Flow Modeling New Orleans - Mississippi River Gulf Outlet

Hurricane Katrina August 2005

FINAL REPORT
Scenario 1, 2A, 2B, 2C, 2D, 3

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23rd June 2008
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Preface

This research project has been carried out in the period January – June 2008. The objective of the project is to gain insight in the flow dynamics during Hurricane Katrina and the influence of the MRGO there on. The results depend on the data available for input and the results might change if new data comes available. In our opinion, the best available data is used.

The project team has the following members: M. Kok Ph.D. MSc. (project manager), B. Maaskant MSc. (all from Delft University of Technology) and L. de Wit MSc. (Svašek Hydraulics). Reviewer of the project is Professor J.K. Vrijling Ph.D. MSc. (Delft University of Technology).

Delft, 23rd June 2008



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1 Introduction

1.1 General introduction

On the morning of August 29, 2005, Hurricane Katrina struck southeast Louisiana and triggered what would become one of the worst disasters ever to befall an American city. The storm overtopped levees and floodwalls throughout southeast Louisiana and also caused the levees and floodwalls in the New Orleans area to fail or breach in more than 50 locations. Water rushed into New Orleans and flooded over 80 percent of the city - more than ten feet deep in some neighborhoods.

Flooding of the city of New Orleans was caused by several sources (or causes): breaches, overtopping (of the levees and flood control structures) and rainfall. One of the causes of the breaches might be the amplified surges generated by the Mississippi River Gulf Outlet (MRGO). The MRGO is a free-flowing man-made navigation channel connecting the Gulf of Mexico to the interior of the City of New Orleans. The MRGO project was approved by the U.S. Congress under the Rivers and Harbor Act of 1956. Construction began in 1958 and was completed in 1965. It was authorized as a 76-mile ship channel with a 36 foot controlling depth, 500 feet wide at the bottom and 650 feet wide at the top, that would cut through the marshes of lower St. Bernard Parish and across the shallow waters of Breton Sound.

Following Hurricane Katrina, engineers and scientists noted that levees and floodwalls adjacent to the MRGO project had failed catastrophically. Other levees and floodwalls failed also, for example on the Orleans Metro drainage canals and the New Orleans East Back Levee (van Heerden and Bryan 2006 [Ref. 1], Team Louisiana 2007, ILIT 2006, IPET 2006, 2007). The scientific question is whether linkage between proximity to the MRGO project and failures of floodwalls and levees constructed under the Lake Pontchartrain & Vicinity Hurricane Protection project (LPV) is entirely coincidental. This study is in support of studies been undertaken by Robinson experts in the determination of the surge dynamics in the Lake Borgne funnel east of New Orleans.

1.2 Objectives

The objectives of this study are to better understand the flow dynamics of the surge event during Hurricane Katrina and the MRGO's impacts on the flooding. This is known as Scenario 1. A second scenario was modeled, one designed to determine the hydrodynamics of a storm such as Katrina, and its impacts, if the MRGO had not been built and there had not been wetlands destruction. The situation without MRGO, with pre-Katrina MRGO levees and the 40 Arpent levee at its pre-Katrina elevation of 6.5 ft is called Scenario 2C. In the Appendix some variations on Scenario 2 without MRGO and without the wetland destruction are included, namely Scenario 2A, 2B and 2D. Scenario 2A was run without MRGO levees and assuming the 40 Arpent levee crest at an elevation of 17.5 ft, because through the discovery process US Army Corps of Engineers officials have stated that if the Lake Pontchartrain and Vicinity (LPV) hurricane protection levees had not been built alongside the MRGO channel, then the 40 Arpent levees would have been the location of the LPV levees. Scenario 2B simulates the situation similar to Scenario 2C, but without MRGO levees. Scenario 2D is equal to Scenario 2B, but spoil piles along MRGO Reach 2 are included. Scenario 3 represents the situation if the MRGO had been maintained at authorized dimensions.

1.3 Modeling approach

The numerical model FINEL generates detailed information about water motion in the area of study. Our present study is focused in Southeast Louisiana being centered on Lake Borgne and the MRGO (see Figure 1.1 for the model area). Three scenario runs are executed; one simulating the actual Katrina event with the topography and geomorphology as present in early August 2005 including the MRGO channel (Reach 1 and 2); the MRGO levees and the highly degraded wetlands. The second simulation (2C) reflects the 1958 healthy wetlands conditions with a no-MRGO situation (No Reach 2, pre-MRGO GIWW/Reach 1, levees along MRGO as

before Katrina, and 40 Arpent levee as is before Katrina). The third simulation reflects the 1958 healthy wetlands conditions with a MRGO maintained at authorized dimensions (depth and width MRGO as designed, pre-Katrina levees along MRGO). The model area for Scenario 1 and 3 includes the IHNC, MRGO Reach 1 and 2, the west part of Lake Borgne including the GIWW, the west boundary is the 40 Arpent levee (see Figure 1.1). For Scenario 2C the area between the 40 Arpent levee and Mississippi is included in the model area. In the appendix some additional Scenario 2 simulations (2A, 2B, 2D) can be found. Scenario 2A is similar to 2C, but without levees along the MRGO and the 40 Arpent levee is at 17.5 ft to represent a potential LPV levee and the grid ends at this levee. Scenario 2B is also similar to 2C, but without levees along the MRGO. Scenario 2D is similar to Scenario 2B, but with spoil piles along MRGO Reach 2. A summary of all scenarios is shown in Table 1.1.

Table 1.1 FINEL MRGO Scenarios for hurricane Katrina conditions

Scenario	**MRGO channel**	**GIWW channel**	**Reach 2 EBSBs**	**40 Arpent Levee**	**Vegetation**
1	Existing 8/2005	Existing 8/2005	Existing 8/2005	Existing 8/2005	Existing 8/2005
2C	None	Pre MRGO	Existing 8/2005	Existing 8/2005 & grid extension to Mississippi	Pre MRGO 1958
3	As authorized	As authorized	Existing 8/2005	Existing 8/2005	Pre MRGO 1958
2A	None	Pre MRGO	None	LPV authorized	Pre MRGO 1958
2B	None	Pre MRGO	None	Existing 8/2005 & grid extension to Mississippi	Pre MRGO 1958
2D	None	Pre MRGO	Spoil piles 8/1965	Existing 8/2005 & grid extension to Mississippi	Pre MRGO 1958

The FINEL numerical model was developed by Svašek Hydraulics and the Fluid Mechanics section of the Civil Engineering faculty of the Delft University of Technology in the Netherlands. The model has been used for hydrodynamic simulations all over the world. The validity and calibration of the model has been extensively tested on projects such as the Western Scheldt estuary, the North Sea (the Netherlands), Dublin flooding (North Ireland), Hazira (India), Posorja (Ecuador), etc. For publications carried out with FINEL and a technical description see [Ref. 2 & 3].

The numerical flow model FINEL is based on the depth averaged equations for 2-dimensional horizontal flow, the equations of Saint Venant. In FINEL this system of equations is solved with a robust numerical finite element method, which can easily handle drying and flooding. The FINEL model is based on the same principles as the SOBEK model, which is used in the flooding study carried out in 2007 [Ref. 4]. The reason that we use the FINEL model is that the model area in FINEL is divided into a number of triangles, the so-called elements, instead of a grid consisting of squares which is used in SOBEK. The size and distribution of the triangles can vary over the grid, so complicated geometries are easily represented in the schematization and the grid can be more detailed in areas of specific interest. (See Figure 2.1). This is very important in the complex area around New Orleans, with channels which require a lot of detail adjacent to higher ground which require less.



Figure 1.1: FINEL flow model area. Solid red line shows model area Scenario 1, 2A and 3, the dashed red line shows the extra area included in Scenario 2B, 2C and 2D.

1.4 Definition

The following definitions are used in this report:

Water level	Water height above or below zero NAVD88
Water depth	Water height or elevation above ground level
IPET	Interagency Performance Evaluation Task Force
NOAA	National Oceanic & Atmospheric Administration
Grid	Computational layer in which the considered area is divided in triangular shaped elements, for each element the water motion is calculated
Polder or bowl	Area that is below sea level and is enclosed by an uninterrupted chain of water retaining structures, levees and/or high ground
MRGO	Mississippi River Gulf Outlet
IHNC	Inner Harbor Navigation Canal
GIWW	Gulf Intracoastal Water Way
NAVD88	NAVD88 2004.65 datum

2 Simulations

2.1 Scenario 1: Katrina

2.1.1 Description of Scenario

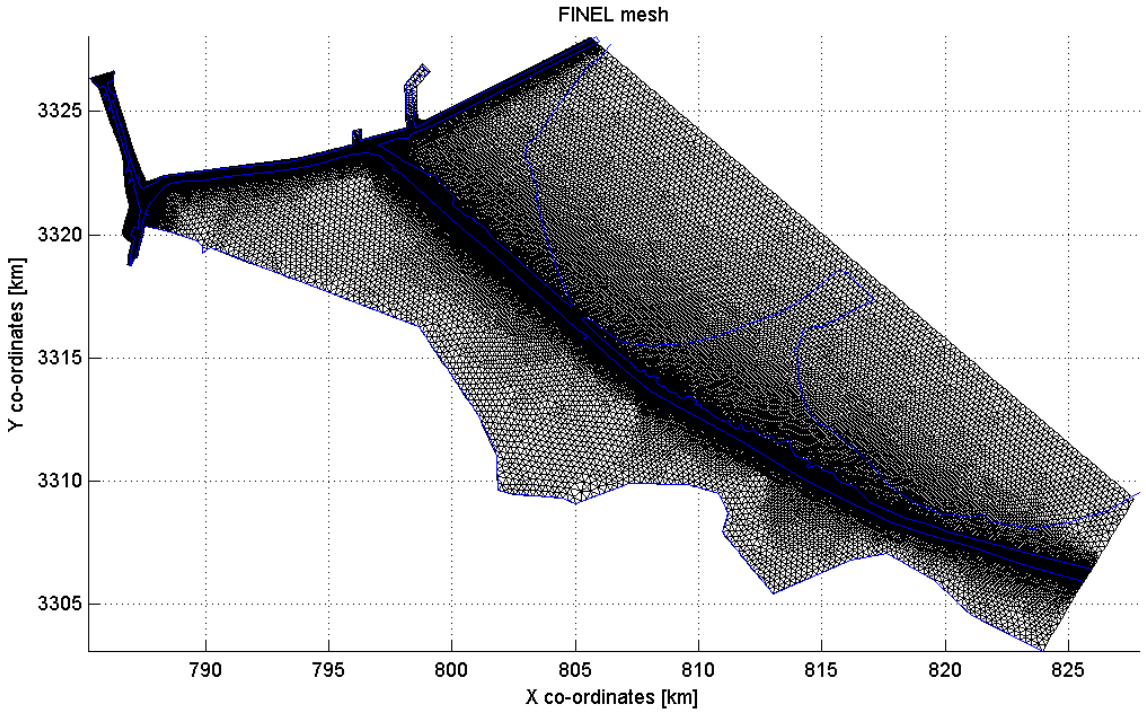
Scenario 1 is the 'Katrina real run'. The Katrina event is simulated in the FINEL model. Here the model is run to as precisely as possible mimic the physical environment immediately prior to Hurricane Katrina's landfall, and the actual Katrina storm. The Finel model allows one to better understand the hydrodynamics and interpret the various impacts of MRGO.

2.1.2 FINEL model input data

The FINEL model is set up to utilize the metric system, so all data is thus subsequently converted to feet. The coordinate system used in the simulations is UTM (zone 15 R). Input data that was received in longitude and latitude was translated accordingly.

Model grid

The model grid used in FINEL consists of triangles with varying size. The elements are small in areas of interest and large in other areas. In this way accurate results can be obtained in an efficient way. The grid size varies from 250 m (820 ft) at Lake Borgne and the St. Bernard polder to 30 m (98 ft) in the channels. The total number of elements is approximately 152,000. See Figure 2.1 below for an impression of the model grid.



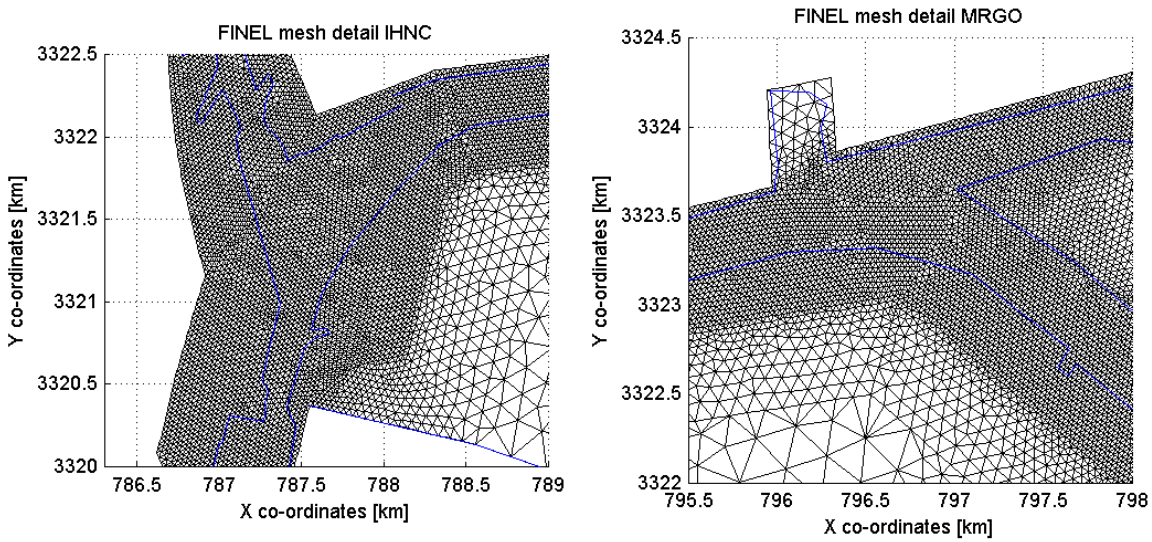


Figure 2.1: Model grid FINEL Scenario 1. Note the grid is denser in channel areas to more accurately simulate the flow conditions.

Bathymetry and Topography

The bathymetry consists of a combination of LIDAR data (land surface), bathymetry data (provided by Robinson experts), GEODAS (US government) data, the actual pre-Katrina levee heights, and the MRGO/IHNC bathymetry provided by the Robinson experts. The GIWW has the dimensions of 150 ft wide and 12 ft deep as provided by the Robinson experts. The resulting depths in the model area are shown in Figure 2.2. Note that Scenario 1 is run with the levee heights as they existed prior to Katrina without breaches; therefore the volume of water flowing into the St. Bernard polder will be an underestimation of the real volume that flowed into St. Bernard during Katrina (during Katrina there were breaches along the MRGO). The main focus of this study is the flow conditions and dynamics in the MRGO fronting of the Lake Pontchartrain and Vicinity (LPV) levees.

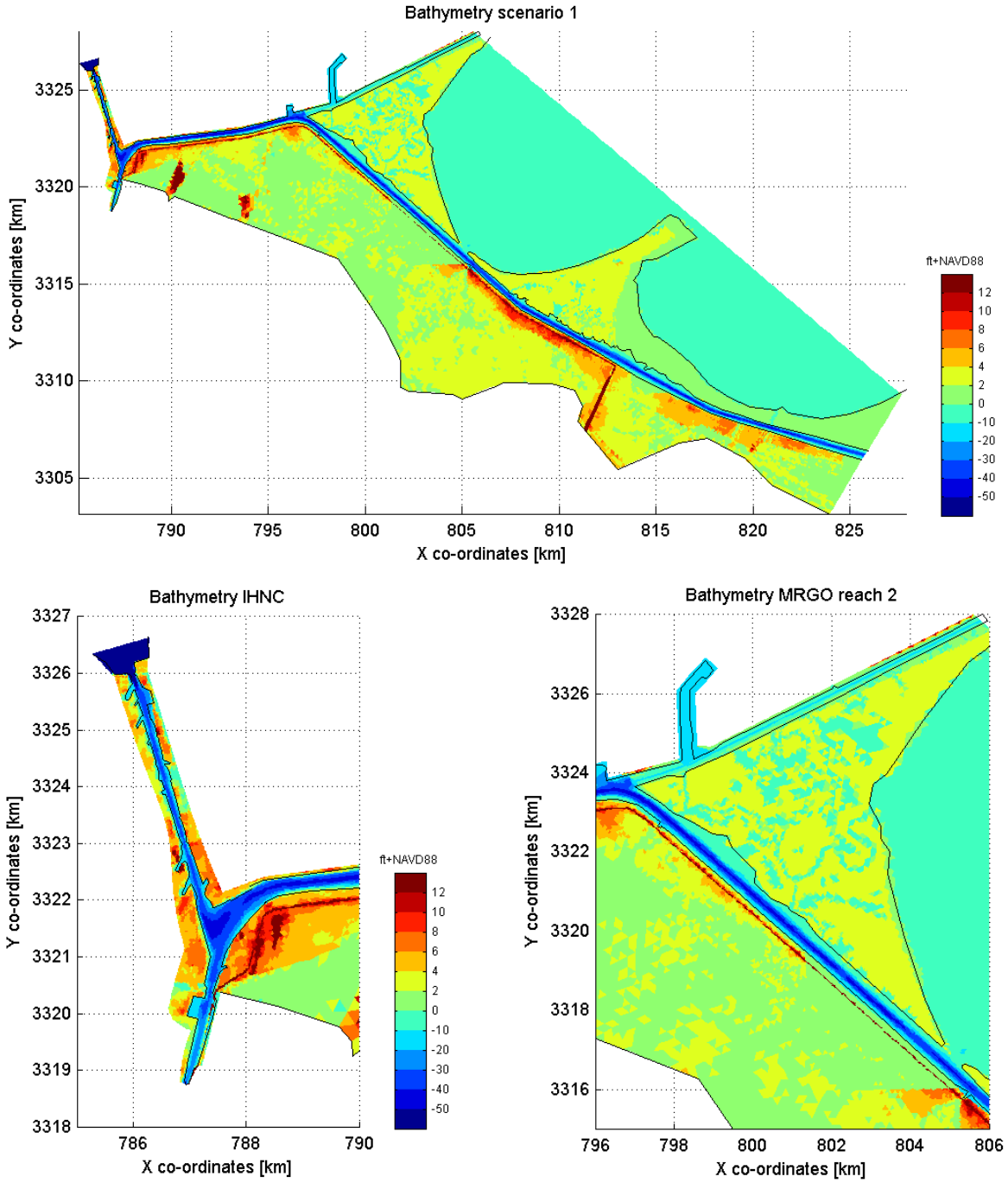


Figure 2.2: Bathymetry FINEL model area Scenario 1

Simulation period

The simulation starts at 12h00 LT 28th August 2005 and continues until 24h00 29th August 2005.

Boundary conditions

The boundary conditions consist of hydrographs compiled using ADCIRC S08 version - Advisory 31 (Team Louisiana 2007) adjusted to match high water marks so that these hydrographs are more accurate than any model output alone. Figure 2.3 shows the locations of the boundary conditions and Table 2.1 gives the corresponding Hydrograph1 locations which are used for every boundary. The boundary time series themselves are shown in Figure 2.4. All boundaries not mentioned in Table 2.1 are closed boundaries.

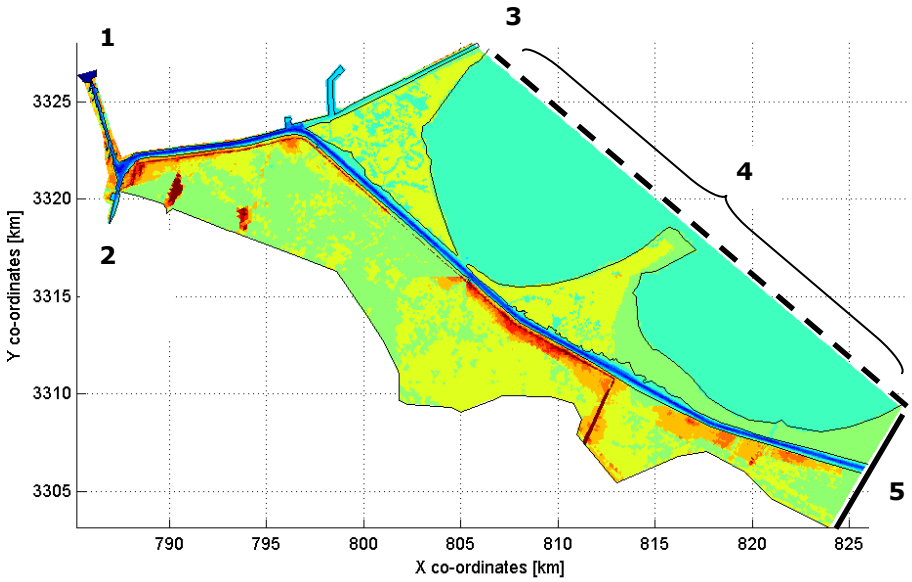


Figure 2.3: Location boundary conditions FINEL flow model

Table 2.1: Boundary conditions

	Boundary	*Used hydrograph1 (ADCIRC)*
1	Lake Pontchartrain	IHNC@LakeP
2	IHNC Locks	Closed boundary (discharge=0)
3	GIWW	NOEbackA
4	Lake Borgne	Interpolation between 3 and 5
5	MRGO	Shell Beach

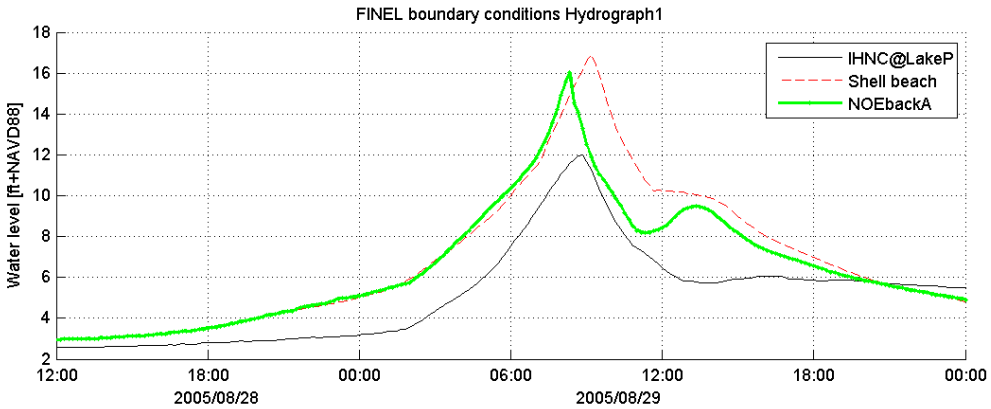


Figure 2.4: Time series of the boundary hydrographs as used in the FINEL flow model Scenario 1.

Bottom roughness

In the model area a spatial variable Manning coefficient is used for the bottom roughness. The Manning roughness coefficients used are based on years of experience in modeling coastal environments. These data were collaborated with other data sets such as from the US Geological Survey (http://www.fhwa.dot.gov/bridge/wsp2339.pdf), the world renowned book Open-channel hydraulics [Ref. 5] and IPET [Ref. 6]. For each scenario the spatial extent of the Manning's used is based on the presence or lack of wetlands; shoreline location and presence; and lack or presence of levees. Manning's coefficients used are shown in Figure 2.5 and summarized in Table 2.2.

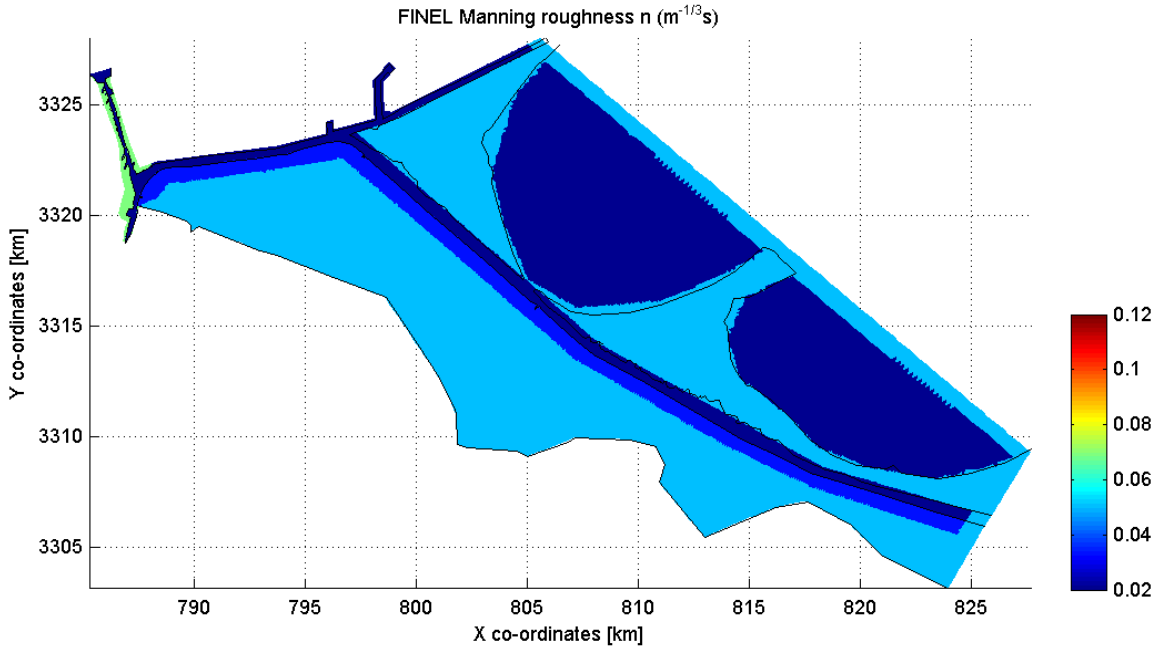


Figure 2.5: Manning roughness coefficient FINEL model area Scenario 1.

Table 2.2: Manning coefficient used for Scenario 1(based on: IPET Volume IV appendix page IV-5-102 [Ref. 6])

Area	*Manning coefficient n ($m^{-1/3}s$)*
Open water	0.02
Marsh along Lake Borgne	0.05
Shrub land St. Bernard	0.05
Grass at levees	0.034
Commercial area next to IHNC	0.07

Wind

To take into account the influence of wind on the water motion, spatial variable wind fields are used in the flow calculations with FINEL. The wind fields are provided to us by the Robinson experts every 30 minutes for the study period. In forests the wind field will be affected by the wind canopy. As the wind flows through a forest the trunks, branches and leaves (solid portion) absorb some of the momentum of the wind and the wind speed is reduced. In addition as the wind blows over the tree canopy it is slowed by the roughness of the surface and the wind speed is reduced. Robinson experts reviewed the literature such as various reports by wind experts at the University of Nebraska (http://www.ianrpubs.unl.edu/epublic/pages/index.jsp?what=publicationD&publicationId=6240 and discussions with world renowned coastal meteorologist Professor S. A. Hsu to determine that a wind reduction of 80% would be realistic for storm conditions in cypress swamps. The wind speed surface stress is calculated by:

$$\frac{\tau_{wind,x}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,x} - U_x),$$

$$\frac{\tau_{wind,y}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,y} - U_y).$$

With:

C_d = wind drag coefficient (-),
W_{10} = wind speed at 10 meter height (m/s),
U = water velocity (m/s).

The wind drag is defined by Garrat's drag formula (Garrat 1977):

$C_d = (0.75 + 0.067W_{10}) \times 10^{-3}$

2.1.3 Calibration

For the calibration of the flow model the results from FINEL are compared with corrected ADCIRC (hydrograph1) output at several locations. The locations of the comparison of the water levels are shown in Figure 2.6. See Figure 2.7 for the calibration results.

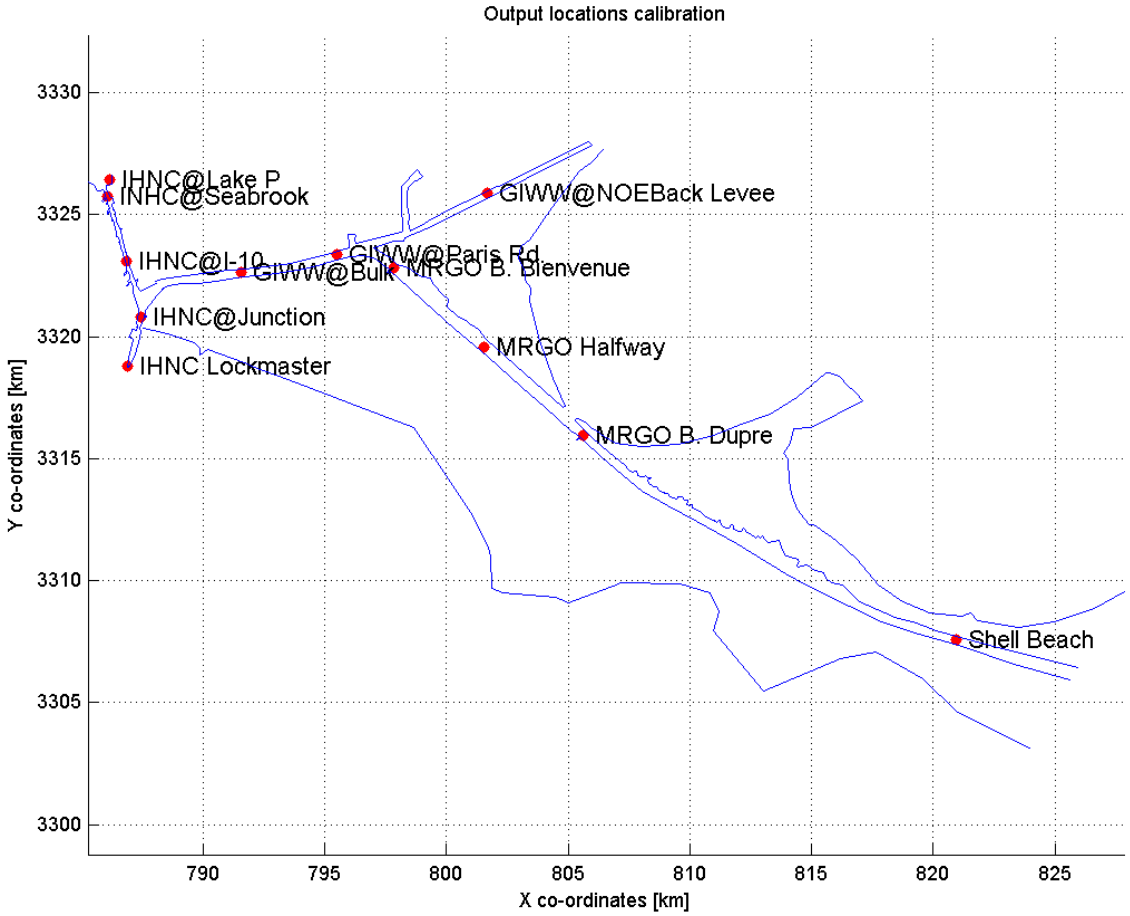


Figure 2.6: Output locations used in the calibration of the FINEL model Scenario 1 with ADCIRC hydrographs.

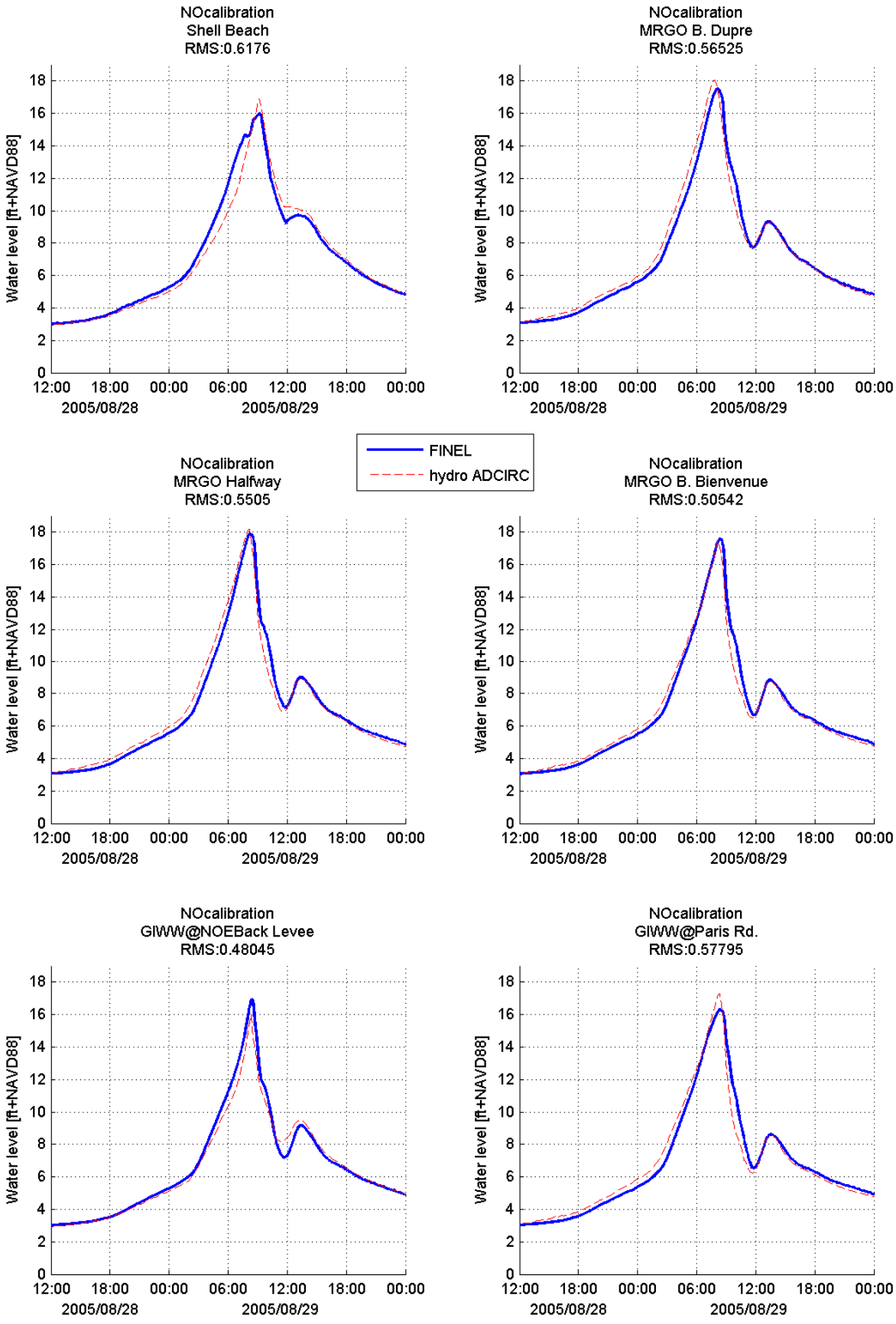


Figure 2.7a: Corrected ADCIRC vs. FINEL calibration results Scenario 1.

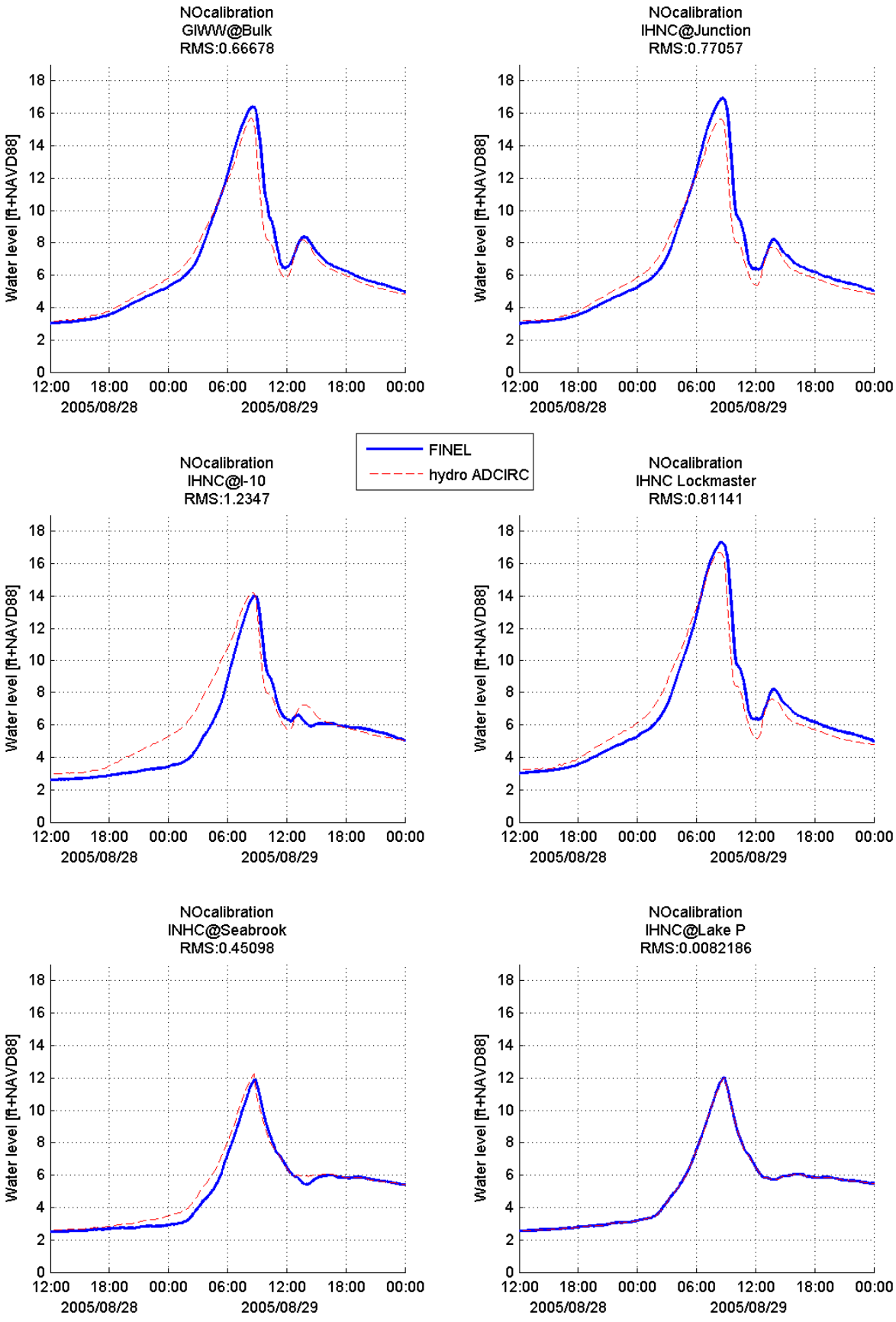


Figure 2.7b: Corrected ADCIRC vs. FINEL calibration results Scenario 1.

The FINEL model does not take into account breachings, it does however model overtopping into the St. Bernard polder (up to 40 Arpent levee). So the FINEL result will be a little higher than what actually occurred, which is reflected in the ADCIRC results. The calibration results show that the results from FINEL along the MRGO Reach 1 and 2 and the GIWW mirror the results from ADCIRC. The RMS (Root Mean Square) of the difference between ADCIRC and FINEL is here in the order of 0.6 ft. The difference in peak water level is less than 1 ft.

On the IHNC the difference between FINEL and ADCIRC is a little larger (RMS average 0.8 ft), but given the difference in bathymetry and roughness of the IHNC channel in both models, the agreement is satisfactory. The ADCIRC model does not account for the narrowing of the flow profile under the bridges in the IHNC; in FINEL the surveyed depths of the IHNC are used which show narrowing at the bridges. Location IHNC@I-10 for example is just north of the bridge in FINEL, the difference in water level with a location just south of the bridge is about 1 foot before surge peak is reached, and this partly explains the difference between ADCIRC and FINEL at this location. In FINEL the harbor areas next to the IHNC are given a higher roughness to account for the obstruction of the flow, in ADCIRC a uniform roughness is used. But even given these differences in input, the agreement in peak water level in the IHNC is very good (difference < 1 ft). The calibration results generate a lot of confidence in the FINEL flow results.

2.1.4 Results

The FINEL flow model is used to produce details of the water currents especially along the MRGO levees. This section shows the results of Scenario 1: Katrina. The results are shown at 6 time steps on the day Katrina struck, 29th August 2005, namely:

1. 4:00am Local Time; which is as the surge is starting to build up along MRGO,
2. 5:00am Local Time; which is as the surge continues to build up along MRGO,
3. 6:00am Local Time; which is as the surge continues to build up along MRGO, the winds are directly blowing across Lake Borgne at MRGO levees and the eye is just short of landfall,
4. 7:00am Local Time; which has the eye just south of the MRGO,
5. 8:00am Local Time; which is close to the peak in the surge,
6. 9:00am Local Time; which is after the peak in the surge and as the winds start to switch to the west.

Area plots

The surge levels for the various time steps s are shown in Figure 2.8 as is the wind direction. The current velocities and extent of surge water coverage are shown in Figure 2.9. A close up of the currents in MRGO Reach 1 is shown in Figure 2.10, and similarly for MRGO Reach 2 in Figure 2.11.

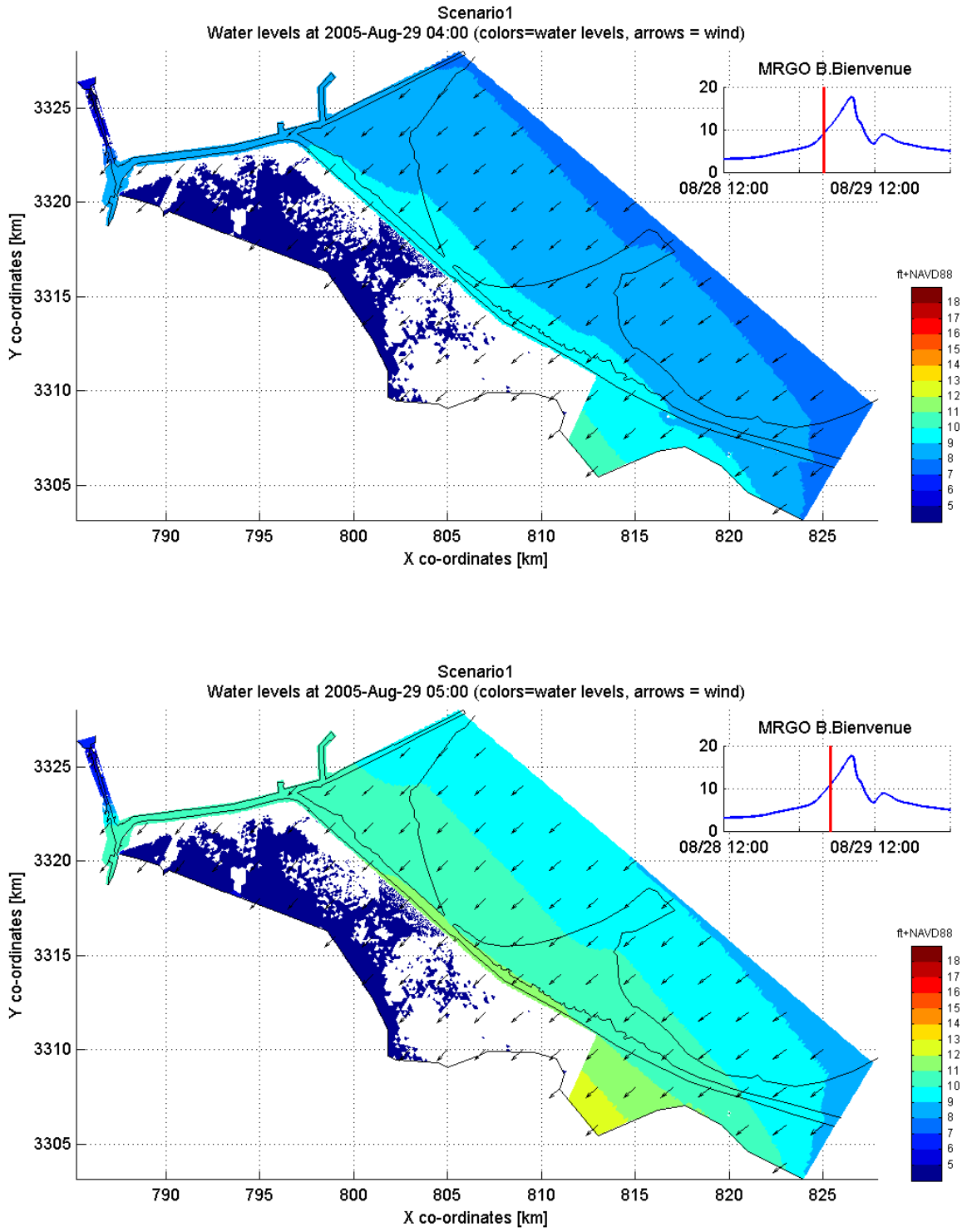


Figure 2.8a: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 1 at 4:00am and 5:00am local time. Note the wind is blowing at approximately 90 degrees to MRGO.

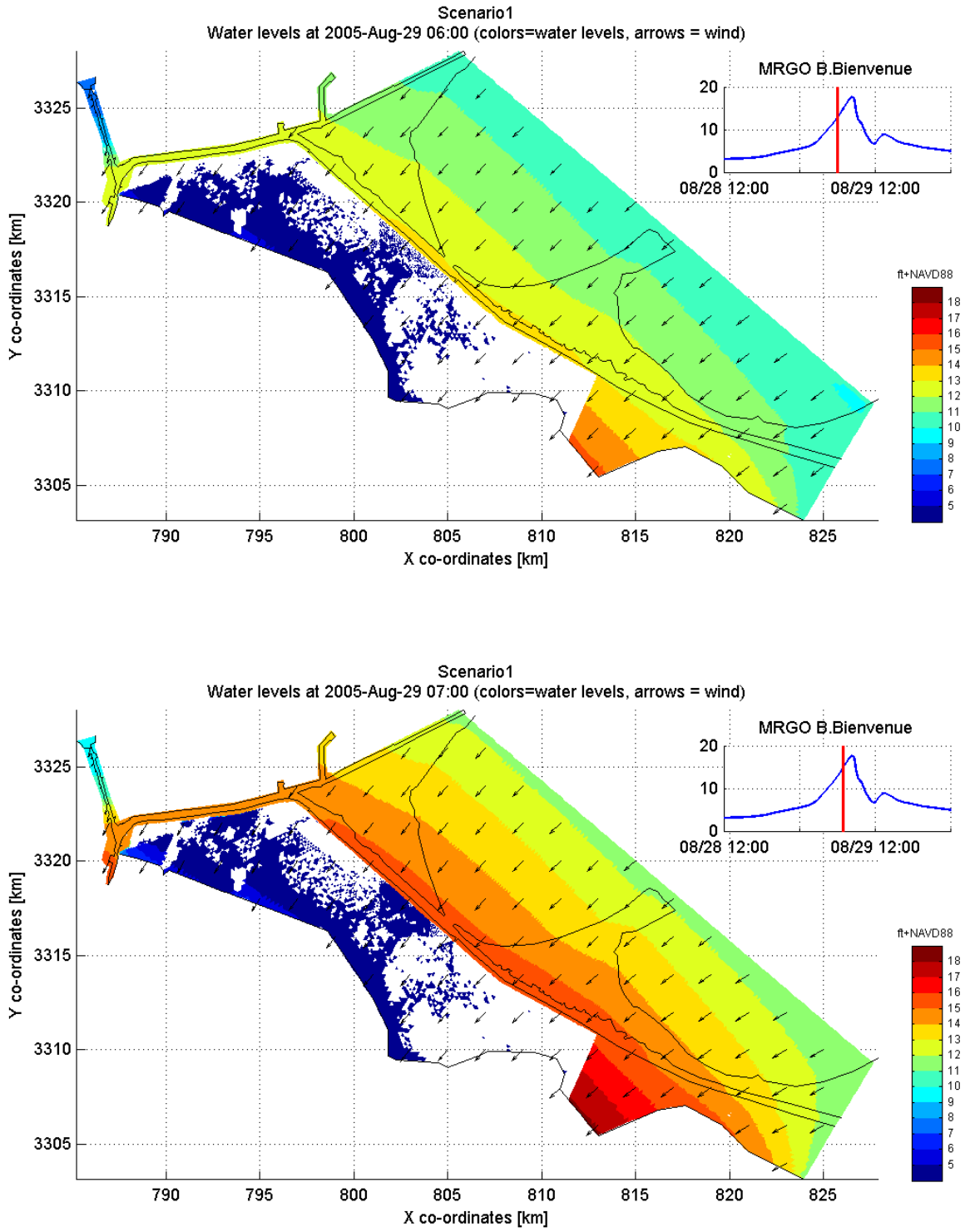


Figure 2.8b: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 1 at 6:00am and 7:00am local time. Note the wind is blowing at approximately 90 degrees to MRGO.

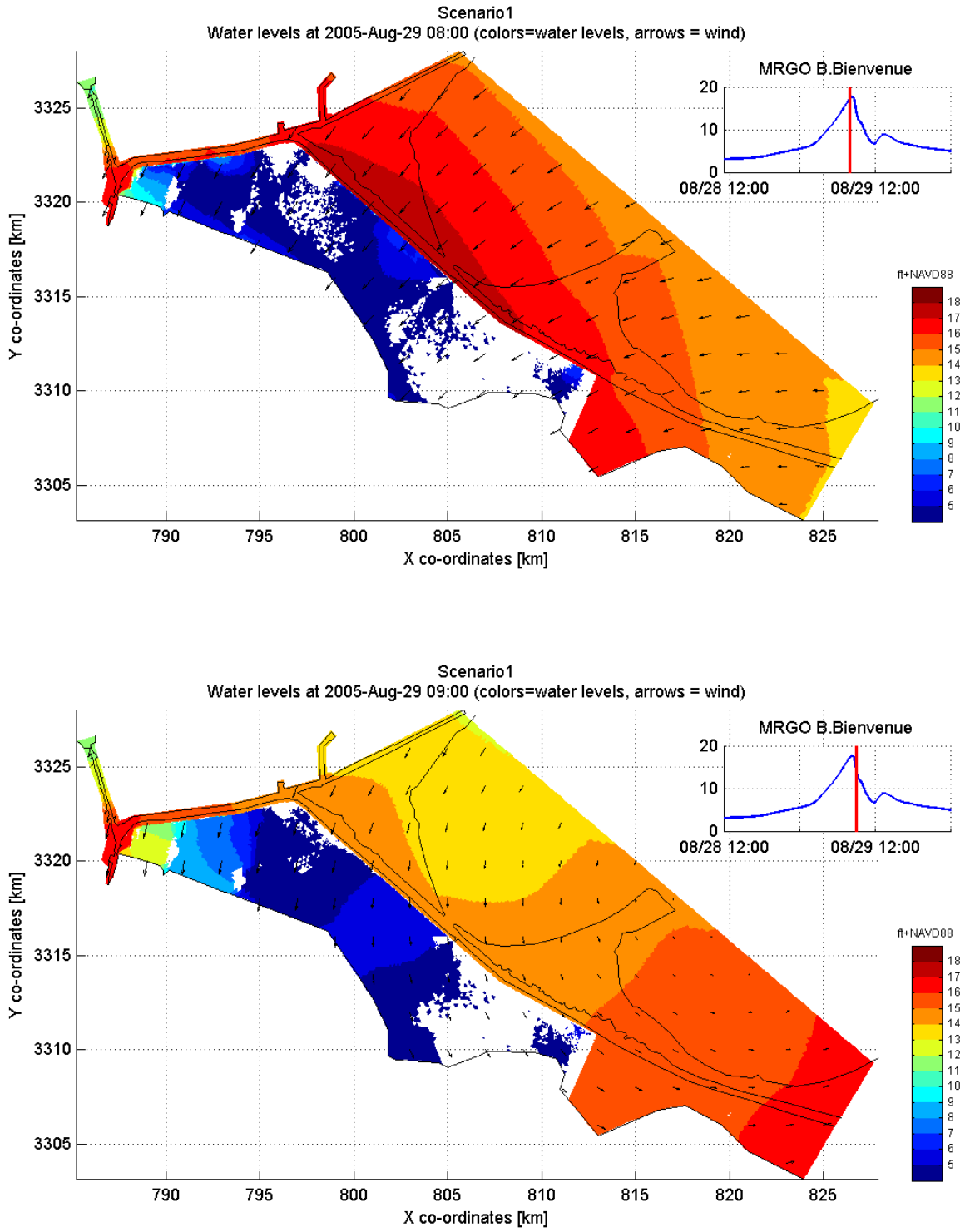


Figure 2.8c: Spatial water levels (surge elevation with color scale) with wind field (arrows) for Scenario 1 at 8:00am and 9:00am local time. Note the wind is blowing at approximately 90 degrees to MRGO at 8:00am; the surge amplification >17 ft NAVD in front of the MRGO levees and flooding in St Bernard Parish. The flooding shown in St Bernard Polder represents contribution from levee overtopping only.

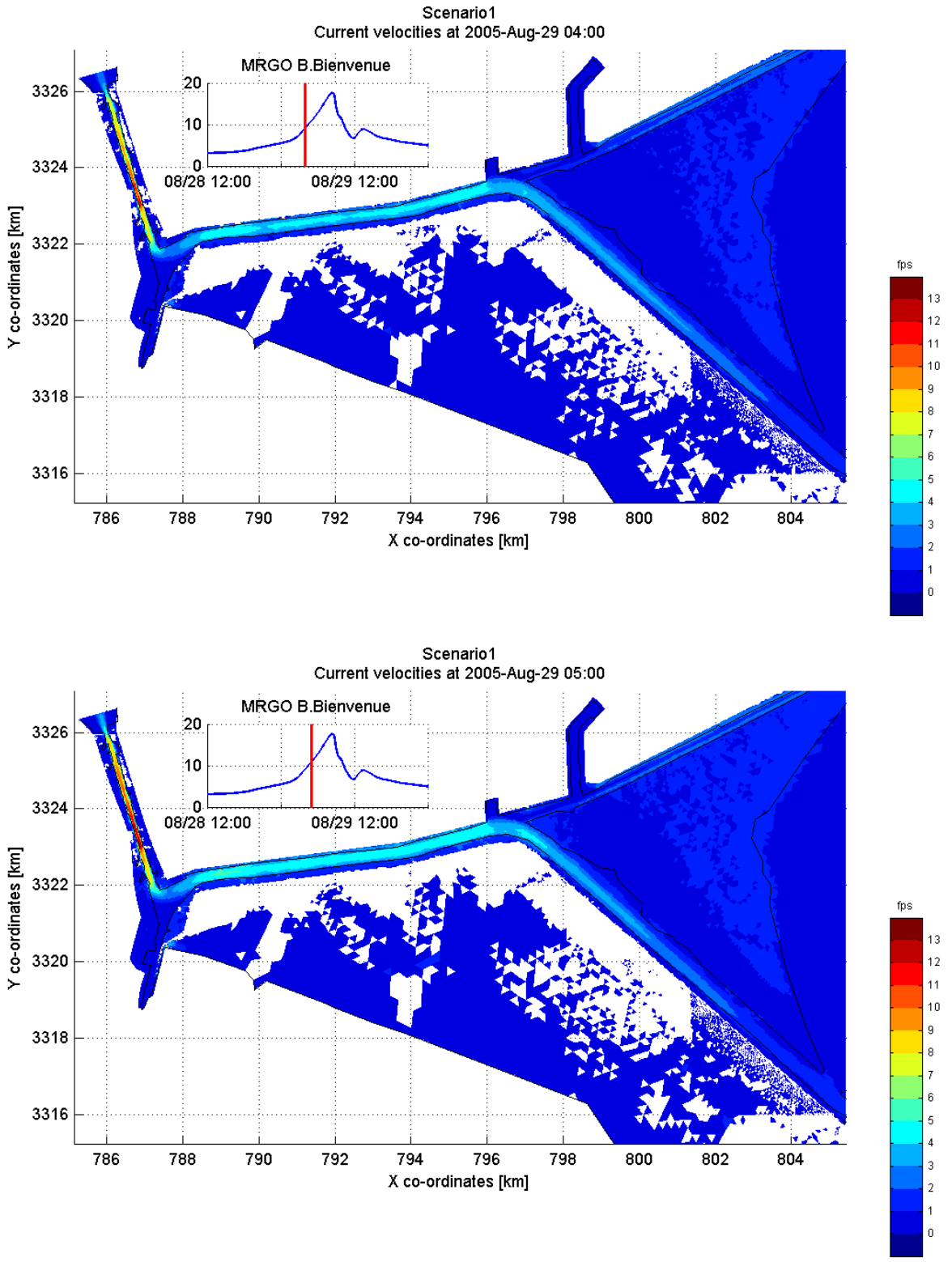


Figure 2.9a: Spatial current velocities for Scenario 1 at 4:00am, 5:00am local time. Note the high current velocities in IHNC and MRGO.

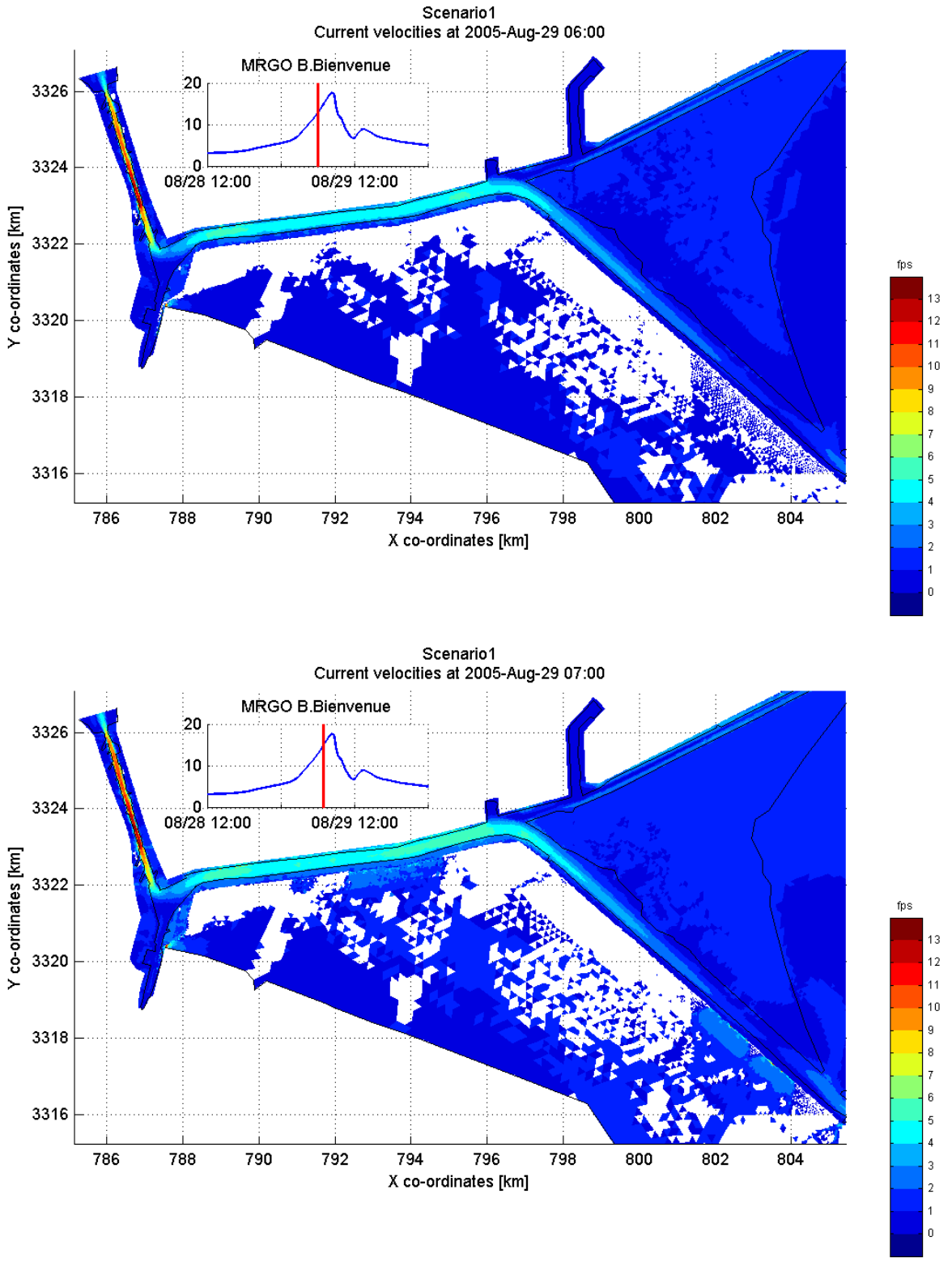


Figure 2.9b: Spatial current velocities for Scenario 1 at 6:00am, 7:00am local time. Note the high current velocities in IHNC and MRGO.

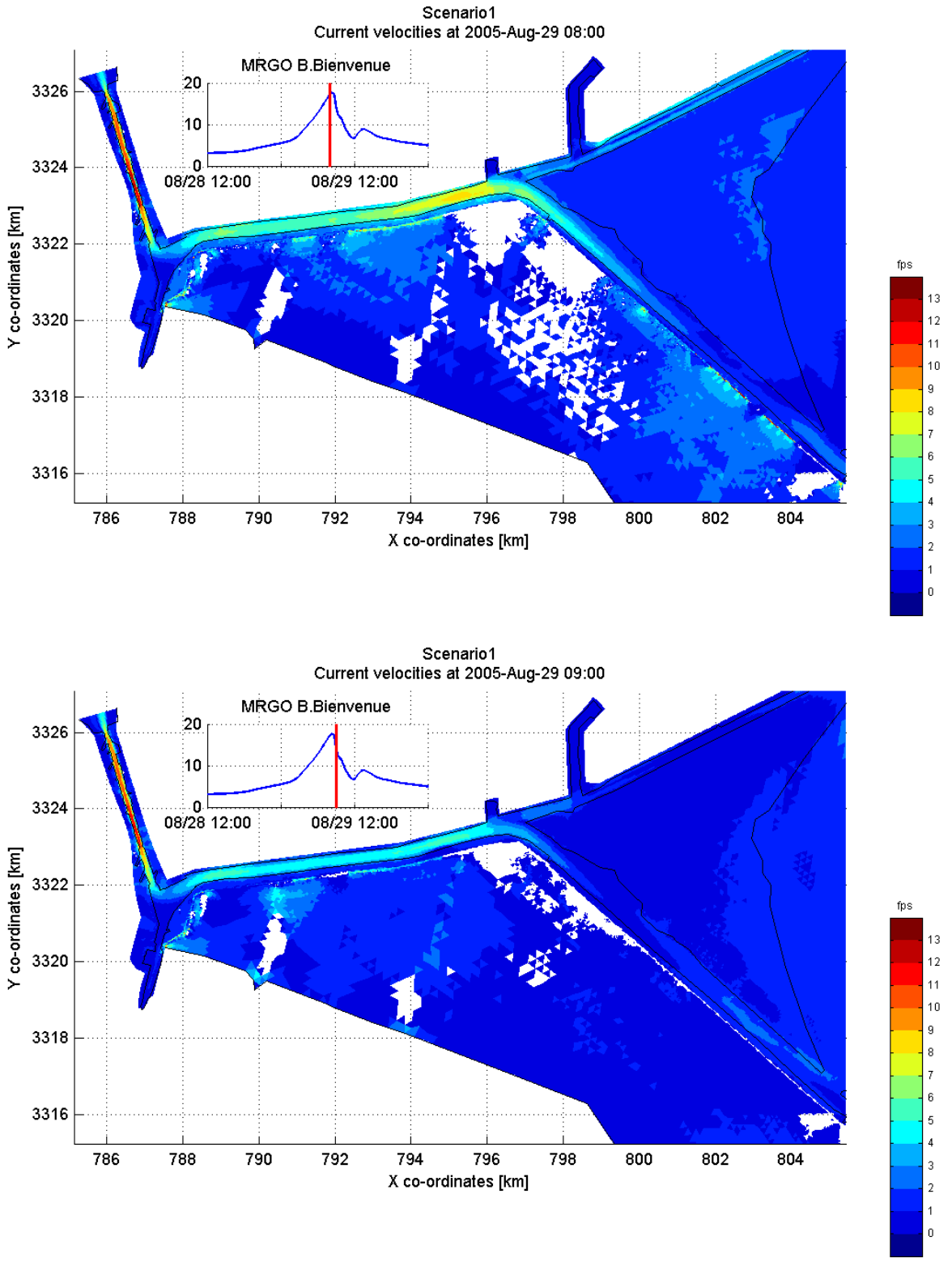


Figure 2.9c: Spatial current velocities for Scenario 1 at 8:00am, 9:00am local time. Note the high current velocities in IHNC and MRGO.

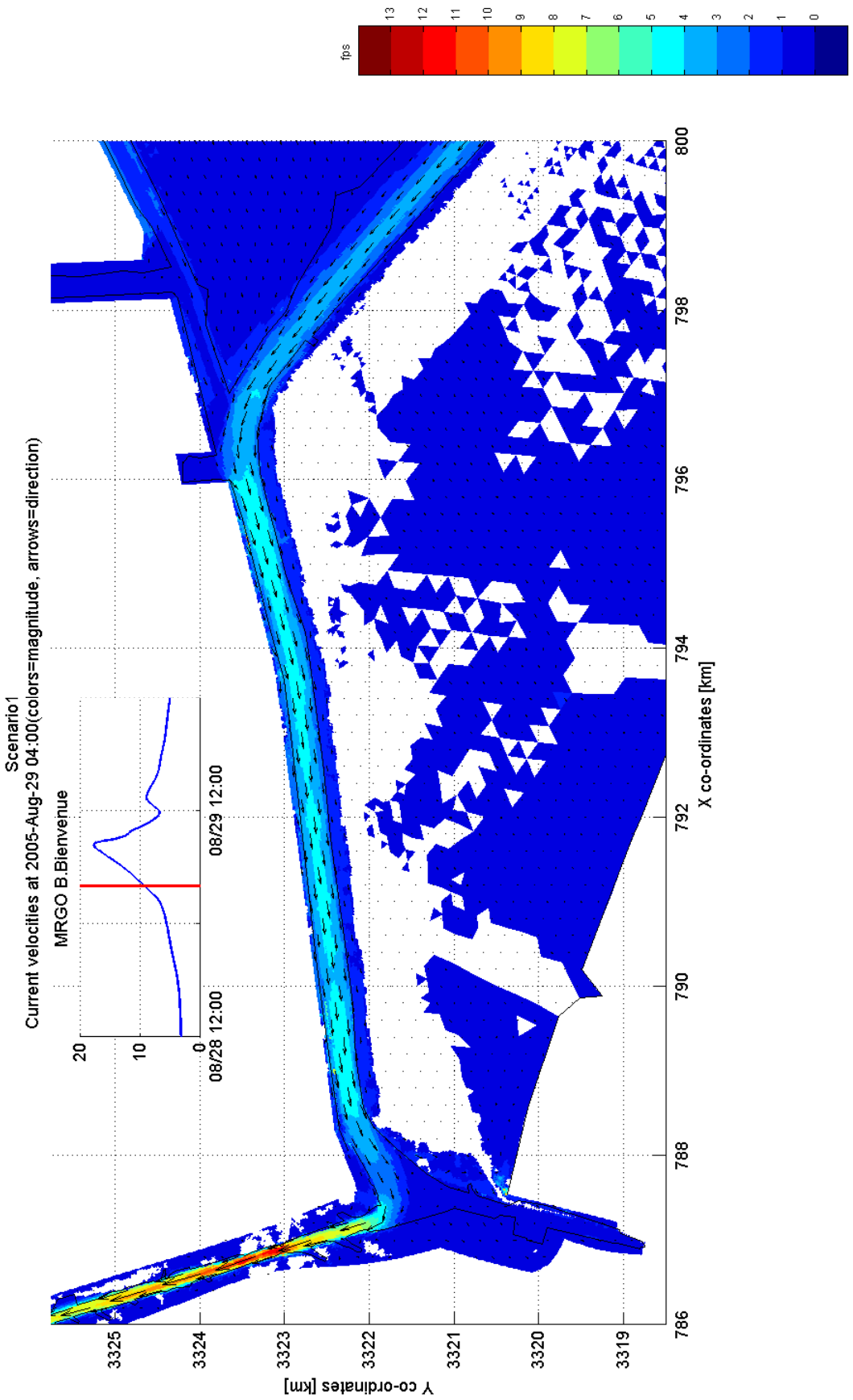


Figure 2.10a: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 1 at 4:00am local time.

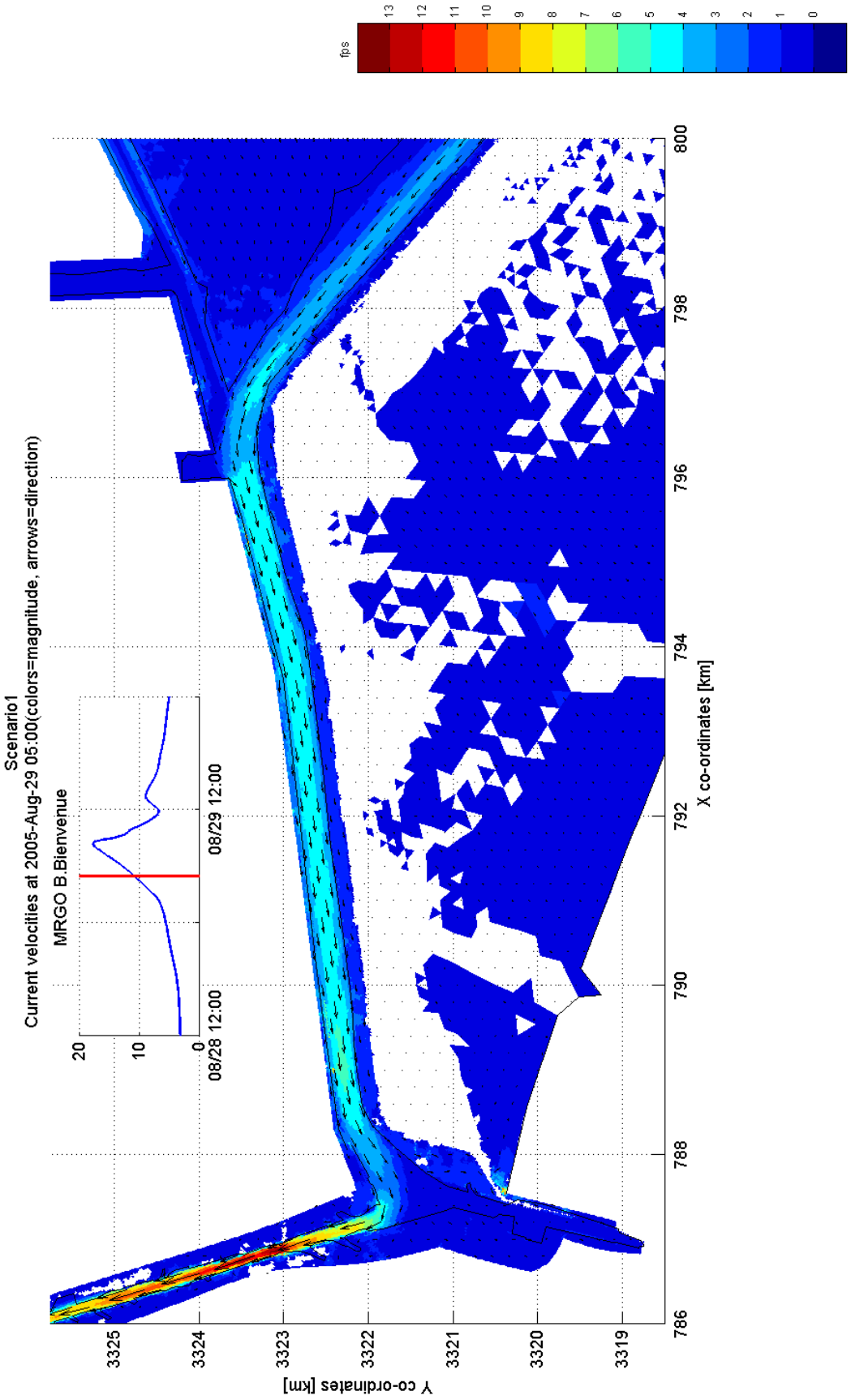


Figure 2.10b: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 1 at 5:00am local time.

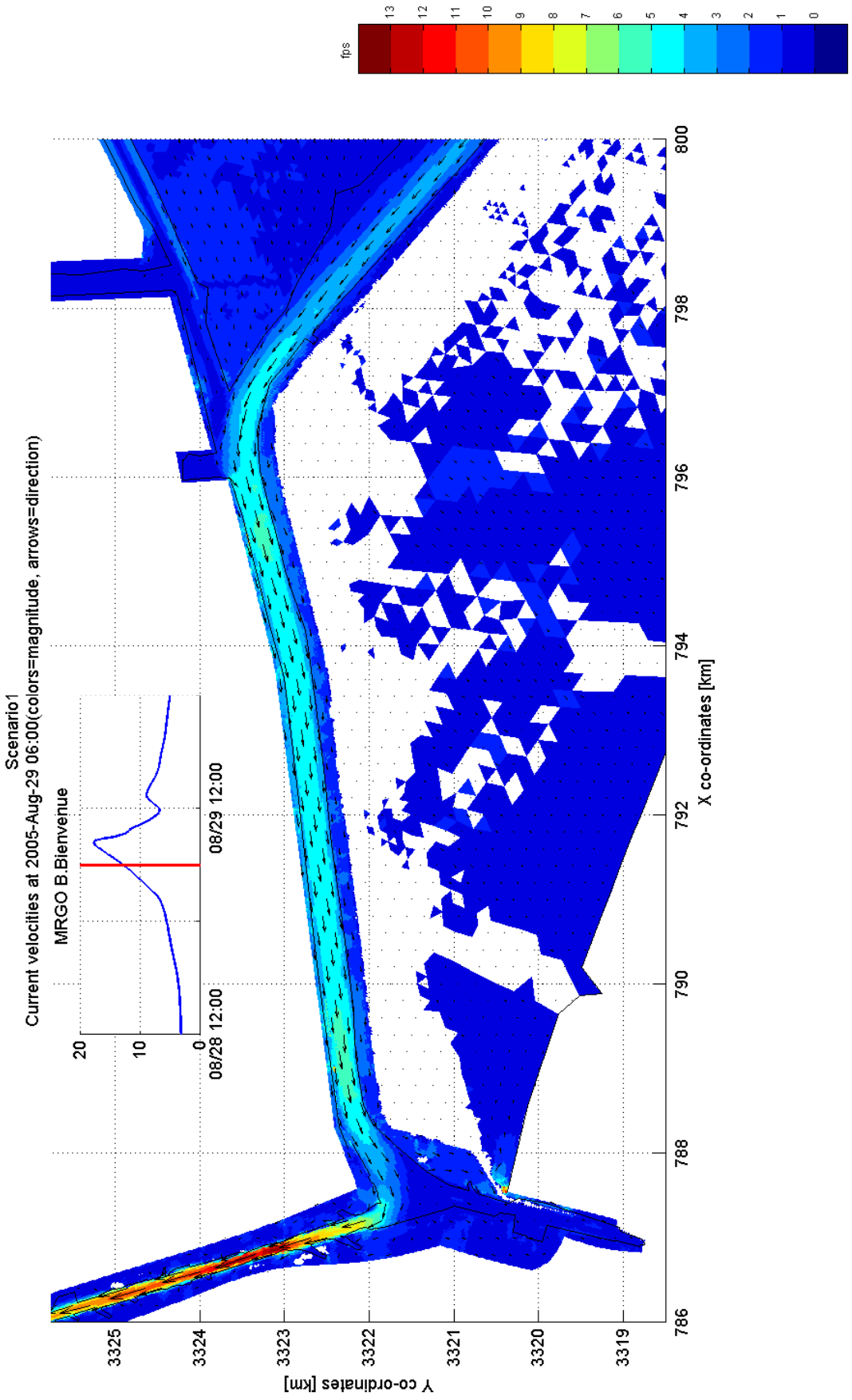


Figure 2.10c: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 1 at 6:00am local time.

