Managed River Realignment as a Nature Based Solution

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Deltares
Enabling Delta Life

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Abstract

The Philippines is currently trying to implement viable flood control infrastructure projects to protect its citizens that reside in urbanized areas of estuaries. Recent directives from developmental agencies call for approaches to serve this function without compromising ecosystem services. This study explores the possible methods of managed river realignment as a Nature Based Solution to storm surge events and how this might perform in the face of climate change driven sea level rise. The data gathered for this study was obtained from multiple sources including remote sensing techniques for 5 separate rivers within the Philippines. Using a morphology estimator tool combined with a 1D-hydrodynamic model it was found that widening the mouth of an estuary has the capabilities of effectively dampening inland tidal amplitude associated with storm surge disturbance events. From the analysis of the results it shows a promising river management solution to flood mitigation associated with storm surge events for urbanized areas residing within estuaries.

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List of Abbreviations

ADB	Asian Development Bank
DREAM	Disaster Risk and Assessment for Mitigation
Eco-DRR	Ecological Disaster Risk Reduction
FRM	Flood Risk Management
IPCC	Intergovernmental Panel for Climate Change
IUCN	International Union for Conservation of Nature
IWMI	International Water Management Institute
IWRM	Integrated Water Resource Management
NBS	Nature Based Solutions
MR	Managed Realignment
NWRB	National Water Resources Board
PAGASA	Philippine Atmospheric, Geophysical and Astronomical Services Administration
PRECIS	Providing Regional Climates for Impact Studies
RCP	Representative Concentration Path
SDGs	Sustainable Development Goals
UN DRR	United Nations Disaster Risk Reduction

1. Introduction

The most common natural disaster event occurring worldwide is flooding, accounting for 43% of all proclaimed disasters (Ahern, Kovats, Wilkinson, Few & Matthies, 2005). According to the United Nations Disaster Risk Reduction (UN DRR) center for disease and epidemiology team there were over 3,062 flood related disaster events between 1995-2015. Storms are considered the second most frequently occurring disturbance event, and when combined with flooding they encompass 70% of all-natural disasters that occurred in this time period. With future climate change likely altering precipitation patterns and creating sea level rise, the intensity and frequency of floods is expected to increase (Ahern et al., 2005). Coastal flood events have been highly fatal in the past and are felt acutely in urban areas, with 22 out 32 of the world's largest cities located in estuaries (National Ocean Service, n.d.). Globally, countries are struggling with climate change pressures, creating adequate urban infrastructures, and ever-increasing rates of urbanization (Johns, 2019). Therefore, the need to channel capital into development programs based on sustainable river and coastal management is imperative. Traditional or "grey" infrastructural projects manage the dangers of flooding events often at the expense of ecological services. Therefore, it would be beneficial to shift resources to "green" river management practices that can address both issues efficiently.

The United Nations projects that the global population is expected to increase by 2 billion, up to 9.7 billion altogether by 2050 (U.N., 2019). Specifically, over two thirds will be in urban areas with 90% of the future growth expected to be concentrated in Asia and Africa (U.N. DESA, 2018). The need to strengthen communities resilience to shocks and stresses within the water sector has been highlighted within serious debates regarding policy changes and questioning why past responses have not been adequate when dealing with water-related crisis linked to the global cycle of flood and droughts (Head, 2014). Although sustainable river management has been underscored as the main intent of various institutions and agencies, it has remained difficult to realize due to over-extended political rhetoric with regards to practical water management (Clark, 2002). The most important considerations are the management and identification of major risks along the river. However, this has to be done while maintaining a balance of expert advice with social public perceptions to the problems being encountered with river management. This requires a greater degree of cultural change in the approach to water resource management and developing integrated long-term strategies that benefit human activities. These activities should also be developed without degradation to the surrounding natural environment (Head, 2014). With these challenges in mind, the shift from the previous grey water management strategies should target green strategies.

Most of the established, engineered infrastructure systems that form the backbone of water systems globally are referred to as "grey infrastructure". However, most of the previously established grey infrastructural projects have become antiquated and face serious maintenance costs and capacity issues (Johns, 2019). There has been a growing consensus among natural resource experts that global jurisdictions need to shift from grey to green infrastructure projects because of the environment, sustainable and economic benefits that green infrastructure can provide (Johns, 2019). Green infrastructure, although a broad concept, has emerged as an approach from research gathered from ecological infrastructure projects, sustainable infrastructure and ecosystem engineering projects. The U.S. Environmental Protection Agency Clean Water Act defined green infrastructure projects as; "The use of vegetation, soils, and other elements and practices to restore some of the natural processes required to manage water and create healthier urban environments" (Clean Water Act, Section 502). For example, two hamlets within the Vietnamese Mekong Delta, Ha Bao and Vinh An, have been highlighted as examples of gaining ecological benefits from allowing regular flooding away from urbanized hotspots (Liao, Le & Van Nguyen, 2016). Green infrastructure is essentially a management approach and use of technologies that can utilize, enhance or mimic the natural hydrological cycle processes of infiltration, reuse, and evapotranspiration (U.S. EPA, n.d.). Commonly applied examples have included riparian buffers, floodplain enhancement, permeable pavements, living shorelines, pocket wetlands and infiltration planters (U.S. EPA, 2008). Recently, four separate projects using green infrastructure in the form of “living shorelines” have been implemented successfully in coastal areas of the United States in the locations of Grand Bay, Graveline Bay, Back Bay and St. Louis Bay, Mississippi (Westerholm, 2015). Using the living shoreline approach, natural materials were used to create multiple breakwaters to decrease shoreline erosion rates by dampening wave energy while simultaneously encouraging reestablishment of habitat that had been lost in the region (Westerholm, 2015). The project also had a secondary impact of encouraging the development of natural reefs that complement the productivity of these living shorelines.

Given the importance of green infrastructure, this study will focus on the impacts of implementing a green structural strategy in 6 different river basins in the Philippines. Specifically, emphasis will be put on downstream environments of the river basins. This is due to the fact that several of these river basins have experienced heavy rates of urbanization in the delta areas, and also that they experience acutely compounded risks from pluvial, fluvial and coastal flood events. Several green infrastructure projects focus on restoring the infiltration of rainfall into soil by using soak ways and setting up semi-pervious ecologically engineered structures that can retard flows from storm events (Culwick, Christina et al., 2019). Within Europe Managed Realignment (MR), the process of removing some flood protection and allowing a larger flood way, has become a more prevalent approach (Esteeves, 2013). When created in an area with salt marshes, MR can achieve multiple aims such as improving flood risk management and more affordable coastal defense creation (Esteeves, 2013). Taking this concept one step further in the pursuit of greater flood protection could involve widening the flood mouth of an estuary area. Recent research has shown that flood risk might be mitigated by widening the mouths of small estuaries (Leuven, Pierik, van der Vegt, Bouma & Kleinhans, 2019). Therefore, widening the mouth of small estuary could be a potential viable green minimal intervention strategy that could alleviate risk in some urban hotspots. Due to this possibility, this study aims to explore MR as a possible green infrastructural strategy that can be implemented in river basins to decrease the risk of flooding in urbanized estuary areas using the same technique.

2. Theoretical Framework

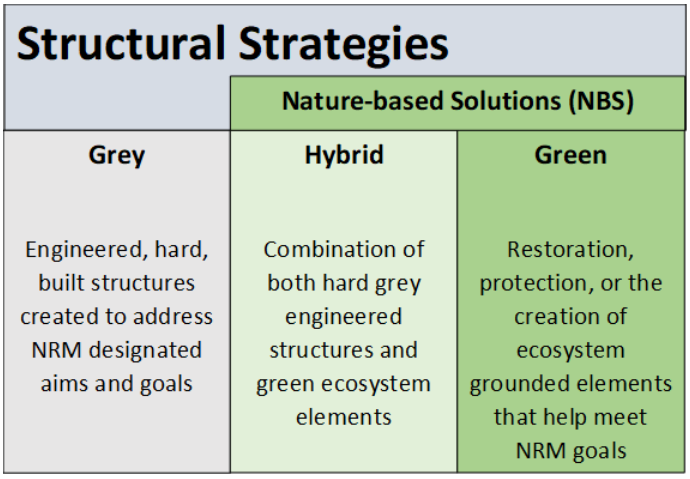
To explore the possible solutions to flood risk in urbanized estuary areas several concepts will be introduced and defined in the context of this paper. Nature Based Solutions and their role in ecosystem management, Integrated Water Resource Management, Flood Risk Management, Ecosystem Services, delta formation and climate change and their significance in ecosystem management will be explored. It is important to note that these are broad and complex concepts and exploring them fully is outside of the scope of this study. Therefore, only the most relevant information will be explained that is essential to this study.

2.1. Nature Based Solutions as Defined in This Study

Within the past quarter century, the active management of natural resources, while increasing biodiversity and sustaining a healthy ecosystem, has become more important in project proposals (Neßhöver, Prip & Wittmer, 2015). This is ultimately due to perspectives changing in how important an ecosystem's function is through the services they provide, and for the wellbeing of local communities (Dedeurwaerdere et al., 2016). The most current modification in perceptions concerning Natural Resource Management (NRM) have highlighted the concept of using natural systems as a solution itself to disaster event mitigation (Cohen-Shacham, Walters, Janzen & Maginnis, 2016). Nature Based Solutions (NBS) can be used as an alternative to hard grey water management infrastructure projects, mitigating environmental hazard impacts effectively, while not compromising the available ecosystem services offered from natural areas (See Fig. 1). Previously NBS were not widely adopted, this was due to an uncertainty regarding their hydrologic performance or fear of a lack of public acceptability, however this has changed (Thorne, Lawson, Ozawa, Hamlin & Smith, 2018). Broad themes have been defined for the purpose of NBS green infrastructure projects highlighting the benefits to environmental planning for societies (Lafortezza, Raffaele et al., 2018):

- Enhancing sustainable urbanization
- Restoring degraded ecosystems
- Developing climate change adaptation and mitigation
- Improving risk management and resilience

This is a grouping of solutions that incorporates conservation, restoration and the sustainable management of areas to maximize the promotion of useful ecosystem services. These services are then used to address issues associated with climate change and natural disasters (UN DRR, 2007). The International Union for Conservation of Nature (IUCN) has also defined NBS as; "Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." It has been highlighted in previous studies that NBS can dramatically increase community's resiliency to disturbance events and help the recovery of their respective essential income generating activities (Rizvi, Baig & Verdone, 2015).



Structural Strategies		
	Nature-based Solutions (NBS)	
Grey	**Hybrid**	**Green**
Engineered, hard, built structures created to address NRM designated aims and goals	Combination of both hard grey engineered structures and green ecosystem elements	Restoration, protection, or the creation of ecosystem grounded elements that help meet NRM goals

Figure 1: Visual of Possible Structural Strategies (Adapted from Schoonees et al., 2019)

2.2. Integrated Water Resource Management

Water is necessary for life, societies, economies and natural systems to flourish. Ancient settlement patterns often can be traced along the banks of rivers and estuaries to capitalize on the valuable services these areas provided (Macklin & Lewin, 2015). Rivers systems are responsible for providing fisheries, navigation means and fresh water supply. Although ecosystems are founding features of human settlement, urbanization in the industrial era often leads to the degradation of these ecosystems to the point that they no longer provide the services for which the settlement initially developed (Everard & Moggridge, 2012). Due to the abundant resources that are provided from water bodies and the multiple societal functions that are involved with their use, it is extremely complicated to create comprehensive management plans. It is often the case that demands on riverine resources exceed the sustainable capabilities of the natural system resulting in pollution, land degradation and over-extraction (Everard & Moggridge, 2012). The failures associated with unsustainable practices are often the direct consequence of poor managerial practices, and inadequate prior use planning (Rosegrant, Cai & Cline, 2002). The generally accepted definition of Integrated Water Resource Management (IWRM) is that “IWRM is a process which promotes the coordinated development and management of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (Green, 2000). This has become important with the global effects of climate change projected to increase the frequency and intensity of disturbance events affecting coastal urban communities and it will be this definition that methods will be evaluated in this study .

2.3. Flood Risk Management

Flood events cause damage to local infrastructure and property and can cause high rates of mortality. Survivors of major flood disasters can be left not just physically damaged, but also negatively impacted psychologically (Bonanno, Brewin, Kaniasty & La Greca, 2010). Flooding can also undermine ecological conservation efforts and disturb sites associated with cultural significance. It is through this lens that Flood Risk Management (FRM) is applied to help mitigate the undesirable impacts of these events in the most competent manner possible (See Fig. 2). FRM has differentiated itself from traditional flood defense strategies by using multiple approaches that manage risk. Strategies that are included in FRM planning involve:

- Reduction of the source of risk activities (i.e. sustainable upstream land management)
- Management and construction of appropriate site-specific flood defenses
- Mapping high flood risk zones and implementing early warning systems

However, it should be stated that these strategies are subject to manipulation on a regional/local basis associated with what residential stake holders find tolerable. FRM planning should only be implemented when it actively promotes services that are regionally valued.

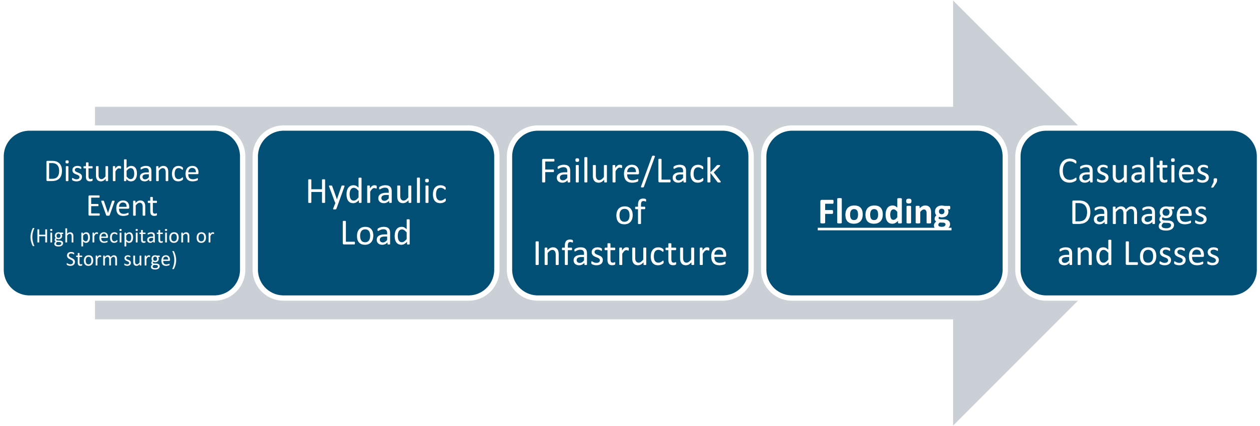


Figure 2: Reviewing the Phases of Flood Events to Ascertain Approaches to Mitigate Risk

2.4. Beneficial Ecosystem Services to Urbanized Areas

Society benefits from a cornucopia of services rendered from ecosystems. This includes, but isn't limited to, the procurement of food and water and regulation of disturbances such as floods, land degradation and droughts. Normal and extreme weather event flow regimes are also impacted by local vegetation and their respective settlement patterns (Stohlgren, Chase, Pielke & Baron, 1998). Local ecosystem vegetation can also have a measurable impact on the dispersal of tidal energy and wave attenuation (Narayan et al., 2016; Paul, Bouma & Amos, 2012). Likewise, nutrient cycling and soil formation/deposition are also services that can be provided by local functioning ecosystems (Reid et al., 2005). It is important to note that ecosystems are essential in regulating meteorological and hydrological processes and the effects they have on storm surge and flood events can be positive. These positive effects are necessary for the safety of urban areas that have been built in delta and estuarine areas. One example of NBS working successfully using beneficial coastal ecosystem services was highlighted in Odisha, India on the 29th of October 1999. In rice croplands protected with low-density mangrove buffers, the productivity rates recovered three years quicker from a cyclone disturbance event than fields lacking the same nature-based protection measures (Rizvi et al., 2015). This evidence of NBS aiding resiliency is also echoed anecdotally from the town of "General MacArthur" in Eastern Samar province, Philippines. At this location, residents claim they were spared from the destruction of Super Typhoon Haiyan due to a naturally occurring shelter barrier island forested with mangroves (Seriño et al., 2017).

2.5. Delta Formation Hydrodynamic Processes

Natural delta formation is largely driven by sediment dynamics and fluvial dispersal. Deltas are triangular deposits of sediments from fluvial systems that are then shaped by coastal dynamics such as waves, currents and tides. However, every delta area is unique, with many delta systems throughout the world currently suffering from a sediment deficit (Batalla, 2003). This deficit can largely be attributed to development in upstream locations from the delta, in the form of water management infrastructure, agricultural projects and sediment mining (Batalla, 2003). Without natural flooding occurring in the delta region, sediment deposition dramatically decreases (Syvitski, Vörösmarty, Kettner & Green 2005). Without flood control measures, damage to essential infrastructure and mortality rates may increase. However, without flooding the benefits of the event and associated ecosystem services are also lost. Consequently, FRM infrastructure projects and planning should be carried out in a way that sufficiently protects urban areas without negatively impacting the natural dynamic nature of estuarine and delta areas.

2.6. Climate Change and Its Relation to Different Regional Areas

Complications associated with the effects of climate change compounded with poor or unenforced managerial practices of surrounded ecosystems can cause a sharp increase in risks impacting local populations. Currently the global mean temperature has been projected to rise at least 1.5-2 °C by 2050, which will have dramatic impacts globally with regional variations (Jevrejeva et al., 2018). Effects and impacts of climate change can be viewed in multiple contexts on societies including environmental, social and economic. Additionally, the effects of climate change are not experienced equally amongst social structures in society, with marginalized groups often bearing the brunt of the most dramatic damages (poor, indigenous groups, elderly, women and children). This effect is also most acutely felt in disaster events with marginalized groups taking the longest to recover to pre-disaster conditions (Tierney & Oliver-Smith, 2012).

Although there have been global efforts to reduce the impacts of climate change by the creation of the Sustainable Development Goals (SDG's) by the United Nations, and several international treaties pledging to reduce greenhouse gas emissions, there is still much to be accomplished. To what extent climate change will affect local communities specifically, varies regionally (Wilbanks & Kates, 1999). The precise regional effects are also still debated and not completely covered by current climate models and projections (Meehl, Zwiers, Knutson, Mearns & Whetton 2000). It is important to mitigate the impacts of climate change at a local and regional level, by focusing on reversing environmental degradation and restoring ecological services that are being provided by local natural resources (Watson et al., 2000). Following this policy of mitigation, it has become essential to focus on adaptation-oriented strategies in order to increase the capacity of local ecosystems and societal resiliency. Without holistic policies addressing the impacts of climate change in urban developments in estuary areas, ecosystem services provided in this area could become compromised. It is important to focus on what unique issues may arise for specific regions and watersheds in different study areas.

3. Research Questions

Based on the understanding of available flood mitigation strategies, the effectiveness of widening the flood plains in river basins will be studied on model areas in the Philippines. The Philippines is a fast-developing country with several urban areas currently emerging in river floodplains. This offers the unique situation of being able to mitigate risks using green infrastructural projects proactively rather than retroactively. As mentioned earlier, this study aims to explore MR as a possible green infrastructural strategy that can be implemented in river basins to decrease the risk of flooding in urbanized estuary areas using the same technique. This will be studied through directives set by the Asian Development Bank (ADB) for further development projects in the Philippines. In order to look into these matters and address knowledge gaps, the following research question and sub questions were stated:

Research Question: *What is the impact of widening the floodplains of 6 river basins in the Philippines, (i.e the Buayan-Malungon, Jalaur, Apayo-Abulug, Abra, Ranao, and Tagum-Libuganon river basins) regarding mitigating flood risk?*

Sub-Question 1**:** *What is the effect of narrowing the floodplain of the 6 rivers overall in the face of storm surge mitigation?*

Sub-Question 2**:** *How effective is widening the mouth of the floodplain under sea level rise scenarios from climate change projections in the next 100 years?*

4. Focus Study Area

4.1. The Philippines

The Philippine archipelago resides in the Philippine Sea and the South China Sea directly due east of Vietnam. The total land area of the Philippines is 298,170 km^2, with 36,289 km of coastline maintaining a tropical marine climate that experiences two distinct monsoon events annually, the Northeast (November-April) and Southwest (May- October). The geomorphology of the Philippines is very diverse and varied including montane environments, interior valleys and coastal plains and tropical forested areas. There are 343 principal river basins which occupy 66.5% of the area of the Philippines (Baig, 2016). The Philippines is experiencing a period of extremely rapid development and population increase. With large public infrastructure projects underway coupled with market liberalization and tax reforms, the pace of this development is only projected to increase in the next decade (International Monetary Fund, 2019).

Increasing rates in urbanization driven by this growth in conjunction with new land-use patterns, have had a strong impact on flood magnitude and the associated hazard risk due to the proximity of settlements in floodplains. The ADB has focused on hotspot areas (areas of settlement or critical infrastructure that would be adversely effected during a disturbance event), with minimal intervention and a preference for green infrastructure strategies (NBS) to mitigate flood risk from storm surge. With that in mind, 6 river basins have been identified that are spread across three islands (Mindanao, Panay and Luzon) as highly prioritized areas to reduce flood risk associated with fluvial flooding, and storm surge disturbance/disaster events (See Fig. 3). Proposals for comprehensive flood risk management plans have been created by the ADB with the aim of increasing resilience to the communities most adversely affected from pervious disaster events. The overall aim for the region is to focus on measures that strike a balance between structural and non-structural to create efficient solutions in relation to the uncertainty of projected future climate change scenarios.

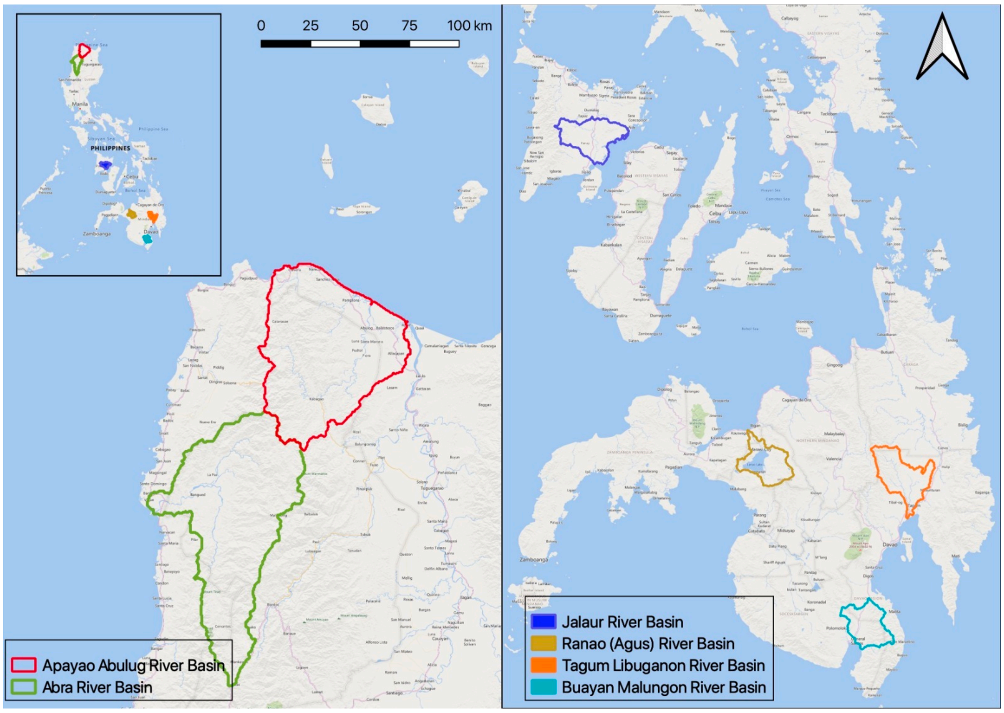


Figure 3: Locations of Targeted River Basins

Not all the watersheds are densely populated, however, the largest clusters of settlement tend to be directly adjacent to the rivers for various reasons. Especially of note are the agriculturalist and populations that are often located in the most precarious flood prone areas, either in pursuit of easily accessible irrigation or fertile soils (See Fig. 4).

Figure 4: Locations of Aquaculture Ponds and Agricultural Fields Adjacent to Estuary Area of the Jalaur River, Philippines

4.1.1. Philippines: Current Impacts of Climate Change

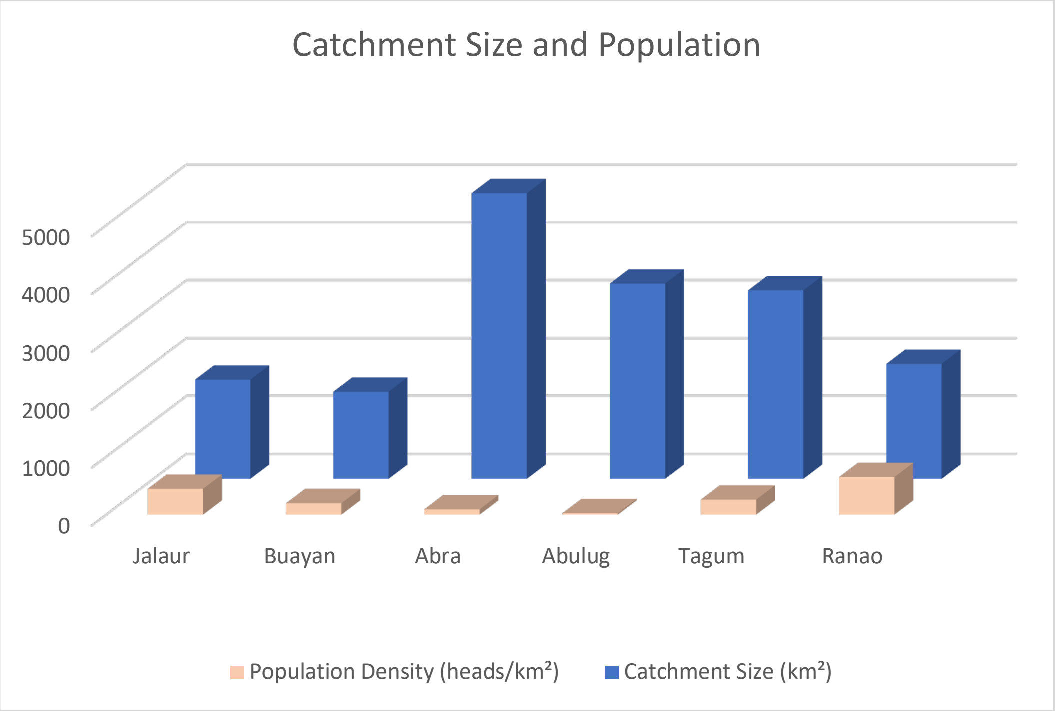
Current climate projections for the Philippines from 2020-2050 have been created by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). Using the current climate projections from the Providing Regional Climates for Impacts Studies (PRECIS) model, it is claimed that mean annual temperatures will increase regionally by up to 2.2 °C in 2050 (PAGASA, 2011). The frequency of days that are categorized as exhibiting extreme temperatures are projected to increase (Easterling, 2000). With regards to precipitation data, the effects are more varied regionally with some areas projected to receive increasing amounts of rainfall and others receiving a deficit from previous normal base line years (PAGASA, 2011). Specifically, the North-Eastern monsoon season is expected to bring increased amounts of precipitation to the provinces of Luzon and Visayas, which will increase the possibility of flooding events in river basins. This compounded with sea level rise being projected from 50 cm in 2030 up to 100 cm in 2060 and an increase in typhoon occurrences could have a drastic impact on the local communities residing in these basin areas (PAGASA, 2011).

