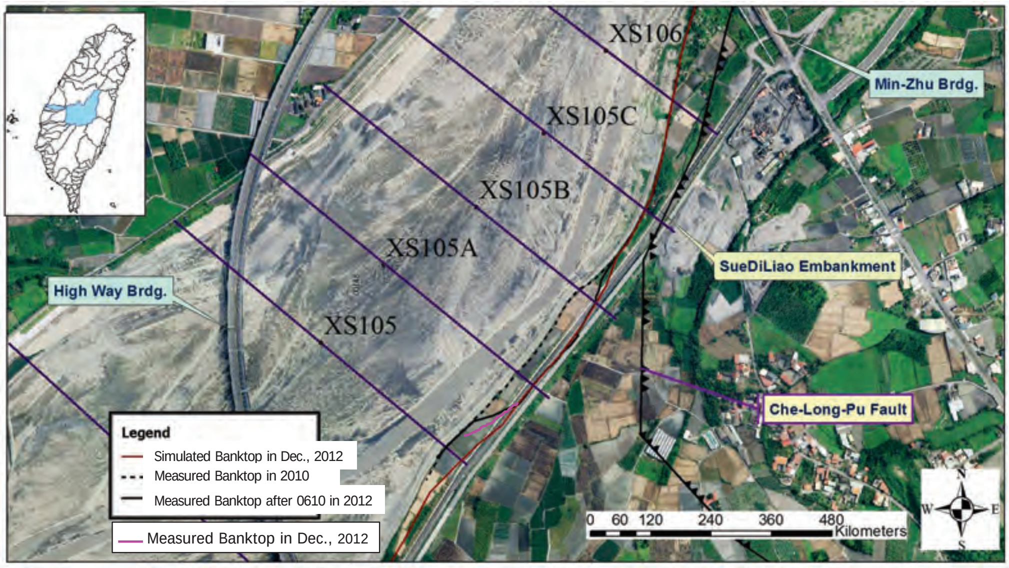




Results

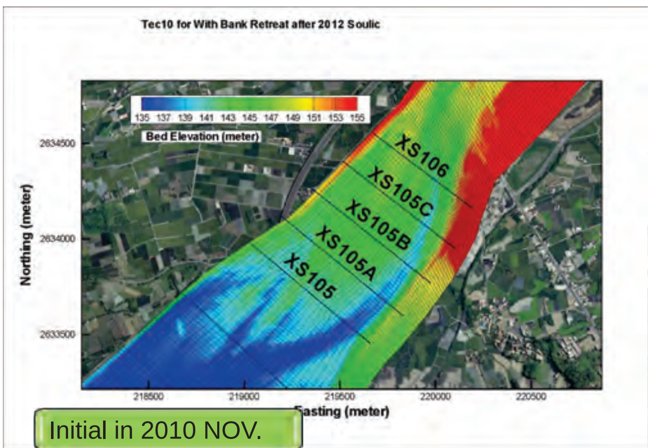
2. Alluvial Bank Erosion

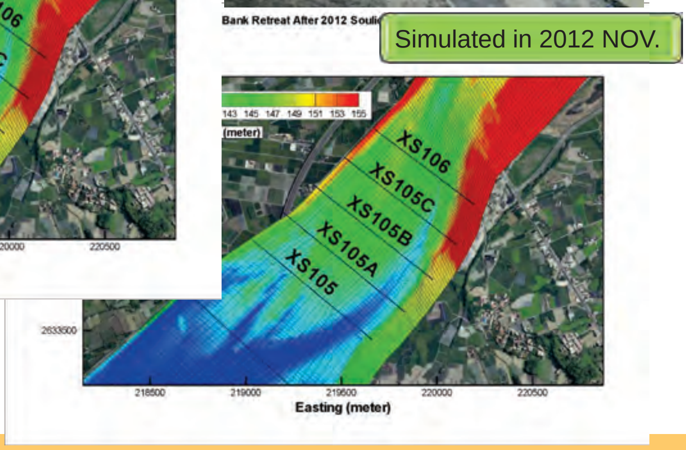
III Model Application



Results

2. Alluvial Bank Erosion

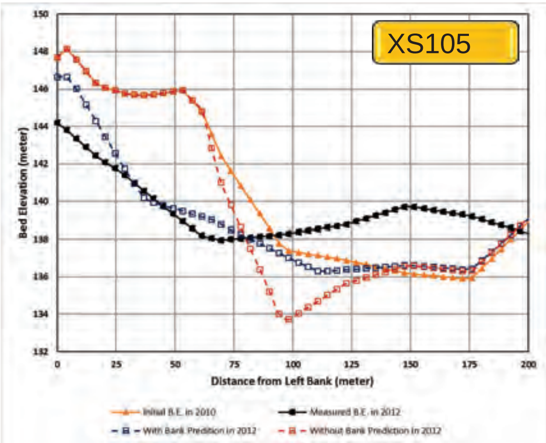




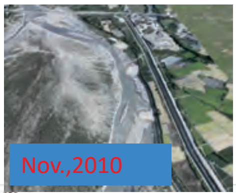
Results

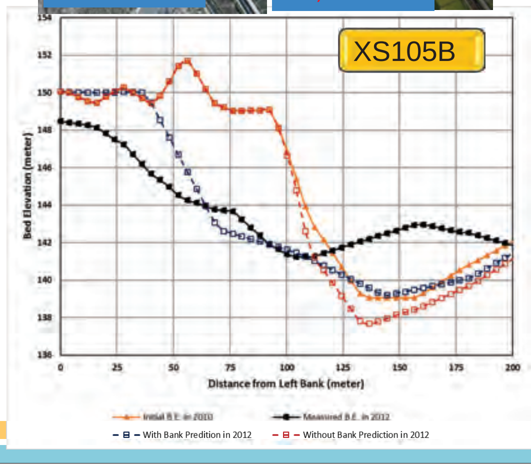
2. Alluvial Bank Erosion

