Increasing Sea Levels and Flash Floods: A Universal Simulation

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***Abstract*—Over the last decade, major hurricane and rainfall events devastated numerous regions of the world. Proven to be consequences of global warming, these unfortunate events have tremendous human and financial costs. In 2018, Hurricanes Florence and Michael caused damages of approximately $50 million and 111 fatalities in the United States. Today there is a critical need to raise awareness on how global warming and increasing sea levels could impact cities and populations. The goal of this project is therefore to give access to a flooding simulation map to anybody anywhere across the globe. Using Google Maps geolocalisation and elevation data, the resulting programme - named Fluss - is offering a 3D visualisation of a defined location as well as a flooding simulation specified by the user.**

I. Introduction

Every year climate change seriously impacts an estimated 325 million people worldwide [1]. Forming geological, biological and ecosystem alterations, climate change is leading to numerous environmental risks, such as rising sea levels, extreme weather and wildlife extinction or relocation [2]. These risks are impacting human lives in many different ways such as food supply, health, migration, drinking water and economic growth. One important risk that climate change has is rising sea levels, which in turn impacts hurricane and rainfall activities. As a consequence, the maximal potential energy that the storm can release, the rainfalls and the storm's reach increase drastically, causing more devastating hurricane and rainfall events. In 2018, Hurricane Florence provoked terrible casualties in the Carolinas with $24 million destruction costs and 52 direct and indirect fatalities. During the heaviest precipitating parts the hurricane rainfalls increased by over 50%. This increase is larger than thermodynamics expectations and would hence be due to human influence on climate change and warmer sea temperature [3]. According to a Cornell University research, an estimated 2 billion people could become climate change refugees by 2100 due to rising sea levels [4]. Thereupon there is a serious need to raise awareness about the impact of climate on people's daily life, more especially in location where those impacts cannot clearly be seen yet. As flooding risks are expected to rise dramatically in the next decades and more especially in the United States, Central Europe and North East and West Africa [5], populations should realize the risk and casualties that they might encounter in the future and adapt their existing infrastructures.

The goal of this project is to provide localities, institutions and individuals with an open source flooding simulation map representing any location on the globe. The resulting program named Fluss offers a 3D visualization of a particular area defined by the user as well as a simplistic flooding simulation given a specified water elevation scenario. The program requests the user to enter the size of the map - in kilometer -, a resolution - describing the number of altitudes per kilometer -, and the location of interest. Using Google Maps geolocalisation and elevation API, the program is retrieving the associated data. Finally depending on the selected water elevation it displays the flooding simulation. This paper will describe the methodology used to develop this program, the different problems encountered, its limits and further improvements to implement in the future.

II. Literature review

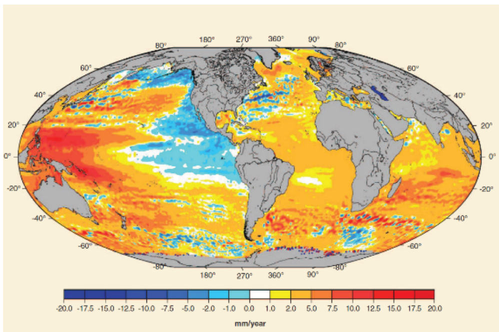
A. Sea level increase

According to IPCC (Intergovernmental Panel on Climate change) global sea level will rise by up to 60 cm by 2100 as a result of global warming and glaciers melting. However, as polar ice sheet mass is declining in an accelerated pace, the sea level rise (SLR) might even be 1 meter or more by 2100. As of today, low-elevation coastal zones below 10 meter elevation accounts for about 10% of the world population. In these places, processes derived from human activities - i.e. anthropogenic processes - often worsen the local vulnerability to sea level rising. How the communities prepare and how they adapt to potential SLR determine how sensitive they are. [6]

Church et al. (2013) shows that the largest increase in the storage of heat in the climate system over recent decades has been in the oceans, this implies that SLR from ocean warming is a crucial part of the Earth's response to increasing greenhouse gas concentration. Regional atmospheric pressure irregularities also cause sea level to vary, from short-lived occurrences such as waves and storm surges, to long-term changes associated with atmospheric and ocean modes of climate variability. The global mean sea level (GMSL) is affected by exchange of water and ice mass between land and the oceans. Increased sea levels spread rapidly around the globe, taking only a few days to be observed thousands of kilometers away from their origin. [7]

Tide gauge data since the late nineteenth century shows that sea level has risen by an average of 1.7 ± 0.3 mm per year since 1950. In the early 1990s, because of technical advancements, high-precision altimeter satellites began to measure SLR. The mean rate from 1993 to 2009 amounts to 3.3 ± 0.4 mm per year. [8].

