Hydrological and geomorphological study of the San Francisco Bay area

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Abstract

California is located in one of the Earth's most tectonically active areas, where San Andreas fault system that crosses the state has provoked a series of major earthquakes. In addition, San Francisco has experienced a long history of such phenomena that almost destroyed the entire city in the past.

In this paper we investigate the hydrological network and the tectonic setting of the San Francisco bay area (fig. 1) which includes a vast number of lakes, rivers and structural systems, among which the most tectonic active parts of San Andreas Fault, making it a quite interest case study.

In order to achieve this information, a Digital Elevation Model (DEM) of San Francisco bay area was processed through ArcGIS and MATLAB softwares which allowed to obtain results such the hydrological network and fault system, while extracted maps and plots provided more specific information. These output showed the composite catchment of the study area which is a result of its complex and dense tectonic background that triggers a lot of seismic breakups.

Keywords: California, tectonic, fault, DEM, MATLAB, ArcGIS

1.1 Introduction

There are a lot of areas around the world that face serious problems due to catastrophic phenomena such earthquakes and floods. In this framework, California, the third largest U.S. state, hosts one of the most important and active fault zones on Earth: the San Andreas fault that crosses almost the whole state area. Generally, this structural system causes thousands of small earthquakes in California each year, while the largest historical earthquakes along the San Andreas fault (USGS) occurred in 1857 at Fort Tejon and in 1906 at San Francisco (Le Pourhie et al.2013). Moreover, this fault zone has created a lot of landforms and landmarks in the country, such as the Colorado River and San Francisco bay. Therefore, these areas exhibit a landscape strongly shaped by natural phenomena; so it is very important to examine and define the whole area morphology by applying methodologies devoted to highlight the river network and the tectonic geomorphology.

In this research an ASTER Digital Elevation Model (GDEM) subset was used to investigate the morpho-structural pattern along the San Francisco bay area (see Fig. 1) related to the activity of the segment of San Andreas fault system.

Figure 1 - Study Area (San Francisco Bay, California State)

There are many fault systems located in the San Francisco bay area like Hayward-Rodgers Creek Fault system which is the most dangerous, Calaveras Fault in the East Bay, and the San Gregorio Fault along the San Francisco Peninsula coast while in the East Bay, near the Central Valley there are the Greenville Fault, the Mt. Diablo Thrust, and the Concord-Green Valley Fault (USGS). In figure 2 a regional tectonic setting of the San Francisco bay area is shown.

There are a lot of different softwares for studying and extracting results based on geomorphology, among them TopoToolbox is a Matlab software tool that gets all the important information from a Digital Elevation Model (DEM) providing tectonics and network profiles. This would be help to create an overview of the San Francisco area morphology that seems a very difficult task. In fact, the area consists of a very rich drainage network and by extension of a rich basin summary too that drain into the bay. San Francisco Bay includes San Pablo Bay, Central Bay, and the South Bay. Tributary rivers that drain into the Bay include the Petaluma, Napa, Guadalupe Rivers, and numerous smaller creeks and streams. The bay sediments consist of five formations of late Quaternary age (Trash et al. 1951).

Figure 2 - USGS geostructural map of San Francisco bay area

1.2. Geo-structural and seismic scenarios

From a geological viewpoint, San Francisco Bay (SF Bay) is of recent origin. Its formation began at the end of the Ice Age about 10,000 years ago. As the continental glaciers melted, the sea level rose and oceanic waters began to penetrate the Golden Gate canyon. Within the next 5000 years, the bay was almost completely formed and the tidal marshes began to spread out. The present size of the SF Bay is 1235 km^2 (Briggs, 2015).

Destructive earthquakes along the San Andreas Fault system have supplied the stimulus for Californians to develop, arguably, the most extensive and sophisticated seismic monitoring systems in the United States. The beginnings of this remarkable network and its supporting legions of technical experts started effectively about the time of the Great San Francisco Earthquake of 1906 (Zbikowski, 2015).

In the Los Angeles (hereafter LA) region, fluctuating values of kinematic aspects of ellipsoidal demand, both individually and when combined, appear to be slightly influencing the triggering of $6.0 \leq M \leq 6.9$ earthquakes and significantly influencing the triggering of $M \geq 7.0$ earthquakes. Although not as completely presented herein, the SF region appears to be similar in its triggering responsiveness, when allowance is made for its less compressive stress regime (Zbikowski, 2015).

Evidence presented herein qualitatively supports significant triggering influence of $M \geq 7.0$ earthquakes in the LA and SF regions by kinematic aspects of ellipsoidal demand, which is crustal displacement produced indirectly by celestial-mechanical forcing, through the related interaction of polar drift and migration of the equatorial bulge (Zbikowski, 2015).

A mathematical combination of the kinematic aspects of the two modes of crustal deformation may yield a quake forecasting algorithm of reasonable accuracy for $M \geq 6.0$ quakes and should be pursued. Additionally, creation of a state-space representation should allow use of the relevant mathematical tools that are available to observe solution regions (in triggering-impetus space) of greater probability of $M \geq 6.0$ quakes (Zbikowski, 2015).

The San Gregorio, San Andreas, and Golden Gate faults do not show a progressive step-over from west to east, but rather form a distributed shear zone across the Golden Gate platform. A kinematic model calculated for a 10,000-yr time span using the new fault geometries shows little vertical motion associated with faulting, except in the block between the San Gregorio and San Andreas faults, which is subsiding. Thus, extension on the Golden Gate platform can be explained by the junction between the San Gregorio and San Andreas faults and does not require a right bend or step between the faults. In addition to determining multicycle deformation, coseismic uplift for a single earthquake event, the 1906 San Francisco earthquake, was calculated to be on the order of 10–15 cm, however, interseismic deformation has recovered about 5–6 cm of this uplift since 1906 (Ryan, 2008).

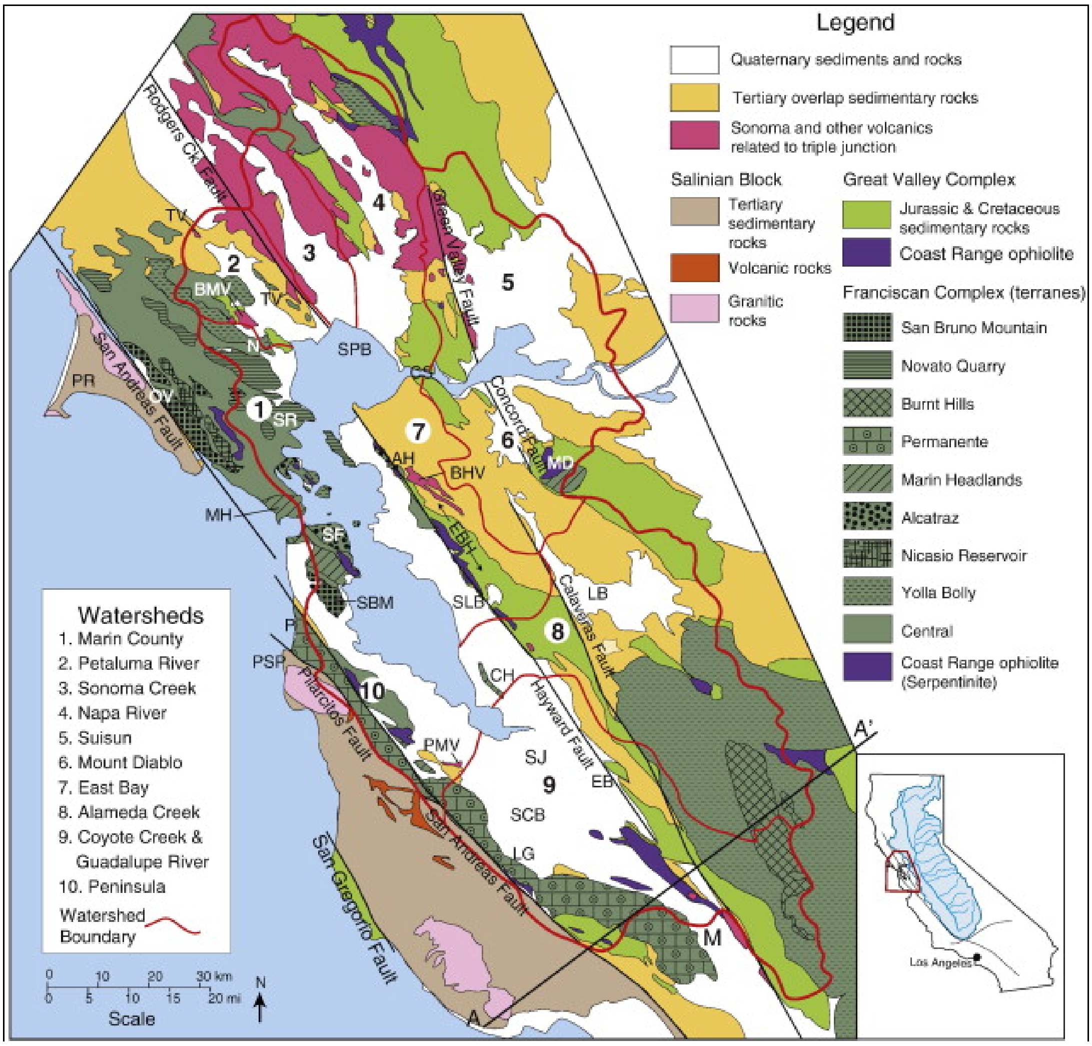
Local watersheds may contribute over half of the sediment load coming into San Francisco Bay today. The bedrock underlying these watersheds is the ultimate source for most of this sediment. The Jurassic to Eocene Franciscan Complex in the Bay Area is the most widespread bedrock. The local Franciscan can be broken into nine tectonic terranes that represent pieces of seafloor that were accreted to the North American margin in over a 100 Myr period of subduction (Elder, 2013).