4.1.2. Philippine Water Management Board

The Philippine national government established the National Water Resources Board (NWRB) in 1974, to facilitate better holistic management of water resources for different projects and purposes. However, the lack of sufficient river basin data collected from field work and contradictory department mandates led this organization’s progress to be hindered. Although several “field offices” have now opened in different regional capitols there are still issues with interregional coordination in river basin use priorities and the facilitation of data collection. Recently there has been a large interest in the NWRB for interregional cooperation regarding river basins and to start focusing on NBS for solutions to mitigate the grave impacts of climate change and repairing the water cycle (Ferrer, 2018). Specifically measures like reforestation, reconnecting rivers to floodplains and restoring wetlands have been highlighted by some provincial leaders as desirable solutions (Ferrer, 2018).

4.2. Study Area Sites

Each river basin listed below has their own unique characteristics and individual concerns. The geomorphology of the surrounding landscape, population, environmental stresses to their respective area will be explored to gain a better insight on what the major influence is for each individual basin. To evaluate the most appropriate measures for each individual systems estuary, a comprehensive understanding of each will be required.



Graph 1: Basin Catchment Size Relative to Population Density (Adapted from Asian Development Bank, 2019)

🔴 Extreme Stress
🟡 Stressed
🟢 No Stress

	Flooding	Drought	Erosion	Deforestation
Jalaur	🔴	🟢	🔴	🟡
Buayan	🔴	🟡	🔴	🟡
Abra	🟡	🟢	🔴	🟡
Abulug	🔴	🟡	🔴	🟡
Tagum	🟡	🟢	🟡	🟡
Ranao	🟡	🟢	🔴	🟡

Figure 5: List of Studied Philippine River Basins and the Issues of Experienced Stress (Adapted from Asian Development Bank, 2019)

4.2.1. Buayan-Malungon River Basin

The Buayan-Malungon river basin (here forward referred to as just Buayan) is classified as a sub-basin of Mindanao river basin with an area of 1505.1 km^2 located in the Central and Southern regions of Mindanao (See Graph 1). From the head waters of the up in Mt. Matutum it drains into the Sarangani Bay. The highest average temperature reading is recorded at 32.9 °C with a recorded lowest average at 22.82 °C. With only one rainfall station on the Buayan river recording data, the General Santos measuring station records an annual approximated average of 80 mm of precipitation a month. With the Koppen classification system the Buayan river basin is classified as an Af climate or "tropical wet climate", with the average driest month of 51.4 mm of precipitation (Asian Development Bank, 2019).

4.2.2. Jalaur River Basin

The Jalaur river basin is predominately located in the province of Iloilo with a small section lying in the province of Antique and Capiz. The entire river basin is found on the southern end of Panay Island. The entire basin covers a total land area of 1714 km^2 although the entire basins boundaries are sometimes contested with 214 km^2 of adjacent watershed should be added into consideration (See Graph 1 (Asian Development Bank, 2019). The Jalaur River is approximately 124 km in length and the second largest river on Panay island. The Jalaur river also experiences a regular stress of flooding events (See Fig. 6).

4.2.3. Abulug River Basin

The Apayao-Abulug river basin (here forward referred to as just Abulug) is situated in the northern area of Luzon Island within the provinces of Apayao and Cagayan and is the sixth overall largest river system in the Philippines (In terms of watershed size) (Asian Development Bank, 2019). It resides between $18^o\ 21'$to $17^o\ 51'$ North Latitude and between $120^o\ 58'$ to $121^o\ 29'$ East Longitude. The total basin area is estimated to be 3,375 km^2 with an overall length of 175 km from the headwaters located in the Kalinga mountains within the Cordillera Administrative Region (See Graph 1). Over 84% of the river basin resides in Apayao province with the northernmost area and delta residing in the Cagayan province (Asian Development Bank, 2019).

4.2.4. Abra River Basin

The Abra river basin covers a total area of 4,936 km^2, making it the largest river basin that will be considered in this study of the Philippines (See Graph 1). The major tributary of the Abra river (the Tineg River) drains an area of 1,555 km^2, and maintains an overall combined drainage area of 3,381 km^2(Asian Development Bank, 2019). The total length of the river is over 208 km and extends into the two regions of Northern Luzon and the Cordillera Administrative Region. The Abra river also extends into four provinces overall, the Ilocos Sur, Abra, Beguet and Mountain province of the Cordillera Administrative Region. This river basin is also highly populated with a total of 487,651 inhabitants spread out over anarea of 4,936 km^2(Asian Development Bank, 2019).

4.2.5. Ranao River Basin

The Ranao river basin (also known as the Agus River) is bounded by the Bukidnon province to the east, Maguindanao and North Cotabato provinces to the south, Illana Bay is in the southwest and finally the Iligan Bay to the North. The total land area of the Ranao river basin is 1,987 km^2 that maintains 5 sub-watersheds known as the Agus, Taraka, Masiu, Gata and Ramain (See Graph 1) (Asian Development Bank, 2018). Although there are additional watersheds, these are the largest and most pronounced in the catchment area encompassing Lake Lanao. The only outlet to Lake Lanao is the Agus River, and it navigates through the municipalities of Pantar, Saguiaran, Baloi and into the Iligan Bay over a maximum distance of 37 km (Asian Development Bank, 2019).

4.2.6. Tagum-Libuganon River Basin

The Tagum-Libuganon (here forward referred to as just Tagum) river basin has an area of 3,258 km^2 in total (See Graph 1) (Asian Development Bank, 2019). The Tagum-Libuganon river basin encompasses four provinces; Davao del Norte, Compostela Valley, Davao del Sur and Agusan del Sur. It also expands into two other neighboring regions (Asian Development Bank, 2019).

5. Methodology

5.1. Data Collection and Requirements

The general research approach of this study will involve using a morphology estimator tool and a hydrodynamic model to explore the changes to flood risk mitigation to urban settlements. The chosen model will be a simplification representing a real system that will demonstrate the flow changes and patterns to aid in the management of the water resources. This will involve changing data input variables that determine the tidal prism in estuary areas (Jarrett, 1976). Based on the difference made in the tidal prism and inland tidal amplitude output from the hydrologic model it will be determined just how effective the chosen method of study would be for mitigating risk on the study area. To determine the effects of widening the mouth of the floodplain change on riverine flooding and storm surge, it will require a reliable model that will be based on some essential data inputs. Firstly, the morphological estimation tool will be used to acquire several of these inputs from online sources such as Google Earth. From this the required spacing between points in the width profile can be obtained and the shape factors for both the channel at the river side and mouth side of the estuary. The data of the tidal amplitude of the estuary and at the riverside of the estuary will also be required. Data will be obtained for the maximum low water to maximum low water hours. Finally, the width of the river at the tidal limit will be needed.

Required inputs for model:	**Variable**	**Variable explanation**
	Name	Name of the River System
	dist	Spacing between points in the width profile (m)
	amp_m	Tidal amplitude at the mouth of the estuary (m)
	amp_r	Tidal amplitude at the riverside of the estuary (m)
	T	Time for one tidal-cycle (from maximum low water to maximum low water (hours)
	s_r	Shape factor of the channel at the river side of the estuary (-)
	s_m	Shape factor of the channel at the mouth side of the estuary (-)
	w_r	Width of the river with at the tidal limit (m)
Not required but improve accuracy:		
	qf	River fresh water discharge (m3/s)
	s0	Salinity at the mouth of the estuary (ppt)
	s_end	Salinity at the riverside of the estuary (ppt) (assumed to be 0)
	rho_0	Density of seawater (kg/m3)
	rho_1	Density of river water (kg/m3)
	r	R value (-)
	z	Z value (-)
	Depth measured	Input data of depth measurement at the mouth and upstream river

Table 1: Morphology Estimator Tool Input Requirements

5.2. Field Observations

The initial method of data collection involves field observations that compile data regarding the location of basins, discharge and settlement patterns. Much of this data has already been accumulated and made available at Deltares through project proposals for water development and LiDAR mapping from the Disaster Risk and Assessment for Mitigation (DREAM) project in the Philippines. Several of the rivers have measuring station gauges that have created relatively reliable data regarding seasonal discharge levels. Governmental organizations of the Philippines continuously gather data and make it available as part of their early flood warning systems. This data will be used in conjuncture with collecting images available on the Google Earth platform of the current status of meandering of each river basin. However, ultimately it will be imperative to use the collected field data in combination with data gained from literature review to gain as a holistic an insight of the current situation as possible.

5.3. Literature Review

The literature review focuses on filling all the missing data requirements that were lacking from field observations to gain a better understanding of the current water basin's situation. The review focuses on topics relevant to strategies to be implemented on the estuaries including widening river mouths to reduce flood risk, knowledge gaps and NBS and Ecological Disaster Risk Reduction (Eco-DRR) strategies.

5.4. Identification of Rivers Estuary Inhabitation "Hotspots"

Although all the rivers to be sampled are within the Philippines, each has its own unique situation with very different characteristics that should be analyzed and noted. The six different river basins will be analyzed based on the inhabitation rates along the river itself, length, and discharge rates. If it is found that all the river basins experience a similar situation in terms of climate drivers than there will not be any significant changes to methodology. However, the varying rates of inhabitation and local infrastructural projects will be analyzed and noted with their respective impacts from implementing the chosen mitigation strategies. Without an in-depth understanding of what areas are of particular concern, it would be too simplistic to make a general statement about what the most appropriate method would be after the analysis of the scenario data. Once a good picture of the working order of each river basin is completed, then appropriate methods of response can be better theorized and explored.

5.5. Identification of Relevant NBS

Different possible uses of NBS scenarios involving river realignment strategies have been identified for the river basins in question. The different combinations of strategies and their results on both the inland water levels, velocities, estuary depths and overall inland tidal amplitude were highlighted. Specifically, the method of widening the mouth of each river was focused on in order to lower the impacts and frequency of flood events. This had recently been proposed as a viable option for flood mitigation and is discussed below (Leuven et al., 2019). However, as the scope of this paper is not limited to just widening the width of the estuary mouth itself, which for this study will be defined as the first third in length of the estuarine area, several other scenarios were also simulated. These included the "normal" or the current situation for comparison, narrowing the mouth, doubling the mouth, widening the first two thirds of the estuary, and widening the entire estuary. Also, to gain a greater insight into estuary realignment, leaving the mouth at its current width while increasing the upper two thirds of the estuary will be simulated, narrowing the upper two thirds, and finally doubling width of the upper two thirds of the estuary as well. To better facilitate the analysis, it was decided that narrowing methods would be viewed as a decrease in area of 50%, widening an increase of 50%, and doubling the area fully for all chosen method applications. From the data provided by this study it should be easier for future analysis of whether or not to increase or decrease these dimensions further to a more appropriate amount.

	Methods:	
River Name:	Normal	Current situation
	Narrowed	Estuary mouth narrowed by 50%
	Widened	Estuary mouth widened by 50%
	Whole Estuary Widened	Entire estuary width widened by 50%
	Widened Lower 2/3	Only the lower two thirds of the river widened by 50%
	Mouth Width Doubled	Completely doubling the mouth of the estuary
	Narrowed Upper 2/3	Only the upper two thirds of the river narrowed by 50%
	Widened Upper 2/3	Only the upper two thirds of the river widened by 50%
	Doubled Upper 2/3	Only the upper two thirds of the river width doubled
Scenarios:		
	4.5 Normal	Current situation but with sea level rise included from RCP 4.5 projections
	4.5 Widened	Current situation estuary mouth widened by 50% with sea level rise included from RCP 4.5 projections
	8.5 Normal	Current situation but with sea level rise included from RCP 8.5 projections
	8.5 Widened	Current situation estuary mouth widened by 50% with sea level rise included from RCP 8.5 projections

Table 2: Methods and Scenarios Explanation

5.6. Widening the Mouth of the River Basin

The methodology for widening the mouth of the river basins will closely follow the methodology stated by Leuven et al. (2019) from the paper; “Sea-level-rise-induced threats depend on the size of tide-influenced estuaries worldwide.” The estuary morphological form will be collected by using satellite imagery obtained from Google Earth along the current tidal range at the mouth of the river. From there empirical tools for assessment will be implemented to quantify the morphology of the estuaries (Estuarine morphology estimator V1.0). The discharge and drainage characteristics of each basin will be sourced through a combination of using the Google Earth Engine, Aqueduct Flood Analyzer, DREAM project and the previously mentioned “FRM Master Plans”. If the data for the discharge isn’t readily accessible, the data regarding the morphology of the river will be used to calculate the discharge (Leuven et al., 2019), or alternately sourced from the International Water Management Institute (IWMI). This will only be necessary if the discharge data is not sourced reliably from online sources due to the lack of consistent gauges supplying data from certain basins, or a preponderance of outliers in data sets. Basic information on topography and tide will be obtained from online platforms and databases supplied by local researchers and authorities in the region. Then the depth estimates will be made from analytical tidal dynamics equations and combined with discharge data calculated from the width and used to find the Canter-Cremer’s flood number (Gisen, 2015). Finally, the output morphology and associated information will be put into a 1D-hydrodynamic model which will provide relevant data on the damping and amplification occurring in the estuaries (Leuven et al., 2019). From there the initial data will be manipulated with an increase on the landward side of the estuary to for comparison of the possible damping effects of widening the river mouth for flood control. When completely finished the data for the normal scenario and widening the river mouth will also be manipulated to represent the effects of widening the river mouth under sea level rise scenarios for each river estuary. This gives the average protection through ought the year, however these rivers are quite seasonal and, in some instances, will even run dry in parts of the year. Therefore, the same calculation was then performed again with the rivers Q10 discharge rate (top 10% of flow rates over a period of time and exceeds 90% of flow measurements) obtained from IWMI to represent how this methodology would look during a storm event with the rivers at high rates of discharge known as compound flood events (Couasnon et al., 2020).

5.7. Initial Morphology Tool Data Input Acquisition

Data for the morphology estimator tool was collected through Google Earth and local wave and tidal data was collected using the Google Earth Engine App with data sourced from a wave tidal energy database (Egbert & Erofeeva, 2002). The tidal data was used to calculate the tidal amplitude at the mouth of each river estuary. From the tidal amplitude the reach of tidal storm surges up the estuary in elevation was calculated and this was used as the data collection point for transect data. From this point a centerline was applied to the rivers and based on the length of the river and used to apply transect lines measuring the width of the river. Planforms of the channel were collected from Google Earth visually, due to a lack of bathymetry data corresponding to the rivers. Google Earth uses multiple sources for their remote sensing data including satellite and air photos taken via remote shuttles that were found to have an accuracy down to 0.1 m when fully zoomed into the individual estuary areas. The measurements of each transect width and spatial corresponding steps were then saved to an Excel spreadsheet and input into the morphology tool alongside the length of the river.

5.8. Validation of Morphology Tool

Discharge values were found using the database from the IWMI ultimately, and were cross checked via the morphology tool and were found to be incredibly consistent and used for the model input. In fact the margin of error found from validating the data of discharge was only 2% for the tested rivers. This was deemed an acceptable margin of error for this study and the methodology of using the morphology tool was deemed as adequate for collecting data.

5.9. Initial 1D-hydrodynamic Model Input

Data pre-processing provided input information for the Metronome model (hereby referred to as just the 1D-hydrodynamic model), and graphics were used for visualizing velocity, discharge and depth of the river (See Appendix). The measurements for each river were then manipulated to represent widening the floodplain, narrowing the floodplain, and widening the entire estuary to create input data for the 1D-hydrodynamic model. The morphology data required for the 1D-hydrodynamic model involved width measurements for the upper reach of the river, discharge, mouth of the estuary, tidal amplitude, average river depth and the average depth of the mouth of the estuary. From here a harmonic analysis was ultimately applied using the Fourier series to assess the inland tidal amplitude of the various scenarios. This allows the possibility of looking at intertidal movement dynamics, and how the velocity is changing or how the water depth will change. From here an analysis of the features of intertidal phenomena using Fourier transform series is used to interpret the data set into one equation. This technique was chosen because it is applied often to various physical problems in mathematic analysis particularly useful for sinusoidal pattern or data trends with constant coefficients.

Fourier Series in sine-cosine format equation:

$$Y(x) = \frac{a_0}{2} + \sum_{n=1}^{N}(a_n \cos(2\pi n x) + b_n \sin(2\pi n x))$$

Y = variable
x = variable
a_0, a_n, b_n= coefficient
N = dimension

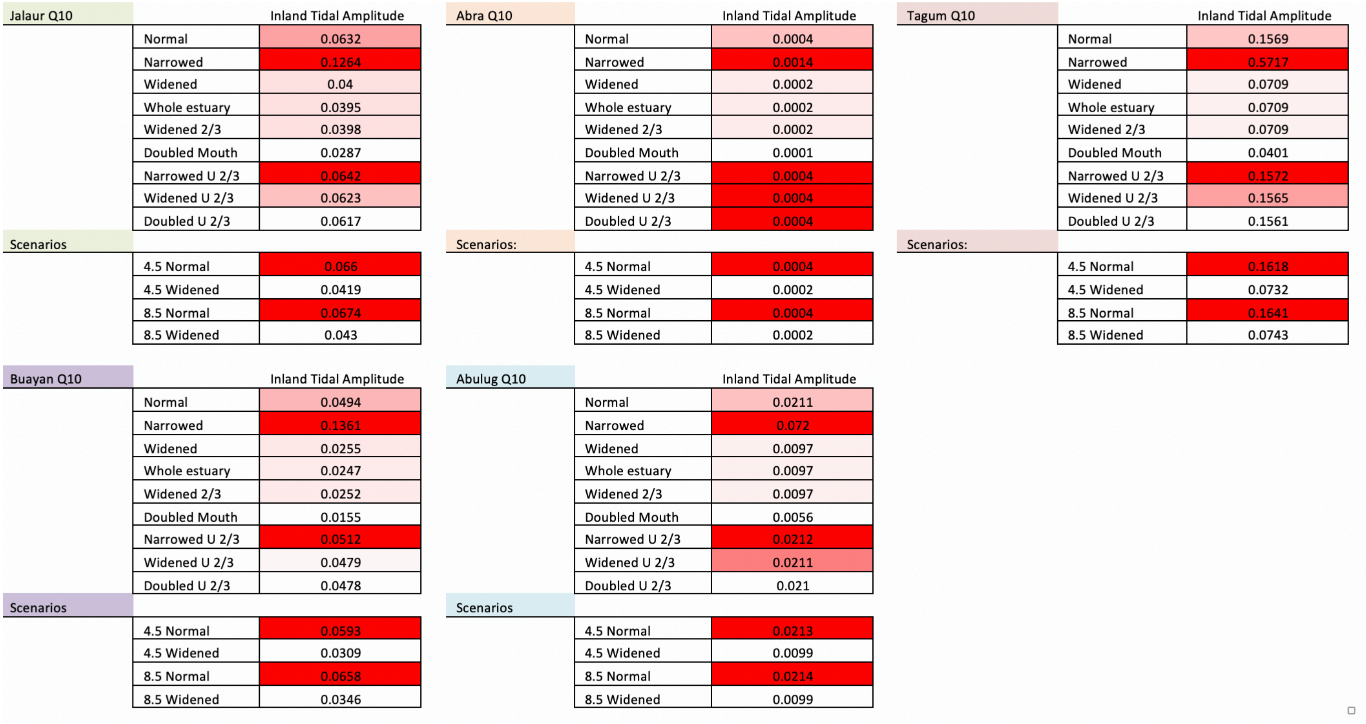
This permits the possibility of looking at intertidal movement dynamics, and how the velocity is changing or how the water depth will change. This also allows analysis of the features of intertidal phenomena using Fourier transform series to interpret the data set into one equation. Essentially, the main driver of the analysis is the simulation of river height. Initial river depth and initial river width, when the tide is higher, naturally the river width is enlarged, and you gain additional river depth. Therefore, you gain additional river discharge which is demonstrated through the cross section. This gives us the initial depth plus the depth change and when seen together gives the new overall depth itself. The additional depth induced by tide was calculated from the equation: Q = flow*river cross section, with all initial values for the 1D-hydrodynamic model being acquired from the Python modelling application morphology tool estimator codes in Spyder.

The 1D-hydrodynamic model was then set up to produce the inland amplitude values and a graphic representation of inland amplitude over the distance of the floodplain for the normal scenario. From here the 1D-hydrodynamic model was used to produce inland water amplitude of the same floodplain with the data produced from the morphology tool representing the scenarios of a narrowed floodplain, widened floodplain (by 1.5 and double), widening two thirds of the estuary, and values for an entirely widened total estuary. Scenarios were also created to show leaving the initial mouth dimensions alone and widening the upper two thirds of the estuary, narrowing the upper two thirds of the estuary and doubling the upper two thirds of the estuary. These different methodologies were set up to mimic a “room for the river” approach to the estuary itself. The data from the normal scenario and widened scenarios were then manipulated to show how these rivers would look under the aggregated mean of sea level rise projections from the Intergovernmental Panel for Climate Change (IPCC) under the 4.5 and 8.5 Representative Concentration Pathways (RCP) circumstances. Although the Philippines is projected to have a higher than average amount of sea level rise, due to levels of uncertainty of that exact rise total, the projected averaged mean by all IPCC simulations was chosen to be applied in the model. Once this information was put into the 1D-hydrodynamic model several calculations were applied that ultimately provided the harmonic analysis of the inland tidal amplitude for 13 different scenarios. The data in the 1D-hydrodynamic model was then run again with the Q10 discharge condition values for comparative results analysis.

6. Results

6.1. The Effects on Inland Tidal Amplitude

Increasing the area of the mouth of the river was successful in lowering the inland tidal amplitude of the rivers, where narrowing the mouth of the river had an inverse relationship for the average yearly discharge data sets (See Table 3). However, the degree of amplification was different for each river estuary. Significantly, the most effective method at decreasing the impacts of tidal amplitude was doubling the size of the estuary mouth. Overall this method reduced the mean inland tidal amplitude to a fraction of its previous values. It also showed that during conditions of Q10 discharge rates of both scenarios 4.5 and 8.5 RCP the widened mouth had both a lower overall inland tidal amplitude and decreased the severity of storm surge. There was one notable exception with inland water heights being higher for the hotspots in Abra under the widened mouth method in scenarios 4.5 and 8.5. However, as to what degree this application would be viewed as successful has to be reviewed on a case by case basis. To facilitate an easier overview of how desirable managed river mouth realignment would be for each estuary, hotspots were identified along the estuary as discussed in the methodology. These areas are locations along the estuary that have been particularly densely settled or are critical infrastructural projects to urbanized areas such as bridges. The projected height difference in storm surge events was then calculated for each individual hotspot area along the estuaries with the most successful and least successful methods identified for each hotspot. To see if there was a linear relationship between the depth of the river mouth and the inland tidal amplitude a Pearson's correlation was performed and found that no estuary had a strong or significant correlation between the depth of the river mouth and the inland tidal amplitude (See Table 12 p.80).



Jalaur Q10		Inland Tidal Amplitude
	Normal	0.0632
	Narrowed	0.1264
	Widened	0.04
	Whole estuary	0.0395
	Widened 2/3	0.0398
	Doubled Mouth	0.0287
	Narrowed U 2/3	0.0642
	Widened U 2/3	0.0623
	Doubled U 2/3	0.0617
Scenarios		
	4.5 Normal	0.066
	4.5 Widened	0.0419
	8.5 Normal	0.0674
	8.5 Widened	0.043

Abra Q10		Inland Tidal Amplitude
	Normal	0.0004
	Narrowed	0.0014
	Widened	0.0002
	Whole estuary	0.0002
	Widened 2/3	0.0002
	Doubled Mouth	0.0001
	Narrowed U 2/3	0.0004
	Widened U 2/3	0.0004
	Doubled U 2/3	0.0004
Scenarios:		
	4.5 Normal	0.0004
	4.5 Widened	0.0002
	8.5 Normal	0.0004
	8.5 Widened	0.0002

Tagum Q10		Inland Tidal Amplitude
	Normal	0.1569
	Narrowed	0.5717
	Widened	0.0709
	Whole estuary	0.0709
	Widened 2/3	0.0709
	Doubled Mouth	0.0401
	Narrowed U 2/3	0.1572
	Widened U 2/3	0.1565
	Doubled U 2/3	0.1561
Scenarios:		
	4.5 Normal	0.1618
	4.5 Widened	0.0732
	8.5 Normal	0.1641
	8.5 Widened	0.0743

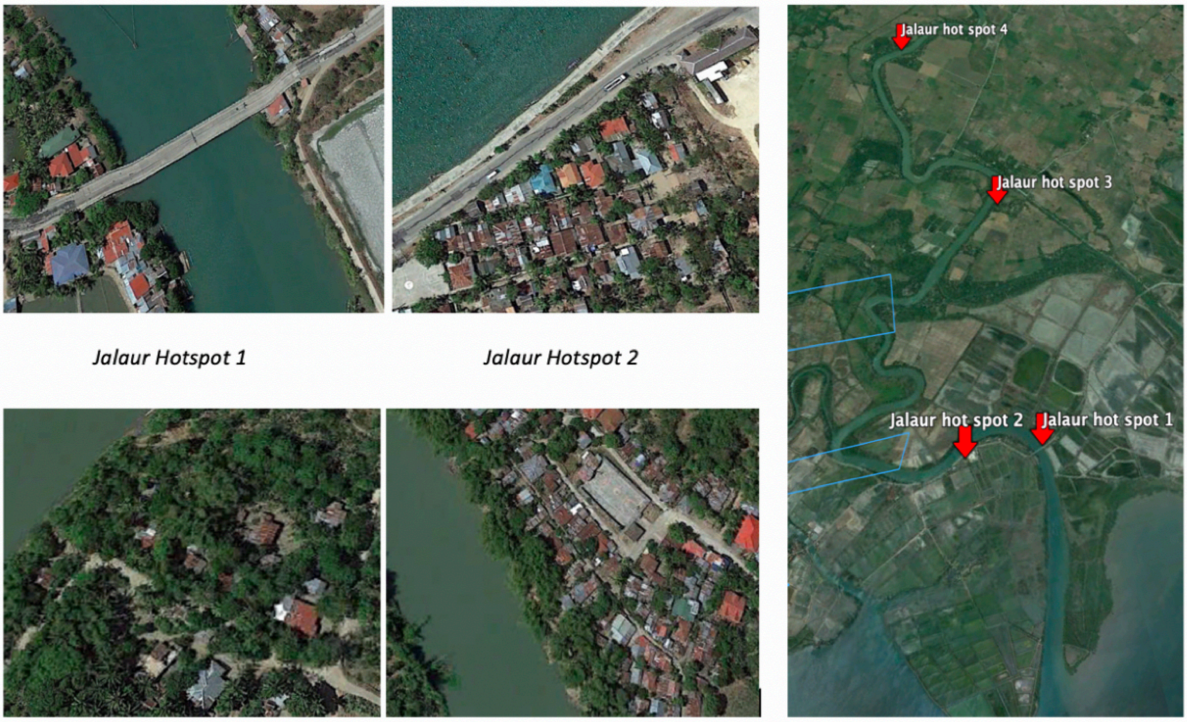
Buayan Q10		Inland Tidal Amplitude
	Normal	0.0494
	Narrowed	0.1361
	Widened	0.0255
	Whole estuary	0.0247
	Widened 2/3	0.0252
	Doubled Mouth	0.0155
	Narrowed U 2/3	0.0512
	Widened U 2/3	0.0479
	Doubled U 2/3	0.0478
Scenarios		
	4.5 Normal	0.0593
	4.5 Widened	0.0309
	8.5 Normal	0.0658
	8.5 Widened	0.0346

Abulug Q10		Inland Tidal Amplitude
	Normal	0.0211
	Narrowed	0.072
	Widened	0.0097
	Whole estuary	0.0097
	Widened 2/3	0.0097
	Doubled Mouth	0.0056
	Narrowed U 2/3	0.0212
	Widened U 2/3	0.0211
	Doubled U 2/3	0.021
Scenarios		
	4.5 Normal	0.0213
	4.5 Widened	0.0099
	8.5 Normal	0.0214
	8.5 Widened	0.0099

Table 3: Inland Tidal Amplitude Q10

6.2. Jalaur (Morphology Maps Appendix pp. 44-49)

The Jalaur river had four hotspots identified along the banks of the estuary. Three areas of densely settled locations and one bridge in various locations spread out through the estuary. However, it became abundantly clear they could be classified in locations farther up the estuary and located closer to the mouth itself. It showed the two hotspots located further along the estuary would favor managed estuary mouth widening as a form of hazard mitigation to decrease inland tidal amplitude (See Table 4). However, inversely the two hotspots located closest the mouth had the most positive results in the scenario where the upper two thirds of the river estuary itself was narrowed (See Table 4). This contrast however is representative of the yearly average where the difference is mainly in millimeters in height. When the same calculations were performed during a peak discharge event (Q10) the differences are in tens of centimeters. Notably the difference for hotspot 4 between the normal and the widened mouth method was over 25 cm in river height (See Table 5). When comparing the method of narrowing the mouth of the river to the widened river method with hotspot 4 the difference exceeds 1 meter. Also, the narrowed method was the least effective method for mitigation even when considering hotspots one and two under a Q10 discharge scenario. When considering the RCP 4.5 and 8.5 scenarios under a Q10 event both hotspots were favorable to the widening of the mouth method (See Graph 4).