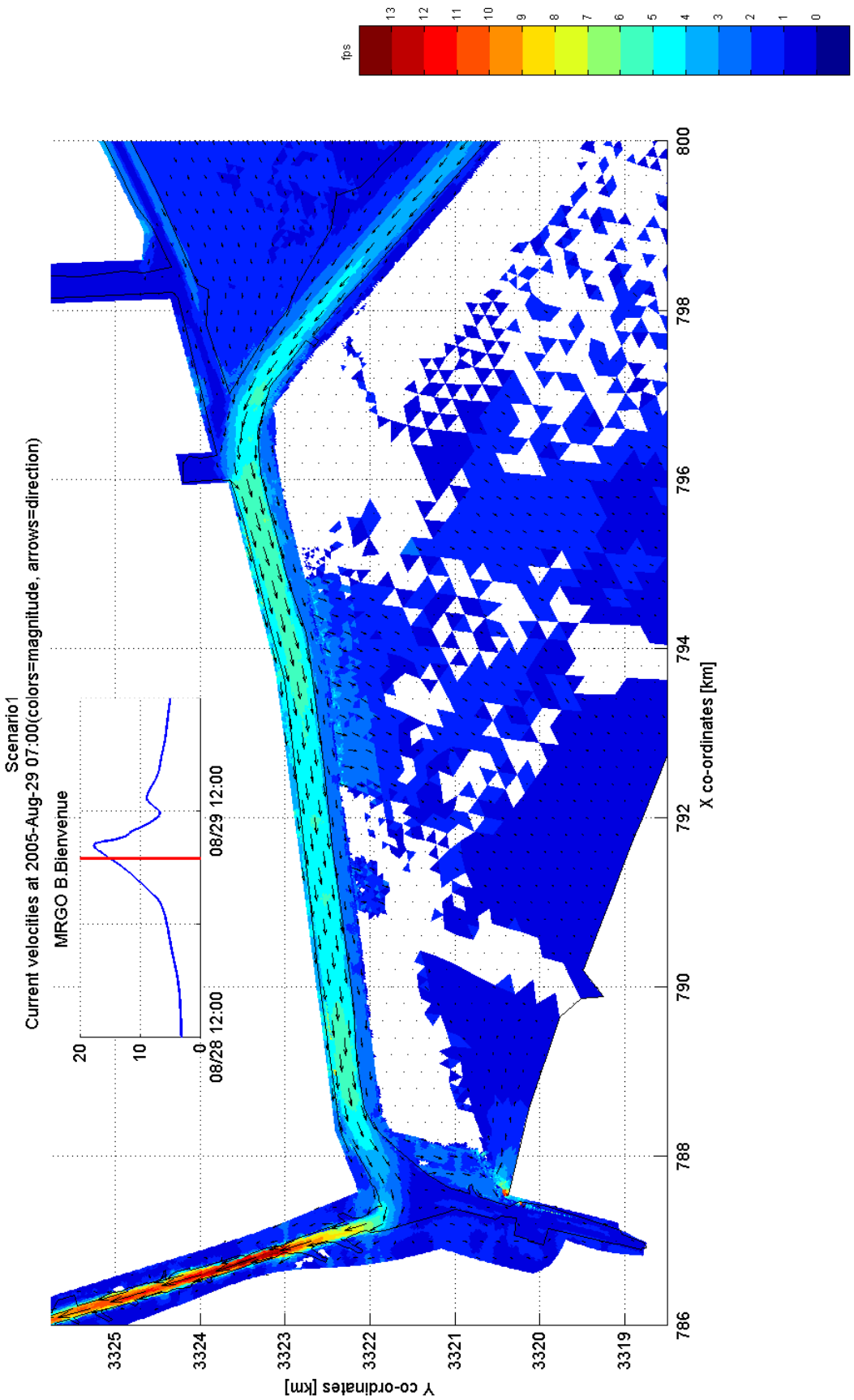


Figure 2.10d: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 1 at 7:00am local time. Note that overtopping has started at southern side MRGO Reach 1. The flooding represents contribution from levee overtopping only.

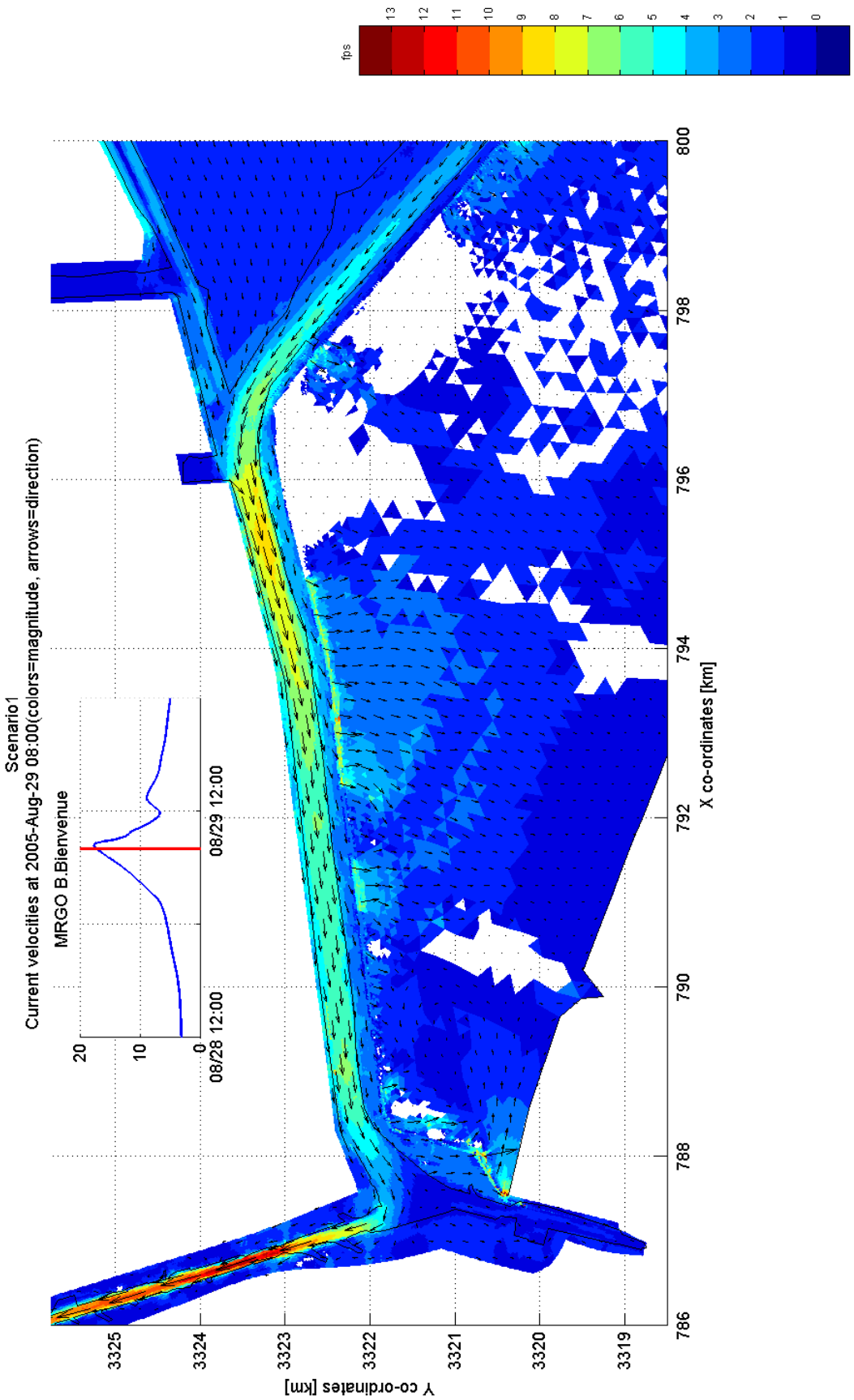


Figure 2.10e: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 1 at 8:00am local time. Note levee overtopping velocities of about 7 feet per second at the levee crest. Flow over both Reach 1 and Reach 2 levees. The flooding represents contribution from levee overtopping only.

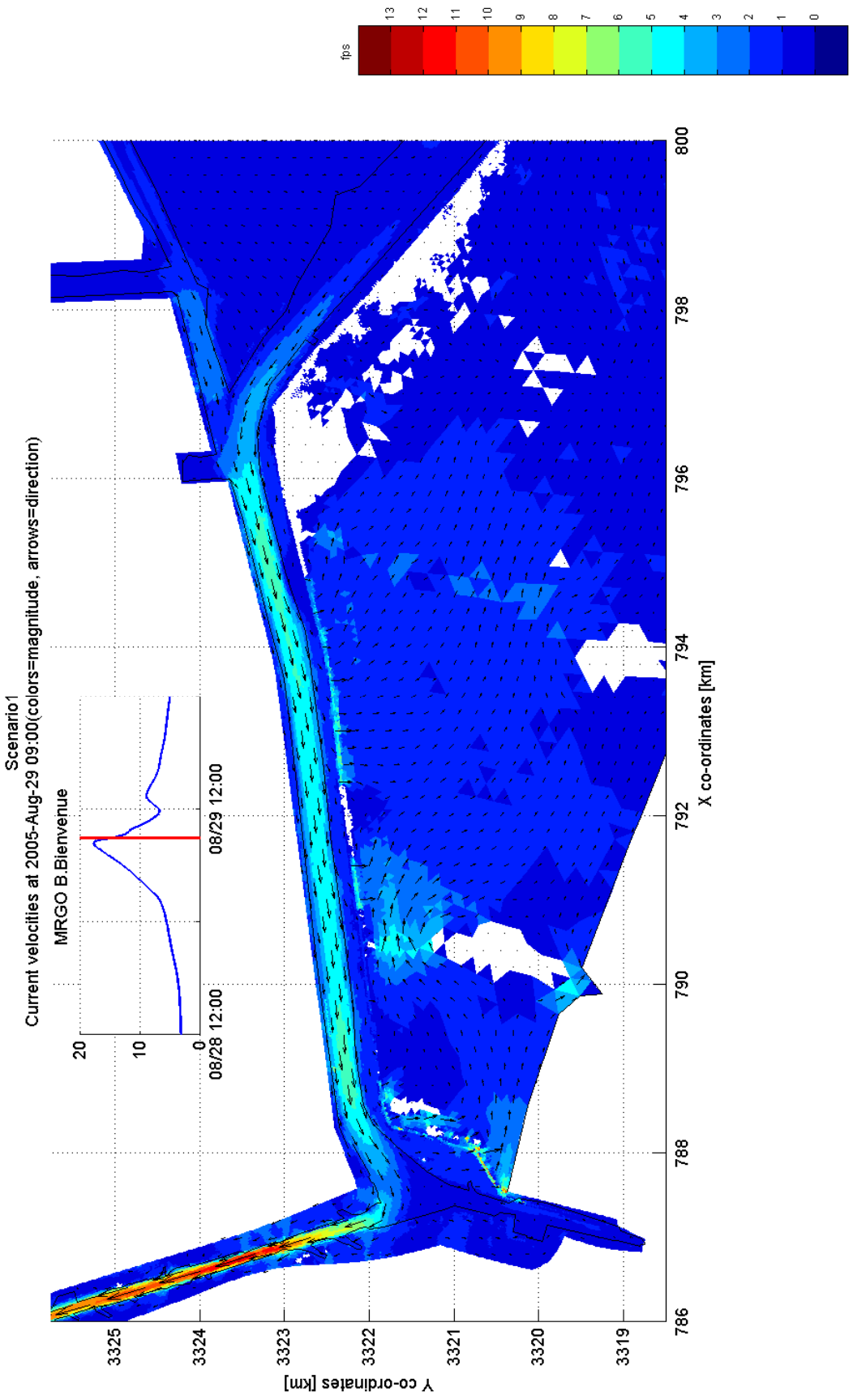


Figure 2.10f: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 1 at 9:00am local time. Note levee overtopping. The flooding represents contribution from levee overtopping only.

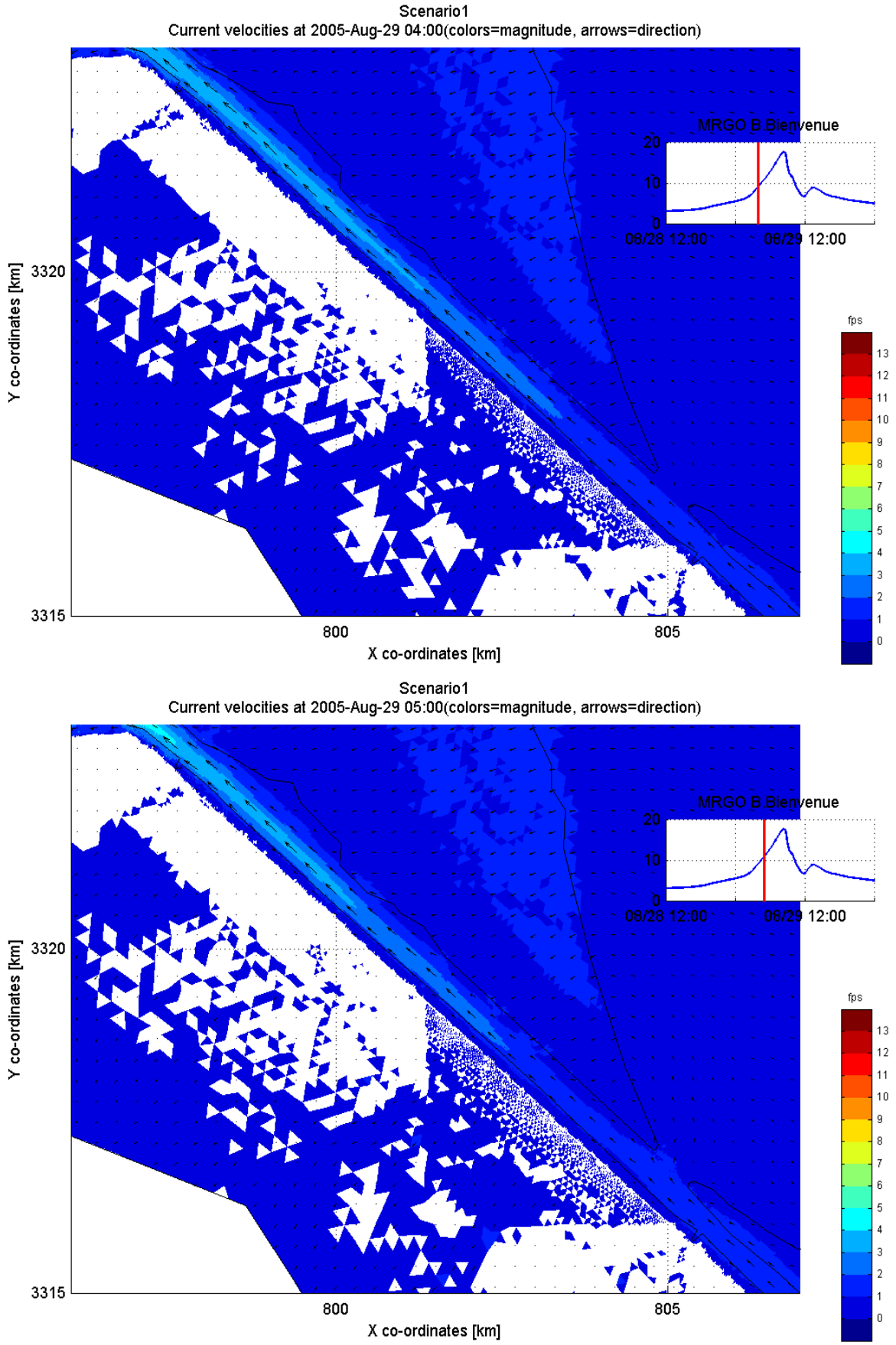


Figure 2.11a: Spatial current velocities (magnitude with color scale, direction with arrows) MRGO Reach 2 for Scenario 1 at 4:00am, 5:00am local time.

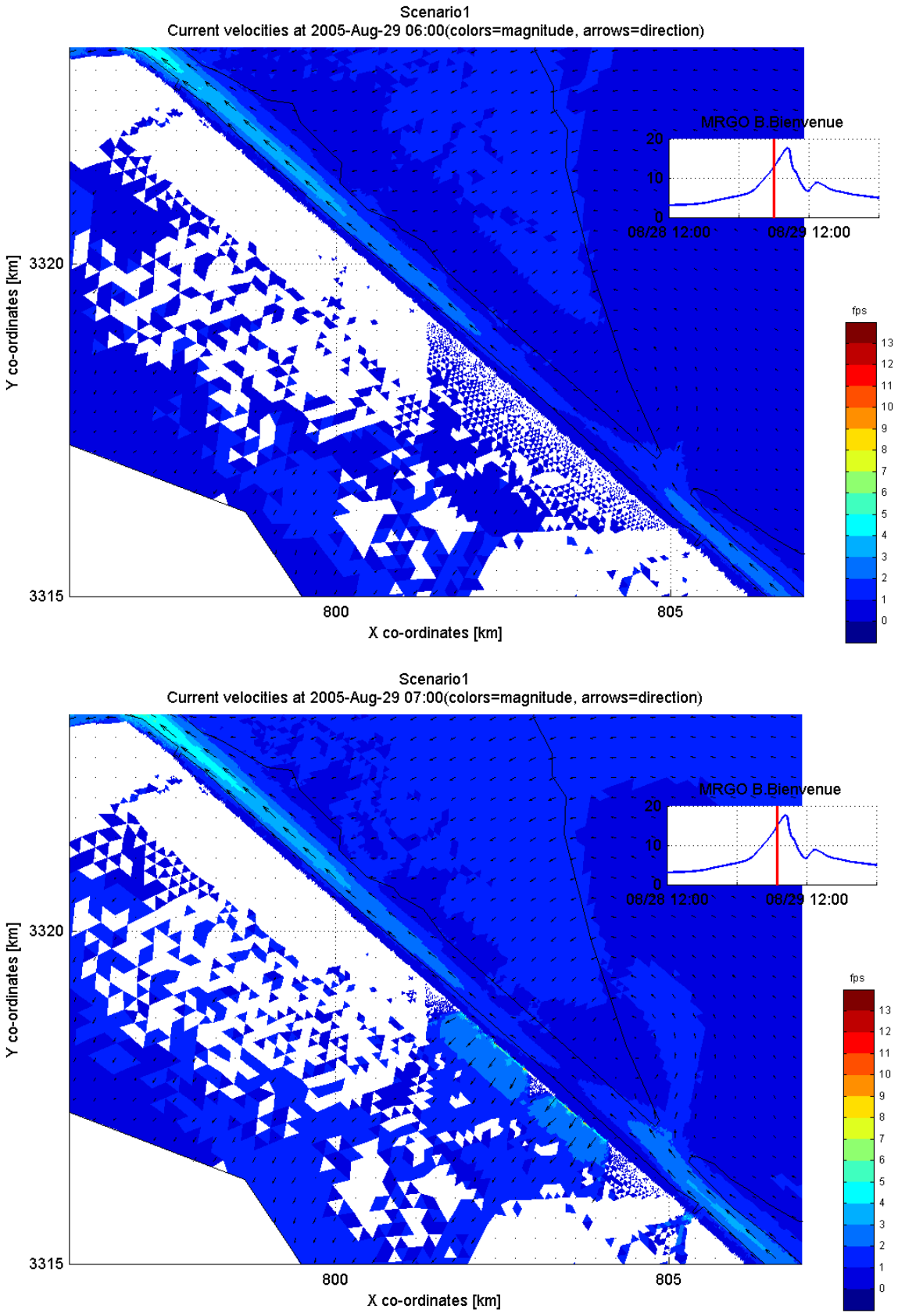


Figure 2.11b: Spatial current velocities (magnitude with color scale, direction with arrows) MRGO Reach 2 for Scenario 1 at 6:00am, 7:00am local time. Note that at 7:00am overtopping has started at MRGO Reach 2. The flooding represents contribution from levee overtopping only.

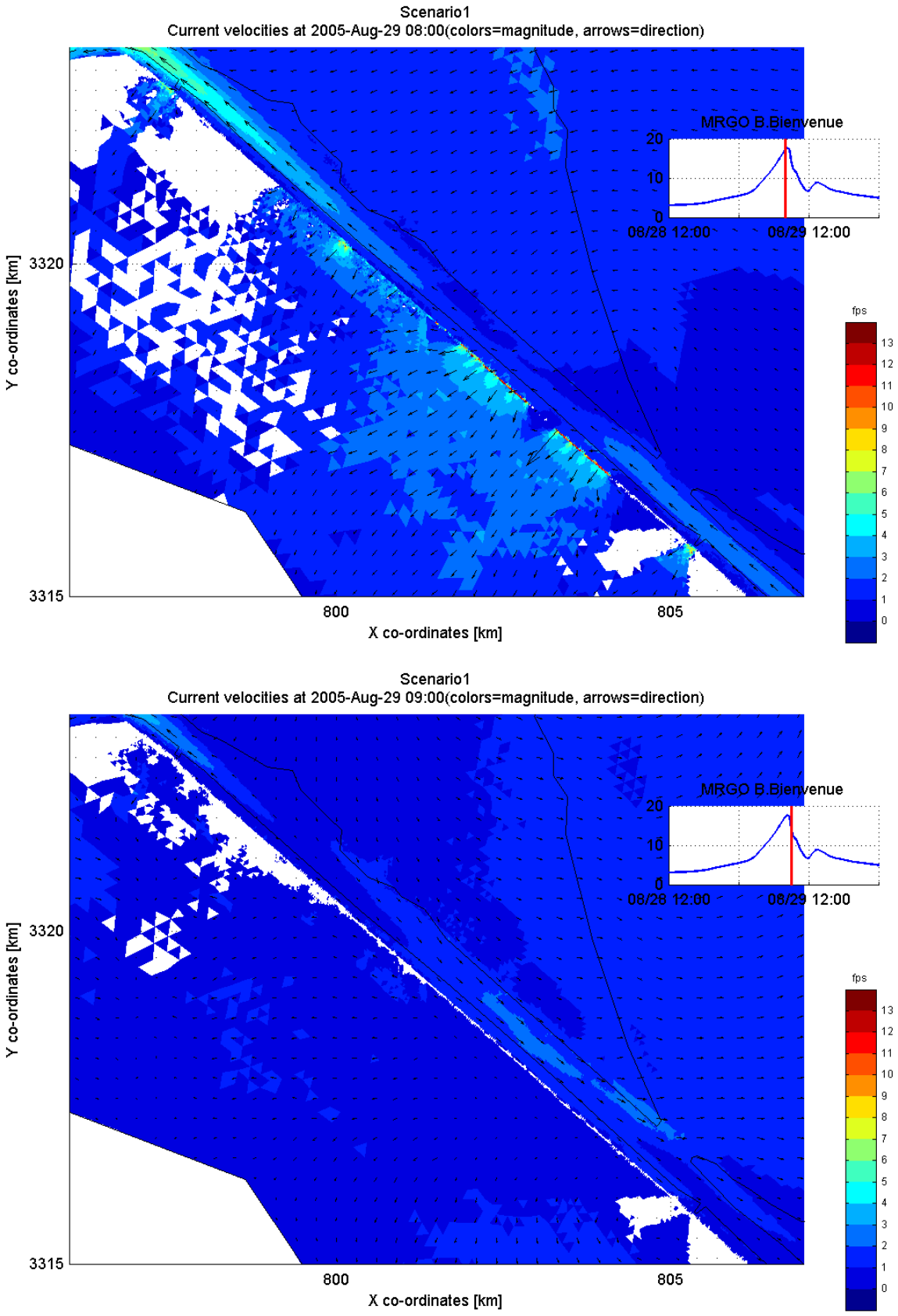


Figure 2.11c: Spatial current velocities (magnitude with color scale, direction with arrows) MRGO Reach 2 for Scenario 1 at 8:00am, 9:00am local time. Note levee overtopping velocities of about 10 feet per second at the levee crest. The flooding represents contribution from levee overtopping only.

Detailed flow information at several locations

For several locations (see Figure 2.12 and Table 2.3) detailed current velocities and water levels are given in Figure 2.13. The details are also summarized in Tables 2.4 through 2.8.

Six output locations were requested along the MRGO by the Robinson experts. Some are close to the levee crown, and others are further away. To aid in data interpretation six additional companion sites were chosen at the water line of the MRGO at normal water level. The different results between the requested locations (1 to 6) and the shifted locations (1a to 6a) reflect different water depths and these locations correspond to output locations (Levee and Toe) in the wave modeling by the SWAN modeling team [Ref. 7].

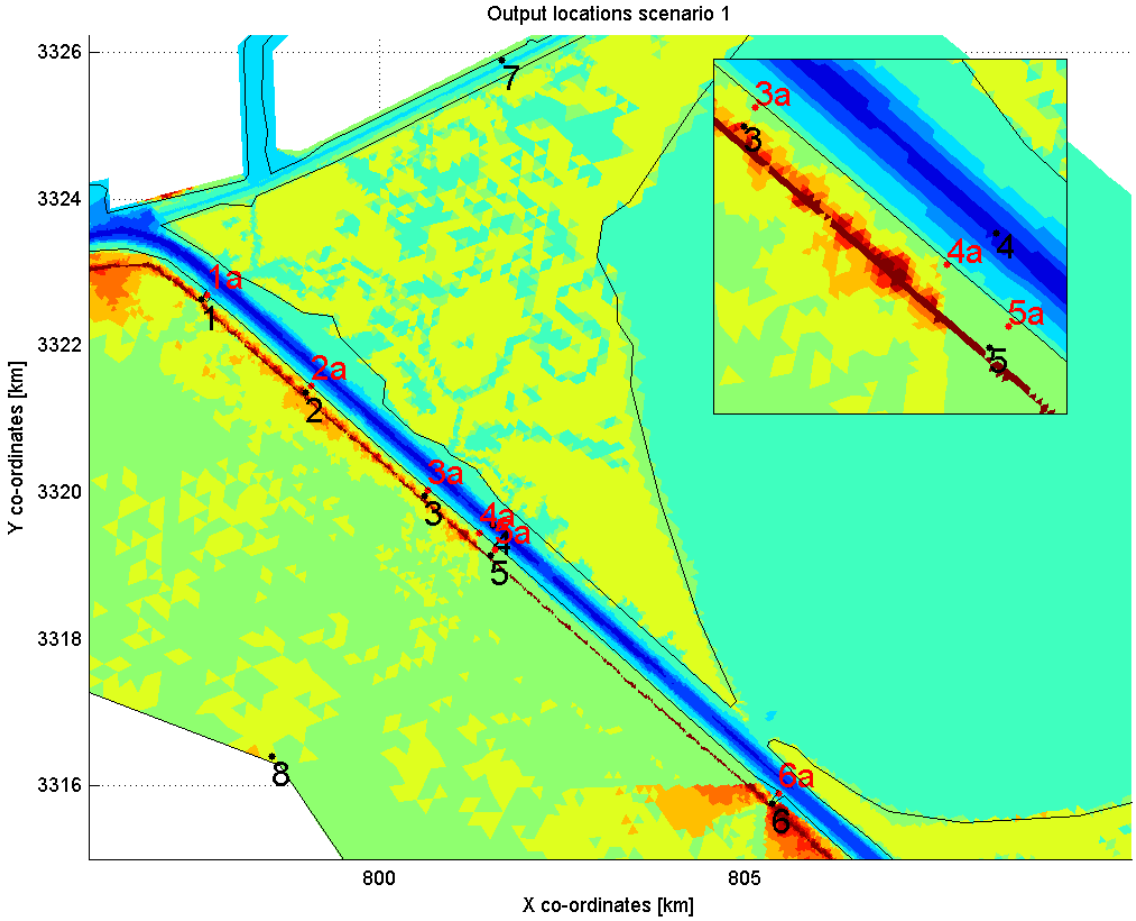


Figure 2.12: Output locations Reach 2 for the Scenario 1 FINEL model run

Table 2.3: Coordinates output locations

		Requested output location				Output location at water line	
Loc	Name	lat [N]	lon [W]	UTM [m]	UTM [m]	UTM [m]	UTM [m]
1	B. Bienvenue	29°59’ 54.51”	89°54’ 55.54”	797571	3322628	797644	3322689
2	Station 430	29°59'12.29"	89°54' 03.80"	798993	3321367	799071	3321457
3	Loc I	29.97368°	89.884833°	800613	3319954	800653	3320023
4	MRGO Halfway	29°58’ 5.11”	89°52’ 40.14”	801540	3319563	801360	3319446
5	Station 540	29°57'58.19"	89°52' 32.15"	801515	3319142	801585	3319221
6	B. Dupre	29°56’ 5.52”	89°50’ 12.26”	805355	3315765	805451	3315898
7	GIWW@BackB	30° 01.597'	89°52.291'	801670	3325901		
8	Loc II 40Arpent			798527	3316406		

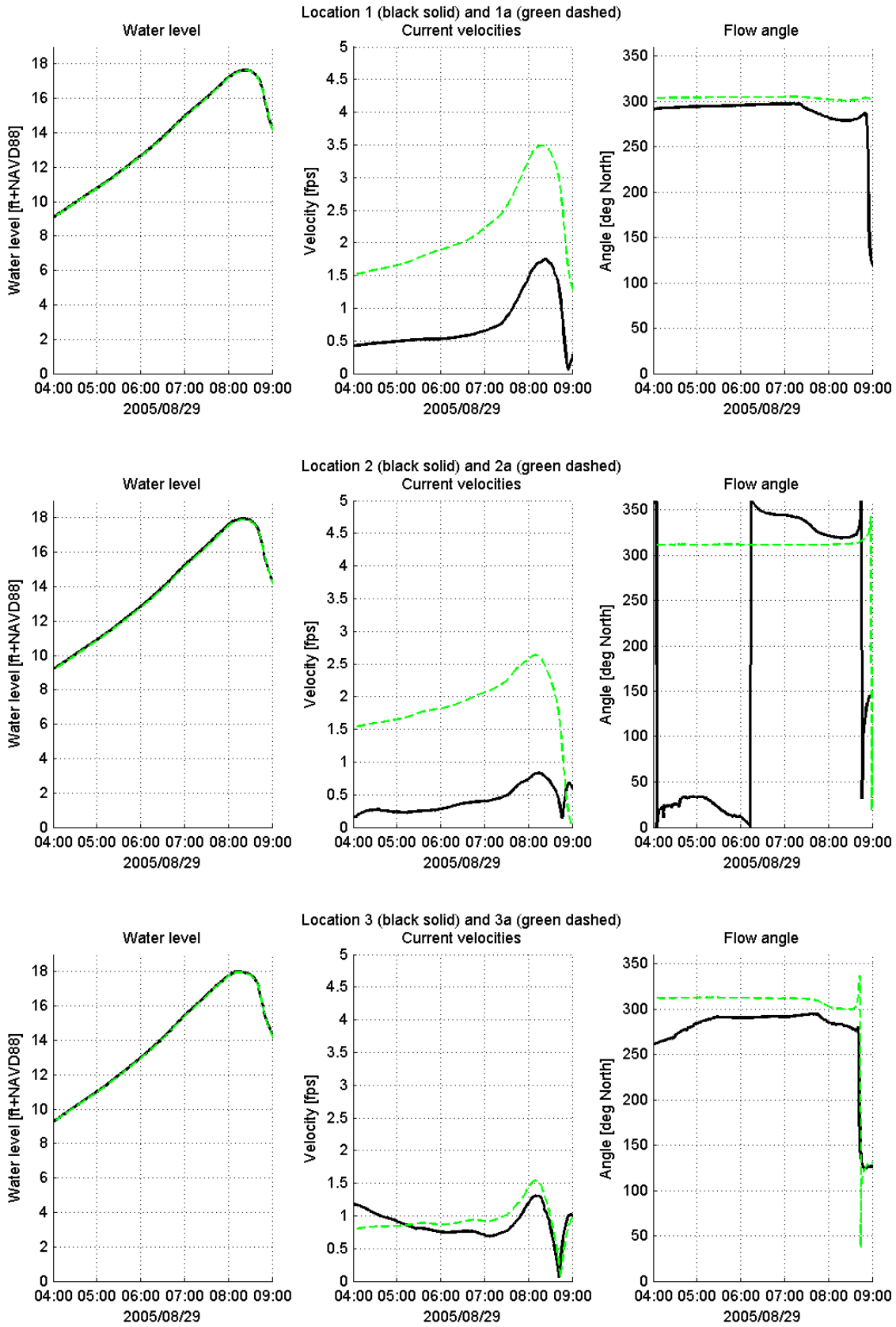


Figure 2.13a: Results Scenario 1 for locations 1, 2 and 3 from 4:00am to 9:00am; Note the maximum surge elevation of 18 ft NAVD just after 8:00am.

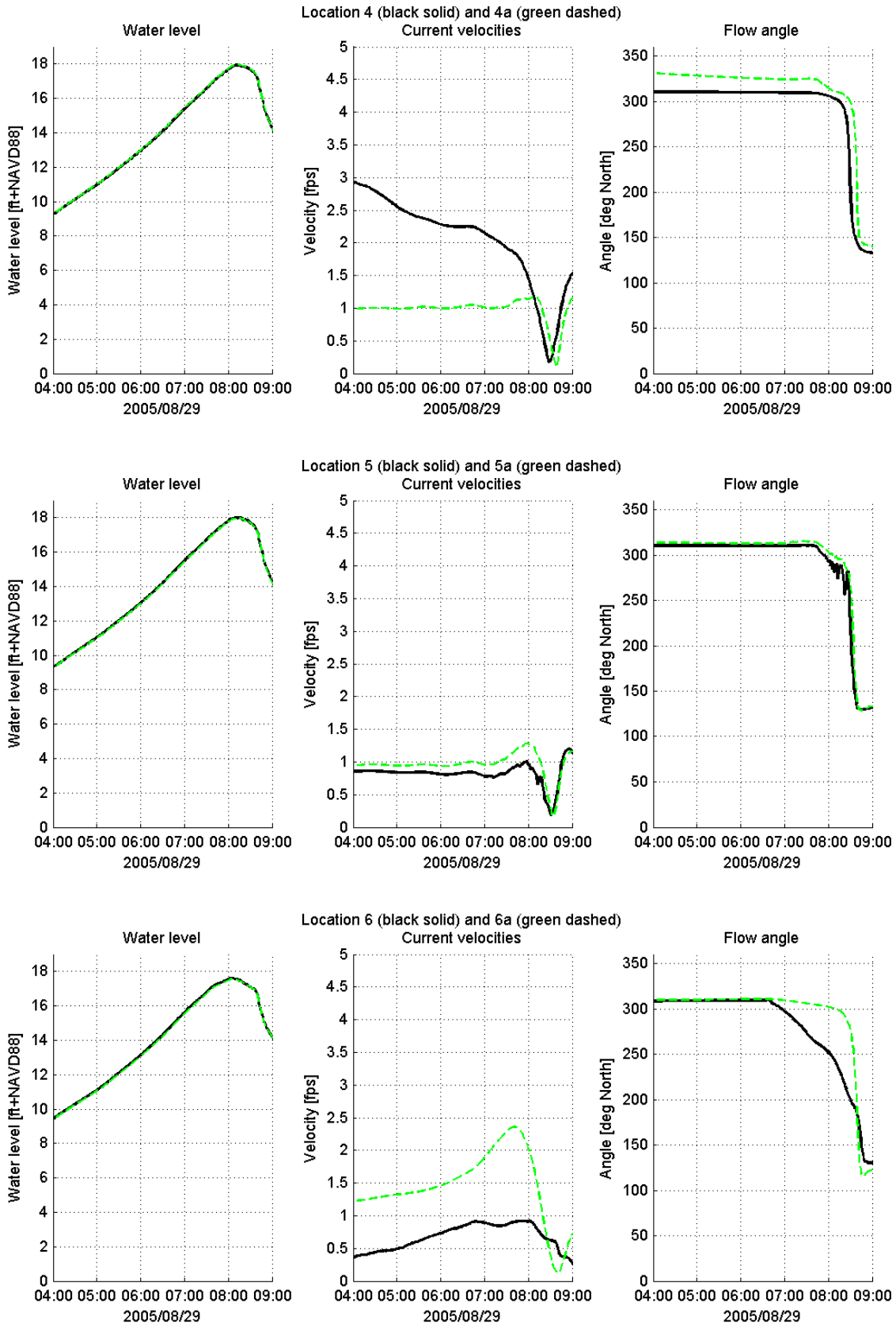


Figure 2.13b: Results Scenario 1 for locations 4, 5, and 6 from 4:00am to 9:00a; Note the maximum surge elevation of 18 ft NAVD just after 8:00am.

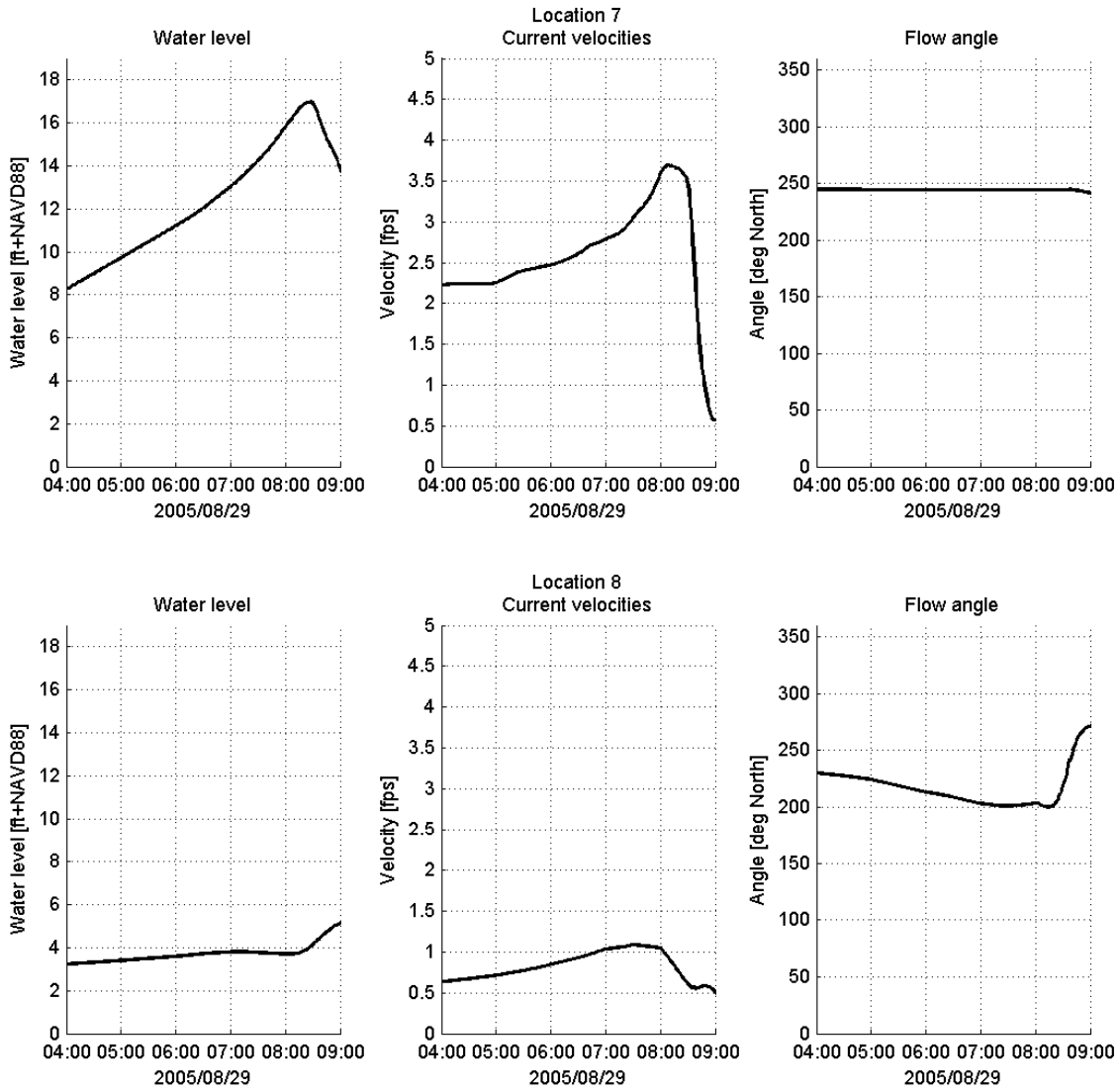


Figure 2.13c: Results for locations 7 and 8 Scenario 1 from 4:00am to 9:00am

Table 2.4: Summary results Scenario 1 at 29th August 2005 4:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	9.08	0.43	291	9.05	1.52	304
2	Station 430	9.21	0.15	356	9.14	1.54	311
3	Loc I	9.27	1.18	261	9.25	0.80	312
4	MRGO Halfway	9.26	2.93	310	9.27	0.99	331
5	Station 540	9.32	0.85	311	9.29	0.94	314
6	B. Dupre	9.44	0.36	308	9.39	1.23	310
7	GIWW@BackB	8.25	2.22	244			
8	Loc II 40Arpent	3.22	0.63	230			

Table 2.5: Summary results Scenario 1 at 29th August 2005 5:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	10.79	0.49	294	10.75	1.66	304
2	Station 430	10.93	0.23	33	10.87	1.65	311
3	Loc I	11.02	0.91	284	10.98	0.84	312
4	MRGO Halfway	10.98	2.56	310	11.00	0.99	328
5	Station 540	11.06	0.84	310	11.02	0.94	313
6	B. Dupre	11.12	0.49	309	11.06	1.32	310
7	GIWW@BackB	9.72	2.26	244			
8	Loc II 40Arpent	3.39	0.71	224			

Table 2.6: Summary results Scenario 1 at 29th August 2005 6:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	12.67	0.53	296	12.63	1.89	304
2	Station 430	12.86	0.28	11	12.79	1.81	312
3	Loc I	13.00	0.75	290	12.96	0.87	312
4	MRGO Halfway	12.97	2.28	310	13.00	1.00	326
5	Station 540	13.07	0.81	310	13.02	0.93	313
6	B. Dupre	13.14	0.73	309	13.07	1.46	311
7	GIWW@BackB	11.22	2.47	244			
8	Loc II 40Arpent	3.58	0.85	213			

Table 2.7: Summary results Scenario 1 at 29th August 2005 7:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	14.96	0.65	297	14.91	2.23	305
2	Station 430	15.24	0.40	344	15.16	2.06	311
3	Loc I	15.43	0.70	291	15.38	0.92	311
4	MRGO Halfway	15.38	2.15	309	15.43	1.01	324
5	Station 540	15.51	0.77	310	15.46	0.95	313
6	B. Dupre	15.63	0.89	297	15.54	1.89	309
7	GIWW@BackB	13.04	2.78	244			
8	Loc II 40Arpent	3.78	1.03	203			

Table 2.8: Summary results Scenario 1 at 29th August 2005 8:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	17.21	1.46	282	17.18	3.26	302
2	Station 430	17.60	0.74	321	17.52	2.58	311
3	Loc I	17.76	1.20	285	17.72	1.43	303
4	MRGO Halfway	17.70	1.44	306	17.74	1.14	314
5	Station 540	17.78	0.95	293	17.77	1.27	304
6	B. Dupre	17.53	0.92	252	17.49	2.04	302
7	GIWW@BackB	15.83	3.58	244			
8	Loc II 40Arpent	3.71	1.04	204			

Table 2.9: Summary results Scenario 1 at 29th August 2005 9:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	14.27	0.26	120	14.26	1.31	302
2	Station 430	14.32	0.61	145	14.30	0.03	76
3	Loc I	14.30	1.01	126	14.29	0.96	131
4	MRGO Halfway	14.25	1.53	133	14.26	1.15	140
5	Station 540	14.26	1.16	131	14.25	1.16	133
6	B. Dupre	14.19	0.27	130	14.18	0.72	122
7	GIWW@BackB	13.82	0.57	241			
8	Loc II 40Arpent	5.11	0.50	271			

2.2 Scenario 2C: The 'virgin' no-MRGO Scenario and a simulated Katrina storm with pre-Katrina MRGO levees and 40 Arpent levee crest at 6.5 ft+NAVD

2.2.1 Description of Scenario

In order to interpret the full impacts of the MRGO we decided to run a Katrina storm with a scenario run without the MRGO channel with the pre-Katrina MRGO levees. For this, we added the pre-Katrina levees to the situation of to the late 1950s. Accordingly, we simulate surge along the shores of Lake Borgne in a model in which we change the Scenario 1 model input in the following ways:

(1) 90% reduction in cross-section area of MRGO Reach 1 to the dimensions of the GIWW (pre-MRGO);
(2) MRGO Reach 2 is removed and replaced with land at the elevation of the surrounding marsh and swamp areas;
(3) The levees along MRGO Reach 1 and 2 are at their pre-Katrina crest elevations (same as in Scenario 1);
(4) Bayou LaLoutre ridge is restored to fill-in the hole dredged for MRGO Reach 2;
(5) The area between the 40 Arpent levee and the Mississippi is added to the model grid. The pre-Katrina crest level of 6.5 ft NAVD is used for the 40 Arpent levee.
(6) The Cypress trees originally present between the MRGO and the 40 Arpent levees have influence on the water current velocities and the wind velocities. A higher Manning's roughness is used for the Cypress forests reflecting their greater frictional impacts on surge currents, and the wind velocities are reduced by 80% inside the Cypress forests due to the wind break/canopy effect of tall forests.

2.2.2 FINEL model input data

The FINEL model is set up to utilize the metric system, so all data is thus subsequently converted to feet. The coordinate system used in the simulations is UTM (zone 15 R). Input data that was received in longitude and latitude was translated accordingly.

Model grid
The model grid used for Scenario 2C is expanded from that used for Scenario 1 with the area between the 40 Arpent levee and the Mississippi River added to the grid. See Figure 2.14.

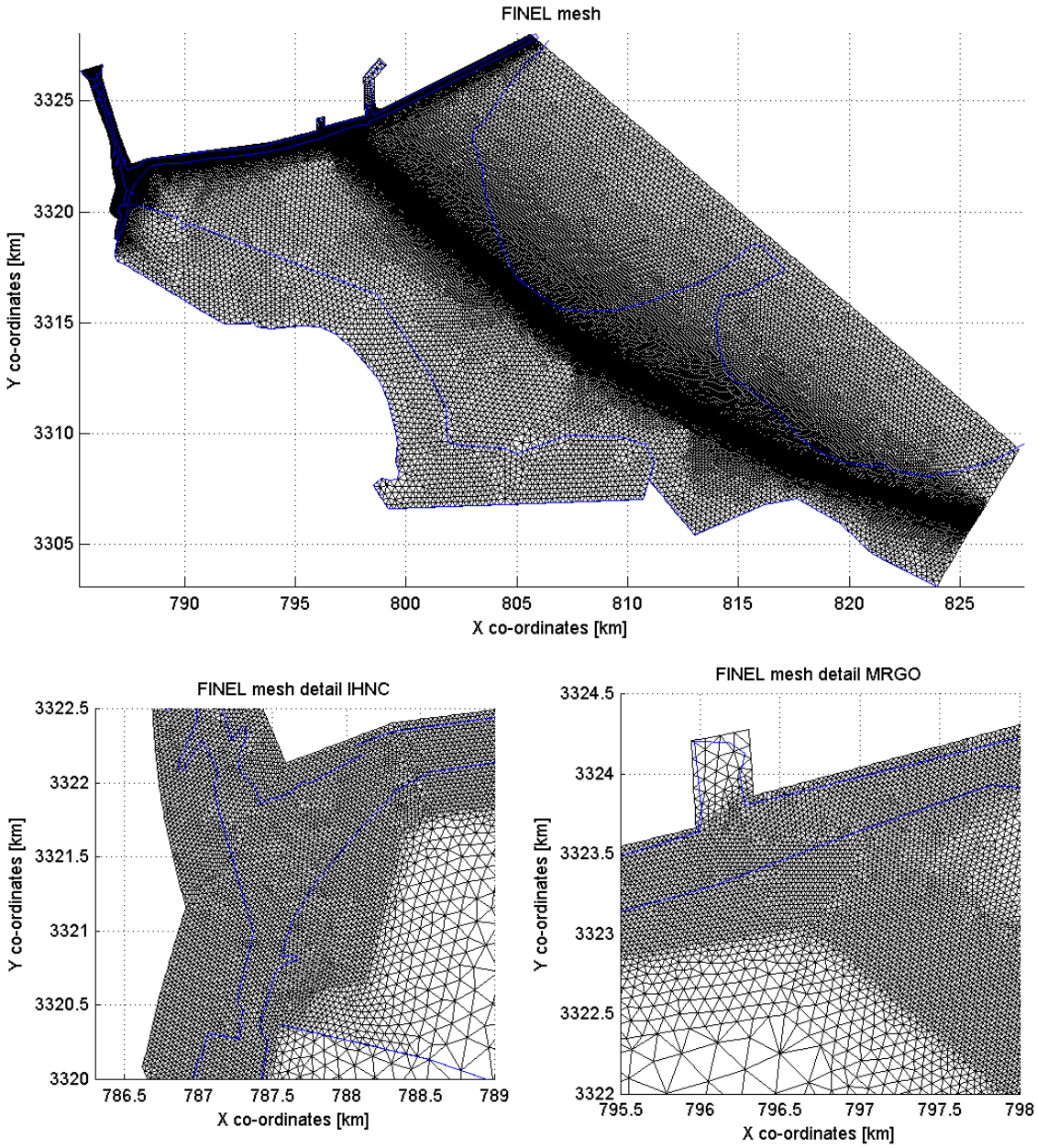


Figure 2.14: Model grid FINEL Scenario 2C, including area between 40 Arpent and Mississippi. Note the grid is denser in channel areas to more accurately simulate the flow conditions.

Bathymetry and Topography

The bathymetry for Scenario 2C is modified to represent the conditions prior to the construction of the MRGO, but with the pre-Katrina levees along the MRGO. Reach 2 of the MRGO is filled to the height of the surrounding marshes and swamps in the grid. Reach 1 is modified to the original GIWW design dimensions of 150 ft wide and 12 ft deep, as provided by the Robinson experts. The levees along MRGO Reach 1 and 2 are input at their pre-Katrina crest elevations provided by the Robinson experts. The marshes and swamps around Lake Borgne are, where needed, restored to a 1950s elevation of 2.5 ft+NAVD88. A land-water map provided by the Robinson experts has been used to construct the original small water streams in the marshes. The topography of the area between the 40 Arpent levee and the Mississippi is taken from LIDAR data, provided by Robinson experts. The 40 Arpent levee has a pre-Katrina crest level of 6.5 ft+NAVD88. The resulting topography and bathymetry for the model area are shown in Figure 2.15.

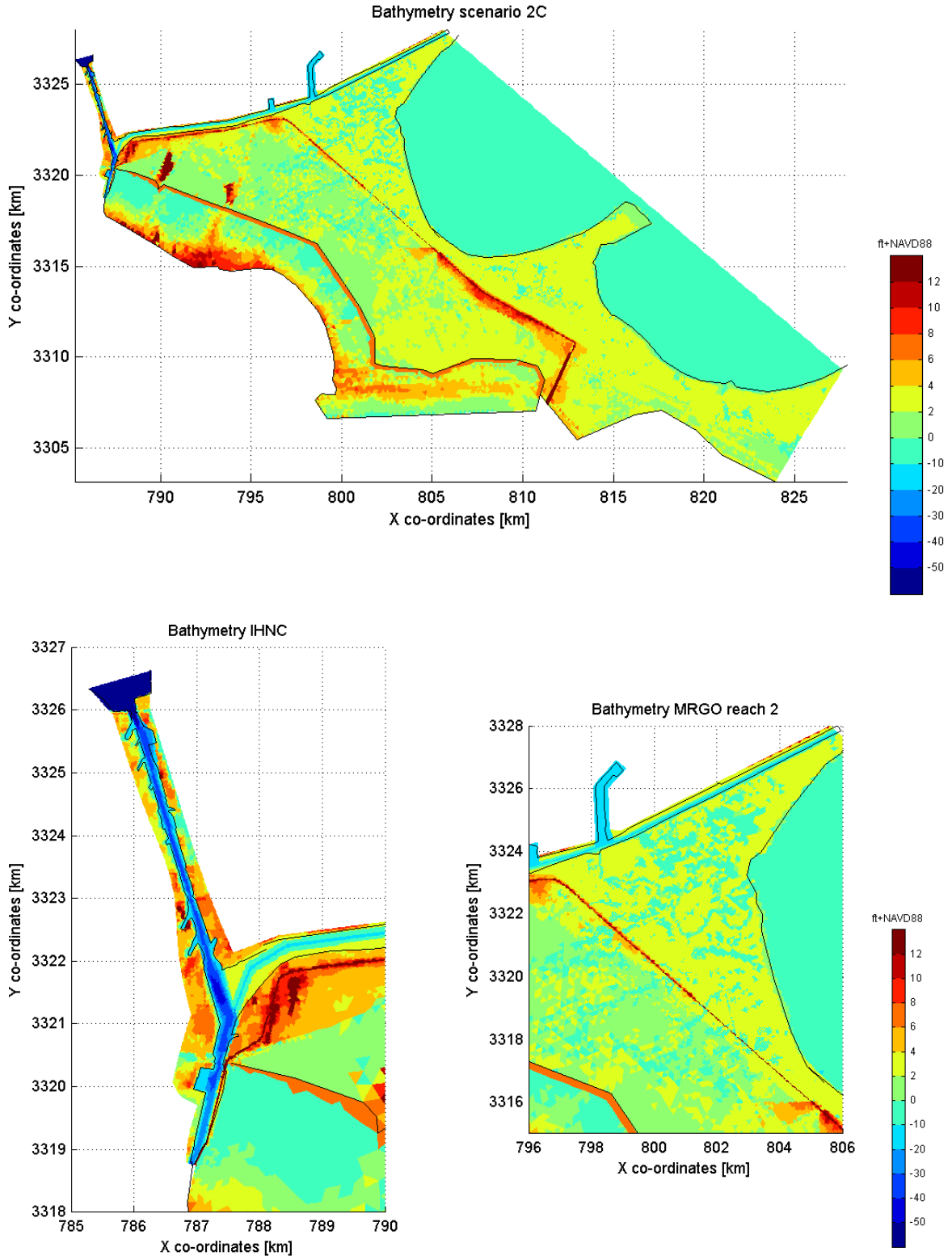


Figure 2.15: Bathymetry FINEL model area Scenario 2C

Simulation period
The simulation starts at 12h00 LT 28th August 2005 and continues until 24h00 29th August 2005.

Boundary conditions
The boundary conditions consist of water level time series from the constructed Scenario 2 hydrographs, provided to us by the Robinson experts. ADCIRC outputs with and without the

MRGO are used to modify Scenario 1 outputs reducing the maximum surge and delaying the peak at Shell Beach at Reach 2.

Figure 2.16 shows the locations of the boundary conditions and Table 2.10 gives the corresponding locations which are used for every boundary. The boundary time series themselves are shown in Figure 2.17. All boundaries not mentioned in Table 2.10 are closed boundaries.

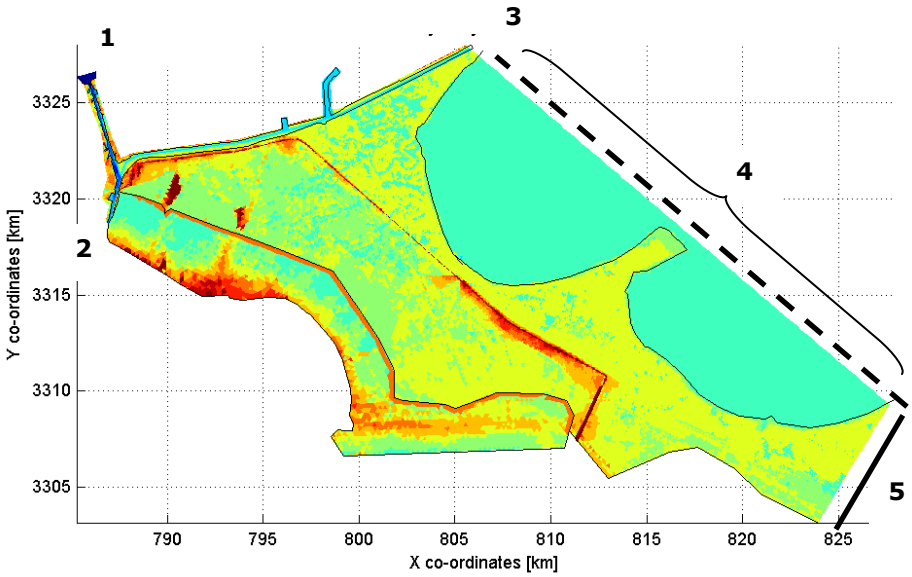


Figure 2.16: Location boundary conditions FINEL flow model

Table 2.10: Boundary conditions

	Boundary	*Used hydrograph2 (modified ADCIRC)*
1	Lake Pontchartrain	IHNC@LakeP
2	IHNC Locks	Closed boundary (discharge=0)
3	GIWW	NOEbackA
4	Lake Borgne	Interpolation between 3 and 5
5	MRGO	Shell Beach

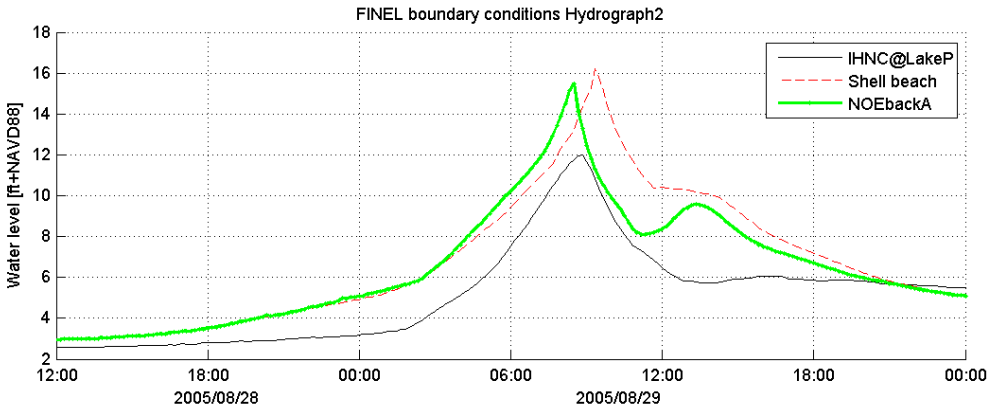


Figure 2.17: Time series boundary conditions FINEL flow model Scenario 2C

Bottom roughness

In the model area a spatial variable Manning coefficient is used for the bottom roughness. The Manning roughness coefficients used are based on years of experience in modeling coastal environments. These data were collaborated with other data sets such as from the US Geological Survey (http://www.fhwa.dot.gov/bridge/wsp2339.pdf), the world renowned book Open-channel hydraulics [Ref. 5] and IPET [Ref. 6]. For each scenario the spatial extent of the Manning's used is based on the presence or lack of wetlands; shoreline location and presence; and lack or presence of levees. In 1958 Cypress forests existed between the MRGO and the 40 Arpent levees (Figure 2.18). The Cypress trees cause friction on the flow, this influence is taken into account by a higher roughness coefficient. In a map provided by Robinson experts, two types of Cypress forests are distinguished: normal (Manning n=0.1 $m^{-1/3}s$) and dense (Manning n=0.12 $m^{-1/3}s$). At the strip of land along the MRGO levees a roughness representing grass (Manning n=0.034 $m^{-1/3}s$) is used. The Manning roughness coefficients are shown in Figure 2.19 and summarized in Table 2.11.



Figure 2.18: Photograph of cypress trees in swampy areas (send to us by Robinson experts)

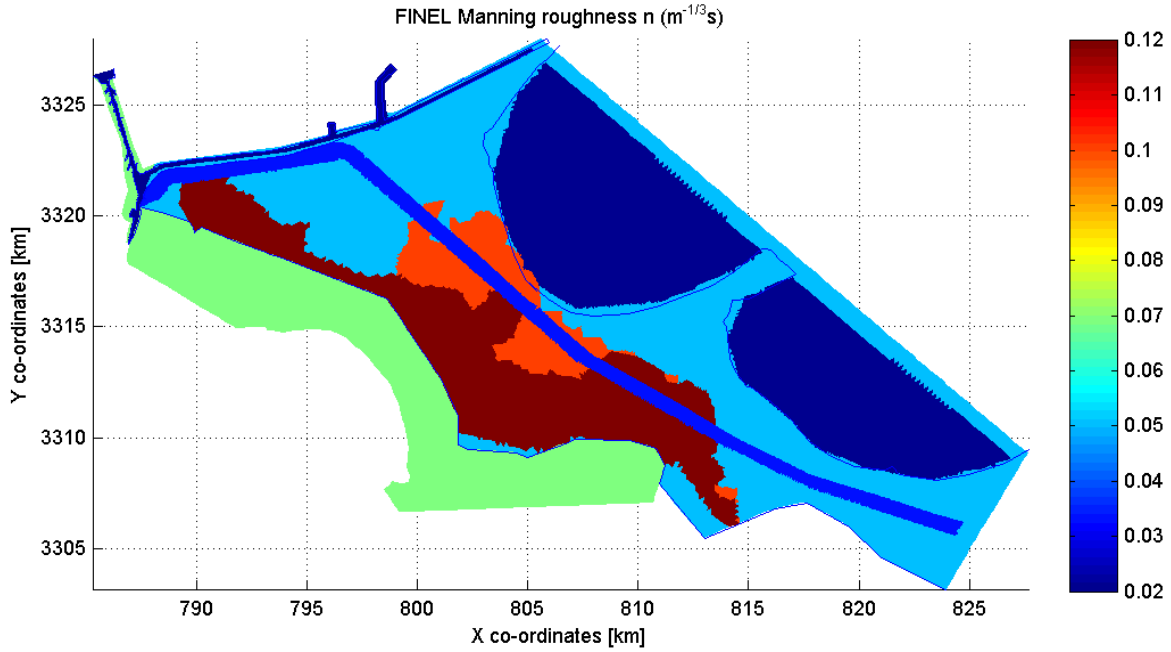


Figure 2.19: Manning roughness coefficient FINEL model area Scenario 2C. The cypress areas are red (dark red = dense cypress trees, light red = normal cypress trees).

Table 2.11: Manning coefficient (based on: IPET Volume IV appendix page IV-5-102 [Ref. 6])

Area	*Manning coefficient n ($m^{-1/3}s$)*
Open water	0.02
Marsh along Lake Borgne	0.05
Grass at levees	0.034
Normal Cypress forest	0.1
Dense Cypress forest	0.12
Commercial area next to IHNC	0.07
Low residential area between 40Arpent and Mississippi	0.07

Wind

To take into account the influence of wind on the water motion, spatial variable wind fields are used in the flow calculations with FINEL. The wind fields were provided to us by the Robinson experts spaced at 30 minute intervals. Within the cypress forest the influence of the wind on water movement is dramatically reduced by the trees. Therefore the wind velocities are reduced by 80% (percentage provided to us by Dr Robinson experts) within the Cypress forests (both dark red and light red areas in Figure 2.19). Also for the strip of levees along the MRGO inside the Cypress forests the wind velocities are reduced. We are confident with this arrangement because for most of the simulation period the wind is blowing perpendicular to the MRGO Reach 2 and the forest northeast of the MRGO would have reduced the winds at the levees. The wind speed surface stress is calculated by:

$$\frac{\tau_{wind,x}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,x} - U_x),$$

$$\frac{\tau_{wind,y}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,y} - U_y).$$

With:

C_d = wind drag coefficient (-),
W_{10} = wind speed at 10 meter height (m/s),
U = water velocity (m/s).

The wind drag is defined by Garrat's drag formula (Garrat 1977):

$C_d = (0.75 + 0.067W_{10}) \times 10^{-3}$

2.2.3 Results

The FINEL flow model is used to produce details of the water current. This section shows the results of Scenario 2C: The 'virgin' no-MRGO Scenario and a simulated Katrina storm with pre-Katrina MRGO levees and 40 Arpent levee crest at 6.5 ft+NAVD. The results are shown on 6 time steps on the day Katrina struck, 29th August 2005, namely:

1. 4:00am Local Time;
2. 5:00am Local Time;
3. 6:00am Local Time;
4. 7:00am Local Time;
5. 8:00am Local Time;
6. 9:00am Local Time.

Area plots

The water levels in the model area for these time steps are shown in Figure 2.20. The current velocities are shown in Figure 2.21. A close up along MRGO Reach 1 is shown in Figure 2.22, and along MRGO Reach 2 in Figure 2.23. Compared with Scenario 1 the surge in the IHNC and MRGO Reach 1 is lower. Overtopping over the MRGO Reach 1 and 2 levees starts approximately 1 hour later and remains less than in Scenario 1. The Cypress forests along Lake Borgne in front of the MRGO Reach 2 levees with high bottom friction and low wind velocities reduce the flow velocities, leading to reduced wind set up and reduced surge elevation.

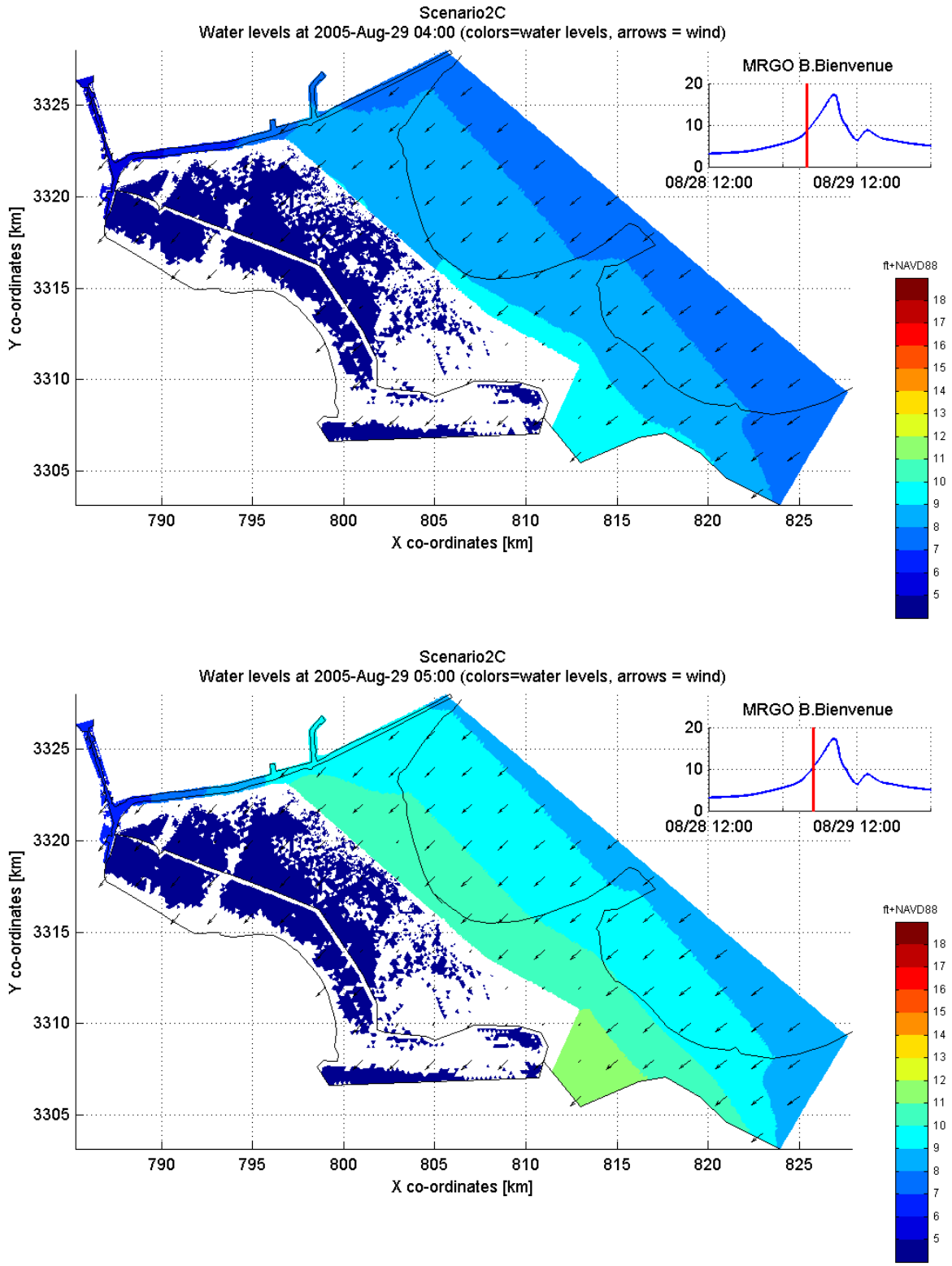


Figure 2.20a: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 2C at 4:00am, 5:00am local time.

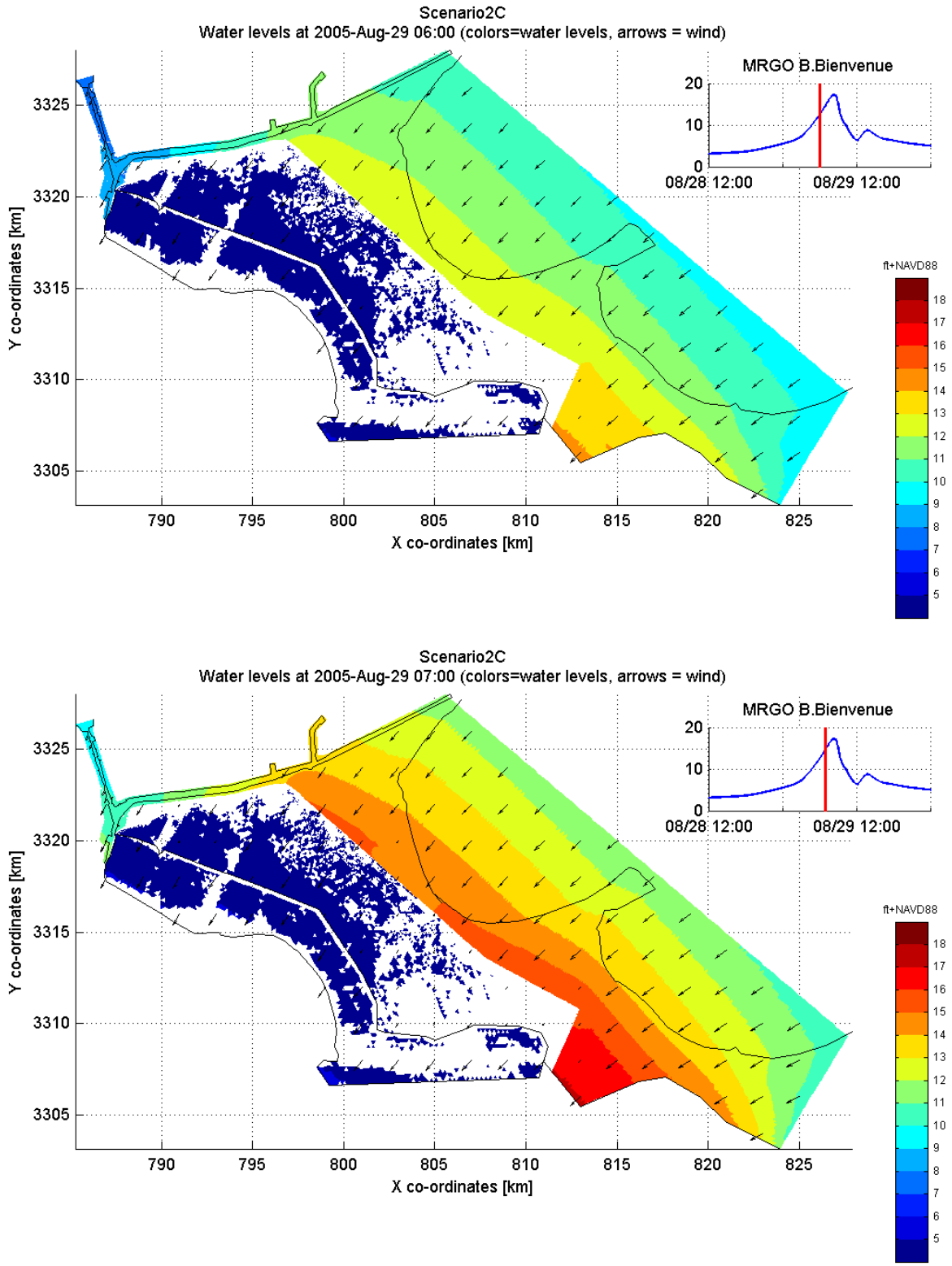


Figure 2.20b: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 2C at 6:00am, 7:00am local time. Note the reduction in surge level of 1 foot in front of the MRGO Reach 2 levees between X=801-805 km caused by the wind reduction inside the Cypress forest.

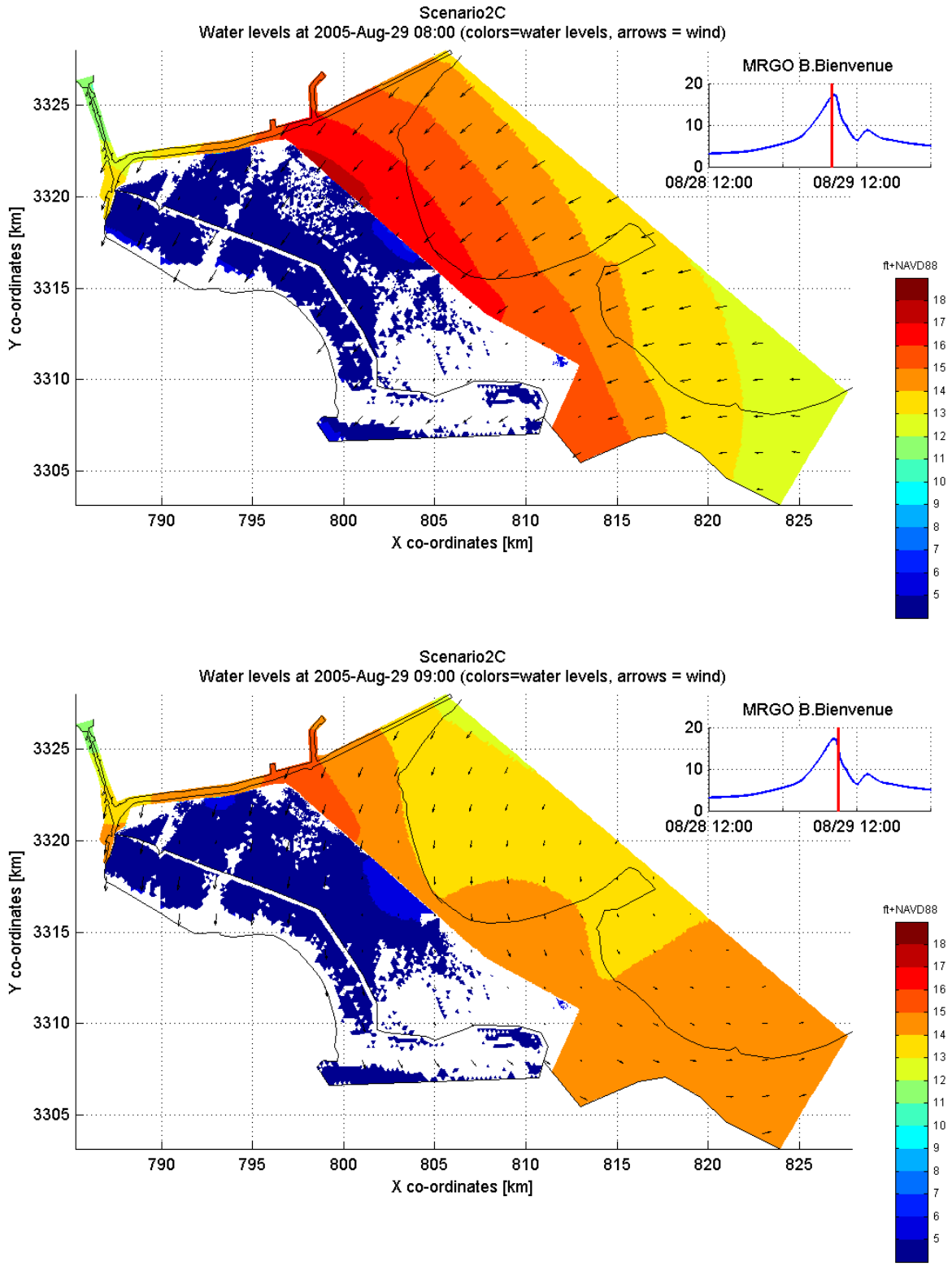


Figure 2.20c: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 2C at 8:00am, 9:00am local time. Note the reduction in surge level of 1 foot in front of the MRGO Reach 2 levees between X=801-805 km caused by the wind reduction inside the Cypress forest. Surge amplification 16-17 ft NAVD in front of the MRGO levees and some flooding in St Bernard Parish. The flooding in St Bernard Polder represents contribution from levee overtopping only.