Today's local San Francisco Bay watershed is comprised of numerous small stream systems around the Bay with headwaters in the surrounding hills and mountains. Active tectonism produces relief in these watersheds of typically 500 m or more, with the ridgelines typically supported by more resistant bedrock units. Steep topography leads to rapid bedrock erosion, particularly of the finer-grained sedimentary rocks. Landslides provide a significant portion of the sediment carried by the streams and several of the bedrock units are more prone to landslides, particularly the Central and Novato Quarry terranes of the Franciscan Complex, and finer-grained units of both the Great Valley Group and Tertiary rocks. Many of the larger streams have dammed reservoirs that trap much of their sediment load before it can reach the bay (Elder, 2013).

As the Bay Area has become increasingly urbanized, increased peak stream flows due to the addition of impervious surfaces, coupled with construction disturbances, have resulted in increased sediment loads in local watersheds, particularly during major storm events when the majority of sediment transport occurs (Elder, 2013).

The local watersheds that drain directly to San Francisco Bay cover an area of about 7600 km^2. Porterfield (1980) divided these local watersheds into ten watershed areas (see fig. 3). In a clockwise direction around the bay, these were: 1) Marin County watersheds (344 km^2) comprised of many small streams that flow into the bay; 2) the Petaluma River watershed (378 km^2), 3) the Sonoma Creek (427 km^2), and 4) the Napa River (1080 km^2) watersheds; 5) Suisun watersheds north of Suisun Bay (891 km^2), and 6) Mount Diablo watersheds (650 km^2) on the south side of Suisun Bay, including the major Pacheco/Walnut Creek watershed; 7) East Bay watersheds (826 km^2) comprised of many small streams that flow into the bay; 8) the Alameda Creek watershed (1930 km^2), and 9) the combined Coyote Creek and Guadalupe River watersheds, plus smaller watersheds west of the bay north to San Francisquito Creek (1810 km^2); the 10) San Francisco Peninsula watersheds from San Francisquito Creek north to the Golden Gate (637 km^2). Marine siliciclastic rocks are the dominant bedrock type under the local San Francisco Bay watersheds (Elder, 2013).

Controls on sediment supplies in local watersheds are complex and include watershed size, topographic relief, bedrock type, land use and urbanization. In addition, short-term events such as major storms, landslides, debris flows, and fires are responsible for the vast majority of sediment transported by local streams. In general, areas of soft siliciclastic bedrock weather rapidly, are easily cut by streams, and are more prone to landslides (Elder, 2013).



AH = Albany Hills, CH = Coyote Hills, CS = Carquinez Straits, EBH = East Bay Hills, LG = Las Gatos, M = Morgan Hill, MD = Mount Diablo, MH = Marin Headlands, N = Novato, OV = Olema Valley, P = Pacifica, PSP = Point San Pedro, PR = Point Reyes, SBM = San Bruno Mountain, SF = San Francisco, SJ = San Jose, SR = San Rafael. Miocene basins mentioned in text are denoted as follows: EB = Evergreen basin, LB = Livermore basin, SCB = Santa Clara basin, SLB = San Leandro basin, SPB = San Pablo basin. Volcanic rocks mentioned in text are denoted as follows: BHV = volcanics of Berkeley Hills, BMV = Burdell Mountain volcanics, PMV = Page Mill volcanics, TV = Tolay volcanics. Inset map shows location of San Francisco Bay Area geology and watershed map in California with major faults (black) and Sacramento/San Joaquin rivers watershed and major tributaries shown in blue (Elder, 2013).

Figure 3 - Generalized geologic map of San Francisco Bay Area showing local watershed areas of Porterfield (1980)

2.1.2 Study Area

The vast San Francisco Bay and Delta region of California is located at the confluence of the Sacramento and San Joaquin Rivers (see fig.4). It is often referred to as the San Francisco

Bay estuary. The consequent land use changes, particularly urbanization, have resulted in the loss of wetlands, alteration of freshwater inflows, contamination of water, sediments and biota, and declines of fish and wildlife species (USGS).

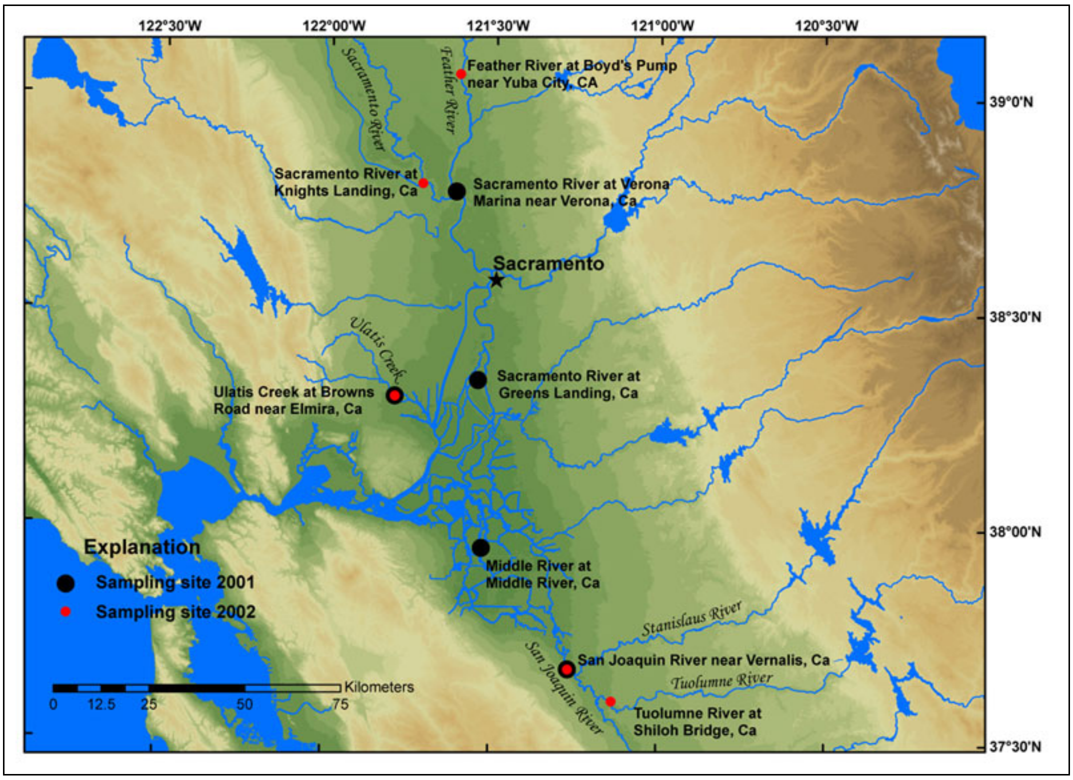


Figure 4 – Map of San Joaquin and Sacramento rivers (USGS)

2. Materials and Methods

2.1.1 Materials (Data)

For this case study a DEM (Digital Elevation Model) was used and more specifically, an ASTER GDEM (Global Digital Elevation Model) which is a product of METI and NASA which has a resolution of about 30 meters (1 arc-second) and TIFF format. The acquisition date is on 2011/10/17, while its ellipsoid is ~~of~~ WGS84. The GDEM covers the central and southern side of San Francisco bay (see fig. 5).

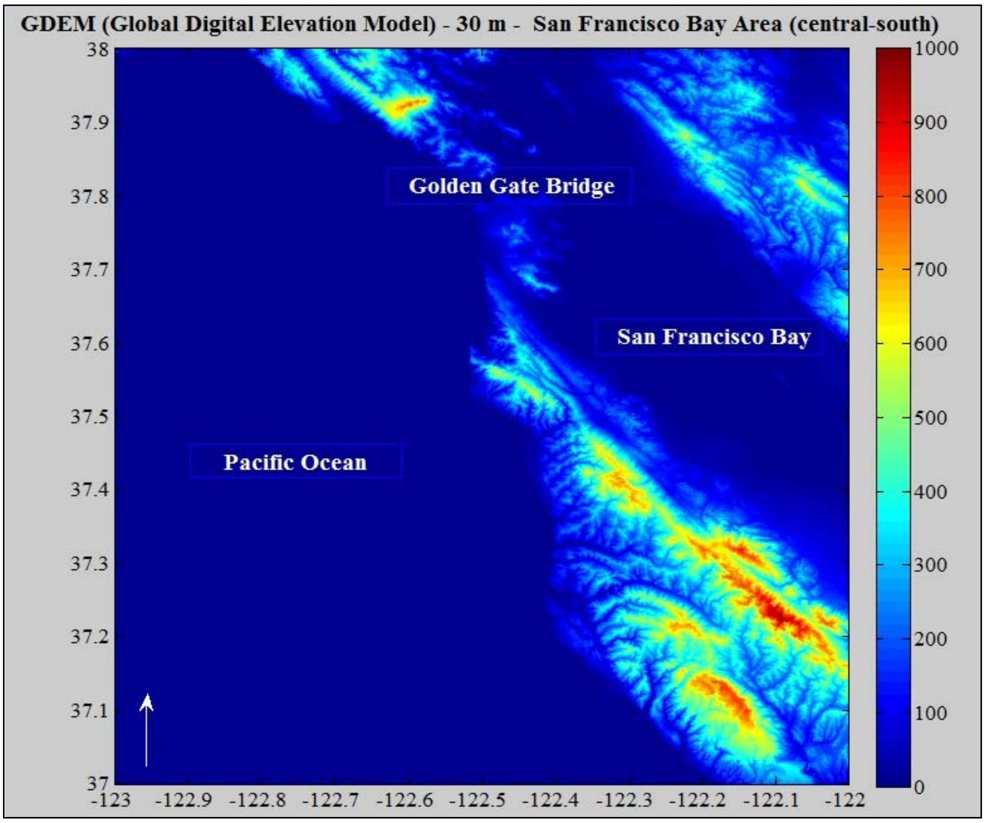


Figure 5 – ASTER GDEM covering the central-southern part of San Francisco Bay

2.2 Methods-Methodology

2.2.1 Basic Dem Processing Outcomes

First of all, DEM use was decided as it contains significant information about topography and it could be easily extracted more information about slope, elevation, drainage network and other geomorphic parameters of the area.