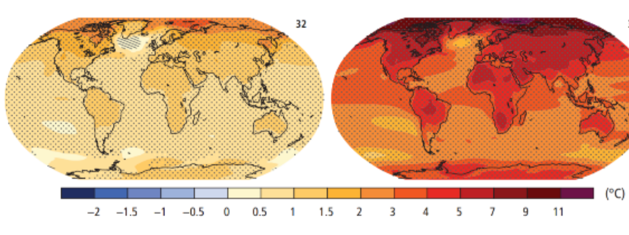
Fig. 1. Regional sea-level trends from satellite altimetry for the period October 1992 to July 2009



Source: Robert J. Nicholls and Anny Cazenave, Sea-Level Rise and Its Impact on: Coastal Zones, 2010

This decade has been characterized by increasing temperatures, compared to the late nineteenth century the Earth is about 0.8°C warmer today. This represents a significant increase, that meaningfully impacts the environment. If the emissions of greenhouse gases such as carbon dioxide are not brought under control this increase is expected to be much larger in the future. This increase would be underpinned by three main causes, (1) thermal expansion of sea waters, caused by ocean heating; (2) melting mountain glaciers, adding significant amounts of water to oceans; (3) disintegrated ice sheets in Greenland and Antarctica, especially at their warmer peripheries. [8]

Fig. 2. Change in average surface temperature - 1986-2005 to 2081-2100



Source: Michael Oppenheimer, Adapting to Climate Change: Rising Sea Levels, Limiting risks. In: Social research Vol.82: No.2, 2015. Notes: 32 and 39 indicate numbers of models used to make each projection

Nicholls et al. (2010) found that thermal expansion of sea water due to ocean warming accounts for about one fourth of the total observed sea level rise since 1960, and as much 50% from 1993 to 2003. Since then, upper-ocean warming has on average been smaller, but technology has also allowed for more precise data collection through satellite altimetry. During 1993 and 2009, the contribution of ocean temperature change to GMSL is estimated to be about 30%. Several findings indicate global decline of glaciers and small ice caps during the recent decade, at an accelerated pace in the 1990s. Melting glaciers contribution to SLR from 1993 to 2009 is about 30%. Technical advancements have simplified data collection on the mass balance of the polar ice sheets. These data indicate that Greenland and West Antarctica mass loss is accelerating. Compared to the ice sheets contribution to SLR between 1993-2003 of 15%, this contribution has nearly doubled since then; increasing glacier and ice sheet mass loss has compensated for reduced ocean thermal expansion. While change in land water storage due to natural climate variability and human activities - e.g. underground water mining, irrigation, urbanization, and deforestation - has lower impact on SLR, its contribution is still of less than 10% to current sea levels. Dam building is one of the activities which has the most severe consequences. Indeed, dam building along rivers in the second half of the twentieth century lowered sea levels by about 0.5mm/year.

B. *What Are the Main Impacts of Sea-Level Rise?*

Li et al. (2009) estimate that a one-meter sea level rise - plus a 10% surge intensification - would put 67 million people at risk. [17] Whereas, Bamber and Aspinall (2013) estimated this number to as high as 187 million people in this century. Hinkel et al. (2014) found that if the sea level rises with 1.2 meter, it can put up to 4.6% of the world global population in danger - i.e. around 345 million people.

Low-elevation coastal zones are typically very populated. In 2000, about 630 million inhabited these zones. These population might grow up to 1.4 billion by 2060. Today, most of the coastal areas with very high concentration of population are located in Asia [10].