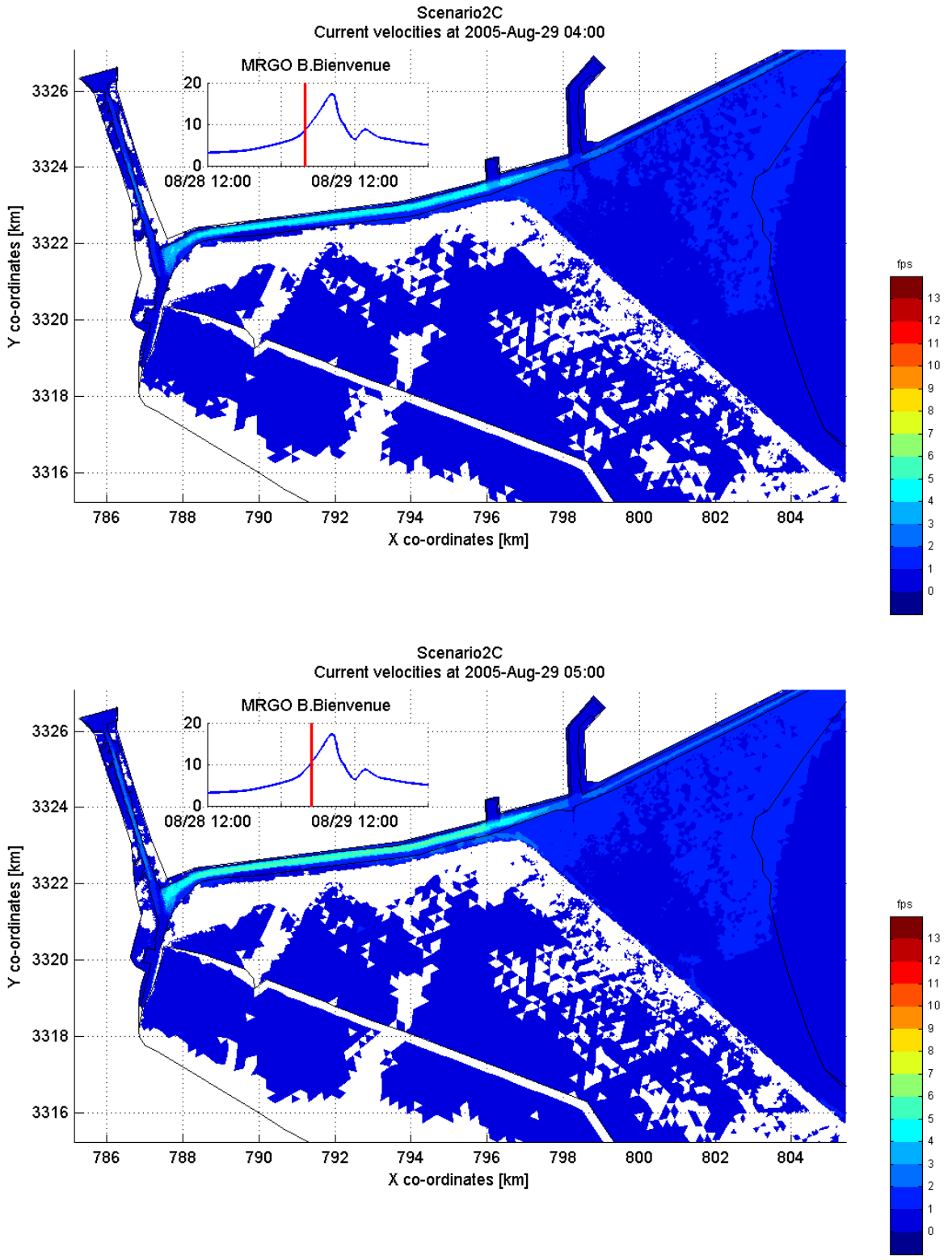


Figure 2.21a: Spatial current velocities for Scenario 2C at 4:00am, 5:00am local time. Note the high current velocities in MRGO Reach 1.

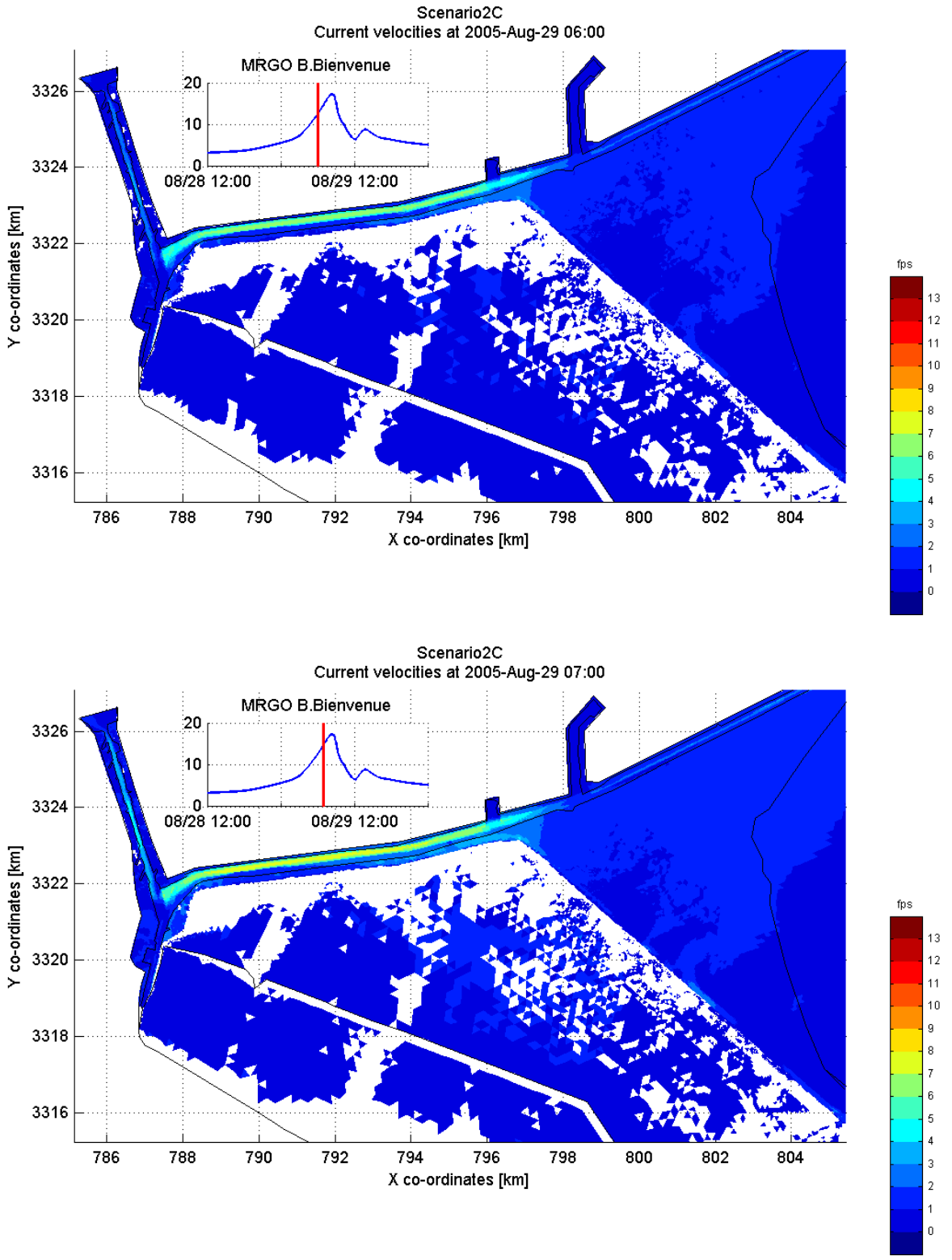


Figure 2.21b: Spatial current velocities for Scenario 2C at 6:00am, 7:00am local time. Note the high current velocities in MRGO Reach 1.

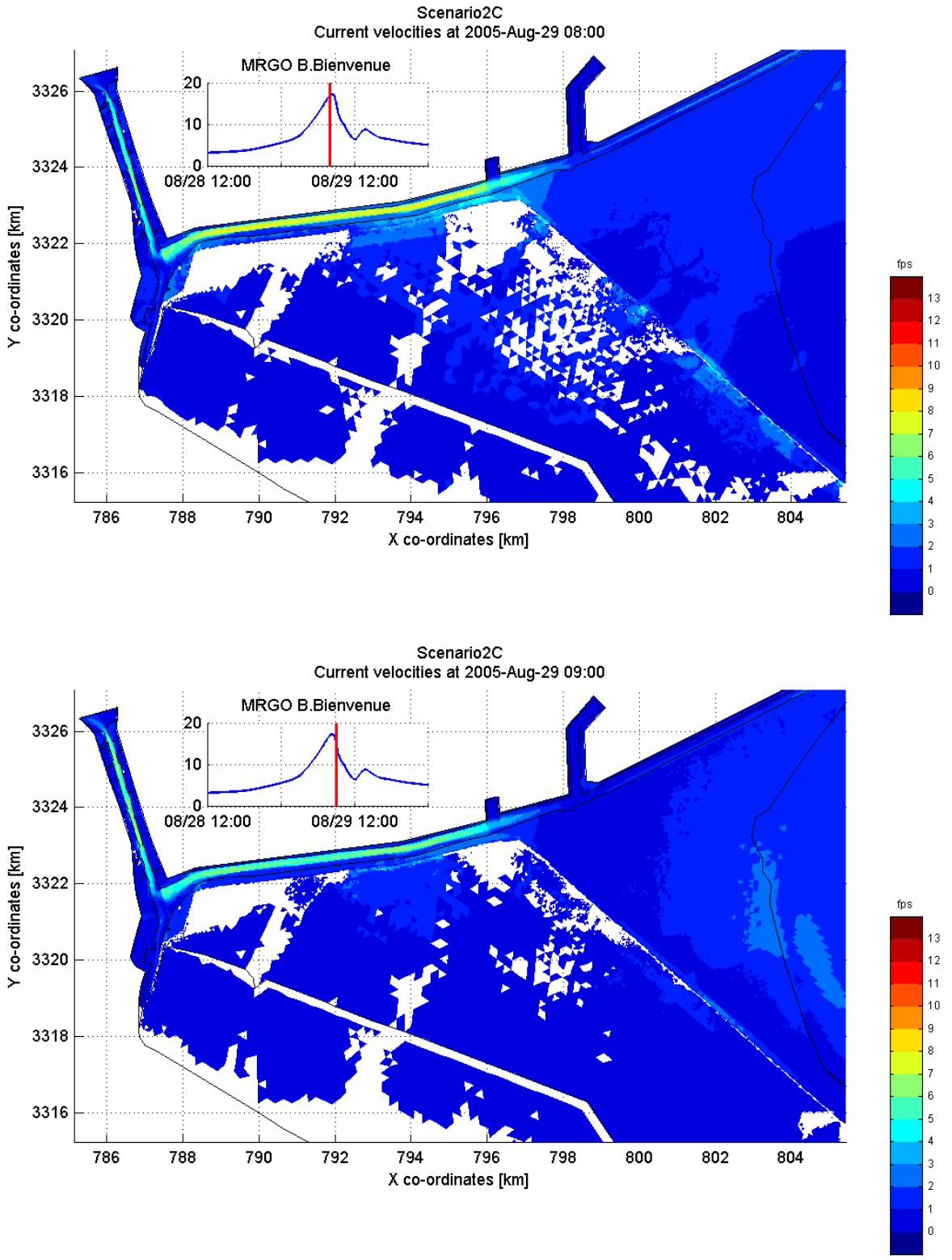


Figure 2.21c: Spatial current velocities for Scenario 2C at 8:00am, 9:00am local time. Note the high current velocities in MRGO Reach 1.

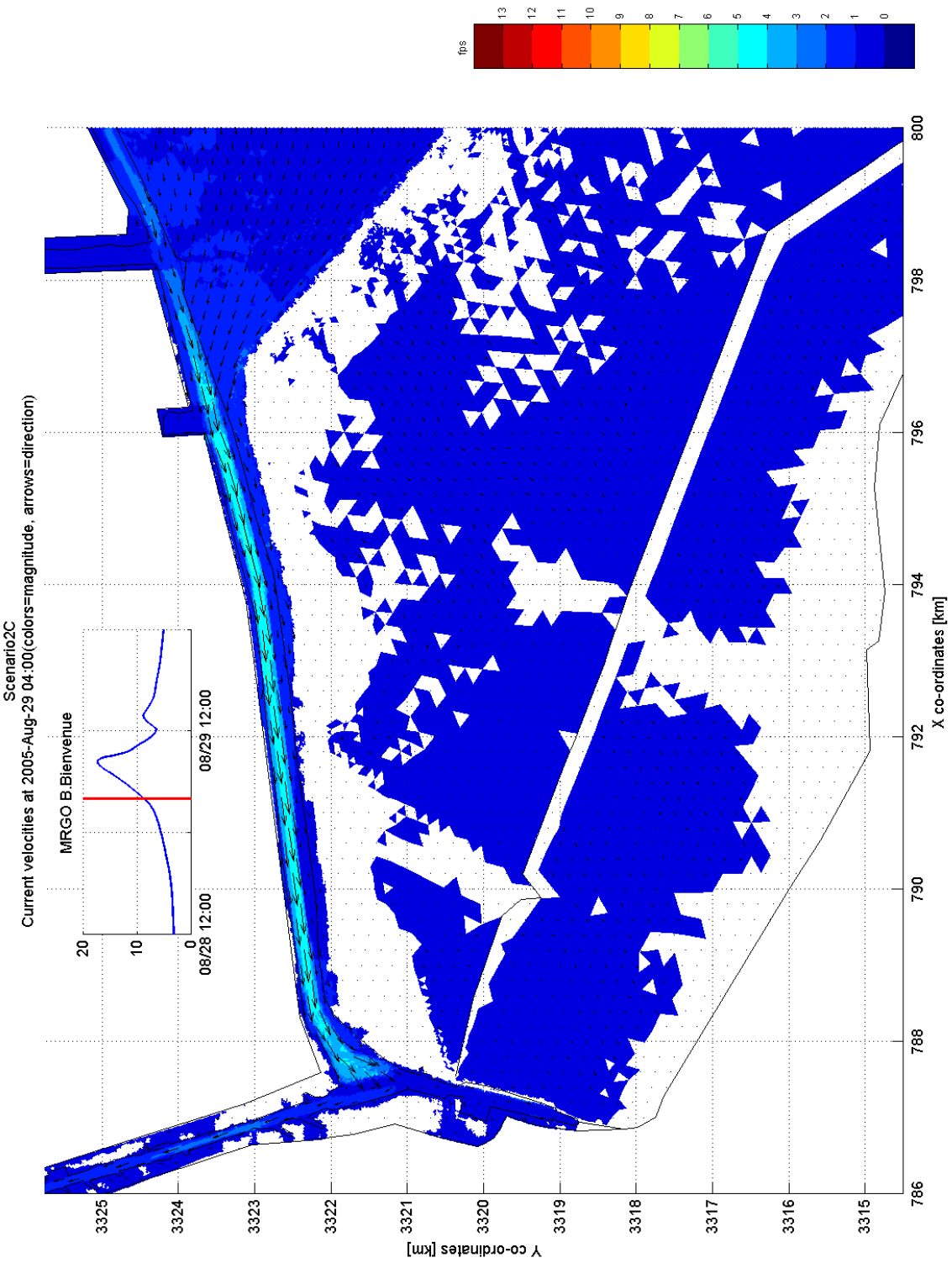


Figure 2.22a: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 2C at 4:00am local time.

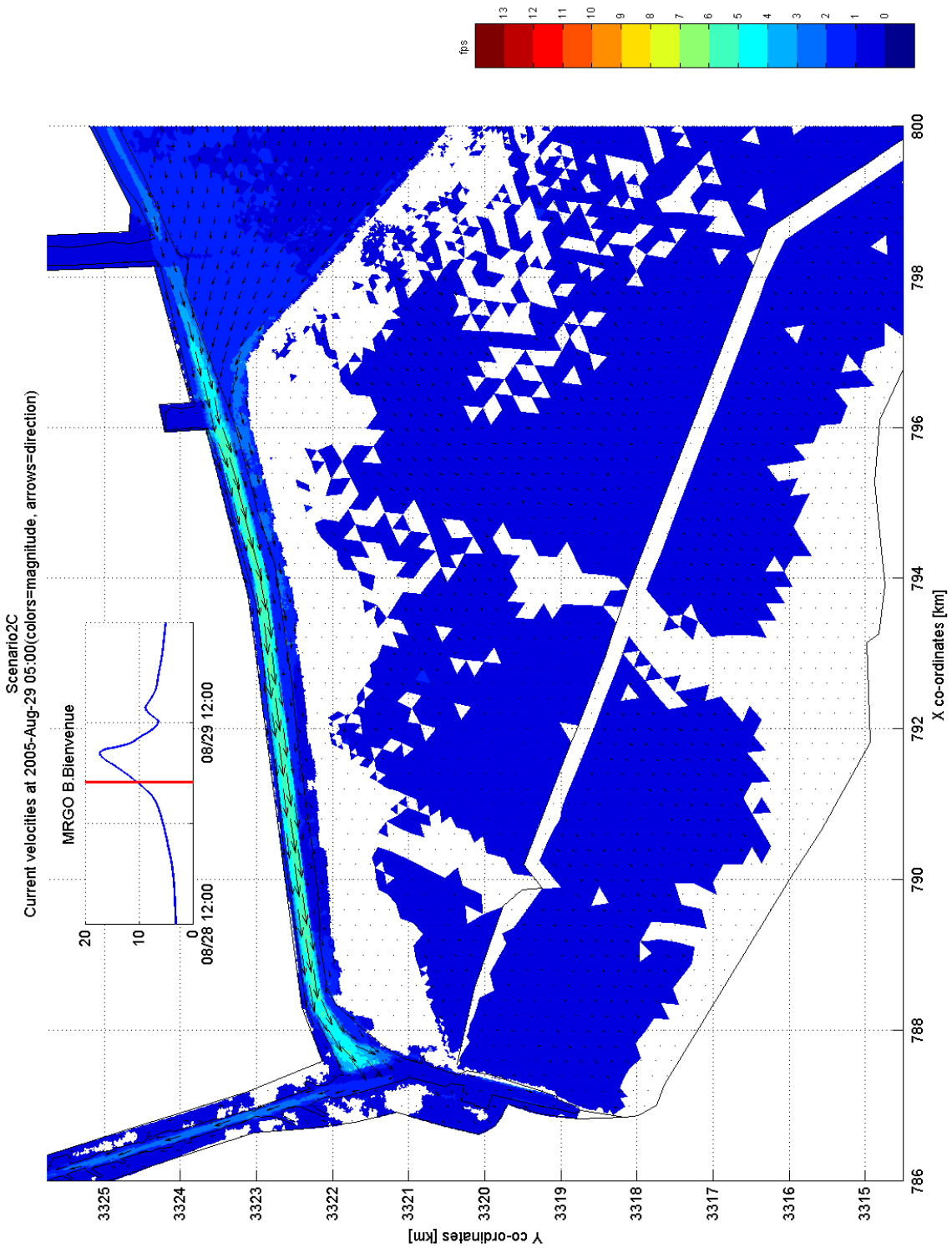


Figure 2.22b: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 2C at 5:00am local time.

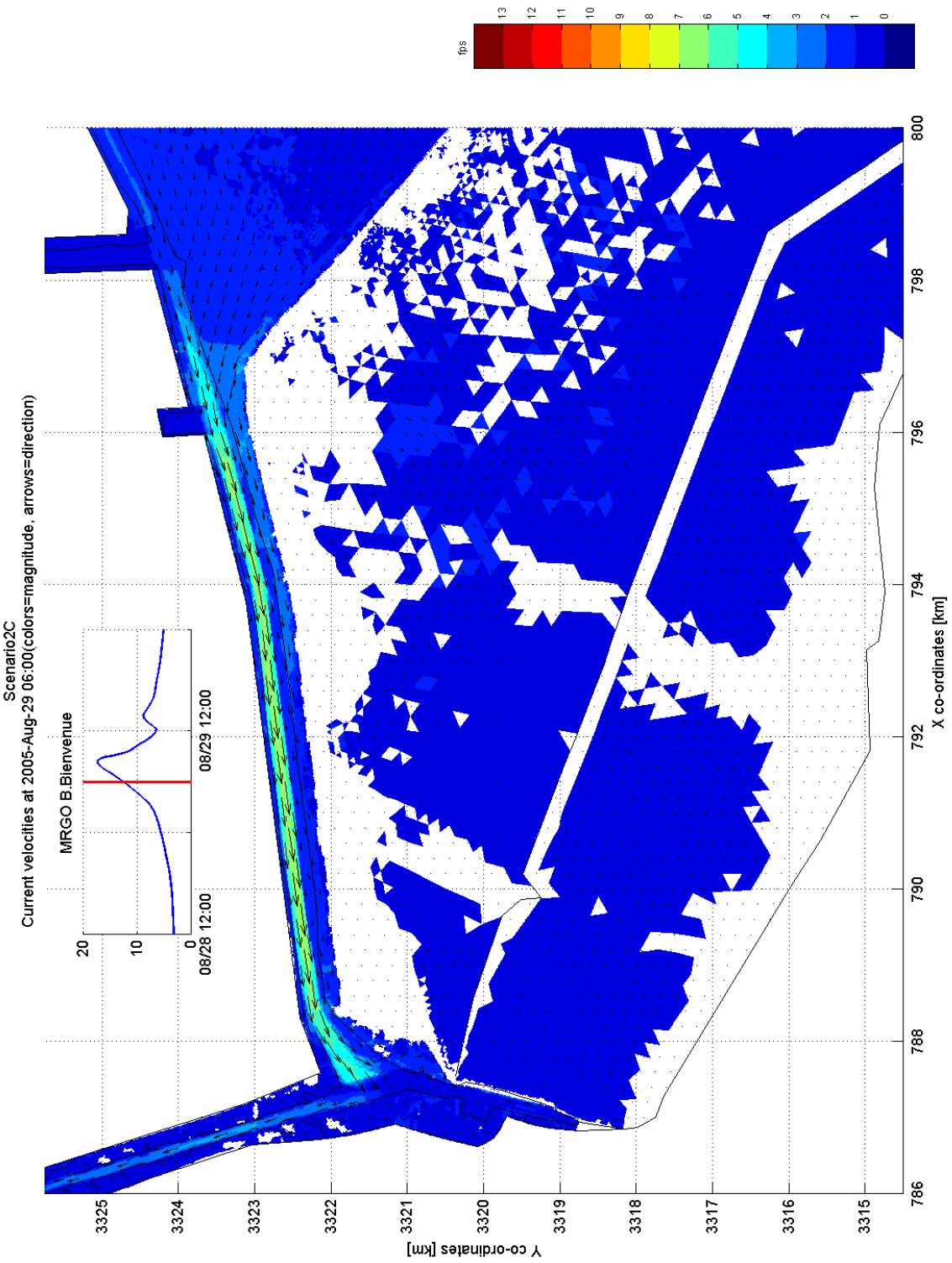


Figure 2.22c: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 2C at 6:00am local time.

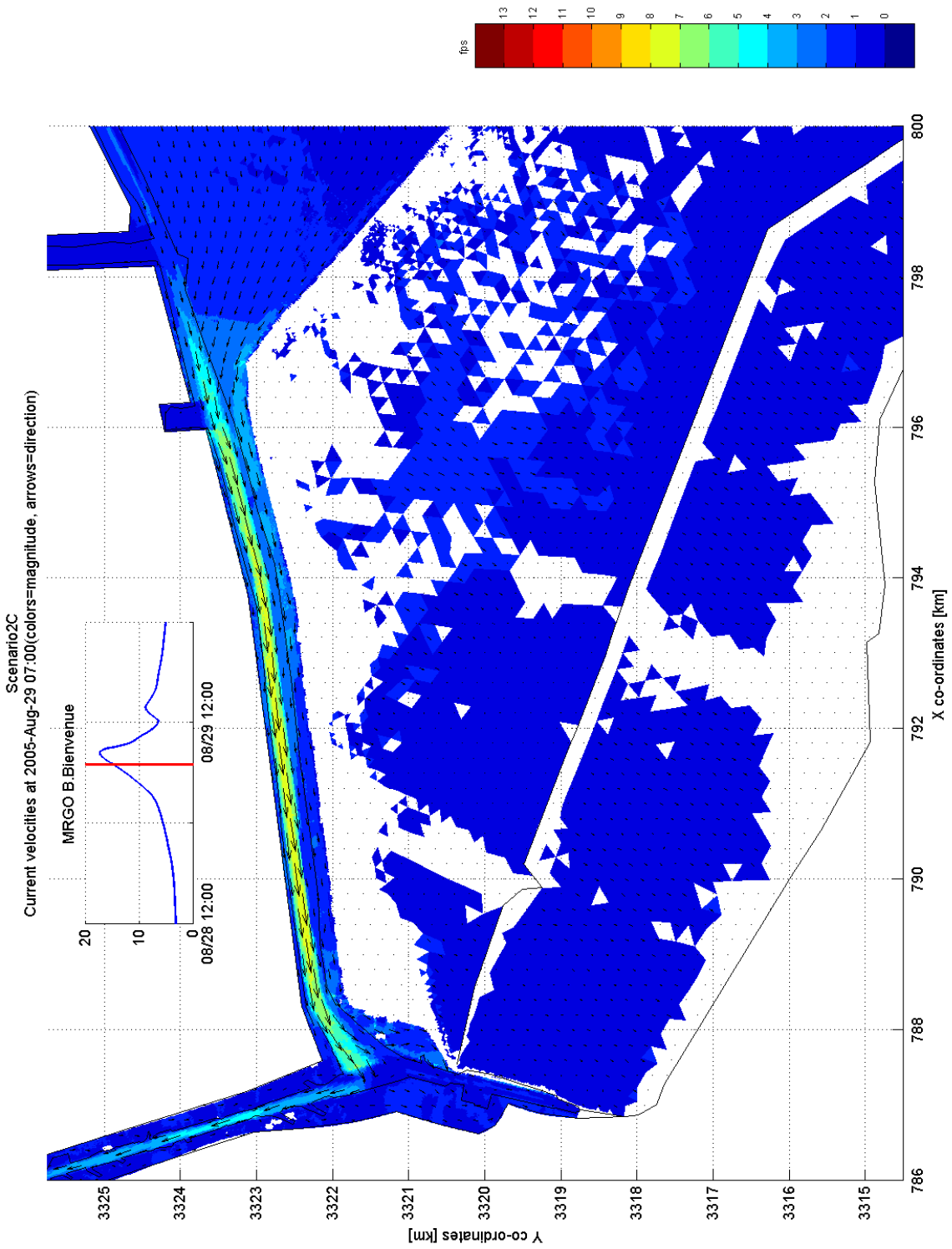


Figure 2.22d: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 2C at 7:00am local time. Note difference with Scenario 1: overtopping at southern side of the MRGO Reach 1 has not started yet.

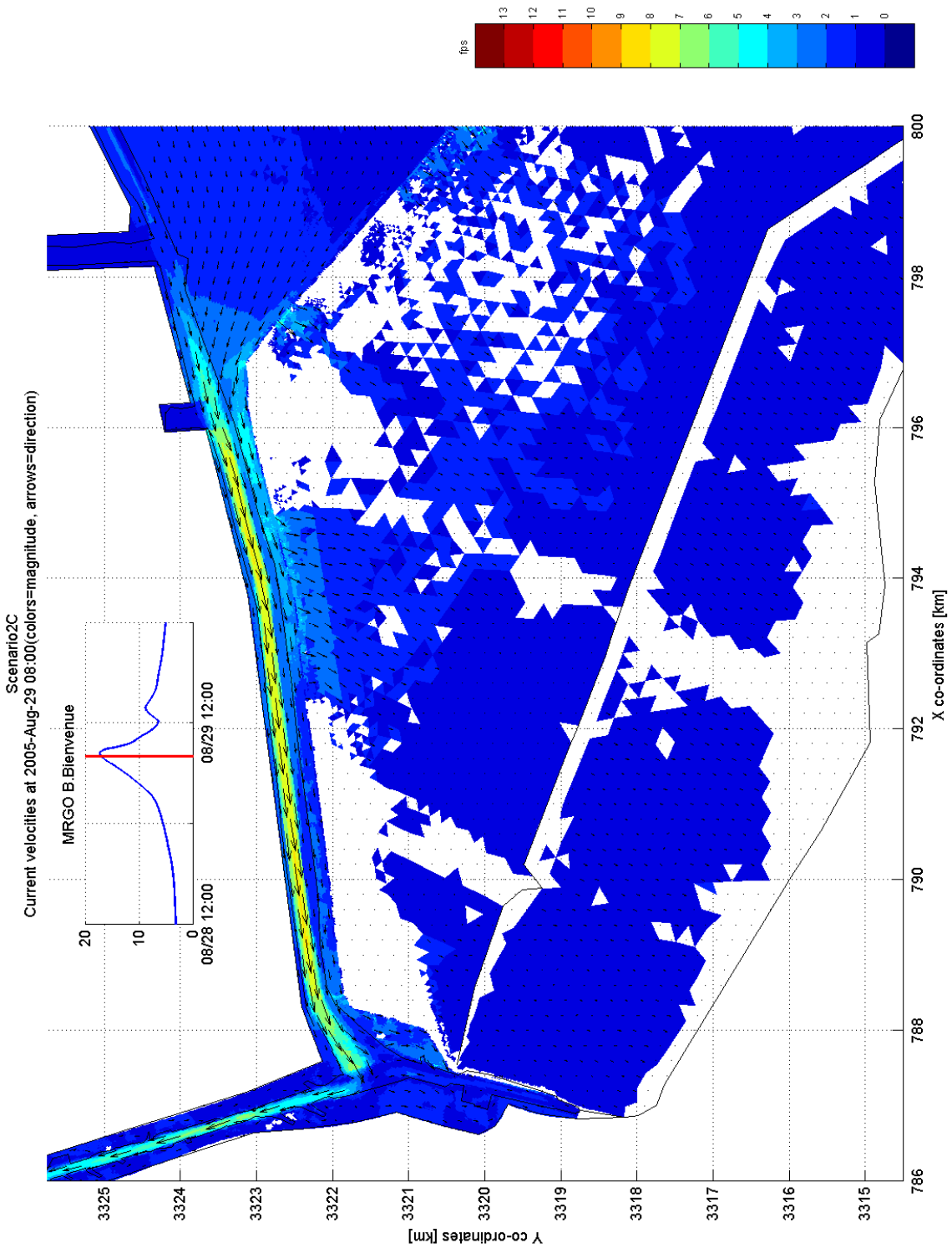


Figure 2.22e: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 2C at 8:00am local time. Note overtopping has started at southern side MRGO Reach 1, one hour later than in Scenario 1. The flooding represents contribution from levee overtopping only.

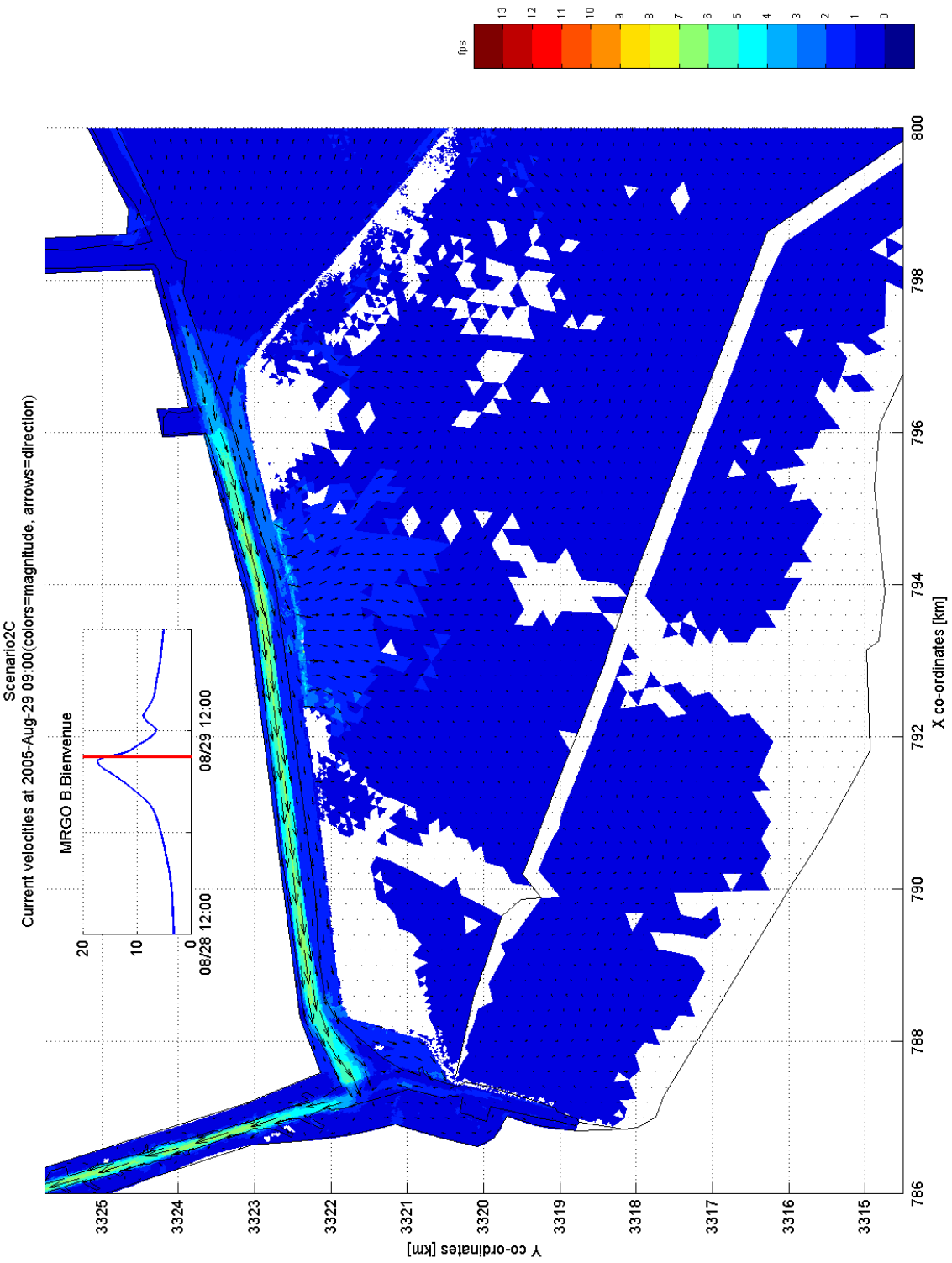


Figure 2.22f: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 2C at 9:00am local time. Note levee overtopping velocities of about 4 feet per second at the levee crest. Only overtopping over part of Reach 1 levees. The flooding represents contribution from levee overtopping only.

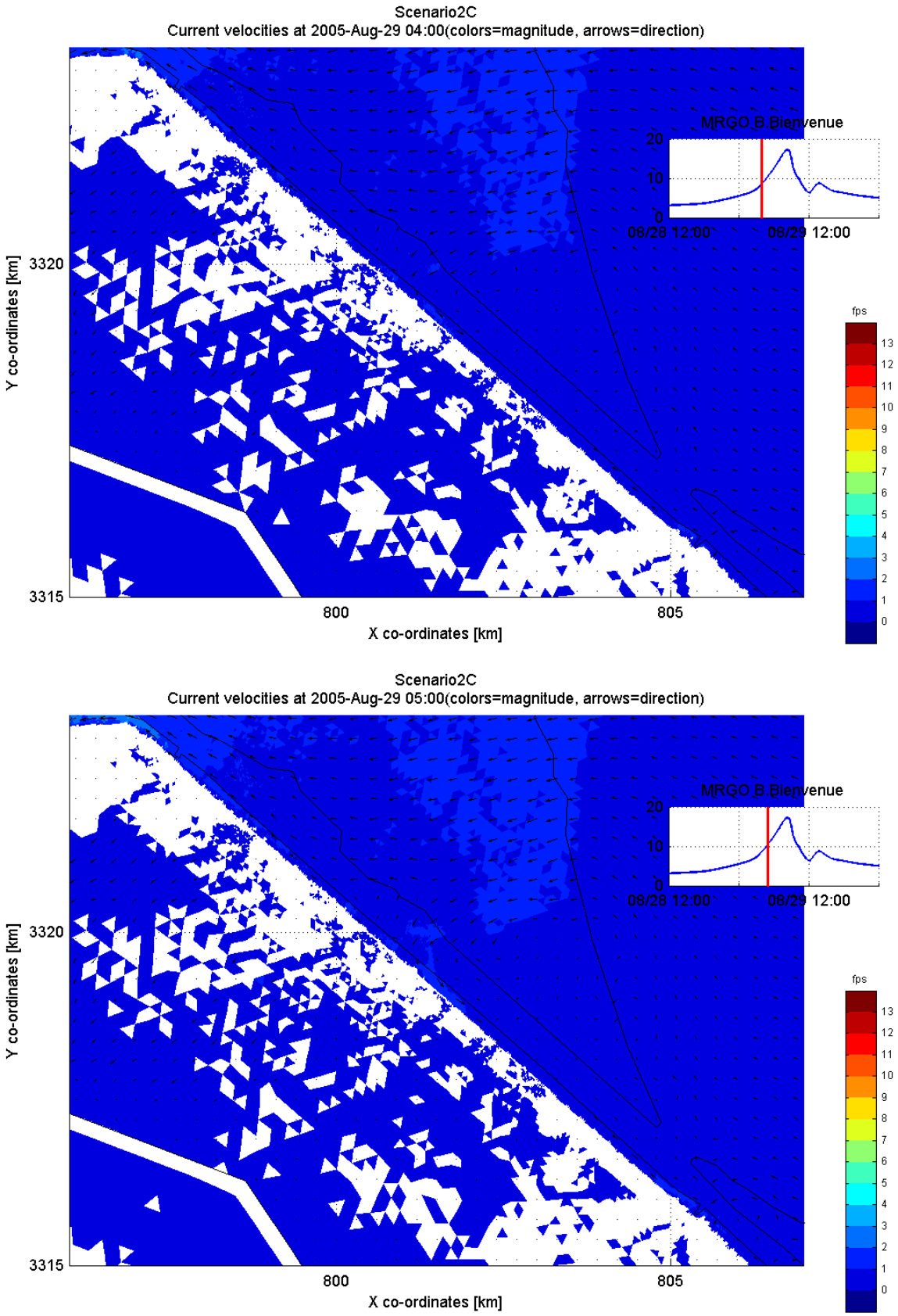


Figure 2.23a: Spatial current velocities (magnitude with color scale, direction with arrows) MRGO Reach 2 for Scenario 2C at 4:00am, 5:00am local time.

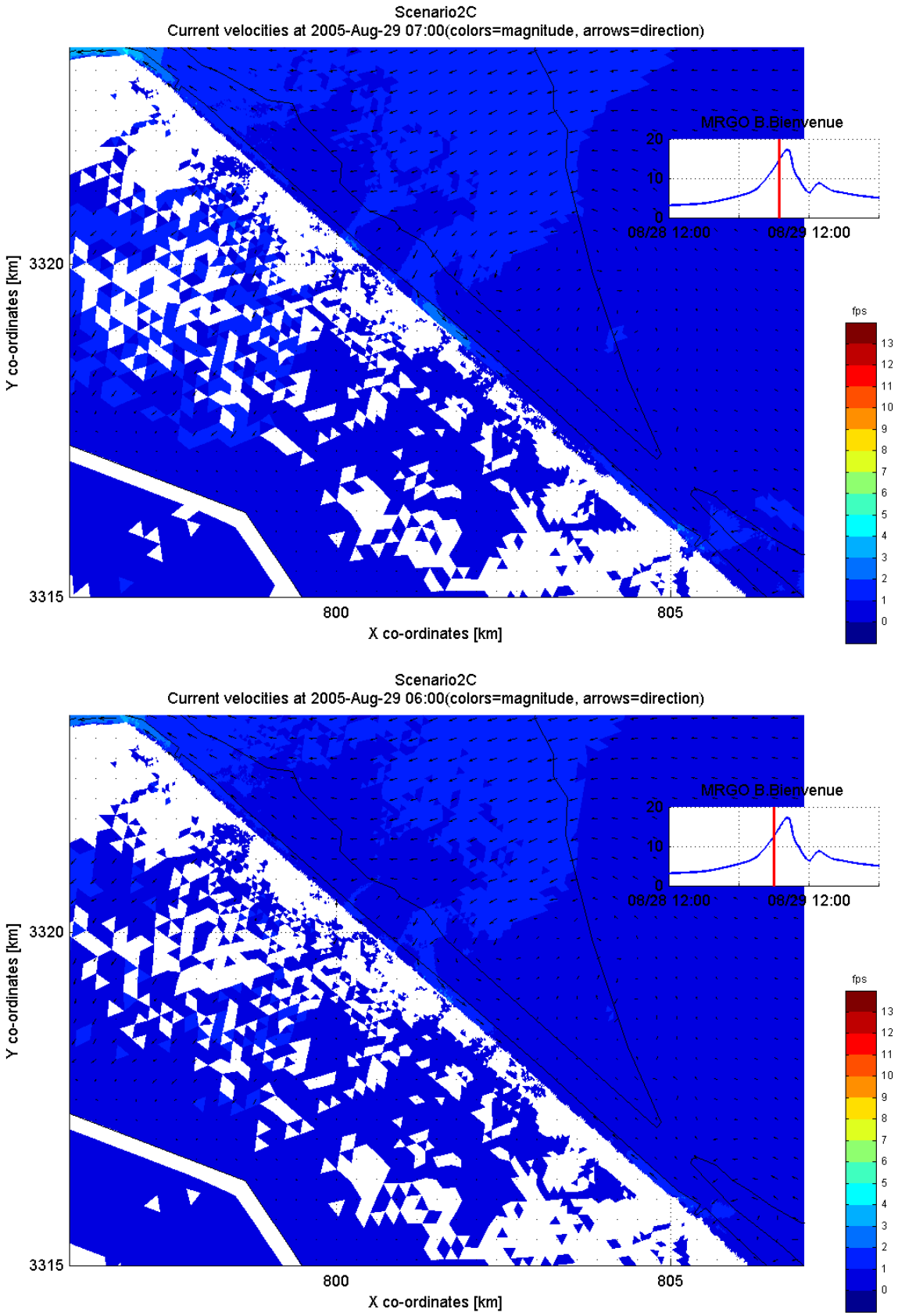


Figure 2.23b: Spatial current velocities (magnitude with color scale, direction with arrows) MRGO Reach 2 for Scenario 2C at 6:00am, 7:00am local time. Note difference with Scenario 1: overtopping at MRGO Reach 2 has not started at 7:00am.

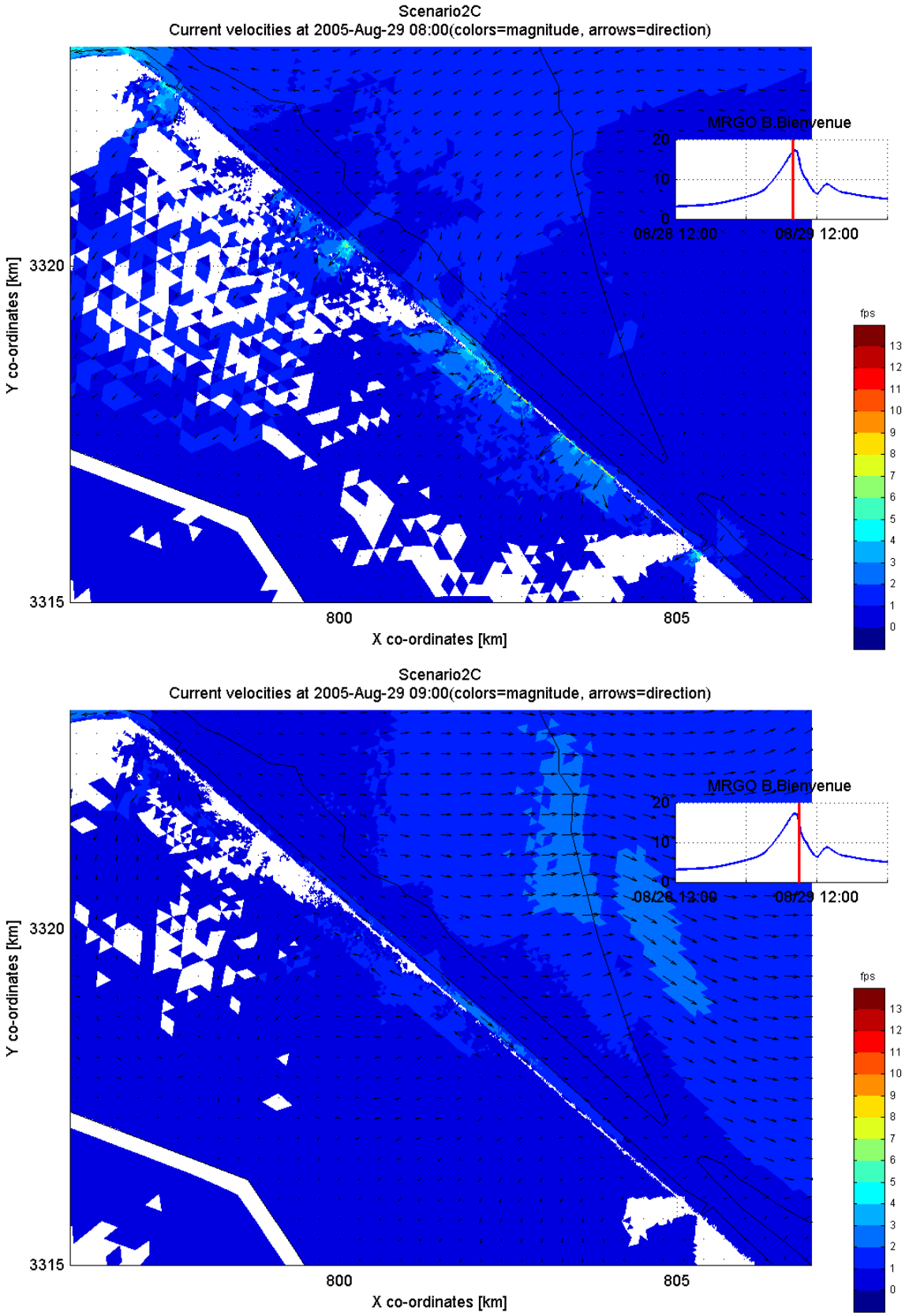


Figure 2.23c: Spatial current velocities (magnitude with color scale, direction with arrows) MRGO Reach 2 for Scenario 2C at 8:00am, 9:00am local time. Note overtopping has started at southern side MRGO Reach 1 at 8:00 am, one hour later than in Scenario 1. Levee overtopping velocities of about 8 feet per second at the levee crest. The flooding represents contribution from levee overtopping only.

Detailed flow information at several locations

At the same locations as in Scenario 1 (see Figure 2.24 and Table 2.12) detailed information about current velocities and water levels are given in Figure 2.25. The details are summarized in Table 2.13 to Table 2.18.

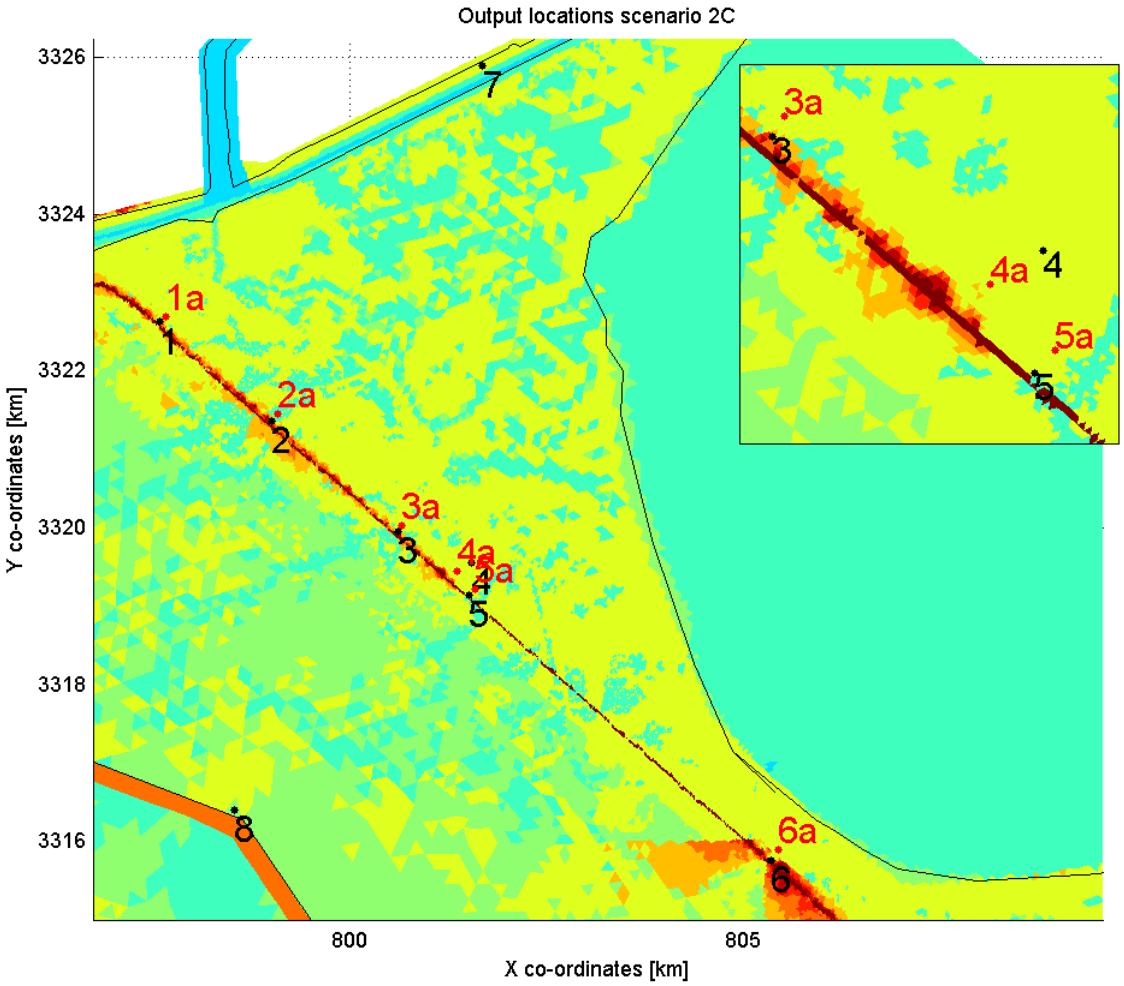


Figure 2.24: Output locations Scenario 2C

Table 2.12: Coordinates output locations

Loc	Name	lat [N]	lon [W]	UTM [m]	UTM [m]
1	B. Bienvenue	29°59’ 54.51”	89°54’ 55.54”	797571	3322628
2	Station 430	29°59'12.29"	89°54' 03.80"	798993	3321367
3	Loc I	29.97368°	89.884833°	800613	3319954
4	MRGO Halfway	29°58’ 5.11”	89°52’ 40.14”	801540	3319563
5	Station 540	29°57'58.19"	89°52' 32.15"	801515	3319142
6	B. Dupre	29°56’ 5.52”	89°50’ 12.26”	805355	3315765
7	GIWW@BackB	30° 01.597'	89°52.291'	801670	3325901
8	Loc II 40Arpent			798527	3316406
9	Loc A 40 Arpent			791213	3319277
10	Loc B 40 Arpent			801991	3309702
11	Loc C 40 Arpent			808892	3310020
12	Loc D 40 Arpent			812966	3305607

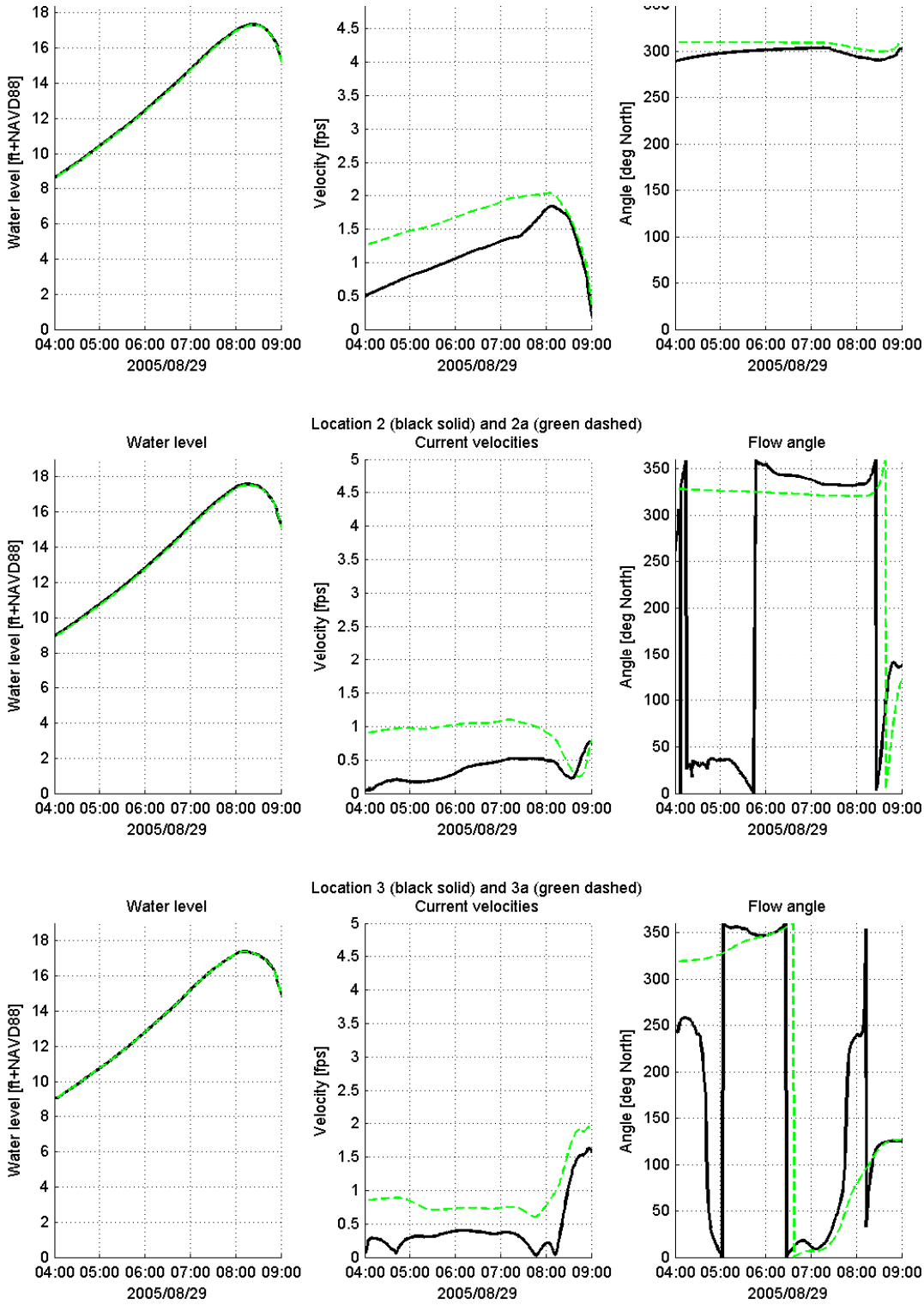


Figure 2.25a: Results for location 1, 2 and 3 Scenario 2C from 4:00am to 9:00am

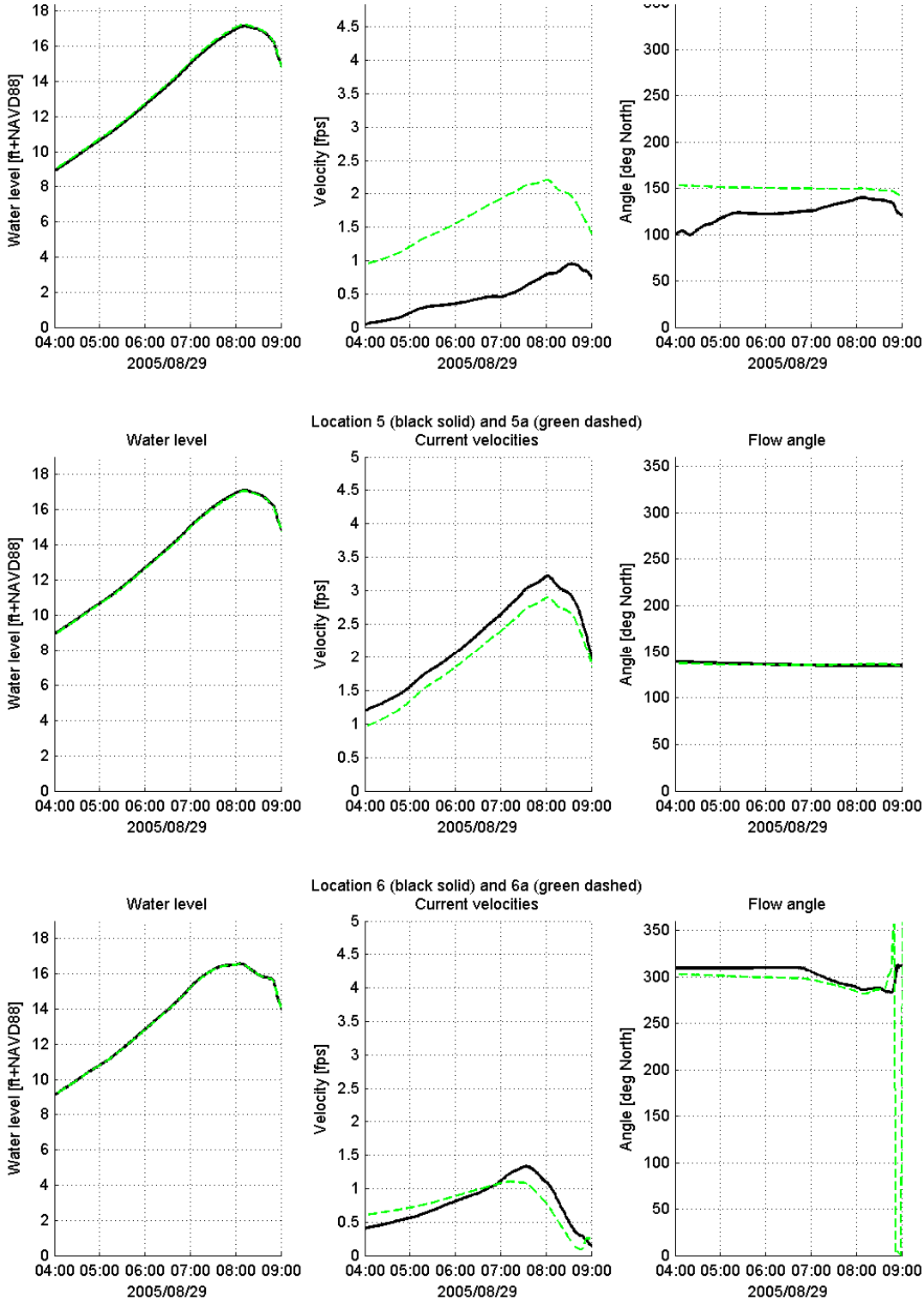


Figure 2.25b: Results for location 3, 4 and 5 Scenario 2C from 4:00am to 9:00am

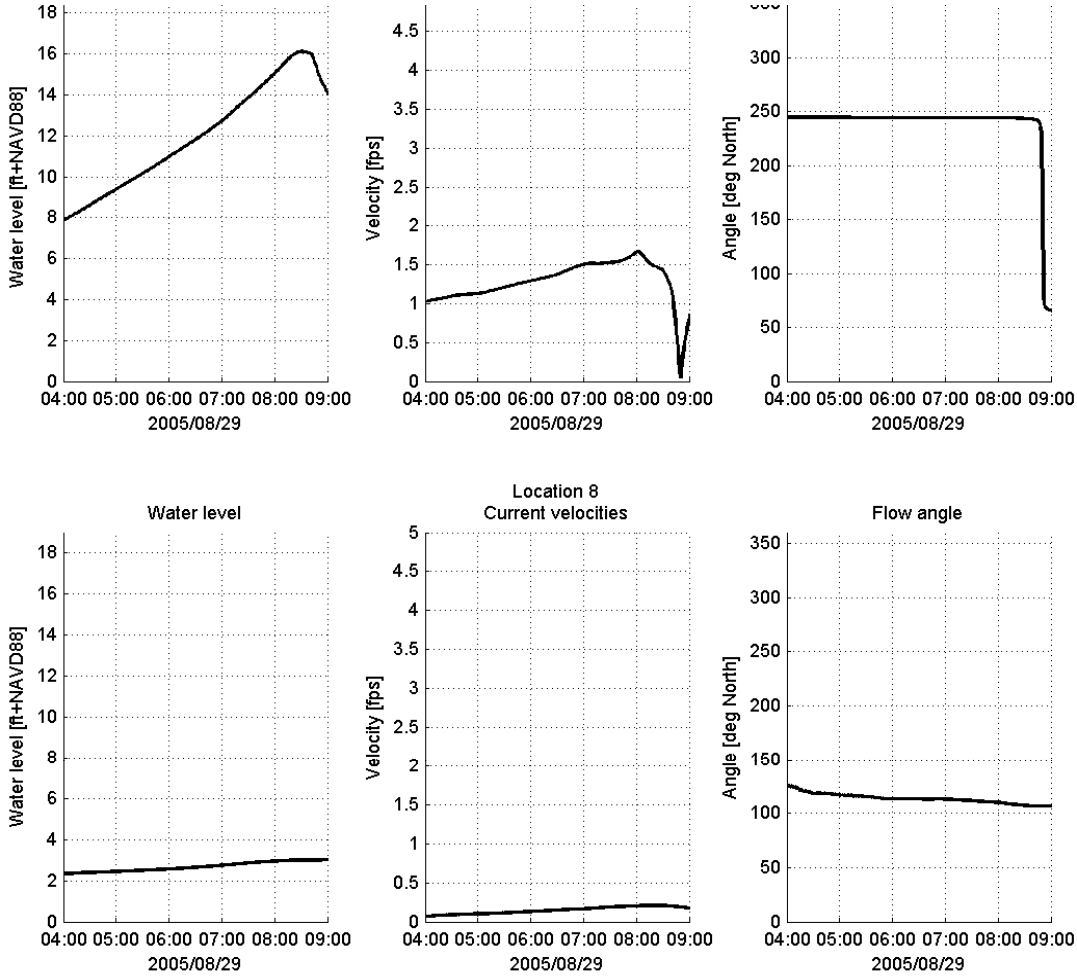


Figure 2.25c: Results for location 7 and 8 Scenario 2C from 4:00am to 9:00am

Table 2.13: Summary results Scenario 2C at 29th August 2005 4:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	8.63	0.50	289	8.59	1.26	309
2	Station 430	8.97	0.05	258	8.91	0.90	328
3	Loc I	9.06	0.09	243	8.98	0.86	318
4	MRGO Halfway	8.91	0.04	101	8.97	0.93	153
5	Station 540	8.95	1.19	139	8.91	0.95	137
6	B. Dupre	9.11	0.41	309	9.10	0.60	303
7	GIWW@BackB	7.85	1.03	245			
8	Loc II 40Arpent	2.33	0.07	126			

Table 2.14: Summary results Scenario 2C at 29th August 2005 5:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	10.44	0.80	297	10.40	1.48	309
2	Station 430	10.79	0.17	36	10.72	0.97	326
3	Loc I	10.76	0.29	3	10.76	0.84	326
4	MRGO Halfway	10.65	0.21	117	10.72	1.21	151
5	Station 540	10.68	1.56	137	10.64	1.34	136
6	B. Dupre	10.80	0.56	309	10.79	0.71	301
7	GIWW@BackB	9.39	1.13	244			
8	Loc II 40Arpent	2.44	0.10	117			

Table 2.15: Summary results Scenario 2C at 29th August 2005 6:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	12.45	1.05	301	12.40	1.68	309
2	Station 430	12.83	0.30	355	12.76	1.02	324
3	Loc I	12.80	0.39	347	12.80	0.73	347
4	MRGO Halfway	12.66	0.35	122	12.75	1.55	150
5	Station 540	12.69	2.06	136	12.64	1.85	136
6	B. Dupre	12.84	0.81	310	12.81	0.89	299
7	GIWW@BackB	10.98	1.29	244			
8	Loc II 40Arpent	2.56	0.13	113			

Table 2.16: Summary results Scenario 2C at 29th August 2005 7:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	14.78	1.31	303	14.72	1.91	309
2	Station 430	15.22	0.48	338	15.14	1.08	322
3	Loc I	15.20	0.36	11	15.19	0.74	7
4	MRGO Halfway	15.00	0.46	126	15.12	1.92	150
5	Station 540	15.04	2.64	135	14.98	2.39	135
6	B. Dupre	15.22	1.12	305	15.20	1.08	297
7	GIWW@BackB	12.73	1.50	244			
8	Loc II 40Arpent	2.75	0.16	113			

Table 2.17: Summary results Scenario 2C at 29th August 2005 8:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	17.00	1.79	294	16.96	2.03	303
2	Station 430	17.41	0.49	333	17.33	0.91	320
3	Loc I	17.23	0.21	240	17.23	0.77	78
4	MRGO Halfway	16.96	0.79	138	17.07	2.21	149
5	Station 540	16.93	3.21	135	16.87	2.90	136
6	B. Dupre	16.51	1.10	288	16.51	0.78	284
7	GIWW@BackB	15.05	1.66	244			
8	Loc II 40Arpent	2.95	0.20	110			

Table 2.18: Summary results Scenario 2C at 29th August 2005 9:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	15.33	0.23	302	15.31	0.39	310
2	Station 430	15.22	0.76	137	15.21	0.78	122
3	Loc I	15.01	1.60	125	15.02	1.92	127
4	MRGO Halfway	14.92	0.75	120	14.94	1.42	142
5	Station 540	14.89	2.01	135	14.88	1.90	134
6	B. Dupre	14.08	0.15	312	14.07	0.24	359
7	GIWW@BackB	14.11	0.80	66			
8	Loc II 40Arpent	3.02	0.17	107			

2.3 Scenario 3: The maintained MRGO Scenario and a simulated Katrina storm

2.3.1 Description of Scenario

Scenario 3 simulates the situation of a MRGO channel maintained at its design dimensions with the levees along the MRGO at their actual pre-Katrina heights and the Katrina storm. For all other input a situation similar to the late 1950s is envisioned:

(1) MRGO Reach 1 and 2 are modeled as approved by the U.S. Congress under the Rivers and Harbor Act of 1956 (PL 84-455) and authorized as a 76-mile ship channel with a 36 foot controlling depth, 500 feet wide at the bottom and 650 feet wide at the top, that would cut through the marshes of lower St. Bernard Parish and across the shallow waters of Breton Sound (USACE, 1999);

(2) The levees along MRGO Reach 1 and 2 are input at their pre-Katrina crest elevations.

(3) The pre-MRGO (1958) wetlands/swamps elevations and shoreline are used;

(4) The Cypress trees originally present between the MRGO and the 40 Arpent levees have influence on the water current velocities and the wind velocities. A higher Manning's roughness is used for the Cypress forests reflecting their greater frictional impacts on surge currents, and the wind velocities are reduced by 80% inside the Cypress forests due to the wind break/canopy effect of tall forests

2.3.2 FINEL model input data

The FINEL model is set up to utilize the metric system, so all data is thus subsequently converted to feet. The coordinate system used in the simulations is UTM (zone 15 R). Input data that was received in longitude and latitude was translated accordingly.

Model grid
The model grid used for Scenario 3 is equal to the model grid used in Scenario 1, see section 2.1.2.

Bathymetry and Topography
The bathymetry for Scenario 3 is modified, starting with the bathymetry of Scenario 2A, to represent the conditions prior to the construction of the MRGO together with the MRGO (Reach 1 and 2) at its design dimensions. MRGO Reach 1 and 2 have dimensions of 36 feet deep, 500 feet wide at the bottom and 650 feet wide at the top and the GIWW has the dimensions of 150 feet wide and 12 feet deep (source Robinson experts). The levees along the MRGO Reach 1 and 2 are at the actual pre-Katrina crest heights, as provided by Robinson experts. The resulting topography and bathymetry in the model area are shown in Figure 2.26.

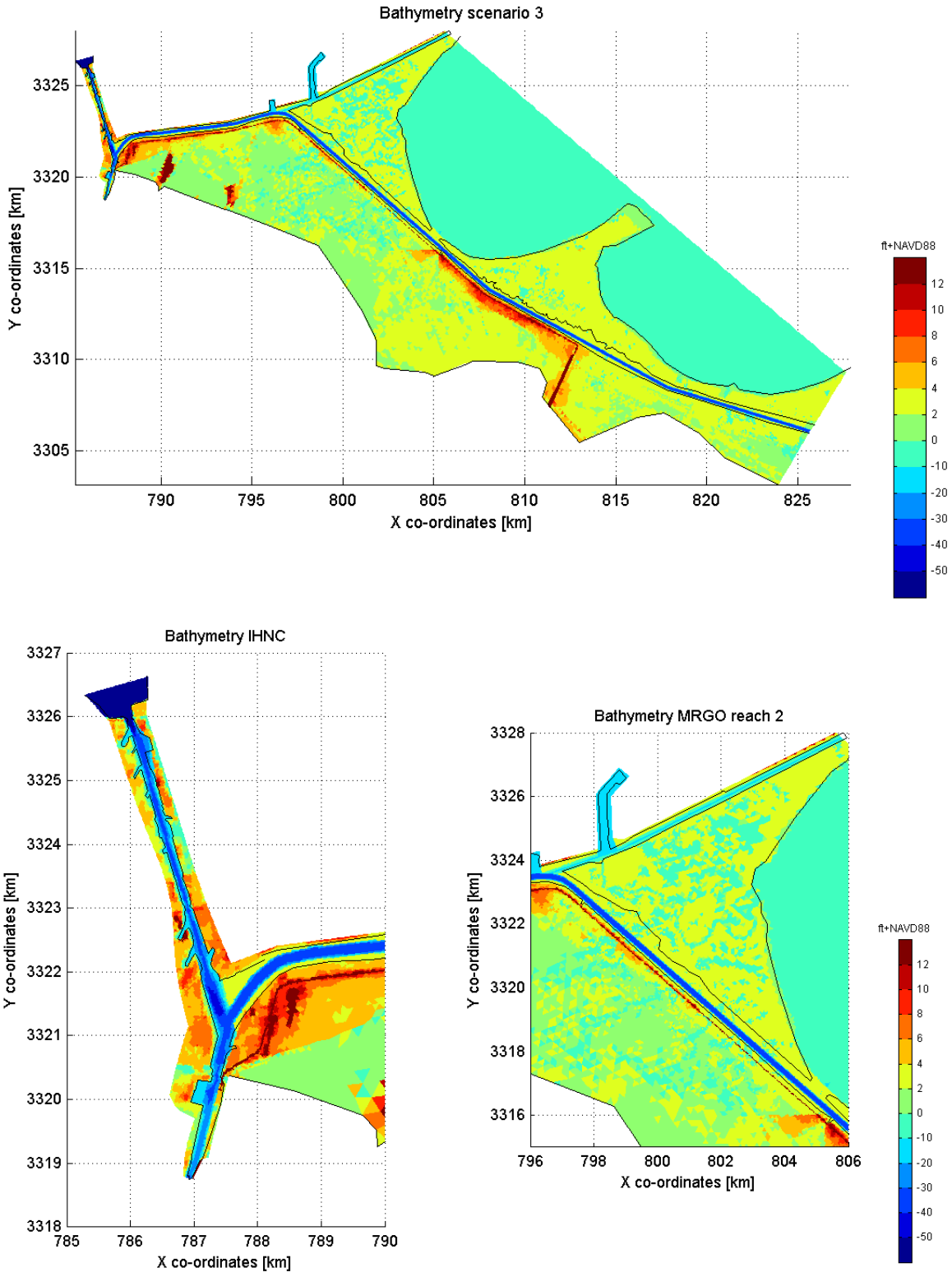


Figure 2.26: Bathymetry FINEL model area Scenario 3

Simulation period
The simulation starts at 12h00 LT 28th August 2005 and continues until 24h00 29th August 2005.

Boundary conditions

The boundary conditions consist of water level time series, ADCIRC Hydrograph3, provided to us by Robinson experts. Figure 2.27 shows the locations of the boundary conditions and Table 2.19 gives the corresponding locations from Hydrograph3 which are used for every boundary. The boundary time series themselves are shown in Figure 2.28. All boundaries not mentioned in Table 2.19 are closed boundaries.

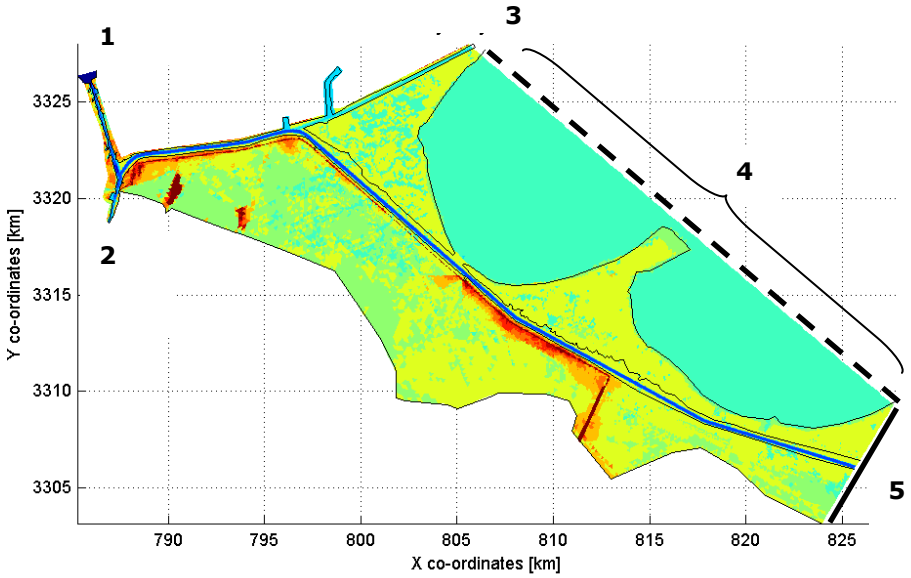


Figure 2.27: Location boundary conditions FINEL flow model

Table 2.19: Boundary conditions

	Boundary	*Used hydrograph3*
1	Lake Pontchartrain	IHNC@LakeP
2	IHNC Locks	Closed boundary (discharge=0)
3	GIWW	NOEbackA
4	Lake Borgne	Interpolation between 3 and 5
5	MRGO	Shell Beach

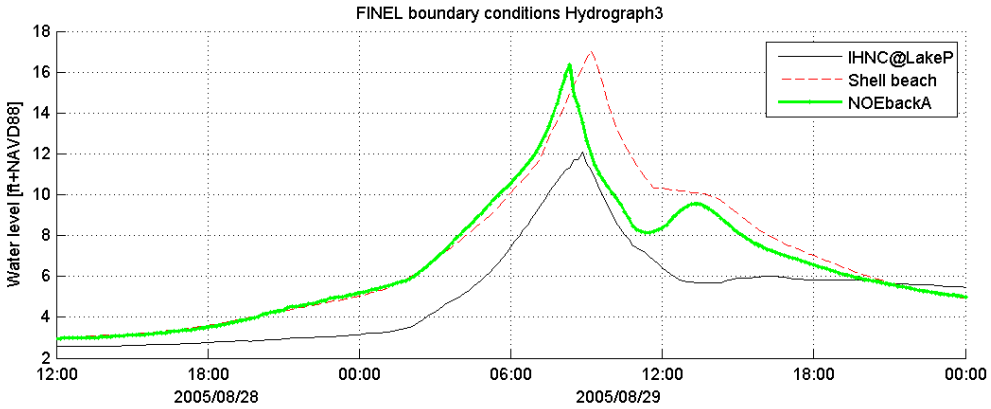


Figure 2.28: Time series boundary conditions FINEL flow model Scenario 3

Bottom roughness

In the model area a spatial variable Manning coefficient is used for the bottom roughness. The Manning roughness coefficients used are based on years of experience in modeling coastal environments. These data were collaborated with other data sets such as from the US Geological Survey (http://www.fhwa.dot.gov/bridge/wsp2339.pdf), the world renowned book Open-channel hydraulics [Ref. 5] and IPET [Ref. 6]. For each scenario the spatial extent of the Manning's used is based on the presence or lack of wetlands; shoreline location and presence; and lack or presence of levees. In 1958 Cypress forests existed between the MRGO and the 40 Arpent levees (Figure 2.29). The Cypress trees cause friction on the flow, this influence is taken into account by a higher roughness coefficient. In a map provided by Robinson experts, two types of Cypress forests are distinguished: normal (Manning n=0.1 $m^{-1/3}s$) and dense (Manning n=0.12 $m^{-1/3}s$). The Manning roughness coefficients are shown in Figure 2.30 and summarized in Table 2.20. In an effort to be as accurate as possible we were careful to use for the MRGO channel, and its levees (that are bounded in part on both sides by swamp) Manning values for open water (MRGO) and grass (levees).