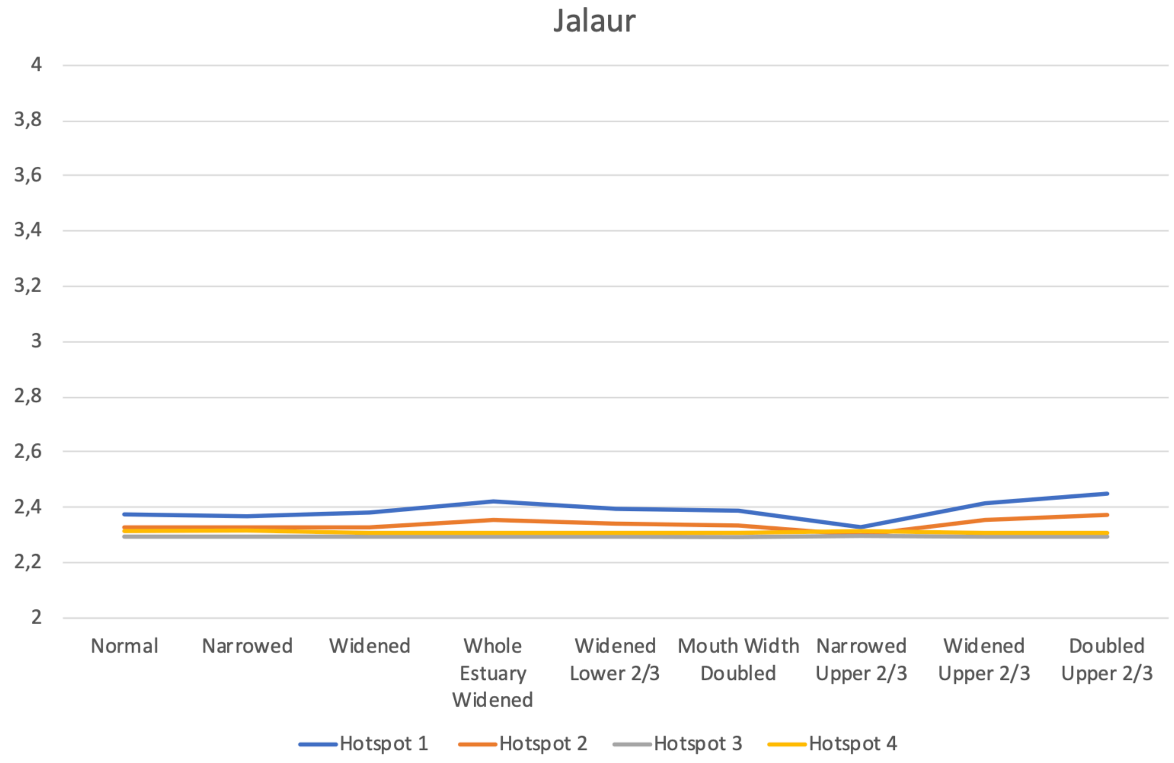
Jalaur Hotspot 1 *Jalaur Hotspot 2*

Jalaur Hotspot 3 *Jalaur Hotspot 4* *Aerial View of Jalaur Hotspots*

Figure 6: Visual Representations of Jalaur Hotspot Locations

		Hotspots			
	Methods:	1	2	3	4
Jalaur	Normal	2.3754	2.3284	2.2962	2.3118
	Narrowed	2.3711	2.3268	2.2963	2.3167
	Widened	2.3815	2.3313	2.2944	2.3098
	Whole Estuary Widened	2.4205	2.3548	2.2938	2.3089
	Widened Lower 2/3	2.3969	2.3406	2.2942	2.3094
	Mouth Width Doubled	2.3883	2.335	2.2931	2.3083
	Narrowed Upper 2/3	2.3288	2.3004	2.2972	2.3132
	Widened Upper 2/3	2.4152	2.3523	2.2953	2.3106
	Doubled Upper 2/3	2.4501	2.3733	2.2946	2.3096
Scenarios:					
	4.5 Normal	2.2581	2.2579	2.2985	2.3151
	4.5 Widened	2.2636	2.2601	2.2958	2.312
	8.5 Normal	2.2114	2.2297	2.2993	2.3162
	8.5 Widened	2.2166	2.2316	2.296	2.3126

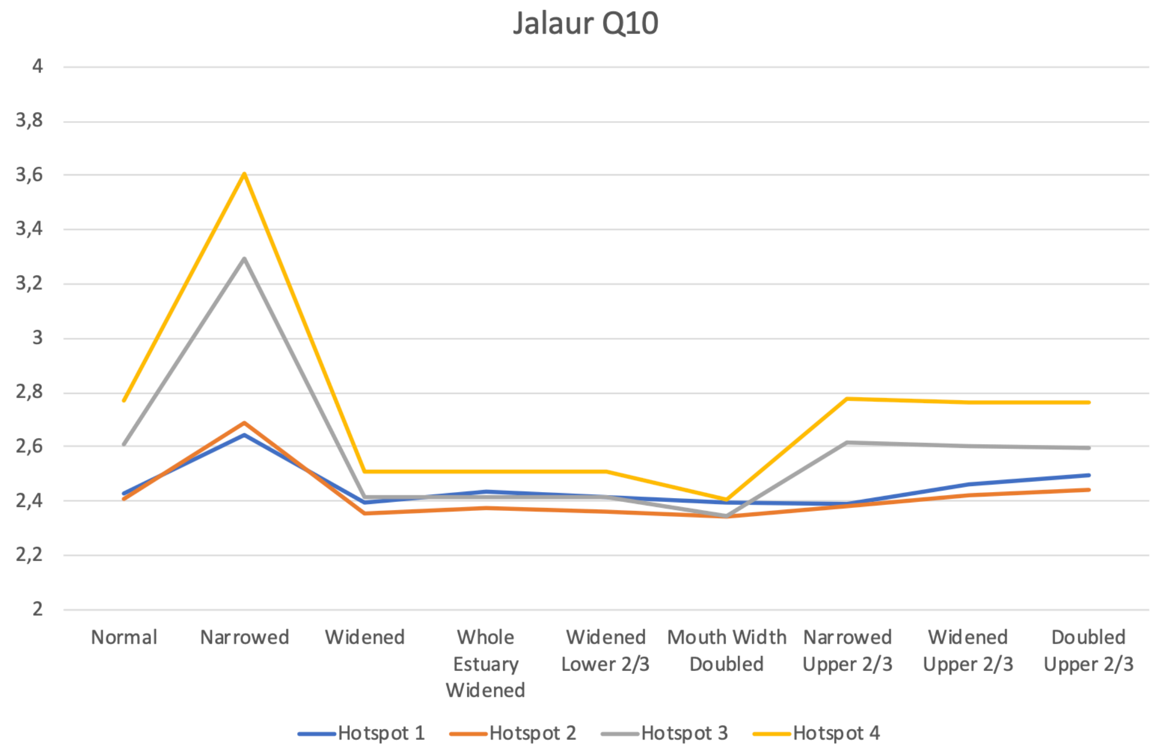
Table 4: Jalaur River Hotspot Inland Water Height in Meters Yearly Average. The darker the gradient of red the higher the water level in comparison to other methods.



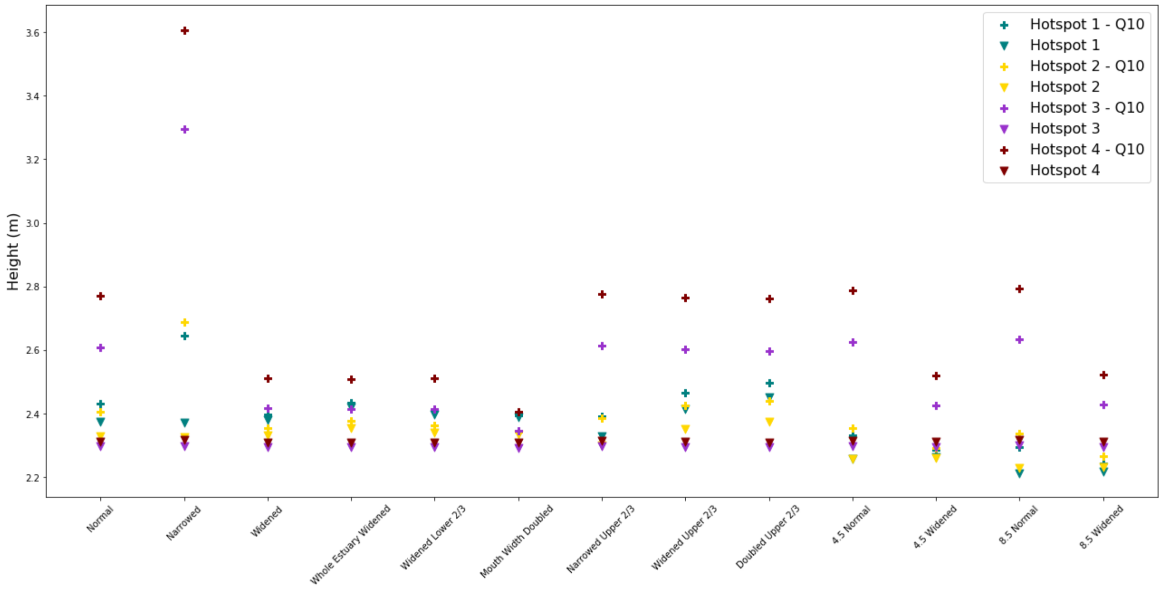
Graph 2: Jalaur River Hotspot Inland Water Height in Meters Yearly Average

		Hotspots			
	Methods:	1	2	3	4
Jalaur Q10	Normal	2.4305	2.4059	2.6071	2.7707
	Narrowed	2.6443	2.6889	3.2939	3.6065
	Widened	2.3974	2.3546	2.4164	2.5119
	Whole Estuary Widened	2.4348	2.3762	2.414	2.5096
	Widened Lower 2/3	2.4122	2.3631	2.4154	2.511
	Mouth Width Doubled	2.3942	2.3436	2.3456	2.4063
	Narrowed Upper 2/3	2.3902	2.385	2.614	2.7768
	Widened Upper 2/3	2.4656	2.4245	2.6017	2.7658
	Doubled Upper 2/3	2.4969	2.4413	2.5972	2.7617
Scenarios:					
	4.5 Normal	2.3313	2.3553	2.6255	2.7864
	4.5 Widened	2.2865	2.2911	2.4245	2.5195
	8.5 Normal	2.2943	2.3376	2.6346	2.7942
	8.5 Widened	2.2434	2.2669	2.4286	2.5233

Table 5: Jalaur River Hotspot Inland Water Height in Meters during Q10 Discharge Event. The darker the gradient of red the higher the water level in comparison to other methods.



Graph 3: Jalaur River Hotspot Inland Water Height in Meters During Q10 Event

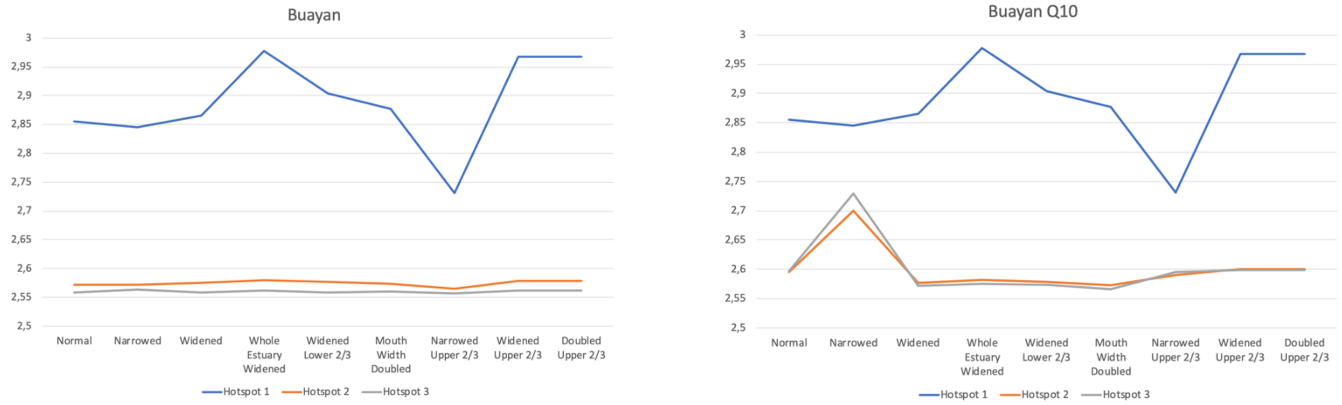


Graph 4: Visual of Water Height Level for Jalaur Hotspots Under both Yearly Average and Q10

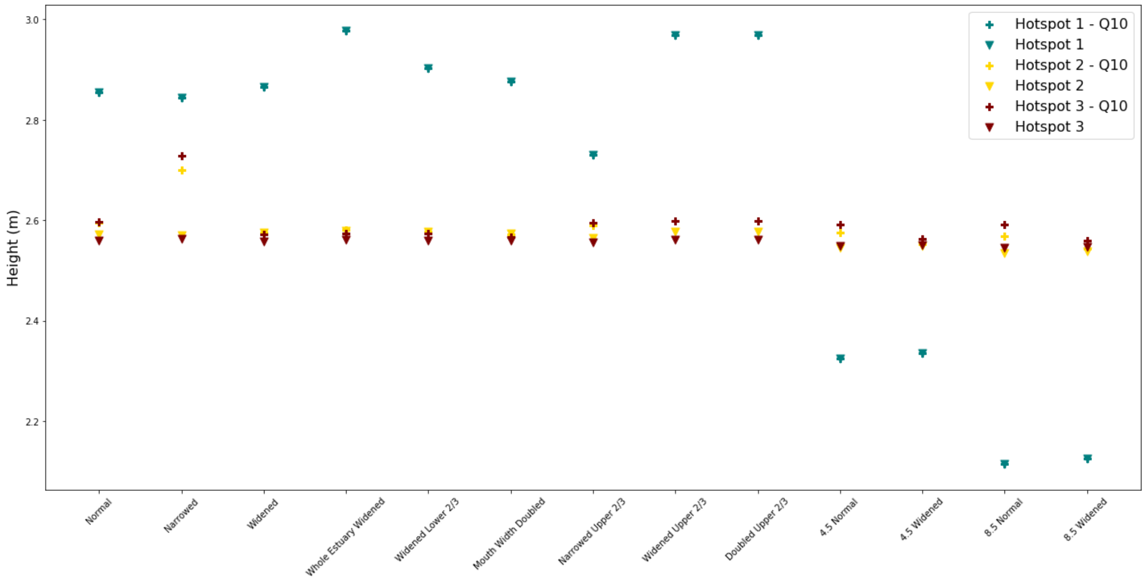
6.3. Buayan (Morphology Maps Appendix pp. 50-55)

The Buayan river had three hotspots identified along the banks of the estuary. Two of which were located closer to the mouth of the river with one further upstream. Interestingly enough the mitigation measure that was viewed as the most favorable are narrowing the upper two thirds of the estuary and leaving the mouth of the river without any changes under average discharge circumstances. When viewing the Buayans hotspots inland river height under Q10 conditions, the best method available for hotspots 2 and 3 was the method of doubling the mouth width of the estuary (See Graph 5-6). However, the difference was only a centimeter to two for both hotspots (See Appendix Table 7, p. 75). Hotspot 1 maintained the same behavior in both yearly average discharge rates and under Q10 conditions. This is likely due to its extremely close proximity to the mouth of the estuary itself. Although under Q10 conditions the method of narrowing the upper two thirds of the river provides similar mitigation standards for hotspots 2 and 3 as the normal scenario, it does still greatly benefit hotspot 1 (See Graph 5-6).

Figure 7: Visual Representations of Buayan Hotspot Locations



Graph 5: Buyuan River Hotspot Inland Water Height in Meters Yearly Average and During Q10 Event



Graph 6: Visual of Water Height Level for Buayan Hotspots Under both Yearly Average and Q10

6.4. Abra (Morphology Maps Appendix pp. 56-61)

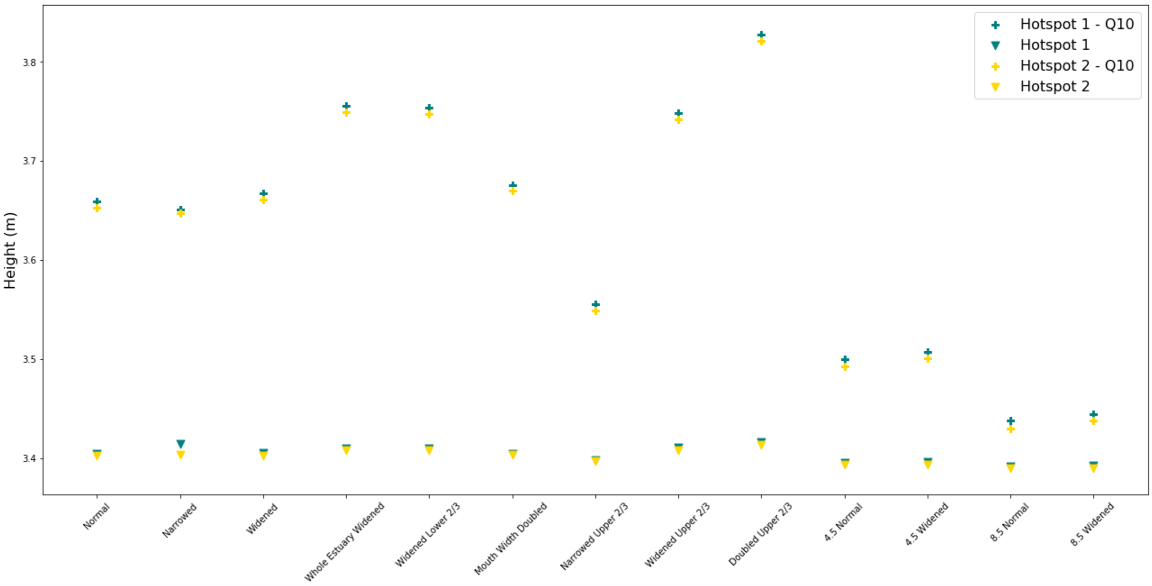
The Abra river had two hotspots identified along the banks of the estuary. In the case of the first hotspot, it was located closer to the mouth of the estuary and narrowing the upper two thirds of the estuary overall was the most effective method tested (See Graph 7). The second hotspot located half way up the estuary also showed that narrowing the upper two thirds of the estuary would be the most effective method. However, in the case of the of the second hotspot this difference was very small, at the millimeter scale (See Table 8, p. 76). This trend was also observed almost exactly under the Q10 discharge scenario with only differences in millimeters in height observed in hotspot 2 (See Graph 8).

Abra Hotspot 1

Abra hotspot 2

Arial view of Abra

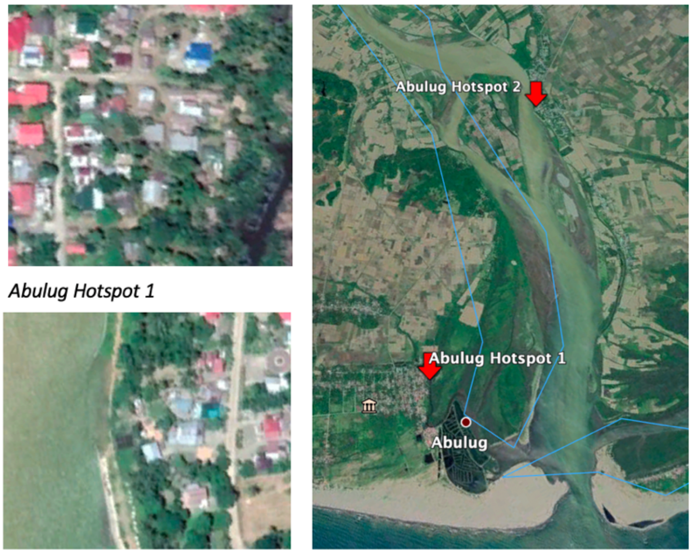
Graph 7: Abra River Hotspot Inland Water Height in Meters Yearly Average and During Q10 Event



Graph 8: Visual of Water Height Level for Abra Hotspots Under both Yearly Average and Q10

6.5. Abulug (Morphology Maps Appendix pp. 62-67)

The Abulug river had two hotspots identified along the banks of the estuary. The hotspot closer to the mouth of the river estuary appeared to gain benefits to storm surge resilience from narrowing the mouth of the estuary itself under average discharge conditions (See Graph 9). Where hotspot 2 located further upstream from the mouth of the estuary benefited the most from the method of doubling the mouth width of the river as a means of storm surge mitigation under average discharge conditions (See Graph 9). Where conversely under Q10 discharge conditions the most effective method was demonstrated to be widening the mouth of the river for both hotspot 1 and 2 (See Graph 10), lowering the levels up to 15 and 12 cm in the event of a storm surge event (See Table 9, p. 77).

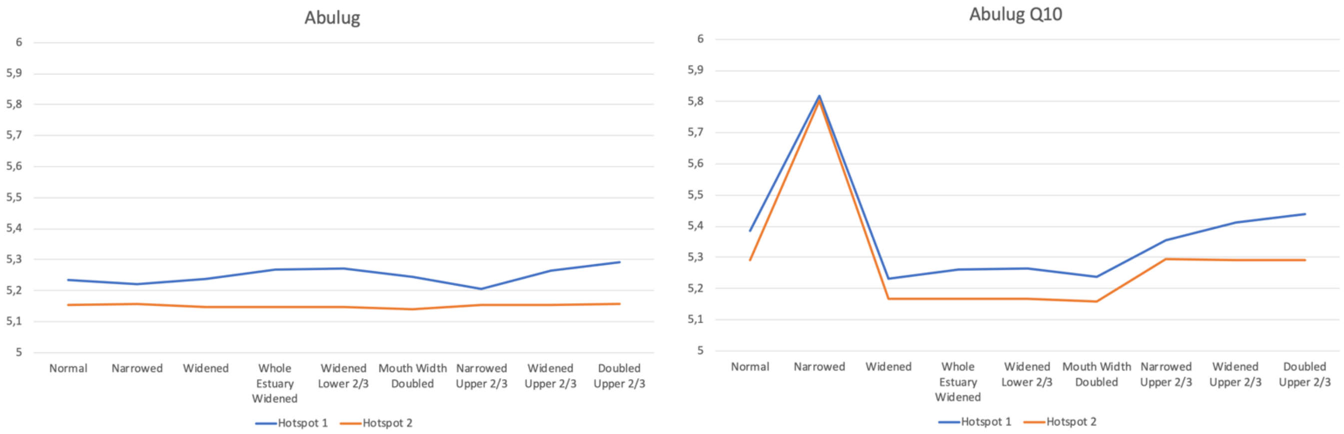


Abulug Hotspot 1

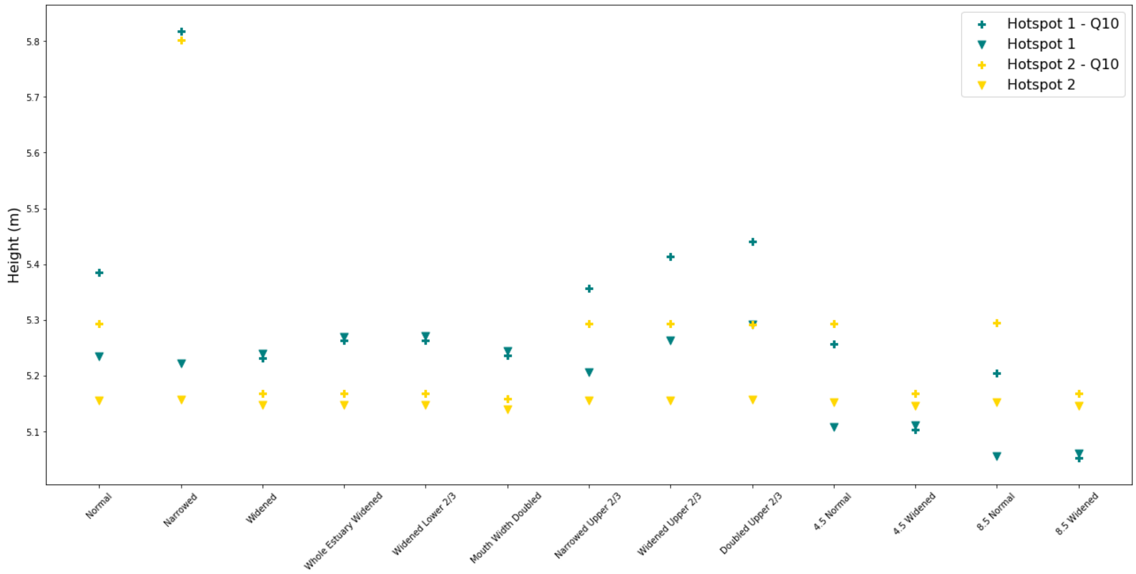
Abulug Hotspot 2

Arial view of Abulug

Figure 9: Visual Representations of Abulug Hotspot Locations



Graph 9: Abulug River Hotspot Inland Water Height in Meters Yearly Average and During Q10 Event



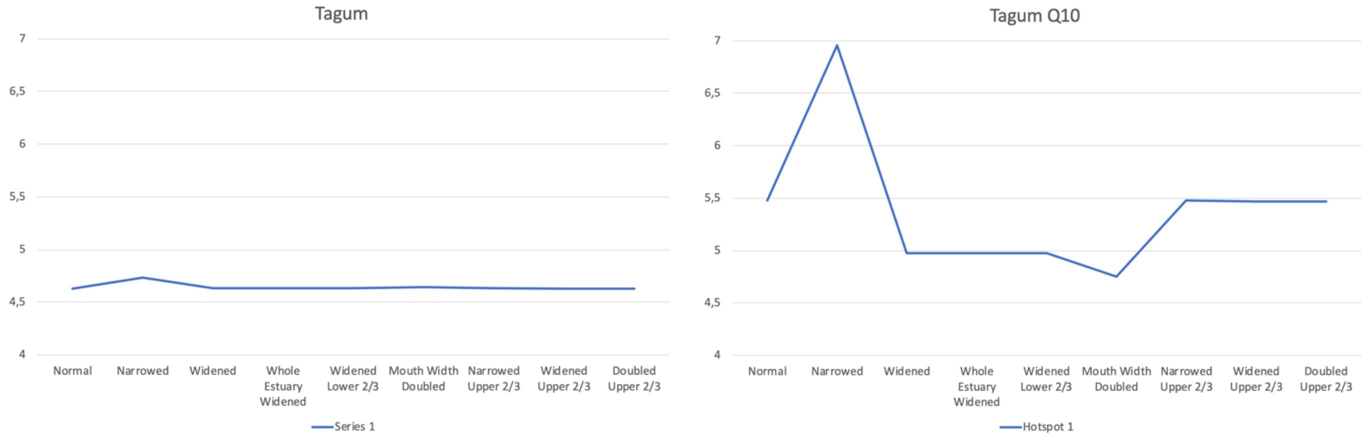
Graph 10: Visual of Water Height Level for Abulug Hotspots Under both Yearly Average and Q10

6.6. Tagum (Morphology Maps Appendix pp. 68-73)

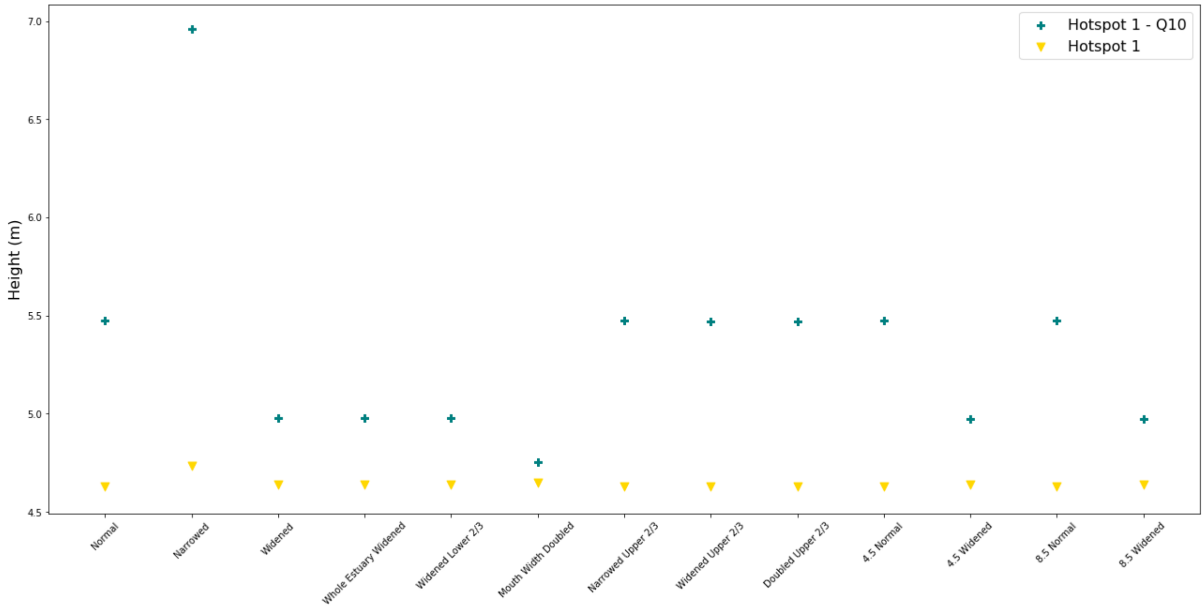
The Tagum river contained only 1 hotspot on the length of the river estuary area. Under normal discharge levels, the normal scenario actually was the best situation under storm surge events (See Graph 11). However, when observing the same hotpot under Q10 discharge levels the most effective method of mitigation was doubling the width of the mouth of the estuary (See Graph 11-12). In fact, compared to the normal scenario in Q10 conditions the difference in height of the method of doubling the mouth was 72 cm overall (See Table 10, p. 78).

