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NUMERICAL INVESTIGATION OF THE IMPACT OF CALCASIEU SHIP CHANNEL ON THE HYDRODYNAMICS AND WATER-SUBSTANCE TRANSPORT IN CALCASIEU LAKE AND SURROUNDING WETLANDS

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ABSTRACT

Calcasieu Lake is located in the heart of the Chenier Plain coastal wetland area, which is a geographical region that extends from Vermillion parish of Louisiana to Chambers county of Texas. On the north side of Calcasieu Lake, there is a heavily industrialized area and the Port of Lake Charles. A ship channel, Calcasieu Ship Channel, was constructed through the Calcasieu Lake connecting Lake Charles and Gulf of Mexico for safe navigation of crude oil, gasoline, and other products for local industries. Due to the increased size of the vessel, the ship channel was widened and deepened in recent years. However, the presence of the wide, deep ship channel made significant impact on the hydrodynamics and water-substance transport in the lake and surrounding wetlands. The impact includes frequent flooding and abnormal salinity, nutrient and pollutant concentrations. In this study, numerical simulations were conducted to study the impact. An unsteady depth-averaged shallow water equation set was implemented to simulate the hydrodynamics (1-4), while for the scalar particulate phase an unsteady depth-averaged scalar transport equation was implemented for the water-substance transport simulations. The results of flow phase agreed well with measurement data (5). The simulations with and without the ship channel were conducted and the results were compared to study the impact.

INTRODUCTION

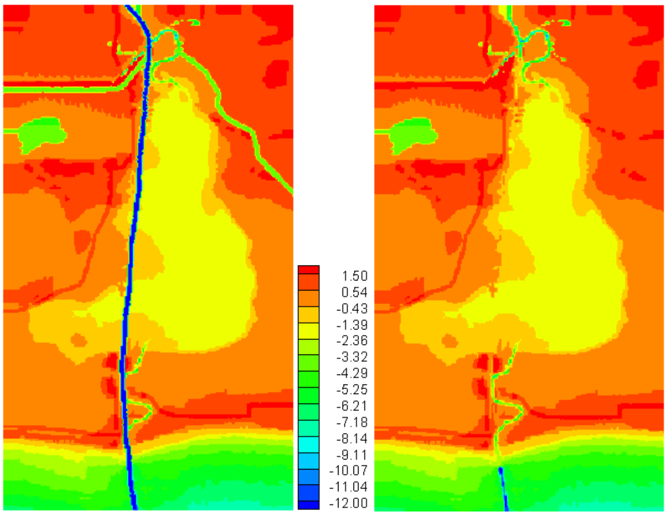
Calcasieu Lake is a shallow water lake with an averaged depth of 1.5m. It has a surface area of 256 km^2. It is downstream of a heavily industrial area, and also the major water sources of two nearby National Wildlife Refuges where are covered mostly by coastal wetlands. Therefore, the pollution, nutrient, salinity and sediment transport in the lake is critical to the health of the wetlands. Man-made structures such as Calcasieu Ship Channel in the lake altered the flows and transports causing abnormal pollution, nutrient and salinity concentrations, and excessive sedimentations. In this paper, a numerical investigation of the impact due to the ship channel was performed.

For the flow phase simulation, 2-d depth-averaged shallow water equation sets were solved (1-4). For the particulate transport simulation, Eulerian type methods were widely used in the similar applications (6, 7). In this study, a depth-averaged Eulerian scalar-transport method was implemented to simulate the pollution, nutrient and salinity transport