Figure 2.29: Photograph of cypress trees in swampy areas (send to us by Robinson experts)

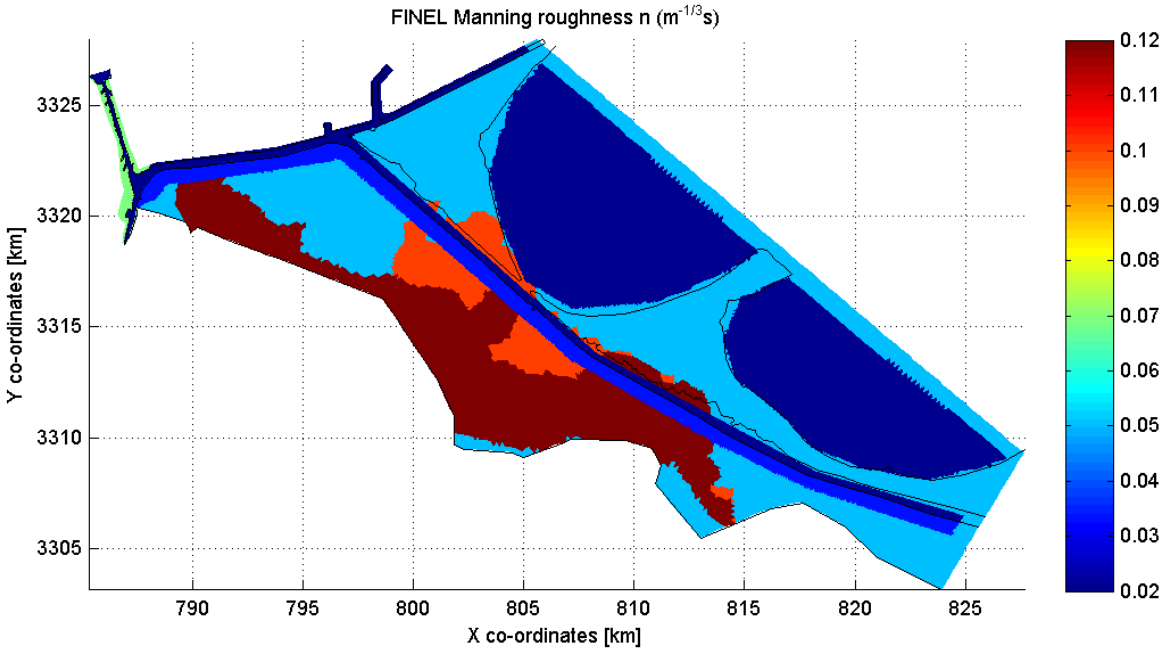


Figure 2.30: Manning roughness coefficient FINEL model area Scenario 3. The cypress areas are red (dark red = dense cypress trees, light red = normal cypress trees).

Table 2.20: Manning coefficient (based on: IPET Volume IV appendix page IV-5-102 [Ref. 6])

Area	*Manning coefficient n ($m^{-1/3}s$)*
Open water	0.02
Marsh along Lake Borgne	0.05
Shrub land St. Bernard	0.05
Grass at levees	0.034
Normal Cypress forest	0.1
Dense Cypress forest	0.12
Commercial area next to IHNC	0.07

Wind

To take into account the influence of wind on the water motion, spatial variable wind fields are used in the flow calculations with FINEL. The wind fields were provided to us by the Robinson experts spaced at 30 minute intervals. Within the cypress forest the influence of the wind on water movement is dramatically reduced by the trees. Therefore the wind velocities are reduced by 80% (percentage provided to us by Robinson experts) within the Cypress forests (both dark red and light red areas in Figure 2.30). For the strip of the MRGO Reach 2 open water with its levees that cuts through the Cypress forests the wind velocities are not reduced.

The wind speed surface stress is calculated by:

$$\frac{\tau_{wind,x}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,x} - U_x),$$

$$\frac{\tau_{wind,y}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,y} - U_y).$$

With:

C_d = wind drag coefficient (-),
W_{10} = wind speed at 10 meter height (m/s),
U = water velocity (m/s).

The wind drag is defined by Garrat's drag formula (Garrat 1977):

$C_d = (0.75 + 0.067W_{10}) \times 10^{-3}$

2.3.3 Results

The FINEL flow model is used to produce details of the water currents along the MRGO Reach 1 and 2. This section shows the results of Scenario 3: The maintained MRGO Scenario and a simulated Katrina storm. The results are shown on 6 time steps on the day Katrina struck, 29th August 2005, namely:

7. 4:00am Local Time;
8. 5:00am Local Time;
9. 6:00am Local Time;
10. 7:00am Local Time;
11. 8:00am Local Time;
12. 9:00am Local Time.

Area plots

The water levels in the model area for these time steps are shown in Figure 2.31. The current velocities are shown in Figure 2.32. A close up along MRGO Reach 1 is shown in Figure 2.33, and along MRGO Reach 2 in Figure 2.34. The main current patterns and water elevations of Scenario 3 are close to the results of Scenario 1.

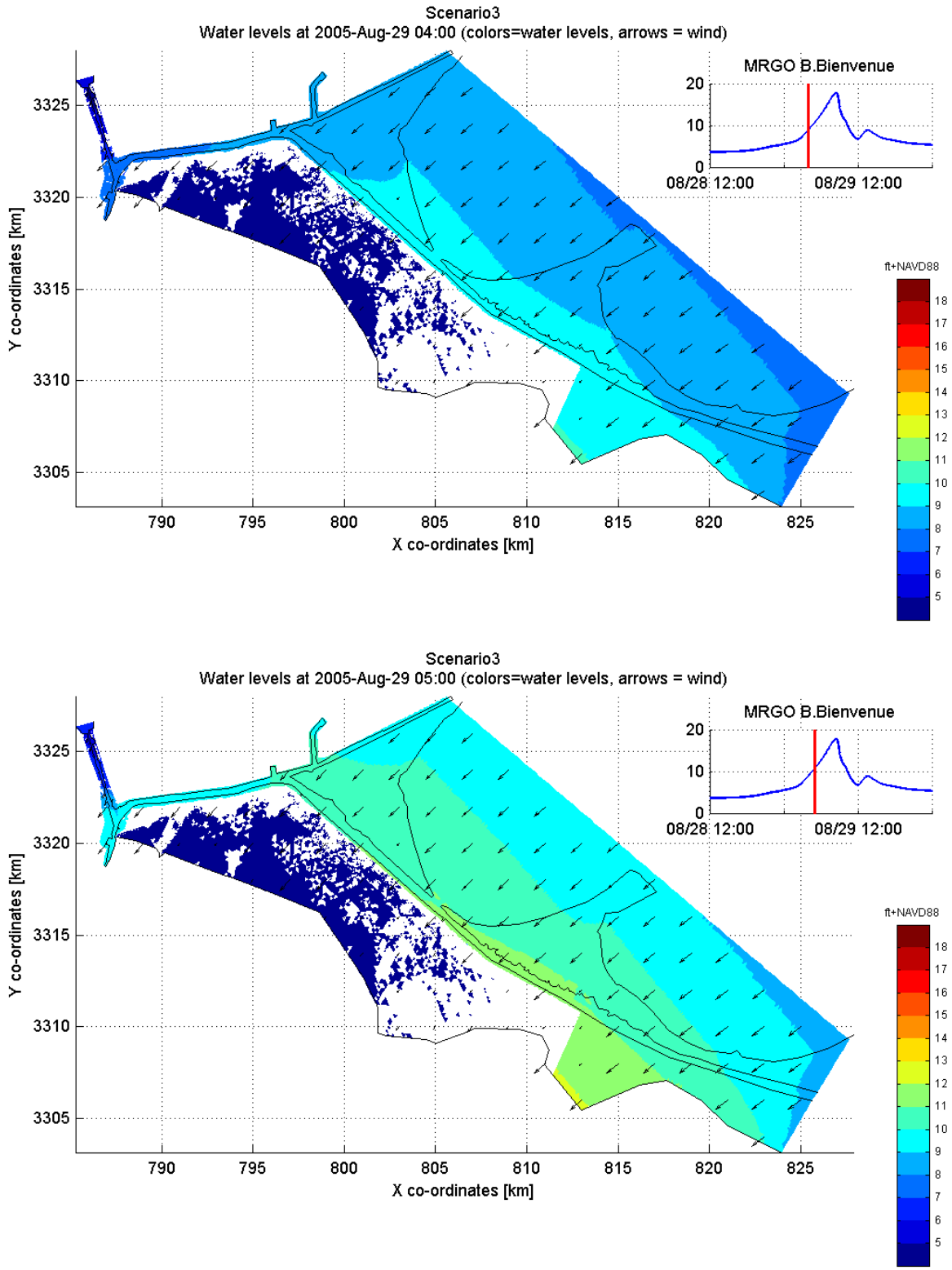


Figure 2.31a: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 3 at 4:00am and 5:00am local time. Note the wind acts approximately 90 degrees to MRGO

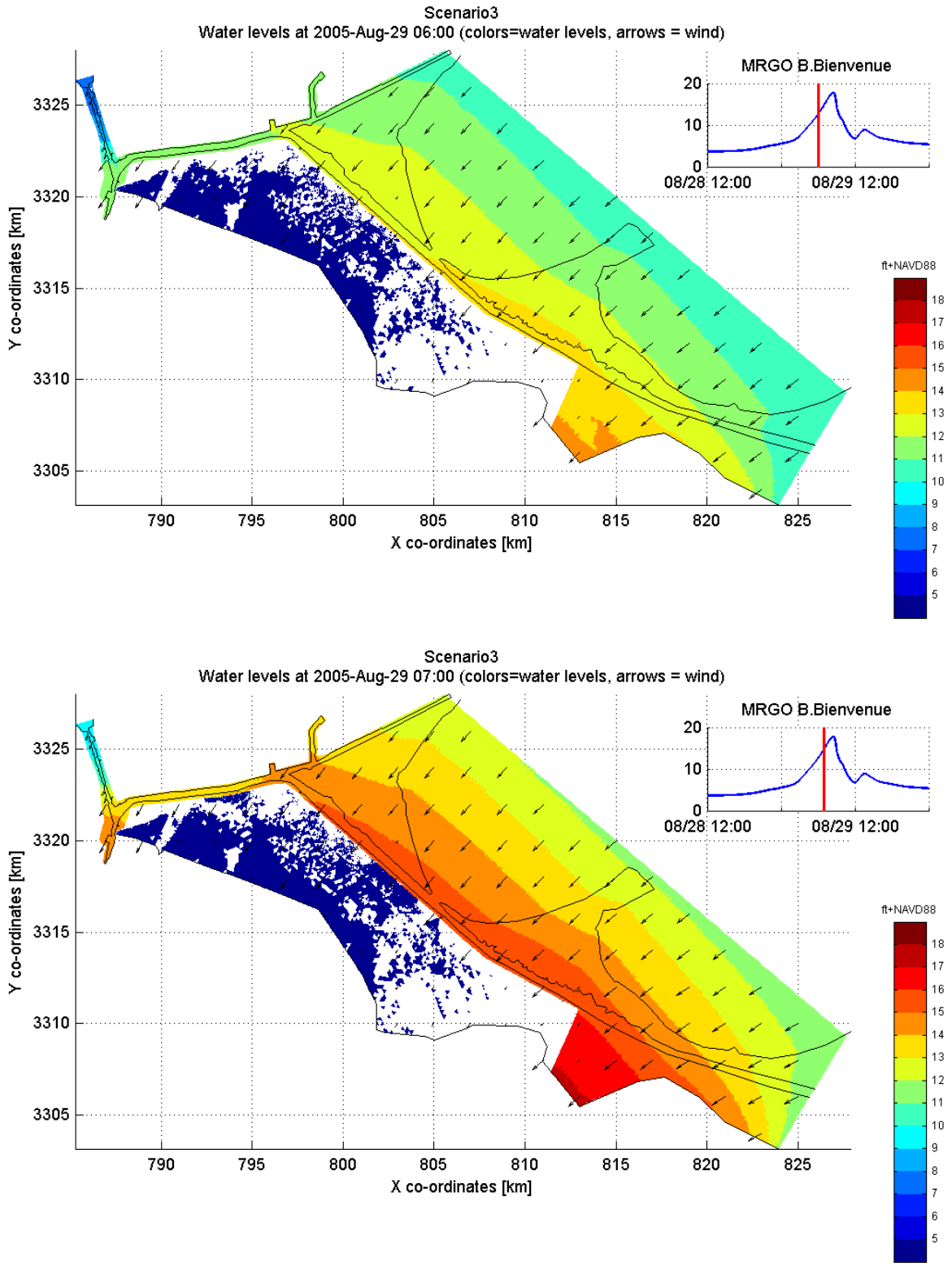


Figure 2.31b: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 3 at 6:00am and 7:00am local time. Note the wind is blowing at approximately 90 degrees to MRGO.

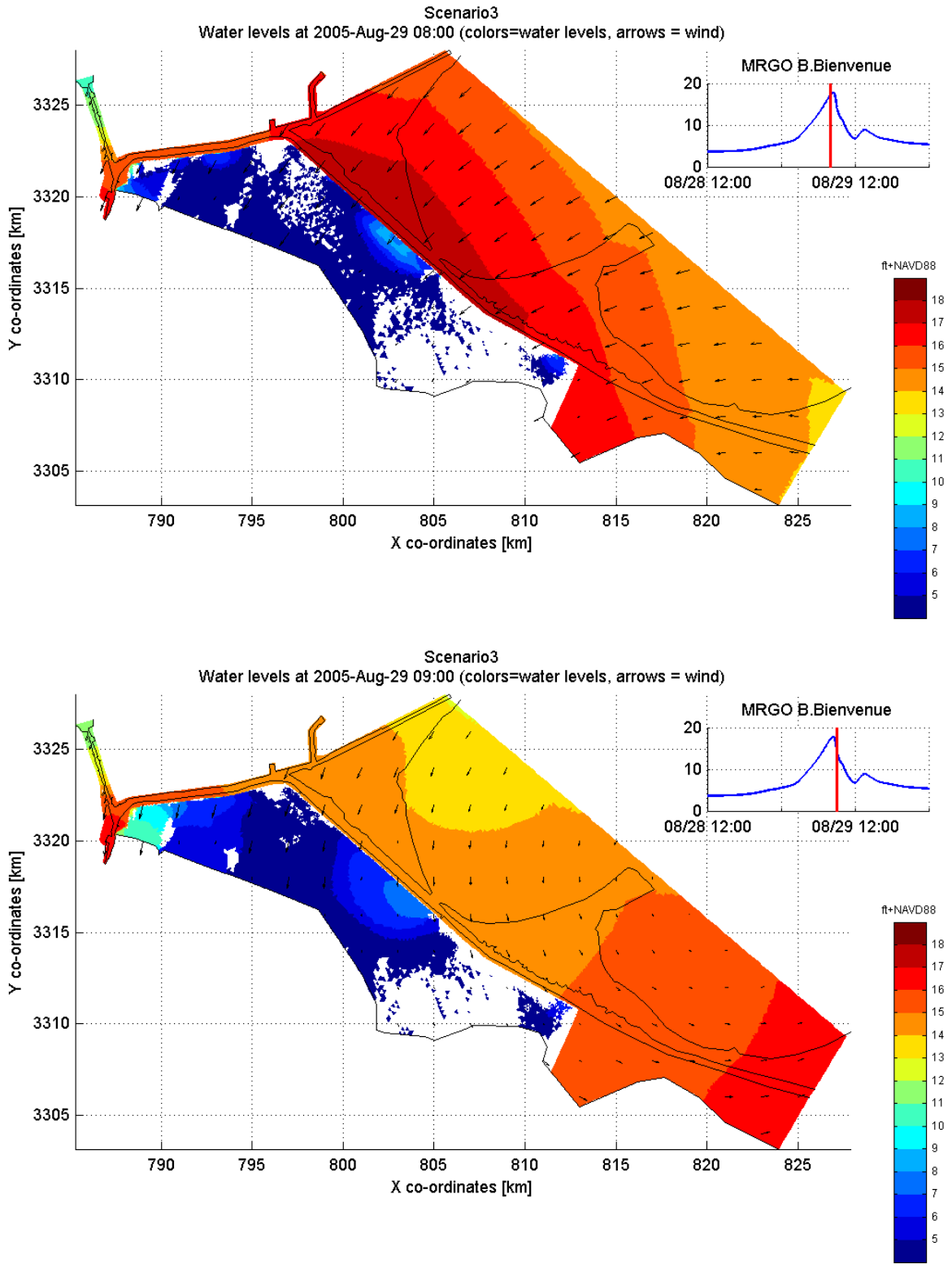


Figure 2.31c: Spatial water levels (surge elevation with color scale) with wind field (arrows) for Scenario 3 at 8:00am and 9:00am local time. Note the wind is blowing at approximately 90 degrees to MRGO at 8:00am; the surge amplification >17 ft NAVD in front of the MRGO levees and flooding in St Bernard Parish. The flooding shown in St Bernard Polder represents contribution from levee overtopping only.

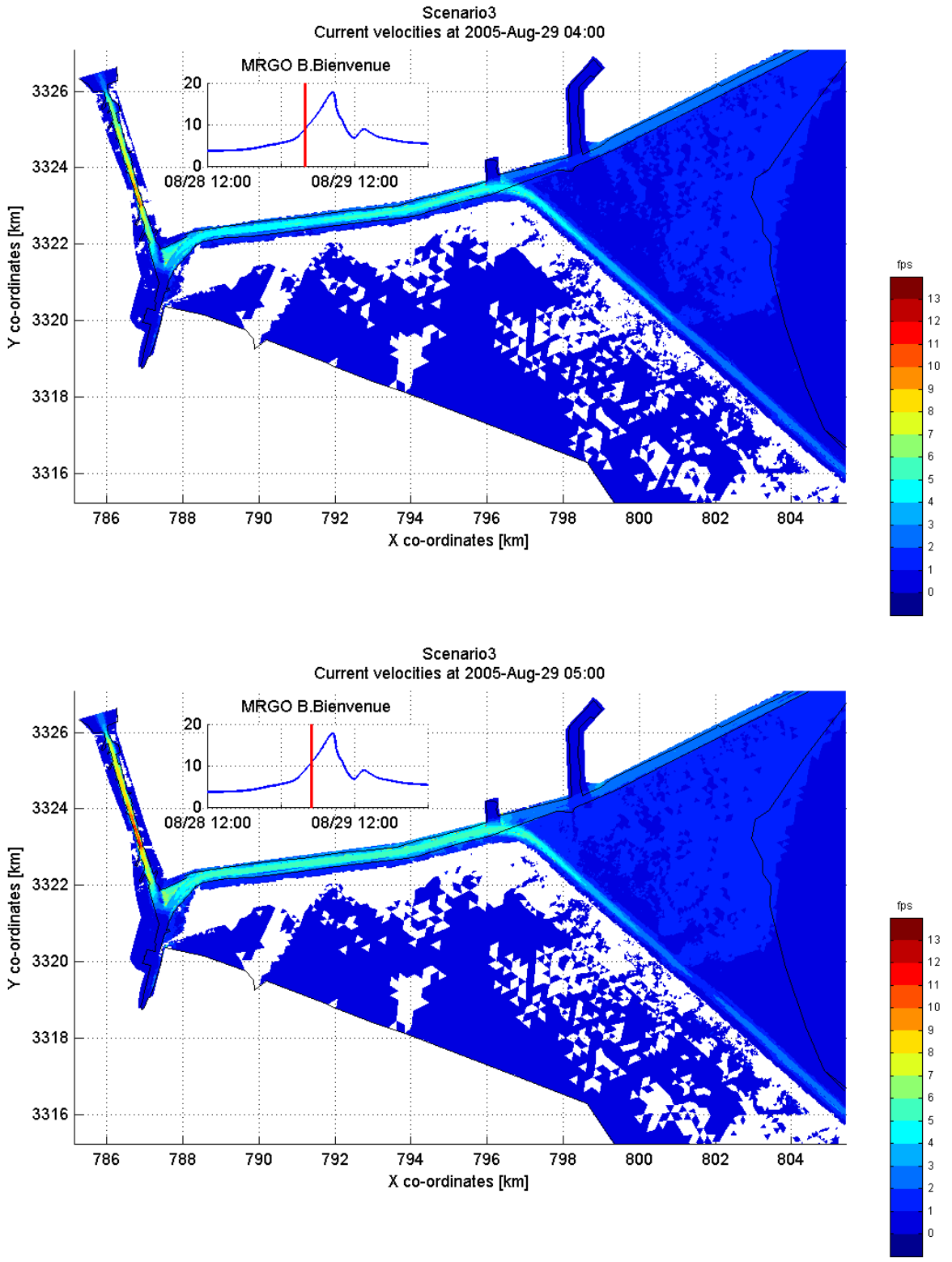


Figure 2.32a: Spatial current velocities for Scenario 3 at 4:00am, 5:00am local time. Note the high current velocities in IHNC and MRGO.

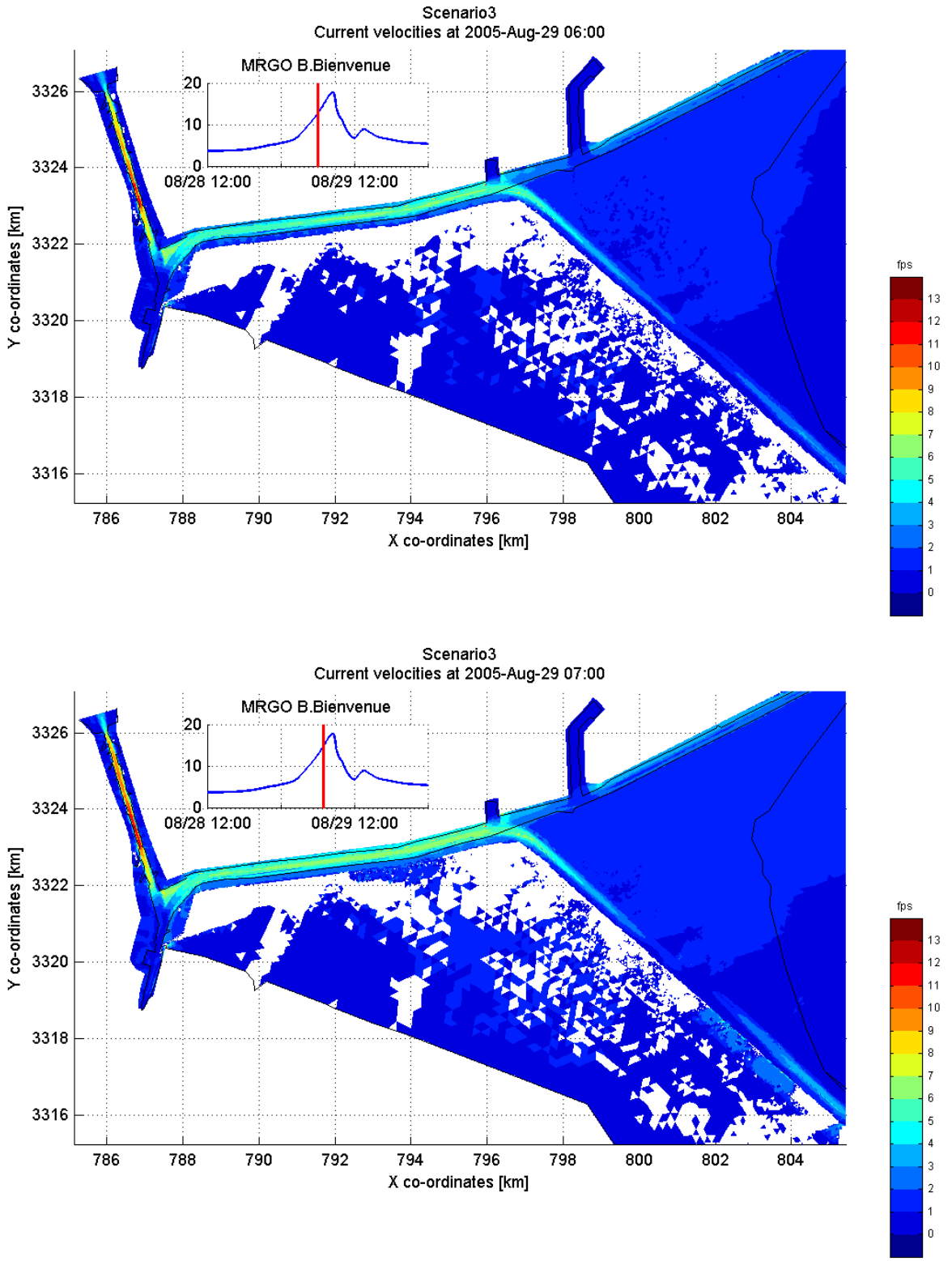


Figure 2.32b: Spatial current velocities for Scenario 3 at 6:00am, 7:00am local time. Note the high current velocities in IHNC and MRGO.

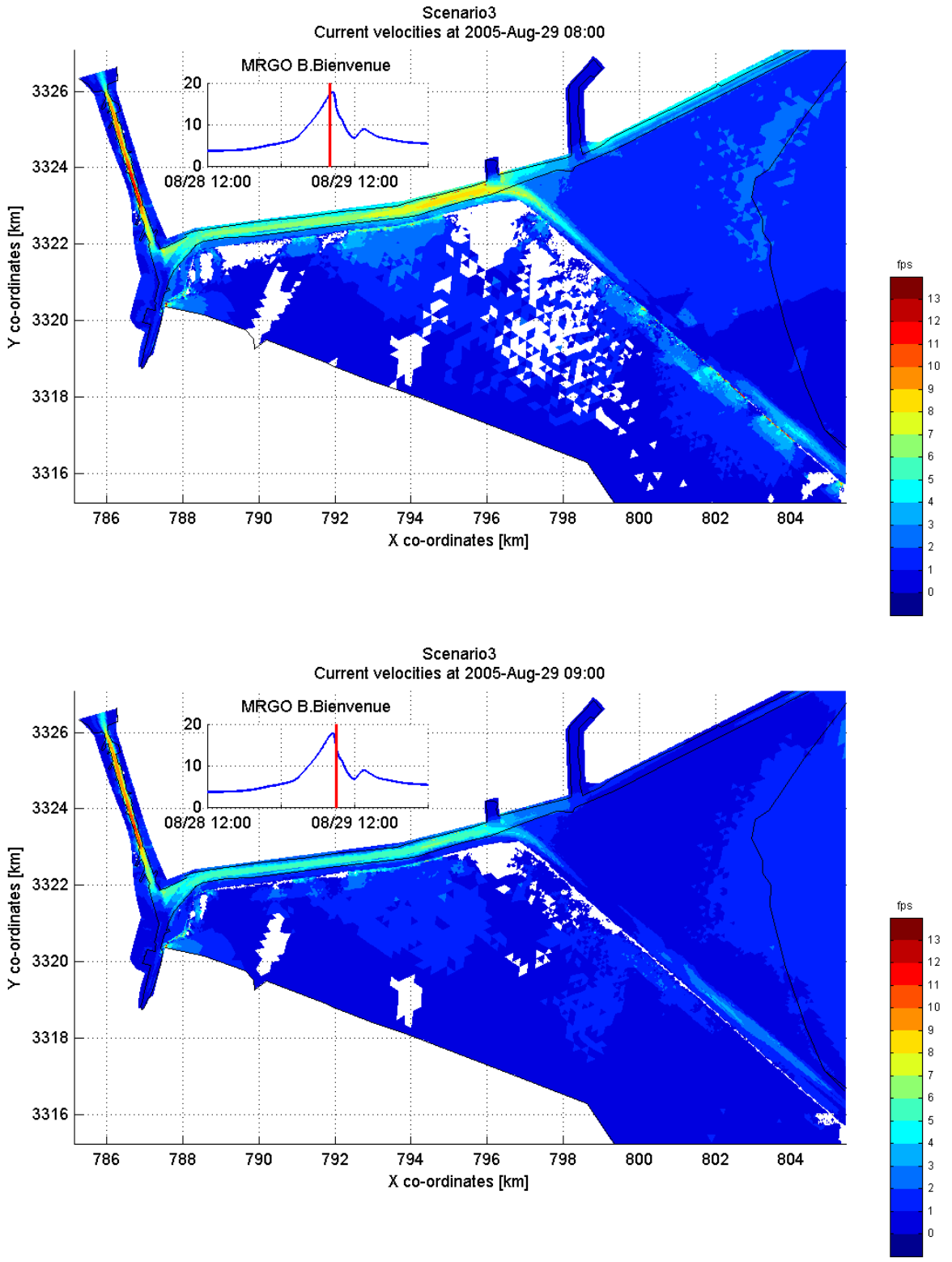


Figure 2.32c: Spatial current velocities for Scenario 3 at 8:00am, 9:00am local time. Note the high current velocities in IHNC and MRGO.

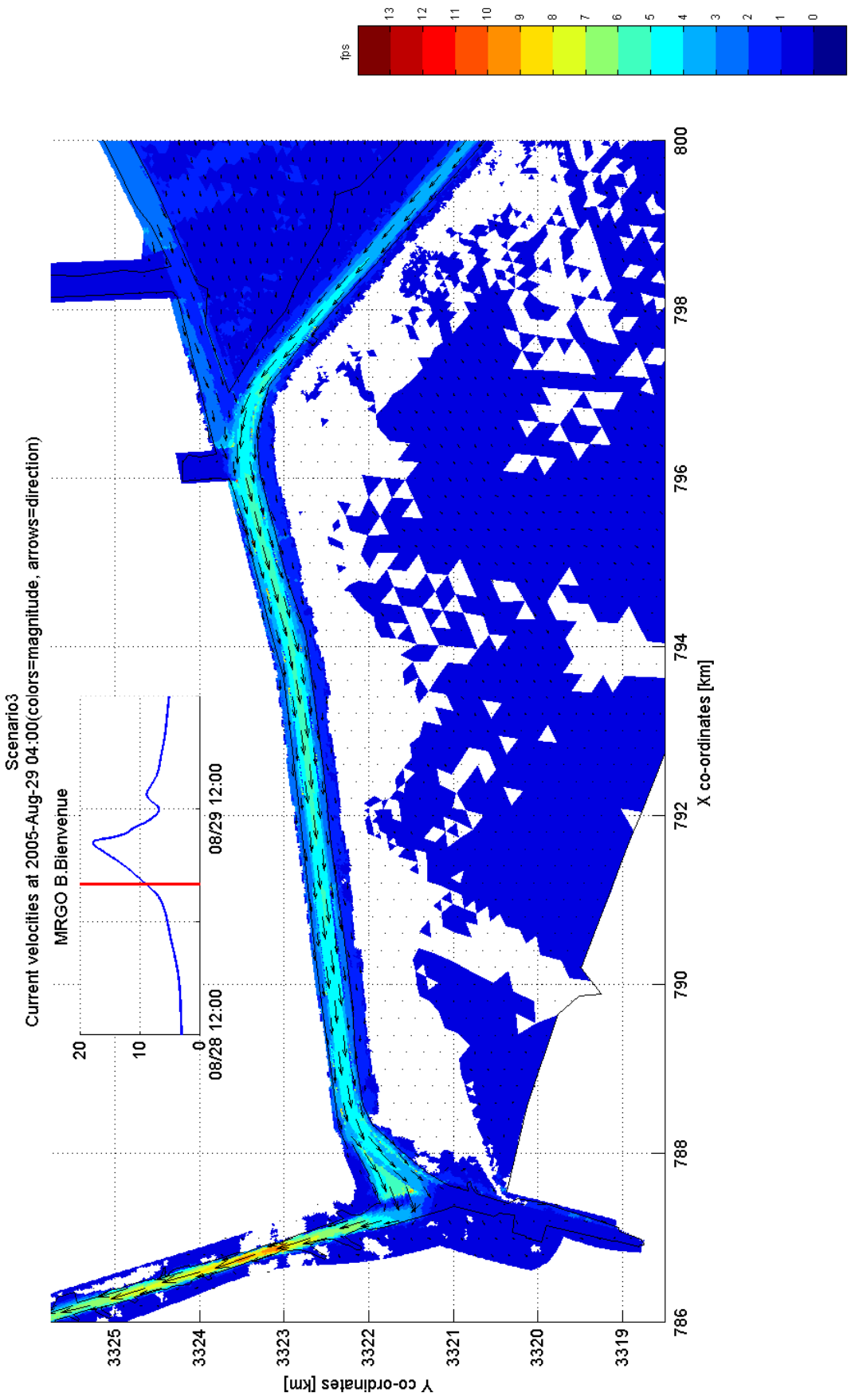


Figure 2.33a: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 3 at 4:00am local time.

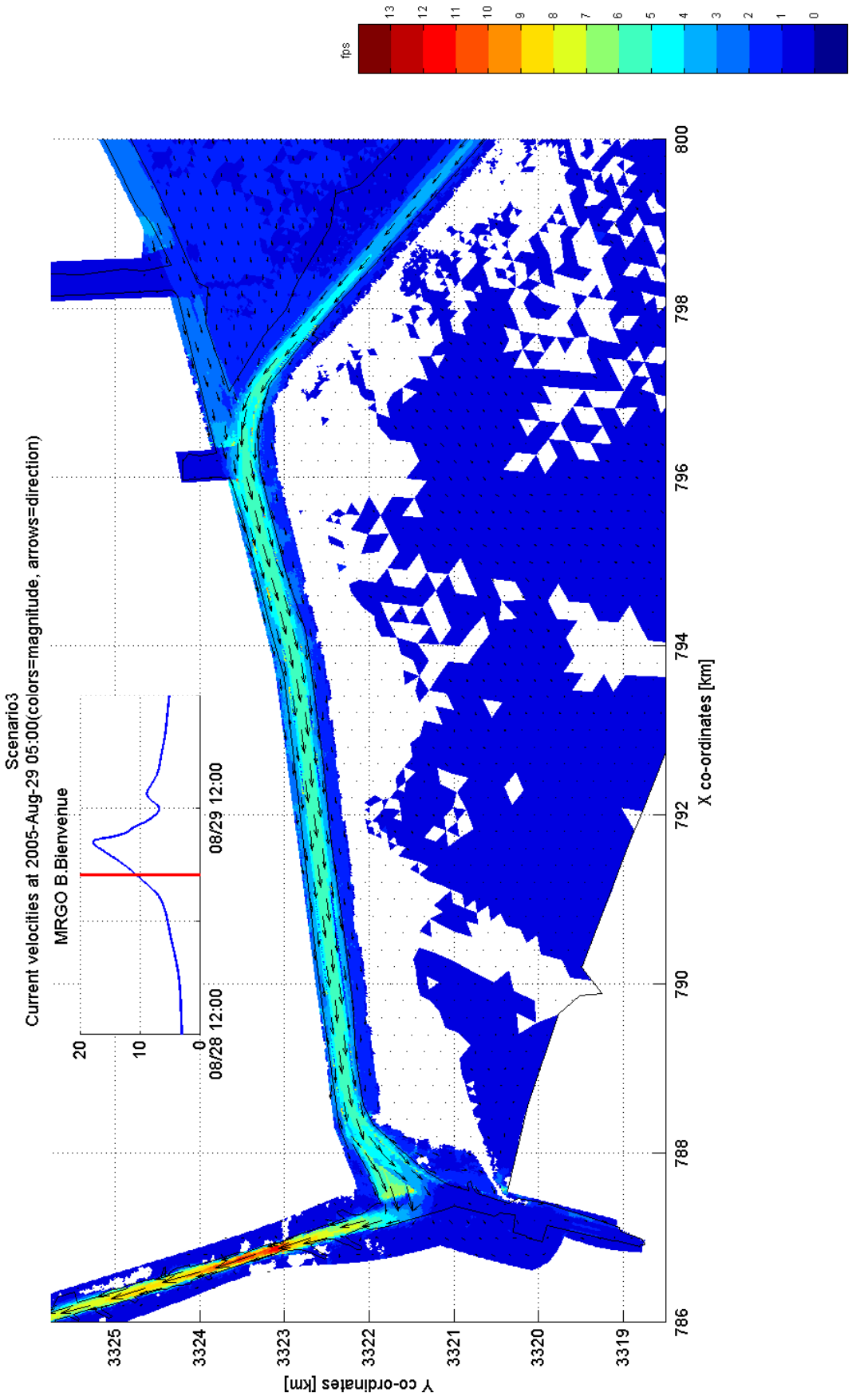


Figure 2.33b: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 3 at 5:00am local time.

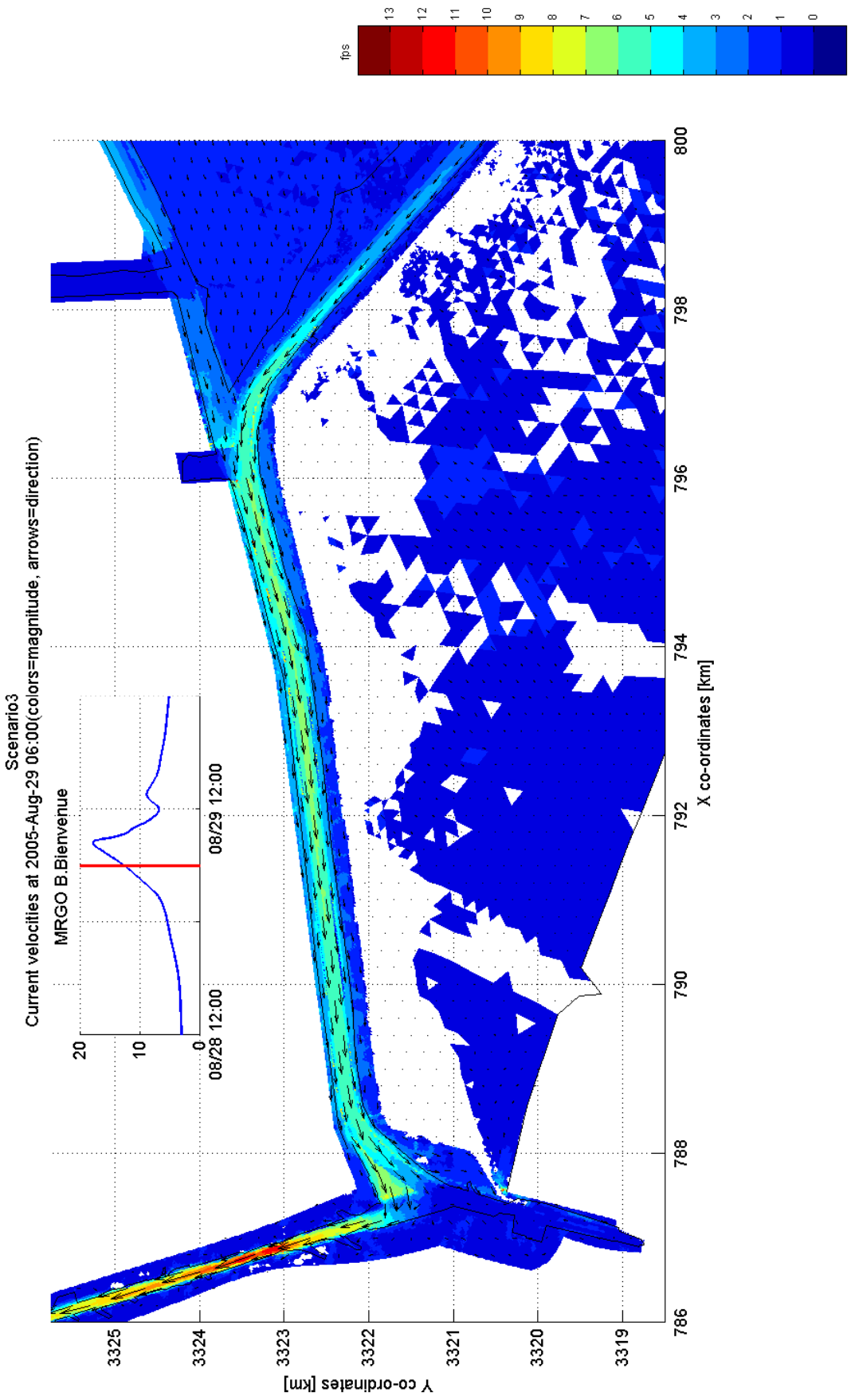


Figure 2.33c: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 3 at 6:00am local time.

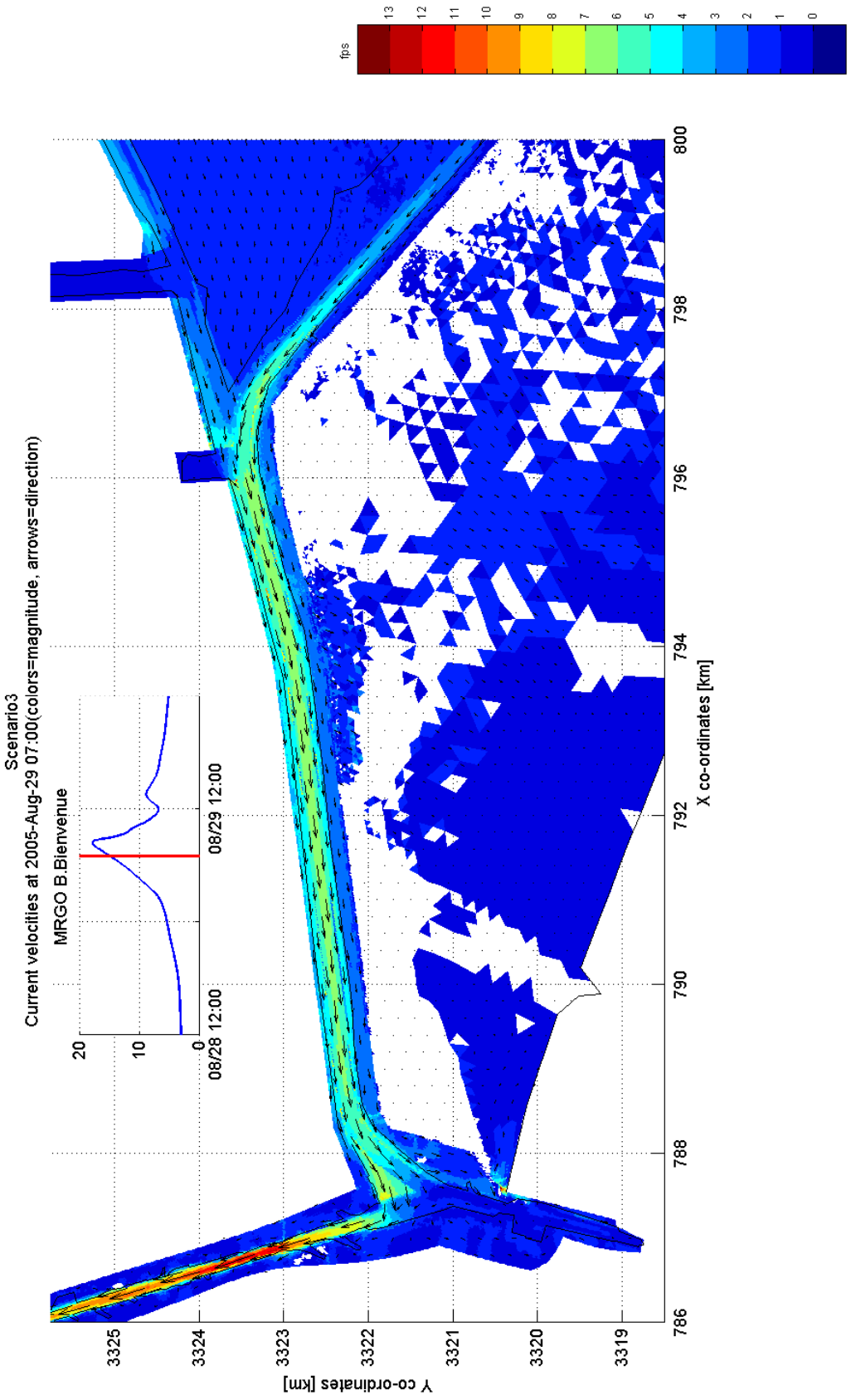


Figure 2.33d: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 3 at 7:00am local time. Note that overtopping has started at southern side MRGO Reach 1. The flooding represents contribution from levee overtopping only.

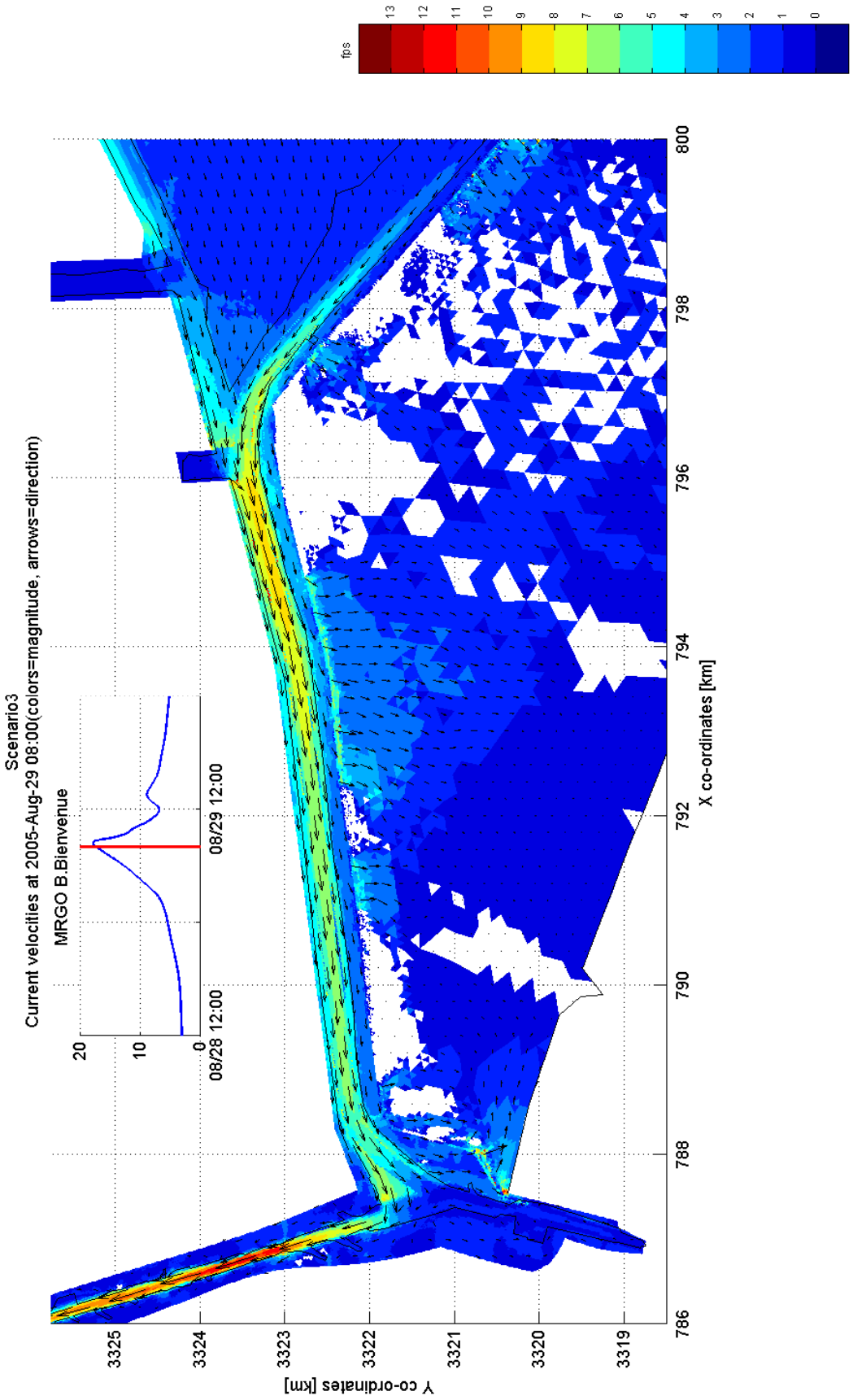


Figure 2.33e: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 3 at 8:00am local time. Note levee overtopping velocities of about 7 feet per second at the levee crest. The flooding represents contribution from levee overtopping only.

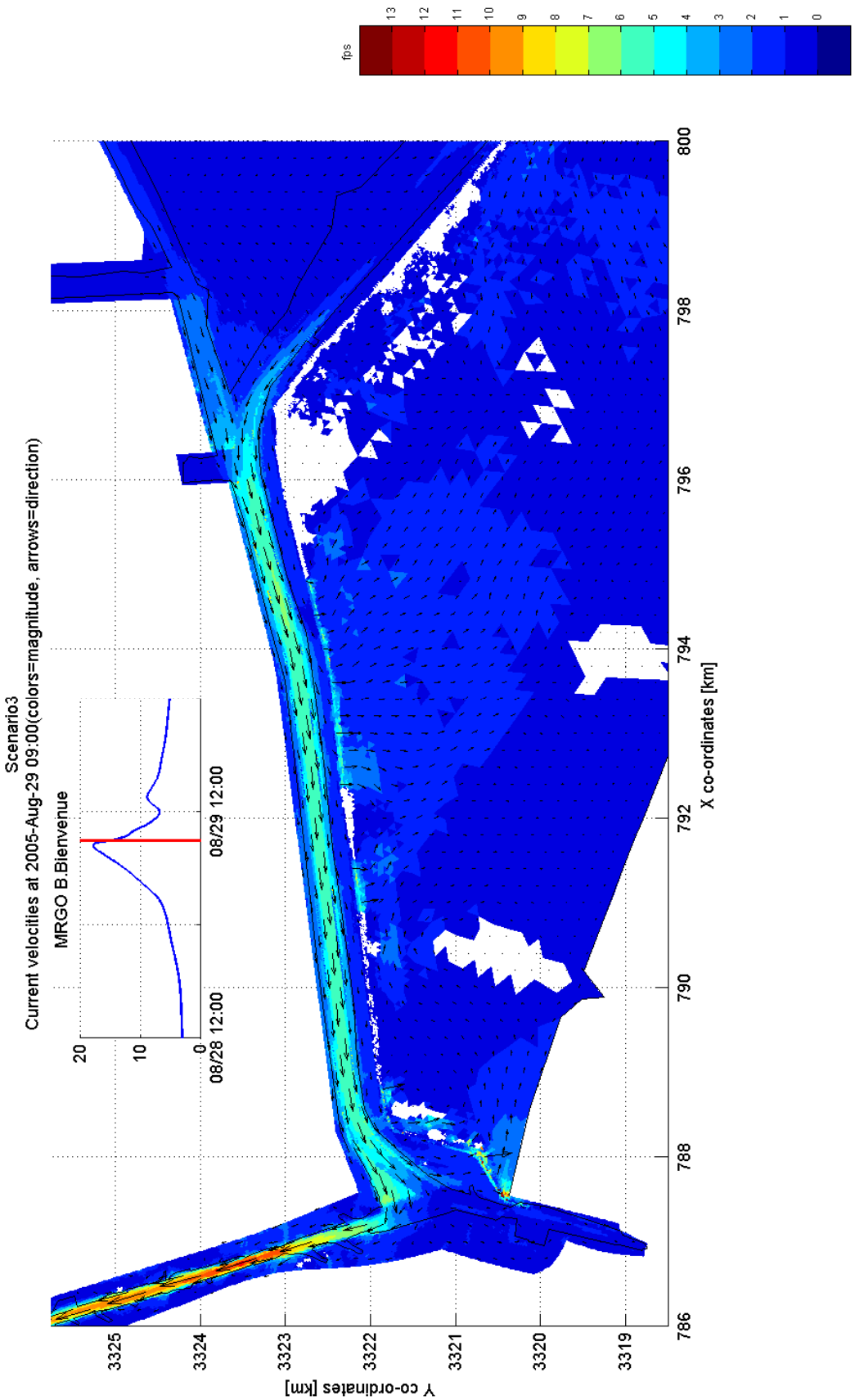


Figure 2.33f: Spatial current velocities (magnitude with color scale, direction with arrows) IHNC, MRGO Reach 1 and funnel for Scenario 3 at 9:00am local time. Note levee overtopping. The flooding represents contribution from levee overtopping only.

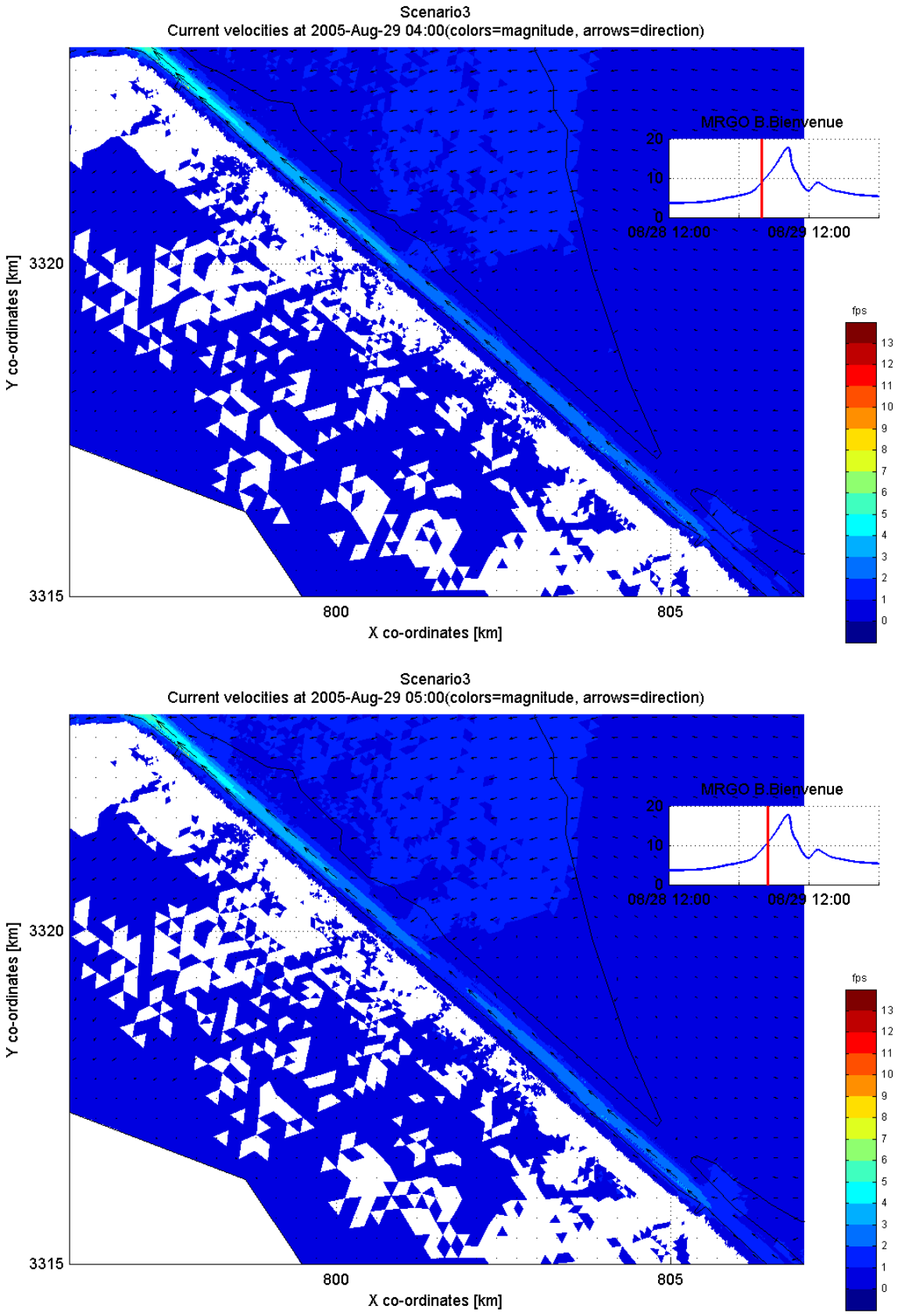


Figure 2.34a: Spatial current velocities (magnitude with color scale, direction with arrows) close up of MRGO Reach 2 for Scenario 3 at 4:00am, 5:00am local time.

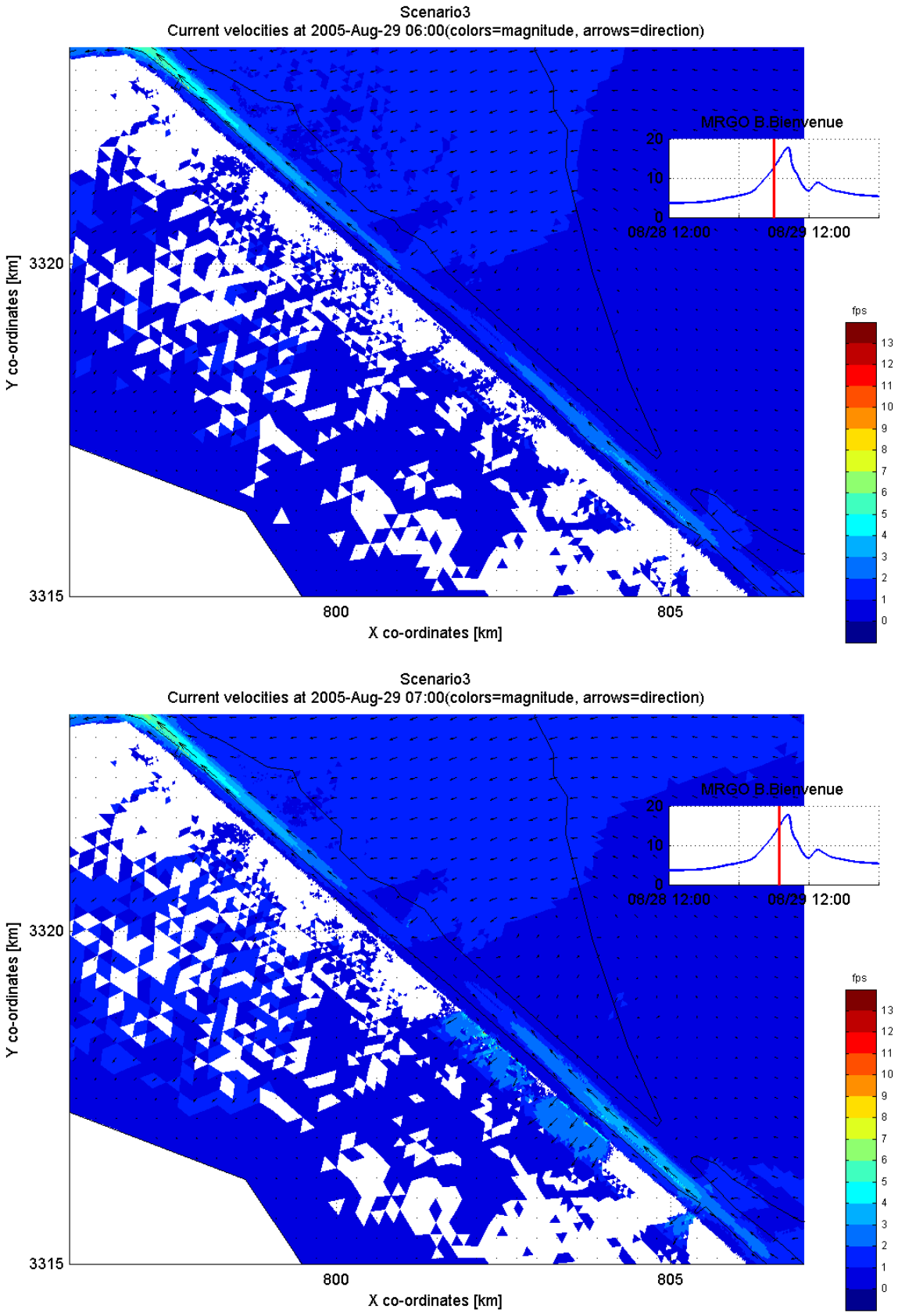


Figure 2.34b: Spatial current velocities (magnitude with color scale, direction with arrows) close up of MRGO Reach 2 for Scenario 3 at 6:00am, 7:00am local time. Note that at 7:00am overtopping has started at MRGO Reach 2. The flooding represents contribution from levee overtopping only.

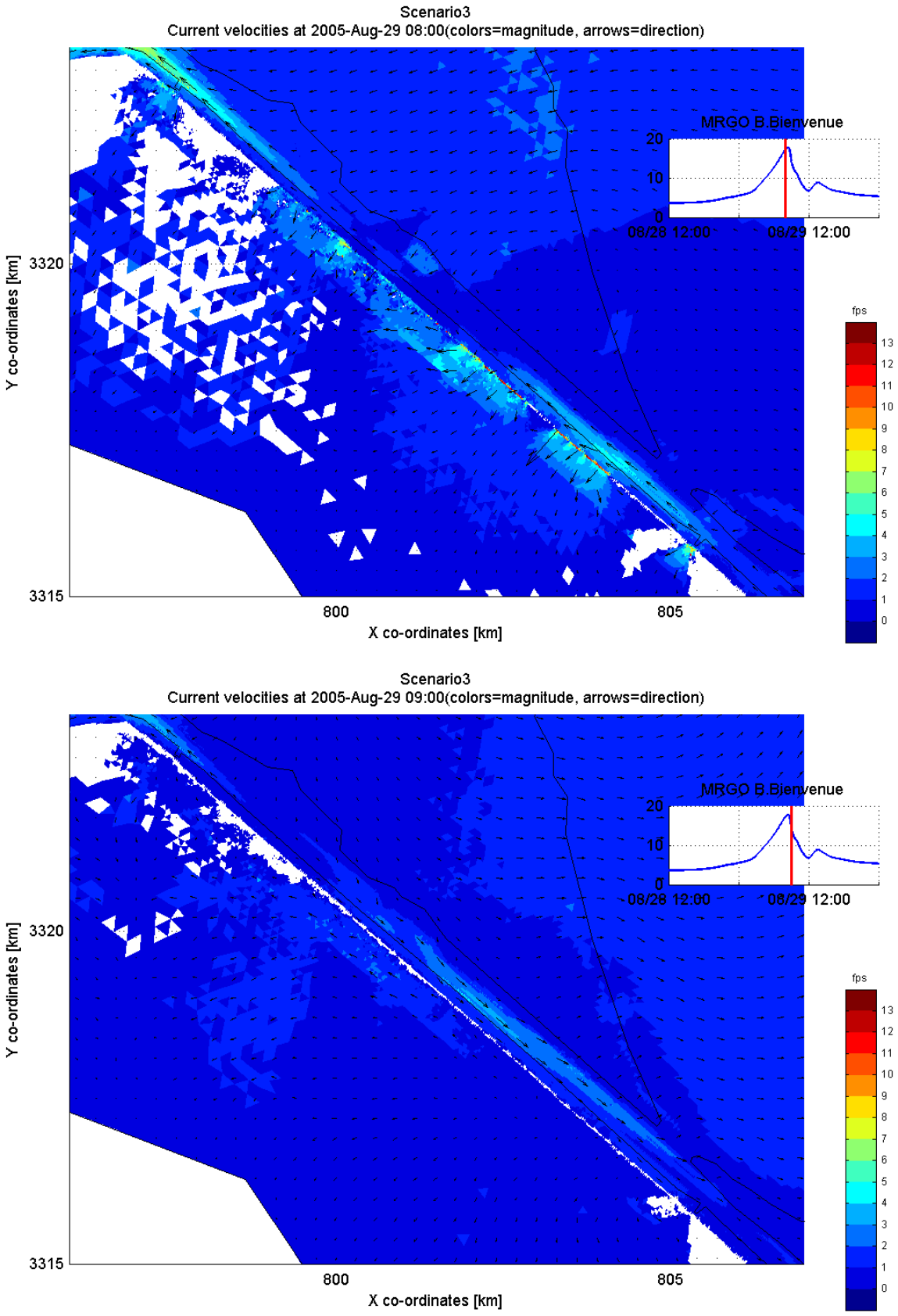


Figure 2.34c: Spatial current velocities (magnitude with color scale, direction with arrows) close up of MRGO Reach 2 for Scenario 3 at 8:00am, 9:00am local time. Note levee overtopping velocities of about 10 feet per second at the levee crest. The flooding represents contribution from levee overtopping only.

Detailed flow information at several locations

For the same locations as in Scenario 1 (see Figure 2.35 and Table 2.21) detailed information about current velocities and water levels are given in Figure 2.36. The details are also summarized in Tables 2.22 through 2.27.

Six output locations were requested along the MRGO by the Robinson experts. Some are close to the levee crown, and others are further away. To aid in data interpretation six companion sites were chosen close to the water line of the MRGO at normal water level. Note the different results between the requested locations (1 to 6) and the shifted locations (1a to 6a). When comparing the current velocities at these shifted locations with Scenario 1, also note the different bottom elevation in both Scenarios (MRGO Reach 2 in Scenario 3 is approx. 1 element shifted to the northeast). This difference does impact the current velocities. These locations correspond to output locations (Levee and Toe) in the wave modeling by SWAN [Ref. 7].

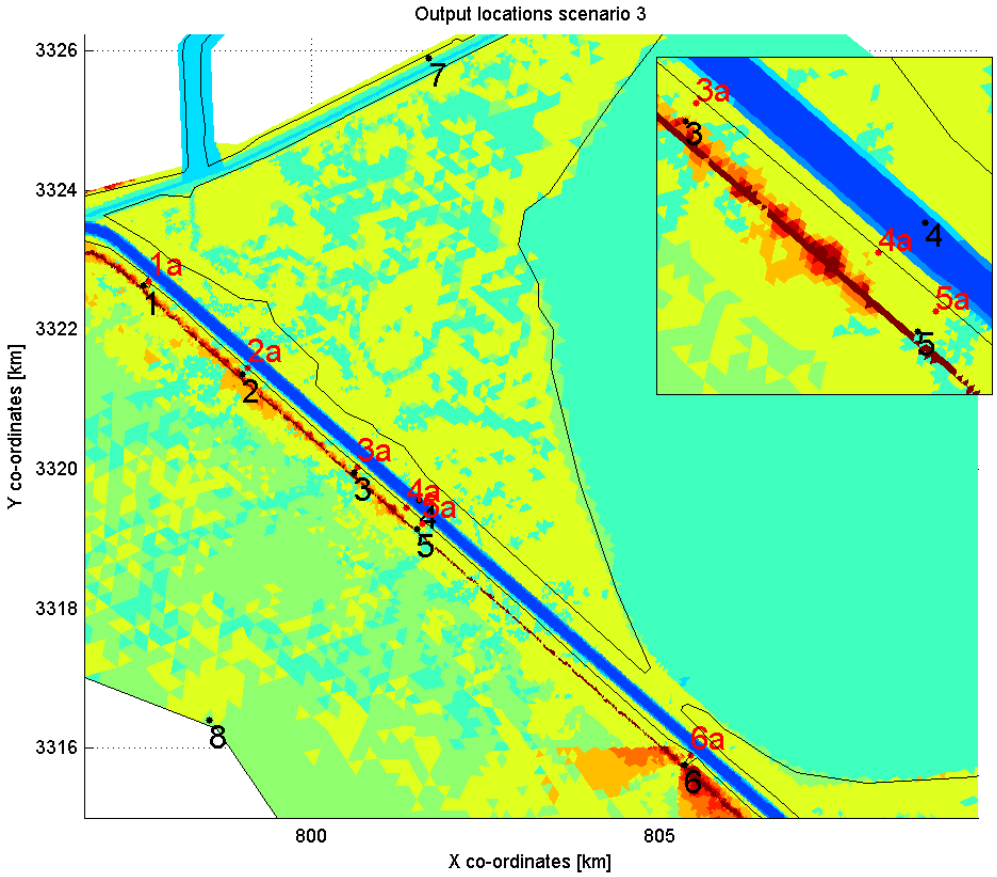


Figure 2.35: Output locations Reach 2 for the Scenario 3 FINEL model run

Table 2.21: Coordinates output locations

		Requested output location				Output location at water line	
Loc	Name	lat [N]	lon [W]	UTM [m]	UTM [m]	UTM [m]	UTM [m]
1	B. Bienvenue	29°59’ 54.51”	89°54’ 55.54”	797571	3322628	797644	3322689
2	Station 430	29°59'12.29"	89°54' 03.80"	798993	3321367	799071	3321457
3	Loc I	29.97368°	89.884833°	800613	3319954	800653	3320023
4	MRGO Halfway	29°58’ 5.11”	89°52’ 40.14”	801540	3319563	801360	3319446
5	Station 540	29°57'58.19"	89°52' 32.15"	801515	3319142	801585	3319221
6	B. Dupre	29°56’ 5.52”	89°50’ 12.26”	805355	3315765	805451	3315898
7	GIWW@BackB	30° 01.597'	89°52.291'	801670	3325901		
8	Loc II 40Arpent			798527	3316406		

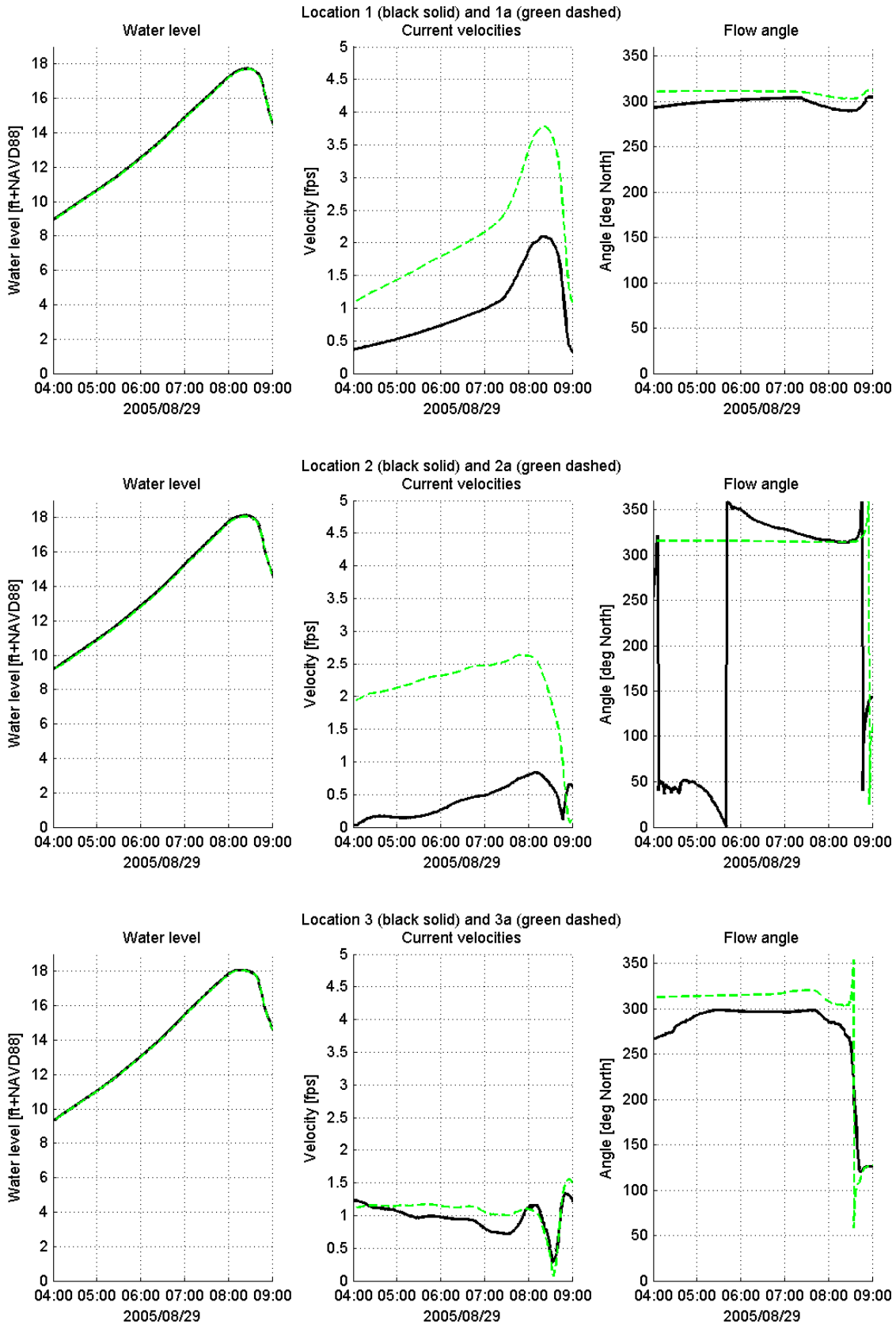


Figure 2.36a: Results for location 1, 2 and 3 Scenario 3 from 4:00am to 9:00am; Note the maximum surge elevation of 18 ft NAVD just after 8:00am.

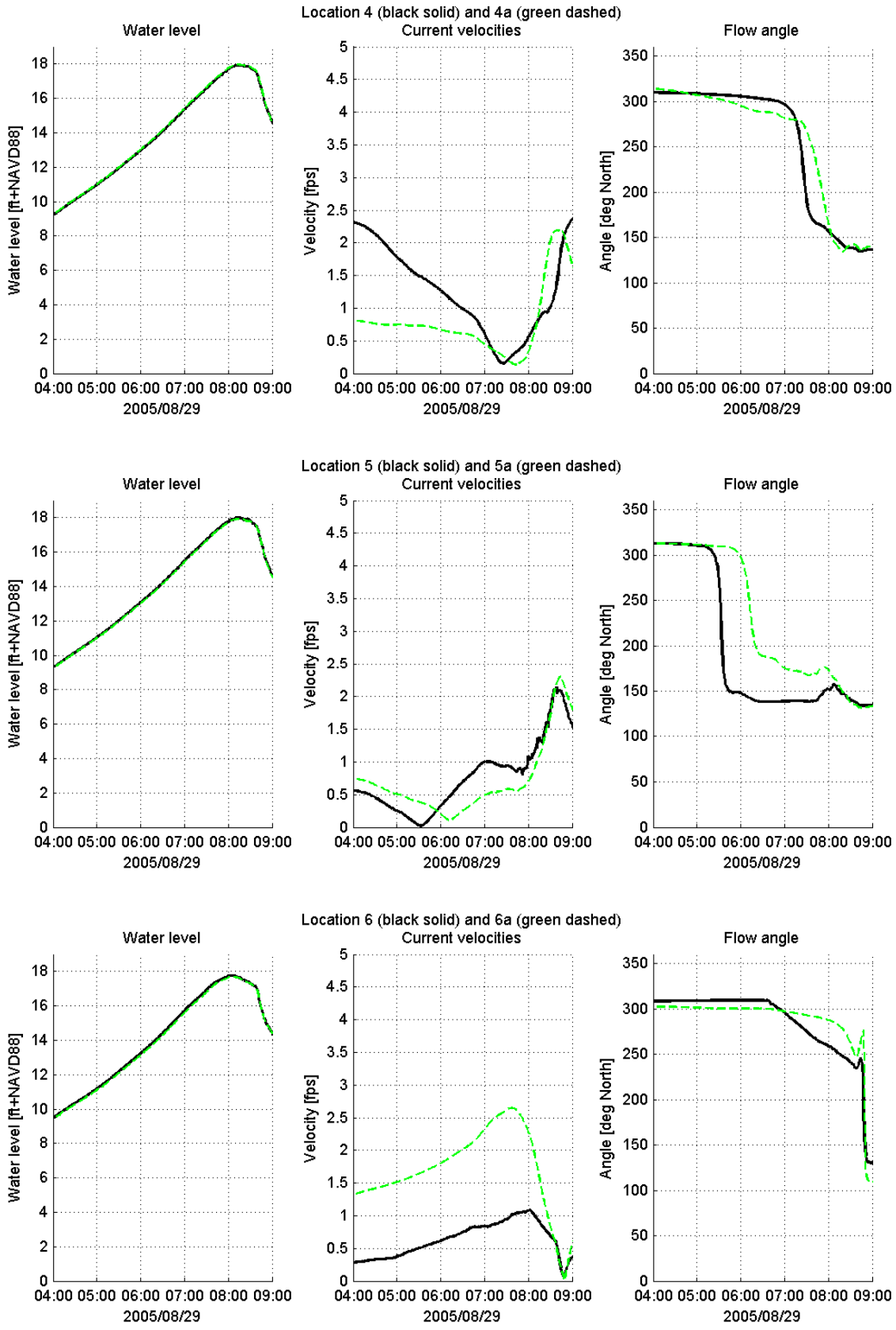


Figure 2.36b: Results for location 4, 5 and 6 Scenario 3 from 4:00am to 9:00a; Note the maximum surge elevation of 18 ft NAVD just after 8:00am.