Initially, while processing DEM file, TopoToolbox has, first, to create another Depression Fill DEM which is, actually, a Fill DEM that its purpose is to eliminate possible model failures for creating an adequate elevation model for future processing. In fact, we applied a drainage enforcement algorithm which automatically removes spurious sinks from a DEM and produce a hydrographically corrected DEM which ensures the delineation of a connected drainage network. Thus, using the TopoToolbox order “fillsinks” it is succeeded to correct or minimize erroneous topographic depressions that may provoke problems to the following processing of DEM and should be filled prior to flow path computation.

In figures 6 and 7 you can see the new DEM after having corrected the topographic depressions where there are contained additional images with examples where the fillsinks method corrected problems. The only additional parameter that we contain into the Fillsinks code was a maximum depth parameter of 200m thinking that it was a satisfying limit in order to eliminate depression problems that existed on the original DEM.

Then, the new elevation model as is calculated from TopoToolbox is extracted while in the two following figures (see fig. 6 & 7) you can see the new corrected DEM plus some areas where topographic depressions have been filled.

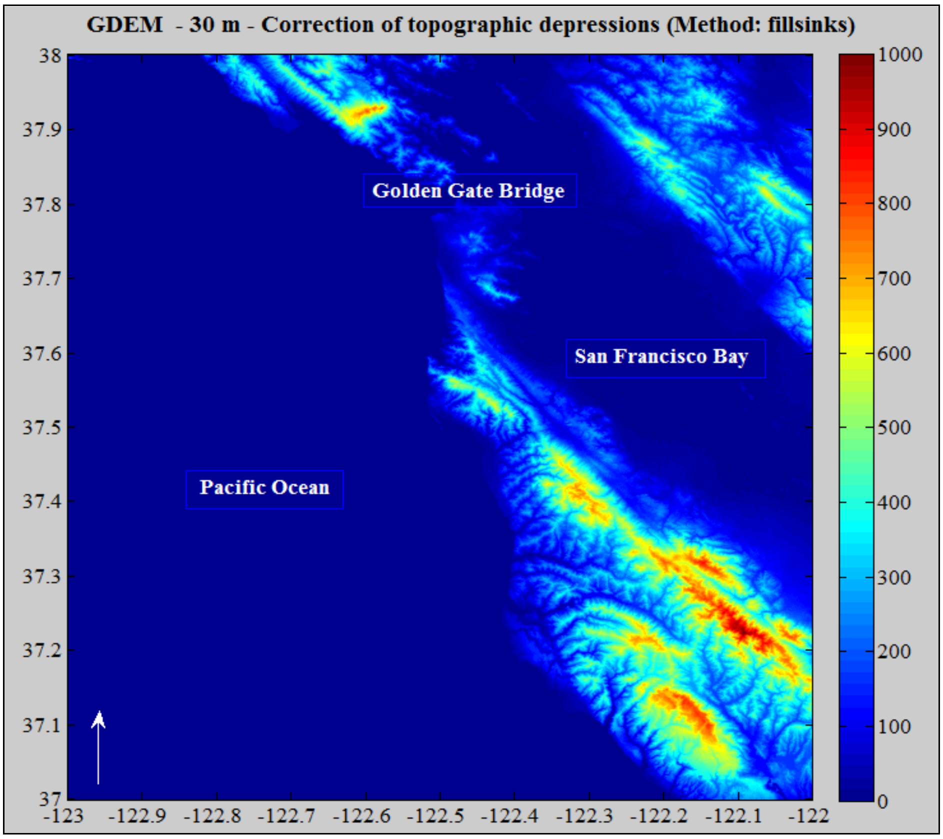


Figure 6 - GDEM after correcting topographic depressions using "fillsinks"

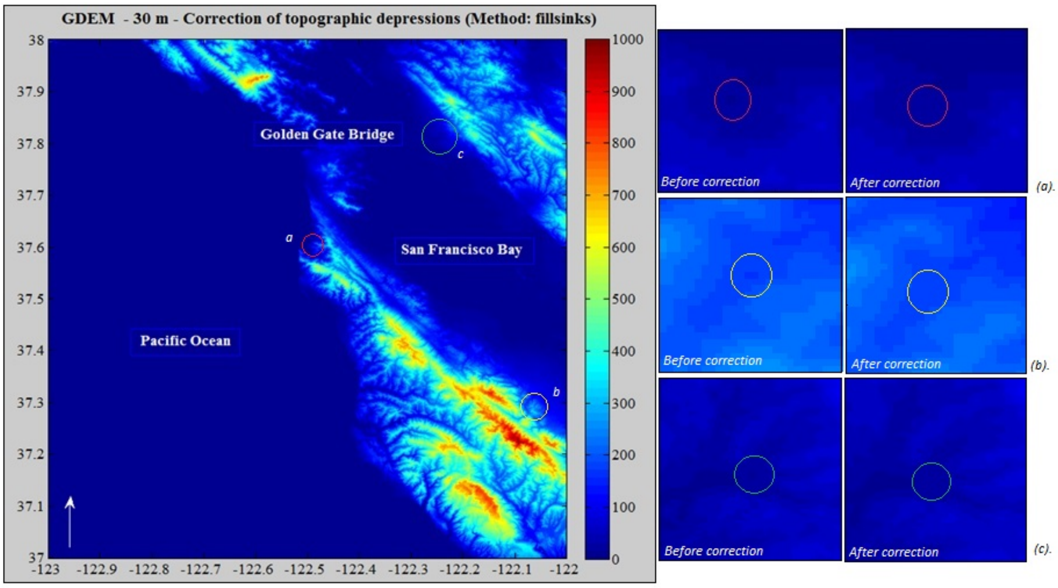


Figure 7 - Fillsinks method - examples of problems corrected

Using TopoToolbox it is possible to extract the aspect or the slope of a specific area. Actually a DEM of the area of interest is being processing and the slope aspect is calculated.

Always, when Flow Direction is calculating, is determining the direction of steepest descent, or maximum drop, from each cell center (ArcGIS Manual). As far as the Drainage extraction is concerned, TopoToolbox contains a couple of Flow related functions that can calculate Flow Direction, Flow Accumulation and Drainage Basin Delineation.

Recent years there have been developed many algorithms that calculate flow direction. All these kinds of algorithms extract the drainage network from a digital elevation model and simulate the overland flow (Rueda 2013). It sorts the cells into 8 different directions (East, Northeast, North, Northwest, West, Southwest, South and Southeast) depending on their flow directions (ArcMAP Tutorial).

Thus, the TopoToolbox Flow functions (FLOWobj) are used here for resolving flow directions on the required topographic surface of San Francisco bay. Actually, it routs flow on each pixel of DEM to possible downward pixel bases upon the lowest neighbor slope. In order to create the grid, as was told previously, it was created a depressionless DEM from generated original DEM, using the “fillsinks” function. This method focuses on centering flow within at valleys and reducing parallel flow.

Then, when all the calculations about the filled Dem and Flow functions are done are extracted various results about the Drainage Network, the Basins plus the flow distances to the outlet of a specific basin. According to the above processing it seems that San Francisco bay land area contains a very rich drainage network and by extension a huge watershed multitude.

2.2.2 Stream Networks

Moreover, TopoToolbox contains another package of functions that have to do with the stream network determination (STREAMobj). While FLOWobj methods store the information on the entire flow network on hillslopes and in channels, STREAMobj is a class that is used to analyze the channelized part of the flow network only. The storage strategy is very similar to the one of the class FLOWobj (Schwanghart et al. 2010).

Again, various methods (functions) are associated with STREAMobj that allow for manipulating, plotting and retrieving information on the stream network geometry and patterns. There are various ways to extract the channelized flow network from DEMs. It can be extracted the largest subnetwork of the channel network or the flow distance along the stream network versus elevation (Schwanghart et al. 2010). Moreover, TopoTollbox in cooperation with Matlab's Mapping Toolbox can export the stream network to a shapefile in order to be read by other GIS software and been able for further processing through these geographic softwares.

2.2.3 Flow Accumulation

When processing a Dem for pinpointing special hydrological results it is highly recommended to calculate the Flow Accumulation of the area. The result of Flow Accumulation is a raster of accumulated flow to each cell, as determined by accumulating the weight for all cells that flow into each downslope cell (ArcGIS Tutorial). Cells of undefined flow direction will only receive flow; they will not contribute to any downstream flow. A cell is considered to have an undefined flow direction if its value in the flow direction raster is anything other than 1, 2, 4, 8, 16, 32, 64, or 128 (ArcGIS Tutorial).

The accumulated flow is based on the number of cells flowing into each cell in the output raster. Output cells with a high flow accumulation are areas of concentrated flow and can be used to identify stream channels. Output cells with a flow accumulation of zero are local topographic highs and can be used to identify ridges (ArcGIS Tutorial).

When using the TopoToolbox there are few methods for calculating the Flow Accumulation. In this case study, has been selected a fast way to calculate Flow Accumulation that is based on the precalcualted sink filled file that had its aim is to correct the potential depressions of the original DEM.

More specifically, after having calculated the Flow direction of the area we could use a second input argument to define spatially variable weights into the flow accumulation e.g. to simulate spatially variable precipitation patterns (Schwanghart, 2010). But, in this case we decided to apply a default Flow Accumulation method so we didn't apply special weights. The third input argument is the runoff ratio (MathWorks). By default, the runoff ratio equals one everywhere. This is the method that we decided to apply too because we wanted to see if the results are quite satisfying using the default settings.

Furthermore, it would be important to say that the flow accumulation grid is dilated a little bit, so that flow paths are more easily appreciated in the figure 9 (Schwanghart et al. 2010). As, it is shown above, there are zoomed areas where there is a high flow accumulation like San Leandro bay and Upper Crystal Springs (see Fig.8).