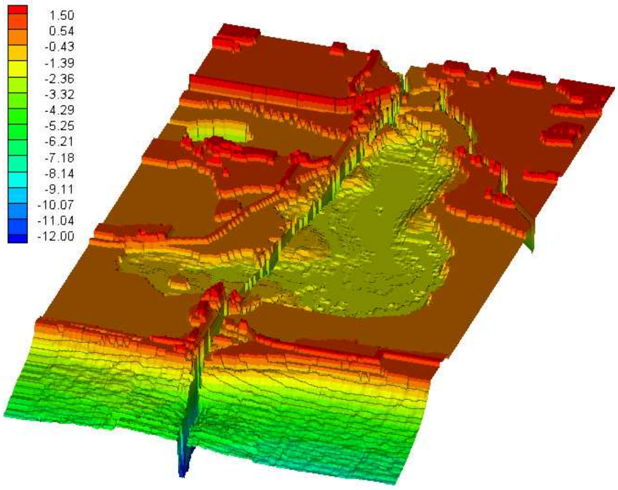
The effects of Calcasieu Ship Channel and Gulf Intracoastal Waterway (GIWW) to the lake hydrodynamics were investigated. A case using the original geometric data (8) without the ship channel and GIWW were simulated. Then both waterways, the ship channel and GIWW, were manually added to the geometric data. The depth of the ship channel is 12m and the depth of GIWW is 3.66m (12 ft). The flow and water-substance concentration results with and without the waterways were compared to study the impact. The topology contours with and without the waterways are plotted in Figure 1. Calcasieu River is located on the north of the lake and is the major source of fresh water. The waterway from west to east on the north of the lake is the GIWW. The flow direction in GIWW is from west to east. In the south, a passage connecting Calcasieu Lake and Gulf of Mexico is Calcasieu Pass. The low lands around the lake are the wetlands of two National Wildlife Refuges. The coastal highway 27 and 82 were manually added to the data too.

NUMERICAL METHOD

The current computational model for flow phase is based on (1-4). The two-dimensional shallow water equations to be solved have the form



(a) with ship channel and GIWW (b) without ship channel and GIWW



(c) 3-d view with the ship channel and GIWW

Figure 1, topology of Calcasieu Lake,

$$\begin{aligned}
\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}&=-g\frac{\partial z}{\partial x}-\gamma u\\
\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}&=-g\frac{\partial z}{\partial y}-\gamma v\\
\frac{\partial z}{\partial t}+\frac{\partial[(h+z)u]}{\partial x}+\frac{\partial[(h+z)v]}{\partial y}&=0\ ,
\end{aligned}\qquad(1)$$

where u and v are the depth-averaged velocity components in the x and y directions, respectively, z is the water surface elevation measured from the undisturbed water surface, h is the water depth also measured from the undisturbed water surface, g is the constant gravitational acceleration, and γ is the bottom friction coefficient given by

$$\gamma=\frac{g\sqrt{u^2+v^2}}{C_z^2H}\ ,\qquad(2)$$

where H=h+z is the total water depth, and C_z is the Chezy friction coefficient. The value of the Chezy number is calculated from the expression as in (9), and it is 71.3 fro Calcasieu Lake. The particulate phase transport equation is based on (7), which has the form

$$\frac{\partial(SH)}{\partial t}+\frac{\partial(USH)}{\partial x}+\frac{\partial(VSH)}{\partial y}=\frac{\partial}{\partial x}\left(\varepsilon H\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon H\frac{\partial S}{\partial y}\right)\qquad(3)$$

where S is the particulate concentration, and ε is the diffusivity. From previous study (10), the diffusivity in Calcasieu Lake varies from 0.25 to 1 m^2/s. In this paper, and average value of 0.625 m^2/s was used in the entire lake area. An Lagrangian particle tracking was also implemented and the results agreed well with results from Eq. (3).