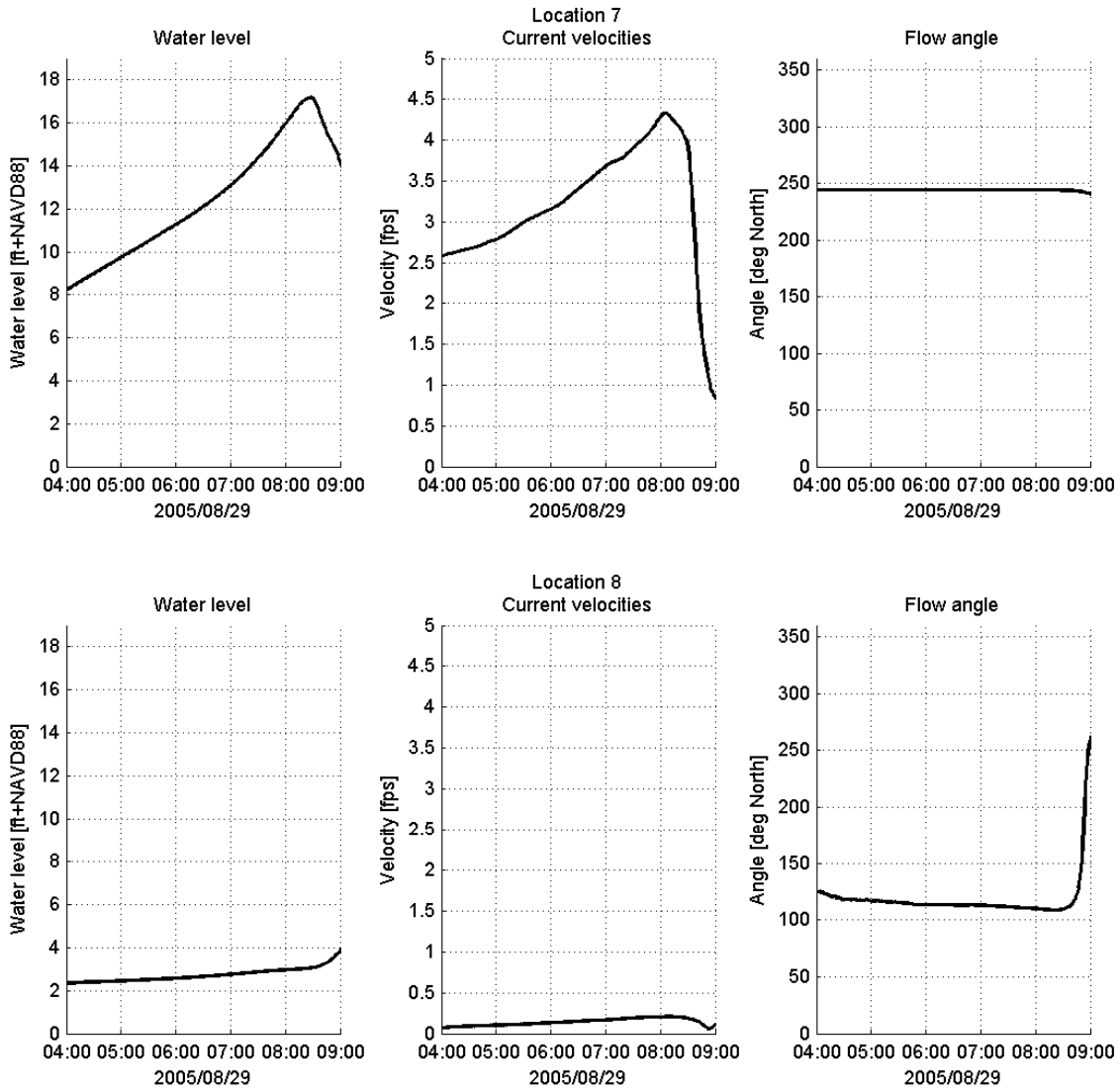


Figure 2.36c: Results for location 8 and 9 Scenario 3 from 4:00am to 9:00am

Table 2.22: Summary results Scenario 3 at 29th August 2005 4:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	8.83	0.36	292	8.79	1.07	310
2	Station 430	9.06	0.09	239	8.99	1.93	316
3	Loc I	9.20	1.22	264	9.17	1.09	313
4	MRGO Halfway	9.21	2.32	310	9.24	0.81	314
5	Station 540	9.30	0.57	313	9.25	0.75	313
6	B. Dupre	9.49	0.28	308	9.41	1.32	302
7	GIWW@BackB	8.22	2.57	244			
8	Loc II 40Arpent	2.33	0.07	126			

Table 2.23: Summary results Scenario 3 at 29th August 2005 5:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	10.60	0.52	298	10.55	1.43	311
2	Station 430	10.87	0.15	47	10.80	2.14	316
3	Loc I	11.00	1.07	292	10.97	1.14	314
4	MRGO Halfway	10.98	1.78	308	11.02	0.75	307
5	Station 540	11.07	0.25	311	11.02	0.50	311
6	B. Dupre	11.20	0.38	309	11.11	1.51	301
7	GIWW@BackB	9.74	2.78	244			
8	Loc II 40Arpent	2.45	0.10	117			

Table 2.24: Summary results Scenario 3 at 29th August 2005 6:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	12.52	0.73	301	12.47	1.79	311
2	Station 430	12.86	0.25	351	12.78	2.31	315
3	Loc I	13.02	0.95	297	12.98	1.13	315
4	MRGO Halfway	12.98	1.27	305	13.03	0.67	295
5	Station 540	13.09	0.33	147	13.03	0.20	297
6	B. Dupre	13.25	0.61	309	13.14	1.80	300
7	GIWW@BackB	11.27	3.15	244			
8	Loc II 40Arpent	2.57	0.13	113			

Table 2.25: Summary results Scenario 3 at 29th August 2005 7:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	14.86	0.98	303	14.80	2.16	311
2	Station 430	15.26	0.48	328	15.17	2.47	315
3	Loc I	15.44	0.79	296	15.39	1.03	318
4	MRGO Halfway	15.36	0.60	296	15.42	0.45	281
5	Station 540	15.49	0.99	138	15.42	0.49	175
6	B. Dupre	15.72	0.84	295	15.59	2.32	297
7	GIWW@BackB	13.09	3.68	244			
8	Loc II 40Arpent	2.75	0.17	113			

Table 2.26: Summary results Scenario 3 at 29th August 2005 8:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	17.23	1.85	293	17.17	3.42	305
2	Station 430	17.75	0.78	316	17.67	2.61	314
3	Loc I	17.83	1.12	286	17.79	1.08	308
4	MRGO Halfway	17.69	0.55	157	17.75	0.33	164
5	Station 540	17.77	1.09	152	17.73	0.71	172
6	B. Dupre	17.73	1.07	258	17.65	2.28	287
7	GIWW@BackB	15.97	4.29	244			
8	Loc II 40Arpent	2.96	0.20	110			

Table 2.27: Summary results Scenario 3 at 29th August 2005 9:00am

		Requested output location			Output location at water line		
Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)	H (ft)	Vel (fps)	Dir (°N)
1	B. Bienvenue	14.61	0.33	305	14.59	1.08	312
2	Station 430	14.71	0.62	143	14.69	0.14	111
3	Loc I	14.67	1.25	126	14.67	1.50	128
4	MRGO Halfway	14.62	2.36	137	14.63	1.66	140
5	Station 540	14.63	1.54	134	14.62	1.81	133
6	B. Dupre	14.41	0.36	130	14.40	0.57	109
7	GIWW@BackB	14.11	0.85	241			
8	Loc II 40Arpent	3.84	0.11	259			

2.4 Hydrographs, overtopping rates and discharges MRGO all Scenarios

2.4.1 Hydrographs all Scenarios

The hydrographs for all Scenarios including Scenario 2A, 2B, and 2D (Appendix) are shown in Figures 2.38 a-h. The locations of the hydrographs are given in Figure 2.37. Surge peaks in the MRGO Reach 2 for Scenario 1 are around 18 ft+NAVD88, in the MRGO Reach 1 around 16.5 ft+NAVD88, and 17.5ft+NAVD88 in the IHNC.

Scenario 2C shows surges between Scenario 1 and 2B (lower than Scenario 1 and higher than Scenario 2B). Compared with Scenario 1, the peak surge is reduced by almost 1.5 ft at Bayou Dupre to about 16.5 ft+NAVD88, by almost 1 ft at MRGO Halfway to just over 17 ft+NAVD88, and by less than 0.5 ft at Bayou Bienvenue to just under 17.5 ft+NAVD88. In Reach 1 the peak surge is lowered by up to 2 ft to 15.5 ft+NAVD88, in the south IHNC the peak surge is lowered by 3 ft to 14.5 ft+NAVD88. Surge durations are also drastically reduced by up to 2 hours (see Figure 2.28.d for example) reflecting a much lower discharge entering the IHNC. The water level conditions on Lake Pontchartrain are unchanged, so the hydrographs close by (IHNC@Seabrook and IHNC@Lake P) are similar. The peak in Scenario 2C is not delayed.

The hydrographs for Scenario 1 and 3 are almost similar; however some small differences are visible. At Lake Borgne (MRGO Reach 2 and GIWW@NOE Back Levee) the surge peak the Scenario 3 hydrograph is a tiny bit higher (increase <0.2 ft) than Scenario 1. Reason is the reduced size of the MRGO in Scenario 3 which reduces the transport capacity of water away from the peak surge at Lake Borgne. At the MRGO Reach 1 and the IHNC this mechanism is also visible, but now it works the other way. The peak surges are reduced in Scenario 3 at the MRGO Reach 1 (reduction up to 0.4 ft) and the IHNC (reduction up to 0.5 ft).

Scenario 2A shows higher peak surges than Scenario 2B, but lower than Scenario 1. Compared with Scenario 1, the peak surge is reduced by almost 1.5 ft at Bayou Dupre to about 16.5 ft+NAVD88, by 2 ft at MRGO Halfway to 16 ft+NAVD88, and by 2 ft at Bayou Bienvenue to just over 15.5 ft+NAVD88. Following the MRGO Reach 2 northeast the peak is delayed; 0 minutes at Bayou Dupre and 30 minutes at Bayou Bienvenue. Also in Reach 1 and in the south part of the IHNC the delay is 30 minutes. In Reach 1 the peak surge is lowered by 1 ft to just under 16 ft+NAVD88, in the south IHNC the peak surge is lowered by 2.5 ft to 15 ft+NAVD88. Surge durations are also drastically reduced by up to 2 hours (see Figure 2.28.d_ for example) reflecting a much lower discharge entering the IHNC as a consequence of the 'blocking action' of the cypress swamps and intact marshes. The water level conditions on Lake Pontchartrain are unchanged, so the hydrographs close by (IHNC@Seabrook and IHNC@Lake P) are similar.

Scenario 2B shows different hydrographs compared to Scenarios 1 and 3. The peak surge is delayed and lowered. The peak surge is reduced by 1.5 ft at Bayou Dupre to about 16 ft+NAVD88, by 3.5 ft at MRGO Halfway to just under 15 ft+NAVD88, and by 4 ft at Bayou Bienvenue to just under 14 ft+NAVD88. Following the MRGO Reach 2 northeast the peak is delayed; 0 minutes at Bayou Dupre and 30 minutes at Bayou Bienvenue. In Reach 1 the peak surge is lowered by 3.5 ft to 13 ft+NAVD88 and delayed by about 40 minutes. In the south IHNC the peak surge is lowered by 4.5 ft to 13 ft+NAVD88 and delayed by about 30 minutes. Surge durations are also drastically reduced by up to 2 hours (see Figure 2.28.d_ for example) reflecting a much lower discharge entering the IHNC as a consequence of the 'blocking action' of the cypress swamps and intact marshes and the overtopping of the 40 Arpent levee. The water level conditions on Lake Pontchartrain are unchanged, so the hydrographs close by (IHNC@Seabrook and IHNC@Lake P) are similar.

The hydrographs in Scenario 2D are similar to the hydrographs in Scenario 2B (difference in peak surge less than 1 ft).

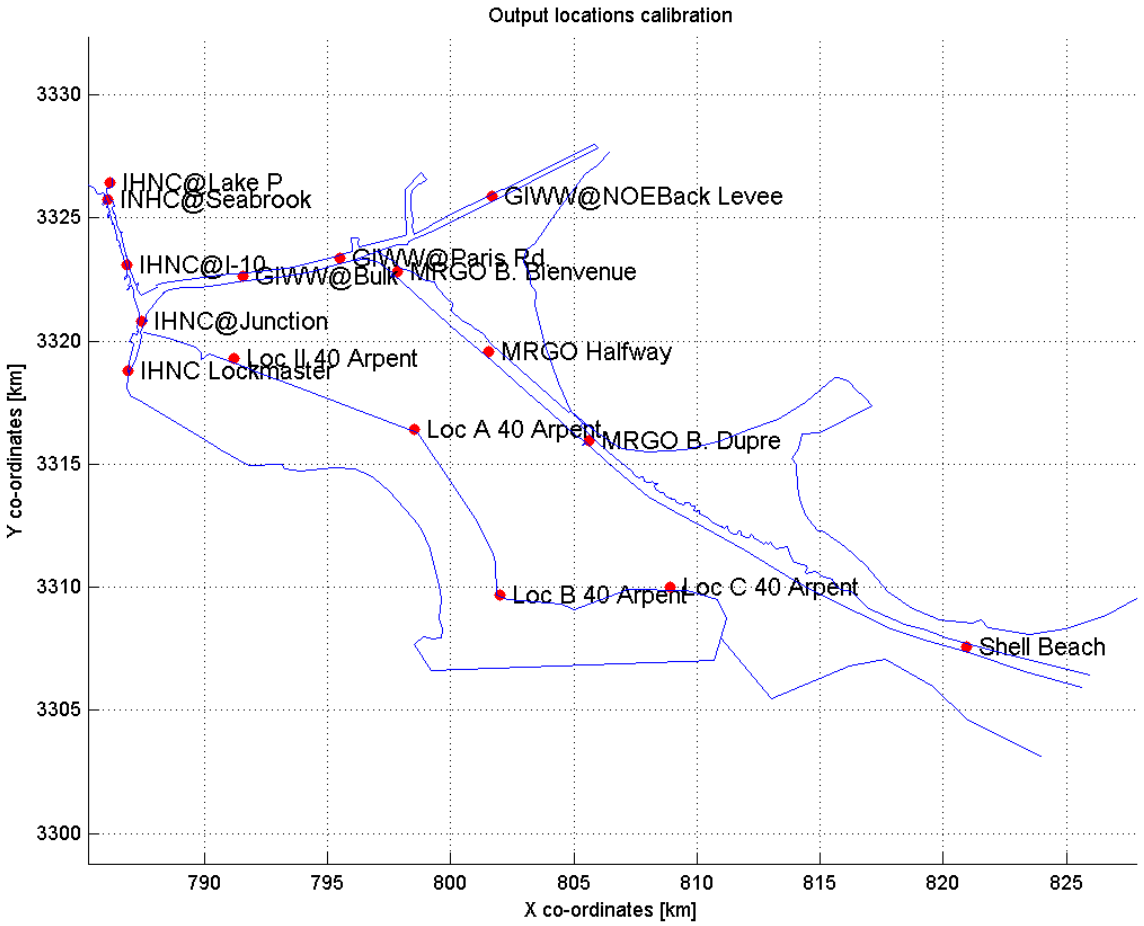


Figure 2.37: Output locations FINEL hydrographs

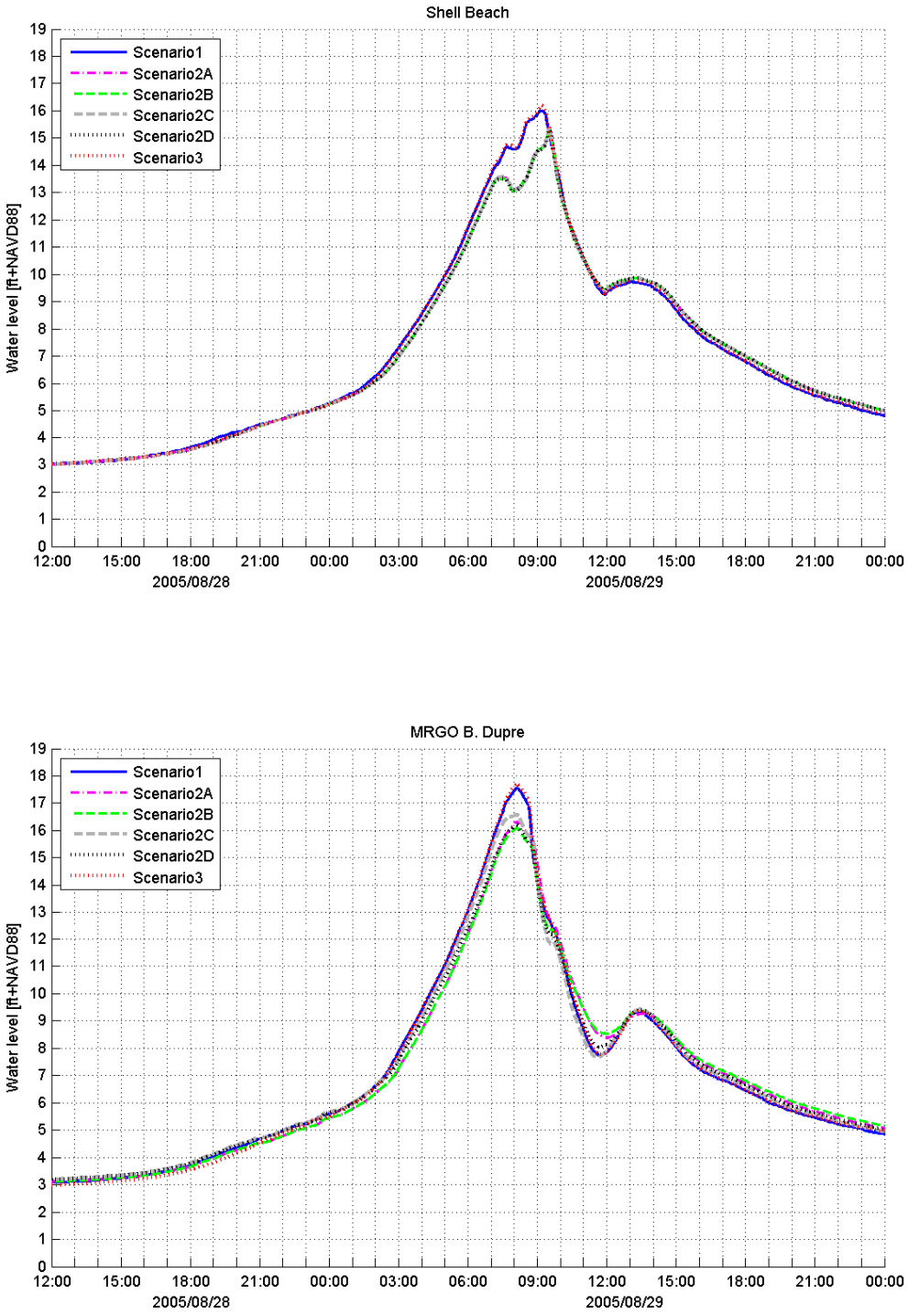


Figure 2.38a: FINEL hydrographs (line of Scenario 3 lies under Scenario 1, also the Scenarios 2 lines lie under each other)

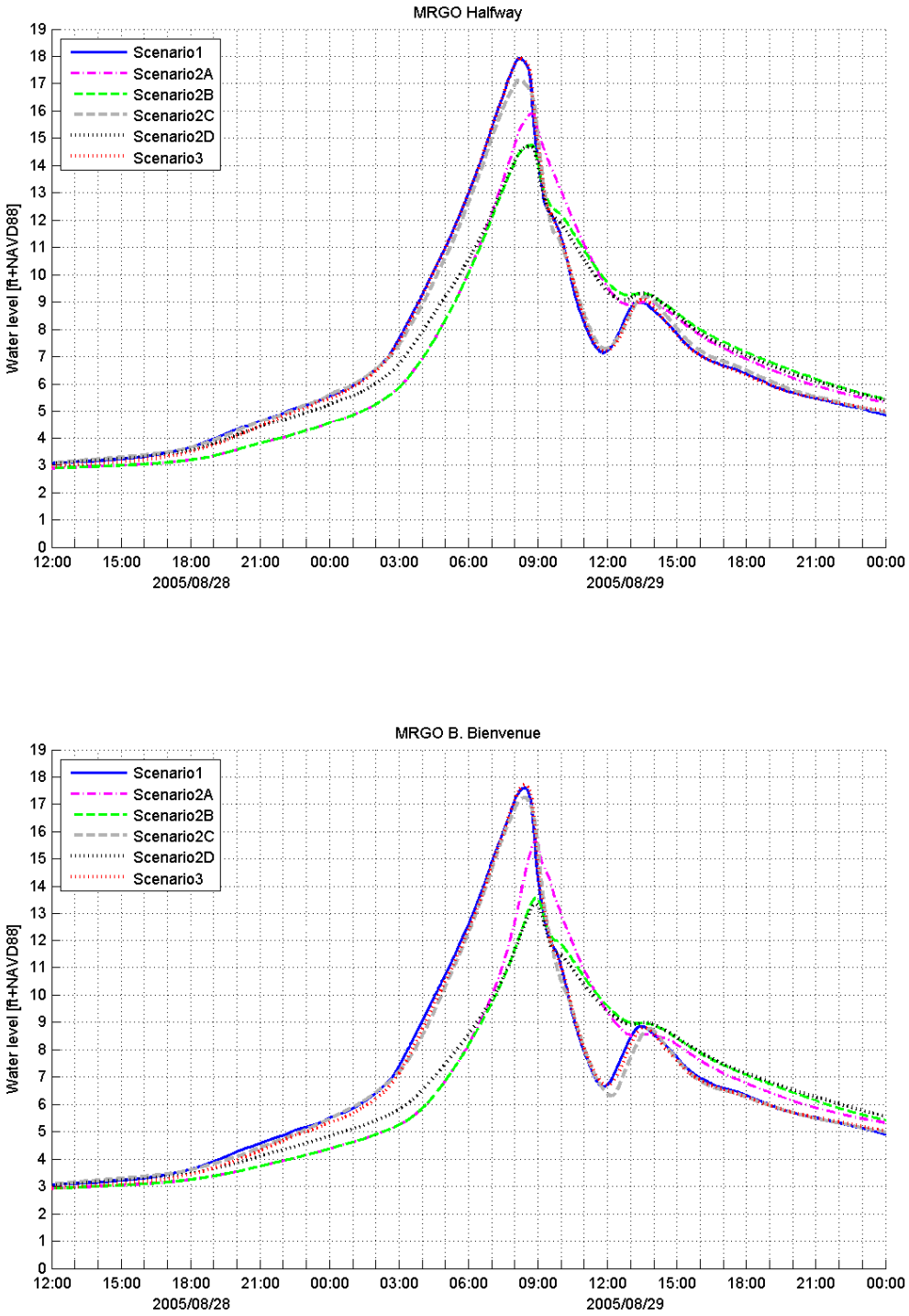


Figure 2.38b: FINEL hydrographs (line of Scenario 3 lies under Scenario 1)

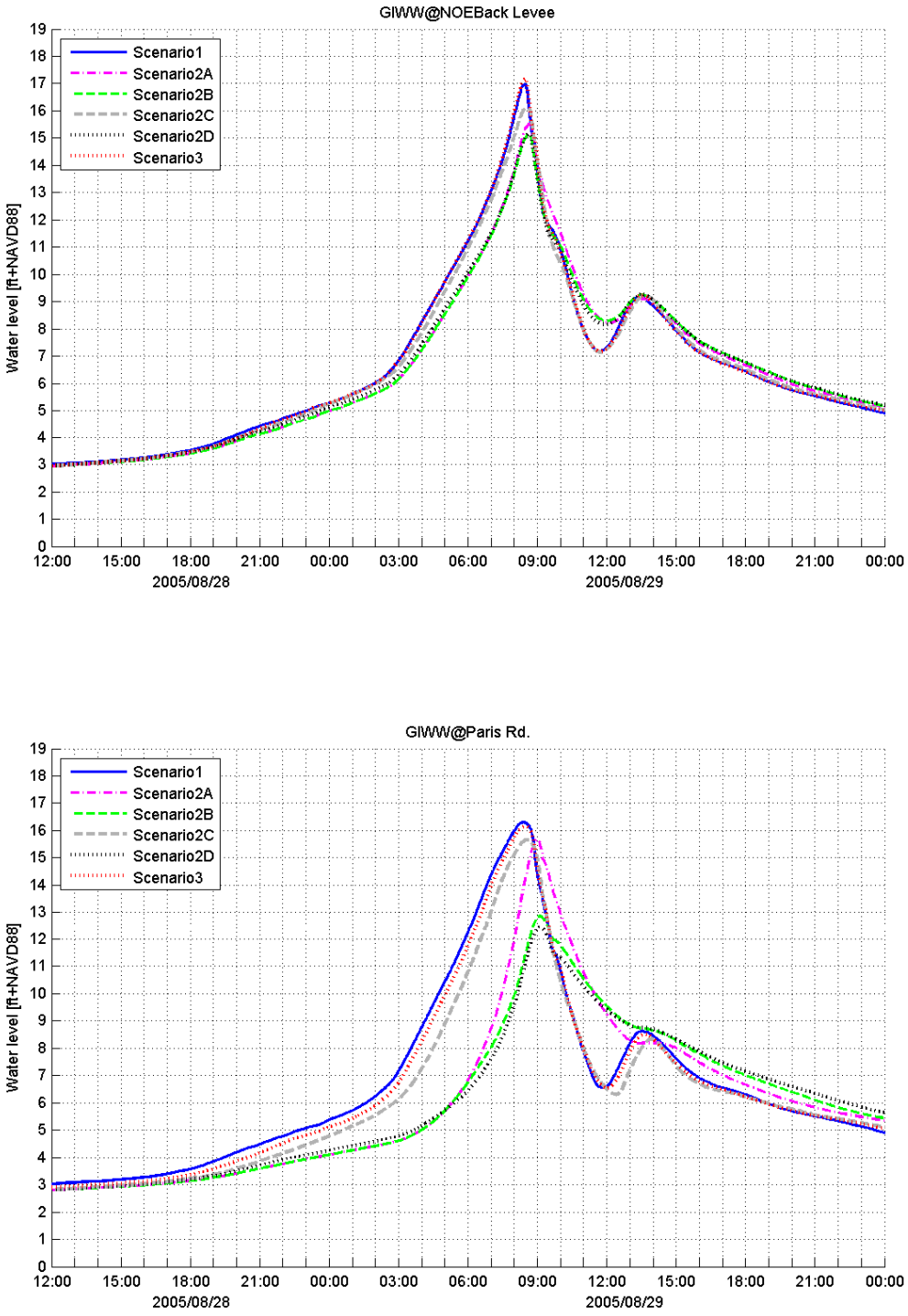
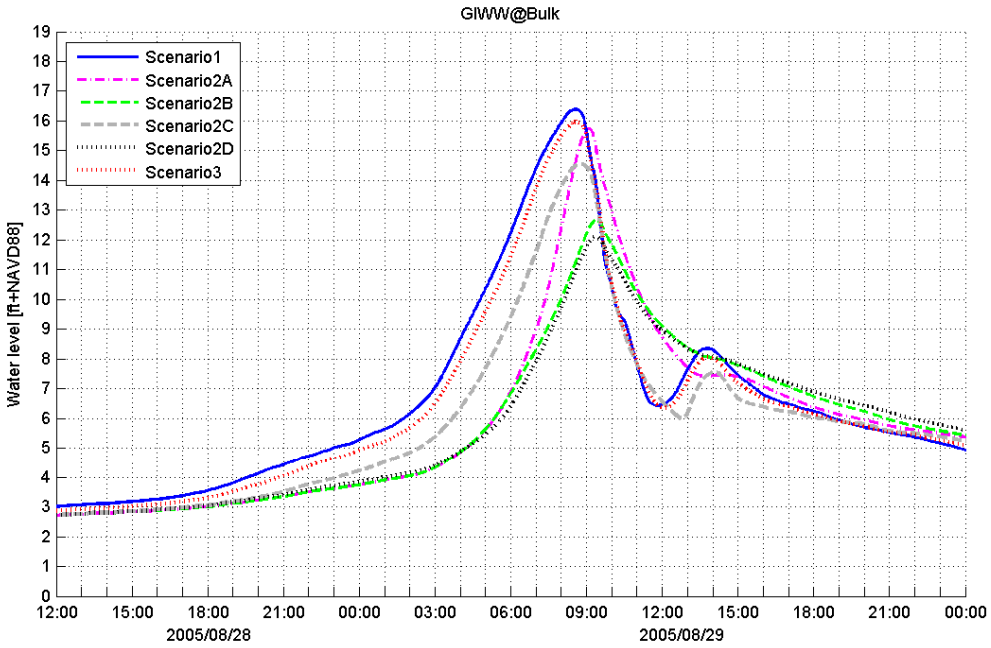


Figure 2.38c: FINEL hydrographs (line of Scenario 3 lies under Scenario 1)



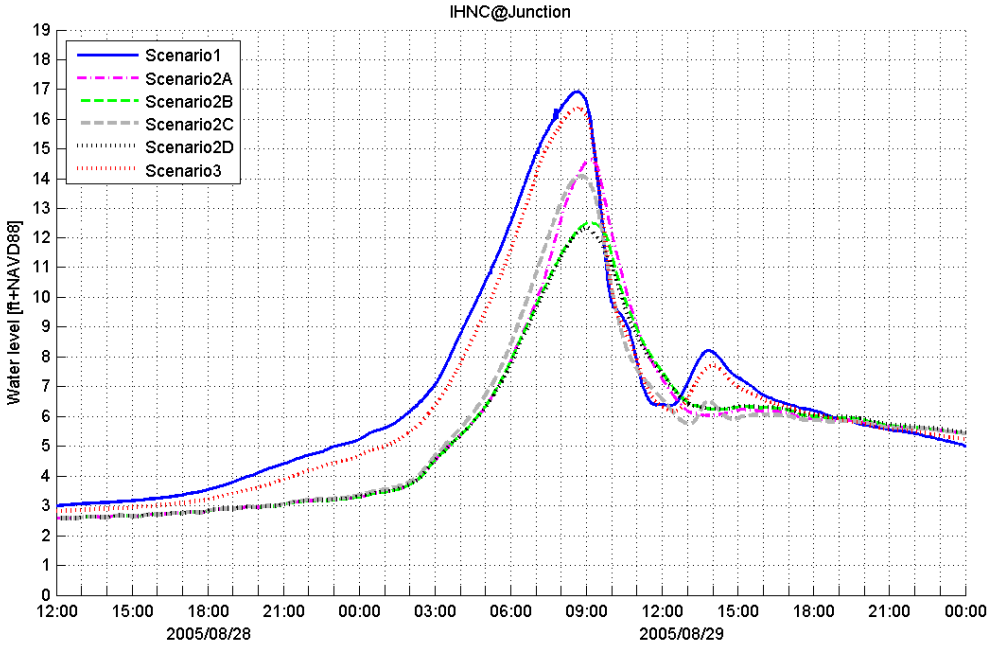


Figure 2.38d: FINEL hydrographs (line of Scenario 3 lies under Scenario 1)

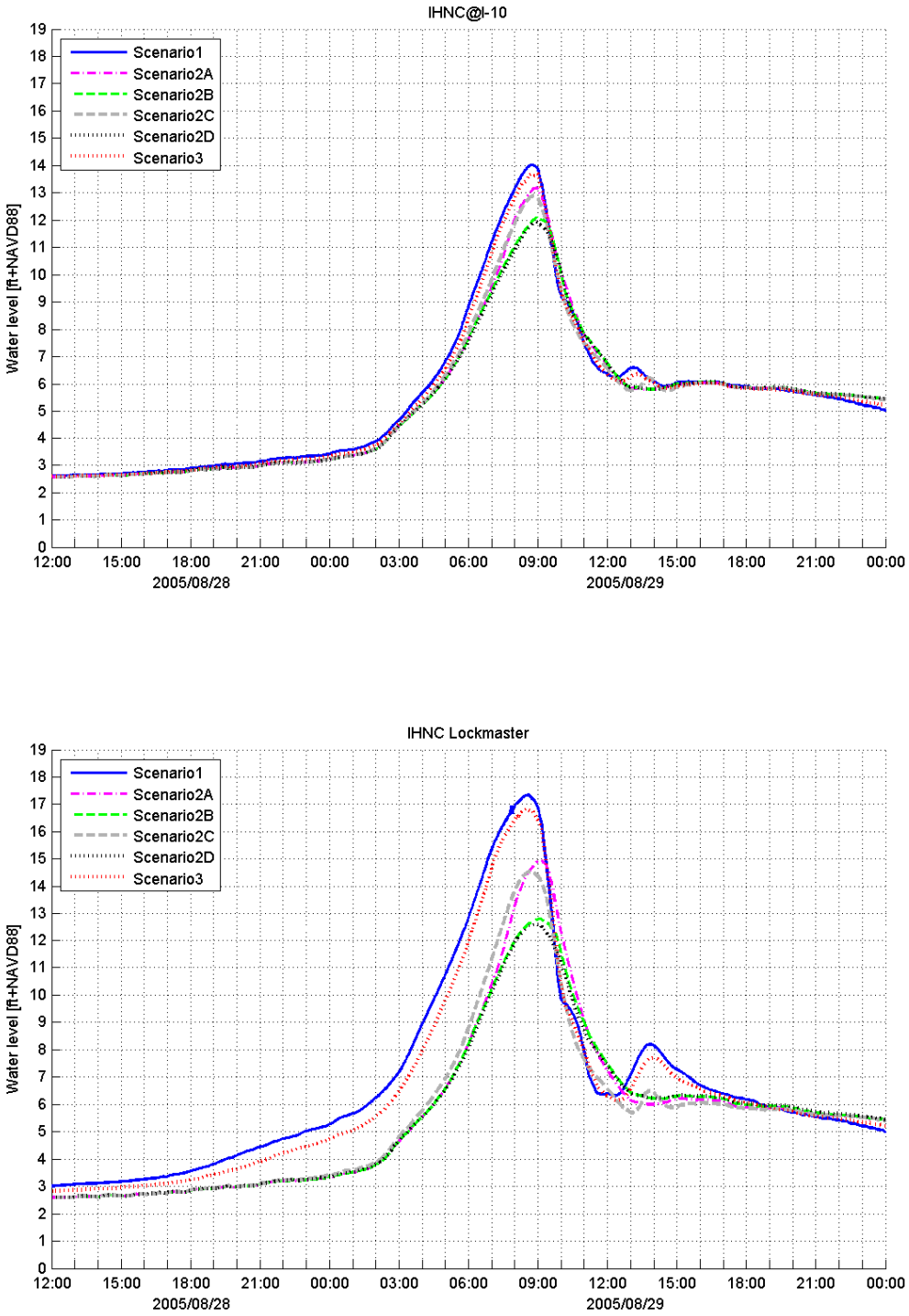


Figure 2.38e: FINEL hydrographs (line of Scenario 3 lies under Scenario 1)

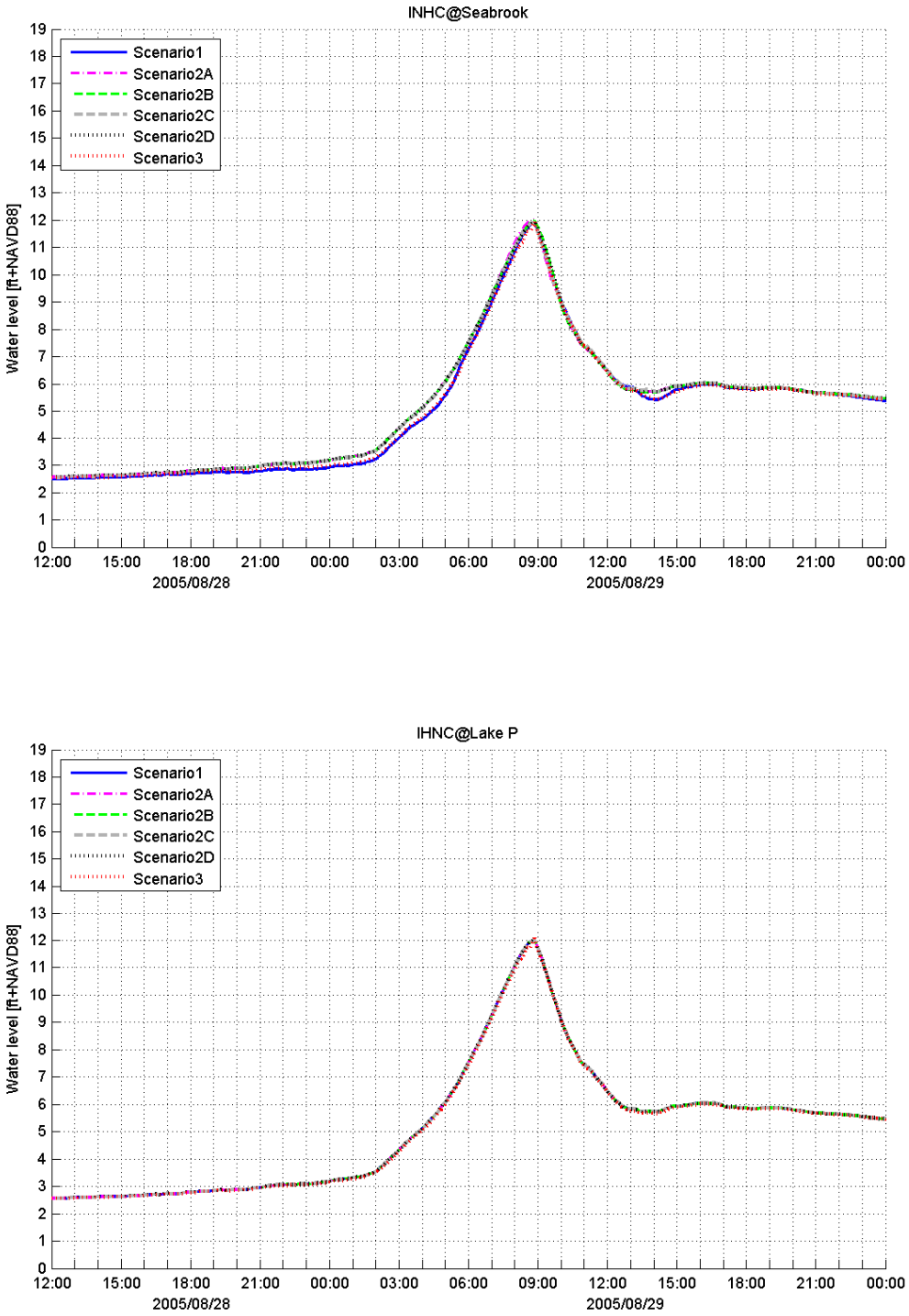


Figure 2.38f: FINEL hydrographs (all Scenarios are similar)

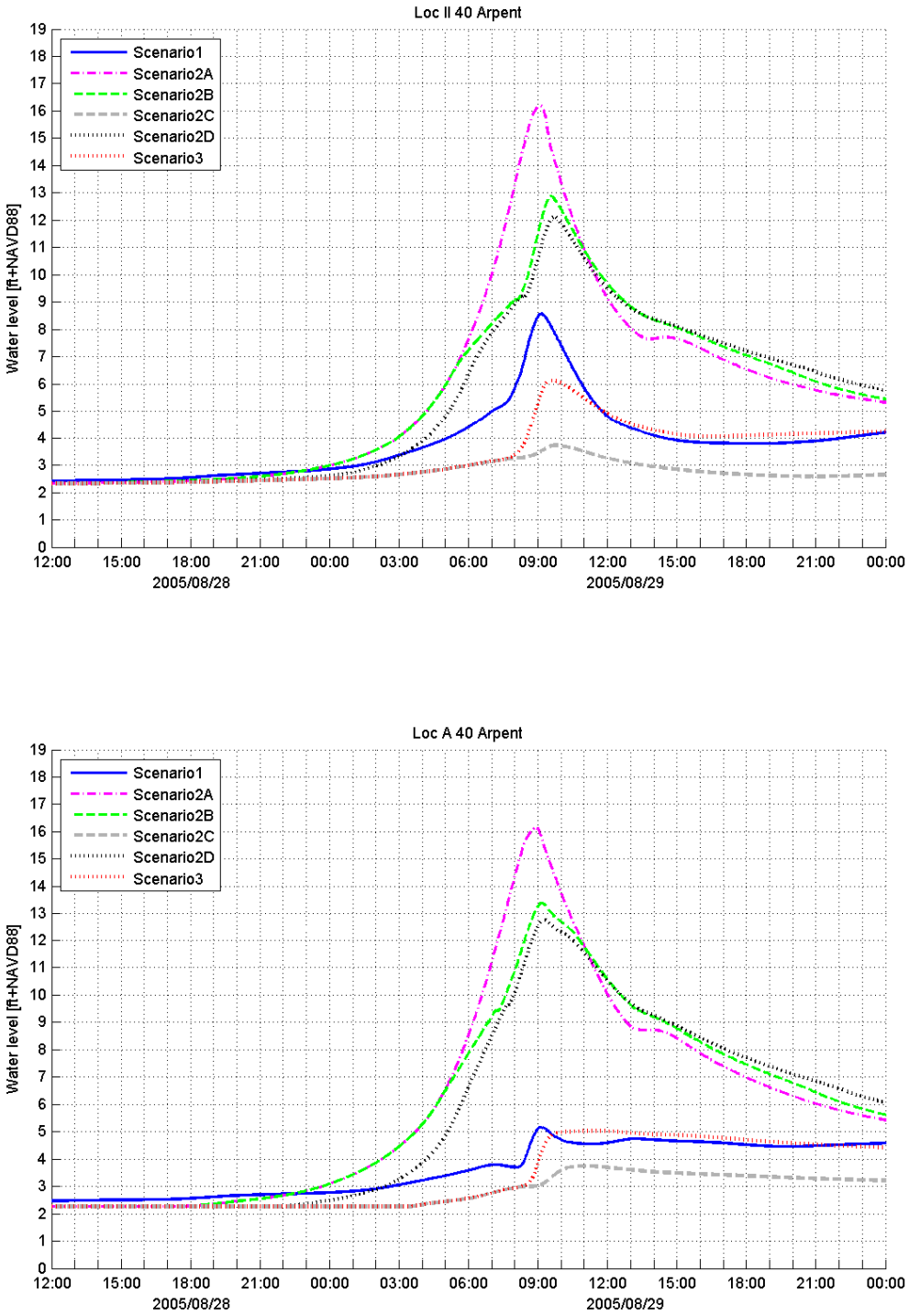


Figure 2.38g: FINEL hydrographs

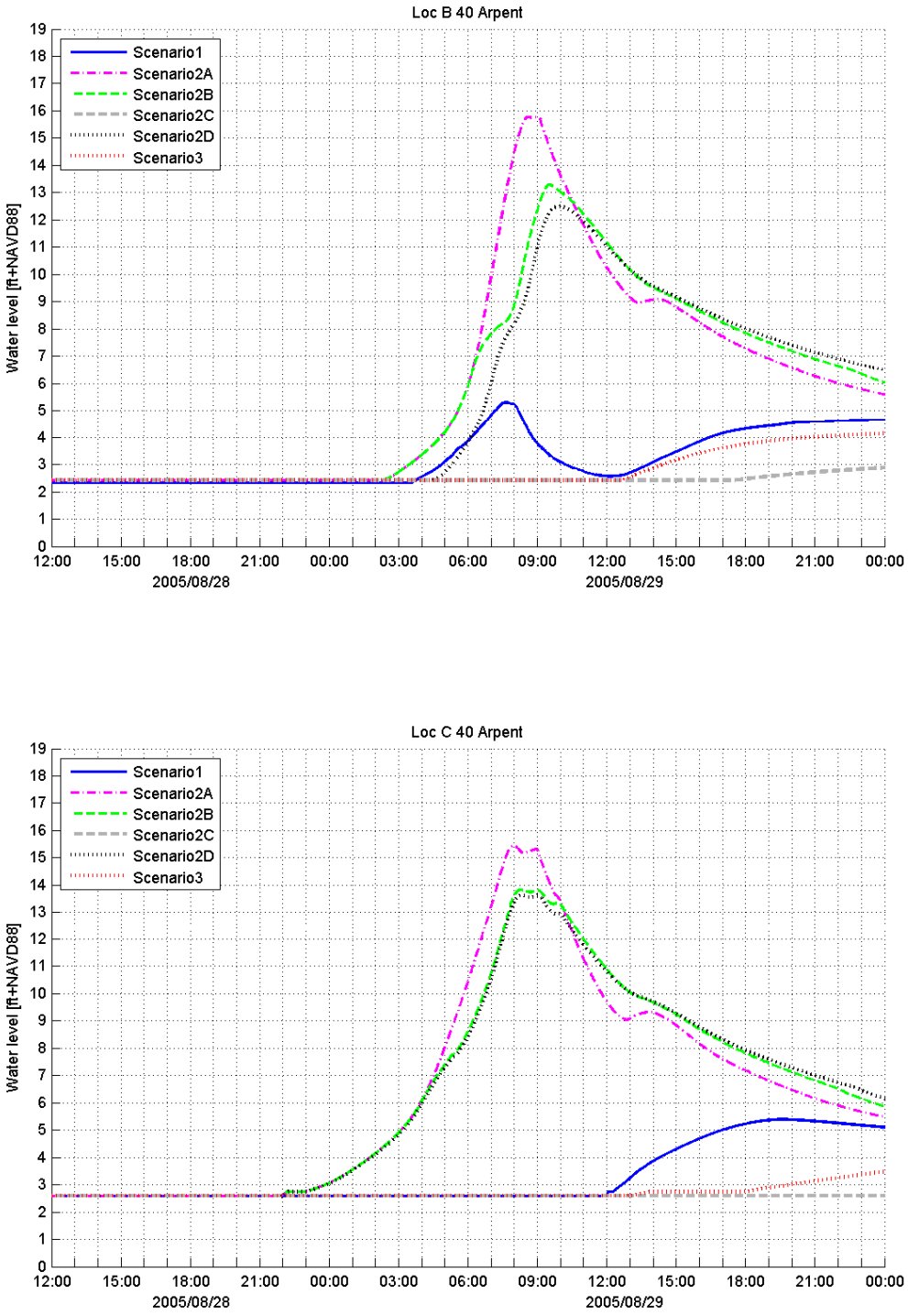


Figure 2.38h: FINEL hydrographs

2.4.2 Overtopping rates all Scenarios

At several locations the LPV levee overtopping rates were calculated. During overtopping the levees can be considered as a perfect weir over which the water flows. The perfect weir discharge can be calculated by:

$$q = C_d 2/3 E \sqrt{2/3 g E} \ .$$

With:

q = discharge per m levee ($m^3/s/m$),
C_d = discharge coefficient (-),
E = upstream energy level with reference to the levee crest (m),
g = gravity constant (9.81 m^2/s).

The upstream energy level can be considered equal to the upstream water level. The Dutch ministry of public works executed a study to determine the discharge coefficient for different levee heights/slopes and for perfect and imperfect weir flow [Ref. 8]. They found that the discharge coefficient $C_d \approx 1$ for perfect weir flow for all investigated levee slopes/heights. Therefore, we use a $C_d=1$ is to determine the overtopping rates.

Knowing the difference between the water level in FINEL and the levee crest, a time line of the overtopping rate can be calculated. The overtopping rates are calculated for the locations shown in Figure 2.39. The levee crest elevation used to determine the overtopping rates are shown in Table 2.28. The overtopping rates and total amount of levee overtopping water volume for all scenarios are shown in Figures 2.40a to 2.40g.

Orleans Metro bowl and Orleans East bowl are not included in the model grid; and therefore overtopping into those bowls does not occur in the FINEL model. Also breaches are not included in the FINEL model. So the FINEL hydrographs in the IHNC and MRGO Reach 1 will be a little higher than what actually would occur in each scenario (see also Section 2.1.3). The overtopping rates calculated with the perfect weir formula will therefore also be a little higher. The overtopping rates for the locations inside MRGO Reach 1 and IHNC must be considered as an upper limit. The surge peak on Lake Borgne is not affected by the overtopping which is not included in the FINEL model. The overtopping rates along Lake Borgne are therefore a realistic estimate (no upper limit) when no breaching occurs

For the four locations along the 40 Arpent Levee in Scenario 2B and 2D the perfect weir discharge assumption is not valid, because the area behind the levee is totally filled. The overtopping discharge for those four locations in Scenario 2B and 2D is determined from the FINEL flow velocities and water depths at the levee crest. In FINEL the elements containing the 40 Arpent Levee have a higher bottom friction value (equal to the bottom friction in the area between the 40 Arpent Levee and the Mississippi River), therefore the current velocities are relatively low and the overtopping discharge in FINEL over the 40 Arpent Levee is a conservative value.

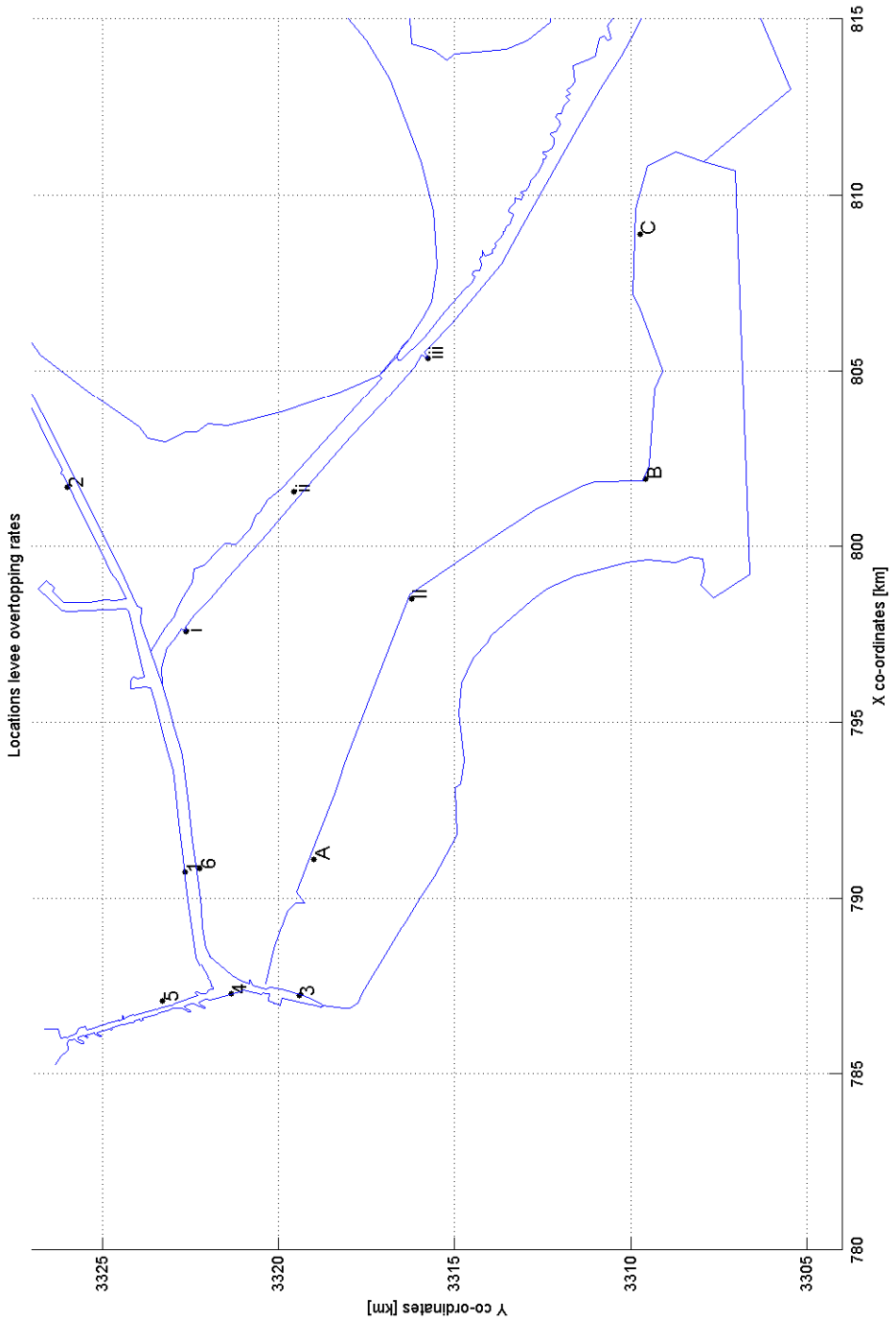


Figure 2.39: Locations where levee overtopping rates are determined

Table 2.28: Levee crest elevation for every location

		Levee crest elevation (ft+NAVD88)	
1	Citrus Back Levee	13.0	
2	New Orleans East Back Levee	16.5	
3	Lower Ninth Ward Floodwall	12.5	
4	IHNC West Floodwall	11.5	
5	IHNC East Floodwall	11.6	
6	Chalmette West of Paris Road	11.6	
I	Bayou Bienvenue	15.5	
Ii	MRGO halfway between the two Bayous	17.0	
iii	Bayou Dupre	14.5	
II	Loc II 40 Arpent	17.5 (Sc 2A)	6.5 (Sc 2B, 2C, 2D)
A	Loc A 40 Arpent	17.5 (Sc 2A)	6.5 (Sc 2B, 2C, 2D)
B	Loc B 40 Arpent	17.5 (Sc 2A)	6.5 (Sc 2B, 2C, 2D)
C	Loc C 40 Arpent	17.5 (Sc 2A)	6.5 (Sc 2B, 2C, 2D)

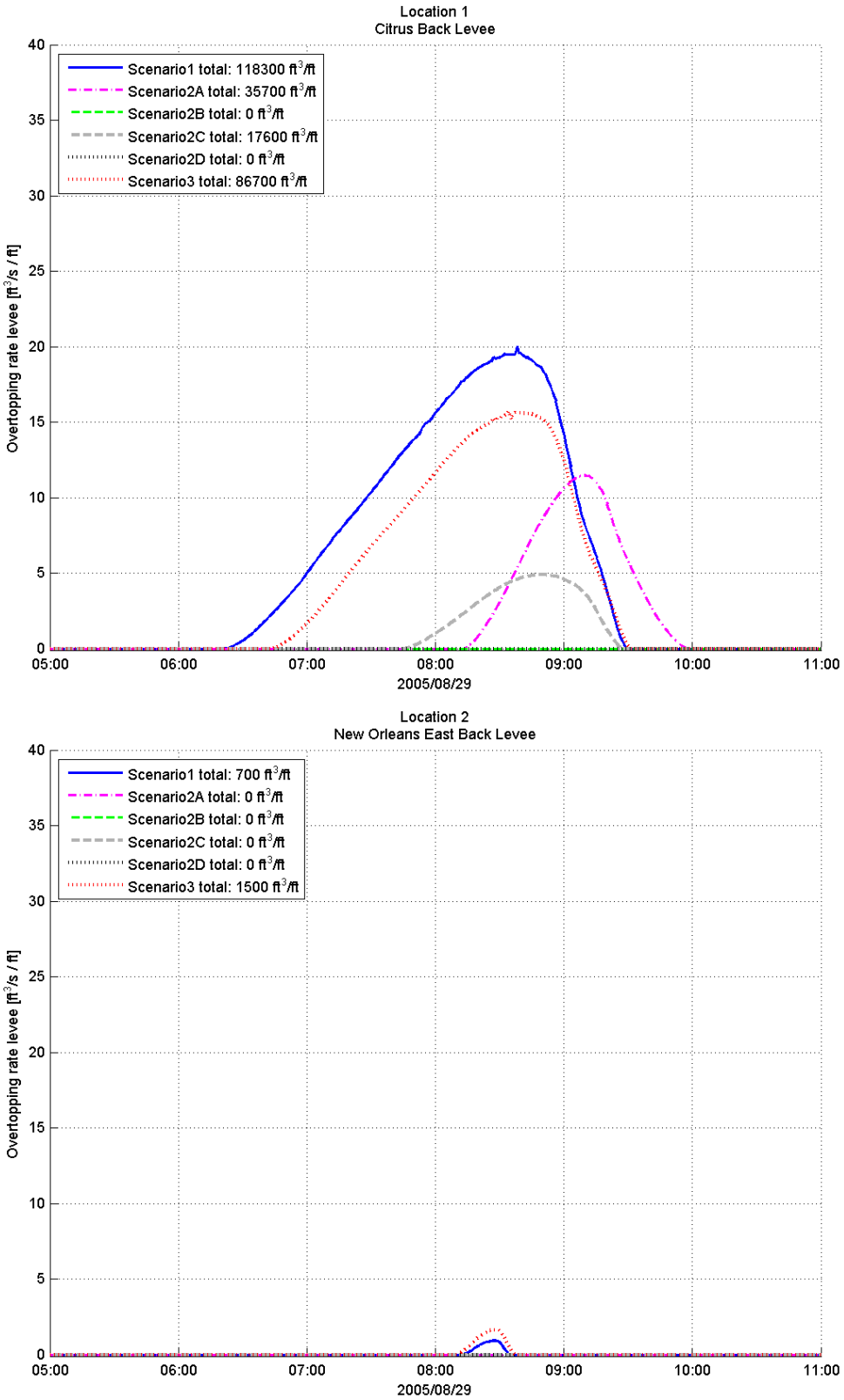


Figure 2.40a: Levee overtopping rates Scenario 1, 2A, 2B, 2C, 2D and 3. Note Orleans Metro bowl and Orleans East bowl are not included in the model grid, therefore overtopping into those bowls does not occur in the FINEL model and the surge peak inside the IHNC and MRGO Reach 1 in FINEL is a little higher than what would actually occur. The overtopping rates for Citrus Back Levee (inside MRGO Reach 1) are therefore an upper limit. The surge peak on Lake Borgne is not affected by the minor overtopping into Orleans East bowl; the overtopping rates at New Orleans East Back Levee are a realistic estimate.

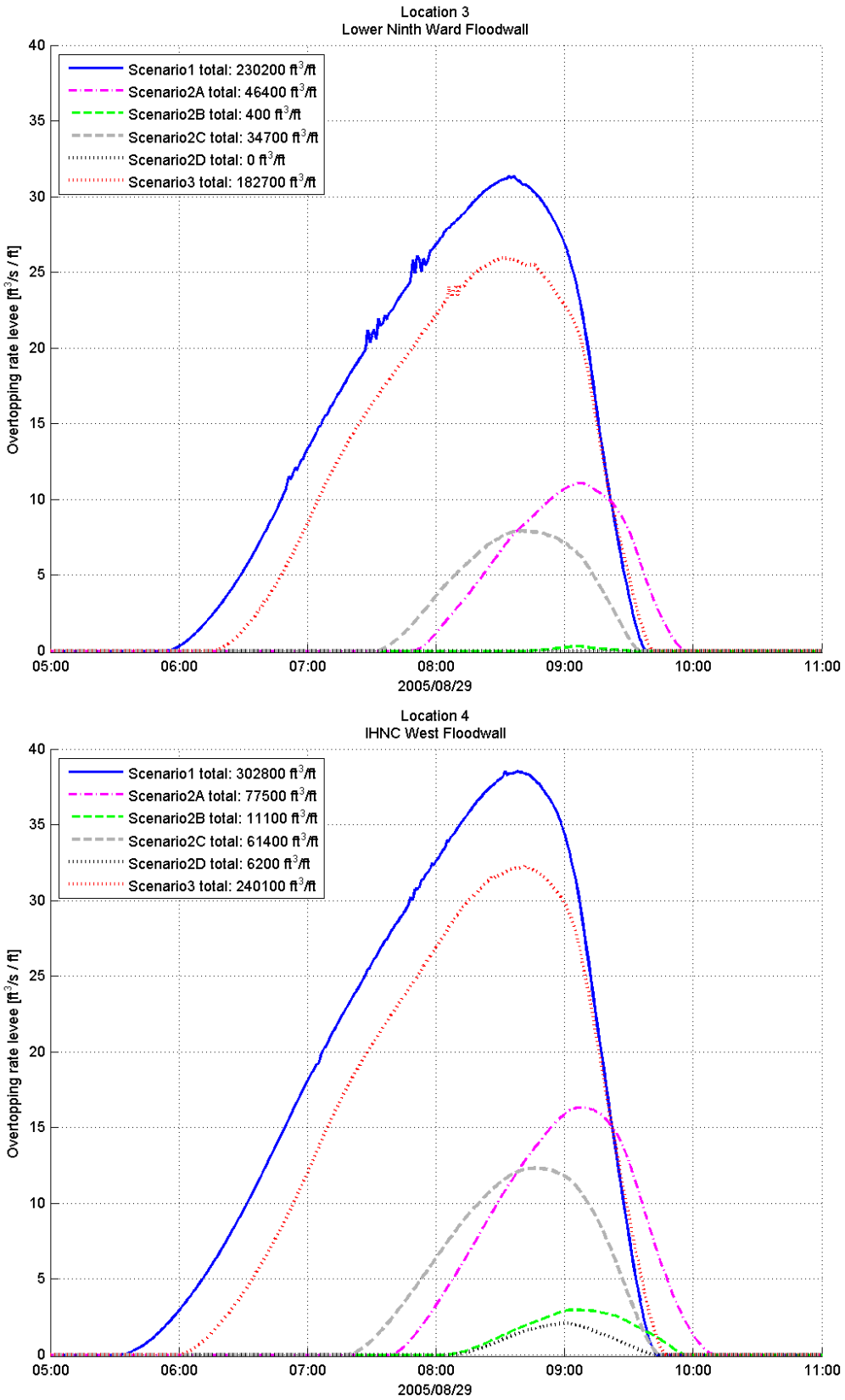


Figure 2.40b: Levee overtopping rates Scenario 1, 2A, 2B, 2C, 2D and 3. Note Orleans Metro bowl and Orleans East bowl are not included in the model grid, therefore overtopping into those bowls does not occur in the FINEL model and the surge peak inside the IHNC and MRGO Reach 1 in FINEL is a little higher than what would actually occur. The overtopping rates for Lower Ninth Ward Floodwall and IHNC West Floodwall (inside IHNC) are therefore an upper limit.

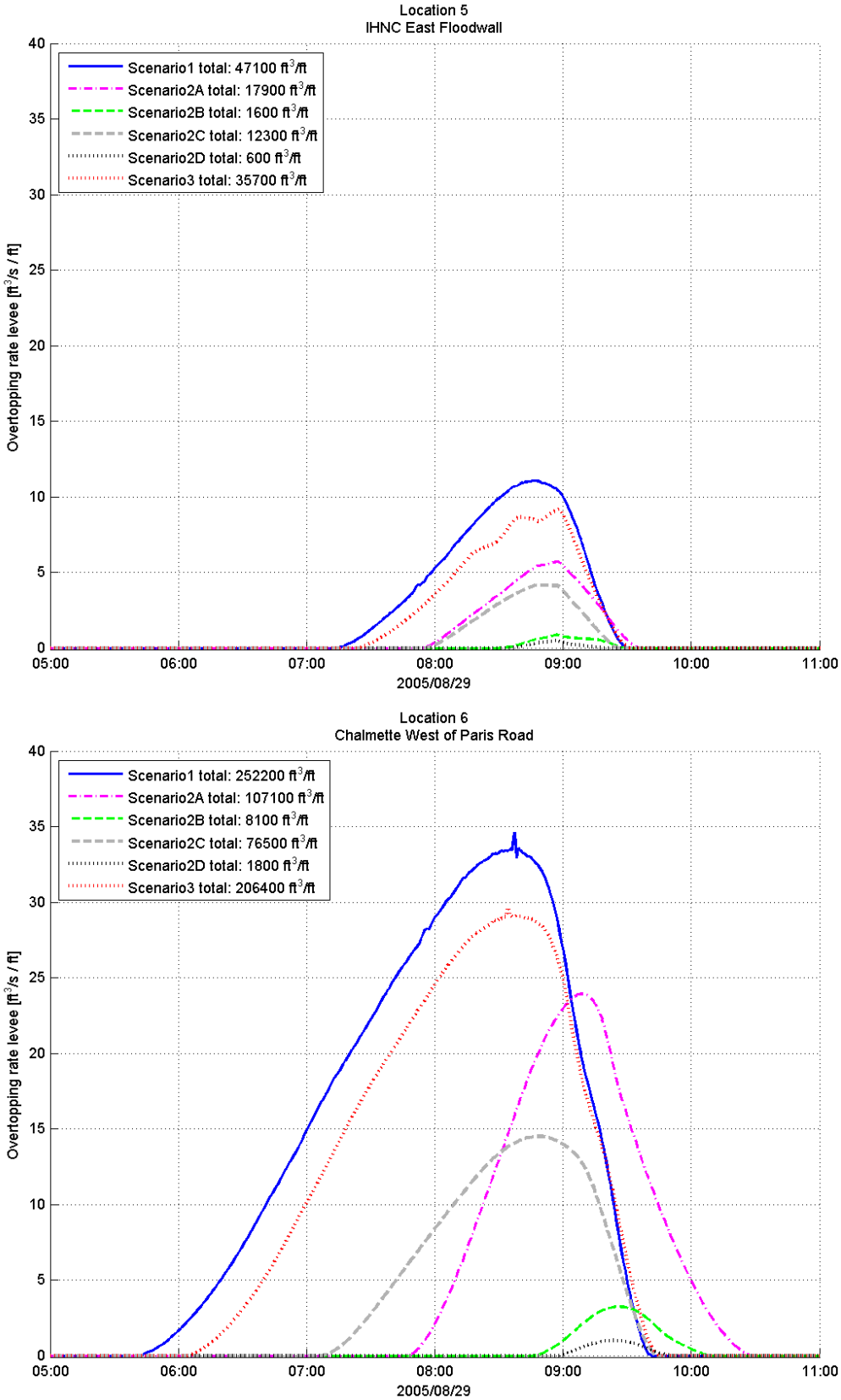


Figure 2.40c: Levee overtopping rates Scenario 1, 2A, 2B, 2C, 2D and 3. Note Orleans Metro bowl and Orleans East bowl are not included in the model grid, therefore overtopping into those bowls does not occur in the FINEL model and the surge peak inside the IHNC and MRGO Reach 1 in FINEL is a little higher than what would actually occur. The overtopping rates for IHNC East Floodwall (inside IHNC) and Chalmette West of Paris Road (inside MRGO Reach 1) are therefore an upper limit.

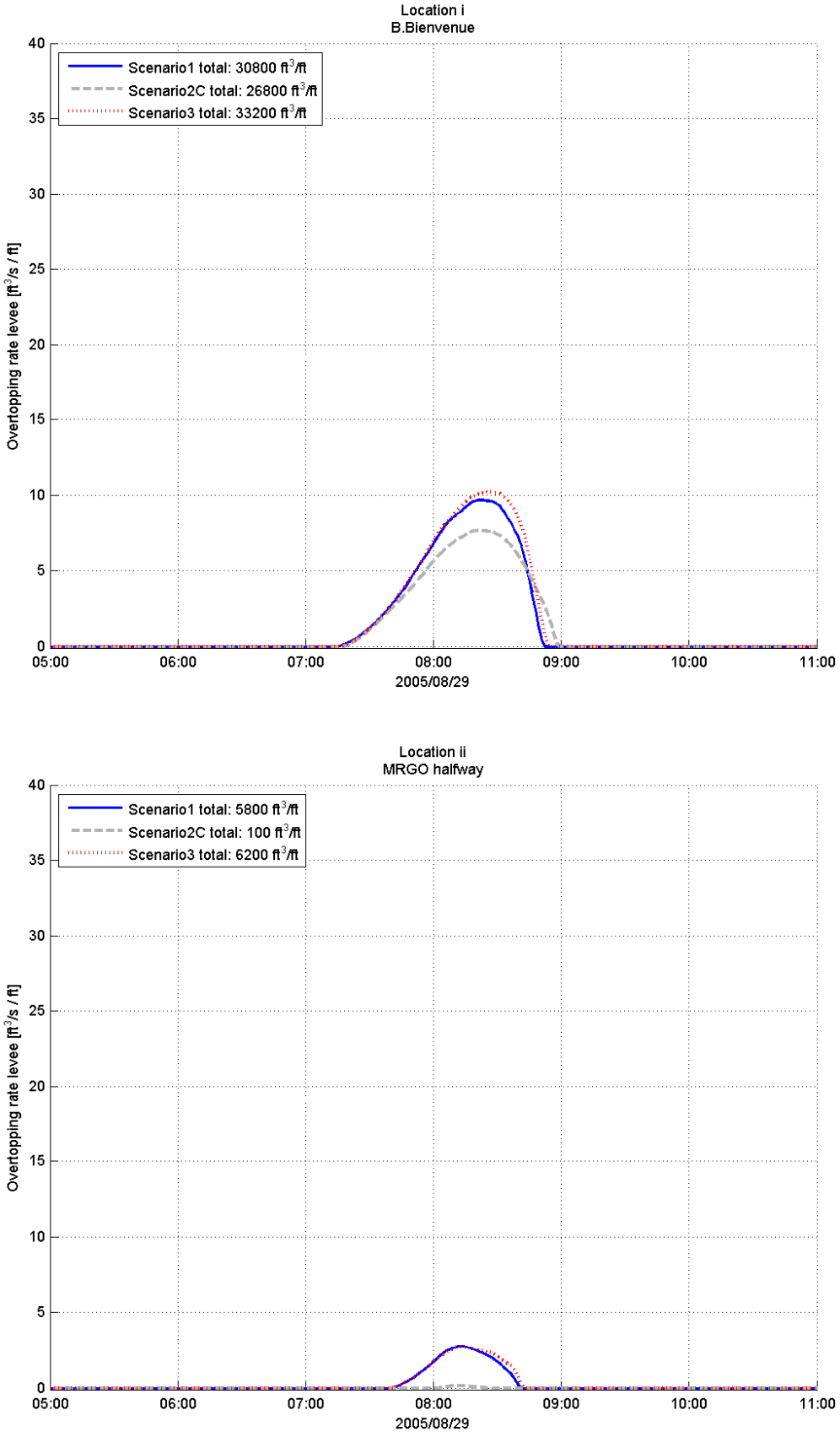


Figure 2.40d: Levee overtopping rates MRGO Reach 2 Scenario 1, 2C and 3

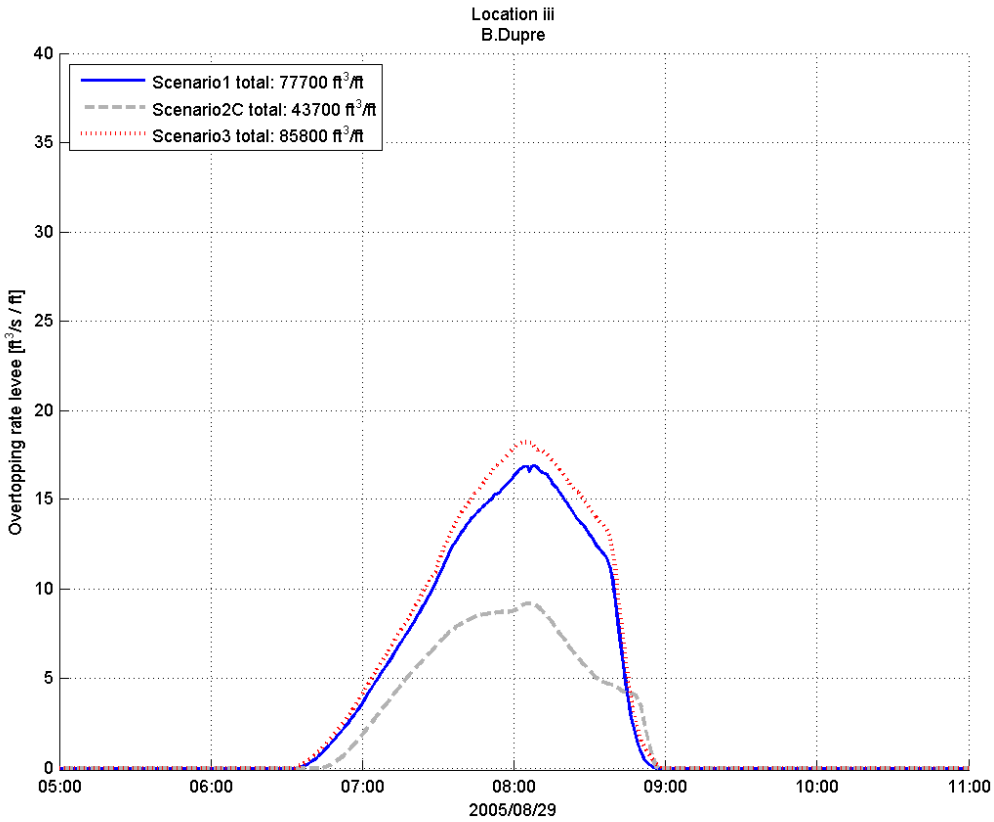


Figure 2.40e: Levee overtopping rates MRGO Reach 2 Scenario 1, 2C and 3

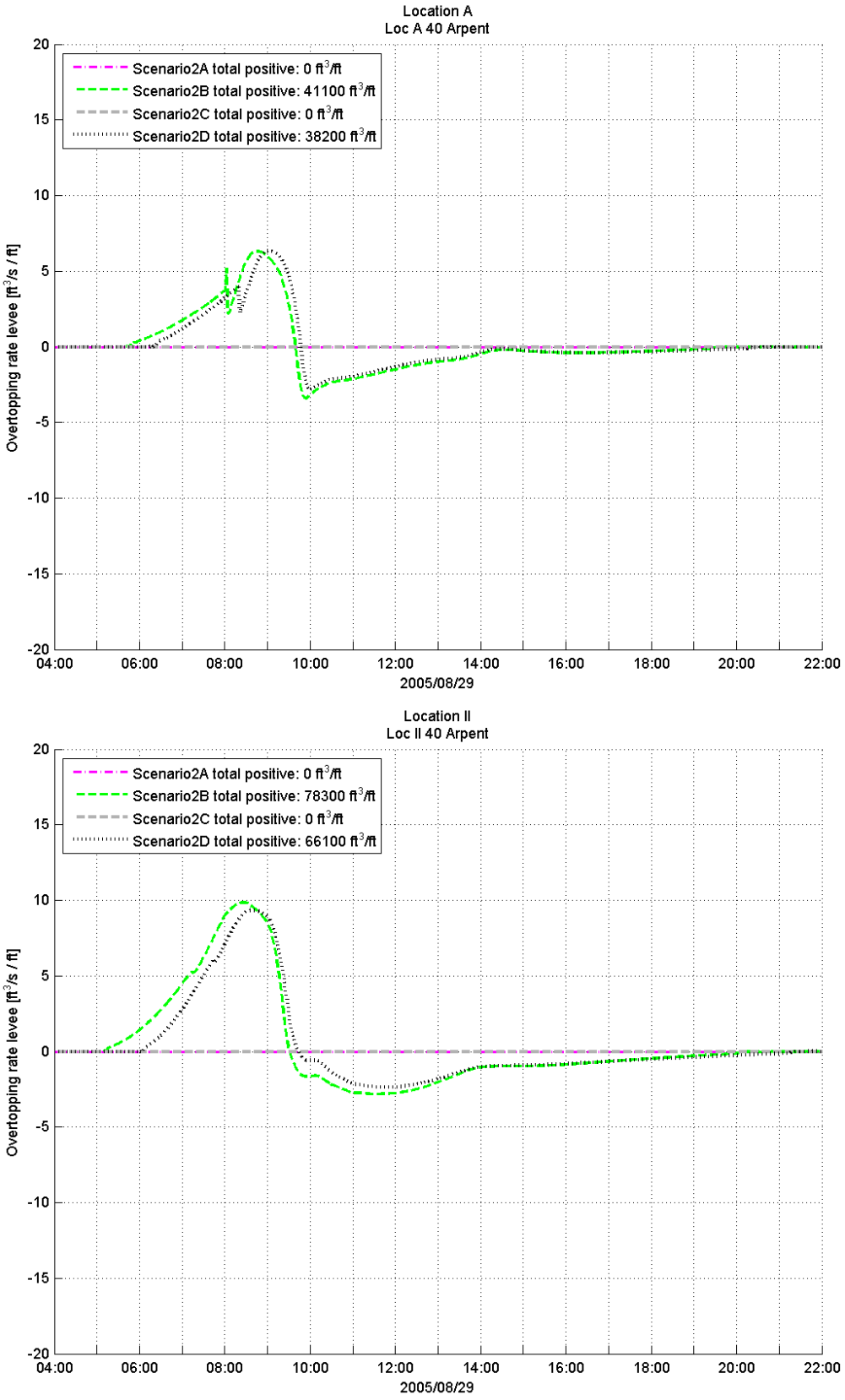


Figure 2.40f: Levee overtopping rates Scenario 2A, 2B, 2C, 2D of the 40 Arpent Levee. Note the overtopping discharges of Scenario 2B and 2D are conservative low values, due to the high bottom friction on the 40 Arpent Levee. Both inflow and outflow occurs. Scenario 2A and 2C show no overtopping of the 40 Arpent Levee.