Moreover, regarding to the slope aspect calculation a special formula was used under which the input information was: the calculated stream network, the DEM of the area after having calculated the topographic corrections and finally the flow accumulation output of the area.

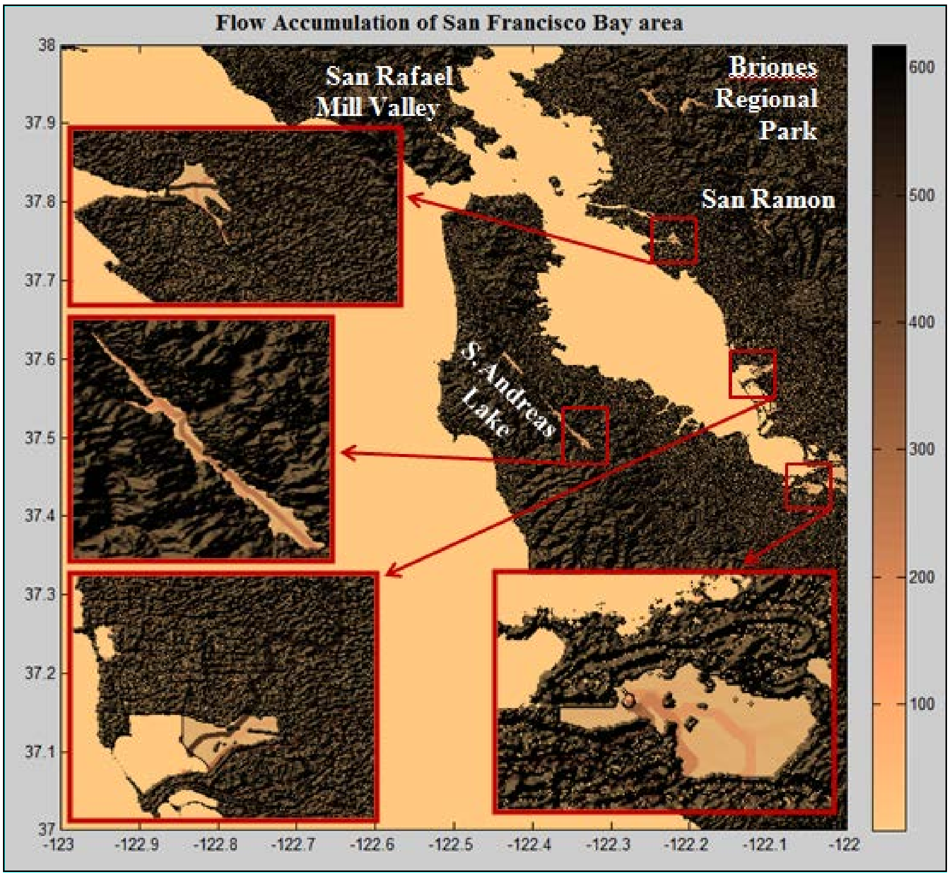


Figure 8 - Flow Accumulation applied to fillsinks DEM

2.2.4 Basins Extraction

A watershed is the upslope area that contributes flow—generally water—to a common outlet as concentrated drainage. It can be part of a larger watershed and can also contain smaller watersheds, called subbasins. The boundaries between watersheds are termed drainage divides. The outlet, or pour point, is the point on the surface at which water flows out of an area. It is the lowest point along the boundary of a watershed (ArcGIS Tutorial).

Using TopoToolbox in Matlab environment, can be, firstly, calculated the Direction of Flow and then the Watersheds. The watershed consists of surface water--lakes, streams, reservoirs, and wetlands--and all the underlying ground water. Larger watersheds contain many smaller watersheds. It all depends on the outflow point; all of the land that drains water to the outflow point is the watershed for that outflow location. Watersheds are important because the streamflow and the water quality of a river are affected by things, human-induced or not, happening in the land area "above" the river-outflow point (USGS). Basically, the watershed is a precipitation collector.

The Dem that was used for the drainage processing consists of 3601 x 3601 pixels which mean that is a quite big file which makes the whole processing slow. Well, after the “fillsinks” computation, the code is equipped with extra settings and orders that have to do with the configuration of the extracted results about the area basins.

More specifically, it is used the order “shufflelabel” which, actually, permits the random color visualization of basins by shuffling the colors so that the drainage basins can be more easily distinguished in the plot.

Moreover, it is ordered to get the number of calculated drainage basins so it is used the related “numel” order and the “regionprops” order with which can be get special extra properties and statistical data about the results for making easier the hydrological analysis of the bay area.

2.2.5 Statistics of Basins Results

From the Statistical data of the basins results, arise the Area of each extent, the Centroid plus the number of pixel information. Actually, 'Centroid' statistics specify the center of mass of the region, where the first element of Centroid is the horizontal coordinate (or x-coordinate) of the center of mass, and the second element is the vertical coordinate (or y-coordinate). All other elements of Centroid are in order of dimension (Mathworks). Moreover, PixelIdxList' is a p-element vector containing the linear indices of the pixels in the region.

On the other hand, can someone add the parameters: ‘FilledArea’, ‘FilledImage’, ‘Image’ and ‘Extrema’. In more detail, ‘FilledArea’ measurement returns a Scalar specifying the number of on pixels in FilledImage while the ‘FilledImage’ measurement returns a binary image (logical) of the same size as the bounding box of the region. The on pixels correspond to the region, with all holes filled in (Mathworks). Moreover, ‘Image’ parameter gives a Binary image (logical) of the same size as the bounding box of the region; the on pixels correspond to the region, and all other pixels are off and finally, ‘Extrema’ parameter returns an 8-by-2 matrix that specifies the extrema points in the region. Each row of the matrix contains the x- and y-coordinates of one of the points. The format of the vector is [top-left top-right right-top right-bottom bottom-right bottom-left left-bottom left-top] (Mathworks).

Actually, ‘FilledImage’ and ‘Image’ return the same result which is a logical image that shows the covered area of every drainage basin. The figures 9-12 shows some examples of logical images using Area plots of the biggest and smallest basins of the study area. An area graph displays elements in Y as one or more curves and fills the area beneath each curve. When Y is a matrix, the curves are stacked showing the relative contribution of each row element to the total height of the curve at each x interval. On the Area (Y) it is plotted the vector Y or the sum of each column in matrix Y. The x-axis automatically scales to 1: size (Y, 1) (IZMIRAN Mathworks).

On the Area (X, Y): For vectors X and Y, the area (X, Y) is the same as plot (X, Y) except that the area between 0 and Y is filled. When Y is a matrix, the area (X,Y) plots the columns of Y as filled areas. For each X, the net result is the sum of corresponding values from the columns of Y (IZMIRAN Mathworks). The area graph shows, the plotting of the pixels corresponding on each drainage basin. The figure colormap controls the coloring of individual areas (IZMIRAN Mathworks).

As it was mentioned above, the Dem that is used in this study area is quite big and consists of 3601 x 3601 pixels covering an area of almost 11670.4809 km^2 in San Francisco bay, California (central and southern part).

Moreover, via TopoToolbox and its possibilities extracting statistical results relevant to the drainage basins it is available to create plots where would be shown the distribution of the sum of Flow Distances to the outlet of each basin (Schwanghart et al. 2013). In this study site, it is plotted the distribution that is referenced to the biggest basin of the San Francisco Bay area that is examined. Thus, it is about the drainage basin that numbers almost 343.766 km^2.

2.2.6 Stream Network Statistics

Previously, it was analyzed many tools of FLOWobj parameter that runs into TopoToolbox. Actually, FLOWobj stores the information on the entire flow network on hillslopes and in channels (Schwanghart et al. 2013). On the other hand, STREAMobj is a class that is used to analyze the channelized part of the flow network only while the storage strategy is very similar to the one of the class FLOWobj (Schwanghart et al. 2013). Furthermore, this special tool can provide various methods (functions) that are associated with STREAMobj and allow the user manipulating, plotting and retrieving information on the stream network geometry and patterns (Schwanghart et al. 2013). He can select a special stream network part of his study area and extract really important information about it. There are various ways to extract the channelized flow network from DEMs (Schwanghart et al. 2013).

On this study site, it is selected an area threshold for showing and analyzing the results that are coming up. This area that is selected, it consists of a minimum of 1,000 cells. That means that is about a drainage area that has a minimum 1,000 extent.

As mentioned above, there are a lot functions that come from STREAMobj tool of TopoToolbox but STREAMobj stores various properties that allow the user to customize his code or build his own functions (Schwanghart et al. 2013).

Moreover, using the Flow Network that was extracted, previously, can be created another plot which will focus on the largest subnetwork of the channel network that was extracted.

STREAMobj, well, gives the opportunity of creating plots that can pinpoint on the largest subnetwork of a stream that has been analyzed and then can be create plots that can show the Distance of these networks according to the elevation of the area.

2.2.7 Creating 3D Plot

TopoToolbox can provide the user with multiple tools for visualizing Dem files. Except for simple ways of visualization there is one that can present 3D Dem option, providing him simultaneously with the opportunity to see the coordinates and latitude on the same plot.

3 Results and Discussion

3.1 Results

On figure 9, it is shown the slope aspect of the central and south part of San Francisco Bay where it can be easily distinguished the geomorphology of the area. Every pixel of the grid gets a value from 0 to 360 degrees where 0^o and 360^o refer to an area oriented to the north and get dark blue or dark red colors respectively, while the areas with light blue colors to the very light blue ones referring to north-east and south-east orientations respectively. Continuing, the pixel getting cyan colors are south-east and south oriented, these with light green colors are south-west oriented, the ones with yellow and orange colors are west oriented and finally, the pixels of the grid that get red colors are north-west oriented.