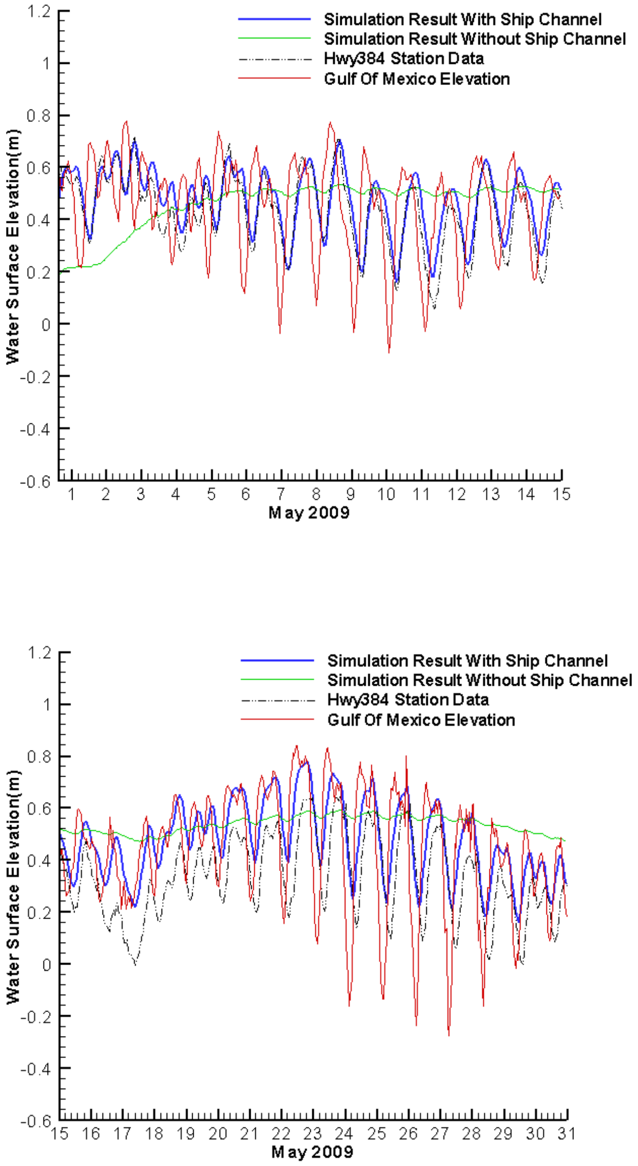
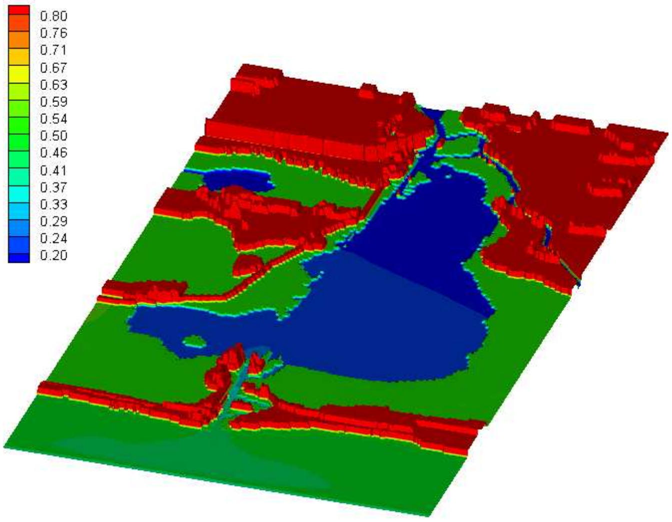
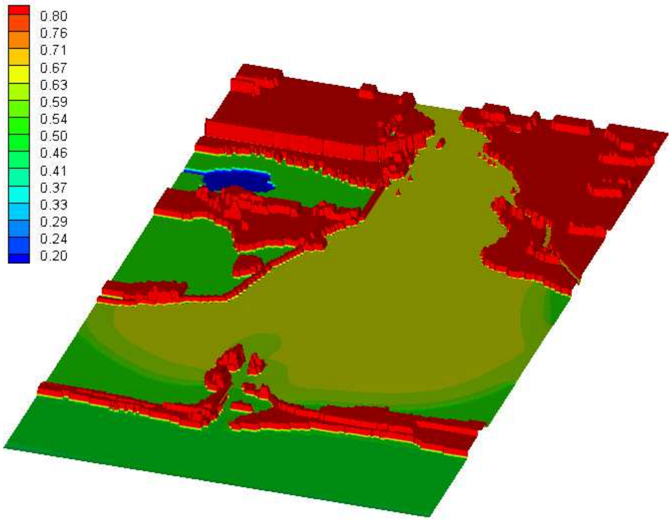