According to the UNHCR (United Nations High Commissioner for Refugees), extreme weather events such as severe drought in Afghanistan, Tropical Cyclone Gita in Samoa, and flooding in the Philippines, caused the need for acute humanitarian needs. IDMC (Internal Displacement Monitoring Centre) [12] estimates that about 18.8 million new displacements were caused by natural disasters in 2017. Most disaster displacements were linked to natural hazards and the impact of climate change is internal to the concerned countries, meaning that those affected remained within their national borders. However, displacements across borders also occur, and may relate to situations of conflict or violence. [13]

In the United States, the most common type of natural disaster is flooding in inland areas. These disasters cause extreme damages to society, such as casualties and destroyed properties. Because of global warming, rainfall is shifting patterns, making heavy rains more frequent in many areas of the country. In addition, human alterations of land, such as engineering of rivers, destruction of natural protective systems, and increased construction in areas of low-lying ground adjacent to a river, are contributing to higher risks of experiencing destructive and costly floods.

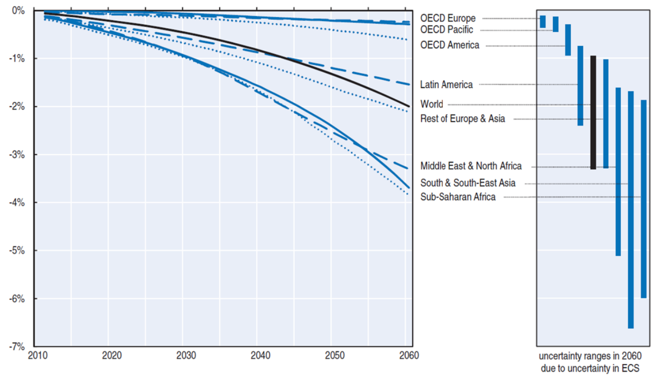
According to the Union of Concerned Scientists, governments and local authorities could - to mitigate increased risks - “fund efforts to map and communicate flood risks, invest in flood resilient landscapes and infrastructures, fund research and monitoring of precipitation and flooding, and cut carbon emissions to limit global warming”. [9]

C. *Economic consequences of climate change*

In 2015 OECD published a detailed quantitative global assessment of the direct and indirect economic consequences of climate change. The model is based on numerous impacts from climate change. It includes impacts from crop yields, loss of land and capital due to SLR, in addition to fisheries catches, capital damages from hurricanes, labor productivity changes and changes in health care expenditure, in tourism flow, and in energy demand for cooling and heating [14]. Their findings indicate that if climate change actions remain unchanged, the effects from climate change will most likely increase over time, and the GDP losses are projected to levels of 1.0% to 3.3% by 2060. The range of impact on the GDP depends on how the Earth’s climate reacts to a doubling of atmospheric CO_2 - i.e. equilibrium climate sensitivity measure (ECS) - using a likely range of 1.5°C to 4.5°C. Assuming a wider range of 1°C to 6°C in the ECS, GDP losses could reach 0.6% to 4.4% in 2060.

On regional levels, the impacts of climate change vary. The most economically vulnerable regions are Africa and Asia with the highest expected GDP losses in 2060 (see Figure 3). In Middle East and Northern Africa, losses amount to 3.3%, in South and South-East Asia to 3.7% and in Sub-Saharan Africa up to 3.8%. The effect is more severe in these regions as they are relatively poor, highly populated and generally do not have the capacities to deal with significant negative impacts. In other areas of the world the losses are closer to the global average. In Latin America the losses are estimated to be about 1.5% by 2060 and in the rest of Europe and Asia (including China and Russia) losses would be of 2.1% by 2060. [14]

Fig. 3. Regional damages projection, percentage change in regional GDP



Source: OECD (2015), The Economic Consequences of Climate Change

D. *Conclusion*

Sea level has raised significantly in the past decade (about 3.3 ± 0.4 mm per year) and is expected to rise in accelerated pace in the future. Researches indicate that thermal expansion of sea waters due to ocean warming and melting glaciers are contributed expressively to the SLR. While the estimated percentage contribution for thermal expansion has decreased, it is still considered to be an important factor. Through technical improvements the data collection has been simplified but also more precise. Data collected with more advanced technology show that the polar ice sheets are declining in an accelerating pace. If sea level rises by one meter, it can put 67 million people at risk, creating streams of climate refugees that would have to move either internally or cross borders. Climate change also has economic consequences, estimated to be around 2% in global GDP losses worldwide.