Tagum Hotspot 1 *Arial view of Tagum*

Figure 10: Visual Representations of Tagum Hotspot Locations



Graph 11: Tagum River Hotspot Inland Water Height in Meters Yearly Average and During Q10 Event



Graph 12: Visual of Water Height Level for Tagum Hotspots Under both Yearly Average and Q10

6.7. Ranao River

The location of the Ranao river didn't work within the capabilities of the model overall. Due to its river's location being comparatively unique to the others on a landlocked lake, the tidal amplitude had to be calculated with a different formula. Once this amplitude was obtained it became abundantly clear that the flooding that occurs is not associated with storm surge scenarios owing to the rapid rise in elevation of several meters within a short spatial step. Flooding within the Ranao floodplain is thus much more likely to occur due to inland precipitation events associated with climate disturbance rather than inland water amplitude associated due to storm surge events. Therefore, inputting the data in the morphology estimator tool would have been limited to within a small length up the river and would not have given a reliable amount of input information for a harmonic analysis within the 1D-hydrodynamic tool. It was therefore decided that this river estuary was unfortunately outside of the scope and feasibility of this study.

6.8. Sea Level Rise Scenarios

Each estuary area also had its data analyzed for the degree of inland tidal amplification/dampening effects under the IPCC RCP scenarios of 4.5 and 8.5. The 8.5 scenario being the "business as usual" scenario and the 4.5 scenario being an optimistic scenario in terms of sea level rise associated with greenhouse gas emissions. Across the board for all river estuaries the inland tidal amplitude was decreased in the sea level rise scenarios as well as the normal scenarios from widening the river mouths compared to the normal. However, the difference was quite varied when looking at the locations of hotspots. However ultimately under Q10 discharge conditions and both RCP scenarios all hotspots benefited from the method of widening the river mouth with the exception of Buayan hotspot 1 and the Abulug river basin (See Tables 6-10, p. 74-79).

7. Discussion

This study was performed to see if managed river mouth realignment would be a viable NBS method of flood control in the face of storm surge events. It was shown through the results that all rivers showed a decrease in inland tidal amplitude with an increased mouth width (See Table 3, p. 26), while the opposite was indeed true for narrowing the mouth of the river. However, when delving deeper into the effects this method would have on the various hotspot locations it was shown that this method wasn't necessarily the most beneficial course of action in terms of mitigation for all estuary hotspot areas with infrastructure built up along the banks.

When discussing and reviewing the results in relation to the research questions, the following observations arose:

Research Question: What is the impact of widening the floodplains of 6 river basins in the Philippines, (i.e the Buayan-Malungon, Jalaur, Apayo-Abulug, Abra, Ranao, and Tagum-Libuganon river basins) regarding mitigating flood risk?

When reviewing all rivers, it was shown empirically that the entire estuary in all five rivers would have a decreased value when considering inland tidal amplitude associated with storm surge events. However, urbanization and sprawl is not distributed evenly throughout the entire estuary area of the rivers itself much like other rivers in the world (Macklin & Lewin, 2015). Hotspots located farther upstream of the estuary benefited highly from this method, while hotspots that were located closer to the mouth of the estuary actually held an inverse relationship under average discharge scenarios. When considering the same hotspots under Q10 conditions associated with large scale compound floods (Couasnon et al., 2020), the vast majority of the hotspots observed would see benefits from widening the floodplains of the river basins.

Sub-Question 1: What is the effect of narrowing the floodplain of the 6 rivers overall in the face of storm surge mitigation?

While initially this was seen as more of a method of observing what the opposite effects would be of widening the estuary mouth, it actually showed that some locations would benefit from this methodology in the respective rivers especially in the upper two thirds of the estuary. Although this method showed that it would increase the overall inland tidal amplitude associated with higher severity storm surge events for the estuary as a whole. Therefore, it would not be highly recommended as a form of storm surge mitigation unless there was no other feasible method, almost to be viewed as a worst-case scenario solution.

Sub-Question 2: How effective is widening the mouth of the floodplain under sea level rise scenarios from climate change projections in the next 100 years?

When considering the two sea level rise scenarios of 8.5 and 4.5 the results were highly encouraging. With the methods of widening mouth of the river decreasing the inland tidal amplitude averaging roughly 45% compared to the normal scenario (See Tables 3, p. 26). This would appear to indicate that this method could be quite beneficial in the face of sea level rise uncertainty.

This shows that managed river mouth realignment and widening would be beneficial to the overall basins resilience to storm surge events and in line with the current priorities of the Philippines governments infrastructural plans (Ferrer, 2018). However, the data regarding the sites which had been designated hotspot areas began to show a different conclusion on further analysis. The data suggests that in all scenarios if the location of the hotspot was close to the mouth the most significant dampening effect on inland tidal amplitude during a storm surge event would also be widening the river mouth, however narrowing the mouth of the river showed to be favorable under normal conditions. However, if any location was over half way up the river estuary or beyond, the trend was completely reversed and the best situation for dampening the amplitude of inland storm surge events was indeed widening the mouth of the estuary under normal conditions. This insinuates that widening the mouth of a river basin would indeed be an excellent idea especially if the pattern of habitation were more upstream of the mouth itself. Therefore, the data would suggest that managed realignment of the mouth of rivers should be done on a case by case basis. If the entire river was inhabited densely throughout the river estuary area, or the population and infrastructure density was further upstream, then widening the mouth of the estuary would be beneficiary strategy to pursue. It would most likely have to be done in conjuncture with resettlement programs of the hotspot areas that are located closer to the mouth of the estuary to locations further upstream. However, the true benefits of widening the mouth of the rivers was clearly demonstrated to be highly beneficial under Q10 scenarios for the majority of all estuaries in this study. With some hotspots possibly mitigating as much as .72 cm in water depth (See Table 10, p. 77).

7.1. Feasibility of Widening Estuary Mouths

Obviously, the ultimate goal of this study was to asses just how effective widening the mouth of the estuary would be on decreasing inland tidal amplitude in the event of storm surge events. The data would suggest that this is a practical option in a certain set of circumstances. However, it is important to keep in mind the actual feasibility of widening the estuary itself (Esteves, 2013). Most of the rivers surveyed were quite small with low rates of discharge on average with maximum estuary widths of fairly modest lengths. So conceivably widening the mouth of most of the estuaries studied would be relatively viable project especially when considering the protection from storm surge they would receive under Q10 discharge conditions and a strong compound flood and storm events that will become an ever-increasing occurrence in the projected future (Couasnon et al., 2020). It is important to highlight that even a minor disturbance can become a natural disaster if the community isn't prepared to cope with the impacts (UN DRR, 2007). However, it would have to be a very site-specific method of mitigation for rivers in need of sustainable storm surge flood risk (Esteves, 2013). It should also be noted that most of the rivers are located in tropical climates that experience large durational periods in the year of extreme precipitation events that could hamper the development of these methods. However, that is a smaller overall concern that will most likely be accounted for before the onset of any mitigation development planning. If the river in question being analyzed for storm surge mitigation has patterns of human settlement that match this description, then the data of this study would appear to heavily suggest this as a favorable method of disturbance mitigation.

7.2. Limitations

Ultimately, the greatest draw back of the data is that the real-world bio-geomorphological responses and feed backs are not considered in this model. Although this study would support the idea of widening the mouth of a river for storm surge and widening the overall the floodplain upper areas on a data level of inland tidal amplitude and flood water levels there are feedbacks in the natural world these models do not explore. If the mouth width is widened, this method of mitigation is something that would have to be maintained over time. The bed load of the river in question should also be measured, that way there would be a possibility of making projections on when sediment deposition at the mouth of the river would render this mitigation strategy no longer feasible. Ultimately, the inlets cross-sectional area is a result of the tidal prism and not the width of the river overall (Jarrett, 1976). Therefore, periodic dredging would unfortunately be required to maintain the width, which come with its own host of ecological and socioeconomic consequences. This being stated, many of these rivers have been experiencing sediment deficiency from illegal mining operations upriver that could counterintuitively benefit the locations if this was implemented as a mitigation strategy. With decreased sediment availability the rates of siltation to a widened mouth would also be decreased while extending the lifetime of this mitigation strategy (Batalla, 2003). For example, in the case of the Tagum river estuary, only one hotspot was recorded along one bank of the river. The opposite side of the river is forested with wetland vegetation and uninhabited. The more viable and cost-effective solution in this circumstance might just be to install a tall earthen berm protecting the inhabited bank of the river (Cohen-Shacham et al., 2016).

In the case of widening the landward estuary areas above the immediate mouth of the river would also require methods of maintaining these alterations to the rivers natural meandering. The actual mouth itself would most likely require some sort of stabilizing infrastructure, either nature based or bank armoring to prevent unwanted alterations from the sea itself. This could also create a situation where the flood currents and waves enter the estuary with a wider range area of bank erosion. This again could be prevented with NBS using a combination of earthen berms and sediment stabilizing flora species. Measuring the rate of feedbacks that create erosion and the time frame associated with it rendering the mitigation methods inadequate for preventing storm surge events was unfortunately outside of the capabilities of the model used in this study.

There was still a lack of detailed bathymetry data that could be obtained for these rivers from academic sources and institutions. Some of these rivers are in contested areas of jurisdiction which complicates the possibility of sending field crews out for accurate data acquisition. In the future if it is possible to make an accurate on the ground field investigation of these river systems that could improve the accuracy of these simulations and create a more accurate insight into just how helpful these methods would be for the systems that are being studied. Finally, the Ranao rivers estuary characteristics prevented it from being analyzed for this mitigation method.

8. Conclusion

While this study confirms that managed river mouth realignment does indeed help decrease the impacts of storm surge events in the overall estuary itself, upstream locations in estuarine areas disproportionately experience the largest benefits during average discharge conditions. It is also important to keep in mind the limitations previously discussed above. However, it should also be noted that the largest benefits will be under circumstances that are associated with the highest levels of discharge (Q10 conditions). Under these conditions widening the mouth of the river proved to be an effective method of storm surge mitigation for both the current situation and under scenarios associated with climate change. Locations of hotspots are dependent on the patterns of human settlement which ultimately is irrational and hard to quantify. However, although river realignment may not be the best scenario for several rivers individually, it does show promising data that when done for specific scenarios, and in the right set of circumstances, this could be a highly beneficial method of hazard mitigation to storm surge events.

8.1. Recommendations for Future Research

This study however was limited to the scope of manipulating the dimensional data of the estuary area itself for river mouth realignment assessment. One of the recommendations for further study of this subject would be to do a deeper analysis of the sediment load of rivers in question and then also model just how long in duration these methods would last without needing further supplementation through dredging, which would have its own negative associated impacts on the environment. Conceivably though if the siltation of the mouths of the estuarine areas rates are low it might take several decades for any real impact to occur, this could be an effective standalone NBS to storm surge for particular estuaries. If this however is not the case it would most likely be best implemented with other NBS and possibly a few “Grey” infrastructures projects to create a robust “hybrid” plan for storm surge mitigation.

8.2. Final Thoughts

Nature Based Solutions are also often most robust when multiple NBS strategies and contingent strategies are implemented together or in conjuncture with “grey” infrastructure in a hybrid form as discussed earlier in this study. Every river is of course different with various settlement patterns along the banks, discharges values, overall morphology and technical uses. There will never be a one size fits all solution to flood mitigation due to storm surge. This study has readily demonstrated that in 5 separate river basins in different locations show a diversity in best fit solutions depending on the location of urban settlement and infrastructure along the estuary areas. The protection managed estuary realignment provides could also be used as part of an overall comprehensive plan with multiple NBS strategies used in tandem creating an especially robust protection strategy in the face of rising sea levels associated with climate change. However, this study provides data that managed river estuary realignment should be an effective measure to mitigating the negative effects of storm surge events for small rivers, especially widening the first third of the estuary. This is a particularly encouraging finding that there are effective NBS mitigation options available to populations inhabiting estuary areas even when considering the uncertainty that climate change will bring in the future.

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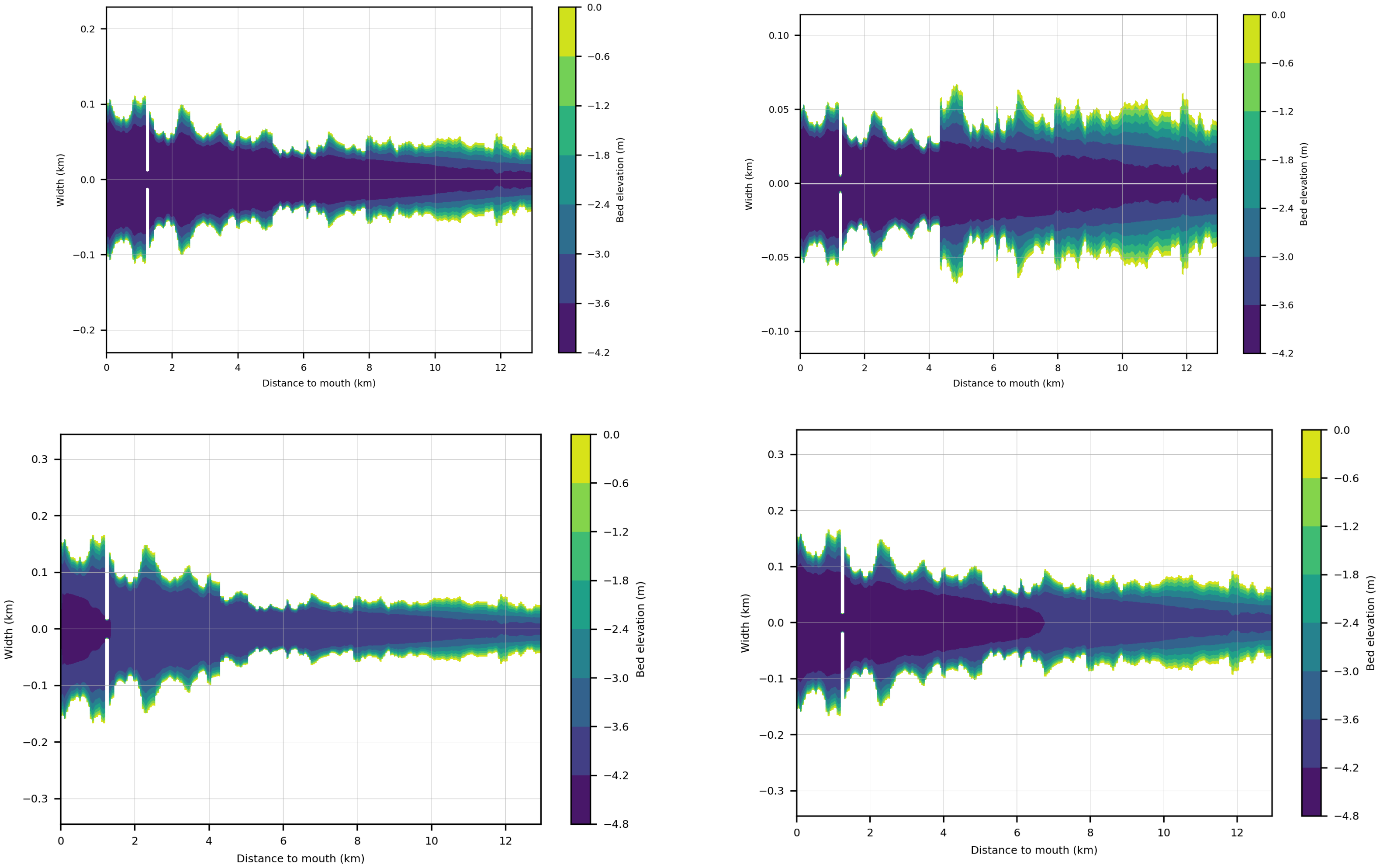
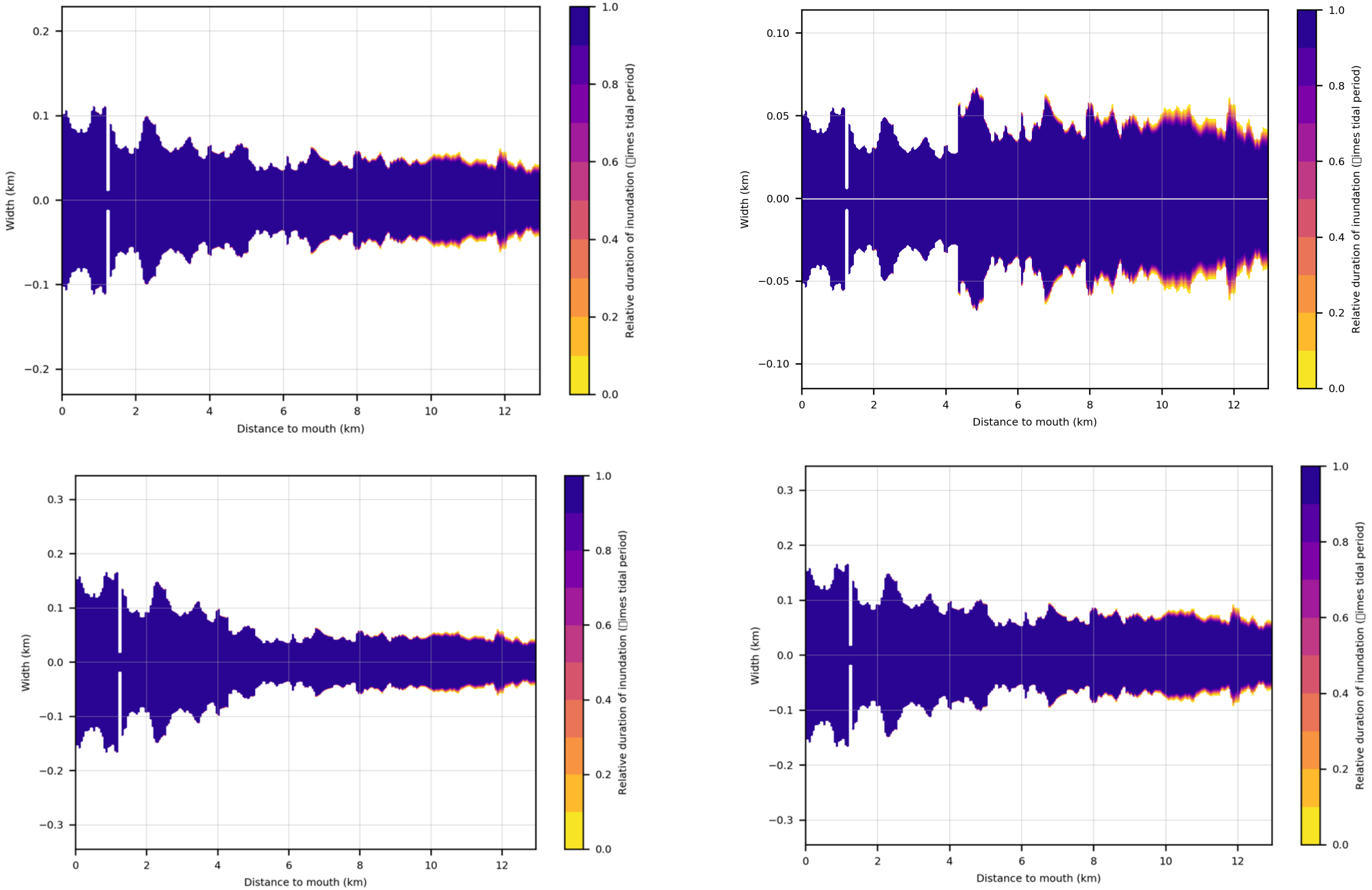
Appendix

Jalaur River (Depth)



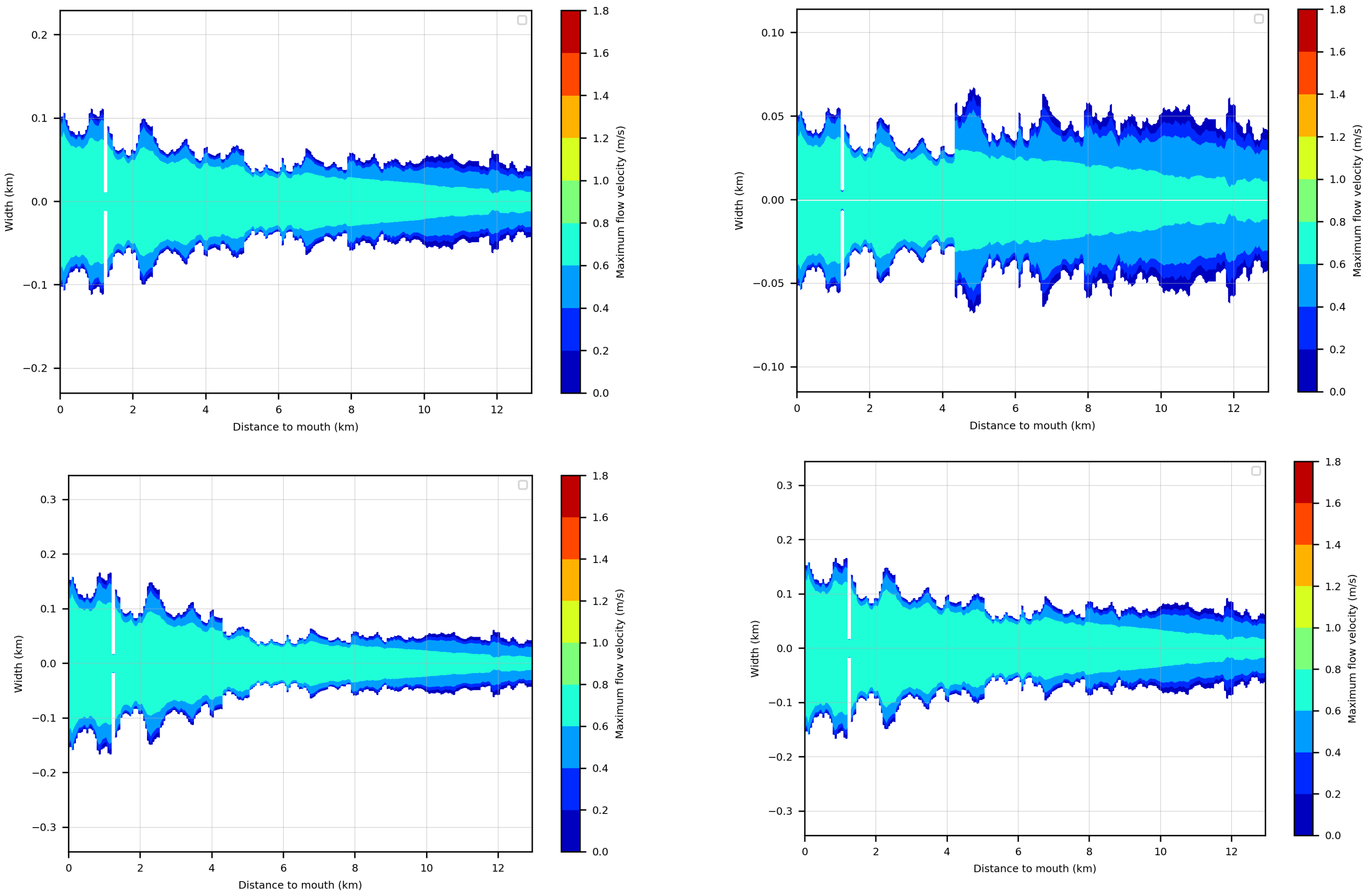
Graph 13: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Jalaur River (Inundation Time)