With and Without Bank Retreat



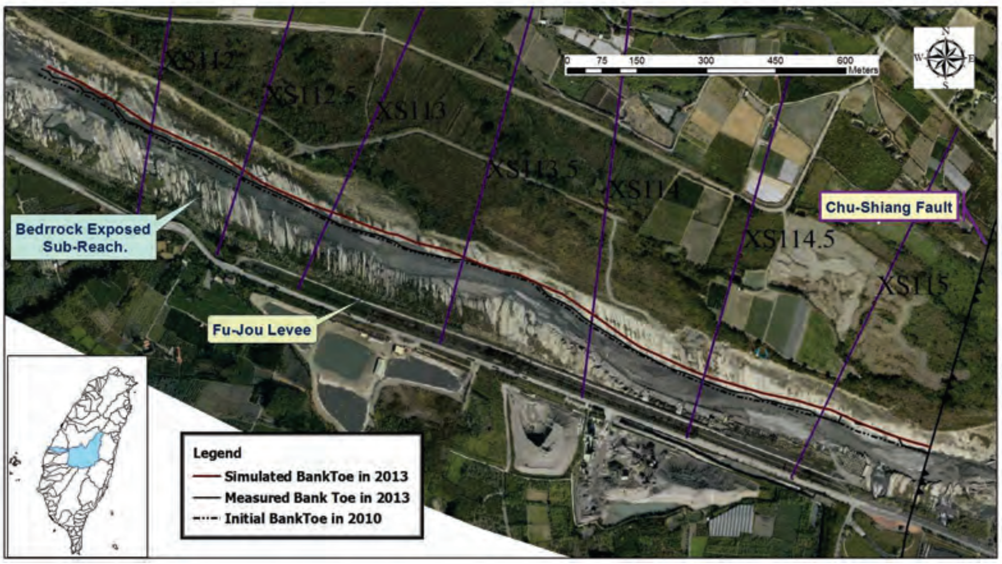
XS Comparison





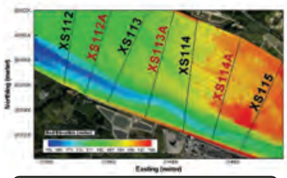
Results

3. Soft Bedrock Lateral Erosion

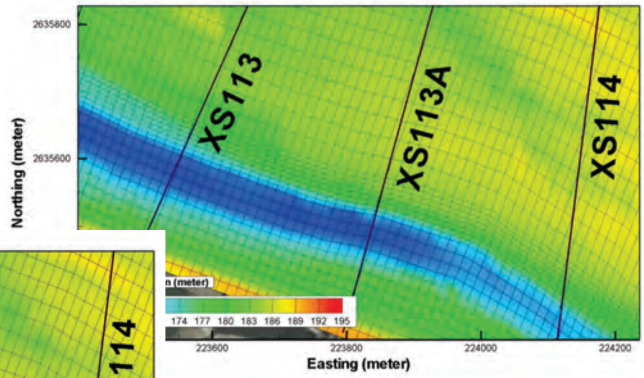


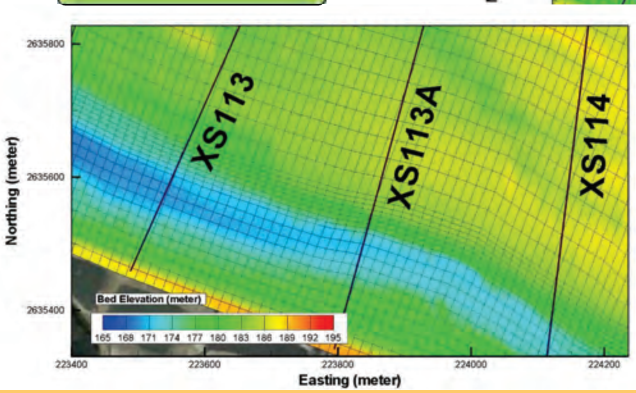
Results

3. Soft Bedrock Lateral Erosion

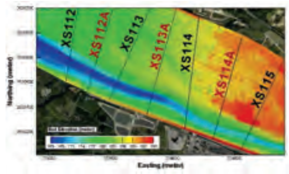


Initial in 2010 NOV.