III. Methodology

A. *Architecture*

Firstly, the user is asked to enter a location - i.e the name of a city, a street or a precise address. This address is then converted into geographic coordinates - also called geocoding. The user is also asked to set the size of the map to generate and its resolution. The resolution defines the number of measurement of elevation per kilometer. An array of coordinates is build based on these two information, from which another array of the same size is populated with elevations. The last array contains binary values stating whether an area is flooded or not following previously-defined rules. Those arrays are used together to plot the different maps. Finally, a satellite map is downloaded and added on the top of these maps.

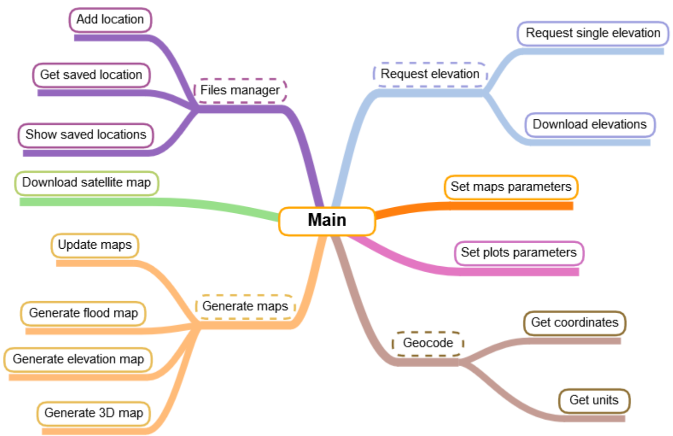
B. *Get geographic coordinates*

Once the user entered the name of a place of interest, this function geocodes the address into geographic coordinates - i.e. latitude and longitude. This conversion is made through the OpenStreetMap Nominatim search engine.

C. *Get units*

In order to shift the referential origin from the center of the map to the north-west corner and to know the incremental step to use when scanning the map, it is necessary to compute

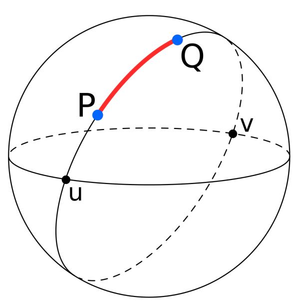
Fig. 4. Overview of program structure



Source: Fluss Graphic Development Team

the value in degrees of a shift of one kilometer along west-east axis and north-south axis. The computation needs to be done for every given latitude as Earth is not a perfect sphere. To calculate distances between these points, one needs to consider the great-circle distance, which is the shortest distance between two points on a sphere. In Euclidean space, the distance is simply the length of a straight line between them. In contrast, on a sphere distances are calculated using geodesics, a curve that takes the shortest path between to points on a sphere. Geodesics are circles around the sphere, the centre of geodesics coincide with the centre of the sphere. They are called orthodrome or great circle [19].

Fig. 5. Great Circle Distance



Source: Wikimedia

D. Distances with Haversine

To calculate the great circle distance between two points, a formula called haversine is used.

Let the central angle Θ be defined as $\Theta = \frac{d}{r}$ with d the distance between to points along a great circle of the sphere and r the radius.

The haversine formula of Θ is given by:

$$hav(\Theta) = h = hav(\varphi_2 - \varphi_1) + cos(\varphi_1)cos(\varphi_2)hav(\lambda_2 - \lambda_1)$$

where φ_1, φ_2 are the latitude of point 1 and point 2 respectively and λ_2, λ_1 are the longitude of point 1 and point 2 respectively.