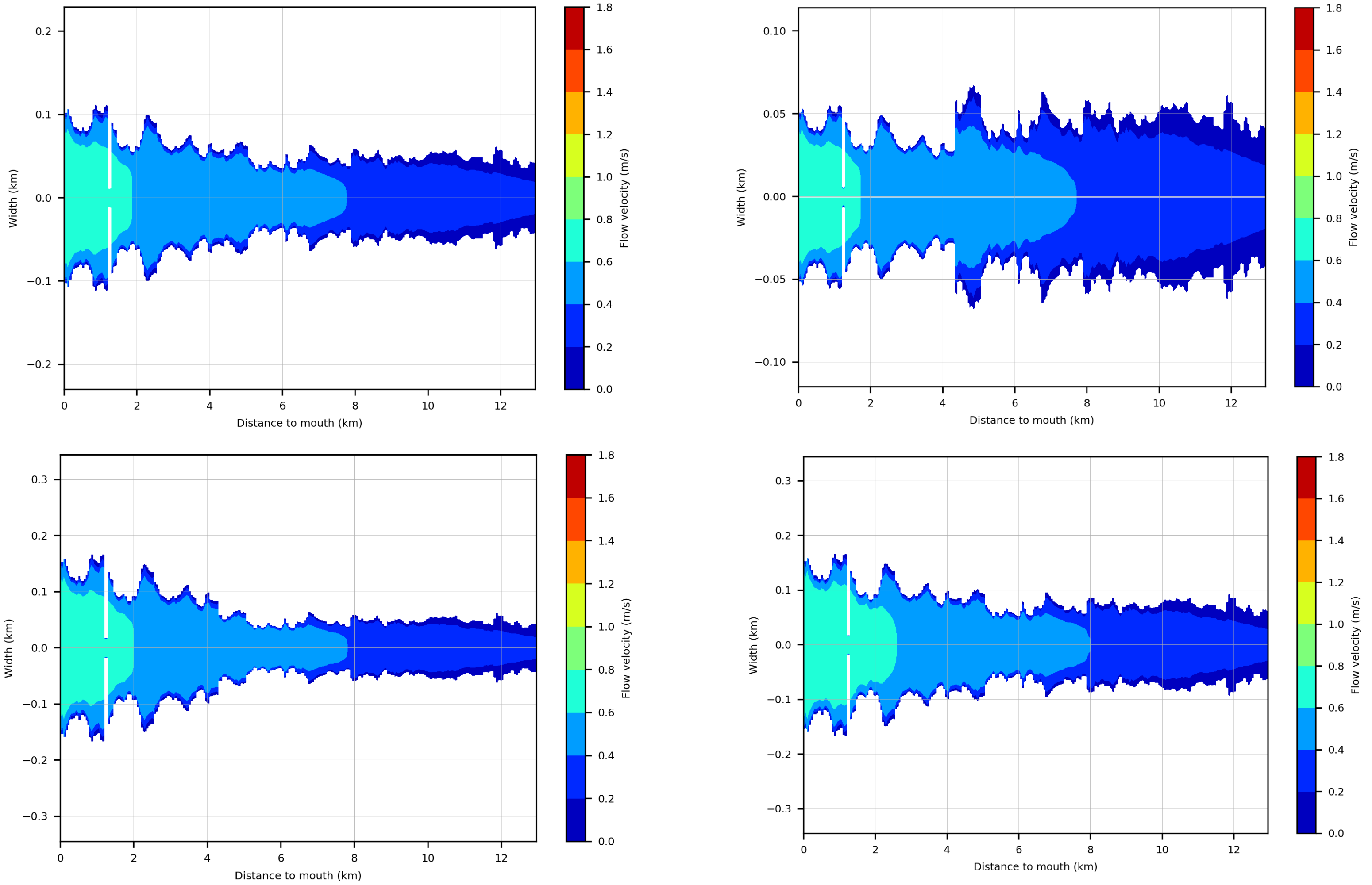
Graph 14: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Jalaur River (Velocity Max)



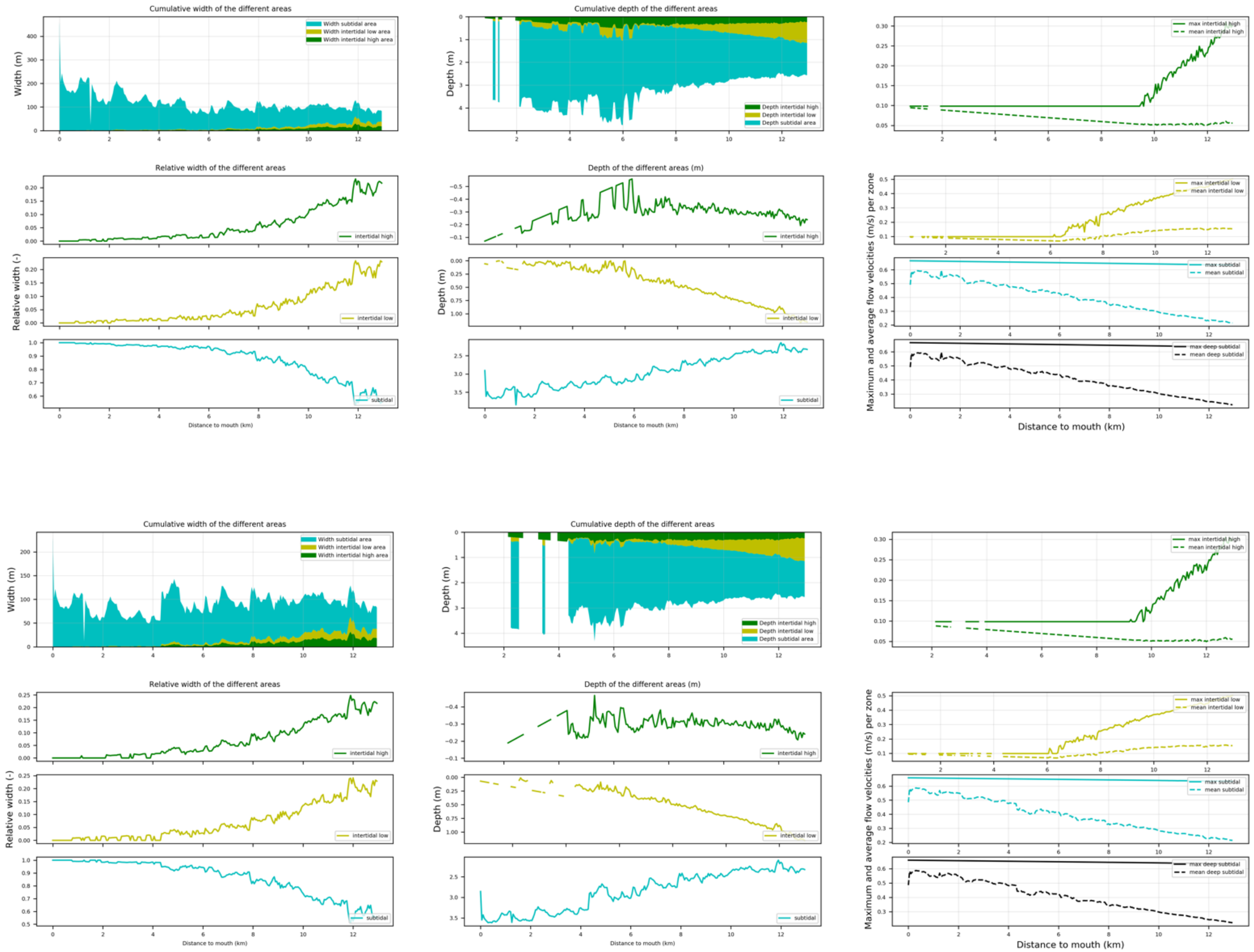
Graph 15: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Jalaur River (Velocity Mean)



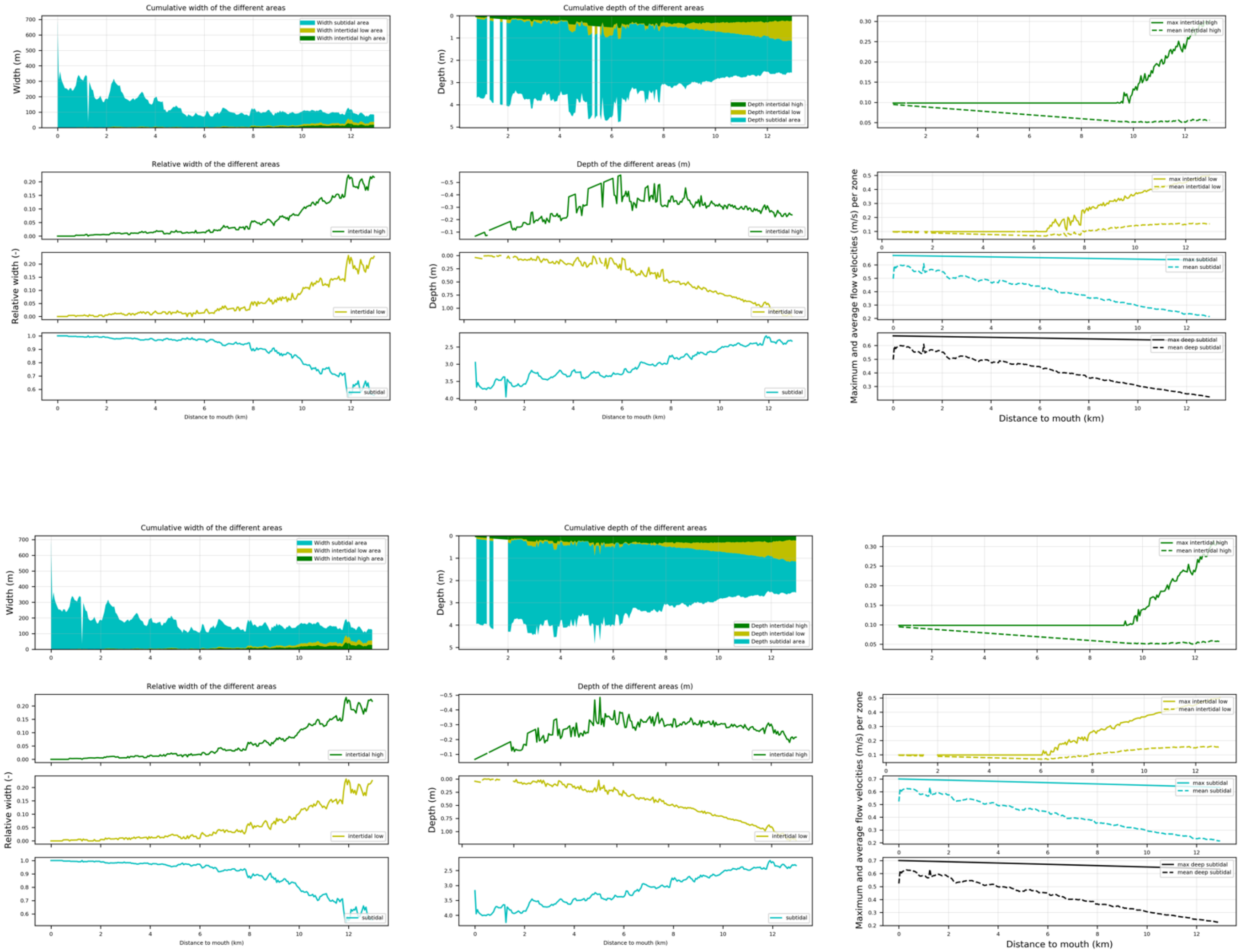
Graph 16: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Jalaur River (Zones Combined- I)



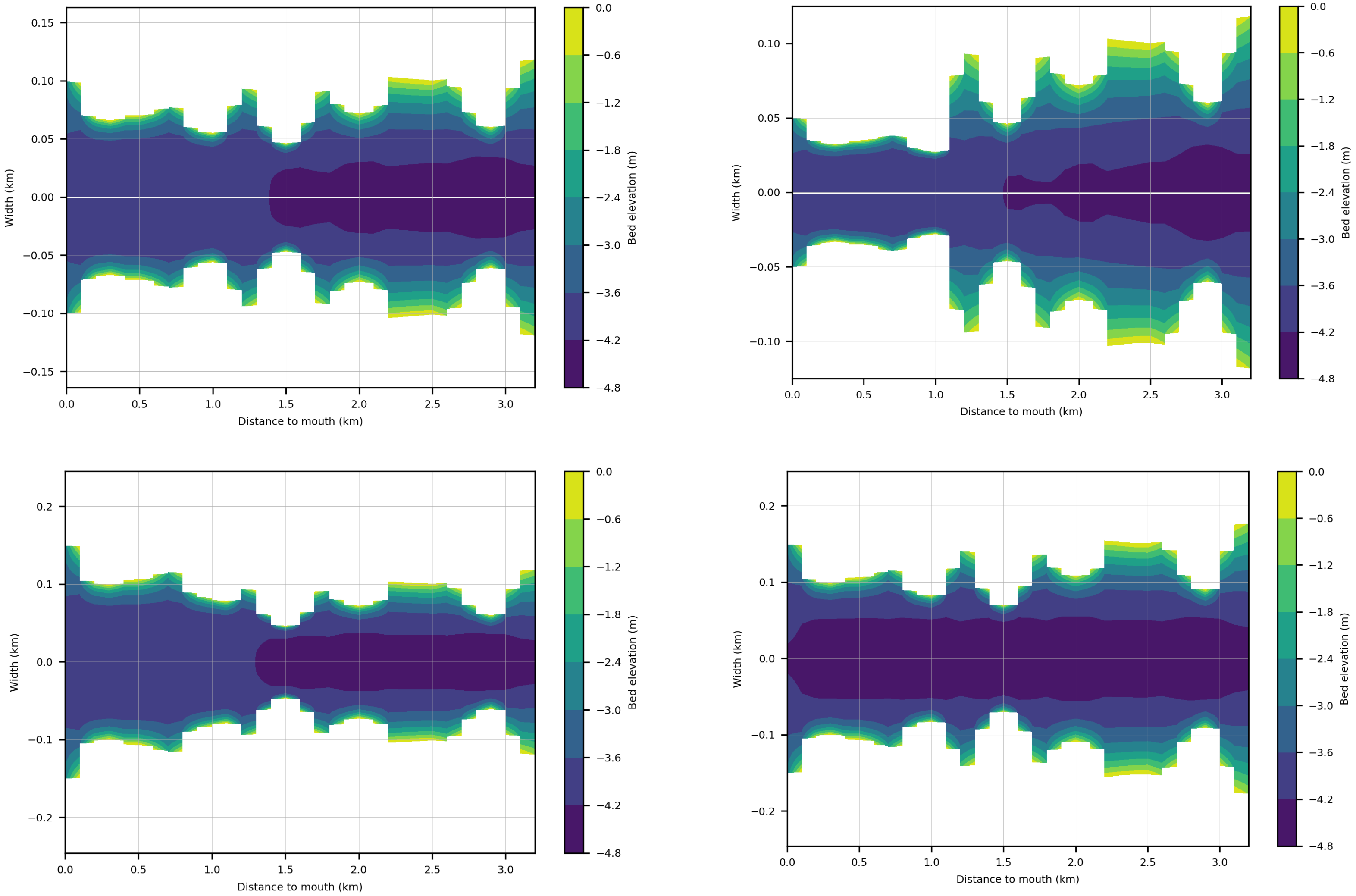
Graph 17: Top (Normal), bottom (Narrowed Mouth)

Jalaur River (Zones Combined- II)



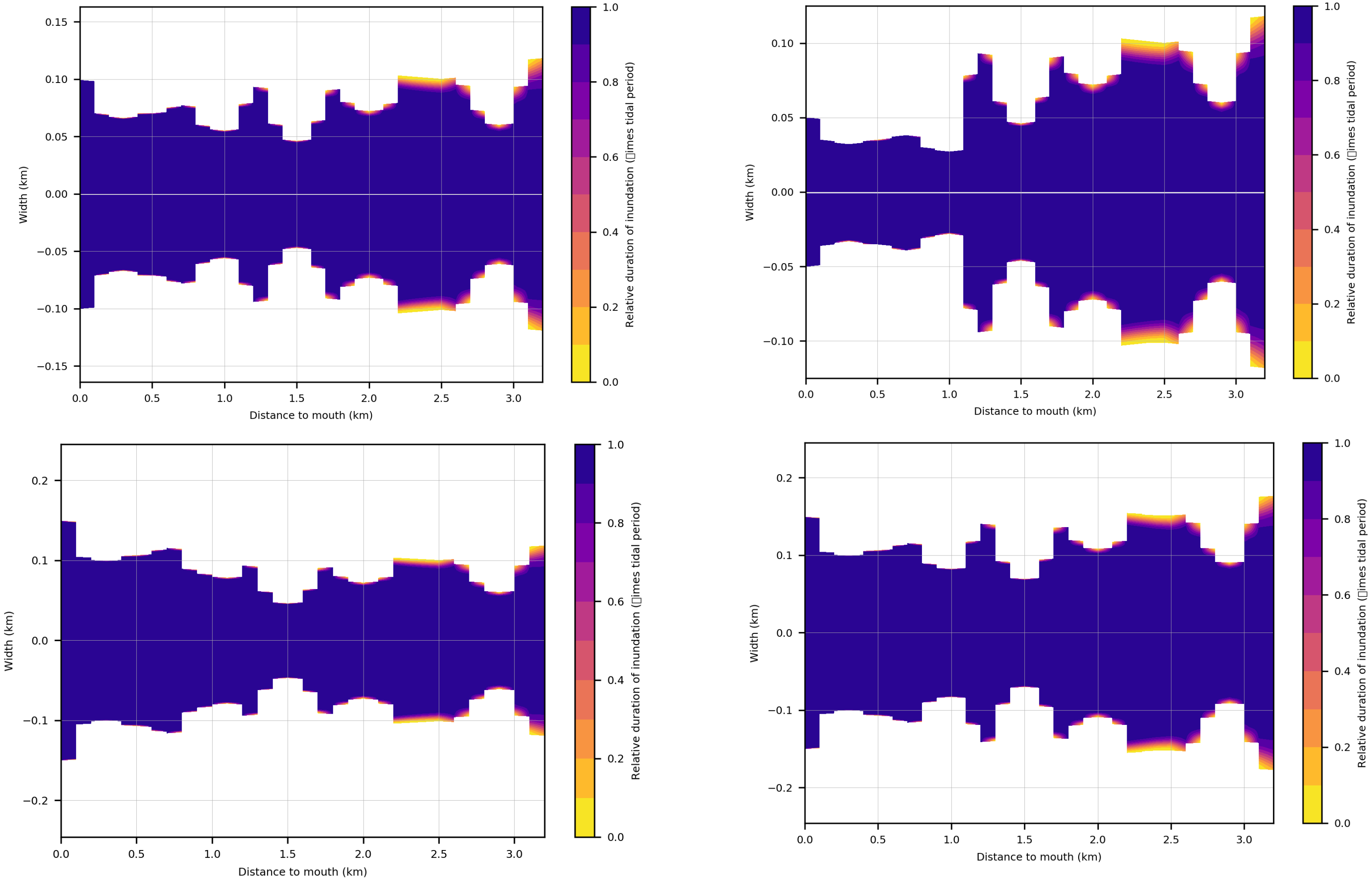
Graph 18: Top (Widened Mouth), bottom (Widened Entire Estuary)

Buayan River (Depth)



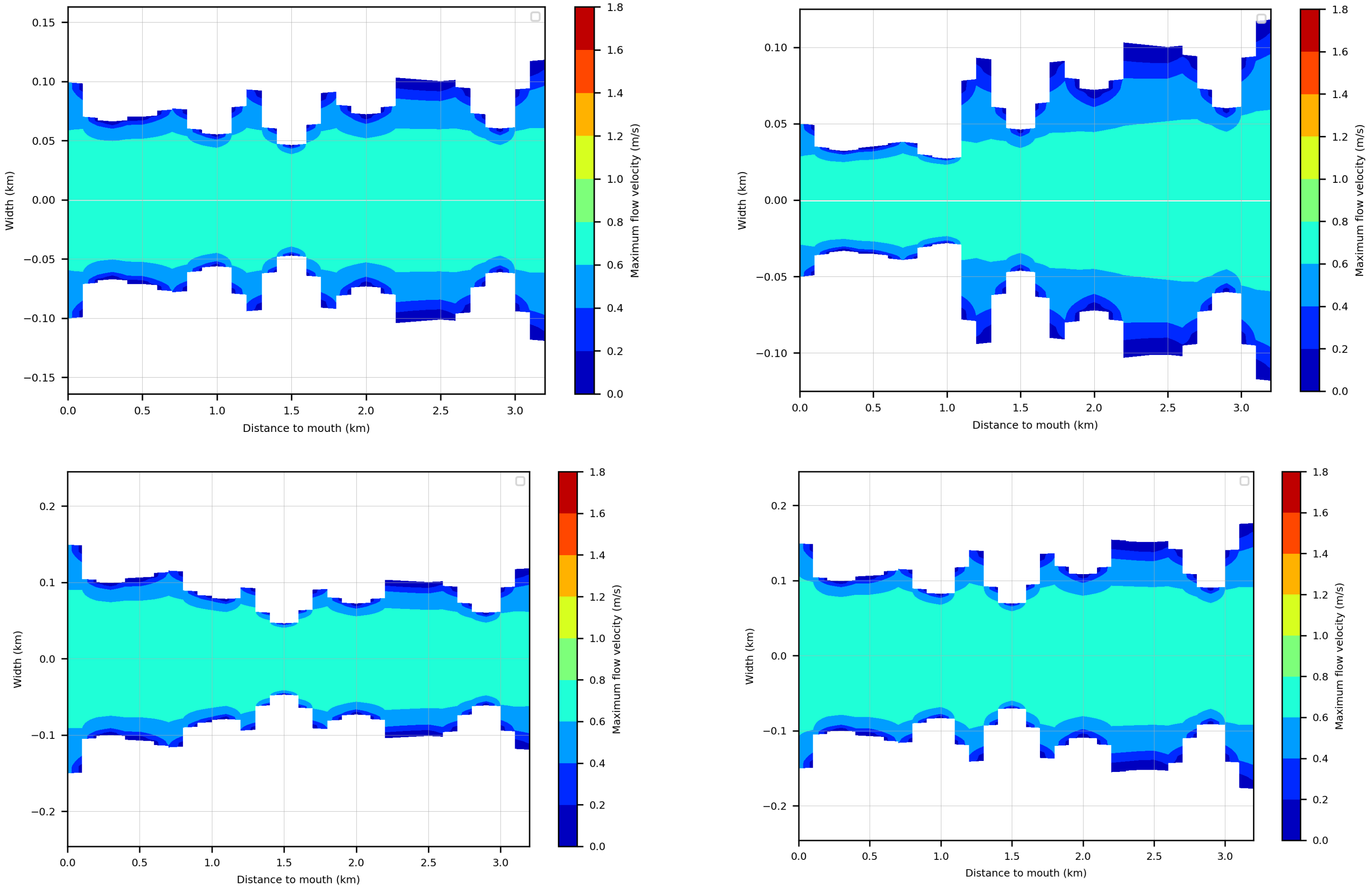
Graph 19: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Buayan River (Inundation Time)



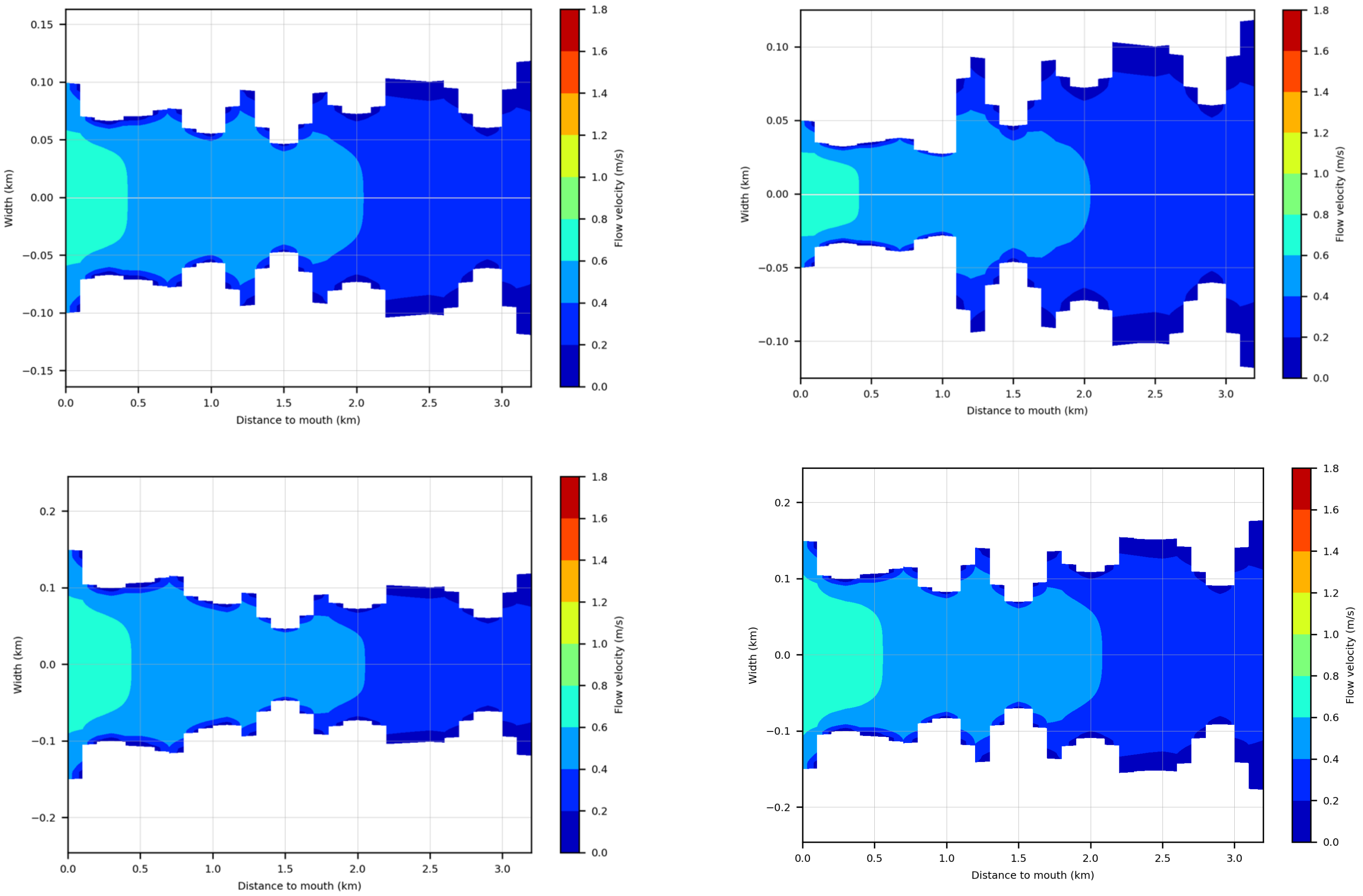
Graph 20: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Buayan River (Velocity Max)



Graph 21: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Buayan River (Velocity Mean)