Figure 2, water-surface elevation comparison

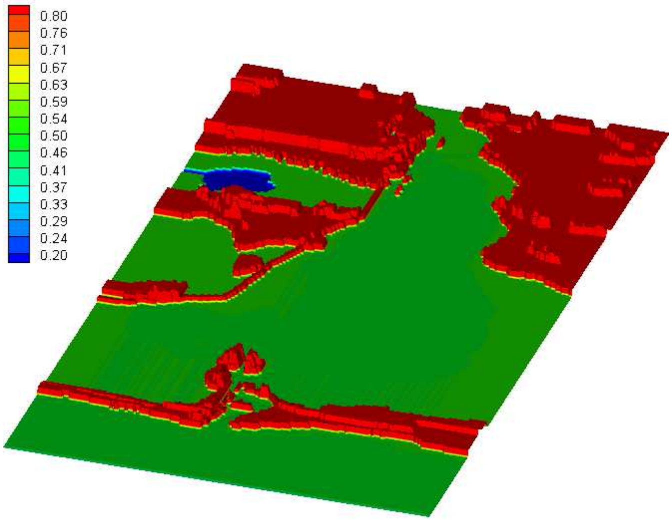


(a) low tide in the lake

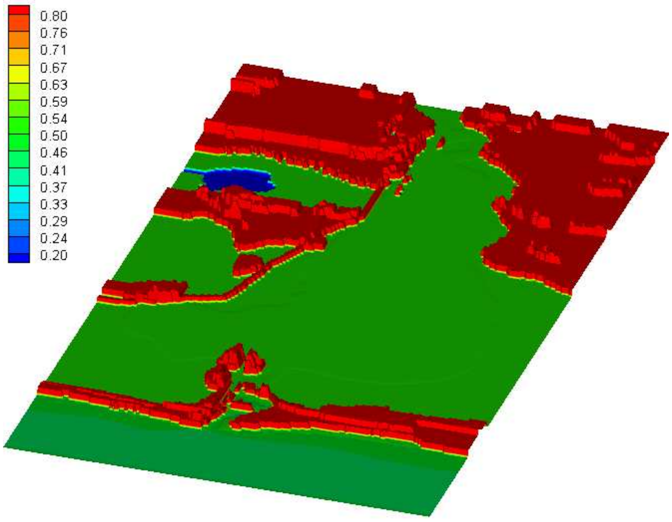


(b) high tide in the lake

Figure 3, water-surface elevation contours with the ship channel



(a) low tide in the lake



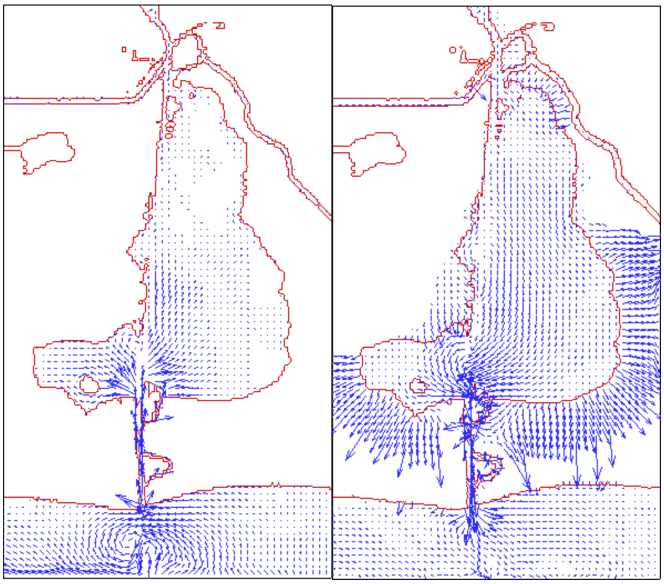
(b) high tide in the lake

Figure 4, water-surface elevation contours with the ship channel

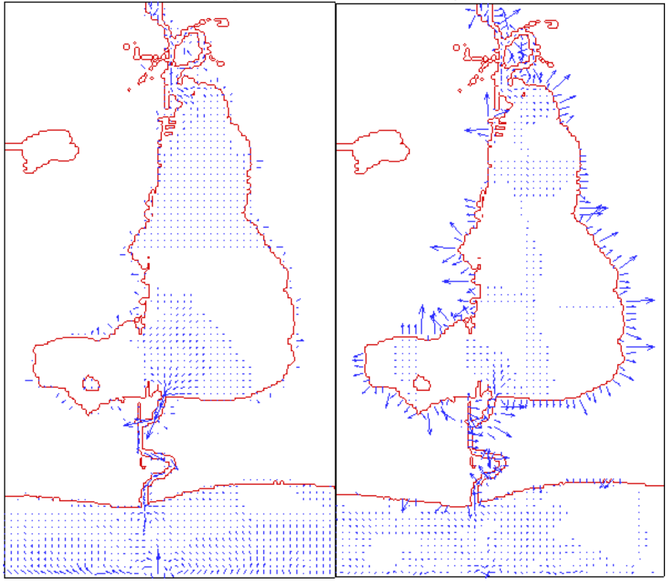
RESULTS AND DISCUSSIONS

The computational domain described in Figure 1 is between latitudes 29.710 to 30.123, and longitudes -93.445 to -93.207, which is a 25.8km by 44.8km rectangular domain. The grid number is 200x348, with dx=129.6m and dy=129.1m. A coarser grid with 1/2 of the number of grids in each dimension was tested, and no significant change was shown, which justified the existence of a grid-independent solution with the current grid resolution. Average inflow from Calcasieu River was 178 m^3/s (11), while the GIWW flow rate was set as 90 m^3/s. The unsteady ocean tidal condition of Gulf of Mexico was implemented in the simulations. A set of ocean surface elevation data from NOAA (12) was available, thus used as the outlet ocean surface elevation boundary condition of the simulation. The set of data starts from May 1st to May 31st 2009, and the time interval of two consequent data is 6 minutes. The corresponding changes of the water-surface elevation inside Calcasieu Lake were monitored and recorded during the simulation. The actual water-surface elevations were also measured inside the lake by Southwest Louisiana National Wildlife Refuge Complex C-21 Hwy 384 Station, located at the northeast corner of the lake (5). Therefore, the simulation results at the same location can be compared with the measurement data to validate the accuracy of the simulation.

Figure 2 is the comparison, which (a) is for the first 15 days and (b) is for the next 15 days of the month. In the figure, the curve for the case without the ship channel is included as well as the actual ocean elevation curve. The agreement between simulation and measurement is good. The simulation predictions match well with the measurement. The agreement proves the accuracy of the simulation.



(a) with the ship channel, left: low tide; right: high tide



(b) without the ship channel, left: low tide; right: high tide

Figure 5, vector field comparison