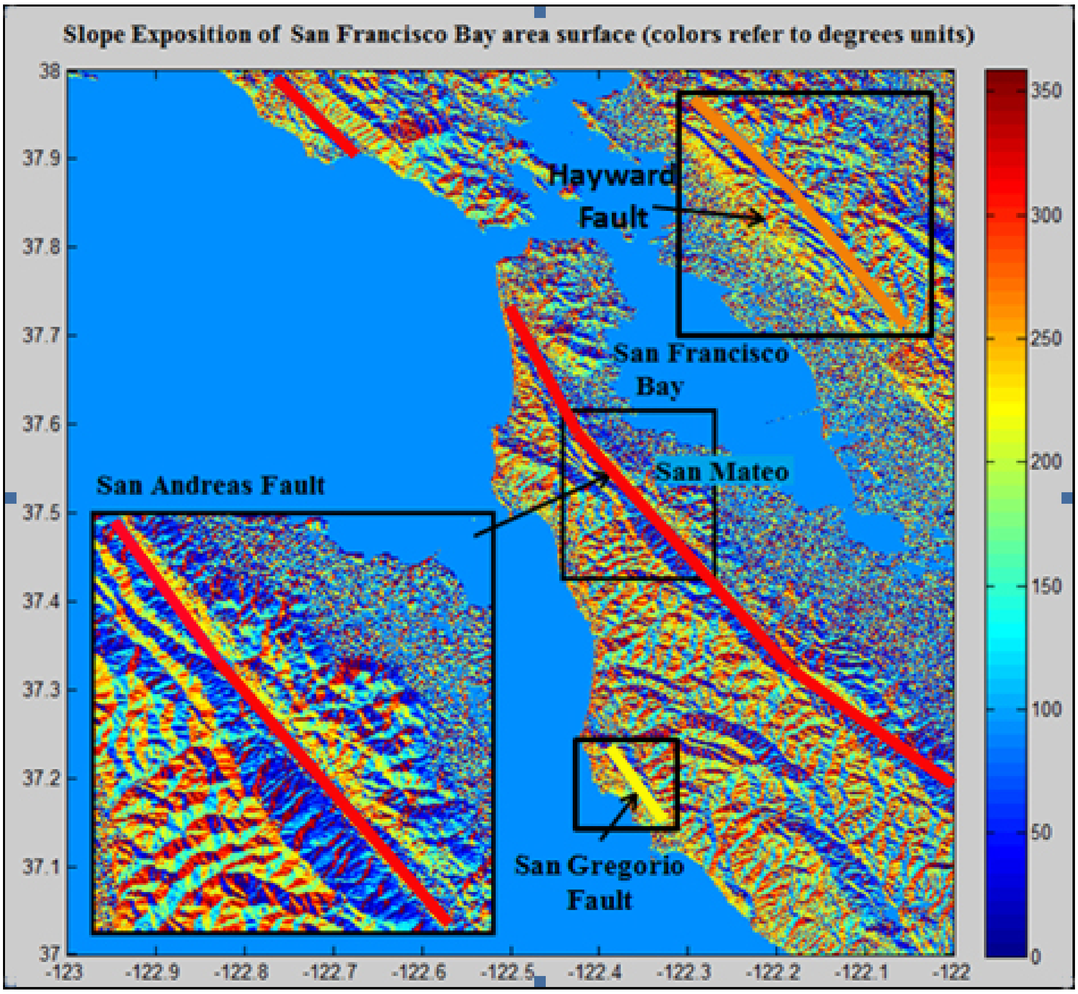


Figure 9 – Slope aspect of San Francisco Bay area (in degrees)

On the zoom image, can be distinguished a part of the west bay area near San Mateo where a San Andreas section is observed. It seems that the fault that passes from the bay area shows that is about a really important fault system as another section is identified on the east bay side. It could be seen, therefore, that the whole bay area has been formed from the region tectonics of which a major role play the complex fault system of San Francisco and other Fault zones. Moreover, there are easily distinguished parts of Hayward and San Gregorio Faults.

The results of the Flow Accumulation of San Francisco study area are shown on the figure 8 which shows the relevant map. Flow Accumulation, basically, returns the number of cells draining in another cell (Schwanghart et al. 2013). Of course, high Flow Accumulation areas located on the south-west part of bay and in more detail, on the Scotts Valley, on the north-east, on San Leandro region and on San Pablo recreation. On the other hand, there are, also, regions that collect high values on the west side of San Francisco bay and more specifically near Castle Rock State Park area.

About the Basins Extraction, from the results, it seems that the extracted drainage basins number in 6506. From the figure 10 below, it is clear that the plurality of basins it is found in the regions: Redwoods Park, Big Basin Redwoods State Park and Castle Rock State Park on the south-west of the map and on the San Pablo recreation on the north-east part of the bay.

The biggest one that numbers an area of almost 343,766 km^2 as shown on figure 10 covers the south-west part of San Francisco bay, on the south of San Francisco Lake.

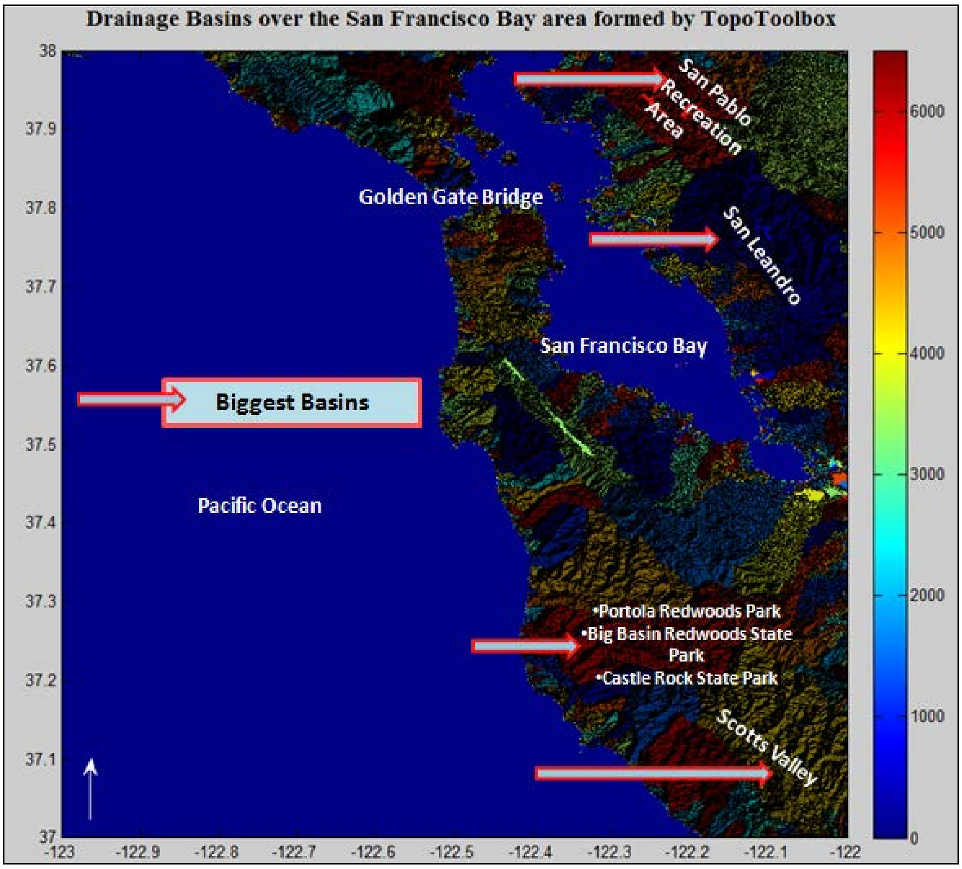


Figure 10 - Extracted basins in San Francisco bay (number of basins)

There are a lot of basins which are very small like 2, 3 or 6 km^2, while there are some others extremely huge which number 247,966 or even 300,000 km^2 and more. Of course, at this point, it is highly recommended to say that these big basins contain a large part of green parks of the bay or lagunes that's why they number so many km^2. These basins seem to frame the vegetated regions of the bay and the smaller bays around the San Francisco wider area. On the figure 10, it can be easily distinguished the extracted drainage basins of the area as they have been formed in the area of the central and south San Francisco bay. The colorbar units next to the map range from 0 till almost 6000 approximately; units that are nothing else but the number of extracted basins. As it was mentioned above, the number of the calculated basins is 6506 and this is the reason why the colorbar ranges up to 6506 units. Furthermore, the colors of basins are just random according to the colorbar shading giving to the basins different colors that don't contain any further information.

On figure 11, is shown the distance of every drainage basin of San Francisco Bay area where it is quite interesting to know the distance from each drainage basin outlet in along the whole area flow network in upstream direction. From the image it seems that the biggest distances occupy the basins on the west part of the bay like Big Basin Redwoods State Park and on the San Pablo Recreation Area. These areas are located on Santa Cruz and Contra Costa counties.

On the other hand, the basins with the smallest distances are located on the north and central part of the bay and more specifically, near Berkeley and east San Rafael on the north and San Jose and San Francisco on the south. The units on the colorbar that range from 0 till something more than 0.4 m actually represent the distance in meters of basins.