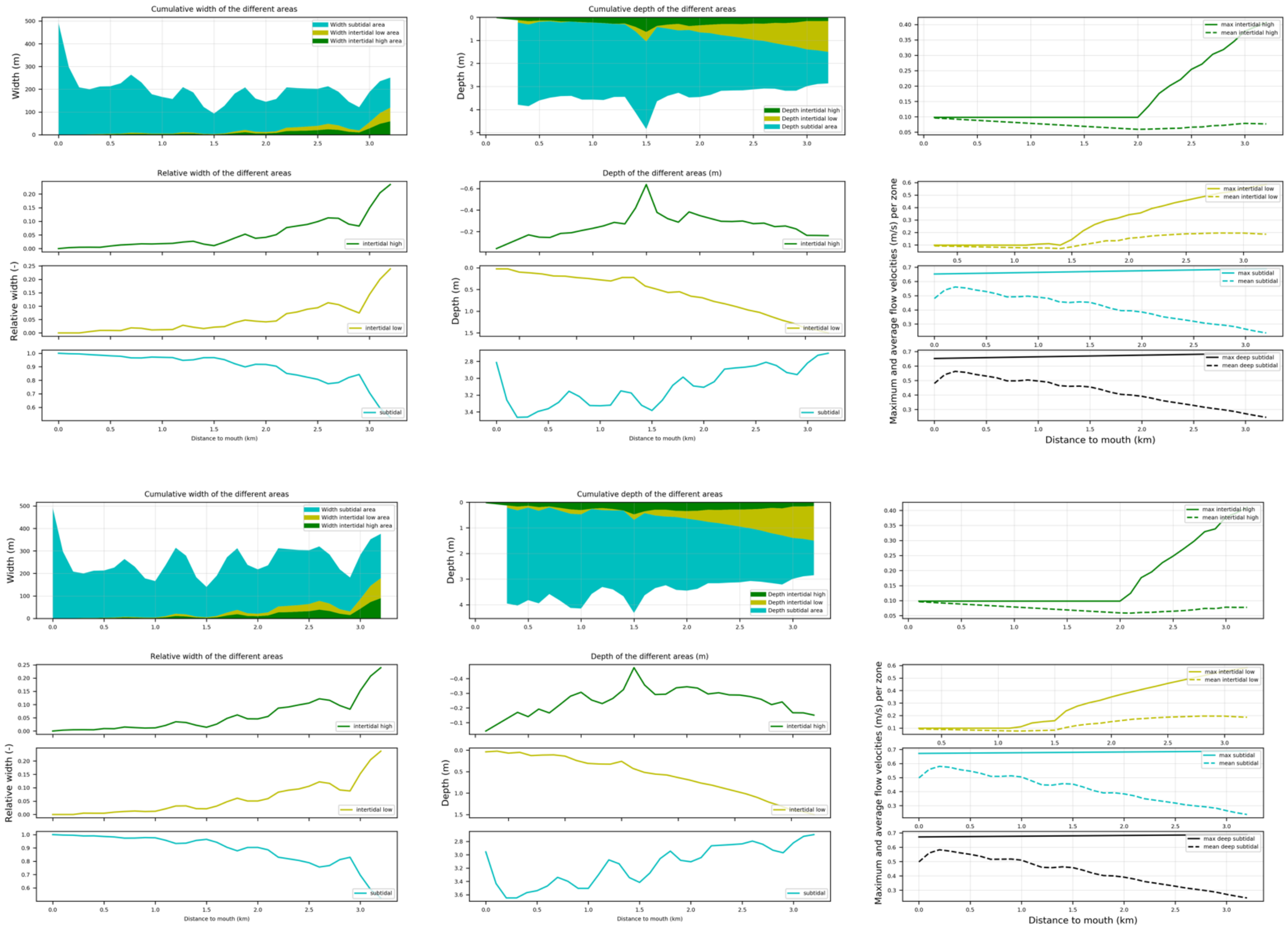


Graph 22: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Buayan River (Zones Combined- I)

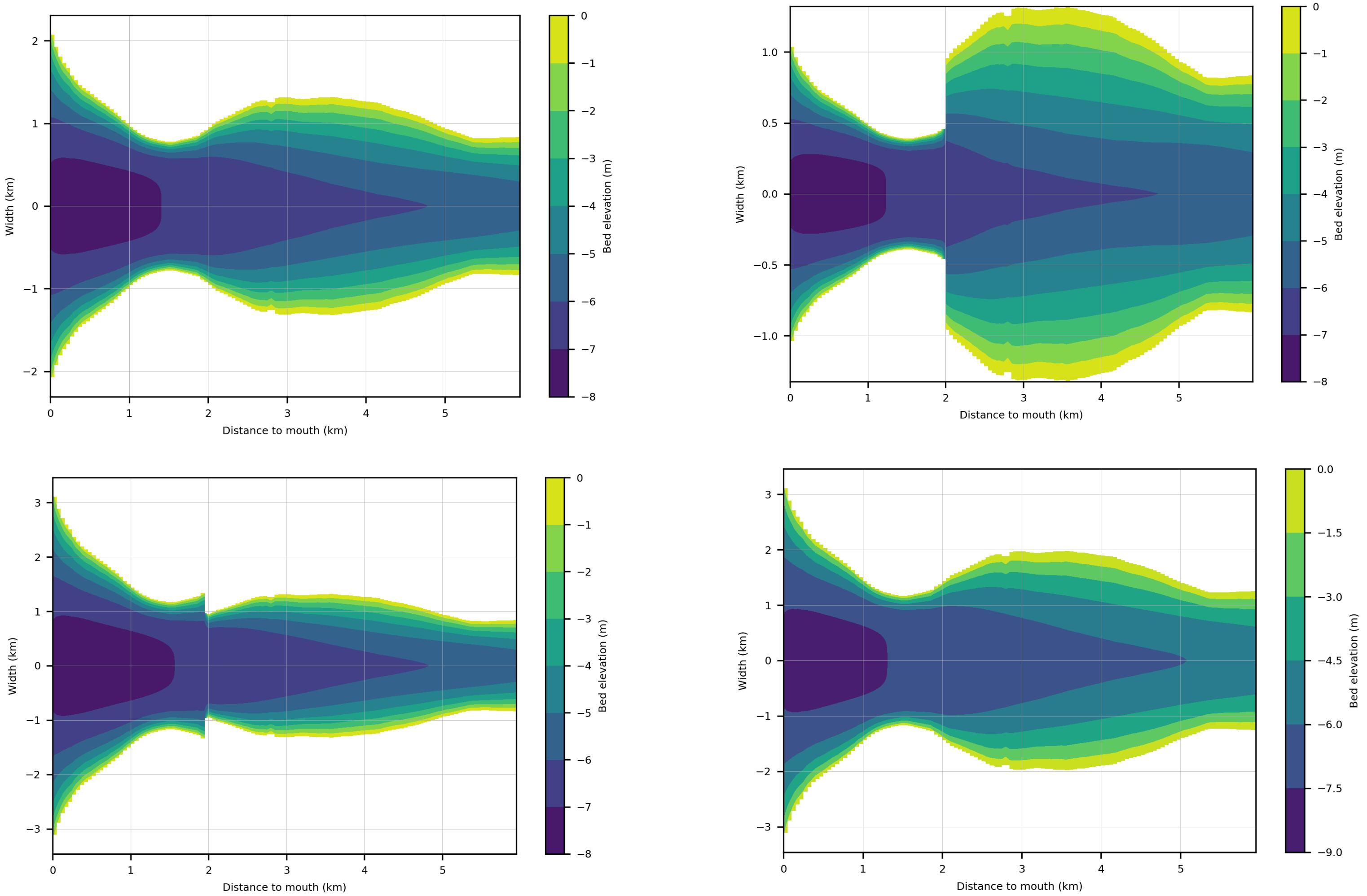
Graph 23: Top (Normal), bottom (Narrowed Mouth)

Buayan River (Zones Combined- II)



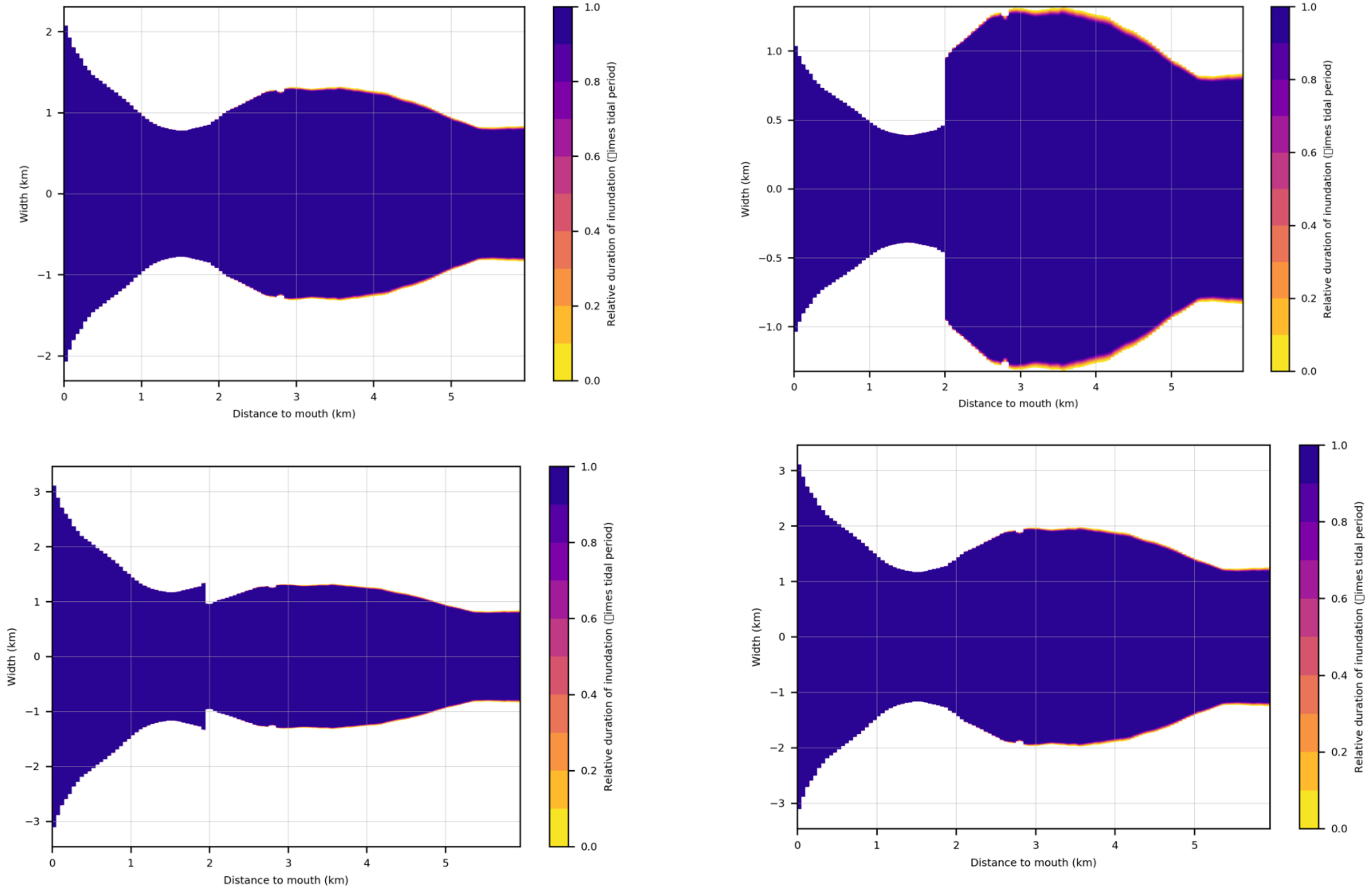
Graph 24: Top (Widened Mouth), bottom (Widened Entire Estuary)

Abra River (Depth)



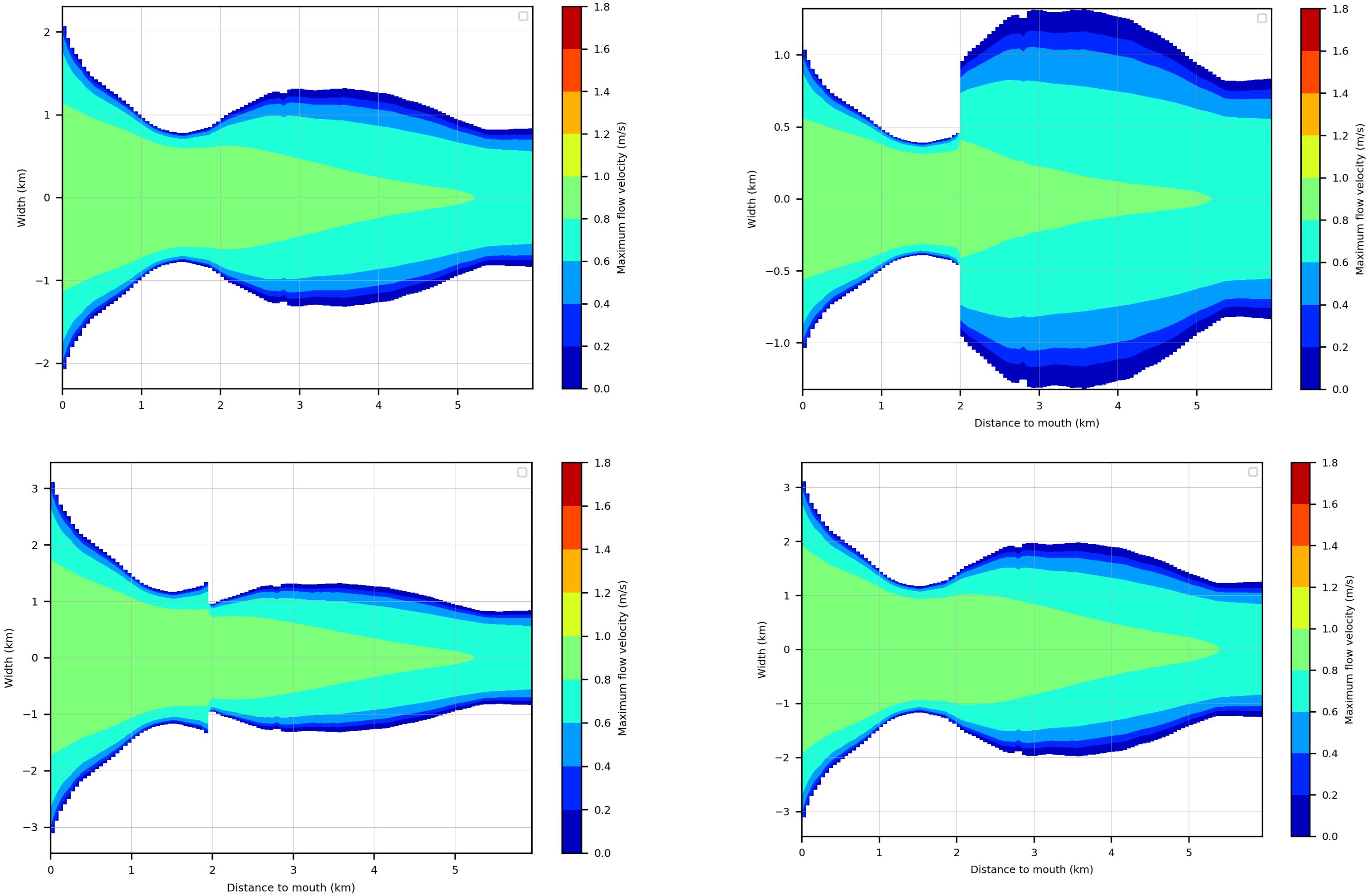
Graph 25: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Abra River (Inundation Time)



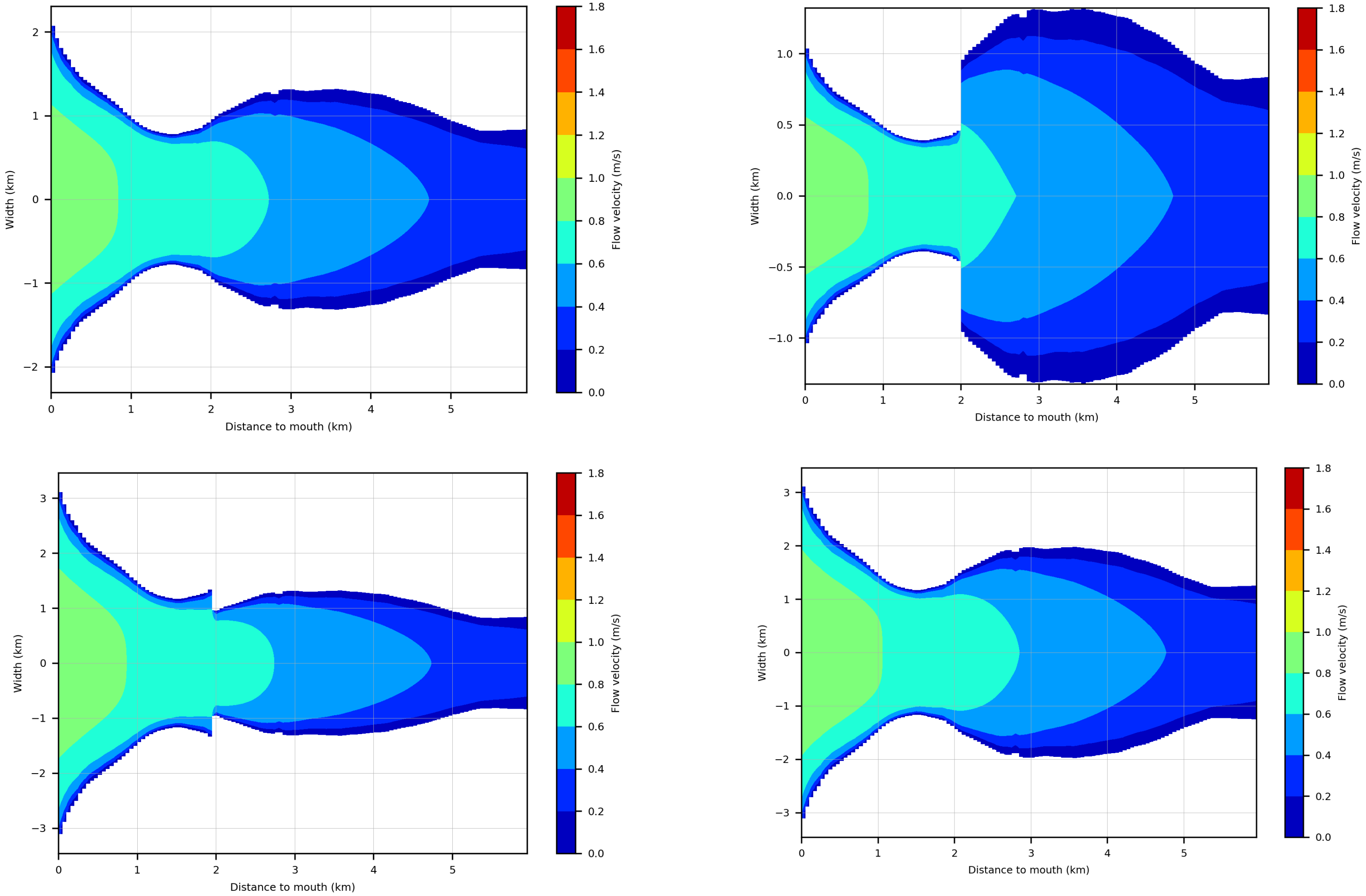
Graph 26: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Abra River (Velocity Max)



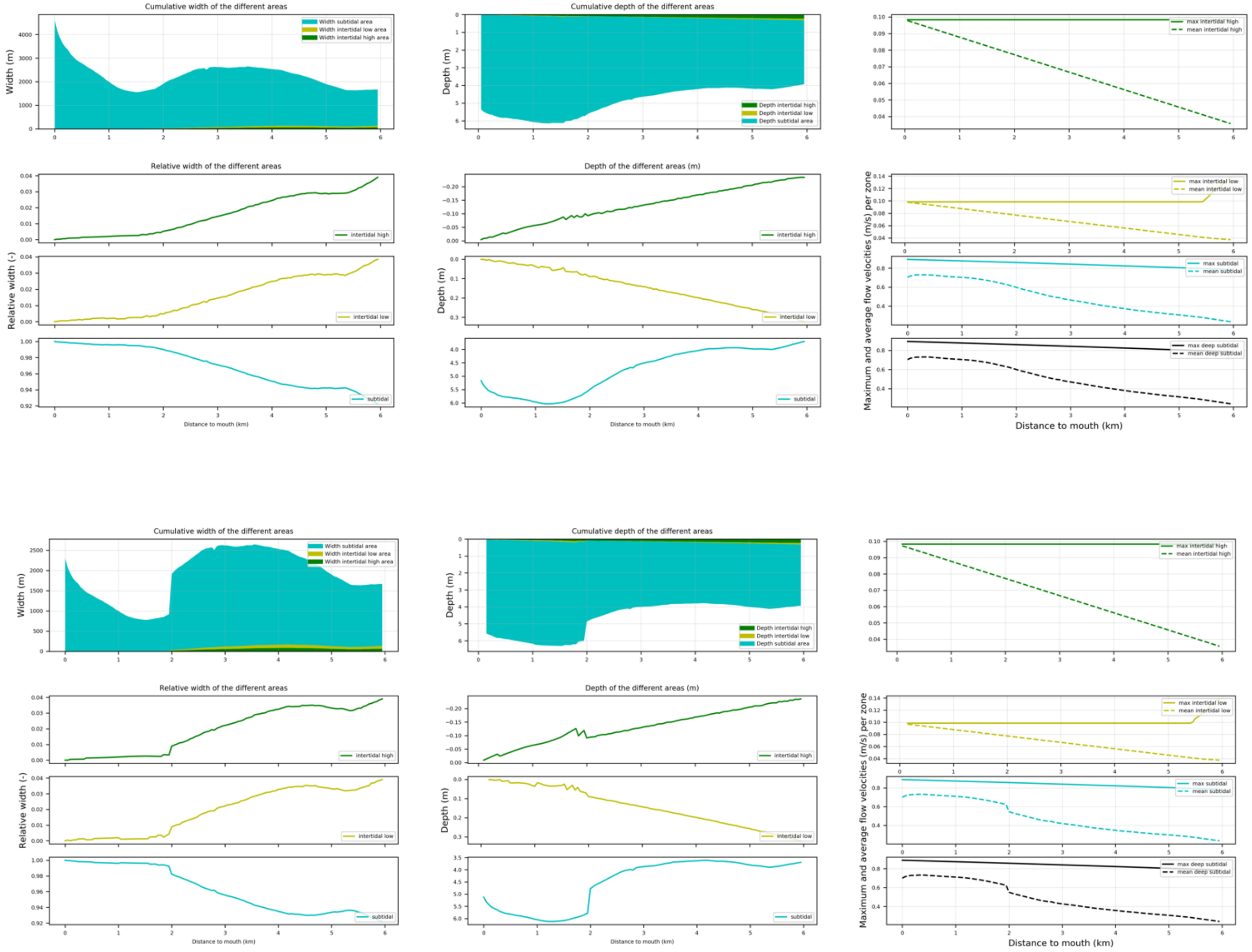
Graph 27: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Abra River (Velocity Mean)



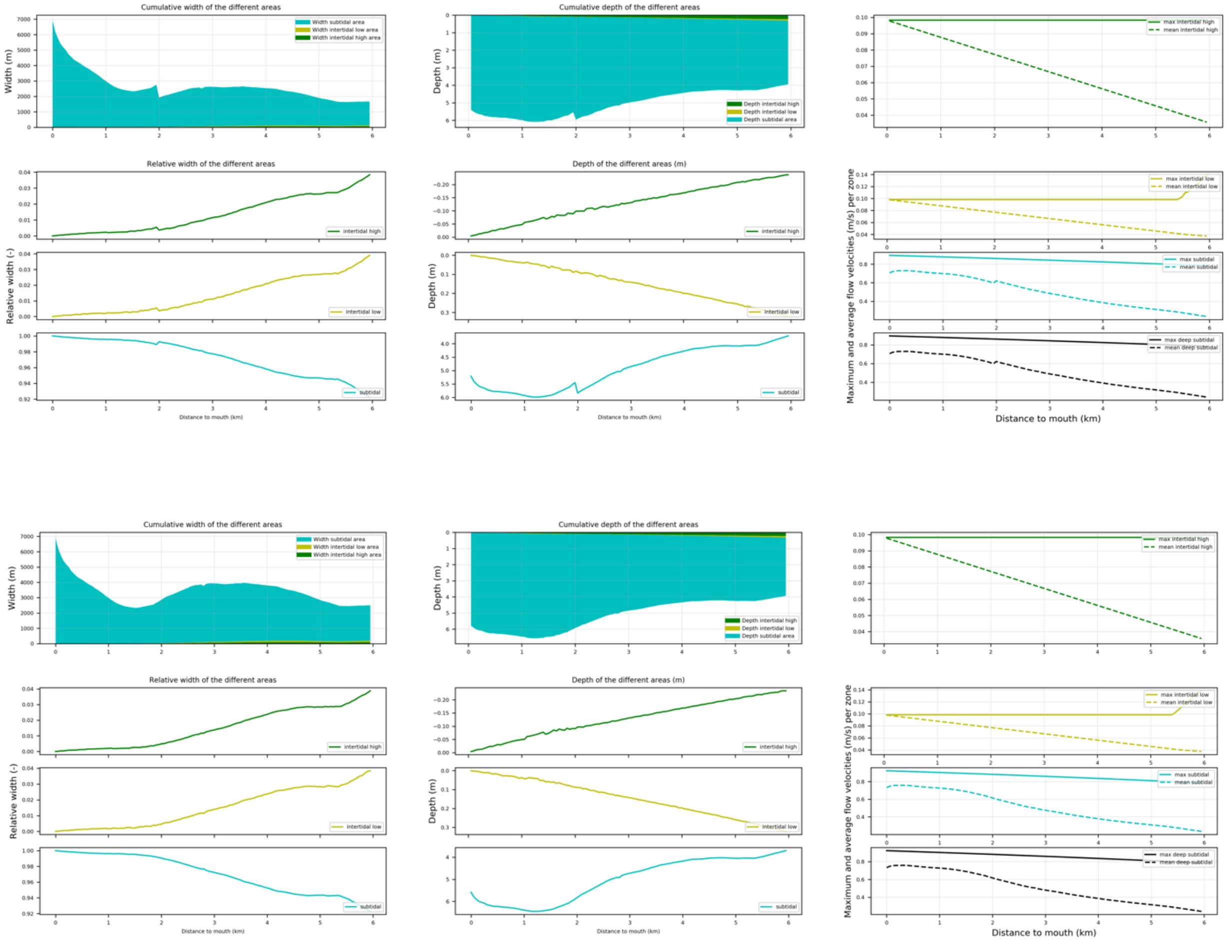
Graph 28: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Abra River (Zones Combined- I)