Simulated in 2013 NOV.



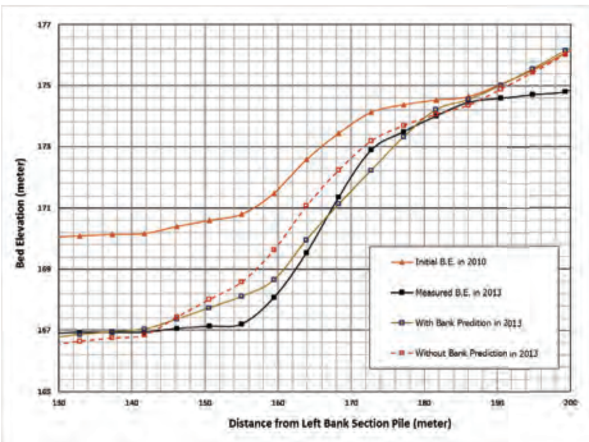
Results

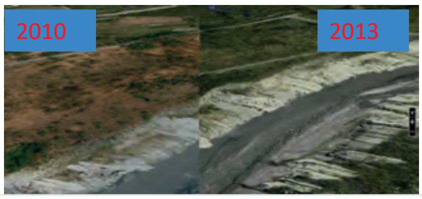
3. Soft Bedrock Lateral Erosion

XS Comparison

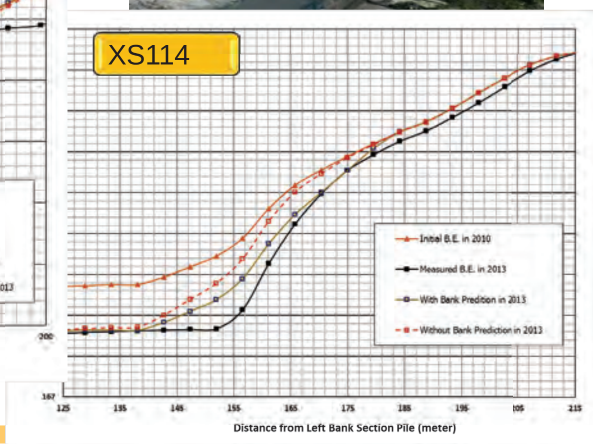
With and Without Bank Retreat

XS113





XS114



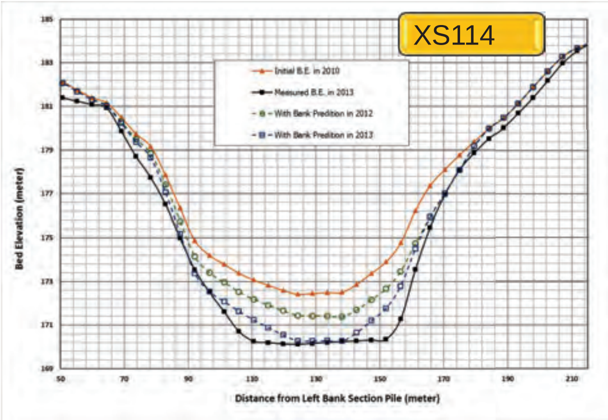
Results

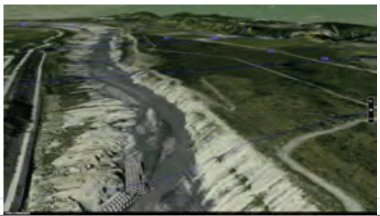
3. Soft Bedrock Lateral Erosion

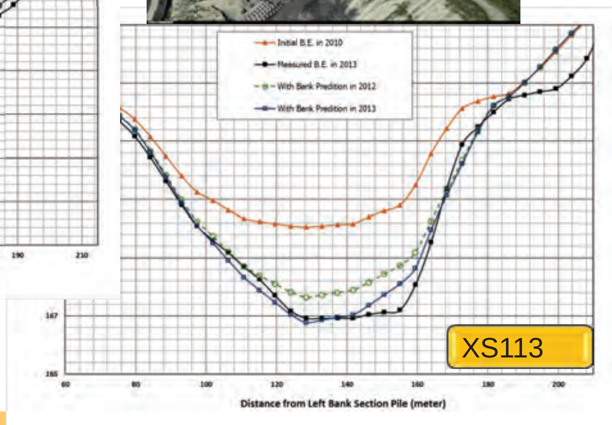
XS Comparison

With Bank Retreat

XS114







XS113

Conclusions

Soft Bedrock Channel Evolution	• The lateral erosion rate of soft bedrock is relative smaller than alluvial one, which imply the channel widening of soft bedrock takes longer time scale.
Bank Erosion Modeling	• The proposed model could capture the bank retreat timing and distance well in both alluvial and bedrock channel.
Model Refinement	The under prediction of bank erosion in the lower part of soft bedrock bank profile points to the need for further refinement.

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