To solve for the distance d, the haversine is inversed to the central angle Θ or the inverse sine function, $arcsine$ is applied:

$$d = r \cdot archav(h) = 2r \cdot arcsin(\sqrt{h})$$

When using the formulae, it must be ensured that h does not exceed 1 due to a floating-point error. Indeed, d is only real for $h \in (0, 1)$. [19]

To compute the distance between two points using their latitude and longitude on Python, the package *haversine* has been used.

E. Request elevation values

This function returns an elevation value for given coordinates by sending requests through the Google Maps Elevation API.

To create the elevation map, the code is written so that the origin - i.e. the address entered into the program - is at the center of the map. Prior to making requests to Google API, the reference point is shifted in order to start the requests from the top left of the map and then moving forward by column and by row through a net of squares, where every sub square is the selected resolution. This simply makes the request process easier.

When the user chooses to download a new map, it has to specify the desired resolution and size. A size of 2 implies that the map is of size 2 kilometer times 2 kilometer. The resolution determines the precision of the map. For example if the size of the map is 2 and the resolution 2 then it means that the requests for elevation are made every 500 metres, while a resolution of 4 means requests are made every 250 metres. This feature is implemented so that the program can be used on any computer and with desired speed, as higher resolution and larger size increase the running time of the program. In addition, lower resolution implies a smaller number of requests sent to Google API which is an important point to take into consideration as without subscription the number of requests to Google API is limited.

After a request is sent for each tile - a square of 250 meters per 250 meters in the example above -, the coordinates and elevation of the tile is saved in two different data frames.

F. Download the satellite picture

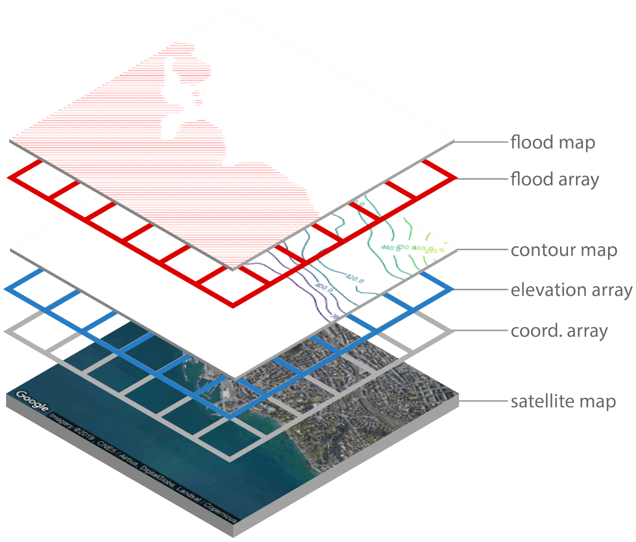
In order to enhance the readability of the maps, a satellite picture of the area of interest can be downloaded using the Google Static Map API. When sending the request, it is possible to select the style of map desired such as road map or satellite.

This functionality still needs to be improved as the zoom level of the satellite picture does not necessarily match the size of the map, creating visual alignments issues (see Section V-C).

G. Maps creation

The maps are made of different layers of information:

Fig. 6. Sub-maps layers



Source: Fluss Graphic Development Team

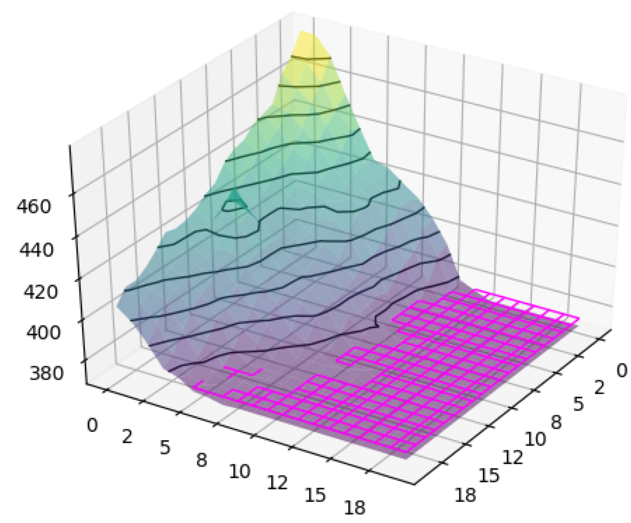
The 2D Contour Map

Based on the elevation data frame, it is now possible to draw contour interval curves. To do so, the first step is to smooth the curves using spline interpolation of degree 3 and the second to plot them. Spline interpolation is a form of interpolation that is often preferred over the polynomial interpolation due to the smaller interpolation error even when using low degree polynomials.