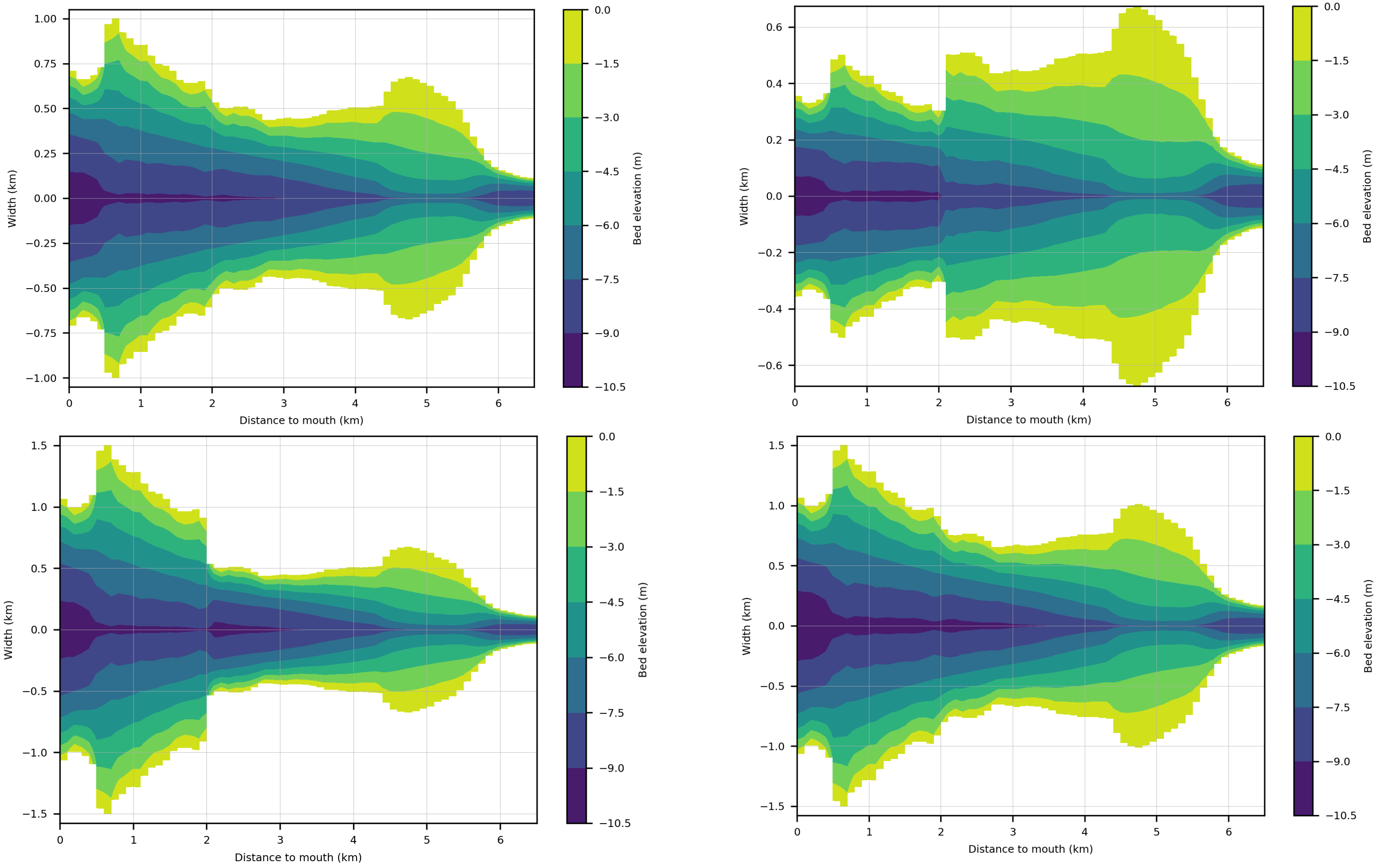
Graph 29: Top (Normal), bottom (Narrowed Mouth)

Abra River (Zones Combined- II)



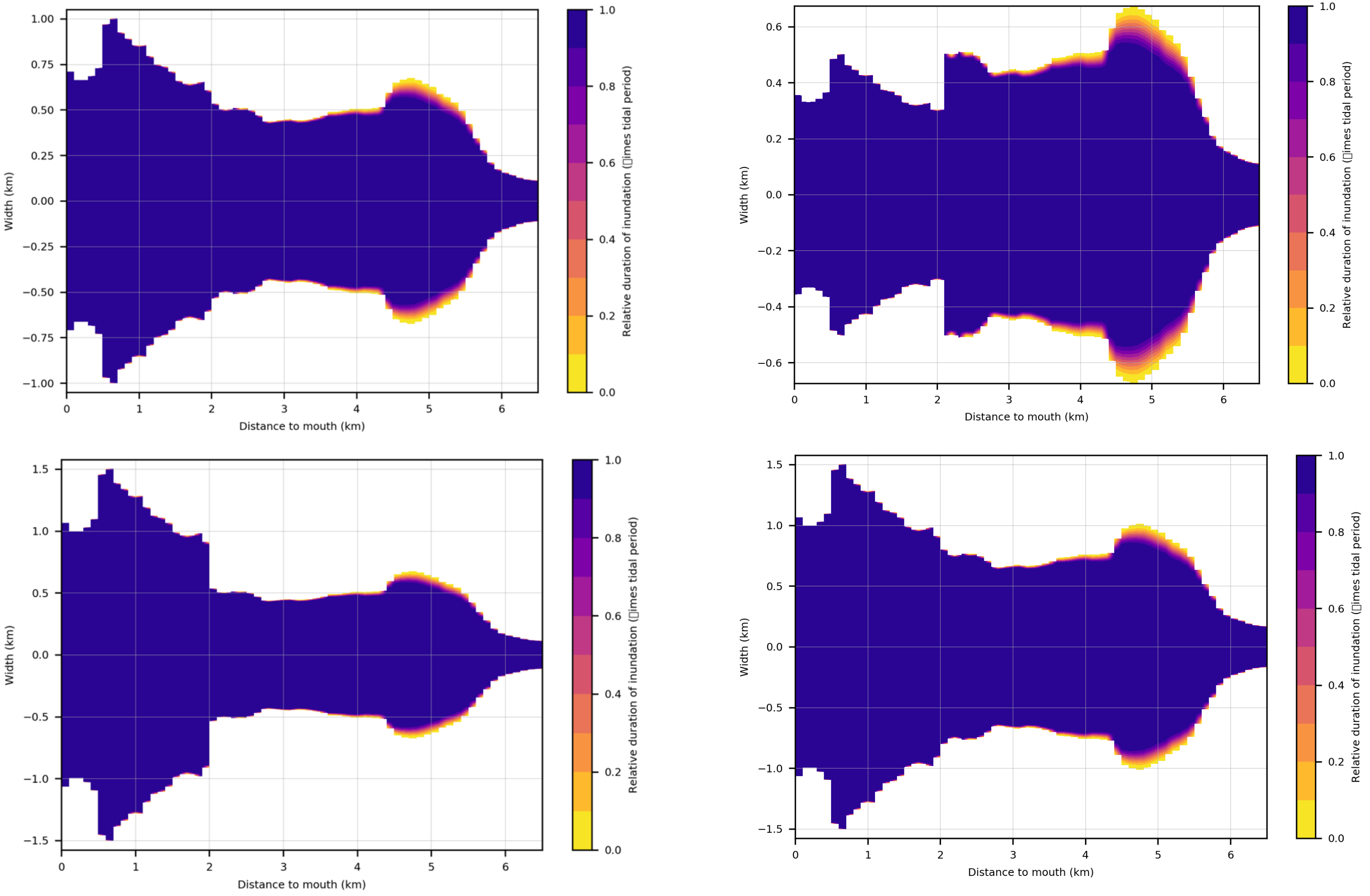
Graph 30: Top (Widened Mouth), bottom (Widened Entire Estuary)

Abulug River (Depth)



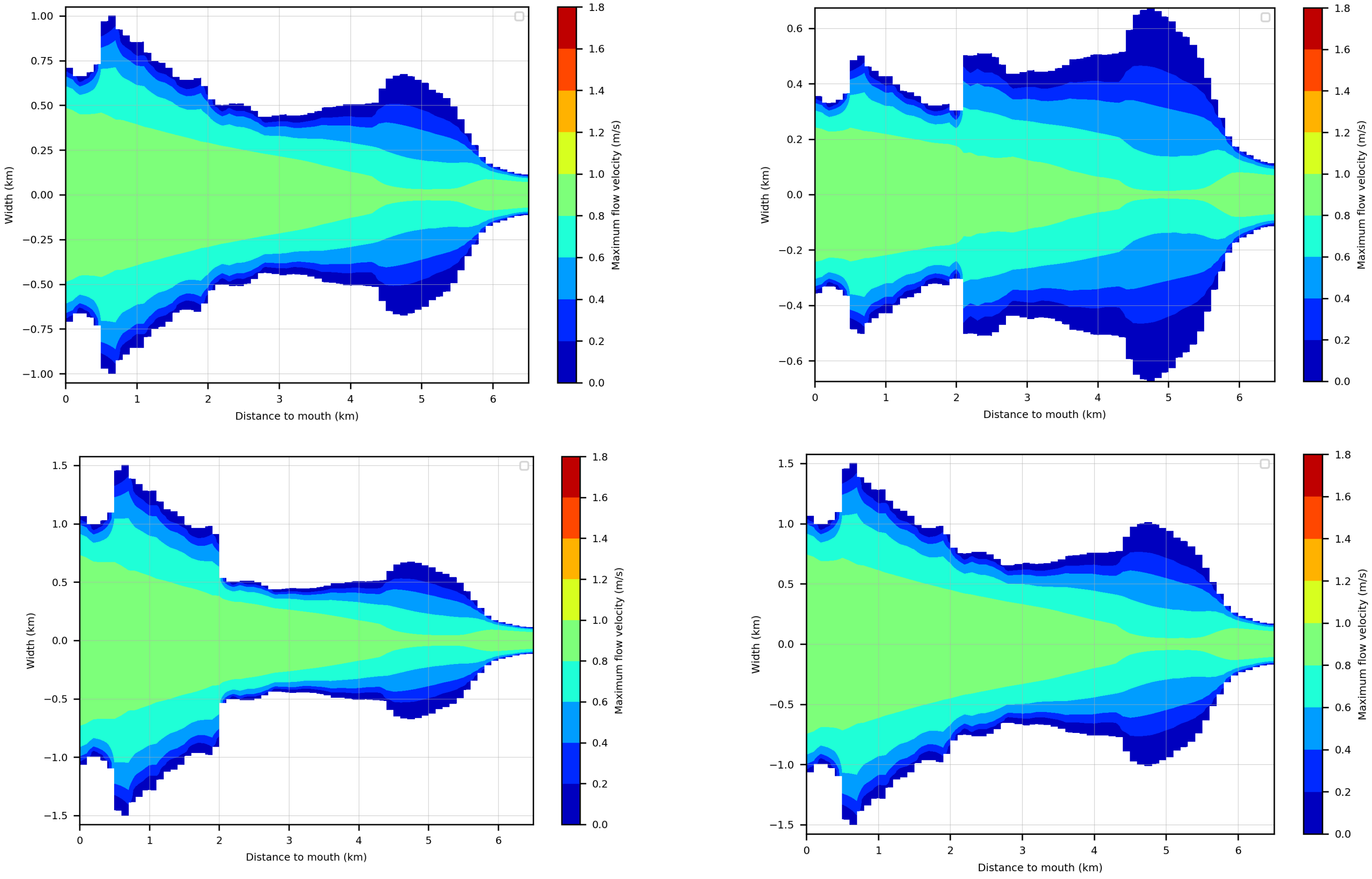
Graph 31: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Abulug River (Inundation Time)



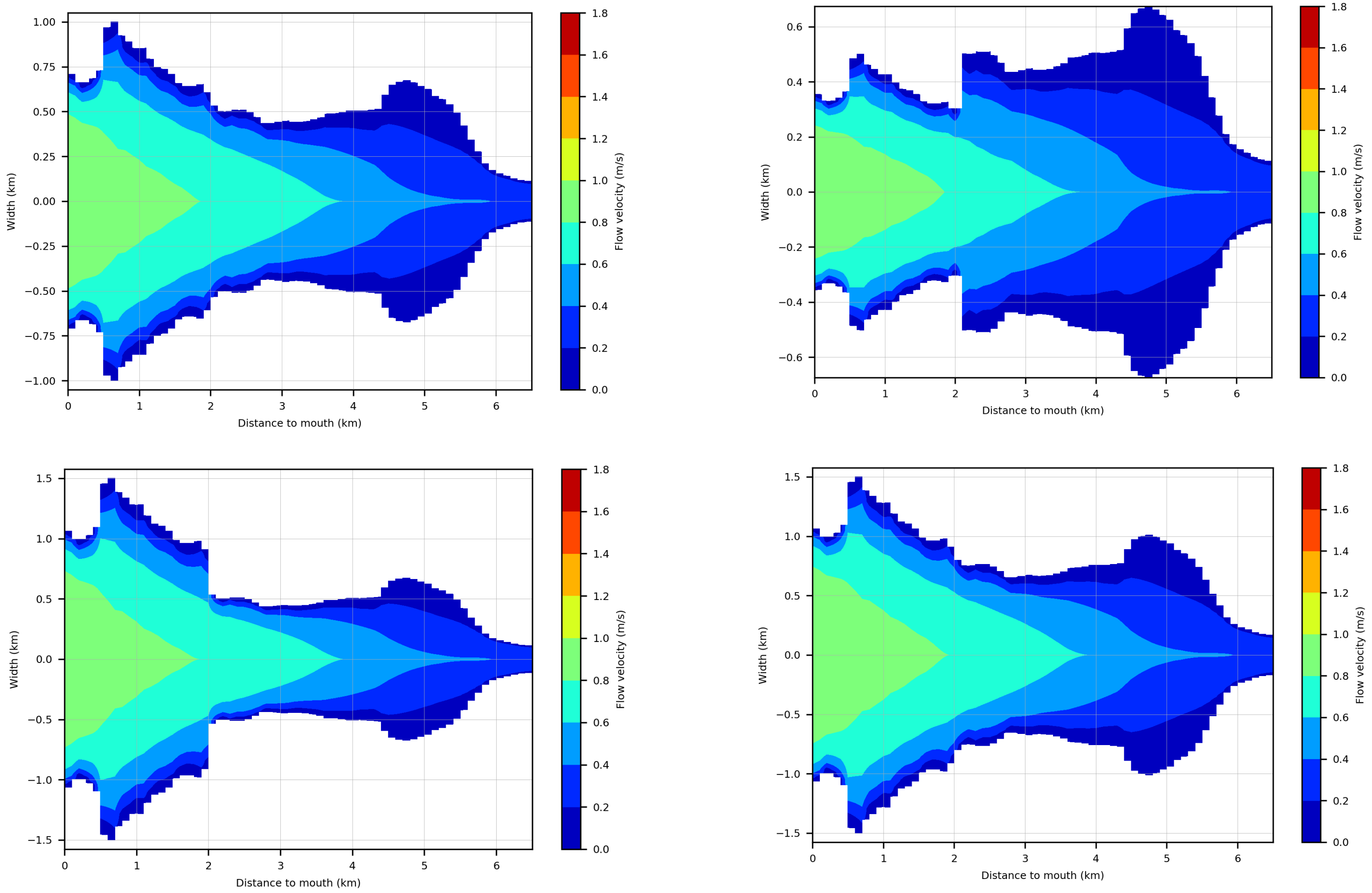
Graph 32: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Abulug River (Velocity Max)



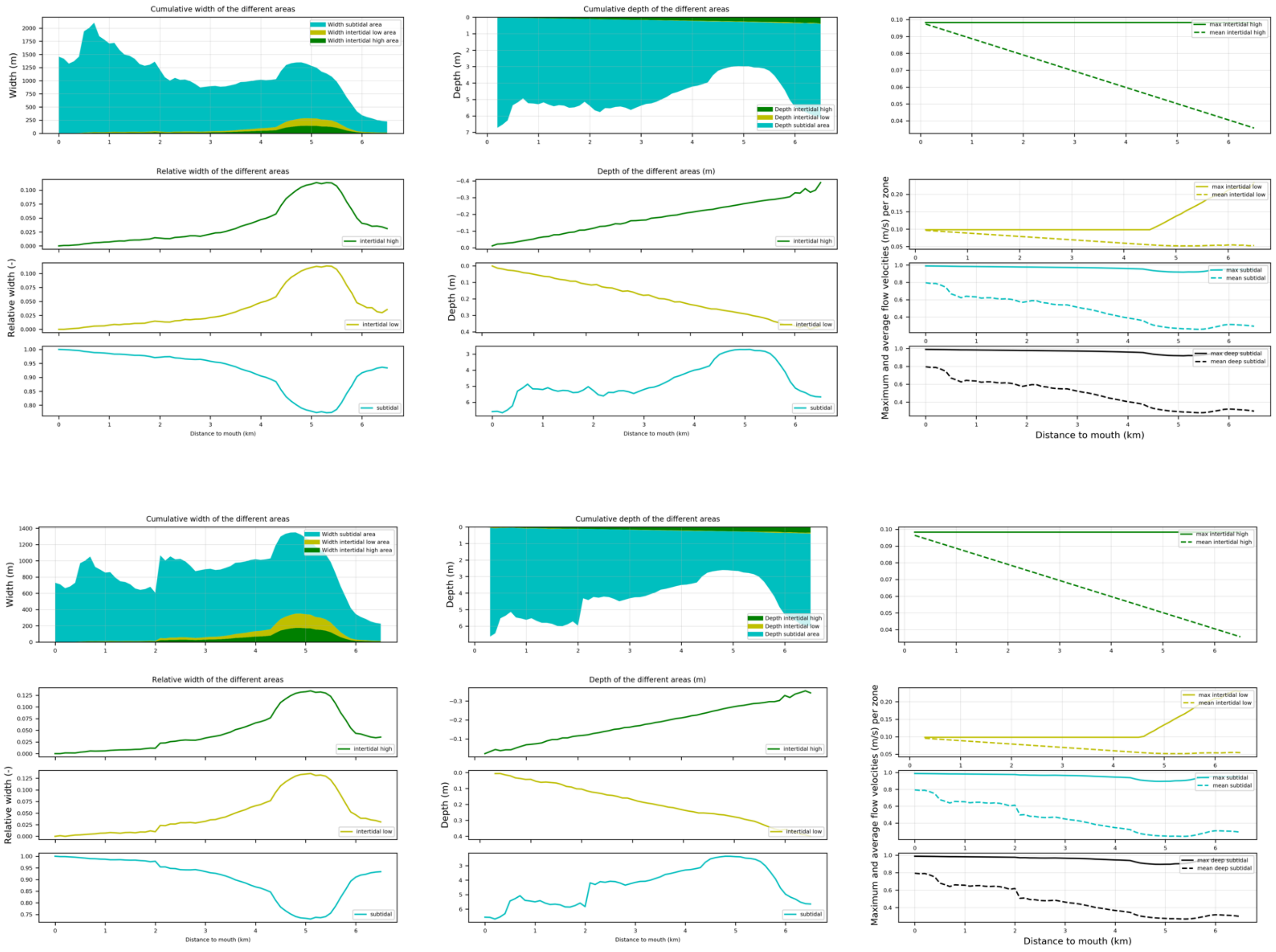
Graph 33: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Abulug River (Velocity Mean)



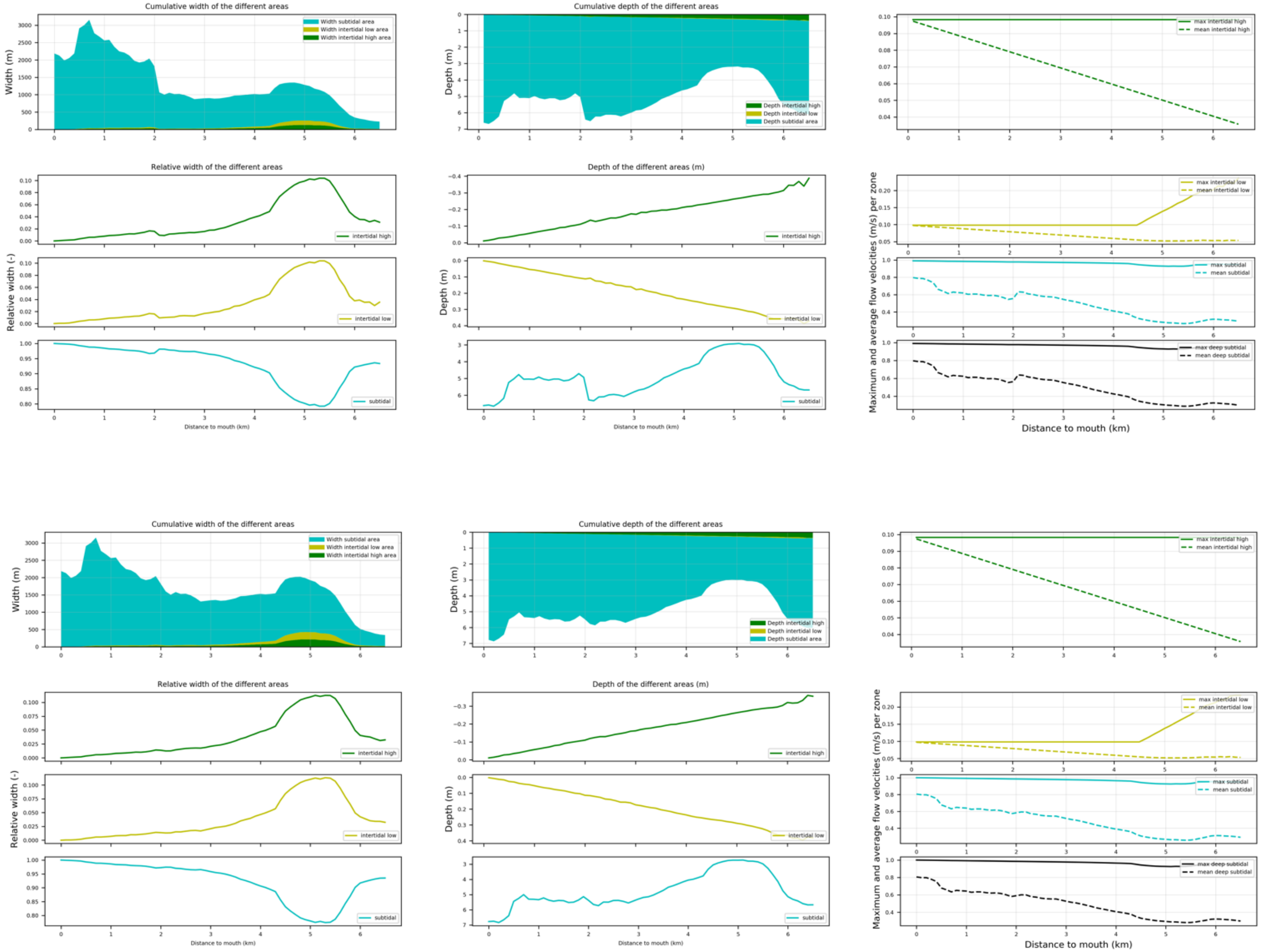
Graph 34: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Abulug River (Zones Combined- I)



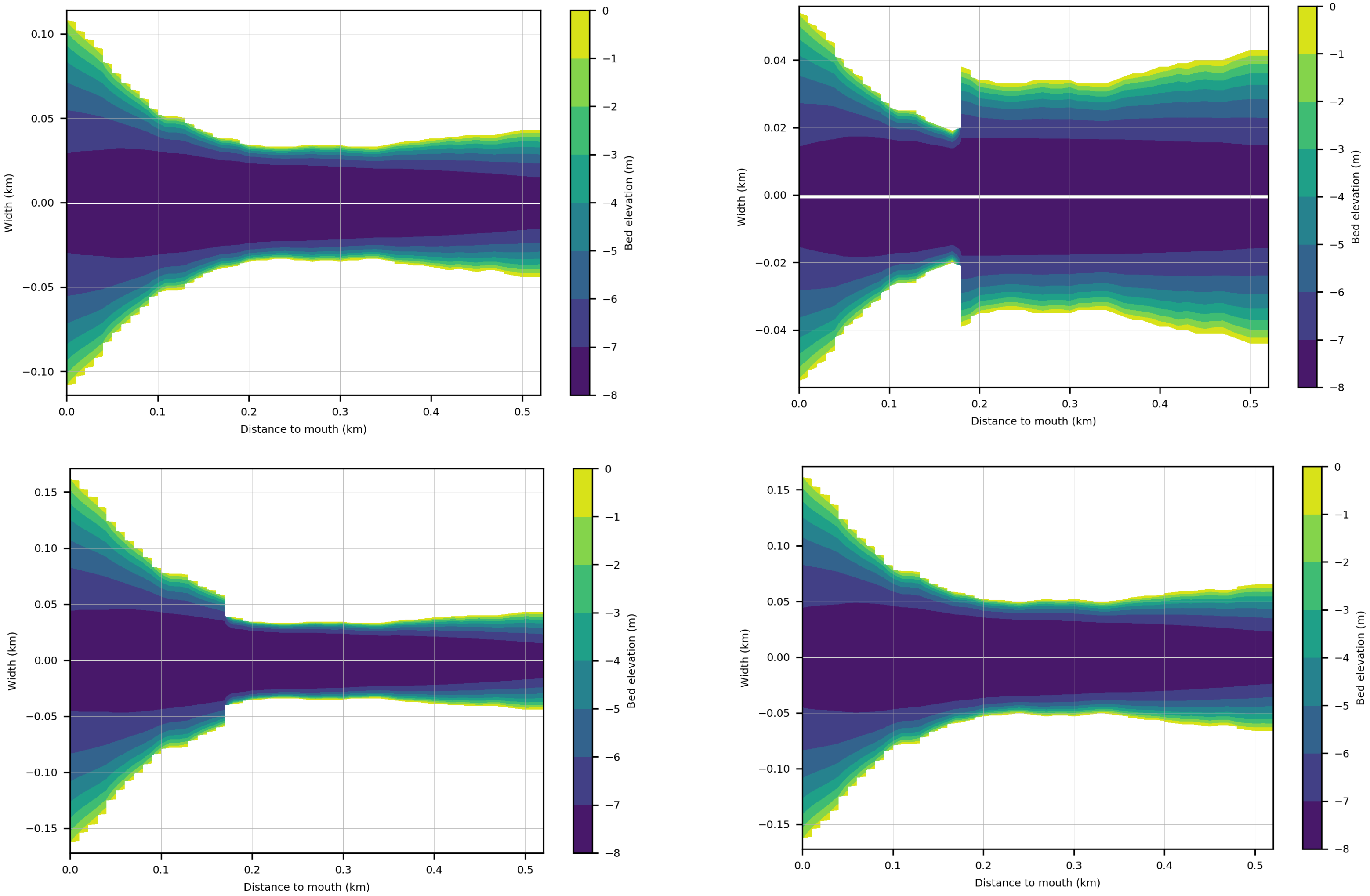
Graph 35: Top (Normal), bottom (Narrowed Mouth)

Abulug River (Zones Combined- II)