One interesting findings from Figure 2 is that the oscillating magnitude of the lake water is not much smaller than the tidal magnitude, which indicates the influences from Gulf of Mexico is great and the shallow lake and surrounding wetlands do not have significant effect on avoiding the ocean flood and protecting the relative inland cities. This is evidenced by severe flooding in recent hurricanes. The oscillation of the curve without the ship channel is much flatter on the other hand, and the higher peaks are lower than with the ship channel. The suspected reason for the difference is the deepening and widening ship channel that allows the ocean water flow more freely into the lake, making the lake a part of the ocean. Without the ship channel, because of much lesser water exchange, the water level in the lake does not rise correspondingly as storm surge caused by a hurricane comes.

Figure 3 shows the water-surface elevation contours at low tide and high tide in the lake for the case with the ship channel. Figure 4 shows the same contours for the case without the ship channel. With the ship channel, during high tide, the surrounding wetlands are flooded. The flood water is stopped by the coastal highways. During low tide, the flood water retreats and the shape of the lake is visible. The water-surface elevation changes a lot between two tidal conditions. Without the ship channel, the water-surface elevations do not change much between low tide and high tide, and they are about the same as the surrounding wetland elevation. It is clear that the water level in the lake responds sensitively to the change of ocean elevation for the case with the ship channel. On the contrary, insensitive responses can be observed for the case without the ship channel.

The detail flow pattern comparisons can be found in Figure 5, the vector fields at low tide and high tide. From Figure 5, the flow for the case without the ship channel is much smaller than the case with the ship channel, which prevents flood from propagating farther. With the ship channel, the water exchange between the ocean and the lake is significantly increased, thus increases the chances of flooding. For the case with the ship channel, the hydrodynamics of the lake is revealed in the figure. When it is low tide in the lake, ocean water flows into the lake through the passage in the south of the lake, Calcasieu Pass. The fresh water input from the Calcasieu River is stopped at the entrance of Calcasieu Pass, which causes complex flow structures and circulations. On the contrary, when it is high tide in the lake, the lake water flows out and the flow structure is less complicated. For the flooded wetlands, the water velocity increases due to very shallow water depth. In both tidal conditions, the flow near the Calcasieu Pass is much stronger than anywhere else in the lake.