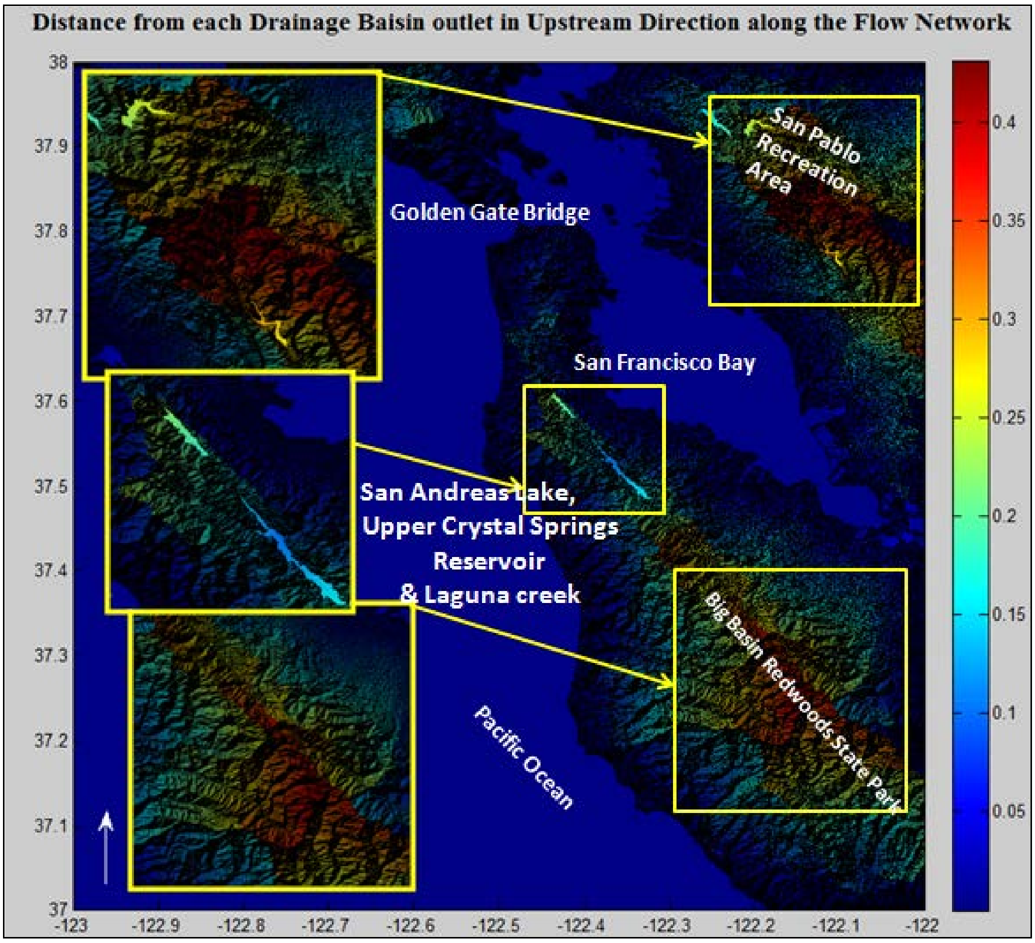


Figure 11 - Distance from San Francisco Bay Basins in Upstream Direction (units: m.)

In detail, according to the basin distance result, it is calculated the horizontal distance along the flow network in upstream (for this case study) direction to the drainage basin outlet. These values are calculated for each drainage basin. So, in figure 11, are shown the distances for every drainage basin where units ranging from 0 till almost 0.4 meters. This, actually is the distance from the flow network inside each basin to its outlet in upstream direction. The biggest distances are located on the basins on the west of bay (Big Basin Redwoods State Park) with values 0.3 m or higher. On the other hand, the smallest distances to the basins outlets are pinpointed on the north and central areas of bay like near San Francisco, San Jose (south) and San Rafael (north).

About the Basins statistics that came out, on the figures 12-14 the area graphs show three basins statistical data about their corresponding pixels. In detail, the adjacent graphs show the three top big basins that via 'Image' and 'FilledImage' measurements give a binary image of 275,518 pixels or 247.9662 km^2 with a logical image of 684 x 618 dimensions, one of 277,953 pixels or 250.1577 km^2 owing a logical image of 446 x 1043 dimensions and another one of 381,963 pixels or 343.7667 km^2 returning a binary image of 938 x 731 dimensions. It important to mention that at three biggest basins plots the graphs are multicolored but the colors can't be seen because the graphs are too dense. Moreover, the smallest basin consists of 2 pixels or 0.0018 km^2 that gives a binary image of 1 x 2 dimensions and covers a very small area.

In conclusion with the drainage basins statistics, the 'FilledArea' and 'Area' measurements return the same result which is the number of the area that covers each basin in pixels. From the plots that have been created about special basins, if someone takes a look at the statistics of the drainage basins file would see that the smaller basin of the study area has an extent of 2 px (0.0018 km^2) while the bigger one covers a 381,963 px (343.7667 km^2) area. There are a lot of basins numbered 0.0018 km^2 but there is only one that has an extent of 343 km^{2}which is, actually, located on the east part of San Francisco Bay, as it was mentioned previously, and covers almost the whole San Pablo. There are, also, other basins quite big but not like ones of 247.9662 km^2, 250.1577 km^{2}and 343.7667 km^2. The three biggest basins are located in Big Basin Redwoods State Park on the southern part of the bay and in San Pablo Recreation Area on the north-eastern part of the bay.