The 2D Flood Map
In order to visualize flooded area on the elevation map, an array of binary value is constructed in which each cell contains the state of a tile: 1 if the tile is flooded, 0 otherwise. To assess whether a tile is affected by a flood, a simple rule was implemented. The algorithm compare the elevation of the tile with a given level of water. If the tile is below this level, the tile is flooded with a probability of one. Of course, this model can be enhanced easily with additional rules. The flood map will be added on the top of the 2D elevation map described above.

The 3D elevations Map
The map gives another perspective to the user by modeling an interactive map in three dimensions. It helps to apprehend the specificities of an area's topology.

Fig. 7. 3D Map



Source: Fluss

Maps update
The sea level can be set through a slider that updates the visual results in real time.

Parameters
All the global parameters used for creating and plotting the maps can be set in the parameter files *plots* and *maps*.

Files managements
For each location, different files are generated. Therefore it is crucial to insure that each file is related to the right location. To do so, the following file management system has been implemented.

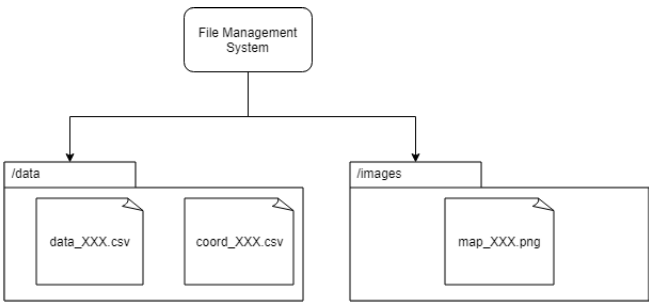
Fig. 8. File Manager

Database.csv		
PK	**Id**	**int**
	Address	string
	Lat	float
	Lng	float
	Size	int
	Res	int

Source: Fluss Graphic Development Team

The time stamp is built by concatenate the year, month, day and time when a new location is added to the database. The database contains the information on Figure 8.

Fig. 9. Time Stamp



Source: Fluss Graphic Development Team

H. Add a new location

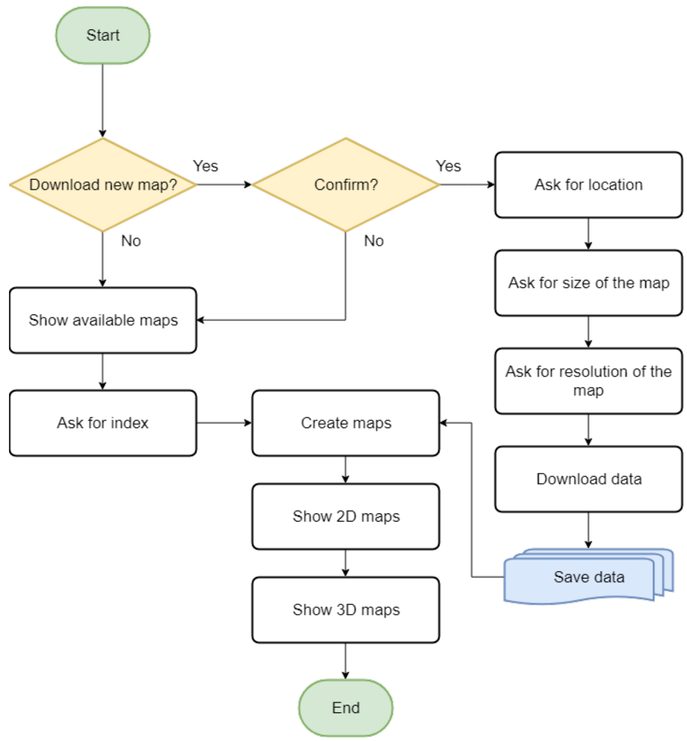
Downloading data for a given location is costly in terms of time and money. When the user creates a new map, this function saves the elevation data, the coordinates array and the satellite image for that location. All these include a timestamp in their names and are linked to a location through a CSV database.