Figure 6 shows the scalar transport results, water-substance concentration contours comparing between with and without the ship channel. The water substance can be treated as small particles in water such as pollutants, nutrients and sediments, which came from the heavily industrial area in the north and west, through Calcasieu River and GIWW. Initially, Calcasieu Rive and GIWW are filled with dimensionless concentration 1. Figure 6 shows the concentration in the lake after 31 days period. It is clear that it is very slow and takes much longer to remove those particles without the ship channel. Almost no particle flows into Calcasieu Lake. With the ship channel, due to the increased water exchanges, the pollution and sediments from upstream rivers moves faster towards Gulf of Mexico. It could be considered as a positive impact. But the moving speed is still slow. Most of the sediments are settled in the lake before moving into the gulf. It is interesting that the sediment concentration in Calcasieu Ship Channel is not that great (except in the upstream part of the ship channel) and most of the sediment particles were transport into the lake area in the east of the ship channel. The particle tracking results in Figure 7 also confirms this observation. In Figure 7, three particles were released at three different locations in the beginning, one is in the upstream ship channel (green); the second is also in the ship channel several miles downstream (pink); the third is in the lake and close to the second point (blue). The entire trajectories of these three particles during 31 day period are shown in Figure 7. The wiggles represent the effect from the ocean tide. In Figure 7, it also shows that the sediment particles tend to flow away from the ship channel into the lake area in the east side. This observation is the evidence that the excessive sediments in the ship channel do not totally come from the upstream rivers and waterways, especially for the downstream part of the ship channel. Instead, it might come from the surrounding wetlands in the west of the ship channel during floods. In addition, more water exchange lead to more salinity transport into the lake, which is another negative impact to the wetlands. Calcasieu Lake is a salt-water lake now.

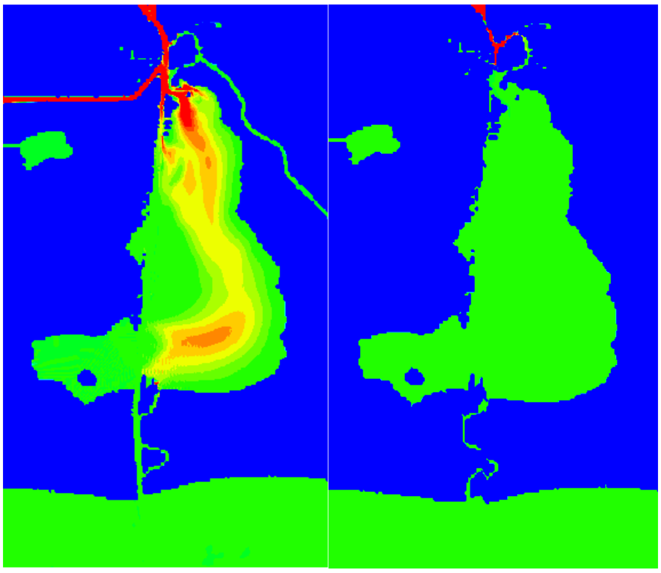

(a) with the ship channel (b) without the ship channel

Figure 6, water-substance concentration contours, 31 days

CONCLUSIONS

Hydrodynamic and scalar transport simulations were performed to study the impact of Calcausieu Ship Channel on Calcasieu Lake and surrounding wetlands. The water-surface elevation results were compared with measurement data and yielded good agreement. The land geometry (elevation) data were utilized thus the flooding can be simulated. The comparisons of the results of the cases with and without the ship channel indicate that the enhanced water exchange between the Gulf of Mexico and Calcasieu Lake results in 1) a similar tidal patterns between the ocean and lake, contributing to more frequent floods in the surrounding areas; 2) a faster transport of nutrient and pollutants from the upstream Calcasieu River, thus lower nutrient and pollutant concentrations in the surrounding wetlands; 3) a possible higher salinity level in lake and the surrounding wetlands.

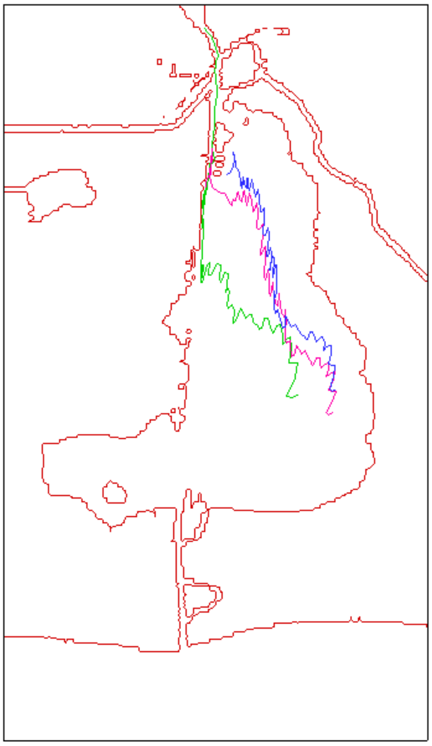


Figure 7, particle tracking during 31 days

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