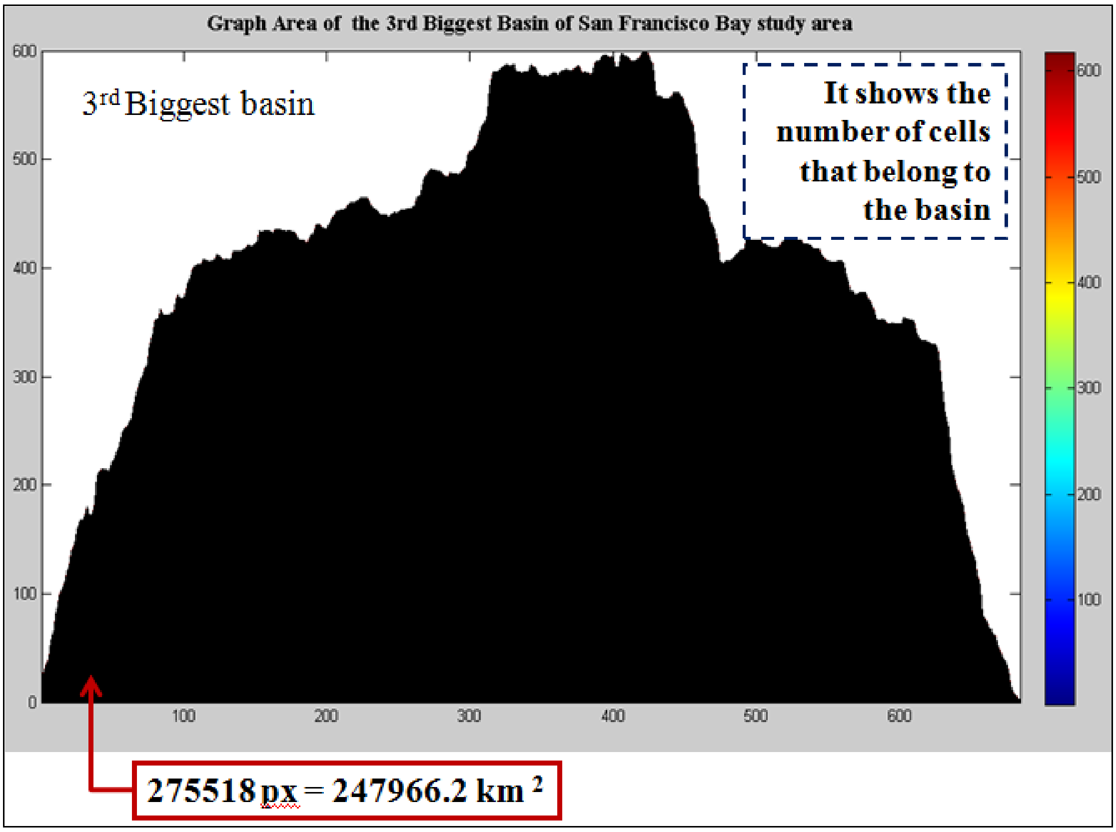


Figure 12 - Graph Area of the third biggest basin in San Francisco Bay

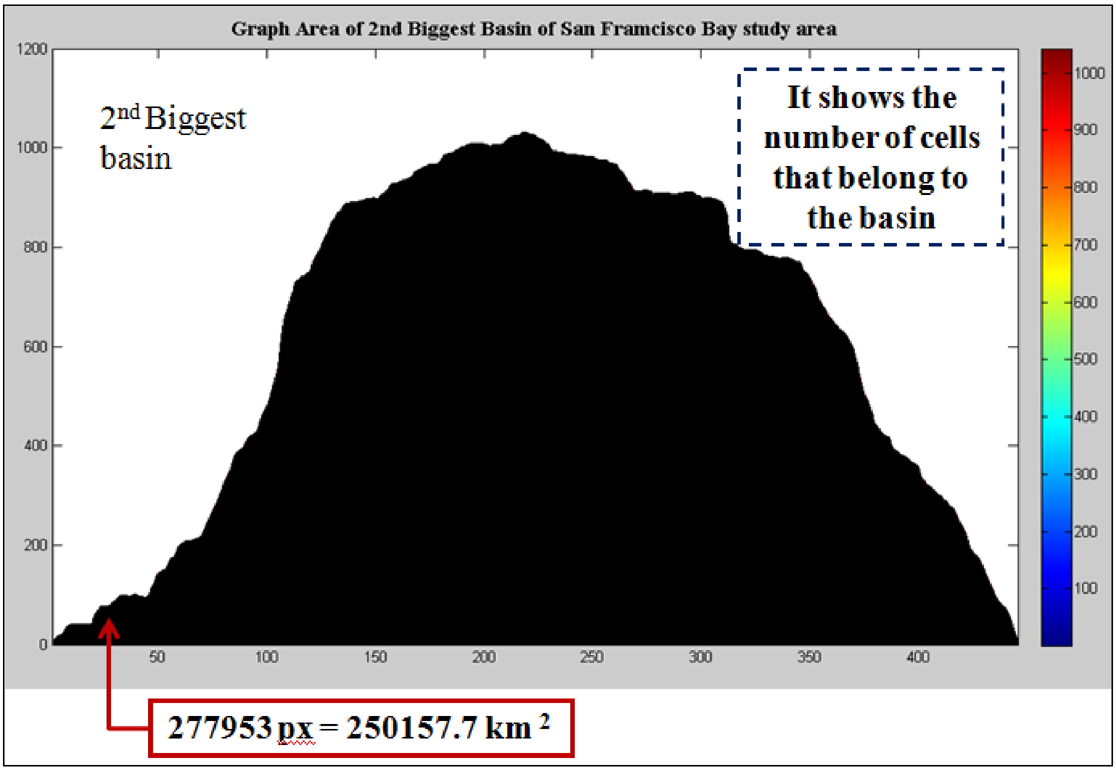


Figure 13 - Graph Area of the second biggest basin in San Francisco Bay

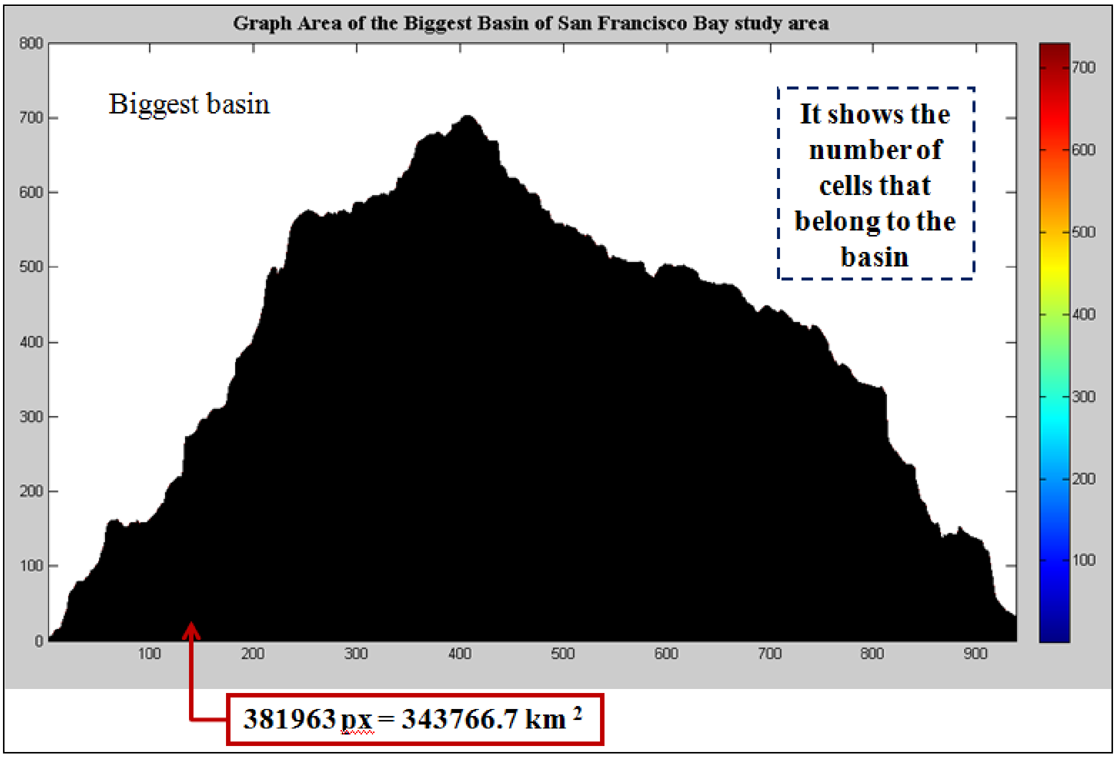


Figure 14 - Graph Area of the biggest basin in San Francisco Bay

Below, in the figure 15, in the plot it is shown the distribution related to the basin located to the west part of San Francisco Bay and in detail, it is shown the Flow Distances Distribution in meters according to the number of cells that correspond to each Flow Distance. It seems, that plot areas corresponding to the 0.15-0.09 and 0.22-0.25 meters distances concentrate the most of cells number like 450 until 850 cells.

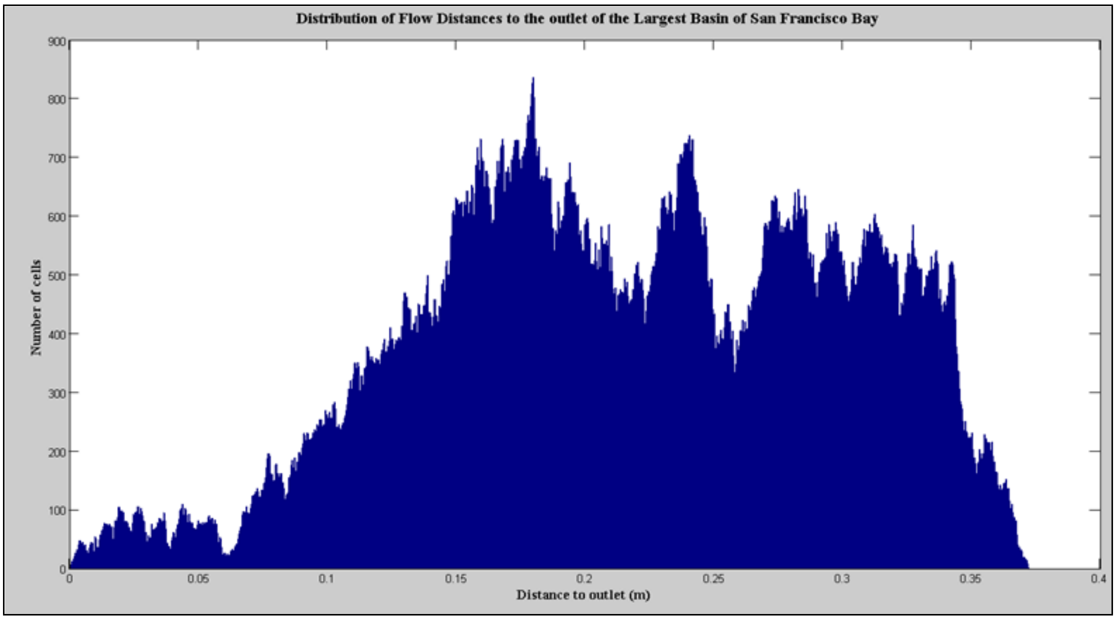


Figure 15 - Distribution of the flow distances to the outlet of the largest basin of Bay

According to the Stream Network Statistics, on the figure 16, it is shown the region of central and south side of San Francisco Bay. The flow network seems quite dense and rich considering that is about a region of a minimum 1,000 cells threshold. If someone takes a look at the figure16, there is shown that the flow network is quite dense around coastline of bay. Moving on, to the figure 17, it is shown the main and largest subnetwork of the Drainage area that was studied before, consisting of at least 1,000 cells. On this plot, can be shown, too the streams that flow into the Pacific Ocean on the west coastline of San Francisco. Ending, on figure 18, it is shown the Flow Distance of the largest subnetwork that was identified on the south San Francisco side region versus to the corresponding elevation. It seems that some streams take really big values and more specifically, the streams that are located on regions with high elevation seem to obtain the biggest distance stream. This is quite expected though that the streams that are pinpointed at high altitudes have to make a long way till they reach to their mouths into the Ocean.