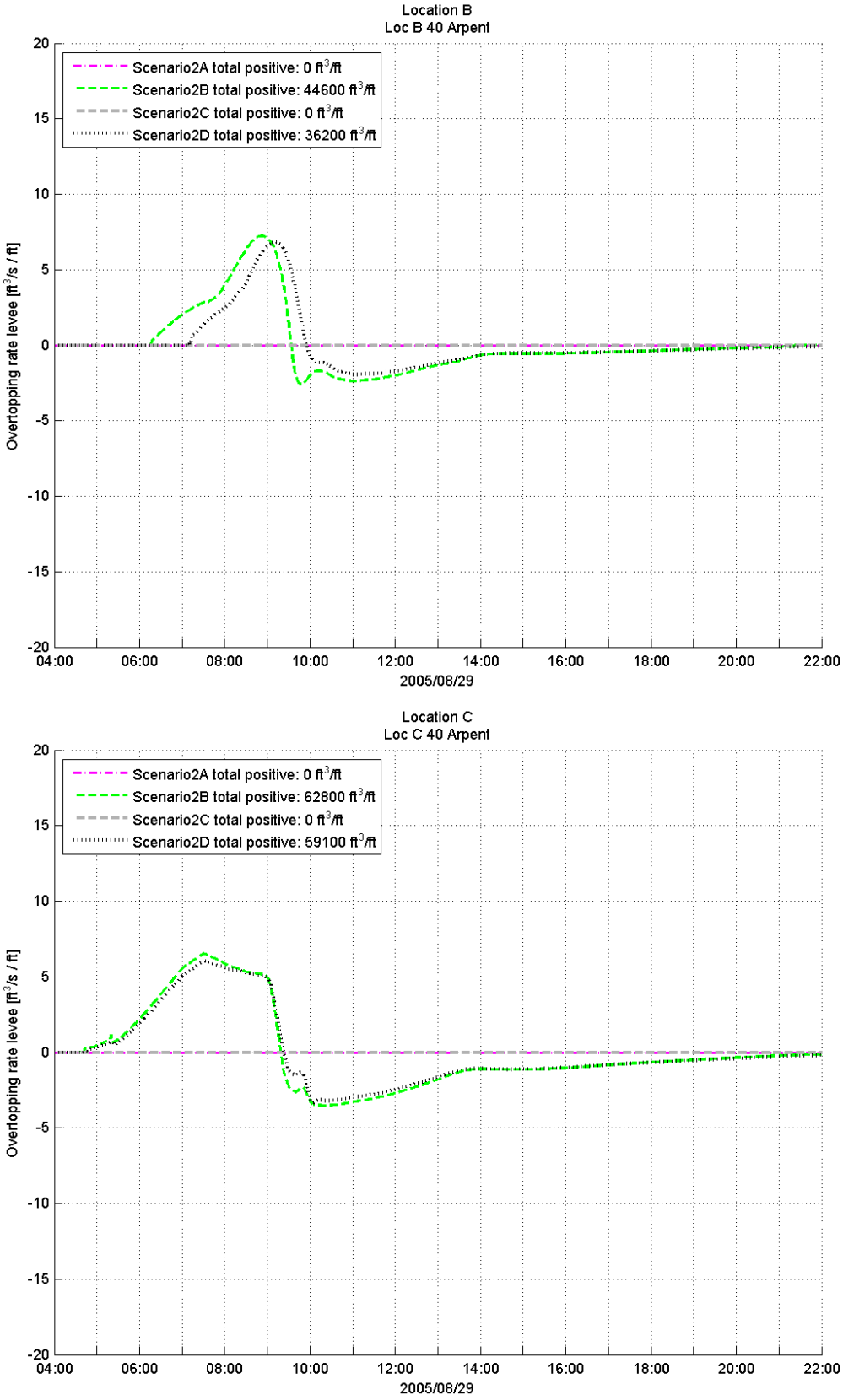


Figure 2.40g: Levee overtopping rates Scenario 2A, 2B, 2C, 2D of the 40 Arpent Levee. Note the overtopping discharges of Scenario 2B and 2D are conservative low values, due to the high bottom friction on the 40 Arpent Levee. Both inflow and outflow occurs. Scenario 2A and 2C show no overtopping of the 40 Arpent Levee.

2.4.3 Discharge at MRGO Reach 1 and 2 all Scenarios

For the MRGO Reach 1 just west of the funnel and MRGO Reach 2 just southeast of the funnel the discharges are calculated. See figure 2.41 for the locations of the cross-sections used to calculate the discharges. For Scenario 2A, 2B and 2D also the volume of water flowing over the wetlands is taken into account in the discharge of Reach 1. Reach 2 doesn't exist in Scenario 2A, 2B and 2D and therefore no discharge can be determined. For Scenario 2C the locations of the cross sections in Scenario 1/3 are used. Table 2.29 reflects the discharges at each time step. Table 2.30 contains the cross-sectional areas for each cross-section when the water level is 16 ft+NAVD. Note no breaches are included in the FINEL model, therefore the discharge, for example, needed for the breaches in the IHNC, is not modeled. This is true for all three scenarios; therefore a comparison between the three scenarios is possible.

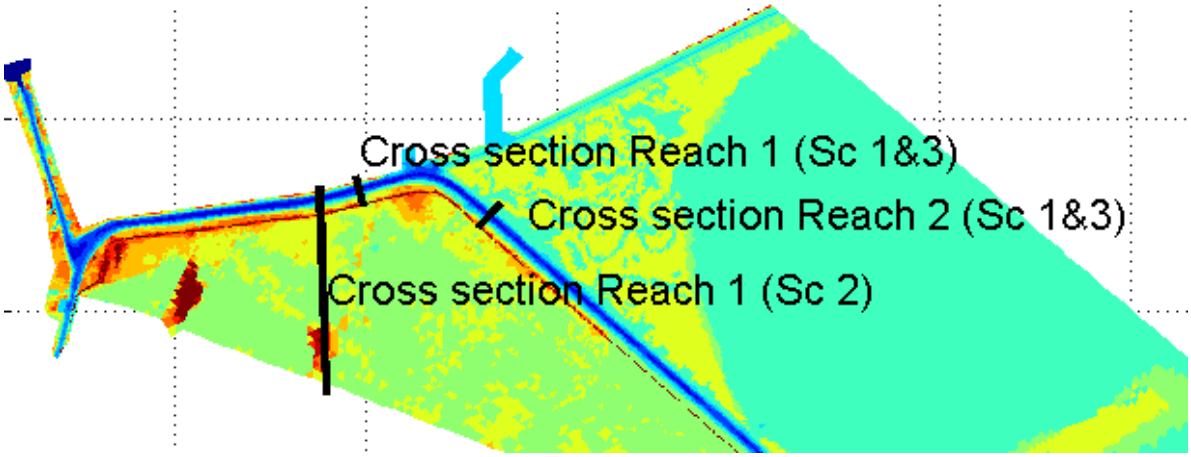


Figure 2.41: Cross-sections used to calculate discharge (black lines).

Table 2.29: Discharges (ft^3/s) MRGO for all Scenarios

		4:00 am	5:00 am	6:00 am	7:00 am	8:00 am	9:00 am
Scenario 1	MRGO Reach 1	173,000	202,000	236,000	293,000	430,000	234,000
	MRGO Reach 2	149,000	161,000	179,000	211,000	264,000	72,000
Scenario 2A	MRGO Reach 1 incl. wetlands	124,000	156,000	205,000	280,000	363,000	246,000
Scenario 2B	MRGO Reach 1 incl. wetlands	50,000	71,000	103,000	154,000	225,000	245,000
Scenario 2C	MRGO Reach 1	44,000	63,000	86,000	117,000	157,000	114,000
	MRGO Reach 2	14,000	20,000	28,000	39,000	48,000	-4,000
Scenario 2D	MRGO Reach 1 incl. wetlands	43,000	61,000	91,000	137,000	206,000	233,000
Scenario 3	MRGO Reach 1	141,000	174,000	209,000	255,000	354,000	213,000
	MRGO Reach 2	107,000	117,000	129,000	145,000	171,000	41,000

Table 2.30 Cross-sectional area with a water level of 16 ft+NAVD

		Cross-sectional area (ft^2)
Scenario 1	MRGO Reach 1	67.000
	MRGO Reach 2	75.000
Scenario 2A	MRGO Reach 1 incl. wetlands	225.000
Scenario 2B	MRGO Reach 1 incl. wetlands	221.000
Scenario 2C	MRGO Reach 1	38.000
	MRGO Reach 2	36.000
Scenario 2D	MRGO Reach 1 incl. wetlands	221.000
Scenario 3	MRGO Reach 1	55.000
	MRGO Reach 2	58.000

3 Conclusions

In this research project a flow simulation model of the area in Southeast Louisiana centered on Lake Borgne and the MRGO has been built. Breaches in levees are not taken into account, as the main focus of this study is the flow conditions and dynamics in the MRGO fronting of the Lake Pontchartrain and Vicinity (LPV) levees. A good agreement between the hydrographs from this study and the ADCIRC hydrographs has been obtained. Orleans Metro and Orleans East bowl are not included in the FINEL model grid, but overtopping into those bowls is assessed from the FINEL water levels.

FINEL is used to model three scenario runs:

1. Katrina.
   Scenario 1 is modeled to better understand the flow dynamics of the surge event during hurricane Katrina and the MRGO's impacts on the flooding.

2C. The 'virgin' no-MRGO Scenario and a simulated Katrina storm with pre-Katrina MRGO levees and 40 Arpent levee crest at 6.5 ft+NAVD.
   Scenario 2C is designed to determine the hydrodynamics of a storm such as Katrina, and its impacts, if the MRGO had not been built. The levees along the MRGO and the 40 Arpent levee are as present during Katrina.

3. The maintained MRGO Scenario and a simulated Katrina storm.
   A third scenario is modeled, one designed to determine the hydrodynamics of a storm such as Katrina, and its impacts, if the MRGO had been maintained at its authorized dimensions.

Conclusions Scenario 1:

- The wind acts at 90 degrees to MRGO at the peak of the storm.
- Just after 8:00am local time maximum surge of 18 ft NAVD is found in front of the MRGO levees. Maximum surge in MRGO Reach 1 is around 16.5 ft+NAVD88, and 17.5 ft+NAVD88 in the IHNC without floodwall or levee failures.
- Flooding of the undeveloped St Bernard Polder occurs; levee overtopping velocities are up to about 10 feet per second at the levee crest. The flooding in this study represents contribution from levee overtopping only.
- Overtopping assessed from the FINEL water levels shows extensive flooding in the Orleans Metro and Orleans East bowls.

Conclusions Scenario 2C:

- The absence of MRGO Reach 2 results in different flow patterns and surge elevations on Lake Borgne, MRGO Reach 1 and 2, and the IHNC.
- Compared with Scenario 1 the surge peak is reduced. At the MRGO Reach 2 the surge peak is reduced by 0.5 to 1.5 ft, in Reach 1 the reduction is 2 ft and in the south part of the IHNC the surge peak is reduced by 3 ft.
- Surge duration in Reach 1 and IHNC reduces by up to 2 hours.
- The small strip of Cypress forest along Lake Borgne outside the MRGO levees reduces the surge elevation by 1 foot compared with areas in Scenario 2C without Cypress forest.
- Flooding of the undeveloped St Bernard Polder is reduced compared with Scenario 1; maximum levee overtopping velocities are reduced to about 8 feet per second at the levee crest and the duration of overtopping is smaller. The flooding in this study represents contribution from levee overtopping only.
- Overtopping assessed from the FINEL water levels shows drastically reduced flooding in the Orleans Metro and Orleans East bowls, the reduction is about 80%.

Conclusions Scenario 3:

- The results for Scenario 3 (water levels and current velocities) are similar to Scenario 1.
- At the MRGO Reach 2 the surge peak is 0.2 ft higher, as in Reach 1 and in the south part of the IHNC the Katrina surge peak is reduced by 0.5 ft.
- Because of the extra bottom friction and reduced wind velocities inside the Cypress forests, the current velocities inside those forests are reduced in Scenario 3. This only impacts the water level surface on the wetlands between the MRGO levees and the 40 Arpent Levee.

- Flooding of the undeveloped St Bernard Polder occurs, similar to Scenario 1. The levee overtopping velocities are up to about 10 feet per second at the levee crest. The flooding in this study represents contribution from levee overtopping only.
- Overtopping assessed from the FINEL water levels shows a maximal reduction of 21-27% of flooding in the Orleans Metro and Orleans East bowls.

Should pertinent new data become available in the near future we would recommend updating the FINEL model outputs. However, we are very confident of the data used in this report.

4 References

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4 Flood simulation New Orleans, Katrina event August 2005, M. Kok, M. Aalberts, B. Maaskant and L. de Wit, July 2007

5 Open-channel hydraulics, Ven Te Chow, international student edition, 1959

6 IPET Volume IV, 2006, 2007: The Storm - Technical Appendices by US Army Corps of Engineers Appendix 5 Storm Surge

7 Wave Modeling New Orleans – Mississippi River Gulf Outlet, Hurricane Katrina August 2005, C.Gautier, M. Kok, and J.K. Vrijling
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8 Overview and synthesis of available data on weir flow experiments, Dutch ministry of public works, wrr memo 2007-003, J. Sieben MsC PhD, 2 March 2007. Note: in Dutch (Overzicht en synthese beschikbare data overlaatproeven, Rijkswaterstaat RIZA, wrr memo 2007-003, Dr ir J. Sieben, 2 maart 2007)

Appendix A: Additional Scenarios

A.1 Scenario 2A: The 'virgin' no-MRGO Scenario and a simulated Katrina storm without MRGO levees with 40 Arpent levee crest at 17.5 ft+NAVD

A.1.1 Description of Scenario

Scenario 2A is similar to Scenario 2D with the following differences: no MRGO levees and the model grid of Scenario 1 is used (without the area between the 40 Arpent Levee and the Mississippi) because the 40 Arpent Levee has a crest elevation of 17.5 ft and no overflowing occurs.

Through the discovery process US Army Corps of Engineers officials have stated that if the Lake Pontchartrain and Vicinity (LPV) hurricane protection levees had not been built alongside the MRGO channel, then the 40 Arpent levees would have been the location of the LPV levees. For this reason Scenario 2 A is run assuming the LPV along the 40 Arpent levees at an elevation of 17.5 ft. For this, we have envisioned a situation similar to the late 1950s. Accordingly, we simulate surge along the shores of Lake Borgne in a model in which we change the Scenario 1 grid in the following ways:

(1) 90% reduction in cross-section area of MRGO Reach 1 to the dimensions of the GIWW (pre-MRGO);
(2) MRGO Reach 2 is removed and replaced with land at the elevation of the surrounding marsh and swamp areas;
(3) The spoil disposal area and LPV EBSB is degraded to natural swamp or marsh elevation depending on the 1955 habitat map;
(4) Bayou LaLoutre ridge is restored filling the hole dredged for MRGO Reach 2;
(5) LPV EBSB is rebuilt on alignment of 40 Arpent/Florida Avenue levee with a crest elevation of 17.5 ft (NAVD88);
(6) The Cypress trees originally present between the MRGO and the 40 Arpent levees have influence on the water current velocities and the wind velocities. A higher Manning's roughness is used for the Cypress forests reflecting their greater frictional impacts on surge currents, and the wind velocities are reduced by 80% inside the Cypress forests due to the wind break/canopy effect of tall forests

A.1.2 FINEL model input data

The FINEL model is set up to utilize the metric system, so all data is thus subsequently converted to feet. The coordinate system used in the simulations is UTM (zone 15 R). Input data that was received in longitude and latitude was translated accordingly.

Model grid
The model grid used for Scenario 2A is equal to the model grid used in Scenario 1, see section 2.1.2.

Bathymetry and Topography
The bathymetry for Scenario 2A is modified to represent the conditions prior to the construction of the MRGO. Reach 2 of the MRGO is filled up to the height of the surrounding marshes and swamps in the bathymetry. Reach 1 is modified to the original GIWW design dimensions of 150 ft wide and 12 ft deep, as provided by Robinson experts. The levees and spoil disposal area next to MRGO Reach 2 are degraded to the height of the surrounding marshes and swamps. The marshes and swamps around Lake Borgne are, where needed, restored to a 1950s elevation of 2.5 ft+NAVD88. A land-water map provided by Robinson experts has been used to construct the original small water streams in the marshes. The resulting depths in the model area are shown in Figure A.1.

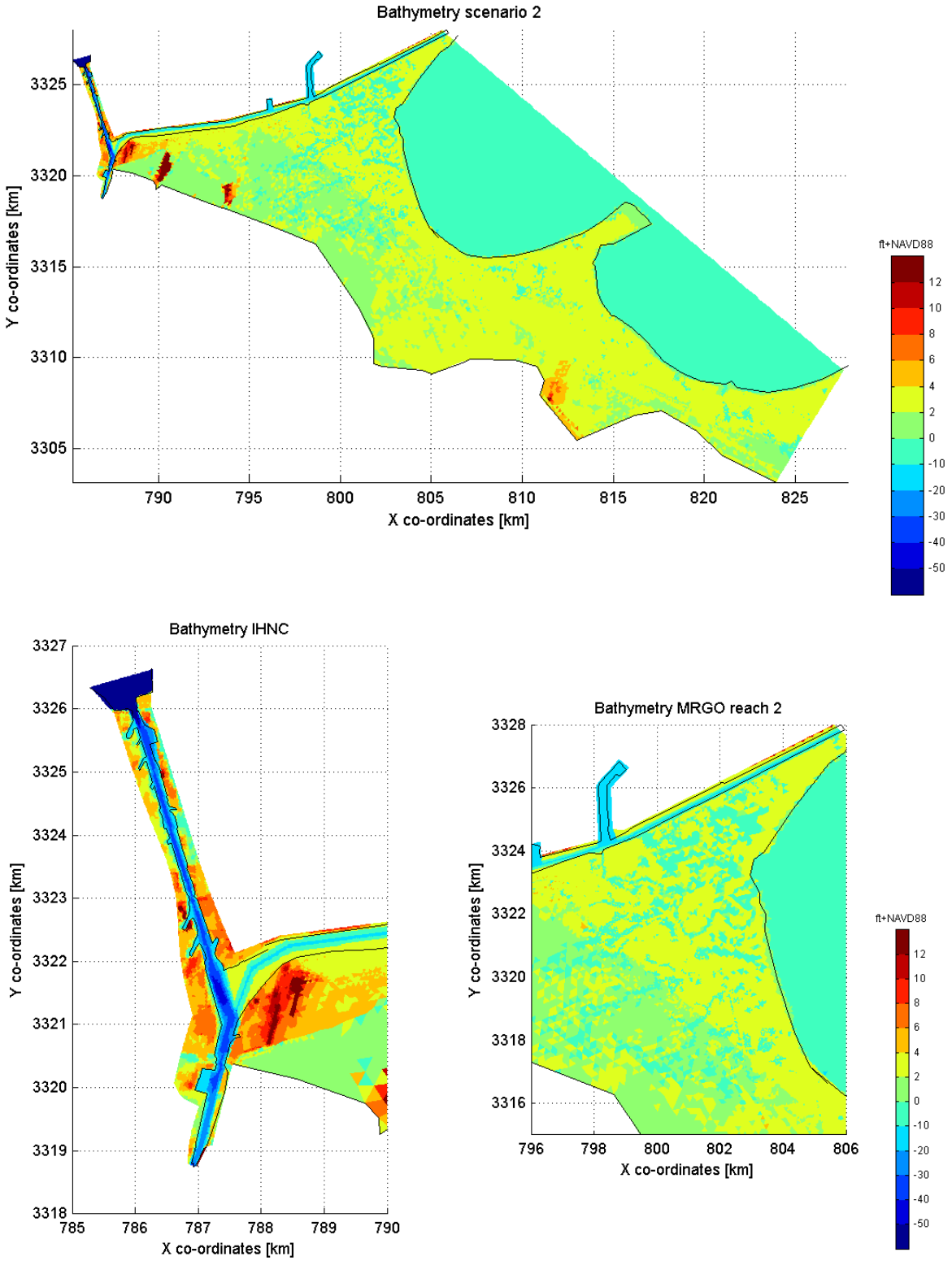


Figure A.1: Bathymetry FINEL model area Scenario 2A

Simulation period

The simulation starts at 12h00 LT 28th August 2005 and continues until 24h00 29th August 2005.

Boundary conditions
The boundary conditions consist of water level time series from the constructed Scenario 2 hydrographs, provided to us by the Robinson experts. ADCIRC outputs with and without the MRGO are used to modify Scenario 1 outputs reducing the maximum surge and delaying the peak at Shell Beach at Reach 2.

Figure A.2 shows the locations of the boundary conditions and Table A.1 gives the corresponding locations which are used for every boundary. The boundary time series themselves are shown in Figure A.3. All boundaries not mentioned in Table A.1 are closed boundaries.

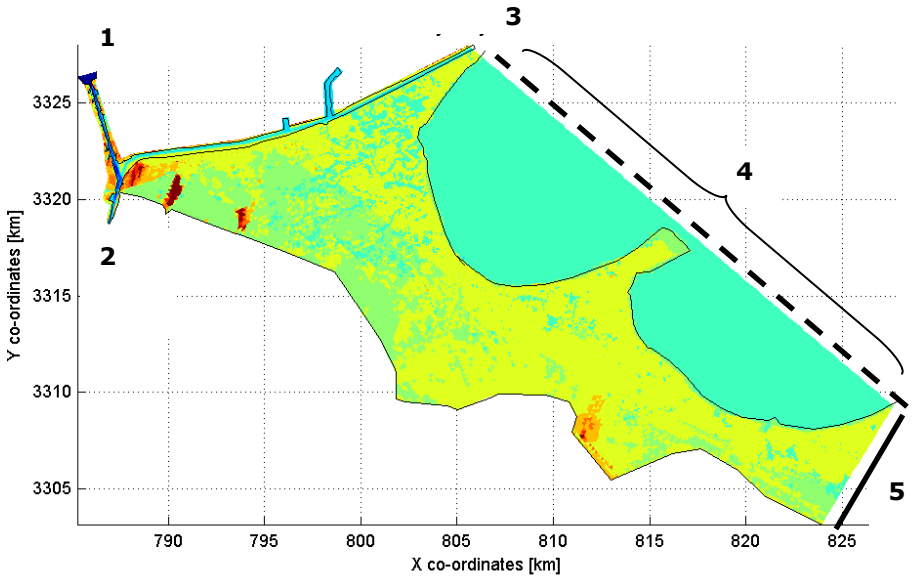


Figure A.2: Location boundary conditions FINEL flow model

Table A.1: Boundary conditions

	Boundary	*Used hydrograph in 10MinuteHydrographsforDelft_pre_post_MRGOScenario 2.xls*
1	Lake Pontchartrain	IHNC@LakeP
2	IHNC Locks	Closed boundary (discharge=0)
3	GIWW	NOEbackA
4	Lake Borgne	Interpolation between 3 and 5
5	MRGO	Shell Beach

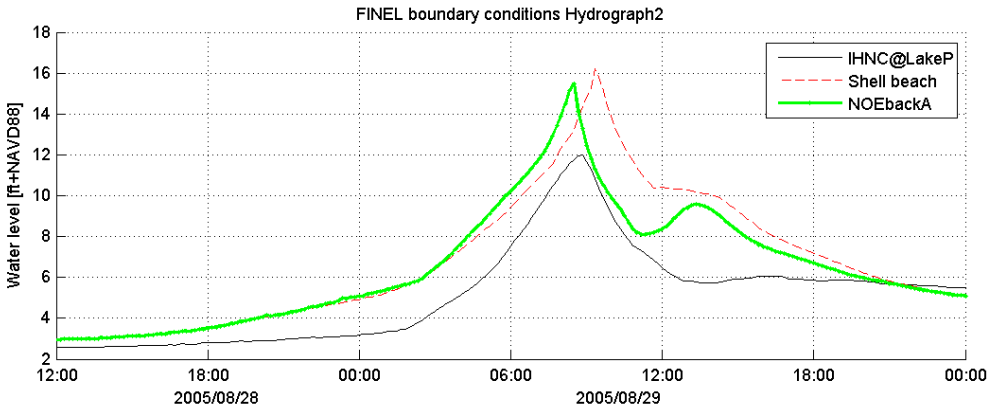


Figure A.3: Time series boundary conditions FINEL flow model Scenario 2A

Bottom roughness

In the model area a spatial variable Manning coefficient is used for the bottom roughness. The Manning roughness coefficients used are based on years of experience in modeling coastal environments. These data were collaborated with other data sets such as from the US Geological Survey (http://www.fhwa.dot.gov/bridge/wsp2339.pdf), the world renowned book Open-channel hydraulics [Ref. 5] and IPET [Ref. 6]. For each scenario the spatial extent of the Manning's used is based on the presence or lack of wetlands; shoreline location and presence; and lack or presence of levees. In 1958 Cypress forests existed between the MRGO and the 40 Arpent levees (Figure A.4). The Cypress trees cause friction on the flow, this influence is taken into account by a higher roughness coefficient. In a map provided by Robinson experts, two types of Cypress forests are distinguished: normal (Manning n=0.1 $m^{-1/3}s$) and dense (Manning n=0.12 $m^{-1/3}s$). The Manning roughness coefficients are shown in Figure A.5 and summarized in Table A.2.



Figure A.4: Photograph of cypress trees in swampy areas (send to us by Robinson experts)

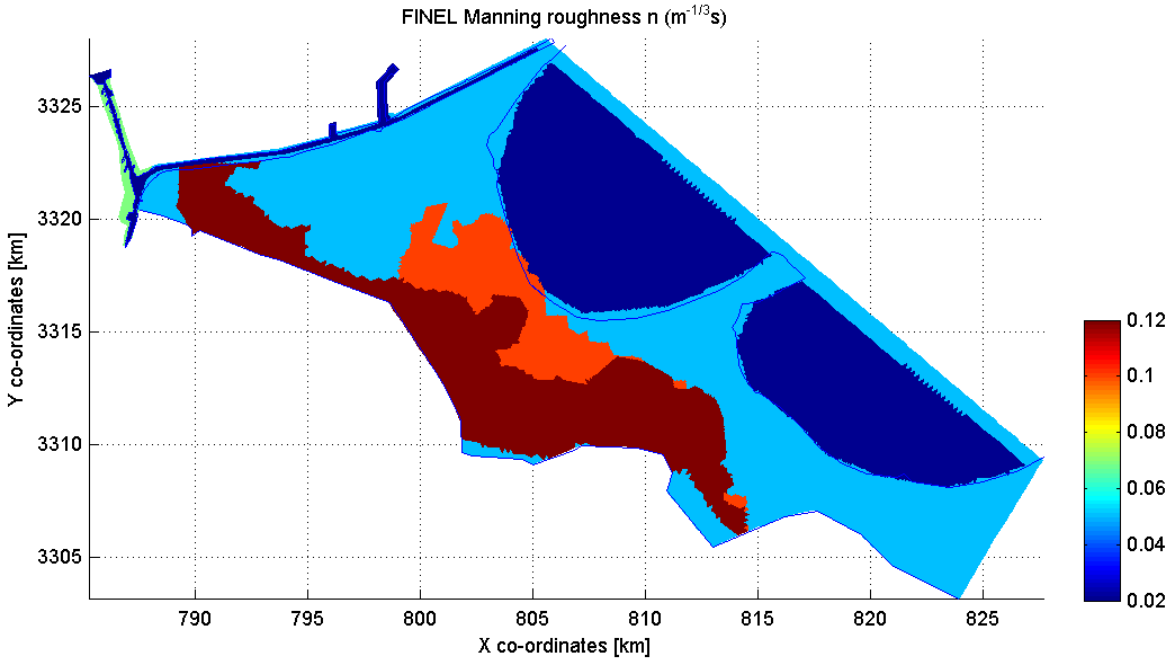


Figure A.5: Manning roughness coefficient FINEL model area Scenario 2A. The cypress areas are red (dark red = dense cypress trees, light red = normal cypress trees).

Table A.2: Manning coefficient (based on: IPET Volume IV appendix page IV-5-102 [Ref. 6])

Area	*Manning coefficient n ($m^{-1/3}s$)*
Open water	0.02
Marsh along Lake Borgne	0.05
Normal Cypress forest	0.1
Dense Cypress forest	0.12
Commercial area next to IHNC	0.07

Wind

To take into account the influence of wind on the water motion, spatial variable wind fields are used in the flow calculations with FINEL. The wind fields were provided to us by the Robinson experts spaced at 30 minute intervals. Within the cypress forest the influence of the wind on water movement is dramatically reduced by the trees. Therefore the wind velocities are reduced by 80% (percentage provided to us by Robinson experts) within the Cypress forests (both dark red and light red areas in Figure A.5). The wind speed surface stress is calculated by:

$$\frac{\tau_{wind,x}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,x} - U_x),$$

$$\frac{\tau_{wind,y}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,y} - U_y).$$

With:

C_d = wind drag coefficient (-),
W_{10} = wind speed at 10 meter height (m/s),
U = water velocity (m/s).

The wind drag is defined by Garrat's drag formula (Garrat 1977):

$C_d = (0.75 + 0.067W_{10}) \times 10^{-3}$

A.1.3 Results

The FINEL flow model is used to produce details of the water currents especially along the MRGO Reach 2. This section shows the results of Scenario 2A: The 'virgin' no-MRGO Scenario and a simulated Katrina storm with 40 Arpent Levee crest at 17.5 ft. The results are shown on 6 time steps on the day Katrina struck, 29th August 2005, namely:

1. 4:00am Local Time;
2. 5:00am Local Time;
3. 6:00am Local Time;
4. 7:00am Local Time;
5. 8:00am Local Time;
6. 9:00am Local Time.

These time steps are identical to the time steps used in Scenario 1, but note that the peak of the storm in Scenario 2A has shifted in time (in the IHNC about 30 minutes later) compared with Scenario 1.

Area plots

The water levels in the model area for these time steps are shown in Figure A.6. The current velocities are shown in Figure A.7. A close up along MRGO Reach 1 is shown in Figure A.8, and along GIWW/Lake Borgne in Figure A.9. The difference in current patterns and water elevations between Scenario 2 and Scenario 1 is obvious. In Scenario 2A there are no levees along the MRGO to build up surge or to guide the flow. The water can flow over the wetlands. There is no MRGO Reach 2 with a large discharge capacity and also Reach 1 is reduced in size and transport capacity. The Cypress forests with higher bottom friction and low wind velocities have a major impact on the water motion. The surge in the IHNC start to build up later and less (peak surge IHNC@Junction is around 9:00 am), therefore a flow towards Lake Pontchartrain start to develop much later than in Scenario 1 and it remains much calmer.

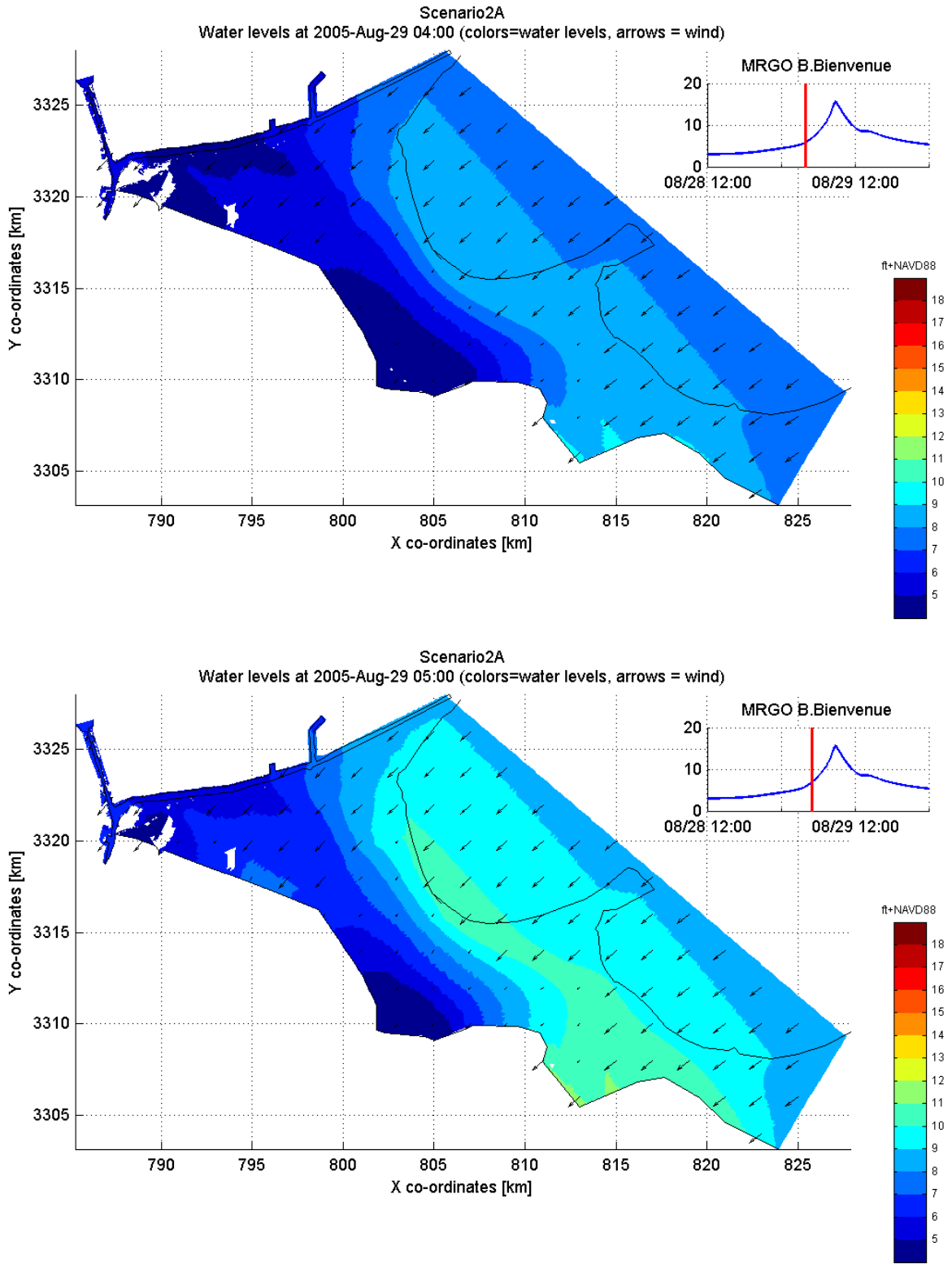


Figure A.6a: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 2A at 4:00am, 5:00am local time. Note surge reduction due to cypress swamp up to 6 feet.

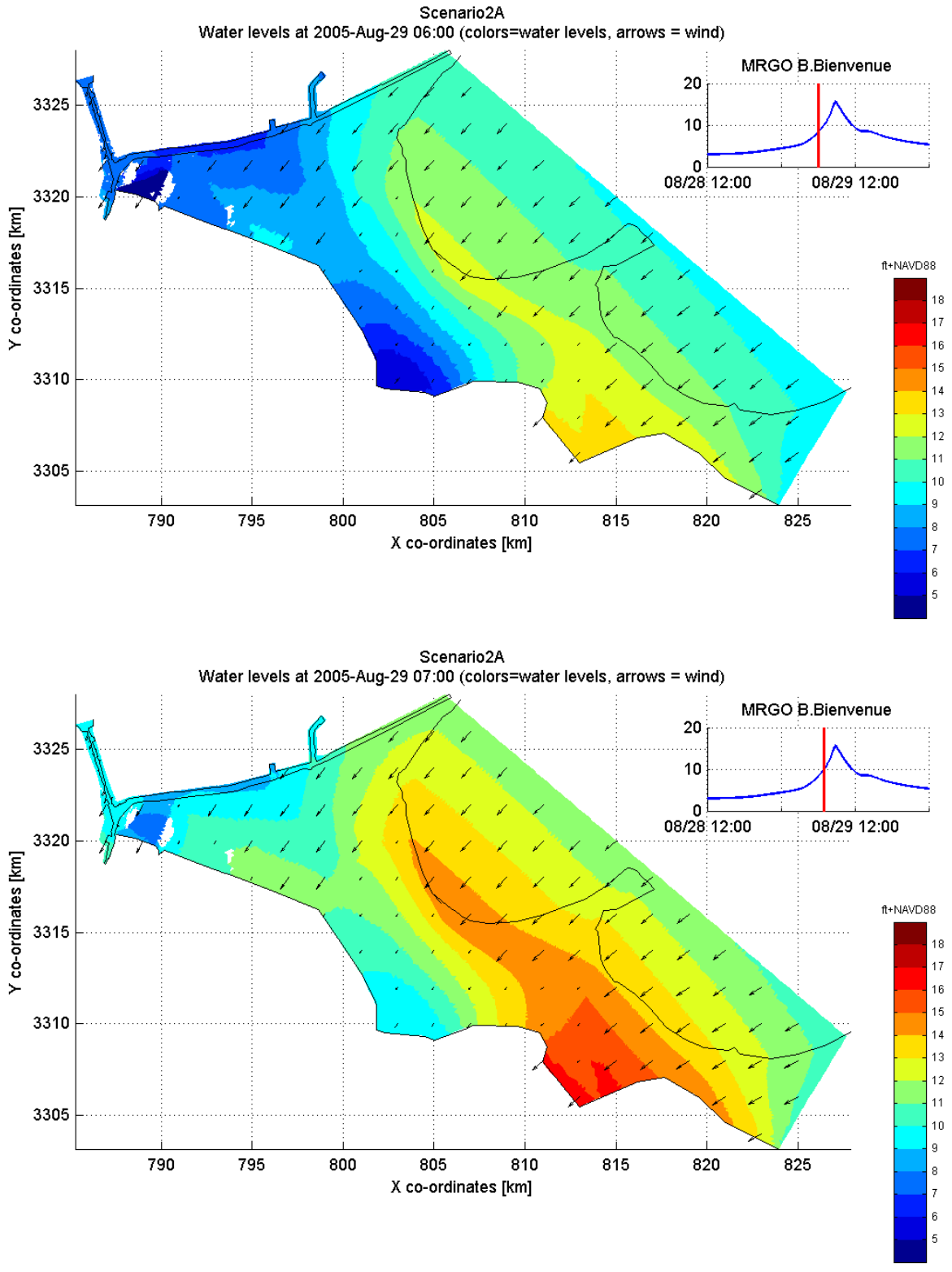


Figure A.6b: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 2A at 6:00am, 7:00am local time. Note surge reduction due to cypress swamp by up to 5 feet.

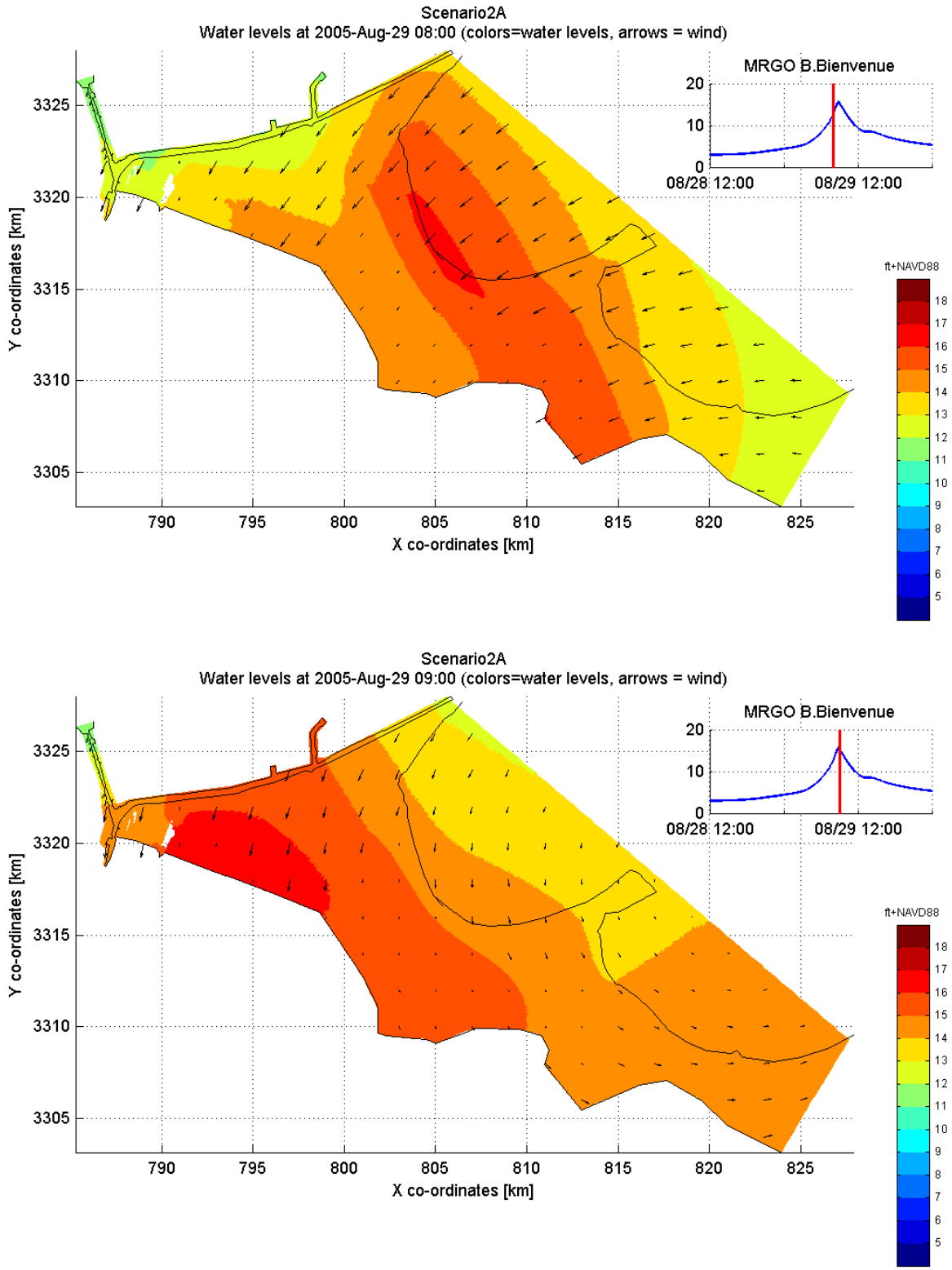


Figure A.6c: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 2A at 8:00am, 9:00am local time.

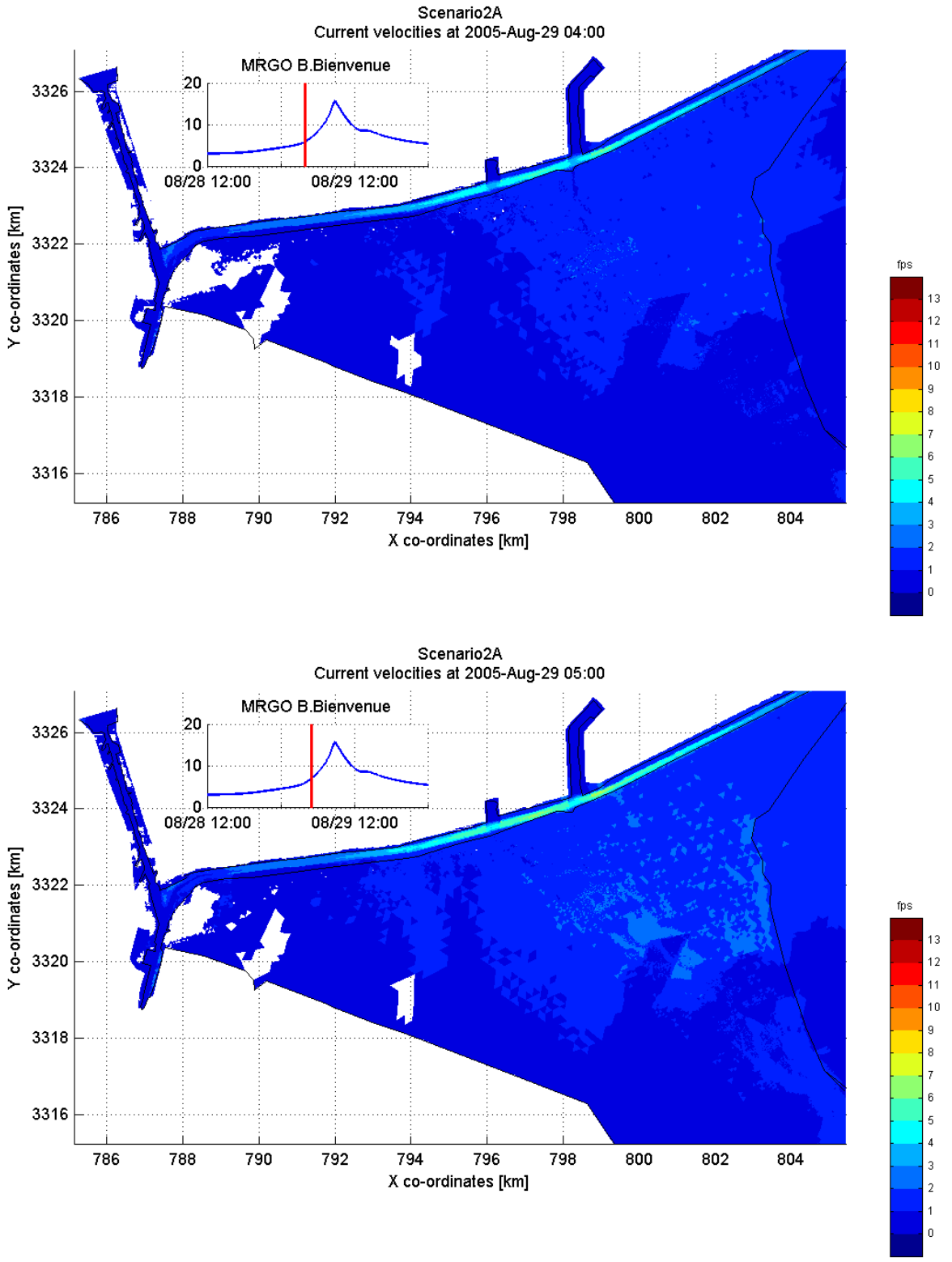


Figure A.7a: Spatial current velocities for Scenario 2A at 4:00am, 5:00am local time. Note low current velocities except in the GIWW, where the surge is making use of the channel opportunity to enhance discharge.

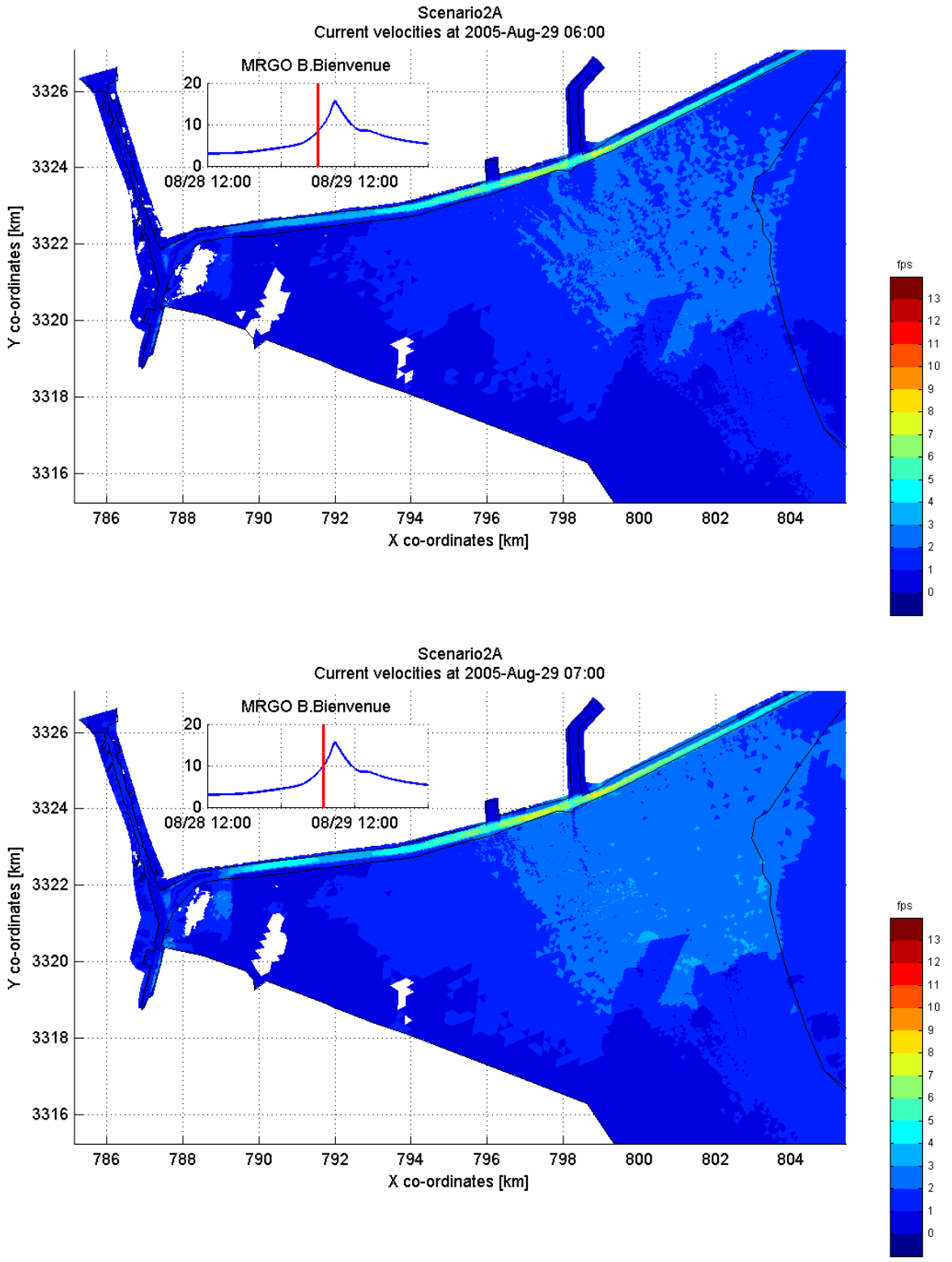


Figure A.7b: Spatial current velocities for Scenario 2A at 6:00am, 7:00am local time. Note the low current velocities except in the GIWW where velocities up to 9 feet per second are found and where the surge is making use of the channel opportunity to enhance discharge.

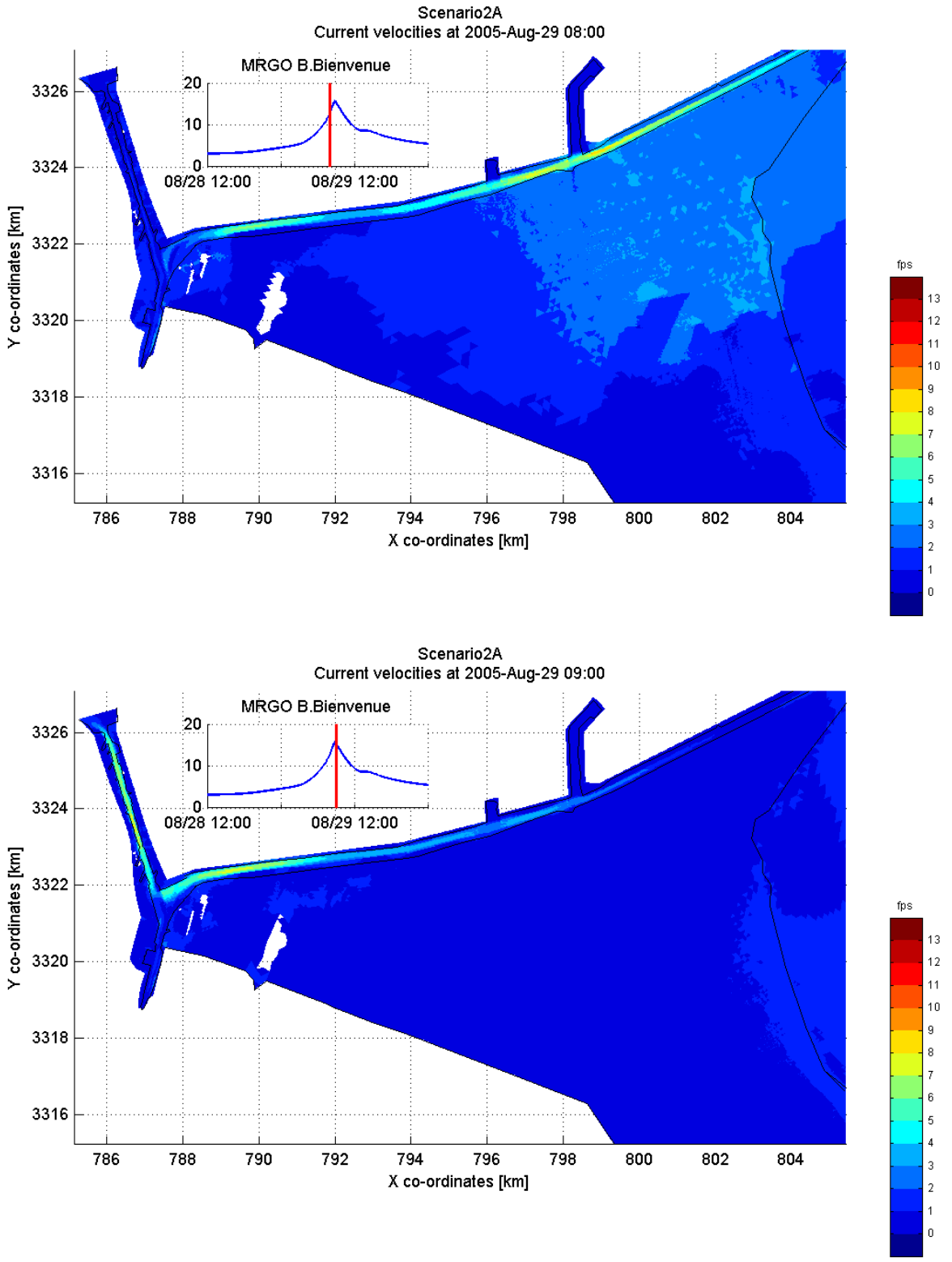


Figure A.7c: Spatial current velocities for Scenario 2A at 8:00am, 9:00am local time. Note the rise of the current velocities in the IHNC; much later than in Scenario 1. The surge is making use of the GIWW channel to enhance discharge.

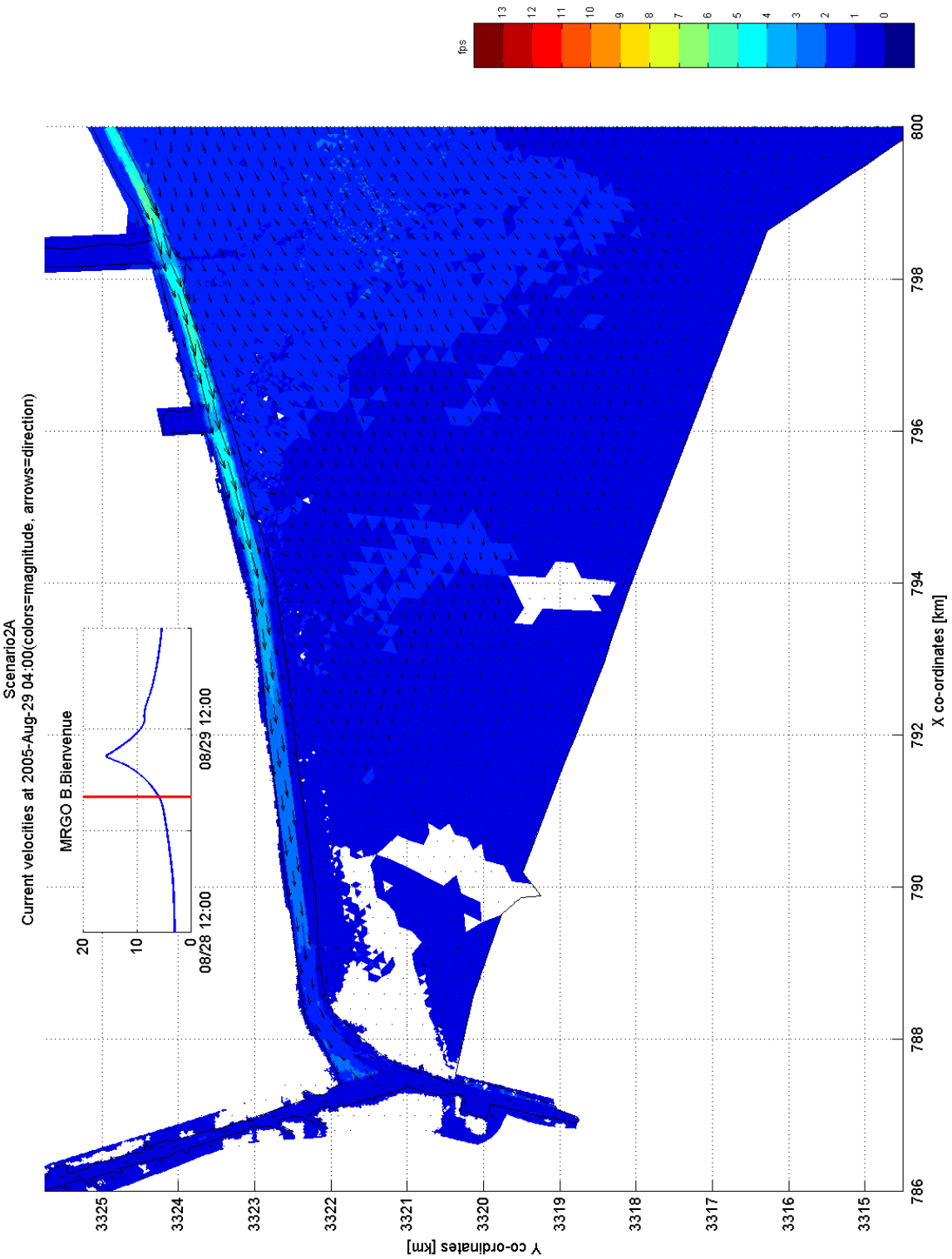


Figure A.8a: Spatial current velocities (magnitude with color scale, direction with arrows) close up at MRGO Reach 1 for Scenario 2A at 4:00am local time. Note not much flow in the MRGO Reach 1.

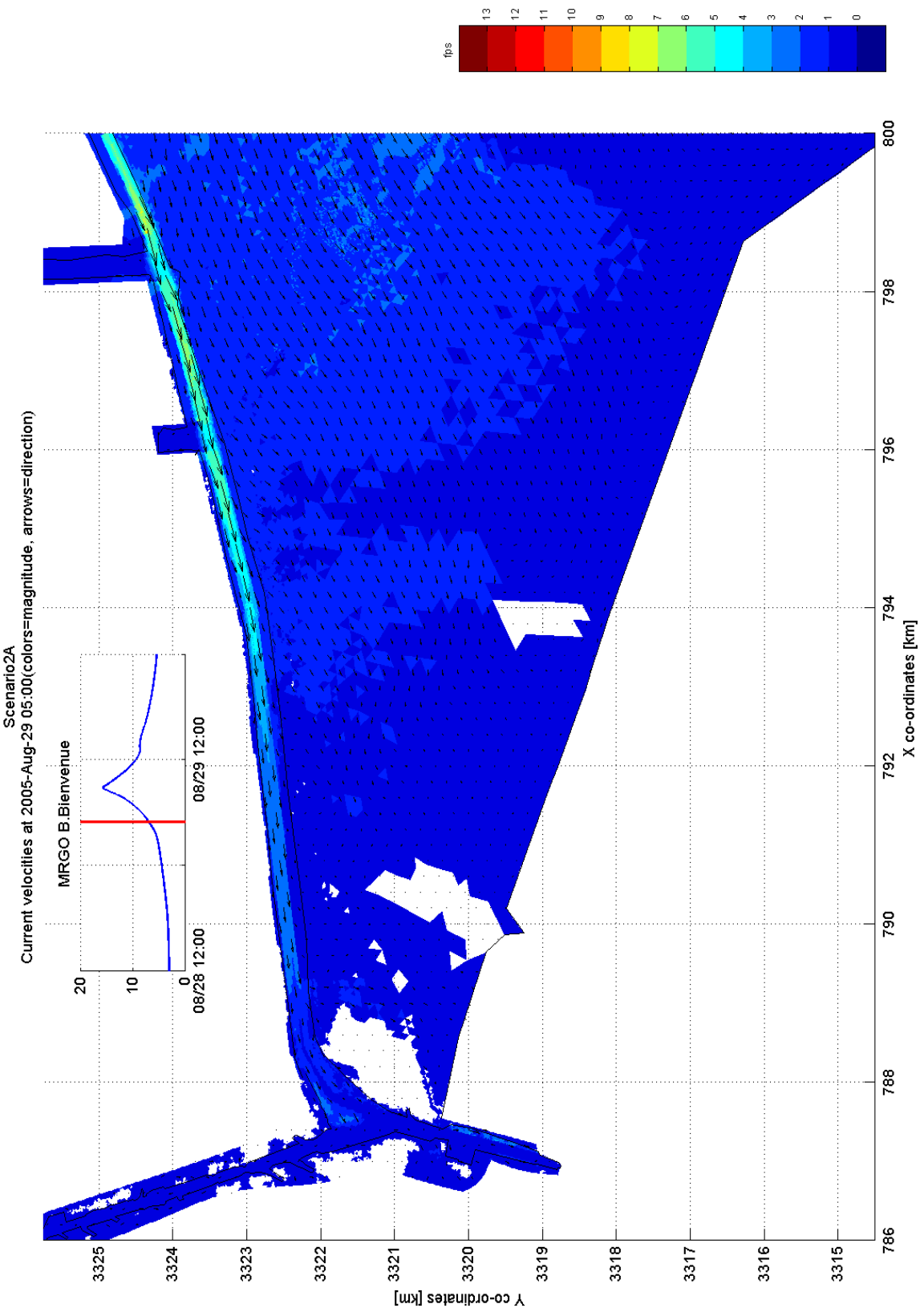


Figure A.8b: Spatial current velocities (magnitude with color scale, direction with arrows) close up at MRGO Reach 1 for Scenario 2A at 5:00am local time.

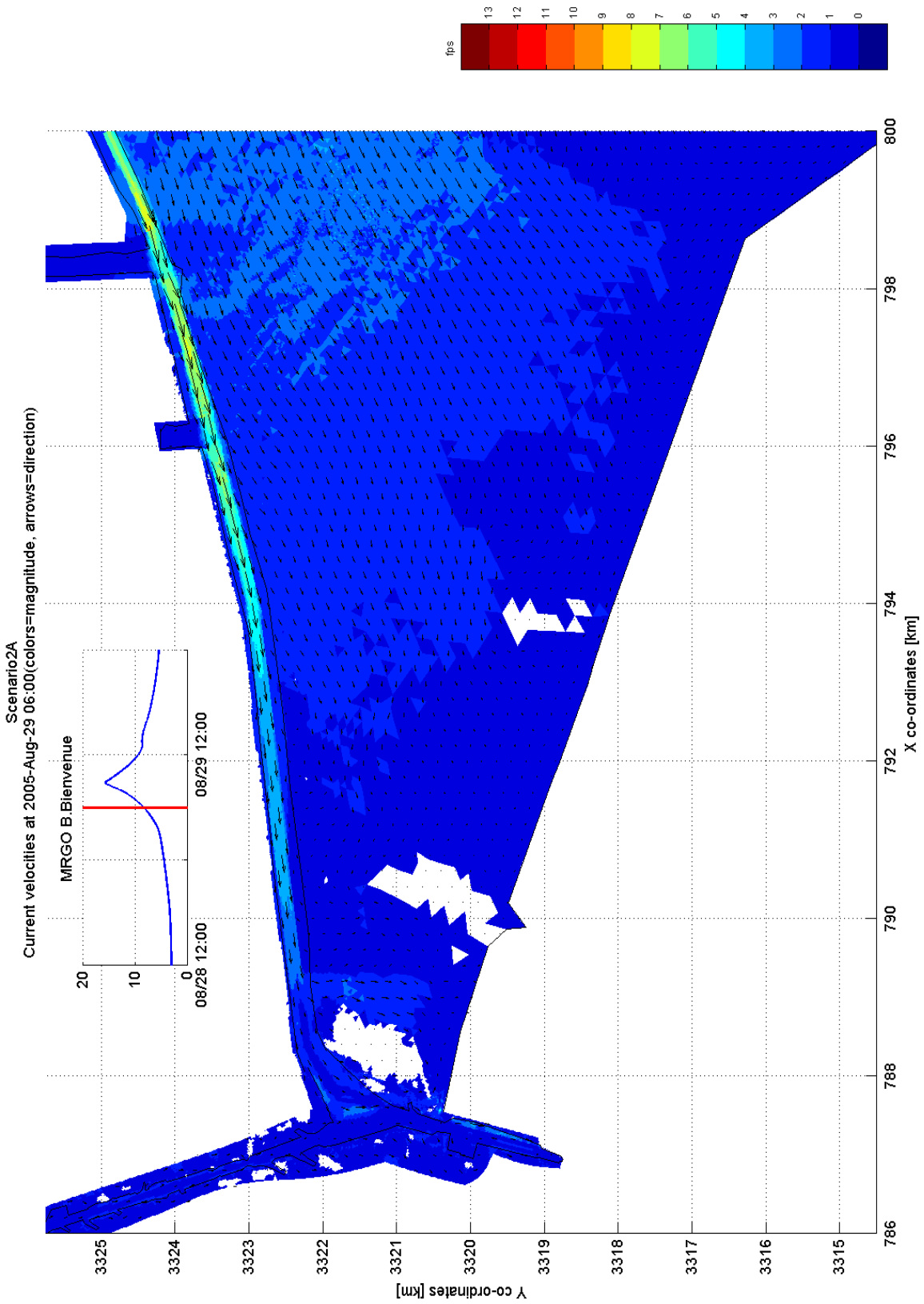


Figure A.8c: Spatial current velocities (magnitude with color scale, direction with arrows) close up at MRGO Reach 1 for Scenario 2A at 6:00am local time. Note some flow concentration in the MRGO Reach 1.

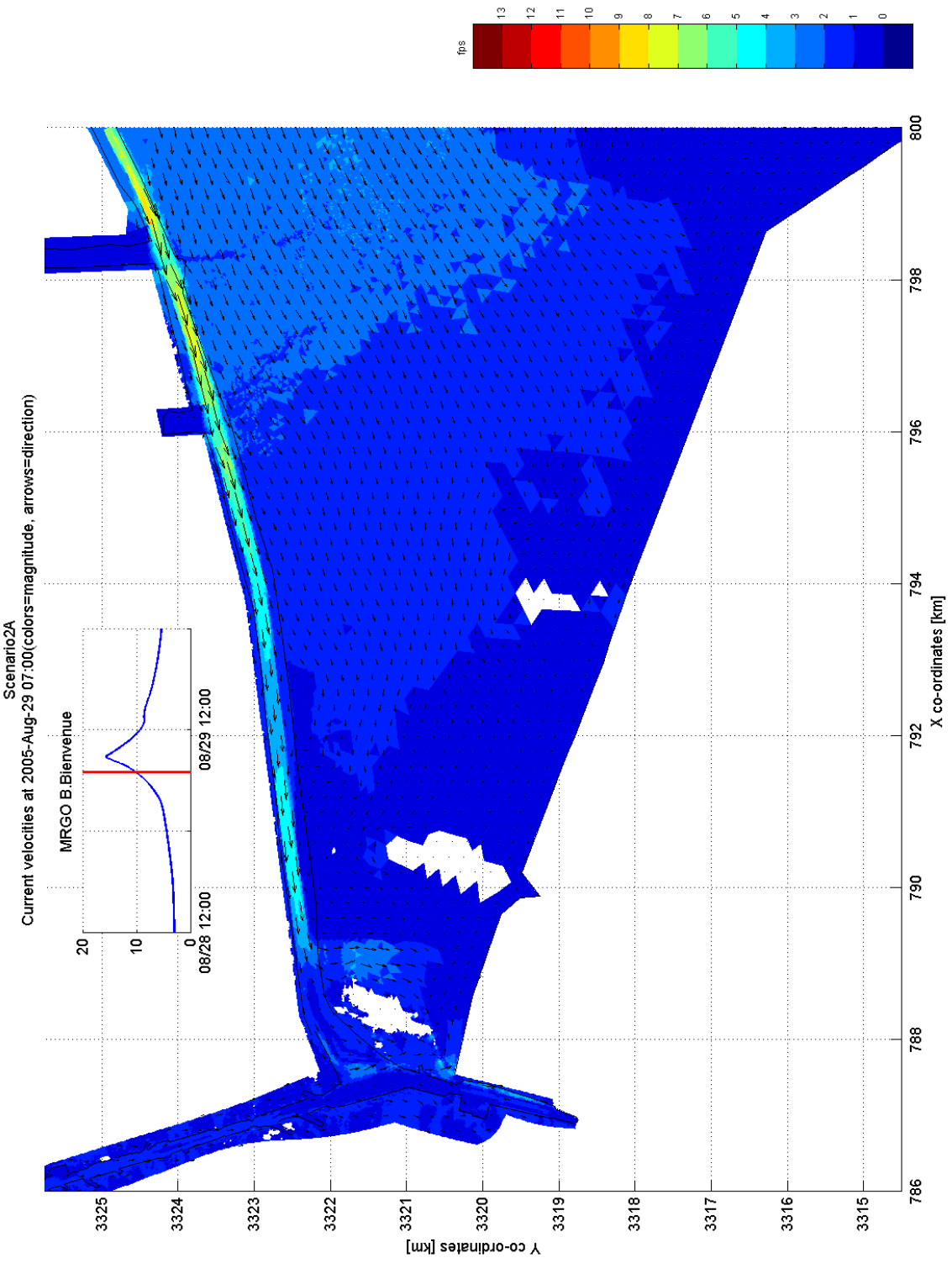


Figure A.8d: Spatial current velocities (magnitude with color scale, direction with arrows) close up at MRGO Reach 1 for Scenario 2A at 7:00am local time. Note the flow concentration in the MRGO Reach 1.

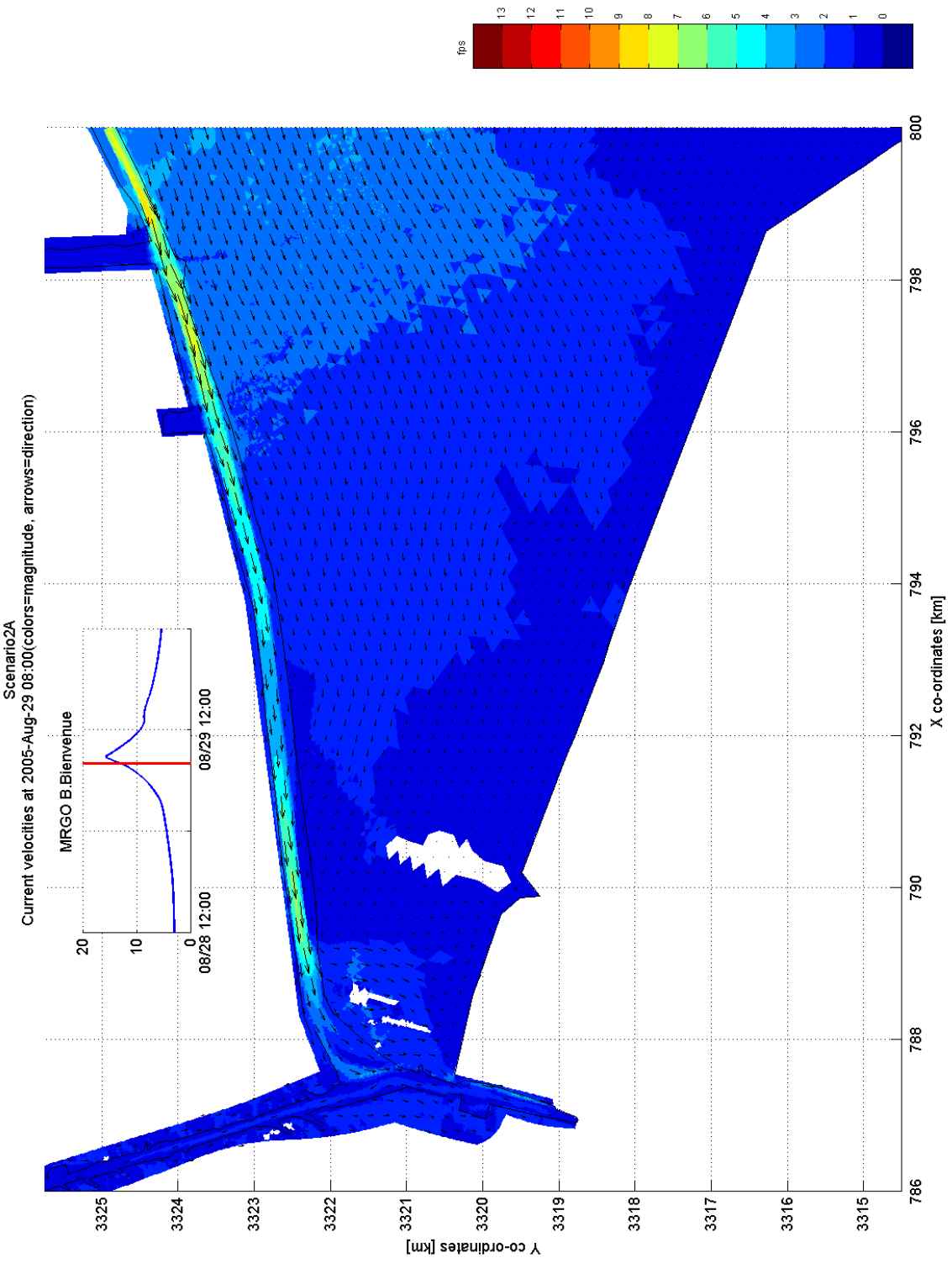


Figure A.8e: Spatial current velocities (magnitude with color scale, direction with arrows) close up at MRGO Reach 1 for Scenario 2A at 8:00am local time. Note the flow concentration in the MRGO Reach 1. Difference with Scenario 1: still no currents in the IHNC.

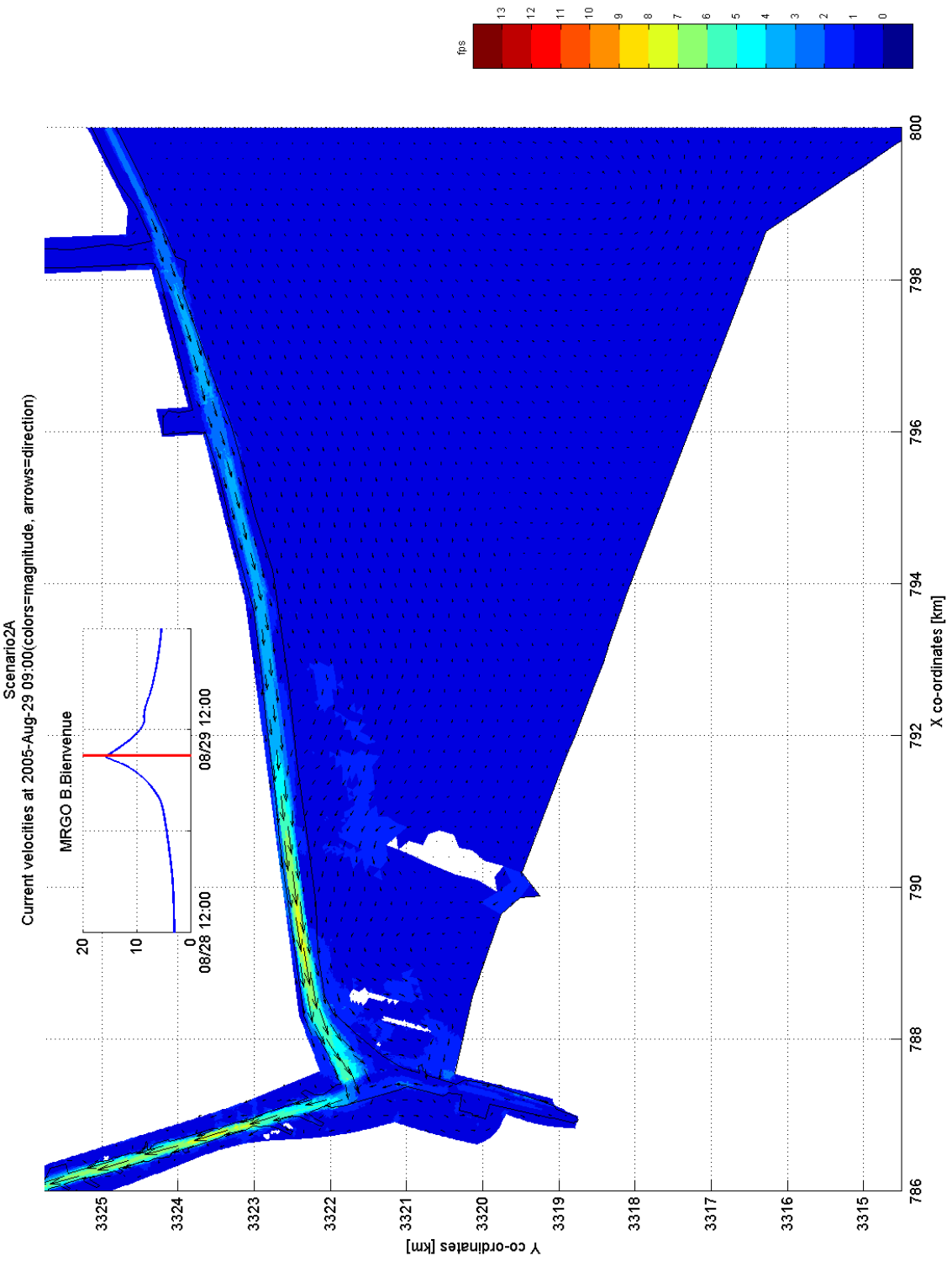


Figure A.8f: Spatial current velocities (magnitude with color scale, direction with arrows) close up at MRGO Reach 1 for Scenario 2A at 9:00am local time. Note the current velocities in the IHNC start to grow at 9:00am; much later than in Scenario 1.