Get saved locations
In order to reuse the already-existing data, the user can select a location in the database through its index. This function returns the data needed to build the maps for a given index.

Show saved locations
This function show a list of available location that have been already downloaded in the past. It allows the user to easily choose which one to use.

Interface
This first version of the application offers the possibility to interact through the command lines.

Fig. 10. Interface



Source: Fluss Graphic Development Team

IV. Implementation

A. Choice of coding language

For this project, the programming language of choice is Python, because of the advantages it offers, such as code readability and syntax that helps developers to code in fewer steps compared to C++. While writing the code in C++ might have resulted in a more efficient running code Python was considered more dynamic when making visualization like the one carried out in this project. However, this project could be improved by replicating it using C++ and implementing parallel processes in order to increase the speed of execution (see Section V-D). It is worth noting that Python has powerful control capabilities as it can directly call C++. Additionally, it has gained importance as Google has made it one of its official programming languages, insuring maintenance of the different API using this language.

B. An approach by layers

To generate readable maps of flooded area, different sub-maps are created before being stacked together. This approach has two main advantages:

1) It allows potential parallelization of the sub-maps generating process.
2) It insures an easy maintenance as each layer is generated independently.
3) It offers a high level of customization of the final map as each layer can be modified or hidden separately.

The final 2D maps consist in 3 graphical layers and new layers can easily be added to match the different needs of the user.

V. Limitation and improvements

A. Requests bottleneck

There is a bottleneck when it comes to sending the requests to the Google Elevation API. Indeed, for each tile on the map a request is sent online causing an important cumulative waiting time for answers - i.e. 100 requests take about 25 seconds to be completed. Multi-threads parallelization is not an answer as this bottleneck occurs at the level of the network cards. The two main lines of thought are about changing the way requests are sent - i.e. sending a pack of requests rather than one per tile - or integrating another API like OpenStreetMap.

B. Google API dependency

Critical data are provided by Google through their APIs. It is hence necessary to create an account and to ask for API keys. The number of total requests and requests per day are limited for free accounts. Therefore it would be interesting to look for another provider with less or no restrictions.

C. Static map discrete zoom level

The Google Static Map API does not allow to set continuous values for the level of zoom, which leads to a shift of the satellite picture and the rest of the submaps. The two possible improvements are to either adjust the size of the image or to use another API that allows to define a more precise zoom level.

D. Parallelization

In order to map large areas with high resolutions, the process of computing the different sub-maps could be parallelized between different process units. Fragmenting a large map into smaller maps could be a solution. Each small area could be computed parallely before being recombined into a larger unique map.

VI. Maintenance and updates

A. Installation

Clone

Clone this repository to your local machine using https://github.com/MalikLe/fluss.git

Requirements

Use the package manager pip to install the dependencies.

- pip install geopy
- pip install haversine
- pip install requests

Usage

Enter the following command line: python main.py

B. Contributing

Contribution can be made through pull requests. For major changes, developers must open an issue first to discuss what changes need to be done.

C. Maintenance

The list of issues opened is available on github. Functions are organized logically in modules and have their own docstring. It insures an easy maintenance and the use of the command *help*.

Unit testing procedure

In order to conduct unit testing, the docstring of each function contains its description, the attributes and what it returns. In this way, each function can be called individually and the result can be compared to what is specified in the docstring.

VII. Results

This section provides a description of the results from this project to the reader.

A. Introduction to Fluss

When entering the program, the user is asked to either download a new map or to choose one of the previously-downloaded maps. Writing “n” to “Download a new map” means that the program will consequently show the available maps and the user will have the opportunity choose among these by writing the corresponding index - i.e. “0” for the address “Creux du van”, “1” for “Ouchy” etc. If the user chooses to download a map, he or she will be asked to enter an address, the size of the map, and finally the desired resolution.