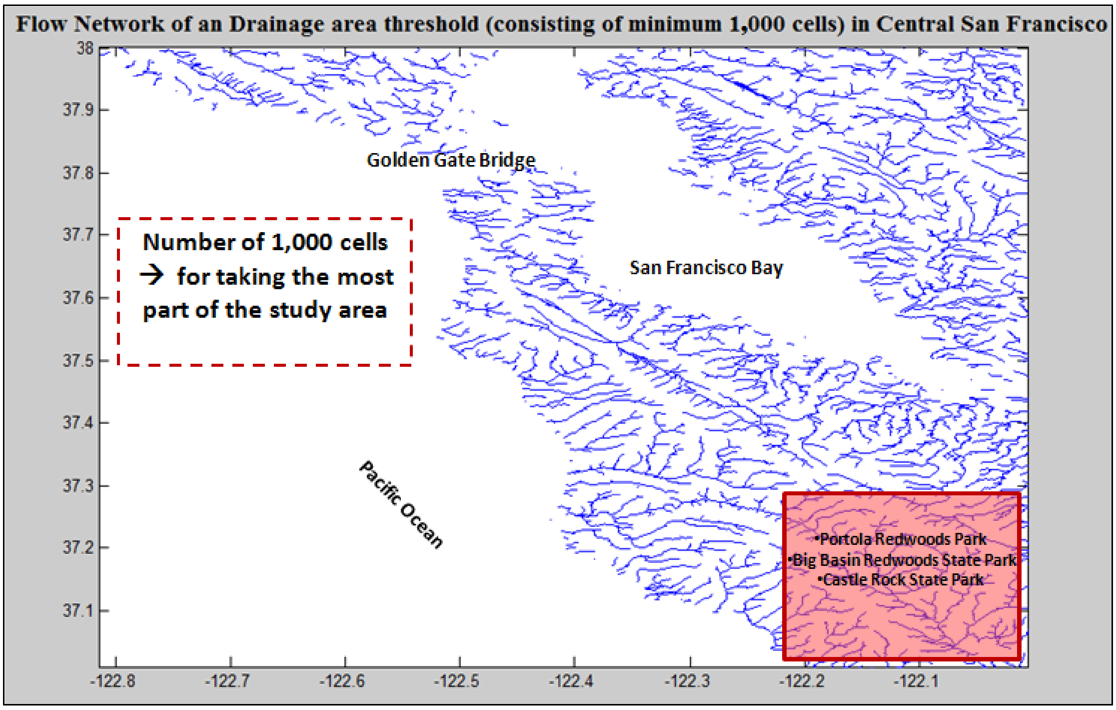


Figure 1 - Flow Network of Threshold San Francisco Bay area

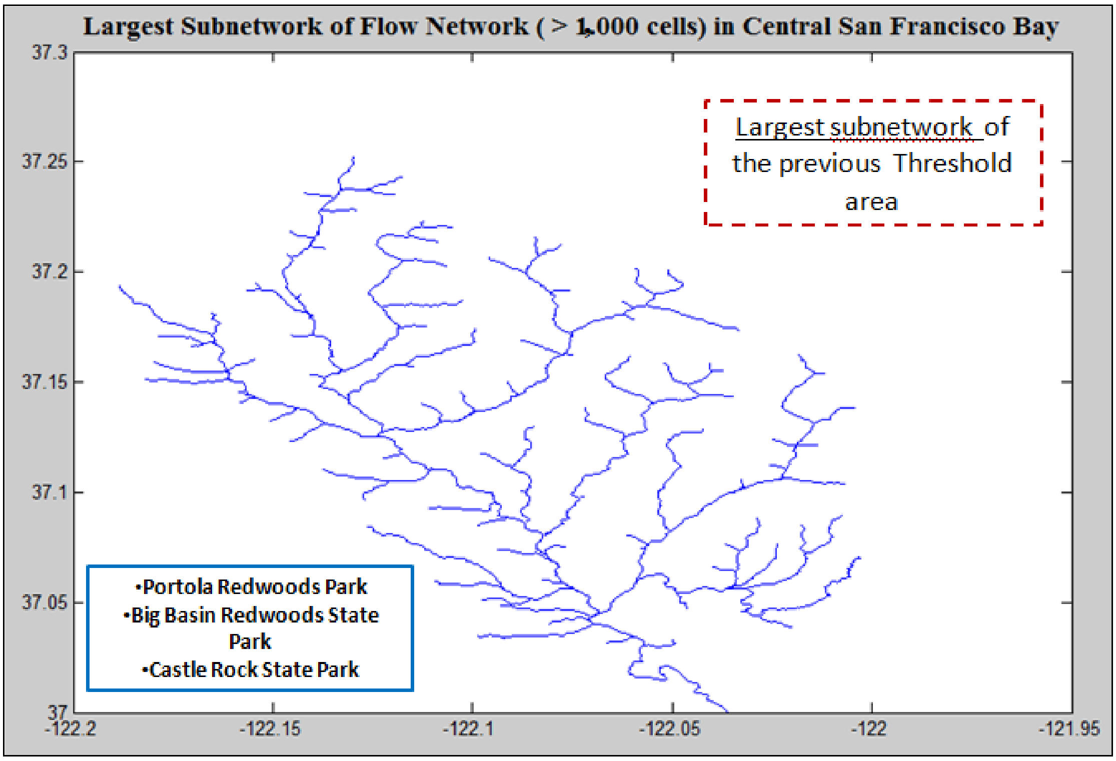


Figure 17 - The largest subnetwork of the Flow Network in Threshold San Francisco Bay (south-west side side)

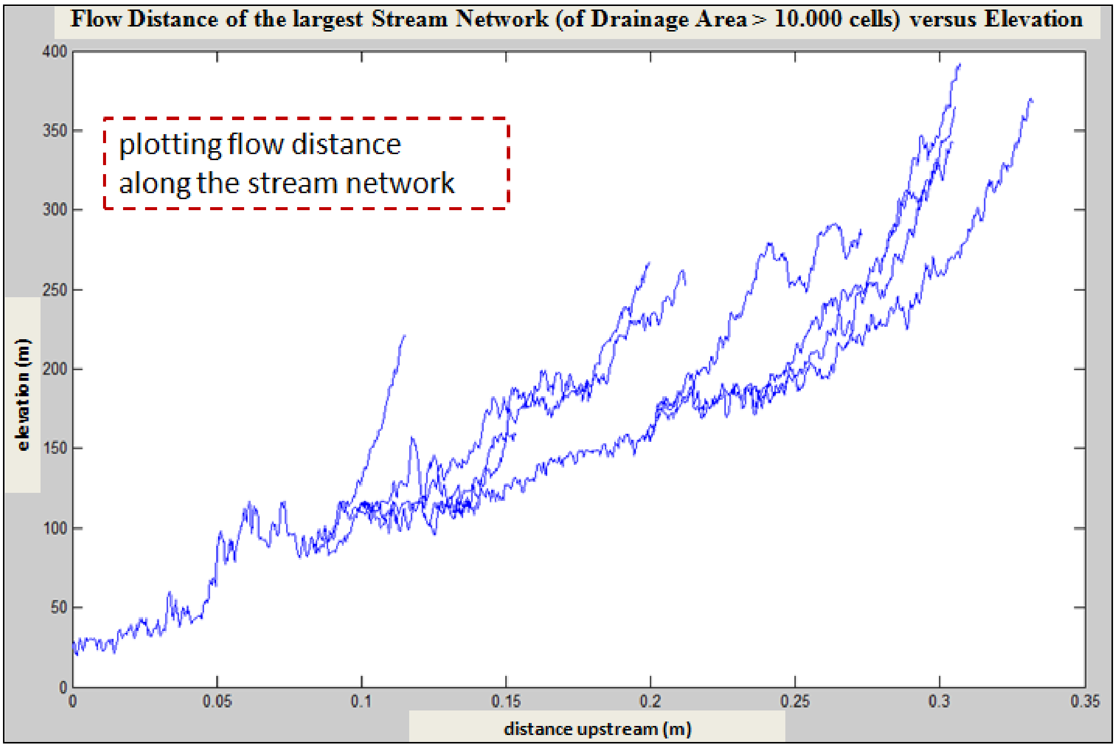


Figure 18 - Flow Distance of the largest Stream Network versus Elevation

Concluding, in this study site, it was created, plus, a 3D plot showing a small part of the interest area, focusing on a south-eastern side of Dem that in reality is located near the south bay. On the plot (see fig.19) are shown the pixel coordinates of the exact area that is visualized and it is quite interesting to mention that it is worth seeing the rugged terrain of the region.

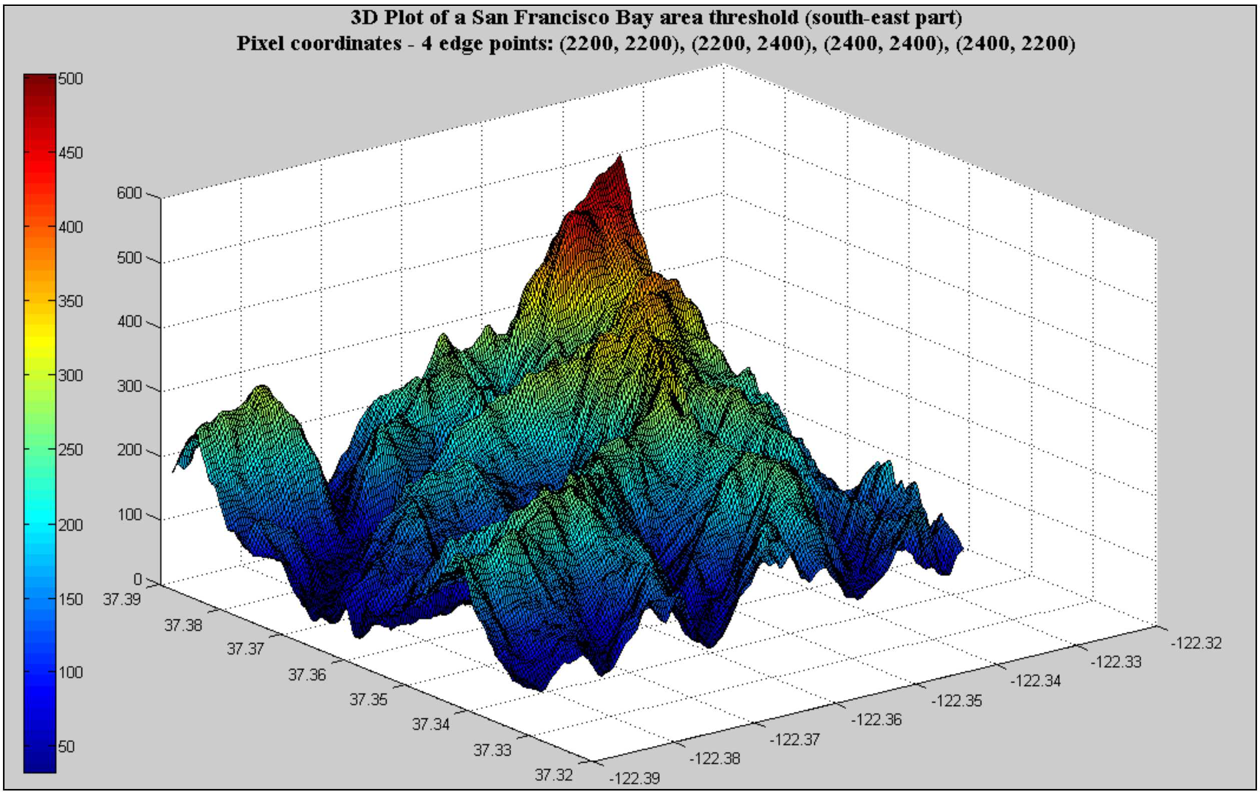


Figure 19 - 3D Plot of a south-east area Threshold of San Francisco Bay

3.2 Discussion

Recent years Digital Elevation Models have taken a very high position into the Geoscientists selections. A lot of scientists that work on special geographical, climate, physical and earth issues get DEMs and they proceed them via multiple software and methods in order to obtain the desired results. Hydrology and morphology are very important subject categories for an area because they can provide really useful information about the hydrographic network or even the tectonics of the area. GIS software are able to provide such potentials but TopoToolbox, on the other hand has a lot of benefits as it may create many results more quickly, automatically while it can manage small or even big size files.

4 Conclusions

In this case research it is presented an approach of making a first study of the morphological and hydrological background of San Francisco Bay that is a so interesting region. Working with software that is easy to use like TopoToolbox the presence study approach seems quite feasible. Of course some algorithms and results need further processing and improvement but it is a very good solution for a quick and overall morphological study using just a Digital Elevation Model.

Software like Matlab carries the next generation processing methods for many scientists. TopoToolbox that was designed, specifically, for working on Matlab has given a lot of easy ways of managing Digital Elevation Methods away from GIS software. It can offer to the user quick and automatic ways to extract important information over the specific area that studies. The tools of TopoToolbox that provide possibilities of Topographical analysis make them develop their own work. Furthermore, except the ready tools that already exist, users are able to create their own algorithms, functions and routines and improve their work.

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