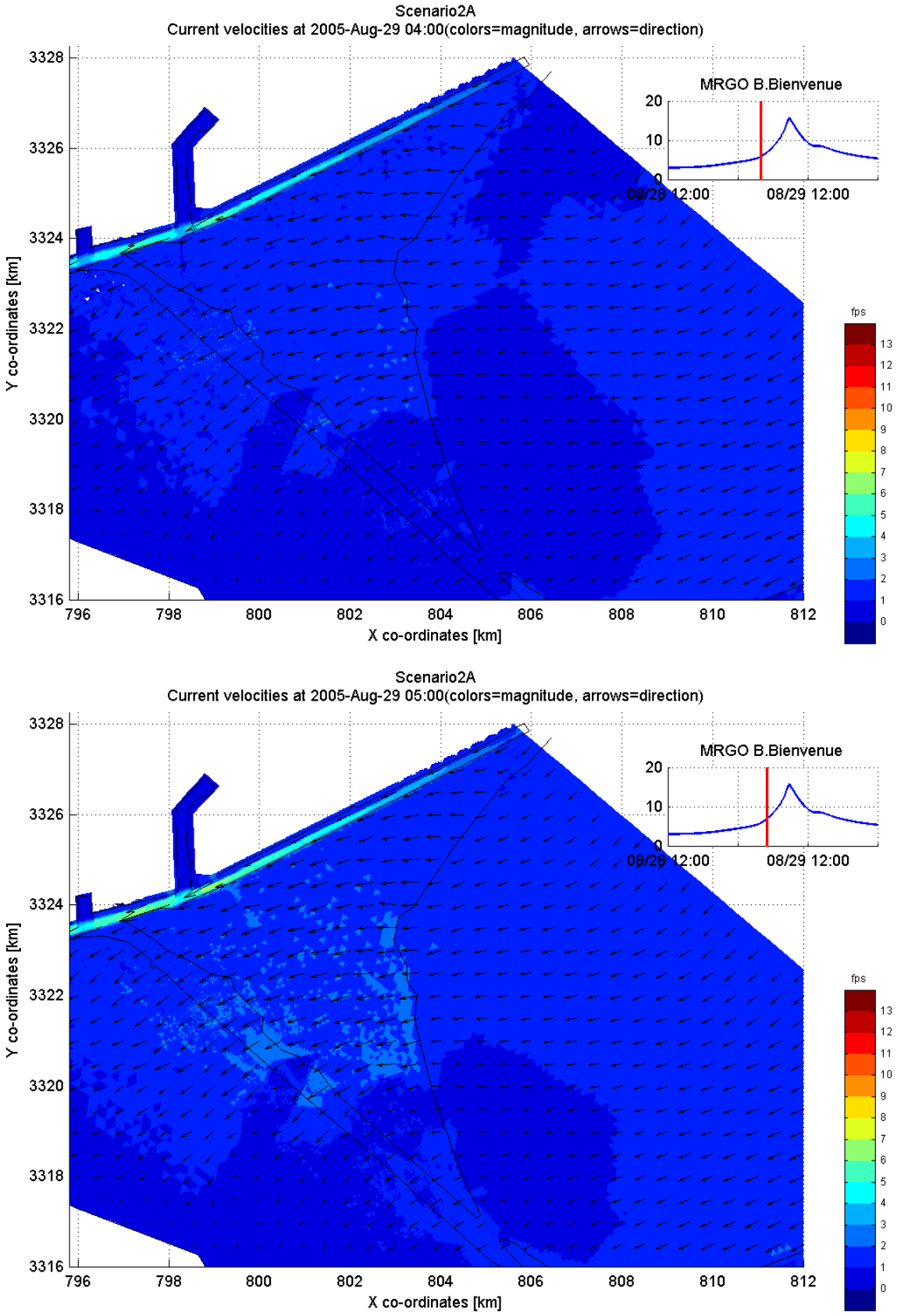


Figure A.9a: Spatial current velocities (magnitude with color scale, direction with arrows) close up at GIWW/Lake Borgne for Scenario 2A at 4:00am, 5:00am local time.

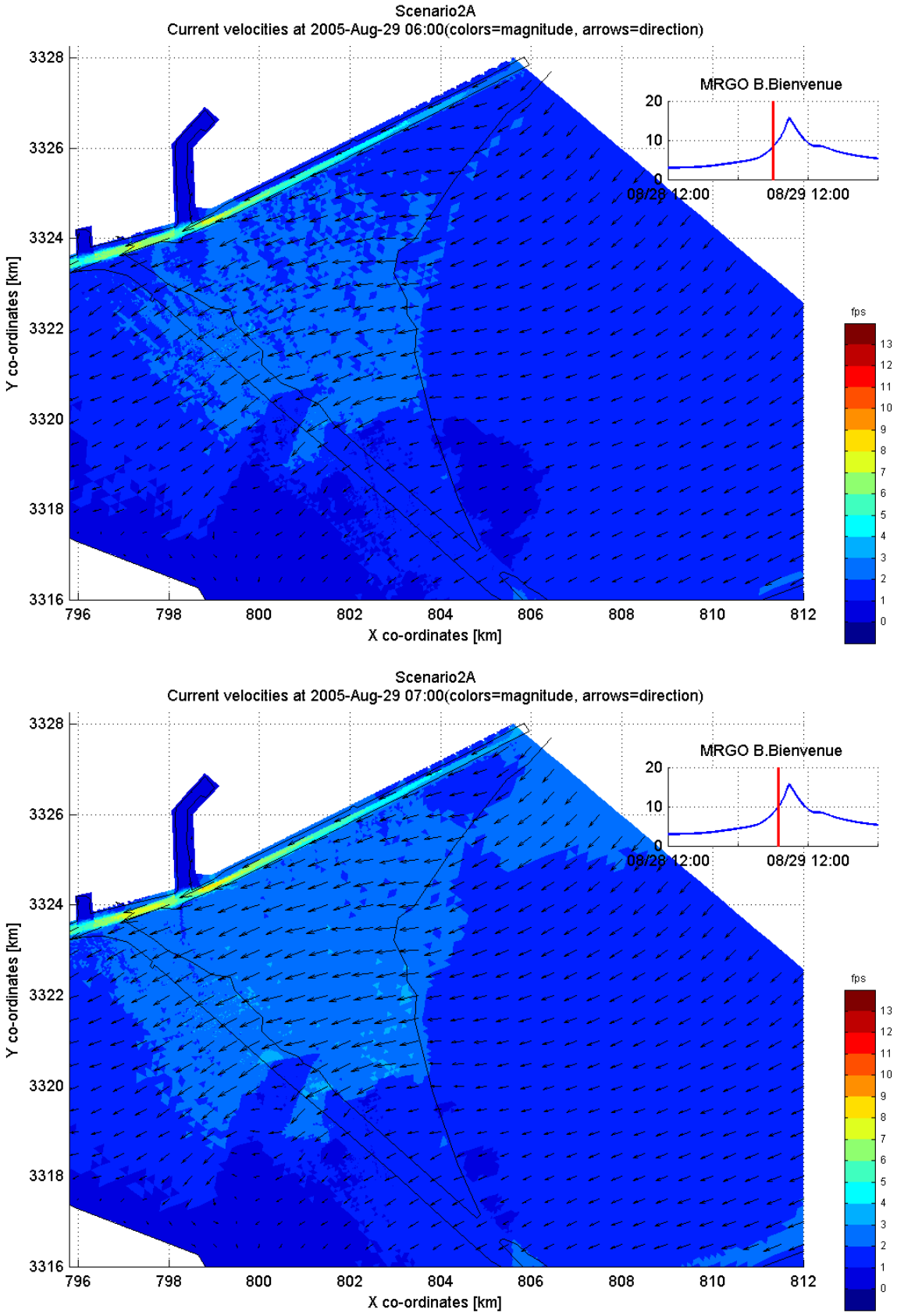


Figure A.9b: Spatial current velocities (magnitude with color scale, direction with arrows) close up at GIWW/Lake Borgne for Scenario 2A at 6:00am, 7:00am local time.

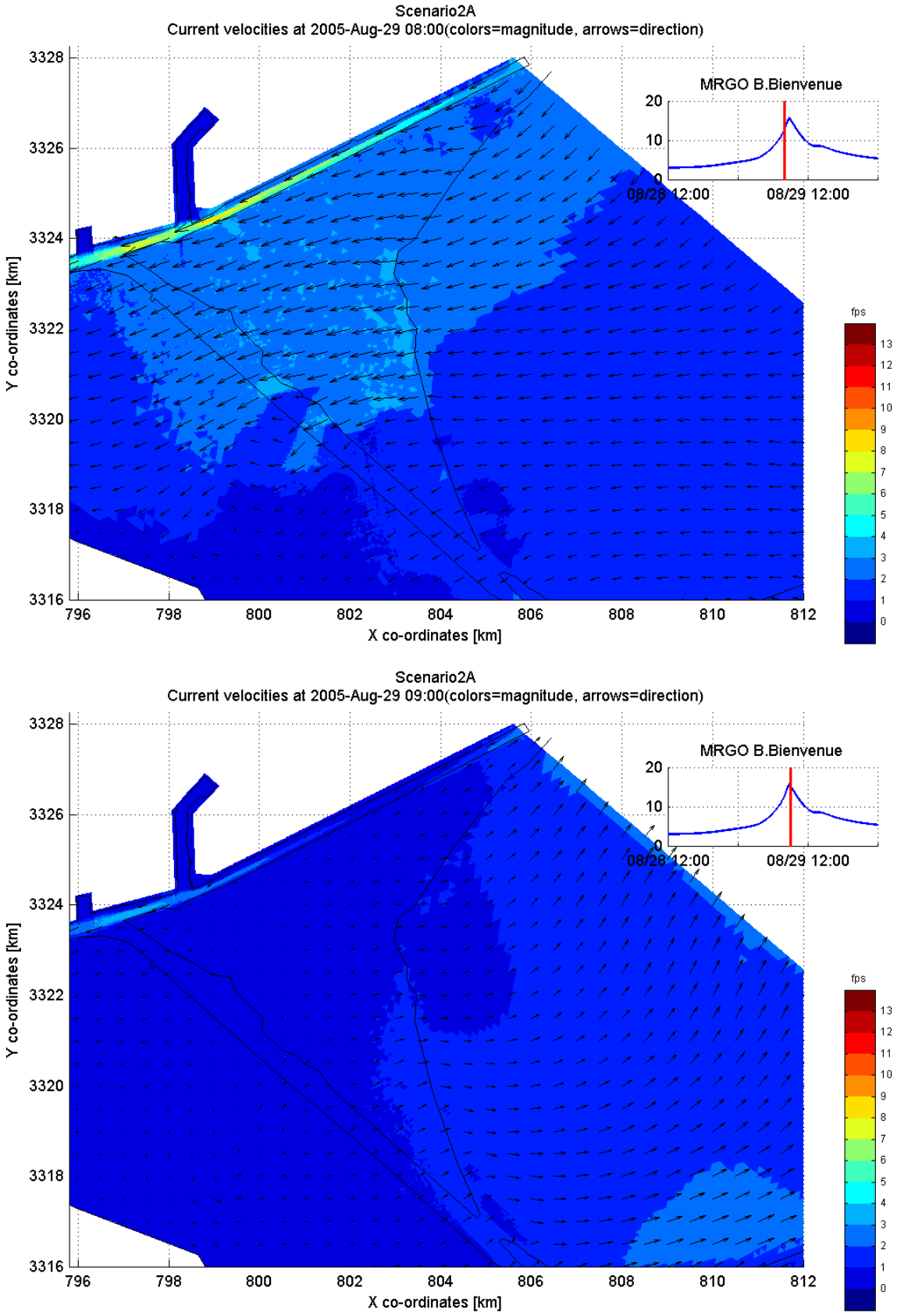


Figure A.9c: Spatial current velocities (magnitude with color scale, direction with arrows) close up at GIWW/Lake Borgne for Scenario 2A at 8:00am, 9:00am local time. Note the flow direction on Lake Borgne has changed to northeast at 9:00am.

Detailed flow information at several locations

At several locations (see Figure A.10 and Table A.3) detailed information about current velocities and water levels are given in Figure A.11. The details are summarized in Table A.4 to Table A.9.

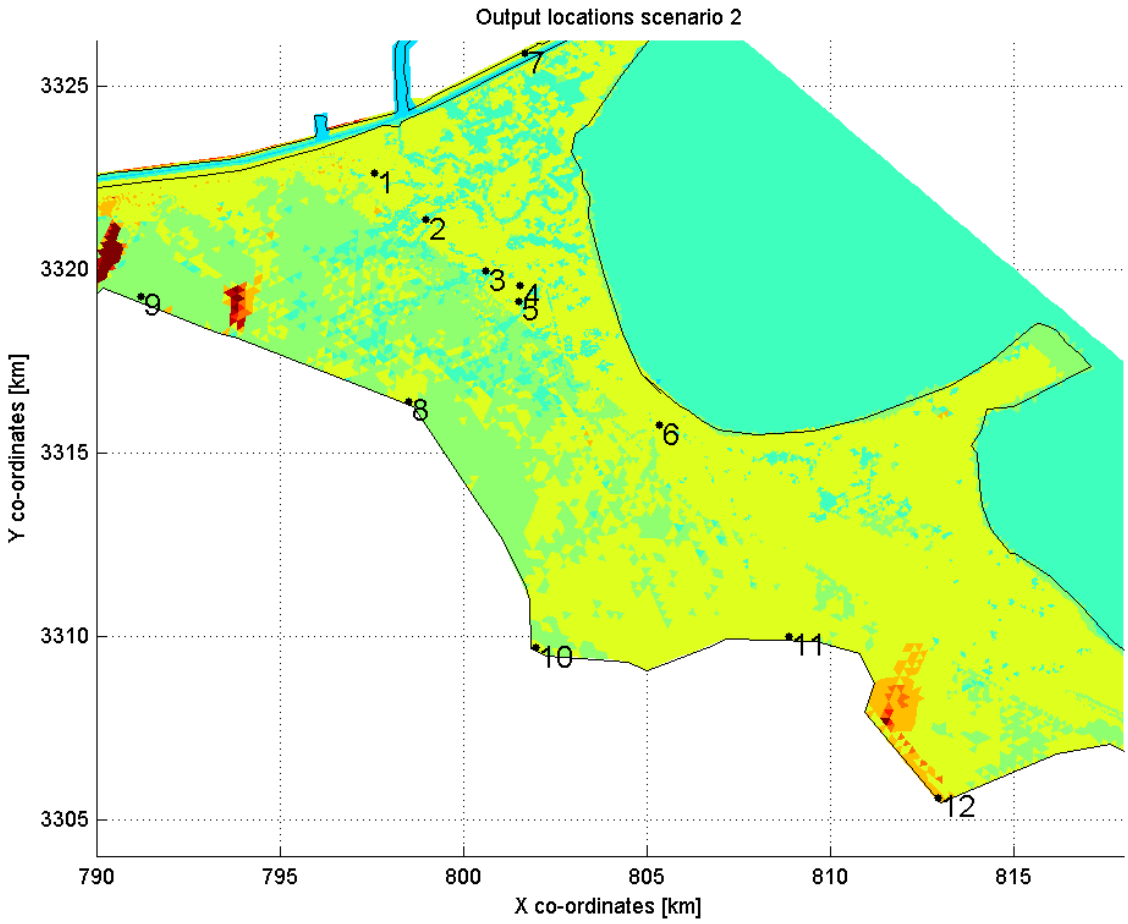


Figure A.10 Output locations Scenario 2A

Table A.3: Coordinates output locations

Loc	Name	lat [N]	lon [W]	UTM [m]	UTM [m]
1	B. Bienvenue	29°59’ 54.51”	89°54’ 55.54”	797571	3322628
2	Station 430	29°59'12.29"	89°54' 03.80"	798993	3321367
3	Loc I	29.97368°	89.884833°	800613	3319954
4	MRGO Halfway	29°58’ 5.11”	89°52’ 40.14”	801540	3319563
5	Station 540	29°57'58.19"	89°52' 32.15"	801515	3319142
6	B. Dupre	29°56’ 5.52”	89°50’ 12.26”	805355	3315765
7	GIWW@BackB	30° 01.597'	89°52.291'	801670	3325901
8	Loc II 40Arpent			798527	3316406
9	Loc A 40 Arpent			791213	3319277
10	Loc B 40 Arpent			801991	3309702
11	Loc C 40 Arpent			808892	3310020
12	Loc D 40 Arpent			812966	3305607

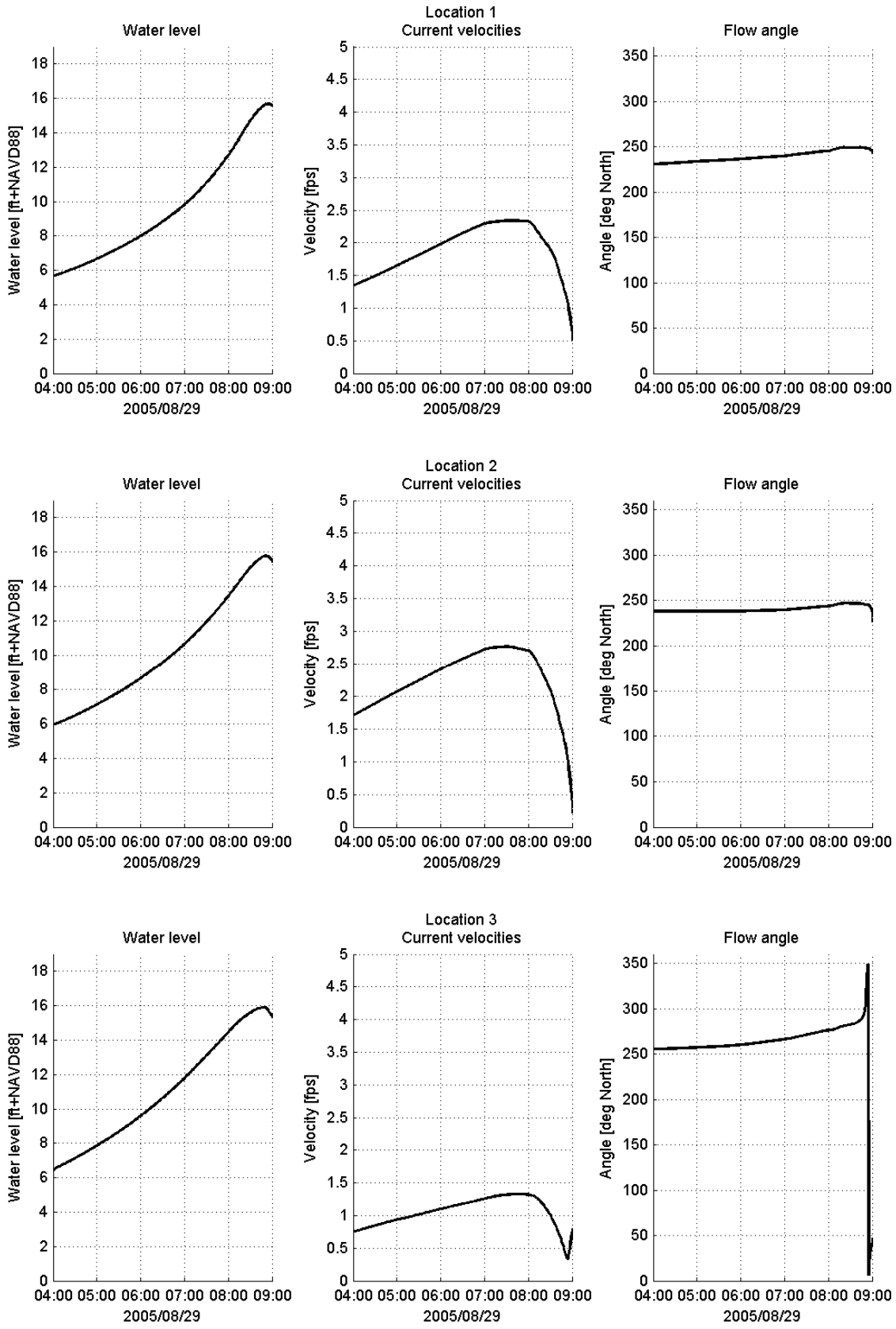


Figure A.11a: Results for location 1, 2 and 3 Scenario 2A from 4:00am to 9:00am

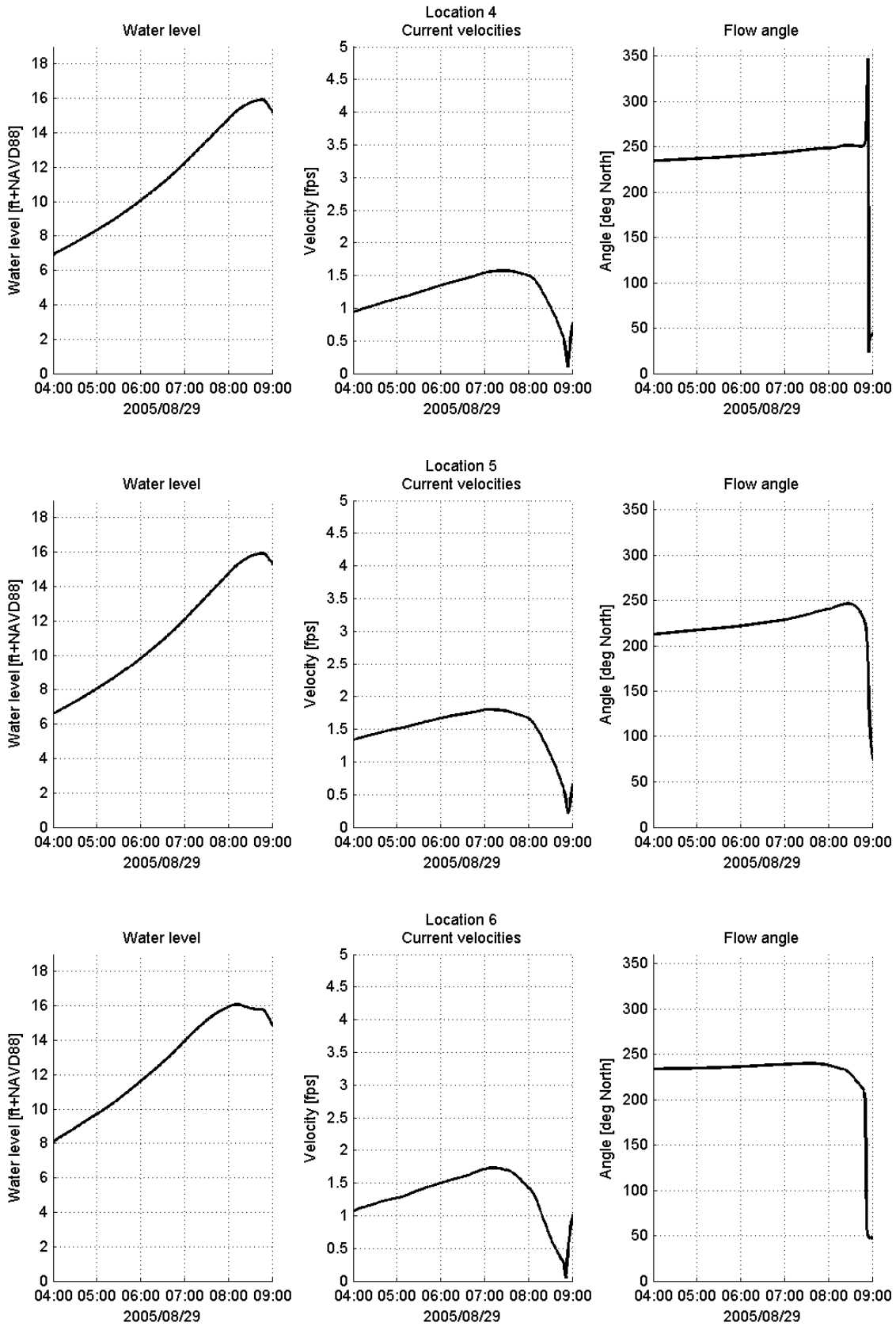


Figure A.11b: Results for location 4, 5 and 6 Scenario 2A from 4:00am to 9:00am

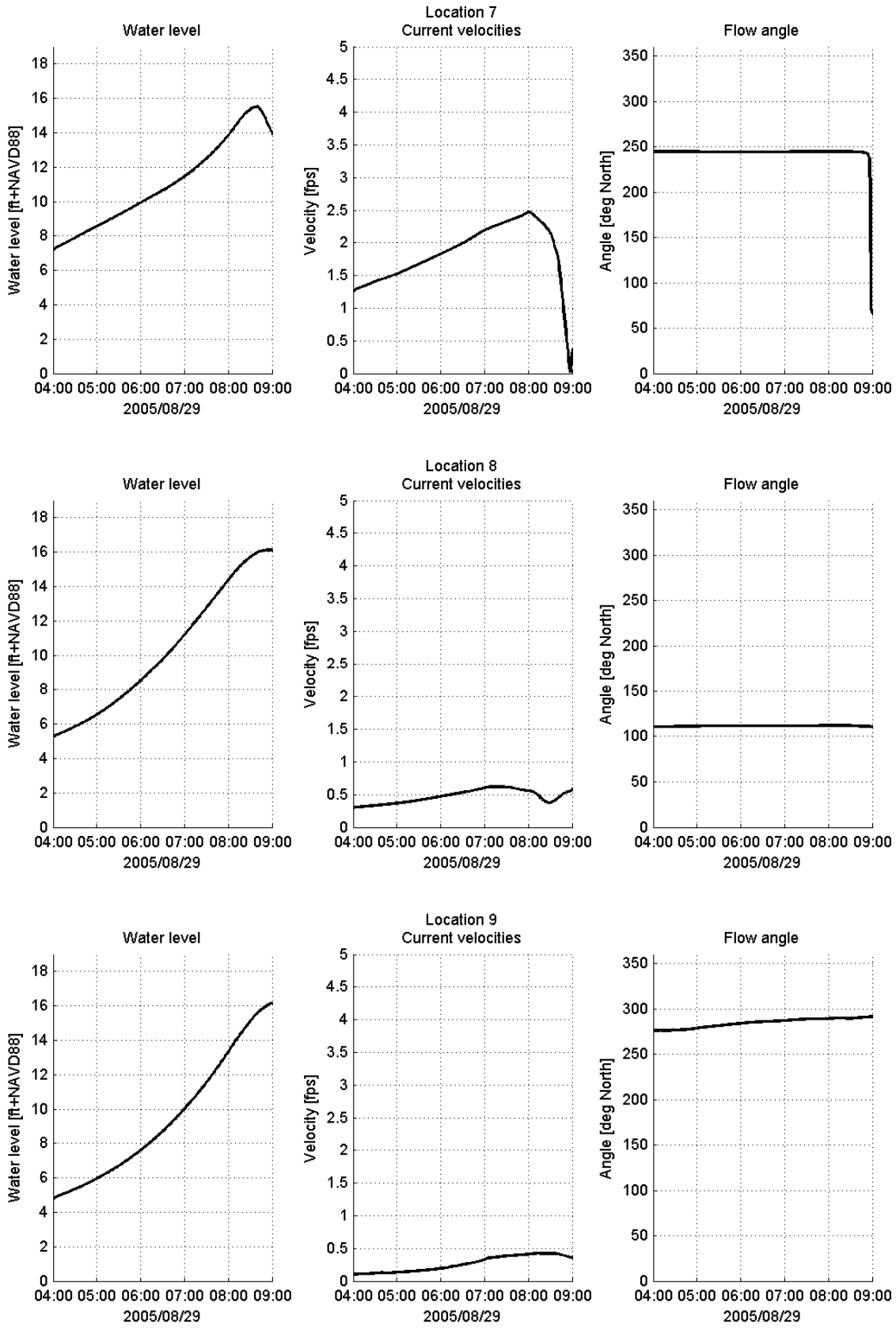


Figure A.11c: Results for location 7, 8 and 9 Scenario 2A from 4:00am to 9:00am

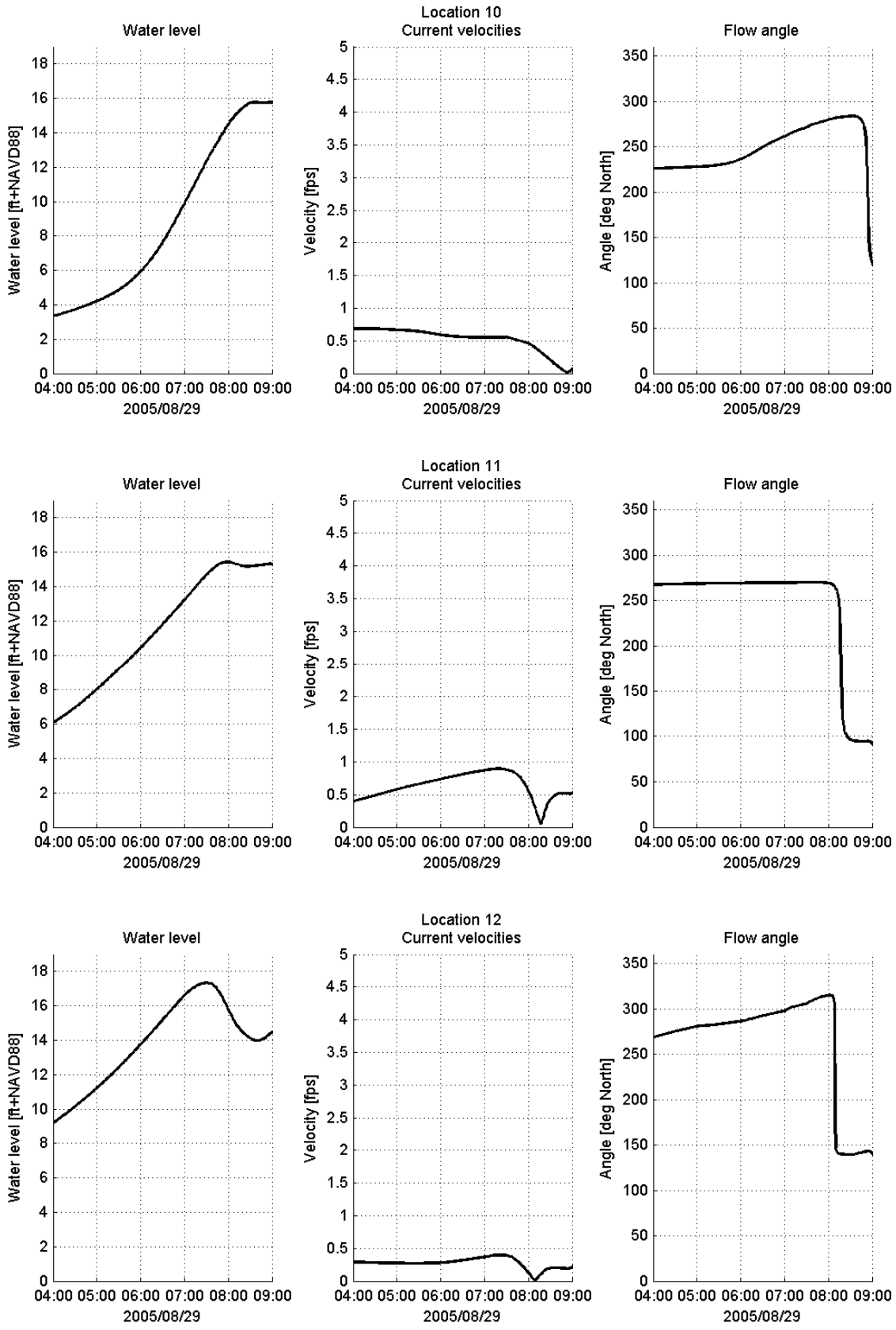


Figure A.11d: Results for location 10, 11 and 12 Scenario 2A from 4:00am to 9:00am

Table A.4: Summary results Scenario 2A at 29th August 2005 4:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	5.67	1.34	231
2	Station 430	5.92	1.70	238
3	Loc I	6.47	0.75	255
4	MRGO Halfway	6.93	0.94	234
5	Station 540	6.59	1.34	213
6	B. Dupre	8.12	1.07	234
7	GIWW@BackB	7.23	1.27	244
8	Loc II 40Arpent	5.27	0.30	110
9	Loc A 40 Arpent	4.82	0.10	276
10	Loc B 40 Arpent	3.34	0.68	226
11	Loc C 40 Arpent	6.07	0.40	268
12	Loc D 40 Arpent	9.20	0.29	269

Table A.5: Summary results Scenario 2A at 29th August 2005 5:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	6.66	1.65	234
2	Station 430	7.11	2.07	238
3	Loc I	7.87	0.94	257
4	MRGO Halfway	8.34	1.15	237
5	Station 540	8.04	1.50	218
6	B. Dupre	9.71	1.27	234
7	GIWW@BackB	8.56	1.52	244
8	Loc II 40Arpent	6.54	0.37	111
9	Loc A 40 Arpent	5.95	0.13	279
10	Loc B 40 Arpent	4.19	0.67	228
11	Loc C 40 Arpent	8.01	0.58	269
12	Loc D 40 Arpent	11.23	0.27	281

Table A.6: Summary results Scenario 2A at 29th August 2005 6:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	7.99	1.98	236
2	Station 430	8.66	2.41	238
3	Loc I	9.60	1.10	260
4	MRGO Halfway	10.07	1.35	240
5	Station 540	9.84	1.67	222
6	B. Dupre	11.62	1.50	236
7	GIWW@BackB	9.93	1.83	244
8	Loc II 40Arpent	8.52	0.47	111
9	Loc A 40 Arpent	7.61	0.20	284
10	Loc B 40 Arpent	5.94	0.59	236
11	Loc C 40 Arpent	10.46	0.74	269
12	Loc D 40 Arpent	13.76	0.28	286

Table A.7: Summary results Scenario 2A at 29th August 2005 7:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	9.82	2.29	240
2	Station 430	10.67	2.72	240
3	Loc I	11.80	1.26	266
4	MRGO Halfway	12.23	1.54	244
5	Station 540	12.09	1.79	229
6	B. Dupre	13.95	1.71	239
7	GIWW@BackB	11.46	2.19	244
8	Loc II 40Arpent	11.22	0.60	111
9	Loc A 40 Arpent	10.02	0.33	287
10	Loc B 40 Arpent	9.90	0.55	261
11	Loc C 40 Arpent	13.24	0.87	270
12	Loc D 40 Arpent	16.63	0.37	298

Table A.8: Summary results Scenario 2A at 29th August 2005 8:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	12.71	2.33	245
2	Station 430	13.46	2.71	244
3	Loc I	14.46	1.32	276
4	MRGO Halfway	14.78	1.50	248
5	Station 540	14.74	1.66	241
6	B. Dupre	15.92	1.43	238
7	GIWW@BackB	13.86	2.47	244
8	Loc II 40Arpent	14.40	0.56	112
9	Loc A 40 Arpent	13.36	0.41	289
10	Loc B 40 Arpent	14.51	0.46	279
11	Loc C 40 Arpent	15.43	0.55	269
12	Loc D 40 Arpent	15.76	0.12	315

Table A.9: Summary results Scenario 2A at 29th August 2005 9:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	15.57	0.60	245
2	Station 430	15.51	0.35	236
3	Loc I	15.39	0.73	44
4	MRGO Halfway	15.27	0.71	44
5	Station 540	15.38	0.59	78
6	B. Dupre	14.90	0.96	47
7	GIWW@BackB	13.99	0.28	66
8	Loc II 40Arpent	16.11	0.57	110
9	Loc A 40 Arpent	16.15	0.35	291
10	Loc B 40 Arpent	15.76	0.06	122
11	Loc C 40 Arpent	15.28	0.52	92
12	Loc D 40 Arpent	14.47	0.22	140

A.2 Scenario 2B: The 'virgin' no-MRGO Scenario and a simulated Katrina storm without MRGO levees with 40 Arpent levee crest at 6.5 ft+NAVD

A.2.1 Description of Scenario

In order to interpret the full impacts of the MRGO we decided to run a Katrina storm with a scenario run modified to a condition as if the MRGO had never existed. For this, we have to envision a situation similar to the late 1950s. Accordingly, we simulate surge along the shores of Lake Borgne in a model in which we change the Scenario 1 model input in the following ways:

(1) 90% reduction in cross-section area of MRGO Reach 1 to the dimensions of the GIWW (pre-MRGO);
(2) MRGO Reach 2 is removed and replaced with land at the elevation of the surrounding marsh and swamp areas;
(3) The spoil disposal area and LPV EBSB are degraded to natural swamp or marsh elevation depending on the 1958 habitat map;
(4) Bayou LaLoutre ridge is restored to fill-in the hole dredged for MRGO Reach 2;
(5) The area between the 40 Arpent levee and the Mississippi is added to the model grid. The pre-Katrina crest level of 6.5 ft NAVD is used for the 40 Arpent levee.
(6) The Cypress trees originally present between the MRGO and the 40 Arpent levees have influence on the water current velocities and the wind velocities. A higher Manning's roughness is used for the Cypress forests reflecting their greater frictional impacts on surge currents, and the wind velocities are reduced by 80% inside the Cypress forests due to the wind break/canopy effect of tall forests

A.2.2 FINEL model input data

The FINEL model is set up to utilize the metric system, so all data is thus subsequently converted to feet. The coordinate system used in the simulations is UTM (zone 15 R). Input data that was received in longitude and latitude was translated accordingly.

Model grid
The model grid used for Scenario 2B is equal to the model grid used in Scenario 2C, see section 2.2.2.

Bathymetry and Topography
The bathymetry for Scenario 2b is modified to represent the conditions prior to the construction of the MRGO. Reach 2 of the MRGO is filled to the height of the surrounding marshes and swamps in the grid. Reach 1 is modified to the original GIWW design dimensions of 150 ft wide and 12 ft deep, as provided by the Robinson experts. The levees and spoil disposal area next to MRGO Reach 2 are degraded to the height of the surrounding marshes and swamps. The marshes and swamps around Lake Borgne are, where needed, restored to a 1950s elevation of 2.5 ft+NAVD88. A land-water map provided by the Robinson experts has been used to construct the original small water streams in the marshes. The topography of the area between the 40 Arpent levee and the Mississippi is taken from LIDAR data, provided by Robinson experts. The 40 Arpent levee has a pre-Katrina crest level of 6.5 ft+NAVD88. The resulting topography and bathymetry for the model area are shown in Figure A.12.

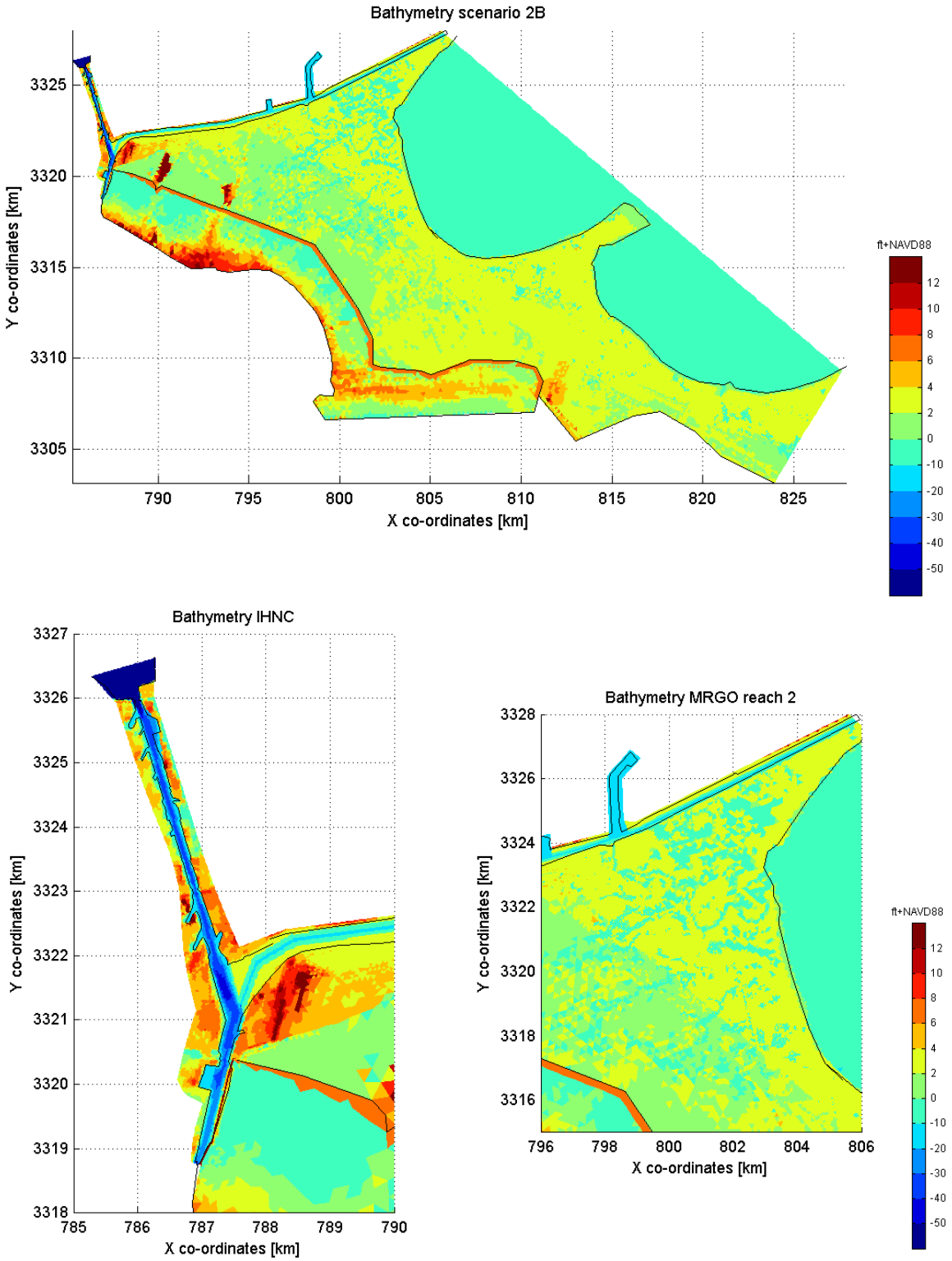


Figure A.12: Bathymetry FINEL model area Scenario 2B

Simulation period
The simulation starts at 12h00 LT 28th August 2005 and continues until 24h00 29th August 2005.

Boundary conditions
The boundary conditions consist of water level time series from the constructed Scenario 2 hydrographs, provided to us by the Robinson experts. ADCIRC outputs with and without the MRGO are used to modify Scenario 1 outputs reducing the maximum surge and delaying the peak at Shell Beach at Reach 2.

Figure A.13 shows the locations of the boundary conditions and Table A.10 gives the corresponding locations which are used for every boundary. The boundary time series themselves are shown in Figure A.14. All boundaries not mentioned in Table A.10 are closed boundaries.

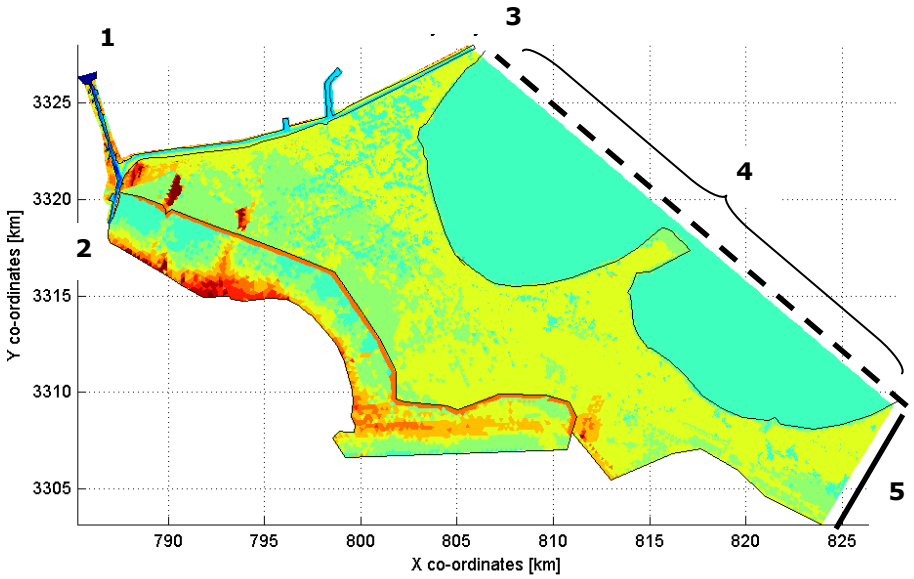


Figure A.13: Location boundary conditions FINEL flow model

Table A.10: Boundary conditions

	Boundary	*Used hydrograph2 (modified ADCIRC)*
1	Lake Pontchartrain	IHNC@LakeP
2	IHNC Locks	Closed boundary (discharge=0)
3	GIWW	NOEbackA
4	Lake Borgne	Interpolation between 3 and 5
5	MRGO	Shell Beach

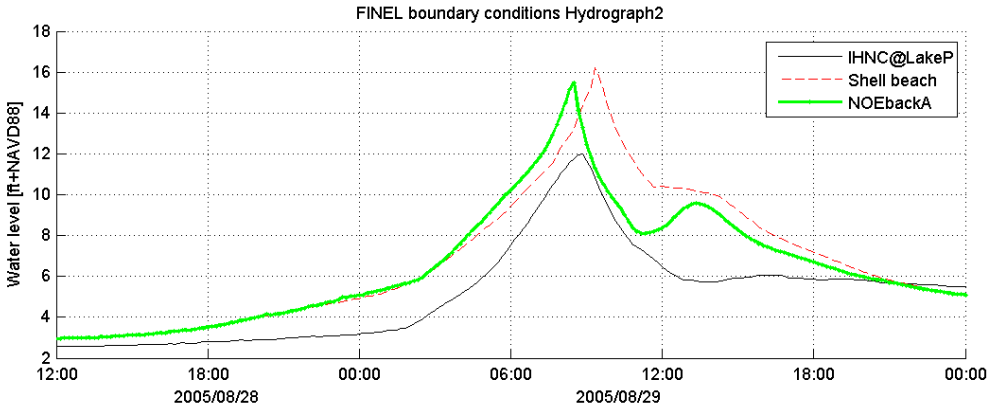


Figure A.14: Time series boundary conditions FINEL flow model Scenario 2B

Bottom roughness

In the model area a spatial variable Manning coefficient is used for the bottom roughness. The Manning roughness coefficients used are based on years of experience in modeling coastal environments. These data were collaborated with other data sets such as from the US Geological Survey (http://www.fhwa.dot.gov/bridge/wsp2339.pdf), the world renowned book Open-channel hydraulics [Ref. 5] and IPET [Ref. 6]. For each scenario the spatial extent of the Manning's used is based on the presence or lack of wetlands; shoreline location and presence; and lack or presence of levees. In 1958 Cypress forests existed between the MRGO and the 40 Arpent levees (Figure A.15). The Cypress trees cause friction on the flow, this influence is taken into account by a higher roughness coefficient. In a map provided by Robinson experts, two types of Cypress forests are distinguished: normal (Manning n=0.1 $m^{-1/3}s$) and dense (Manning n=0.12 $m^{-1/3}s$). The Manning roughness coefficients are shown in Figure A.16 and summarized in Table A.11.



Figure A.15: Photograph of cypress trees in swampy areas (send to us by Robinson experts)

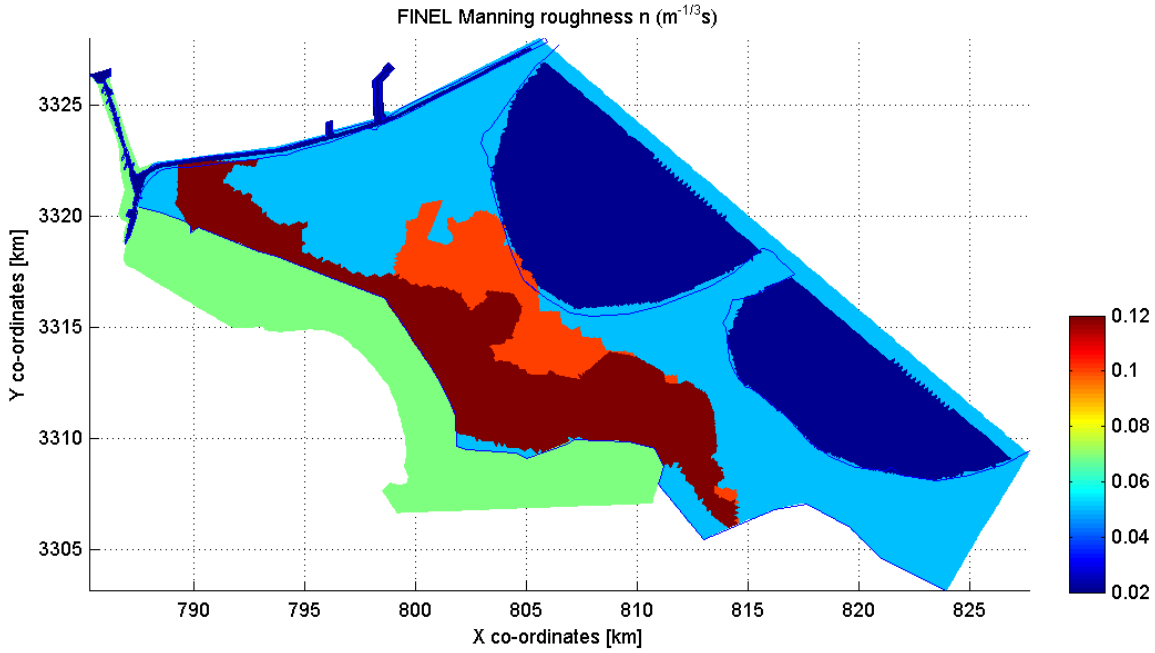


Figure A.16: Manning roughness coefficient FINEL model area Scenario 2B. The cypress areas are red (dark red = dense cypress trees, light red = normal cypress trees).

Table A.11: Manning coefficient (based on: IPET Volume IV appendix page IV-5-102 [Ref. 6])

Area	*Manning coefficient n ($m^{-1/3}s$)*
Open water	0.02
Marsh along Lake Borgne	0.05
Normal Cypress forest	0.1
Dense Cypress forest	0.12
Commercial area next to IHNC	0.07
Low residential area between 40Arpent and Mississippi	0.07

Wind

To take into account the influence of wind on the water motion, spatial variable wind fields are used in the flow calculations with FINEL. The wind fields were provided to us by the Robinson experts spaced at 30 minute intervals. Within the cypress forest the influence of the wind on water movement is dramatically reduced by the trees. Therefore the wind velocities are reduced by 80% (percentage provided to us by Dr Robinson experts) within the Cypress forests (both dark red and light red areas in Figure A.16). The wind speed surface stress is calculated by:

$$\frac{\tau_{wind,x}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,x} - U_x),$$

$$\frac{\tau_{wind,y}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,y} - U_y).$$

With:

C_d = wind drag coefficient (-),
W_{10} = wind speed at 10 meter height (m/s),
U = water velocity (m/s).

The wind drag is defined by Garrat's drag formula (Garrat 1977):

$C_d = (0.75 + 0.067W_{10}) \times 10^{-3}$

A.2.3 Results

The FINEL flow model is used to produce details of the water current. This section shows the results of Scenario 2B: The 'virgin' no-MRGO Scenario and a simulated Katrina storm without MRGO levees with 40 Arpent levee crest at 6.5 ft+NAVD. The results are shown on 6 time steps on the day Katrina struck, 29th August 2005, namely:

1. 4:00am Local Time;
2. 5:00am Local Time;
3. 6:00am Local Time;
4. 7:00am Local Time;
5. 8:00am Local Time;
6. 9:00am Local Time.

These time steps are identical to the time steps used in Scenario 1, but note that the peak of the storm in Scenario 2B has shifted in time (about 40 minutes later in MRGO Reach 1) compared with Scenario 1.

Area plots

The water levels in the model area for these time steps are shown in Figure A.17. The current velocities are shown in Figure A.18. A close up along MRGO Reach 1 is shown in Figure A.19, and along GIWW/Lake Borgne in Figure A.20. The difference in current patterns and water elevations between Scenario 2B and Scenario 1 is obvious. In Scenario 2B there are no levees along the MRGO to build up surge or to guide the flow. The water can freely flow over the wetlands, there is no MRGO Reach 2 with a large discharge capacity and also Reach 1 is reduced in size and discharge capacity. The Cypress forests with high bottom friction and low wind velocities reduce the flow velocities, leading to reduced wind set up and reduced surge elevation. The surge in the IHNC start to build up later and less (peak surge IHNC@Junction is around 9:00 am), therefore a flow towards Lake Pontchartrain has not developed at 9:00am.

The 40 Arpent levee is readily overtopped and the bowl area between the 40 Arpent and the Mississippi is filled to 10-13 ft+NAVD88 at 9:00am (same water levels in front of and at the back of the 40 Arpent levee). The filling of this area calculated with FINEL is a conservative result, in reality it could happen faster. In the FINEL model for Scenario 2B the area between the 40 Arpent Levee and the Mississippi has a uniform higher bottom roughness (low residential area; Manning = $0.07 m^{-1/3}/s$). Also the grid elements containing the 40 Arpent Levee have this higher bottom roughness. Therefore the current velocities over the 40 Arpent Levee in FINEL are lower than when a grass bottom roughness is used on the levee itself, leading to a lower discharge over the levee, leading to a conservative result of the filling of the bowl.

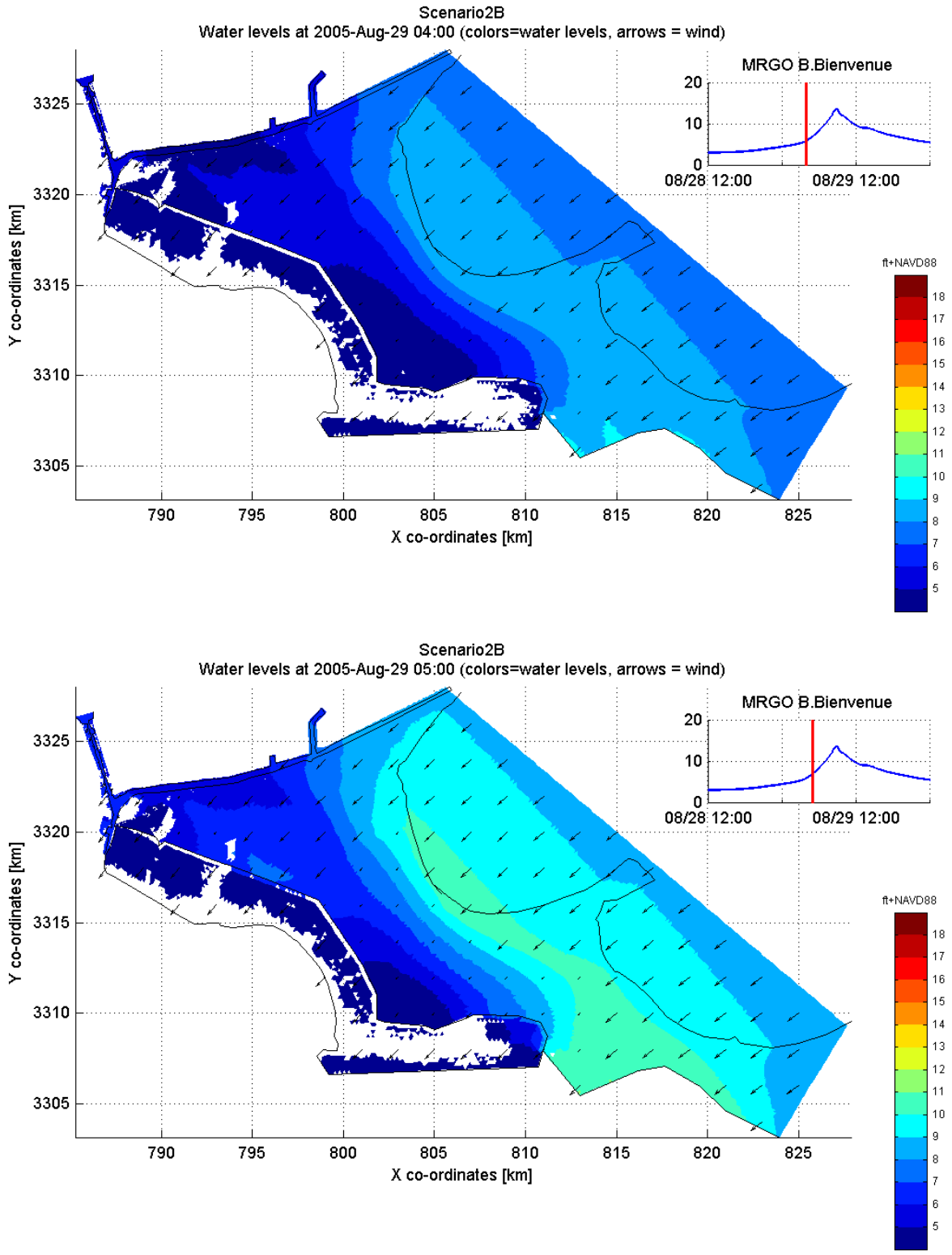


Figure A.17a: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 2B at 4:00am, 5:00am local time. Note the start of overtopping of the pre-Katrina level 40 Arpent levee and the strong differential in surge elevation (6 ft at 5:00am) between Lake Borgne and the area in front of the 40 Arpent levees where dense swamp is present.

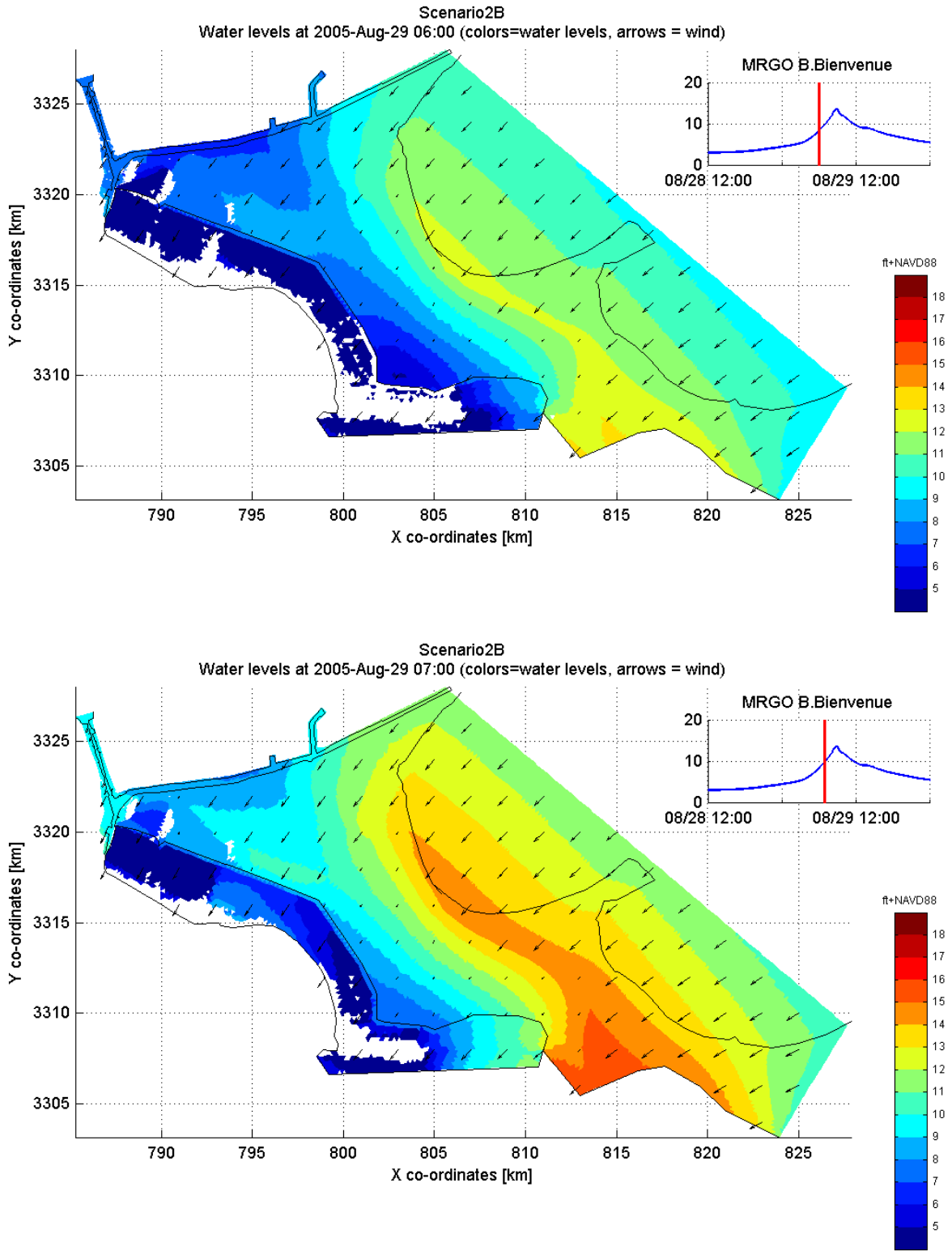


Figure A.17b: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 2B at 6:00am, 7:00am local time. Note the strong differential of 7 ft in surge elevation between Lake Borgne and the area in front of the 40 Arpent levees caused by the dense swamp and overtopping of the 40 Arpent Levee.

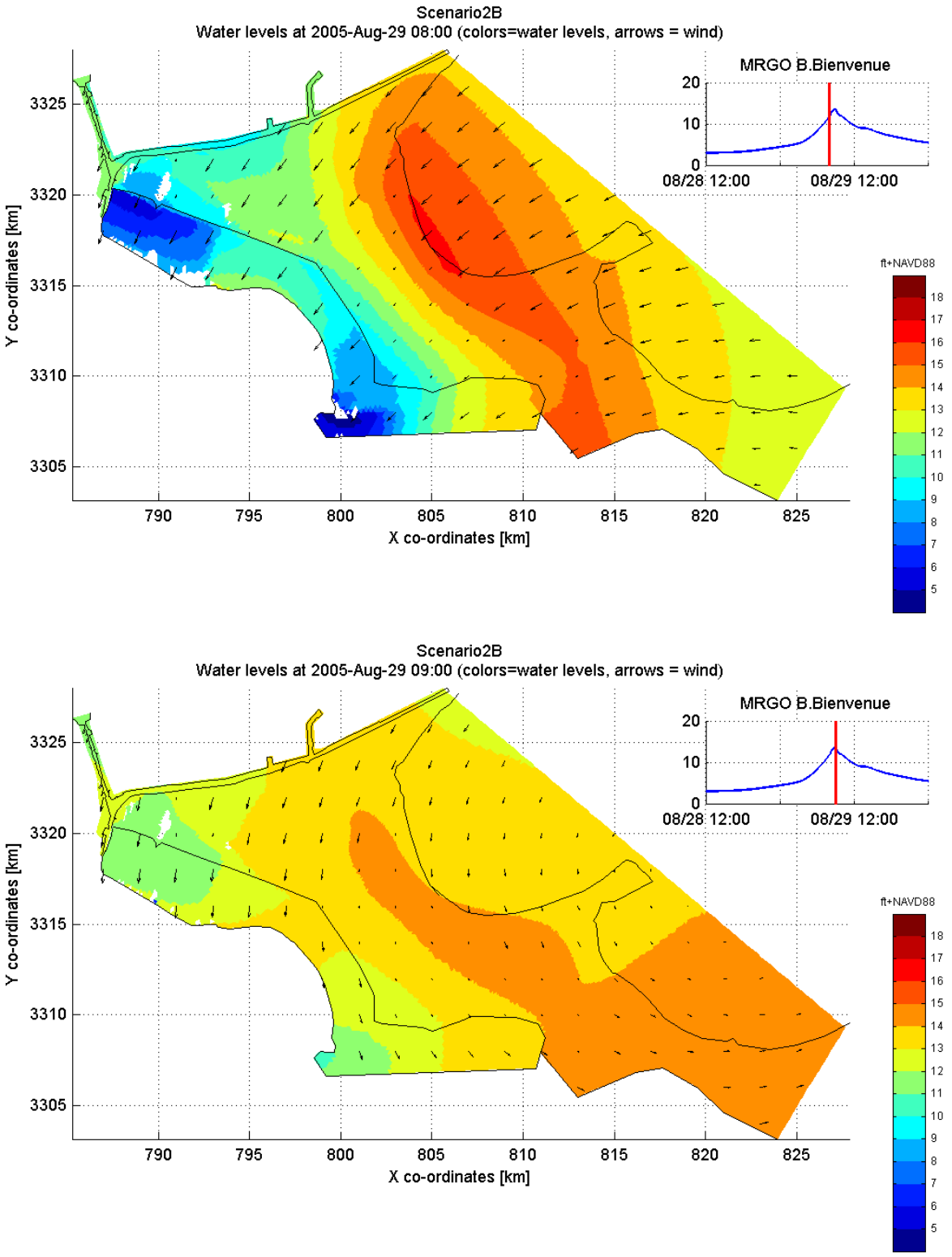


Figure A.17c: Spatial water levels (surge elevations with a color scale) with wind field (arrows) for Scenario 2B at 8:00am, 9:00am local time. Note the area between the 40 Arpent and the Mississippi has filled up to 10-13 f +NAVD88 at 9:00am, there is no water level difference over the 40 Arpent levee anymore. At 08:00 the strong differential in surge elevation is 8 ft between Lake Borgne and the area in front of the 40 Arpent levees, this is caused by the dense swamp and overtopping of the 40 Arpent Levee. However, by 09:00 the wind has gone north and flows from Reach 1 area now impact the surge against the southern section of the 40 Arpent levee, in essence short circuiting the flow path.

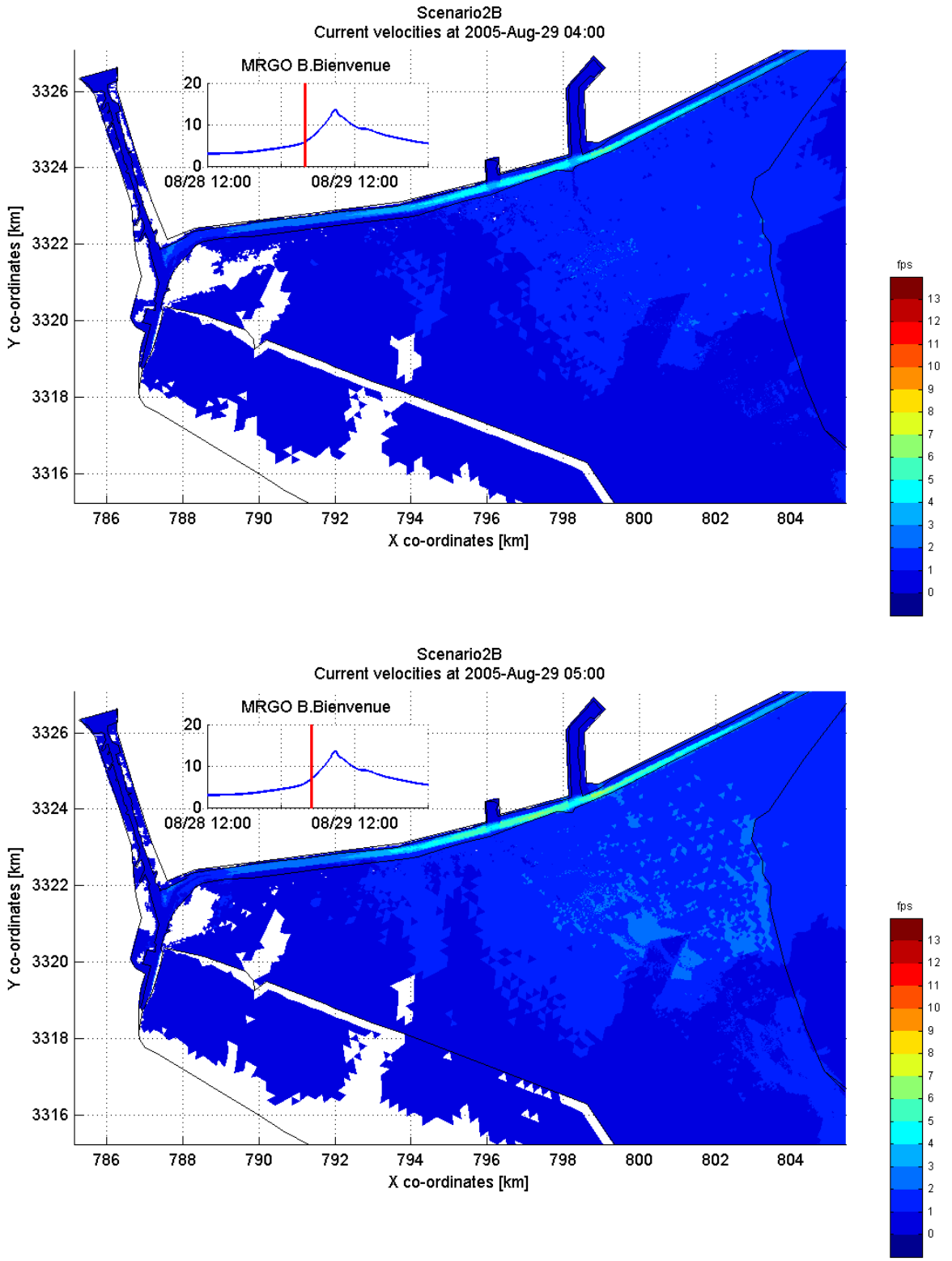


Figure A.18a: Spatial current velocities for Scenario 2B at 4:00am, 5:00am local time. Note low current velocities except in the GIWW, where the surge is making use of the channel opportunity to enhance discharge.

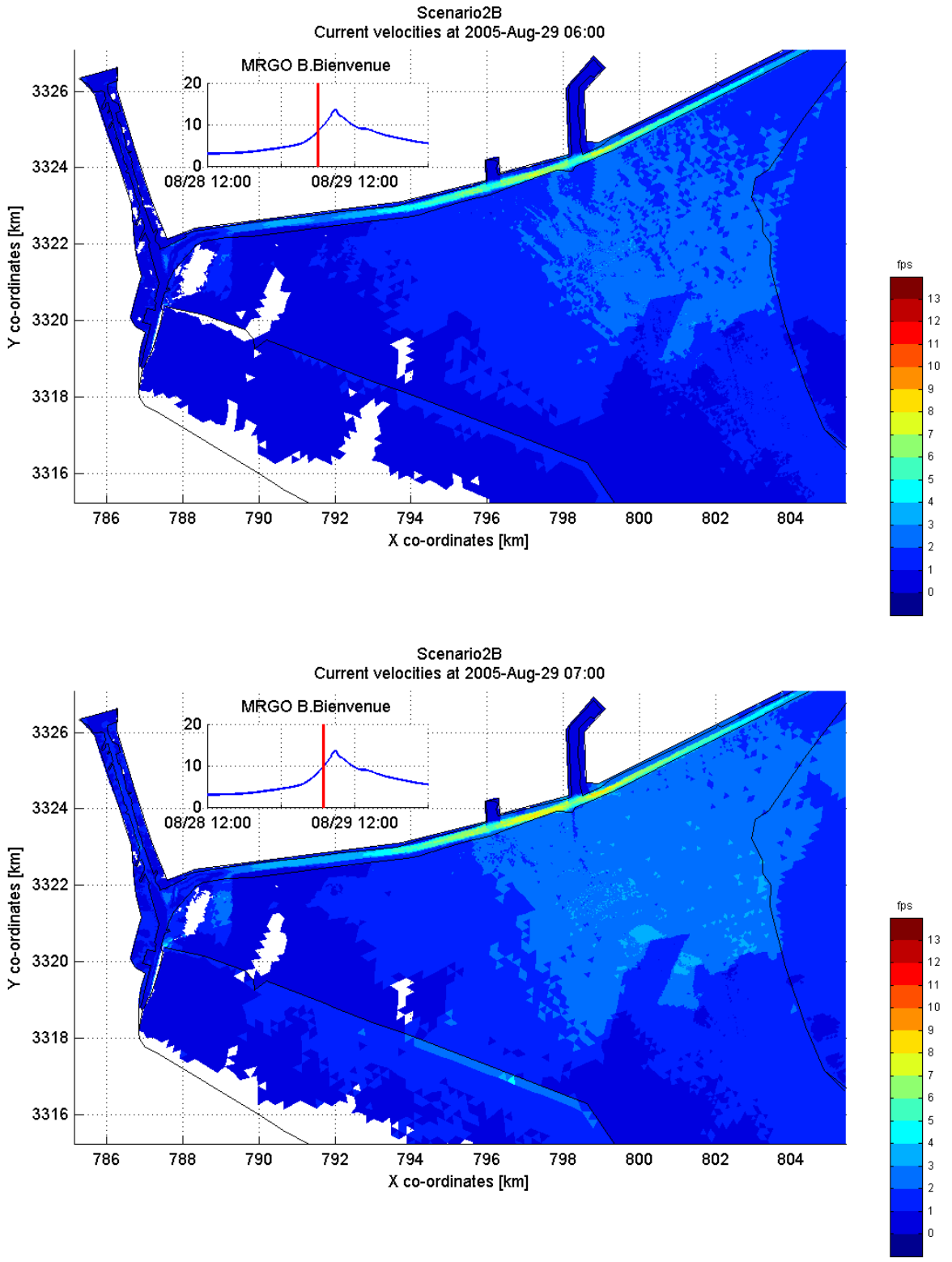
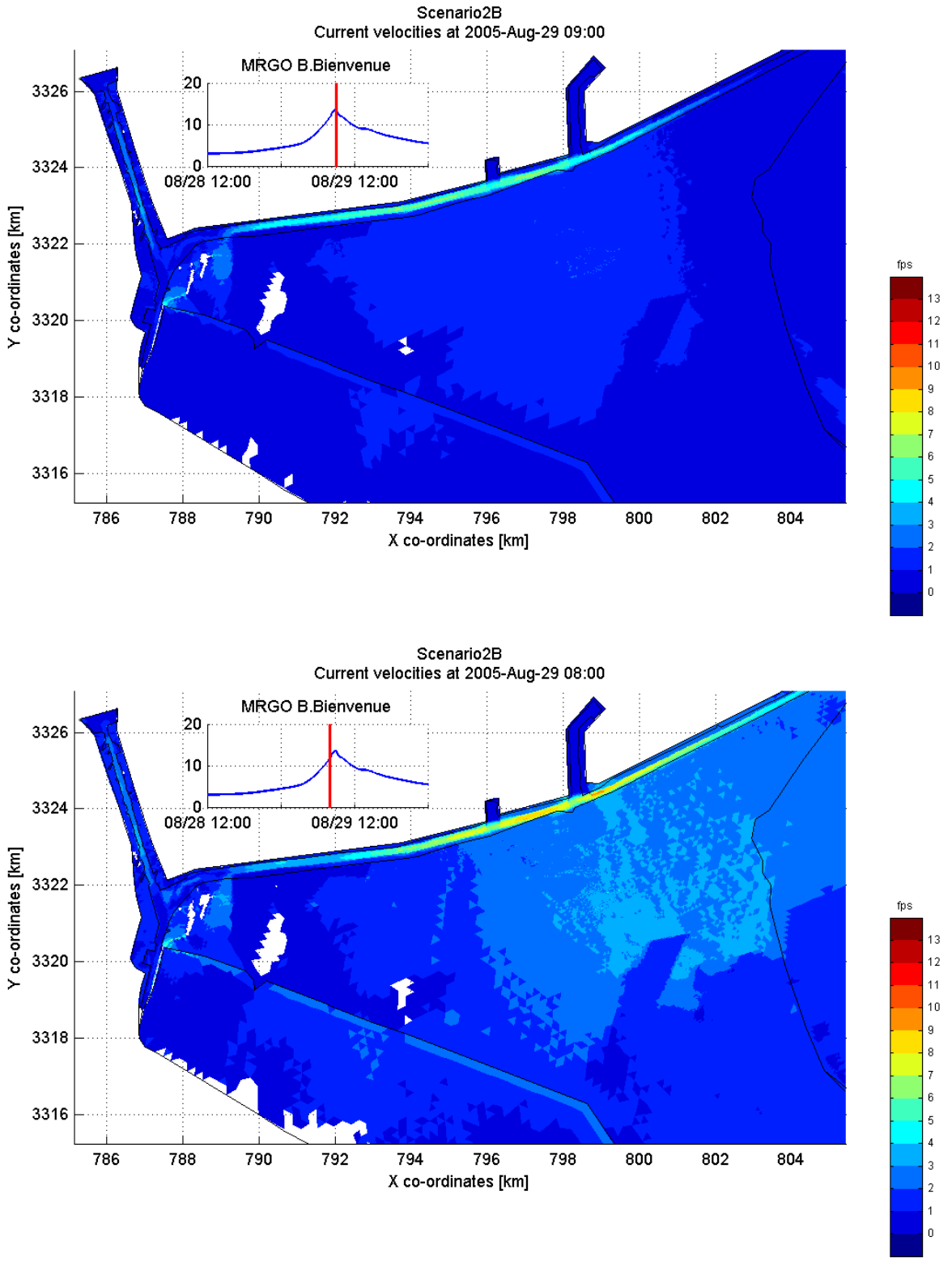


Figure A.18b: Spatial current velocities for Scenario 2B at 6:00am, 7:00am local time. Note the low current velocities except in the GIWW where velocities up to 9 feet per second are found and where the surge is making use of the channel opportunity to enhance discharge.