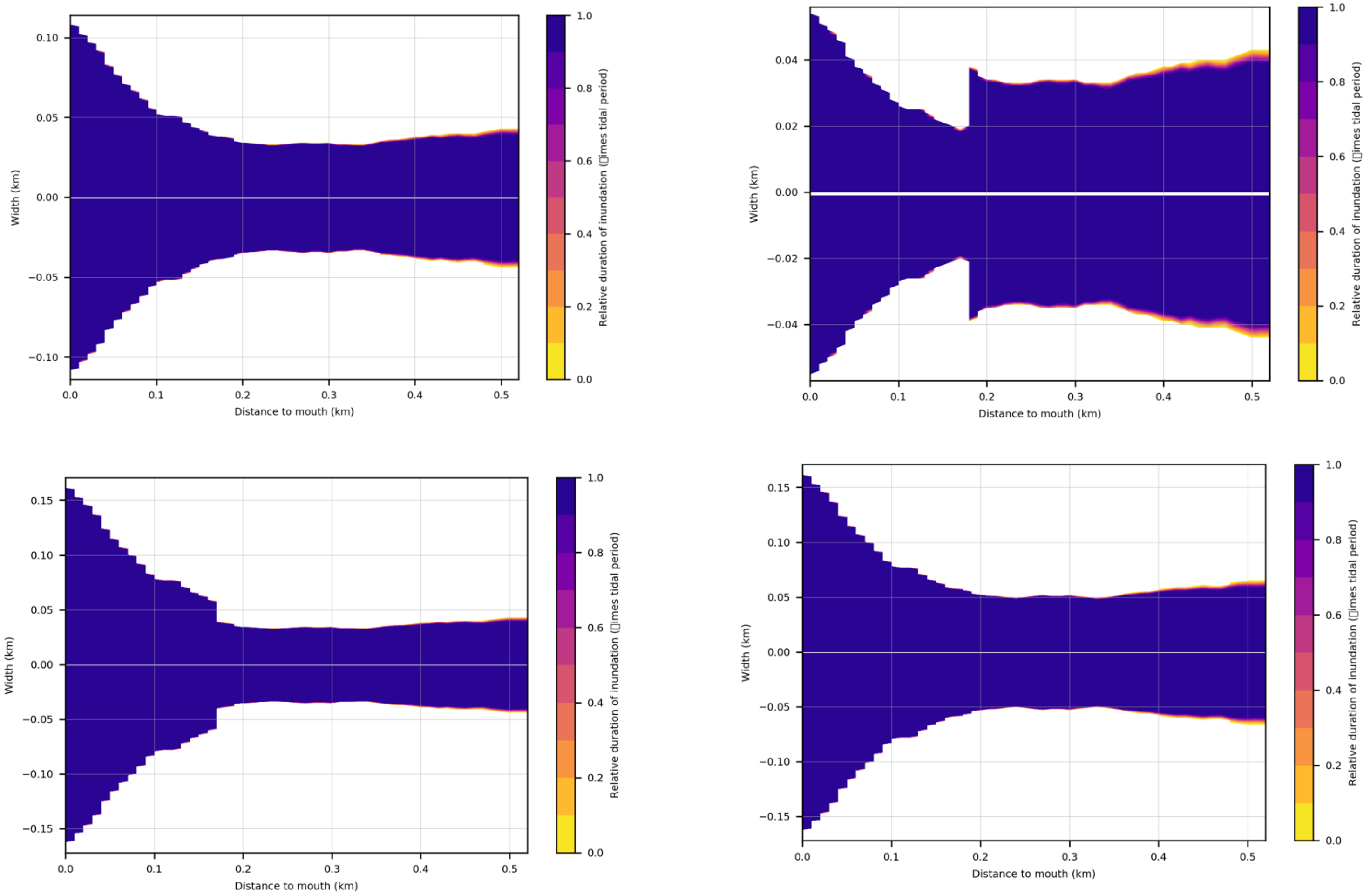
Graph 36: Top (Widened Mouth), bottom (Widened Entire Estuary)

Tagum River (Depth)



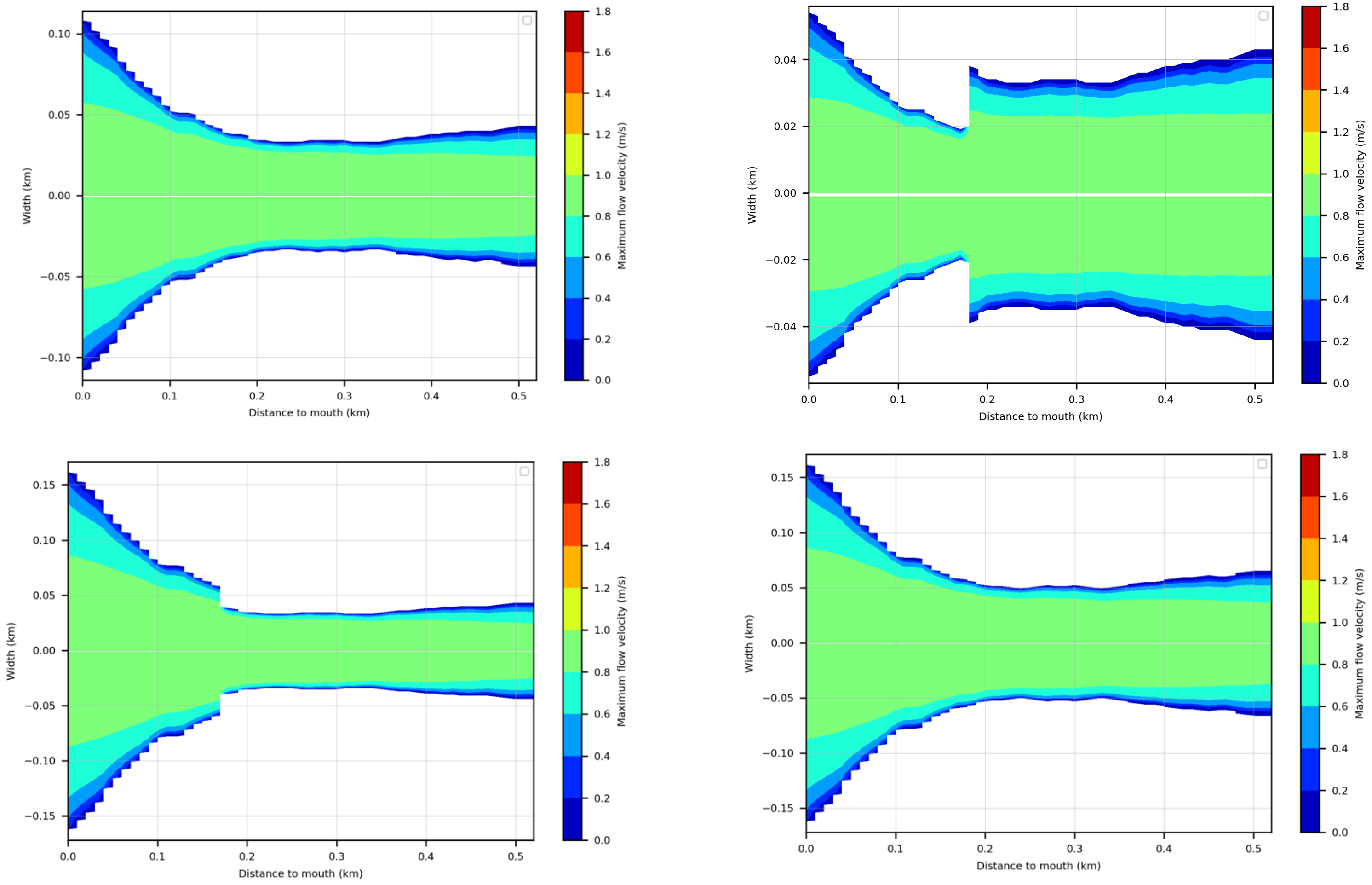
Graph 37: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Tagum River (Inundation Time)



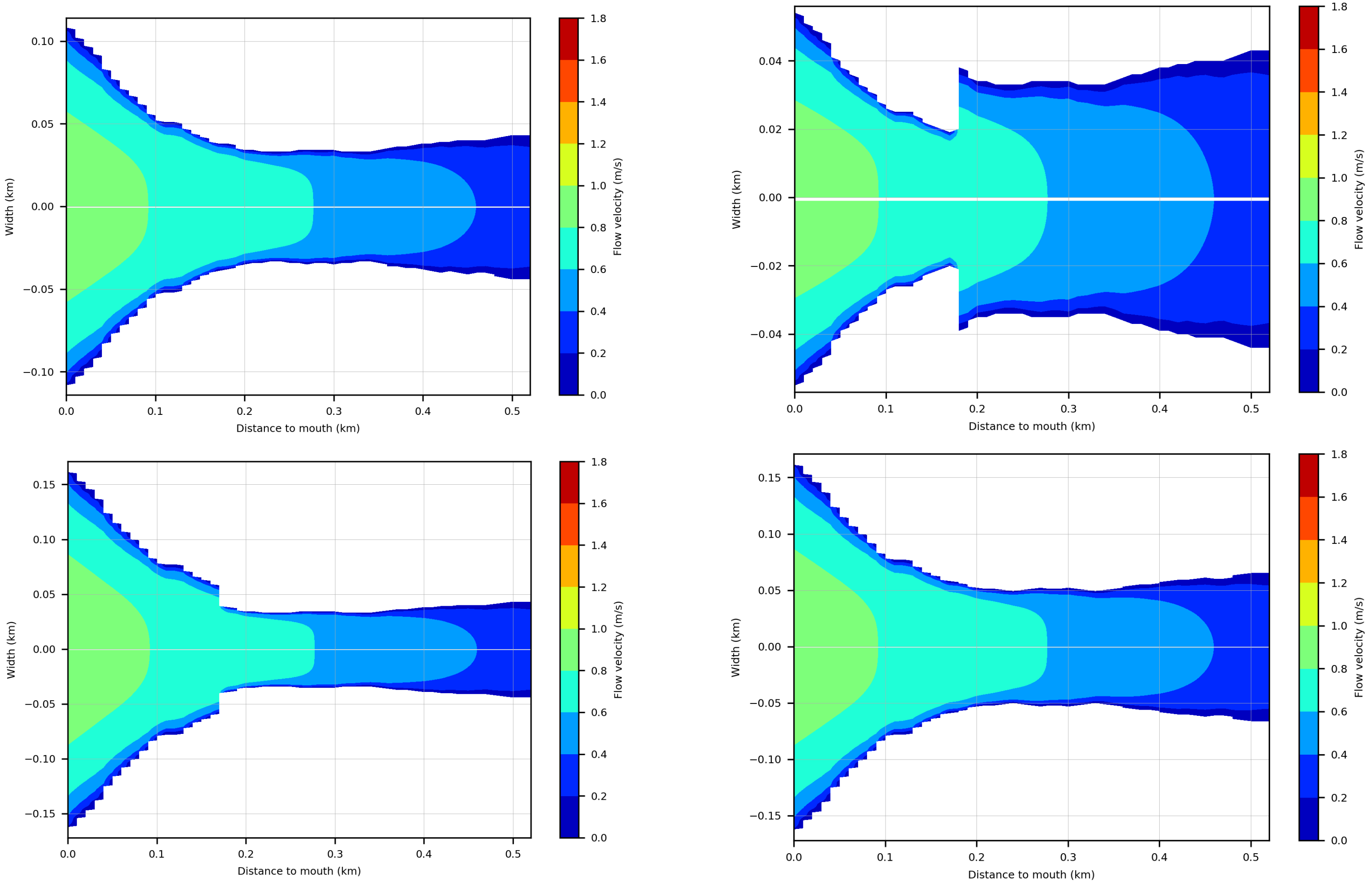
Graph 38: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Tagum River (Velocity Max)



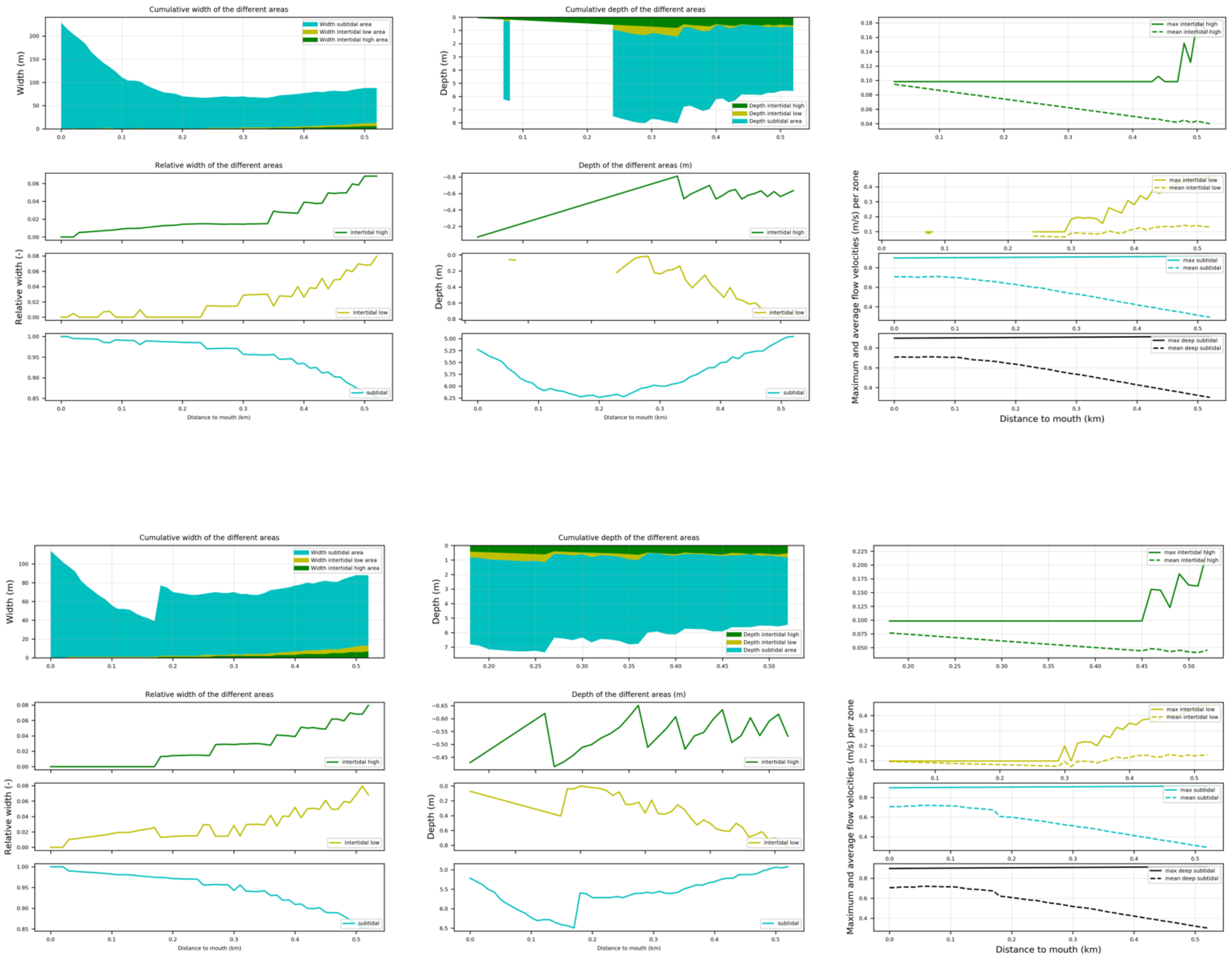
Graph 39: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Tagum River (Velocity Mean)



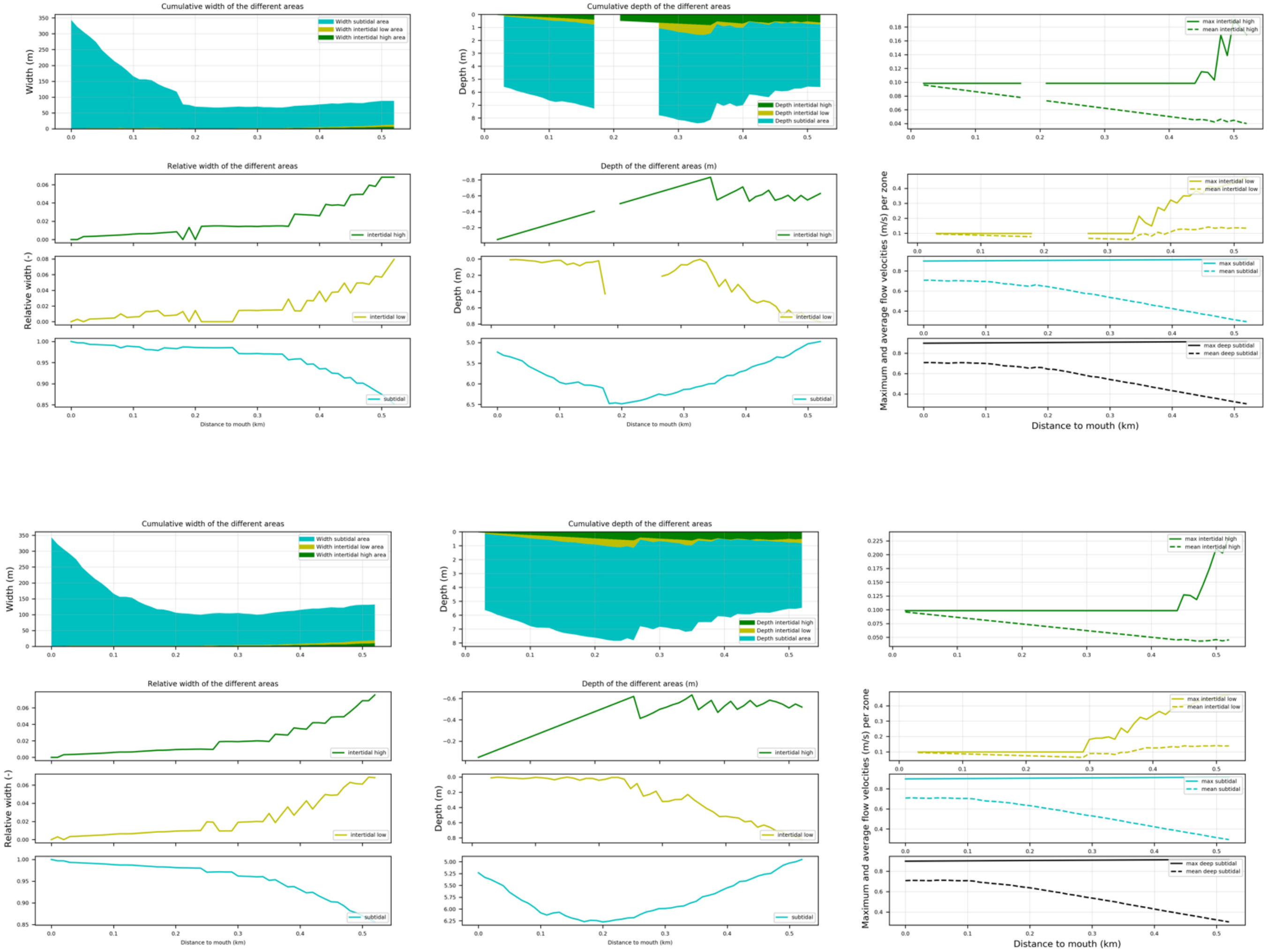
Graph 40: Top left (Normal), top right (Narrowed Mouth), bottom left (Widened Mouth), bottom right (Widened Entire Estuary)

Tagum River (Zones Combined- I)



Graph 41: Top (Normal), bottom (Narrowed Mouth)

Tagum River (Zones Combined- II)



Graph 42: Top (Widened Mouth), bottom (Widened Entire Estuary)

		Hotspots			
	Methods:	1	2	3	4
Jalaur Q10	Normal	2.4305	2.4059	2.6071	2.7707
	Narrowed	2.6443	2.6889	3.2939	3.6065
	Widened	2.3974	2.3546	2.4164	2.5119
	Whole Estuary Widened	2.4348	2.3762	2.414	2.5096
	Widened Lower 2/3	2.4122	2.3631	2.4154	2.511
	Mouth Width Doubled	2.3942	2.3436	2.3456	2.4063
	Narrowed Upper 2/3	2.3902	2.385	2.614	2.7768
	Widened Upper 2/3	2.4656	2.4245	2.6017	2.7658
	Doubled Upper 2/3	2.4969	2.4413	2.5972	2.7617
Scenarios:					
	4.5 Normal	2.3313	2.3553	2.6255	2.7864
	4.5 Widened	2.2865	2.2911	2.4245	2.5195
	8.5 Normal	2.2943	2.3376	2.6346	2.7942
	8.5 Widened	2.2434	2.2669	2.4286	2.5233

		Hotspots			
	Methods:	1	2	3	4
Jalaur	Normal	2.3754	2.3284	2.2962	2.3118
	Narrowed	2.3711	2.3268	2.2963	2.3167
	Widened	2.3815	2.3313	2.2944	2.3098
	Whole Estuary Widened	2.4205	2.3548	2.2938	2.3089
	Widened Lower 2/3	2.3969	2.3406	2.2942	2.3094
	Mouth Width Doubled	2.3883	2.335	2.2931	2.3083
	Narrowed Upper 2/3	2.3288	2.3004	2.2972	2.3132
	Widened Upper 2/3	2.4152	2.3523	2.2953	2.3106
	Doubled Upper 2/3	2.4501	2.3733	2.2946	2.3096
Scenarios:					
	4.5 Normal	2.2581	2.2579	2.2985	2.3151
	4.5 Widened	2.2636	2.2601	2.2958	2.312
	8.5 Normal	2.2114	2.2297	2.2993	2.3162
	8.5 Widened	2.2166	2.2316	2.296	2.3126

Table 6: Jalaur Hotspot Water Height

Buayan Q10		Hot Spots		
	Methods:	1	2	3
	Normal	2.8555	2.5954	2.5976
	Narrowed	2.8451	2.7	2.7294
	Widened	2.8662	2.5767	2.5727
	Whole Estuary Widened	2.9778	2.5819	2.5748
	Widened Lower 2/3	2.9034	2.5784	2.5734
	Mouth Width Doubled	2.8766	2.573	2.5662
	Narrowed Upper 2/3	2.7311	2.5906	2.5963
	Widened Upper 2/3	2.9683	2.5998	2.5988
	Doubled Upper 2/3	2.9683	2.5997	2.5988
Scenarios:				
	4.5 Normal	2.3255	2.5758	2.5927
	4.5 Widened	2.3362	2.5522	2.5631
	8.5 Normal	2.1155	2.569	2.5917
	8.5 Widened	2.1262	2.5433	2.5599

Buayan		Hot Spots		
	Methods:	1	2	3
	Normal	2.8555	2.5724	2.5592
	Narrowed	2.8451	2.5712	2.5636
	Widened	2.8662	2.5751	2.5587
	Whole Estuary Widened	2.9778	2.5799	2.5611
	Widened Lower 2/3	2.9034	2.5769	2.5593
	Mouth Width Doubled	2.8766	2.5745	2.5595
	Narrowed Upper 2/3	2.7311	2.5651	2.557
	Widened Upper 2/3	2.9683	2.5783	2.5614
	Doubled Upper 2/3	2.9683	2.5784	2.5614
Scenarios:				
	4.5 Normal	2.3255	2.5456	2.55
	4.5 Widened	2.3362	2.5486	2.5514
	8.5 Normal	2.1155	2.5356	2.5456
	8.5 Widened	2.1262	2.5381	2.5481

Table 7: Buayan Hotspot Water Height

Abra Q10		Hot Spots	
	Methods:	1	2
	Normal	3.6586	3.4045
	Narrowed	3.6508	3.4137
	Widened	3.6675	3.4046
	Whole Estuary Widened	3.7554	3.4097
	Widened Lower 2/3	3.7535	3.4096
	Mouth Width Doubled	3.6758	3.4044
	Narrowed Upper 2/3	3.555	3.3975
	Widened Upper 2/3	3.7479	3.4109
	Doubled Upper 2/3	3.827	3.4157
Scenarios:			
	4.5 Normal	3.5	3.3946
	4.5 Widened	3.5073	3.3956
	8.5 Normal	3.4377	3.3911
	8.5 Widened	3.444	3.3923

Abra		Hot Spots	
	Methods:	1	2
	Normal	3.6528	3.4024
	Narrowed	3.6467	3.4035
	Widened	3.6609	3.4025
	Whole Estuary Widened	3.7489	3.4078
	Widened Lower 2/3	3.7469	3.4077
	Mouth Width Doubled	3.6699	3.4028
	Narrowed Upper 2/3	3.5489	3.3964
	Widened Upper 2/3	3.7421	3.4076
	Doubled Upper 2/3	3.821	3.4129
Scenarios:			
	4.5 Normal	3.4927	3.3931
	4.5 Widened	3.501	3.393
	8.5 Normal	3.4294	3.3899
	8.5 Widened	3.4376	3.3895

Table 8: Abra Hotspot Water Height

Abulug Q10		Hot Spots	
	Methods:	1	2
	Normal	5.3854	5.2929
	Narrowed	5.8184	5.8025
	Widened	5.2319	5.168
	Whole Estuary Widened	5.2628	5.1683
	Widened Lower 2/3	5.2638	5.1683
	Mouth Width Doubled	5.237	5.1587
	Narrowed Upper 2/3	5.356	5.2932
	Widened Upper 2/3	5.4136	5.2926
	Doubled Upper 2/3	5.4405	5.2922
Scenarios:			
	4.5 Normal	5.2564	5.2928
	4.5 Widened	5.1031	5.1682
	8.5 Normal	5.2051	5.2944
	8.5 Widened	5.052	5.168

Abulug		Hot Spots	
	Methods:	1	2
	Normal	5.2354	5.1548
	Narrowed	5.2214	5.1571
	Widened	5.2387	5.1483
	Whole Estuary Widened	5.2696	5.148
	Widened Lower 2/3	5.2705	5.148
	Mouth Width Doubled	5.2435	5.1402
	Narrowed Upper 2/3	5.2057	5.155
	Widened Upper 2/3	5.264	5.1554
	Doubled Upper 2/3	5.2918	5.1565
Scenarios:			
	4.5 Normal	5.1074	5.1525
	4.5 Widened	5.111	5.1467
	8.5 Normal	5.0559	5.1522
	8.5 Widened	5.0597	5.1464

Table 9: Abulug Hot Spot Water Height

Tagum
Q10

Methods:	Hot Spot
Normal	5.4741
Narrowed	6.9592
Widened	4.9754
Whole Estuary Widened	4.9754
Widened Lower 2/3	4.9754
Mouth Width Doubled	4.7513
Narrowed Upper 2/3	5.4766
Widened Upper 2/3	5.4716
Doubled Upper 2/3	5.4691

Table 10: Tagum Hot Spot Water Height

Tagum

Methods:	Hot Spot
Normal	4.6285
Narrowed	4.7334
Widened	4.638
Whole Estuary Widened	4.6381
Widened Lower 2/3	4.638
Mouth Width Doubled	4.6472
Narrowed Upper 2/3	4.6286
Widened Upper 2/3	4.6285
Doubled Upper 2/3	4.6285

		Inland Tidal Amplitude
Jalaur	Normal	0.0034
	Narrowed	0.0075
	Widened	0.002
	Whole estuary	0.0019
	Widened 2/3	0.0019
	Doubled Mouth	0.0013
	4.5 Normal	0.0038
	4.5 Widened	0.0023
	8.5 Normal	0.0041
	8.5 Widened	0.0025
	Narrowed U 2/3	0.0035
	Widened U 2/3	0.0033
	Doubled U 2/3	0.0032

		Inland Tidal Amplitude
Abulug	Normal	0.0012
	Narrowed	0.0048
	Widened	0.0006
	Whole estuary	0.0006
	Widened 2/3	0.0006
	Doubled Mouth	0.0003
	4.5 Normal	0.0013
	4.5 Widened	0.0006
	8.5 Normal	0.0013
	8.5 Widened	0.0006
	Narrowed U 2/3	0.0012
	Widened U 2/3	0.0012
	Doubled U 2/3	0.0012

Buayan		Inland Tidal Amplitude
	Normal	0.0032
	Narrowed	0.0107
	Widened	0.0017
	Whole estuary	0.0016
	Widened 2/3	0.0017
	Doubled Mouth	0.0011
	4.5 Normal	0.0042
	4.5 Widened	0.0022
	8.5 Normal	0.0049
	8.5 Widened	0.0026
	Narrowed U 2/3	0.0034
	Widened U 2/3	0.0031
	Doubled U 2/3	0.0031

Tagum		Inland Tidal Amplitude
	Normal	0.0247
	Narrowed	0.1041
	Widened	0.0108
	Whole estuary	0.0108
	Widened 2/3	0.0108
	Doubled Mouth	0.006
	4.5 Normal	0.0255
	4.5 Widened	0.0112
	8.5 Normal	0.0259
	8.5 Widened	0.0113
	Narrowed U 2/3	0.0247
	Widened U 2/3	0.0246
	Doubled U 2/3	0.0245

Table 11: Average Inland Tidal Amplitude

Pearson's Test Results:

Jalaur	Abulug	Buayan	Tagum	Abra
-0.114899111	0.23735373	-0.031858012	0.3134047	0.001165481

Table 12: Comparison of Inland Tidal Amplitude and River Mouth Depth