FigureA.18c: Spatial current velocities for Scenario 2B at 8:00am, 9:00am local time. Note almost no current velocities in the IHNC, in contrast with Scenario 1.The surge is making use of the GIWW channel to enhance discharge

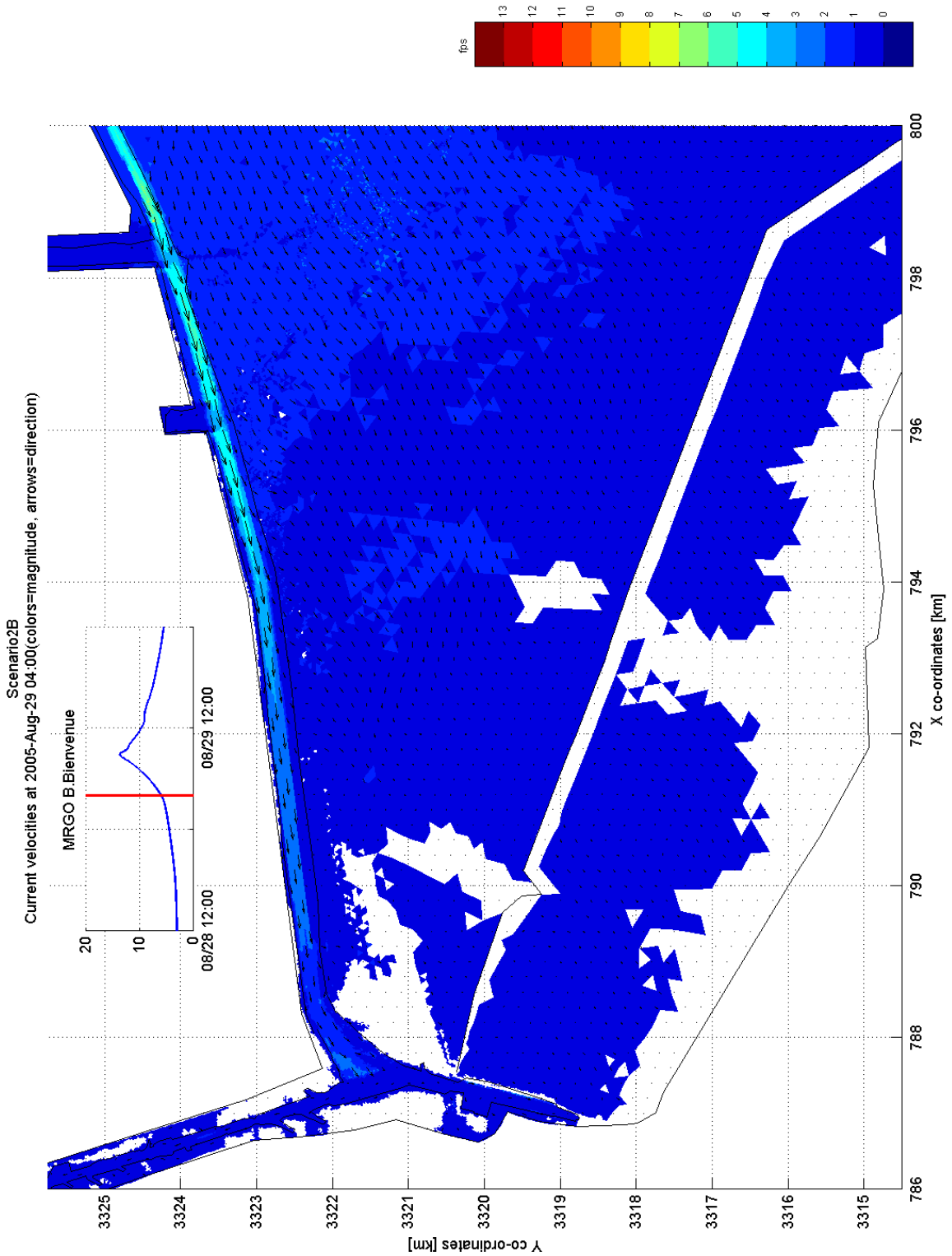


Figure A.19a: Spatial current velocities (magnitude with color scale, direction with arrows) close up of MRGO Reach 1 for Scenario 2B at 4:00am, 5:00am local time. Note not much flow in the MRGO Reach 1.

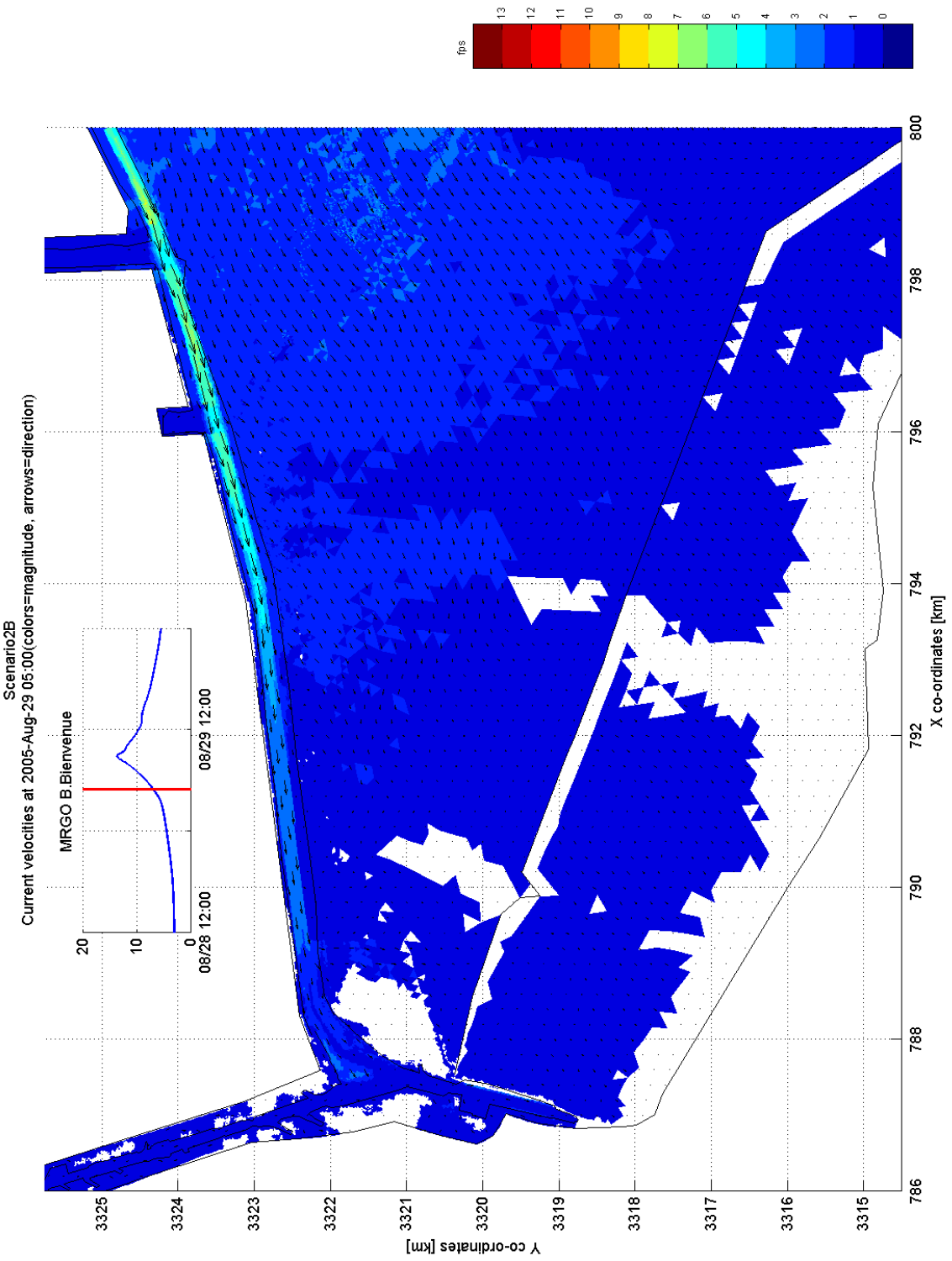


Figure A.19b: Spatial current velocities (magnitude with color scale, direction with arrows) close up of MRGO Reach 1 for Scenario 2B at 5:00am local time. Note overtopping of the 40 Arpent levee has started.

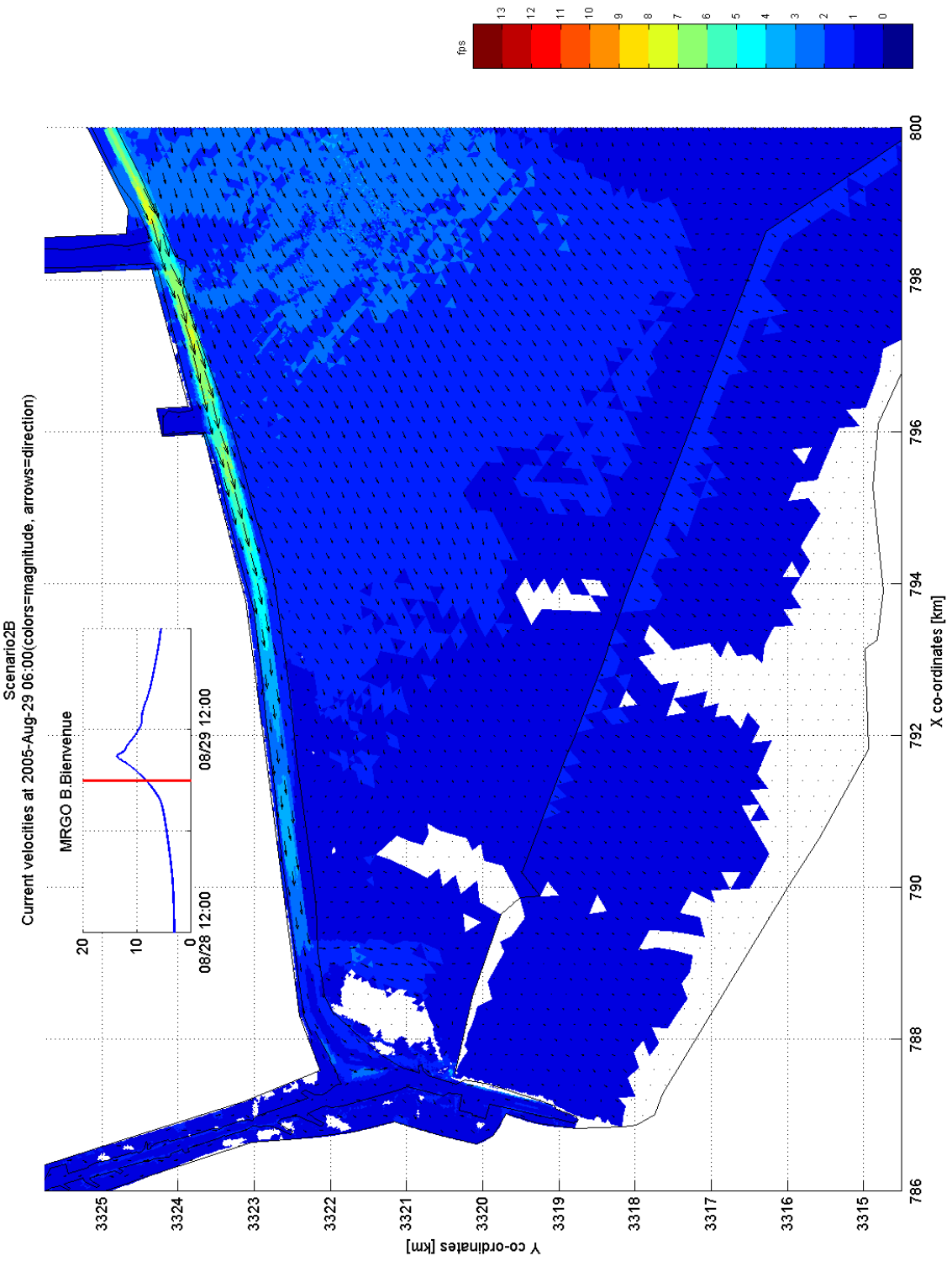


Figure A.19c: Spatial current velocities (magnitude with color scale, direction with arrows) close up of MRGO Reach 1 for Scenario 2B at 6:00am local time. Note almost the total length of the 40 Arpent levee is overflowing.

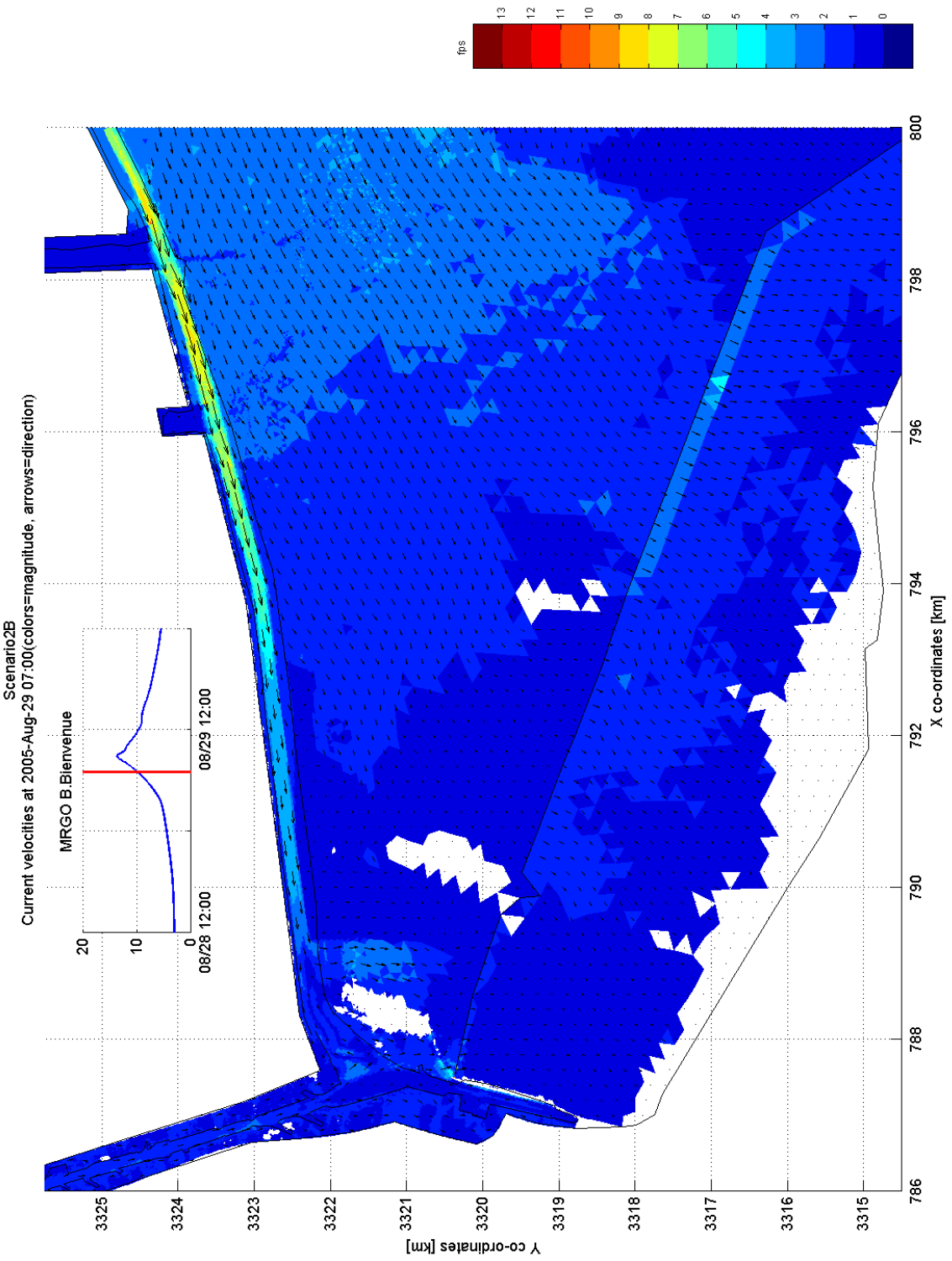


Figure A.19d: Spatial current velocities (magnitude with color scale, direction with arrows) close up of MRGO Reach 1 for Scenario 2B at 7:00am local time. Note overtopping over total length of 40 Arpent levee at maximum velocities of 3 to 5 feet per second.

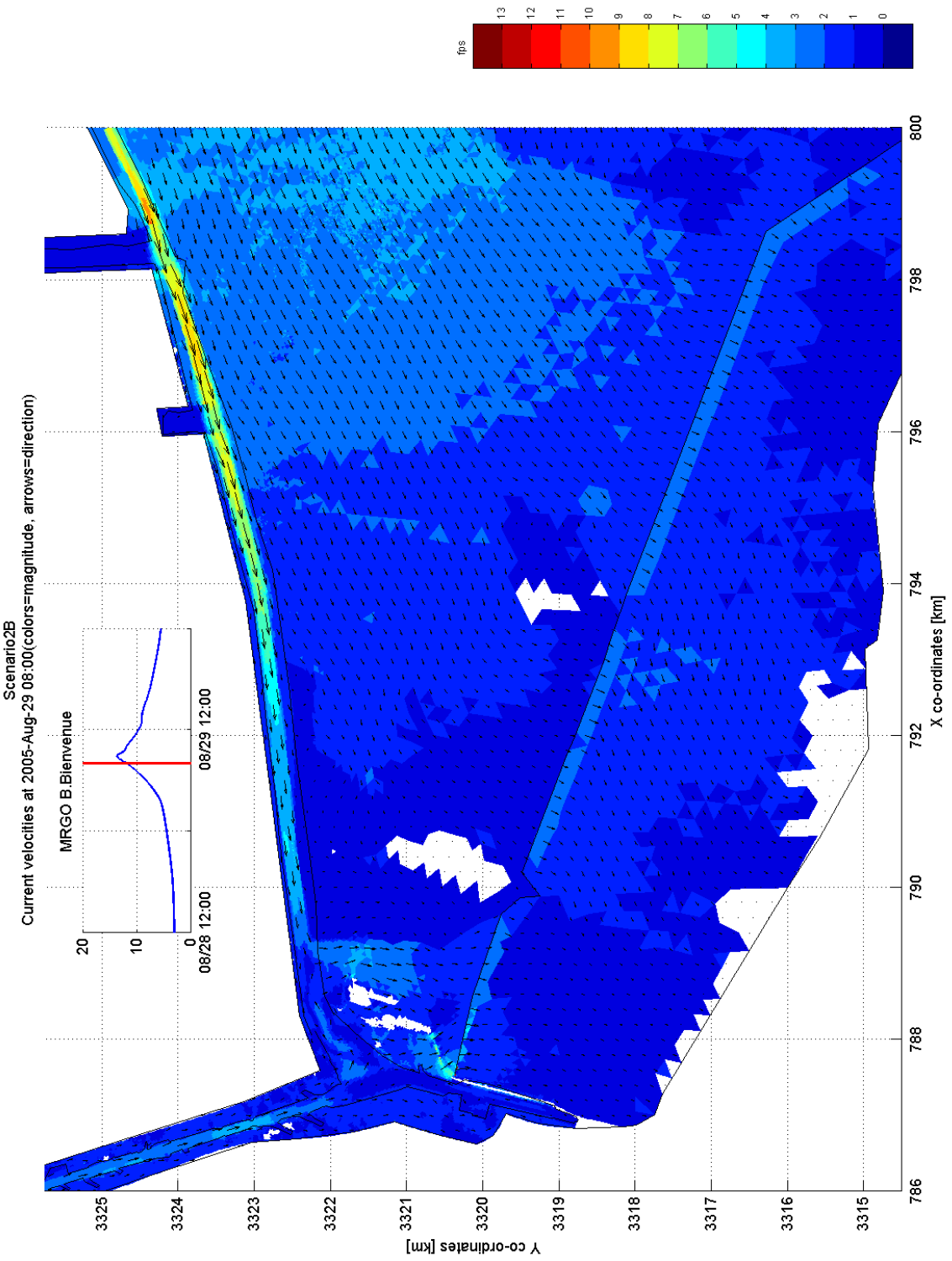


Figure A.19e: Spatial current velocities (magnitude with color scale, direction with arrows) close up of MRGO Reach 1 for Scenario 2B at 8:00am local time. Note the currents in the IHNC are directed to the south in contrast with Scenario 1. The overtopping of the 40 Arpent levee continues at 3 feet per second.

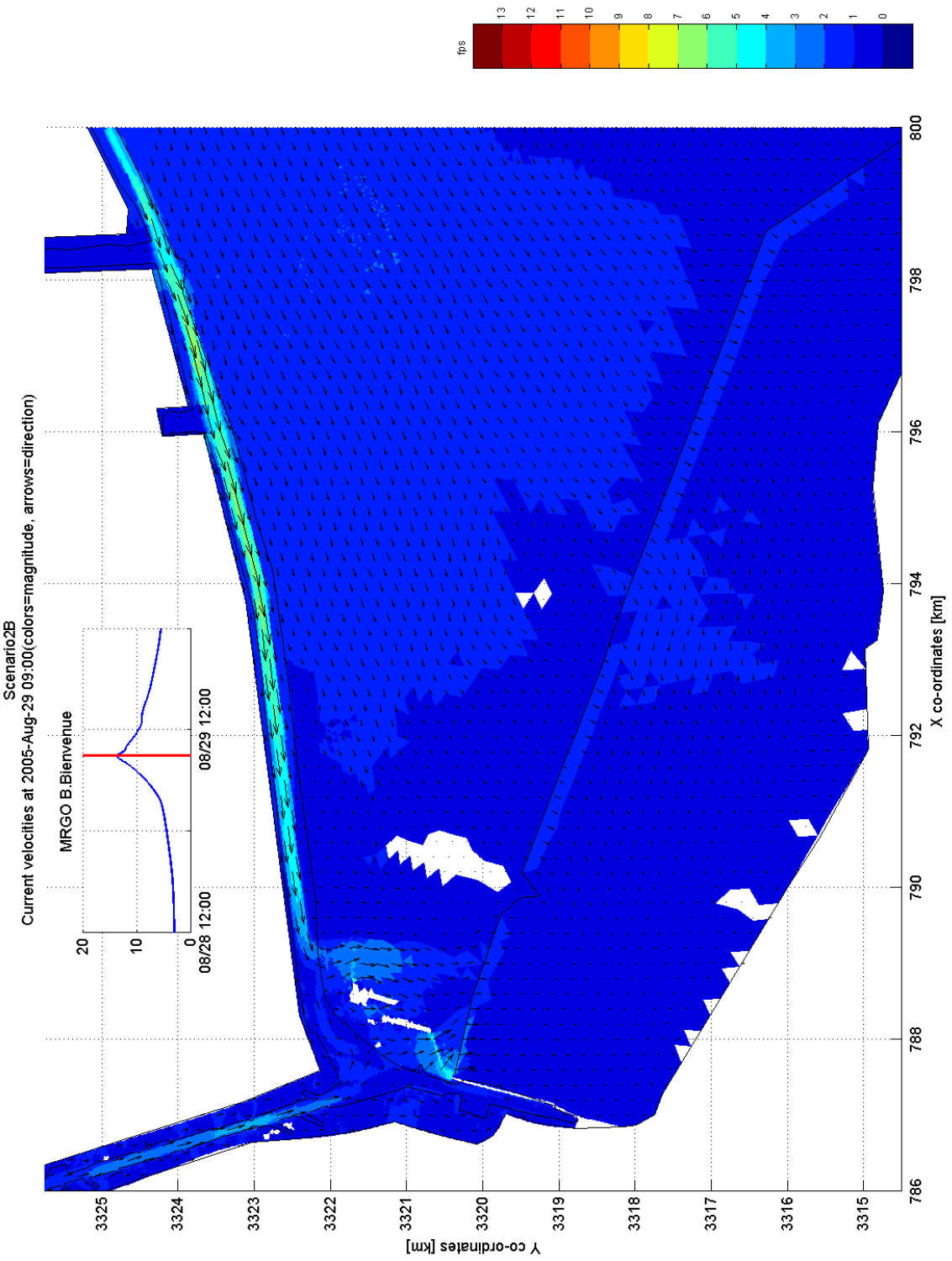


Figure A.19f: Spatial current velocities (magnitude with color scale, direction with arrows) close up of MRGO Reach 1 for Scenario 2B at 9:00am local time. Note the currents in the IHNC are still southwards, in contrast with Scenario 1. The overtopping of the 40 Arpent levee slows down to 1-2 feet per second.

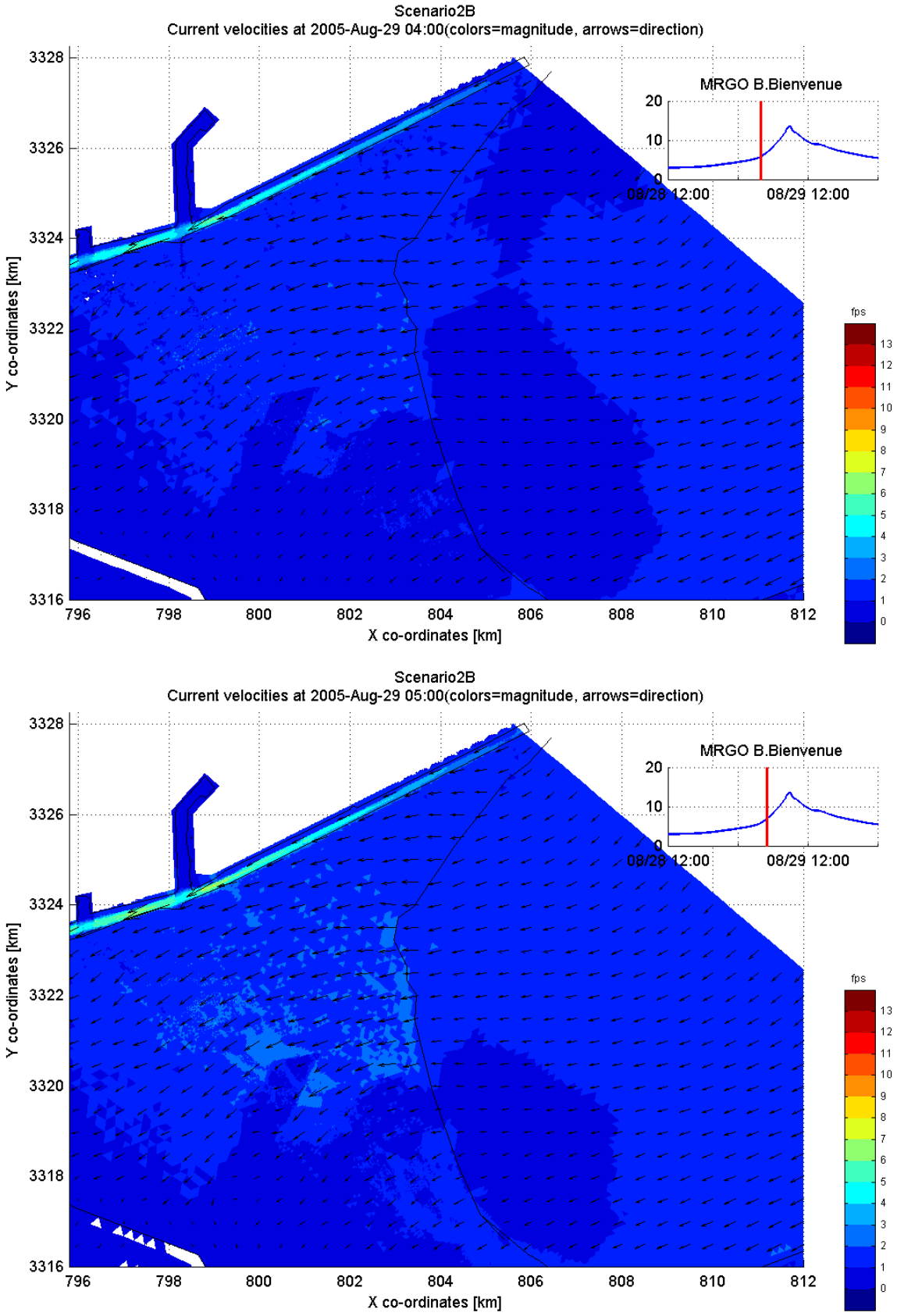


Figure A.20a: Spatial current velocities (magnitude with color scale, direction with arrows) close up of GIWW/Lake Borgne for Scenario 2B at 4:00am, 5:00am local time.

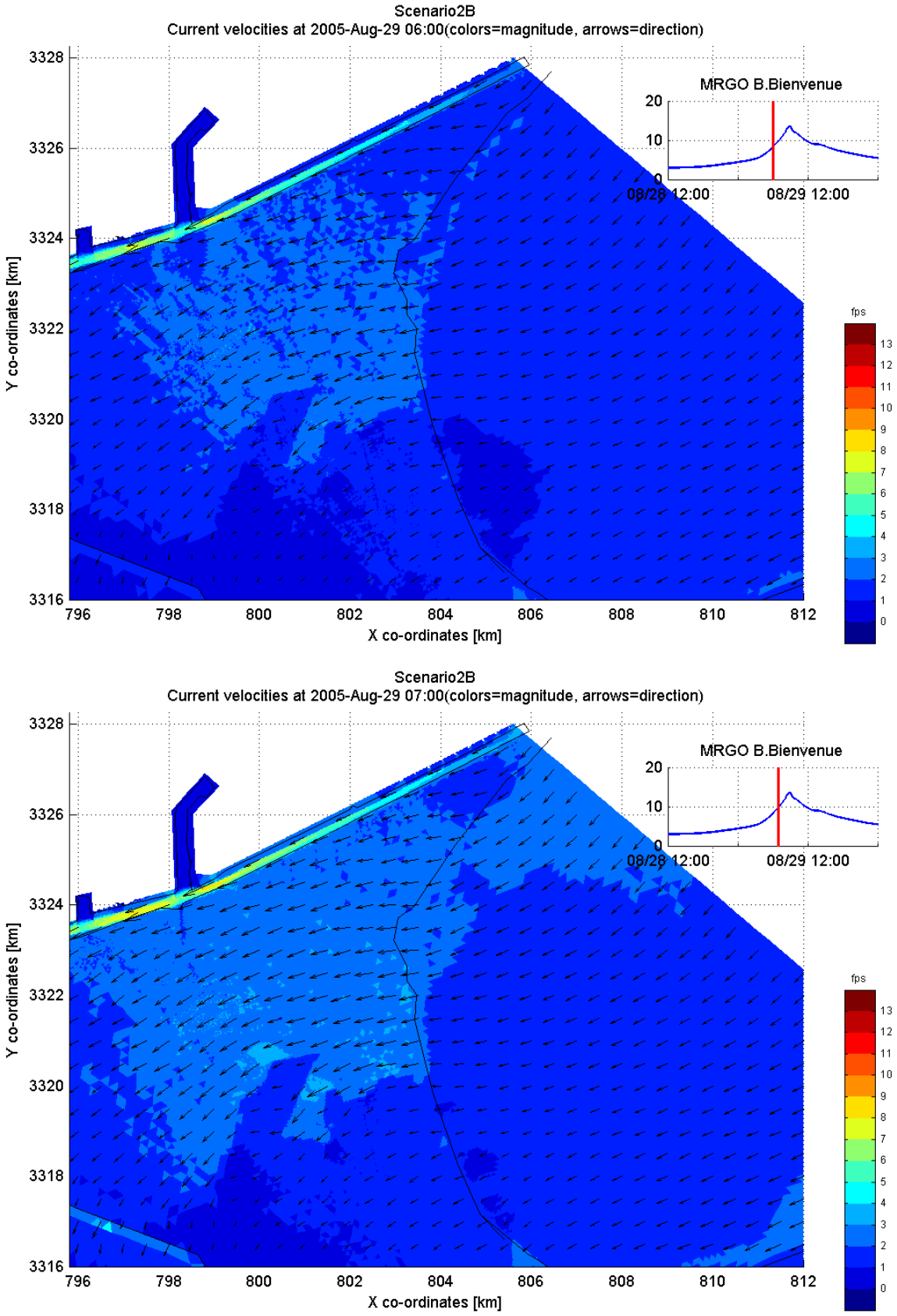


Figure A.20b: Spatial current velocities (magnitude with color scale, direction with arrows) close up of GIWW/Lake Borgne for Scenario 2B at 6:00am, 7:00am local time.

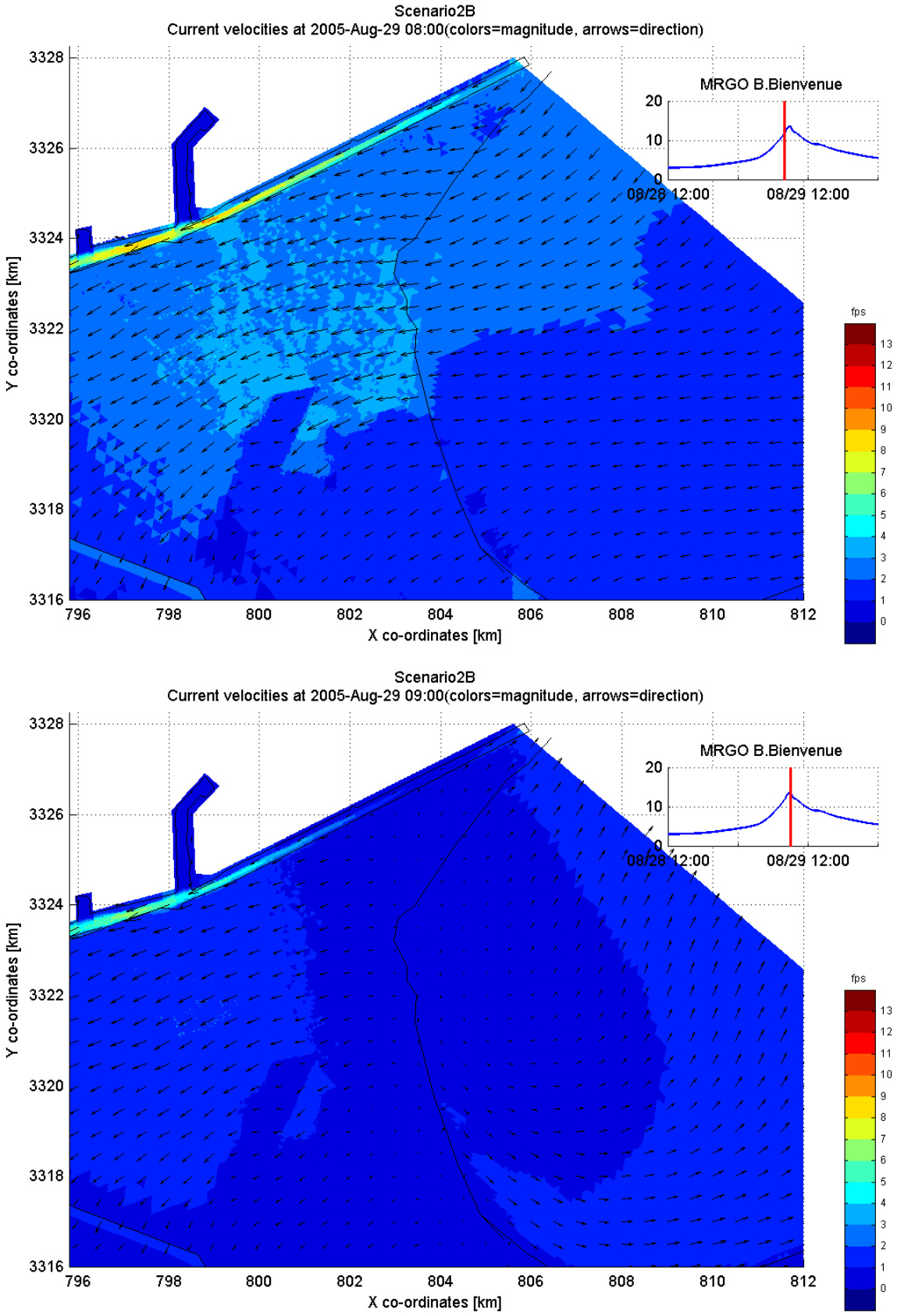


Figure A.20c: Spatial current velocities (magnitude with color scale, direction with arrows) close up of GIWW/Lake Borgne for Scenario 2B at 8:00am, 9:00am local time. Note the flow direction on Lake Borgne is changing to northeast at 9:00am.

Detailed flow information at several locations

At several locations (see Figure A.21 and Table A.12) detailed information about current velocities and water levels are given in Figure A.22. The details are summarized in Table A.13 to Table A.18.

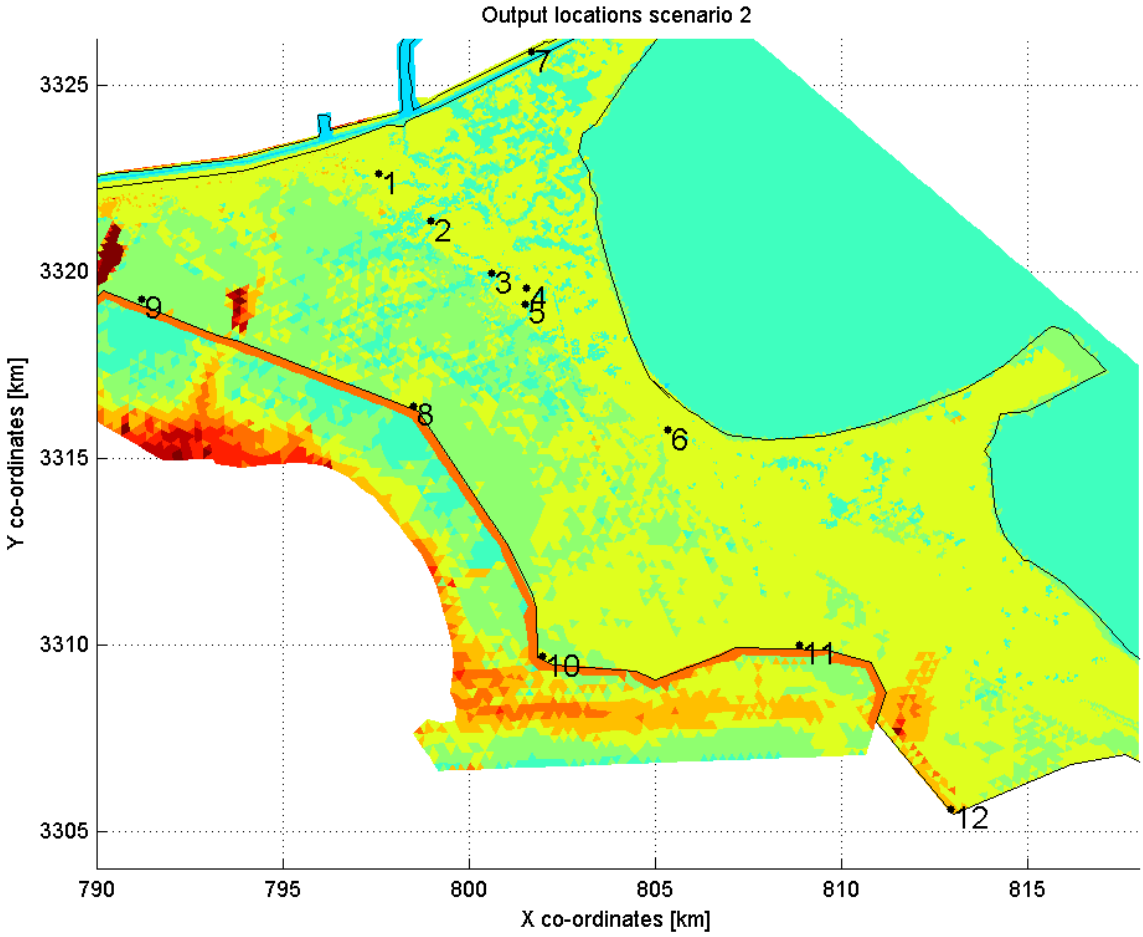


Figure A.21: Output locations Scenario 2B

Table A.12: Coordinates output locations

Loc	Name	lat [N]	lon [W]	UTM [m]	UTM [m]
1	B. Bienvenue	29°59′ 54.51″	89°54′ 55.54″	797571	3322628
2	Station 430	29°59'12.29"	89°54' 03.80"	798993	3321367
3	Loc I	29.97368°	89.884833°	800613	3319954
4	MRGO Halfway	29°58′ 5.11″	89°52′ 40.14″	801540	3319563
5	Station 540	29°57'58.19"	89°52' 32.15"	801515	3319142
6	B. Dupre	29°56′ 5.52″	89°50′ 12.26″	805355	3315765
7	GIWW@BackB	30° 01.597'	89°52.291'	801670	3325901
8	Loc II 40Arpent			798527	3316406
9	Loc A 40 Arpent			791213	3319277
10	Loc B 40 Arpent			801991	3309702
11	Loc C 40 Arpent			808892	3310020
12	Loc D 40 Arpent			812966	3305607

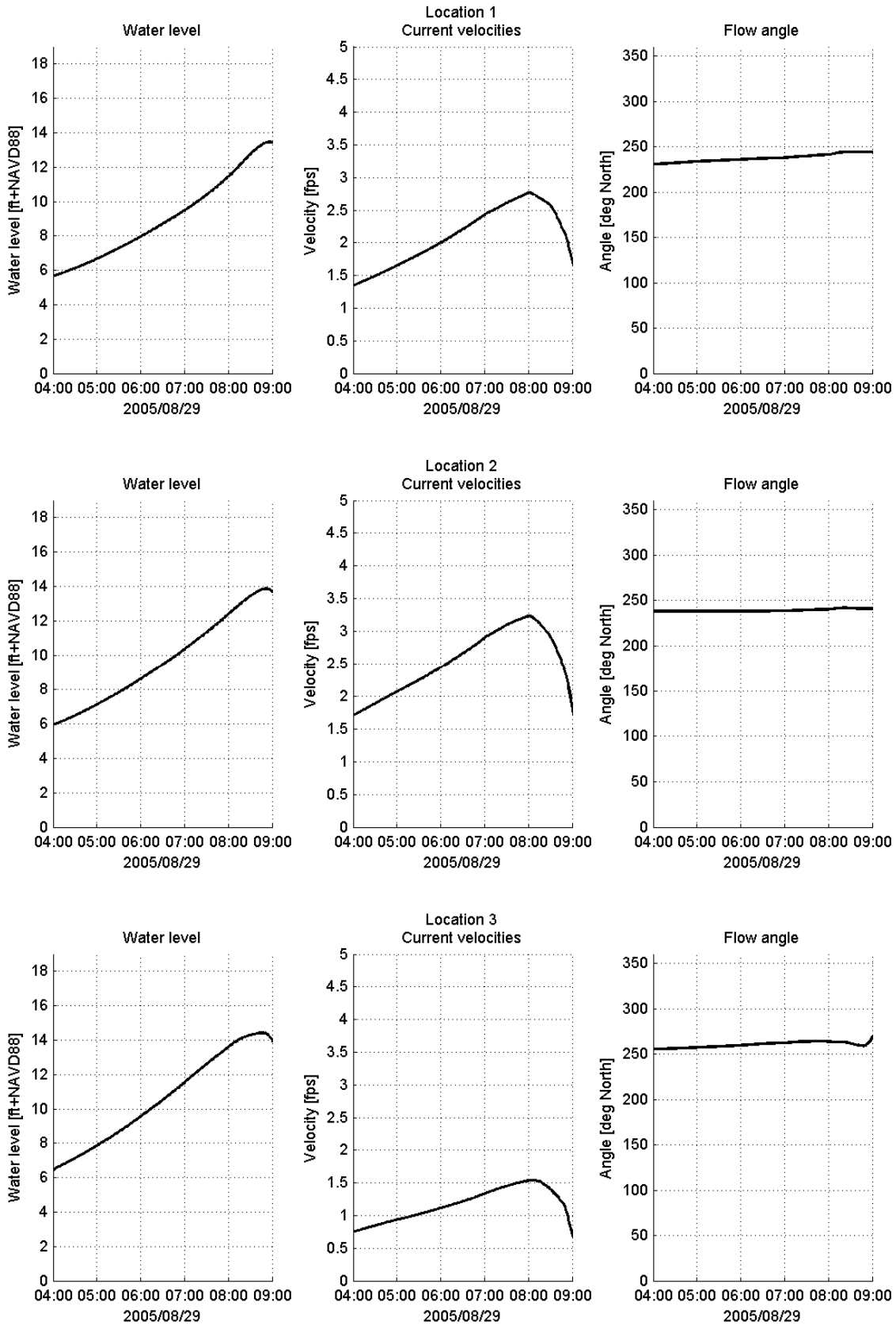


Figure A.22a: Results for location 1, 2 and 3 Scenario 2B from 4:00am to 9:00am

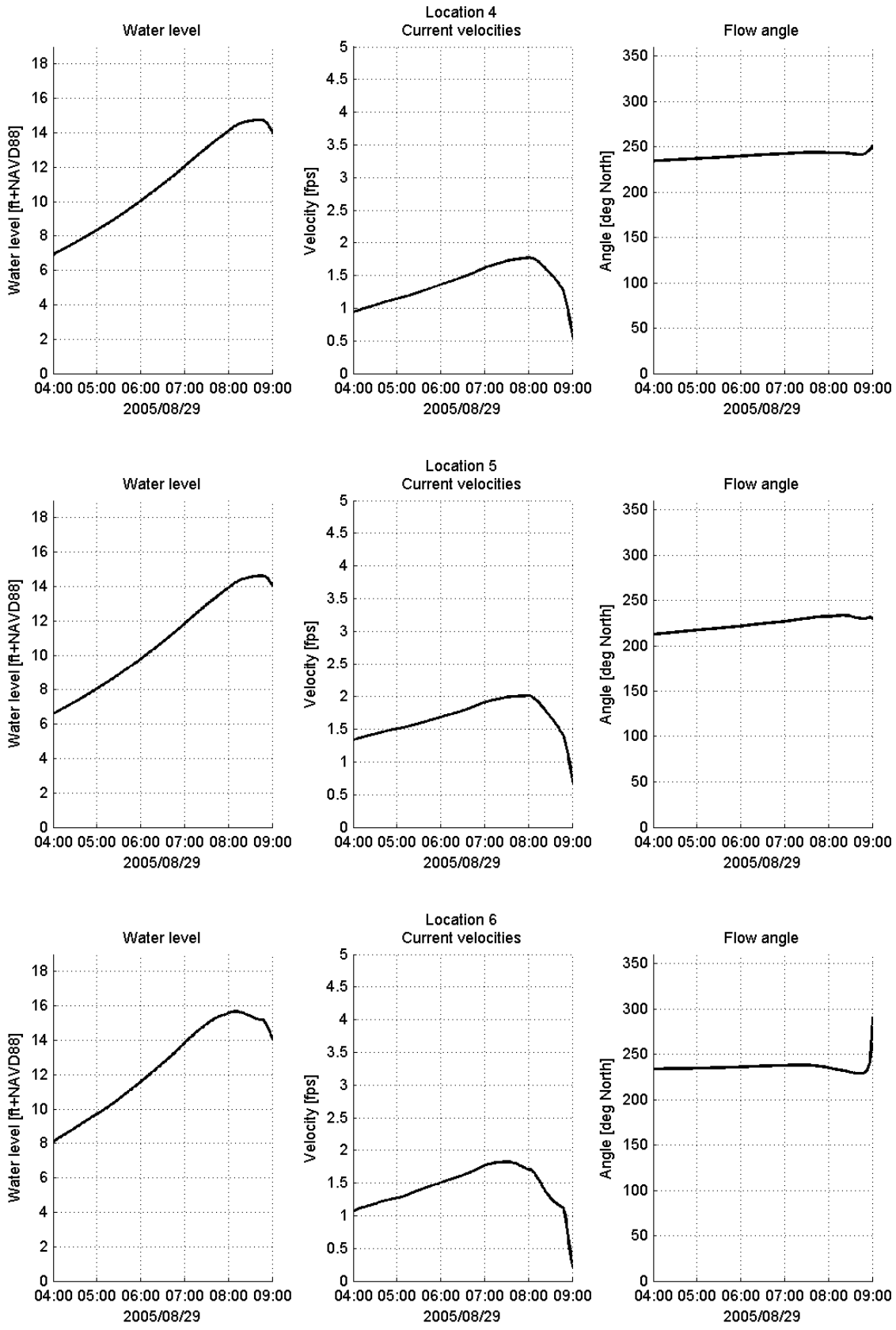


Figure A.22b: Results for location 3, 4 and 5 Scenario 2B from 4:00am to 9:00am

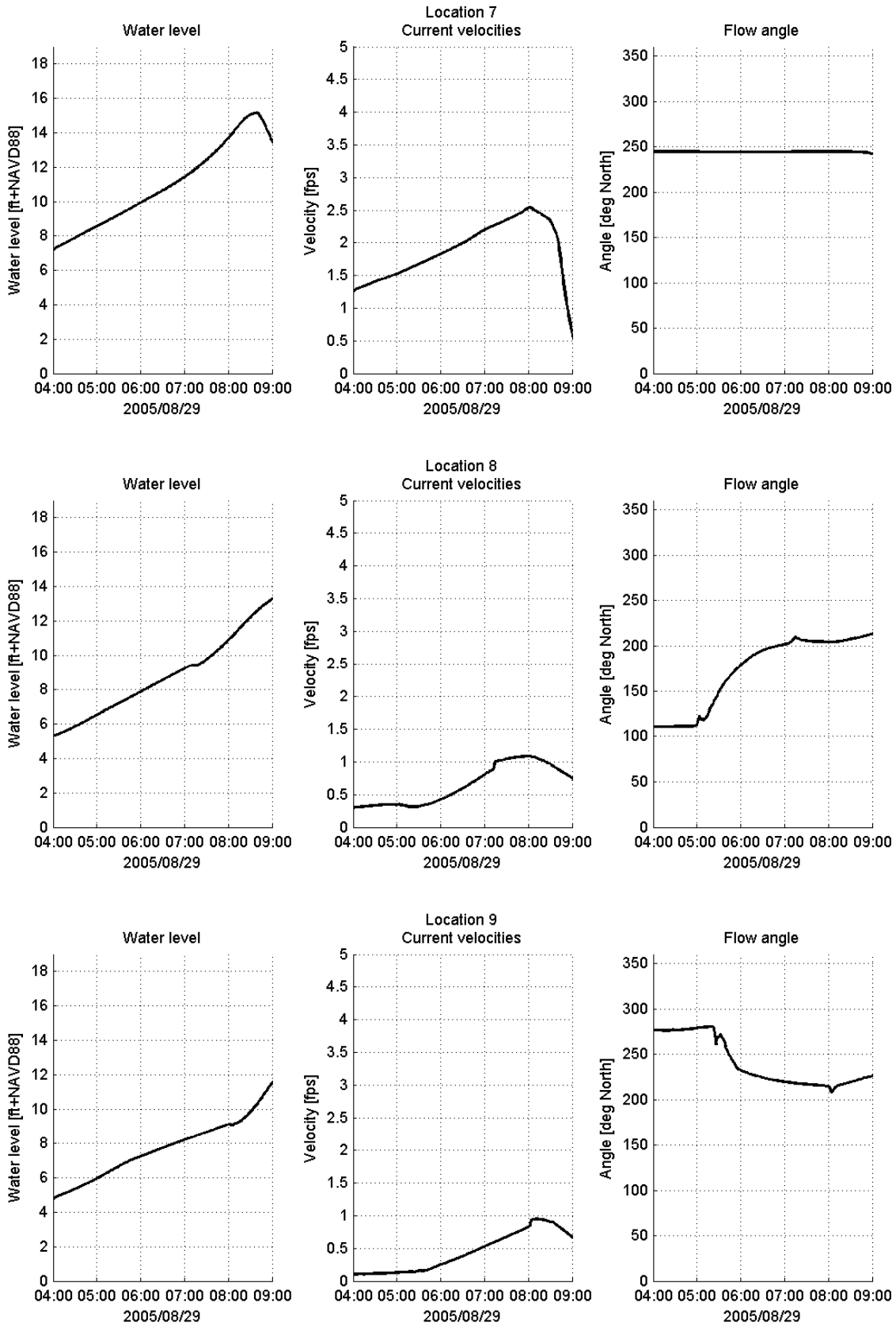


Figure A.22c: Results for location 7, 8 and 9 Scenario 2B from 4:00am to 9:00am

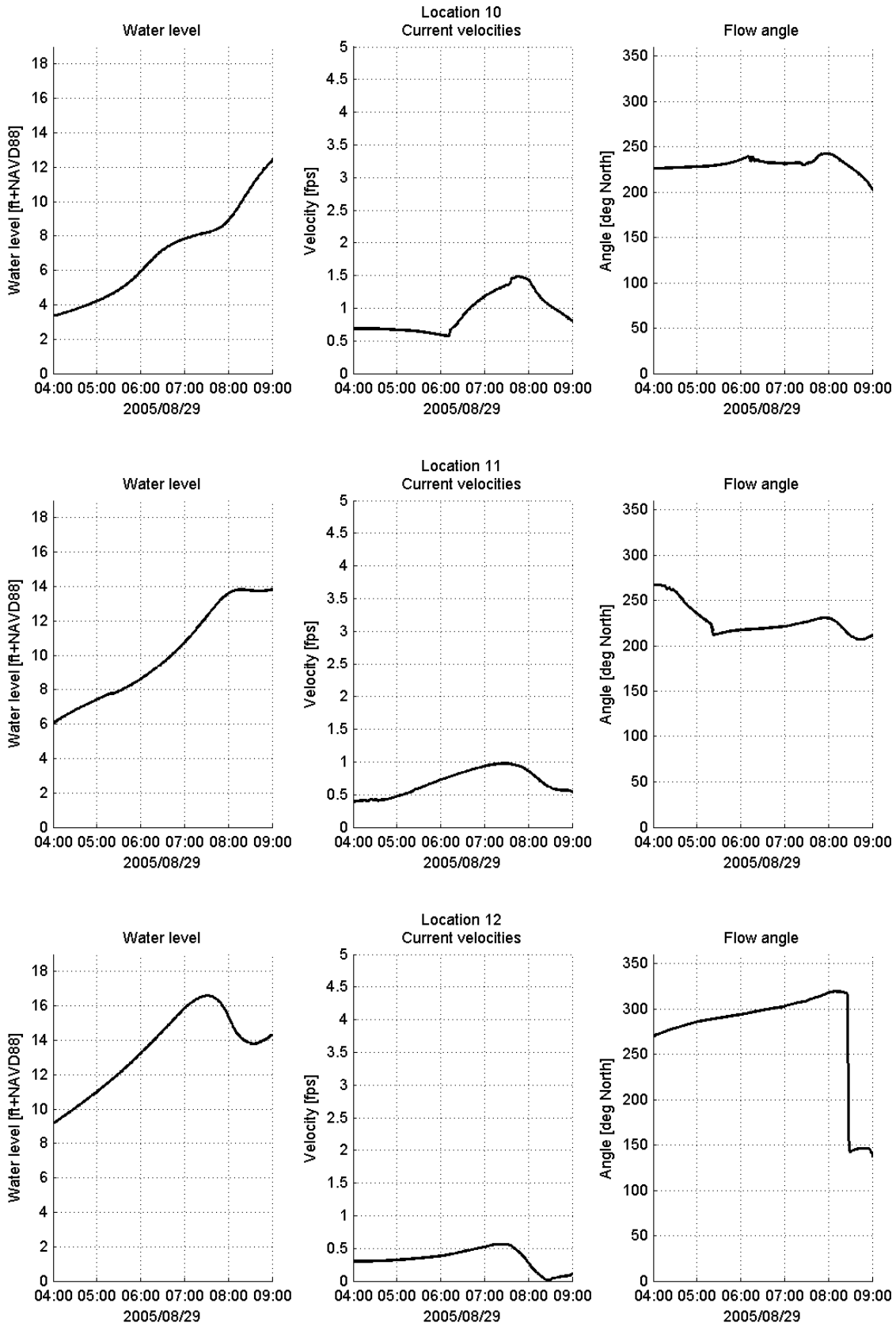


Figure A.22d: Results for location 10, 11 and 12 Scenario 2B from 4:00am to 9:00am

Table A.13: Summary results Scenario 2B at 29th August 2005 4:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	5.67	1.34	231
2	Station 430	5.92	1.70	238
3	Loc I	6.47	0.75	255
4	MRGO Halfway	6.93	0.94	234
5	Station 540	6.59	1.34	213
6	B. Dupre	8.12	1.07	234
7	GIWW@BackB	7.23	1.27	244
8	Loc II 40Arpent	5.27	0.30	110
9	Loc A 40 Arpent	4.82	0.10	276
10	Loc B 40 Arpent	3.34	0.68	226
11	Loc C 40 Arpent	6.06	0.39	267
12	Loc D 40 Arpent	9.16	0.30	270

Table A.14: Summary results Scenario 2B at 29th August 2005 5:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	6.66	1.65	234
2	Station 430	7.11	2.07	238
3	Loc I	7.87	0.94	257
4	MRGO Halfway	8.34	1.15	237
5	Station 540	8.04	1.50	218
6	B. Dupre	9.71	1.27	234
7	GIWW@BackB	8.56	1.52	244
8	Loc II 40Arpent	6.51	0.33	112
9	Loc A 40 Arpent	5.96	0.13	279
10	Loc B 40 Arpent	4.19	0.67	228
11	Loc C 40 Arpent	7.40	0.47	236
12	Loc D 40 Arpent	11.01	0.32	286

Table A.15: Summary results Scenario 2B at 29th August 2005 6:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	7.96	2.00	236
2	Station 430	8.61	2.44	238
3	Loc I	9.56	1.12	259
4	MRGO Halfway	10.05	1.36	240
5	Station 540	9.80	1.68	222
6	B. Dupre	11.59	1.50	236
7	GIWW@BackB	9.93	1.83	244
8	Loc II 40Arpent	7.86	0.42	179
9	Loc A 40 Arpent	7.25	0.25	232
10	Loc B 40 Arpent	5.92	0.59	236
11	Loc C 40 Arpent	8.60	0.72	218
12	Loc D 40 Arpent	13.24	0.38	294

Table A.16: Summary results Scenario 2B at 29th August 2005 7:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	9.49	2.43	238
2	Station 430	10.37	2.90	239
3	Loc I	11.54	1.33	262
4	MRGO Halfway	12.04	1.61	242
5	Station 540	11.85	1.91	227
6	B. Dupre	13.84	1.77	238
7	GIWW@BackB	11.43	2.20	244
8	Loc II 40Arpent	9.22	0.80	202
9	Loc A 40 Arpent	8.21	0.53	220
10	Loc B 40 Arpent	7.82	1.18	231
11	Loc C 40 Arpent	10.76	0.93	222
12	Loc D 40 Arpent	15.86	0.52	302

Table A.17: Summary results Scenario 2B at 29th August 2005 8:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	11.45	2.76	241
2	Station 430	12.40	3.23	240
3	Loc I	13.60	1.53	264
4	MRGO Halfway	14.10	1.77	243
5	Station 540	13.93	2.01	233
6	B. Dupre	15.56	1.71	235
7	GIWW@BackB	13.70	2.54	244
8	Loc II 40Arpent	10.88	1.08	205
9	Loc A 40 Arpent	9.09	0.82	214
10	Loc B 40 Arpent	8.90	1.43	242
11	Loc C 40 Arpent	13.61	0.86	231
12	Loc D 40 Arpent	15.37	0.28	318

Table A.18: Summary results Scenario 2B at 29th August 2005 9:00am

Loc	Name	H (ft+NAVD)	Vel (fps)	Dir (°N)
1	B. Bienvenue	13.44	1.71	244
2	Station 430	13.72	1.80	241
3	Loc I	14.01	0.70	268
4	MRGO Halfway	14.07	0.59	250
5	Station 540	14.09	0.71	231
6	B. Dupre	14.10	0.24	273
7	GIWW@BackB	13.50	0.59	242
8	Loc II 40Arpent	13.27	0.75	213
9	Loc A 40 Arpent	11.54	0.67	226
10	Loc B 40 Arpent	12.37	0.80	203
11	Loc C 40 Arpent	13.82	0.54	212
12	Loc D 40 Arpent	14.30	0.10	139

A.3 Scenario 2D: The 'virgin' no-MRGO Scenario and a simulated Katrina storm with spoil piles along the MRGO and 40 Arpent levee crest at 6.5 ft+NAVD

A.3.1 Description of Scenario

In order to interpret the full impacts of the MRGO we decided to run a Katrina storm with a scenario run without the MRGO channel and with spoil piles along the MRGO Reach 1 and 2. For this, we added the spoil piles to the situation similar to the late 1950s. Accordingly, we simulate surge along the shores of Lake Borgne in a model in which we change the Scenario 1 model input in the following ways:

(1) 90% reduction in cross-section area of MRGO Reach 1 to the dimensions of the GIWW (pre-MRGO);
(2) MRGO Reach 2 is removed and replaced with land at the elevation of the surrounding marsh and swamp areas;
(3) Spoil piles along MRGO Reach 2 are added to the topography;
(4) Bayou LaLoutre ridge is restored to fill-in the hole dredged for MRGO Reach 2;
(5) The area between the 40 Arpent levee and the Mississippi is added to the model grid. The pre-Katrina crest level of 6.5 ft NAVD is used for the 40 Arpent levee.
(6) The Cypress trees originally present between the MRGO and the 40 Arpent levees have influence on the water current velocities and the wind velocities. A higher Manning's roughness is used for the Cypress forests reflecting their greater frictional impacts on surge currents, and the wind velocities are reduced by 80% inside the Cypress forests due to the wind break/canopy effect of tall forests.

A.3.2 FINEL model input data

The FINEL model is set up to utilize the metric system, so all data is thus subsequently converted to feet. The coordinate system used in the simulations is UTM (zone 15 R). Input data that was received in longitude and latitude was translated accordingly.

Model grid
The model grid used for Scenario 2D is equal to the model grid used in Scenario 2C, see section 2.2.2.

Bathymetry and Topography
The bathymetry for Scenario 2D is modified to represent the conditions prior to the construction of the MRGO (similar to Scenario 2B), but with the spoil piles along MRGO Reach 2. Reach 2 of the MRGO itself is filled to the height of the surrounding marshes and swamps in the grid. Reach 1 is modified to the original GIWW design dimensions of 150 ft wide and 12 ft deep, as provided by the Robinson experts. The location, elevation and slopes of the spoil piles along MRGO Reach 2 were provided by the Robinson experts and added to the topography.
The marshes and swamps around Lake Borgne are, where needed, restored to a 1950s elevation of 2.5 ft+NAVD88. A land-water map provided by the Robinson experts has been used to construct the original small water streams in the marshes. The topography of the area between the 40 Arpent levee and the Mississippi is taken from LIDAR data, provided by Robinson experts. The 40 Arpent levee has a pre-Katrina crest level of 6.5 ft+NAVD88. The resulting topography and bathymetry for the model area are shown in Figure A.23.

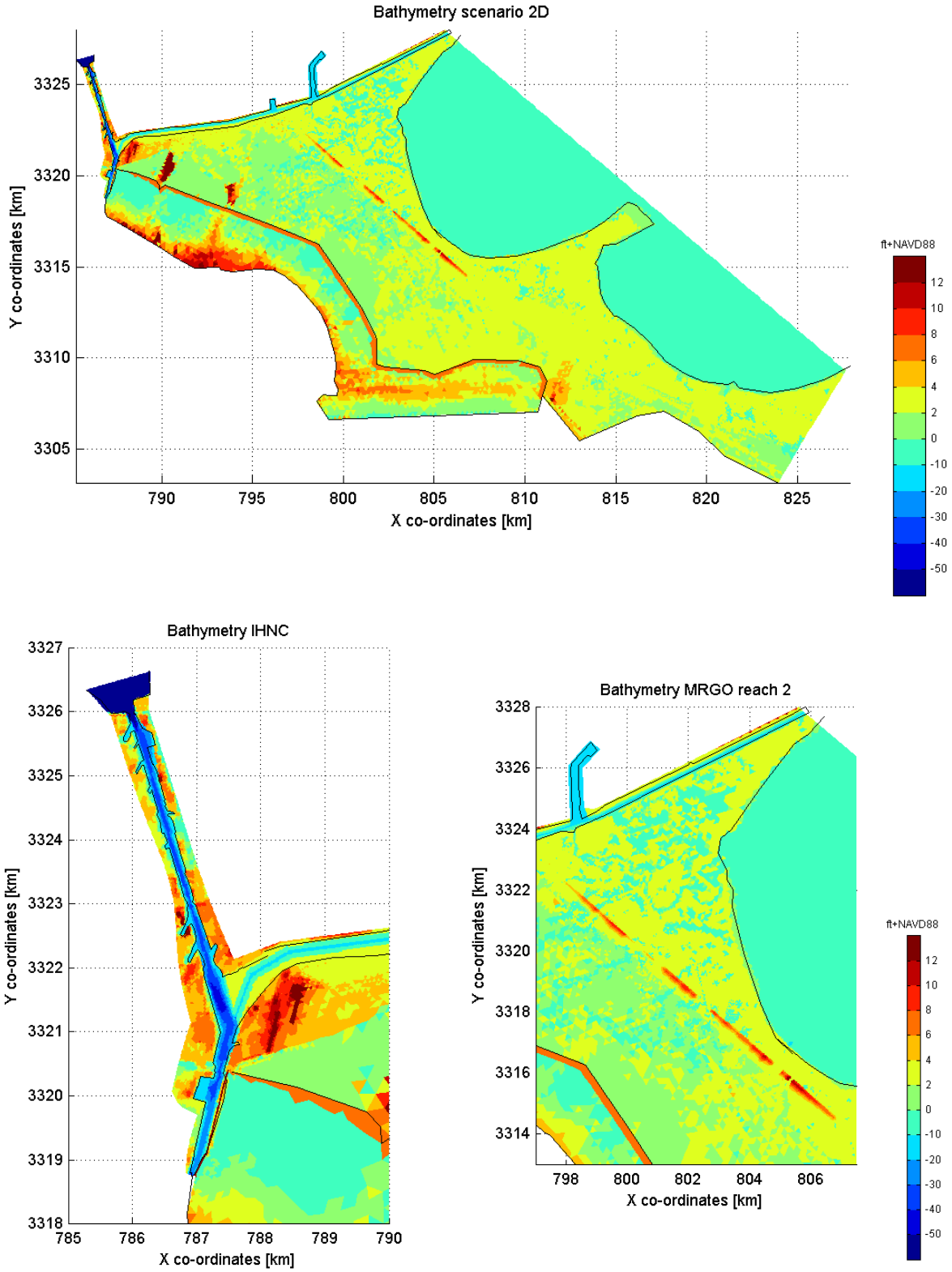


Figure A.23: Bathymetry FINEL model area Scenario 2D

Simulation period

The simulation starts at 12h00 LT 28th August 2005 and continues until 24h00 29th August 2005.

Boundary conditions
The boundary conditions consist of water level time series from the constructed Scenario 2 hydrographs, provided to us by the Robinson experts. ADCIRC outputs with and without the MRGO are used to modify Scenario 1 outputs reducing the maximum surge and delaying the peak at Shell Beach at Reach 2.

Figure A.24 shows the locations of the boundary conditions and Table A.19 gives the corresponding locations which are used for every boundary. The boundary time series themselves are shown in Figure A.25. All boundaries not mentioned in Table A.19 are closed boundaries.

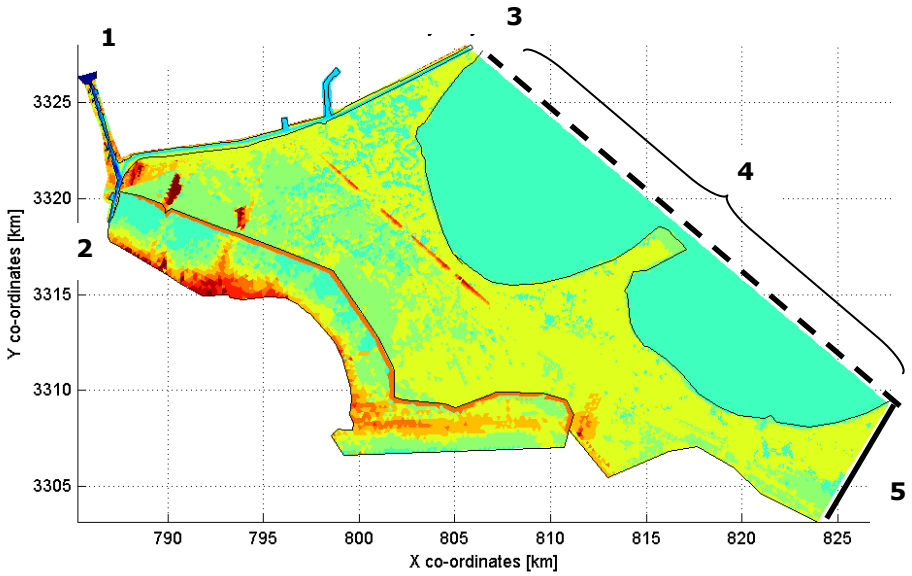


Figure A.24: Location boundary conditions FINEL flow model

Table A.19: Boundary conditions

	Boundary	*Used hydrograph2 (modified ADCIRC)*
1	Lake Pontchartrain	IHNC@LakeP
2	IHNC Locks	Closed boundary (discharge=0)
3	GIWW	NOEbackA
4	Lake Borgne	Interpolation between 3 and 5
5	MRGO	Shell Beach

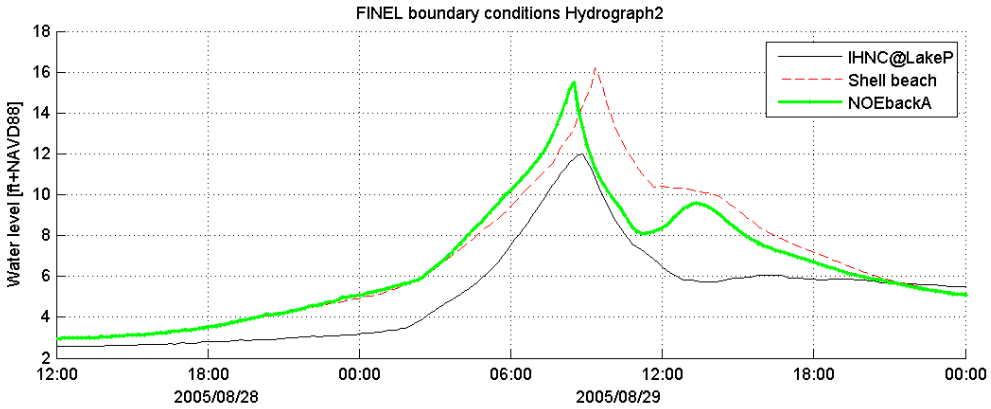


Figure A.25: Time series boundary conditions FINEL flow model Scenario 2D

Bottom roughness

In the model area a spatial variable Manning coefficient is used for the bottom roughness. The roughness coefficients used in Scenario 2D are equal to the ones used in Scenario 2B. The Manning roughness coefficients used are based on years of experience in modeling coastal environments. These data were collaborated with other data sets such as from the US Geological Survey (http://www.fhwa.dot.gov/bridge/wsp2339.pdf), the world renowned book Open-channel hydraulics [Ref. 5] and IPET [Ref. 6]. For each scenario the spatial extent of the Manning's used is based on the presence or lack of wetlands; shoreline location and presence; and lack or presence of levees. In 1958 Cypress forests existed between the MRGO and the 40 Arpent levees (Figure A.26). The Cypress trees cause friction on the flow, this influence is taken into account by a higher roughness coefficient. In a map provided by Robinson experts, two types of Cypress forests are distinguished: normal (Manning n=0.1 $m^{-1/3}s$) and dense (Manning n=0.12 $m^{-1/3}s$). The Manning roughness coefficients are shown in Figure A.27 and summarized in Table A.20.



Figure A.26: Photograph of cypress trees in swampy areas (send to us by Robinson experts)

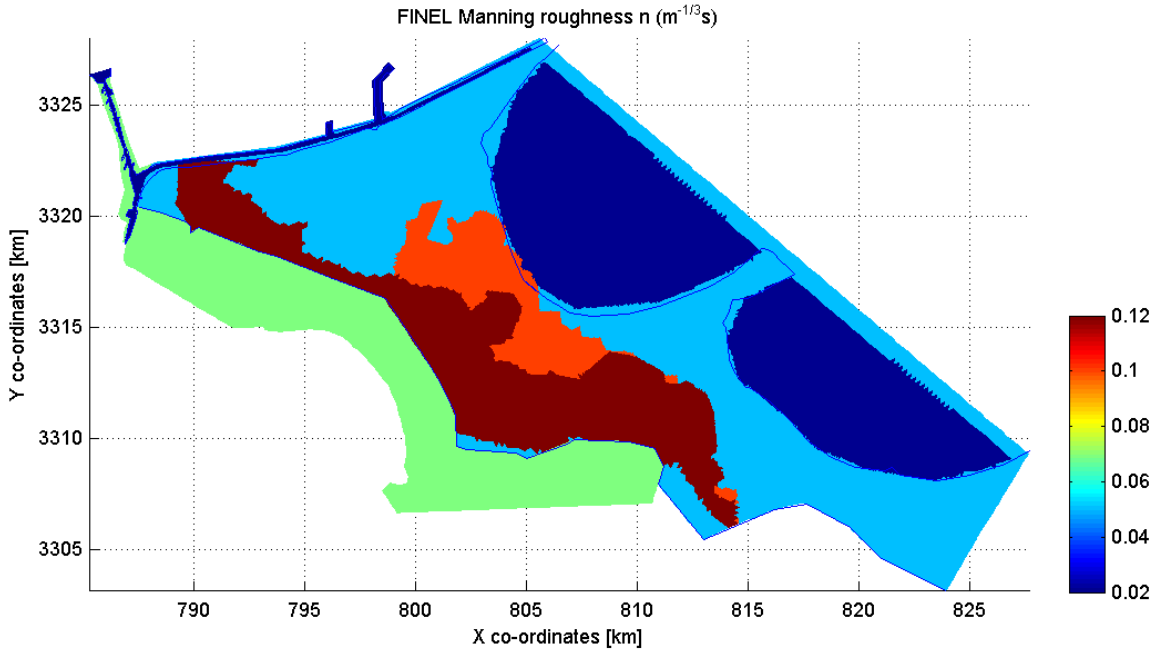


Figure A.27: Manning roughness coefficient FINEL model area Scenario 2D. The cypress areas are red (dark red = dense cypress trees, light red = normal cypress trees).

Table A.20: Manning coefficient (based on: IPET Volume IV appendix page IV-5-102 [Ref. 6])

Area	*Manning coefficient n ($m^{-1/3}s$)*
Open water	0.02
Marsh along Lake Borgne	0.05
Grass at levees	0.034
Normal Cypress forest	0.1
Dense Cypress forest	0.12
Commercial area next to IHNC	0.07
Low residential area between 40Arpent and Mississippi	0.07

Wind

To take into account the influence of wind on the water motion, spatial variable wind fields are used in the flow calculations with FINEL. The wind fields were provided to us by the Robinson experts spaced at 30 minute intervals. Within the cypress forest the influence of the wind on water movement is dramatically reduced by the trees. Therefore the wind velocities are reduced by 80% (percentage provided to us by Dr Robinson experts) within the Cypress forests (both dark red and light red areas in Figure A.27). The wind speed surface stress is calculated by:

$$\frac{\tau_{wind,x}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,x} - U_x),$$

$$\frac{\tau_{wind,y}}{\rho_{water}} = C_d \frac{\rho_{air}}{\rho_{water}} |W_{10} - U|(W_{10,y} - U_y).$$

With:

C_d = wind drag coefficient (-),
W_{10} = wind speed at 10 meter height (m/s),
U = water velocity (m/s).

The wind drag is defined by Garrat's drag formula (Garrat 1977):

$C_d = (0.75 + 0.067W_{10}) \times 10^{-3}$

A.3.3 Results

The FINEL flow model is used to produce water level hydrographs, overtopping rates and discharges MRGO for Scenario 2D. See Section 2.4 for these results.