Fig. 11. Welcome to Fluss

```
Welcome on Fluss 0.1
Download a new map? [y, n]n
Choose a map:
              Id       Address        Lat       Lng  Size  Res
0  2019517202716  creux du van  46.932020  6.723013     4    5
1   201951721623         ouchy  46.507291  6.625909     2   10
2   201951722426      fleurier  46.905048  6.584749     2   10
Enter an index: 
```

Source: Fluss

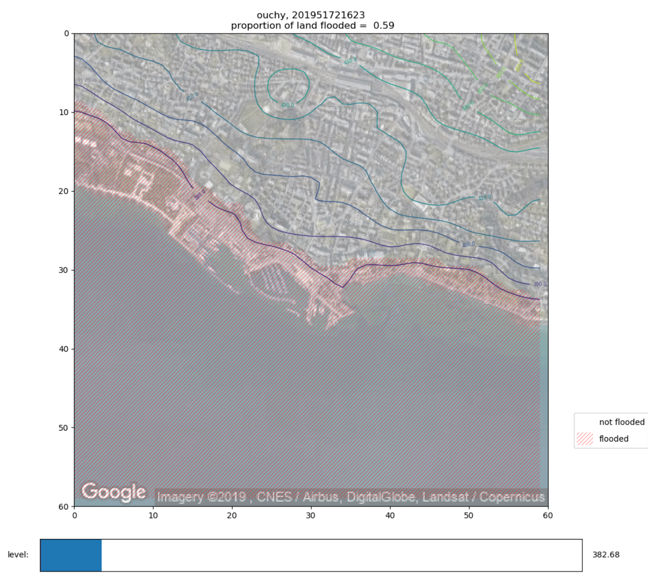
B. 2D map

Once the index of choice or a new address entered, the user will be directed to a map showing the address of interest. The map shows the area that the user has picked, as well as the different elevation zones. For example in Ouchy (see Figure

12), the elevation increases from 380 meters above the sea - the first line from the water - to 390 meters in the second etc. The user can then drag the slider to choose the proportion of land to flood.

When dragging the slider to the right, the map will show the associated flooded area. The user can use this function to identify the water level increase that would cause a flood in the selected area.

Fig. 12. Results showing flooded 2D Map of Ouchy flodded



Source: Fluss

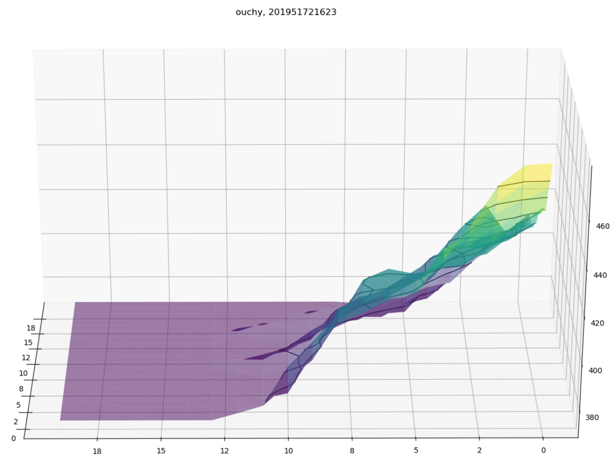
C. 3D Map

When exiting the map over the selected area, another window shows up: a 3D map showing the elevation of the area in details. This map is interactive, enabling the user to turn it around and look from every direction he or she wishes.

VIII. Conclusion

Research indicates that sea levels are increasing at an accelerating pace and the consequences are severe. Global GDP losses are estimated to be around 1% to 3% by 2060 and only in 2017 there were 18.8 million displacements due to natural disasters. Scientists have expressed that risks can be mitigated by governments funding to map and communicate flood risks. To increase awareness and to extend understanding around flooding consequences the program developed on Python enables users to create 2D and 3D flooding maps of coastal and non-coastal areas. By using geocoding and sending elevation requests through Google API, the user can choose an area and the program then generates an interactive map meant to give easy and intuitive illustration of areas vulnerable to flooding disasters. The method may be extended by changing the way requests are sent or by integrating another API like OpenStreetMap. Furthermore, the process of computing the different sub-maps could be parallelized between different process units to map large areas with high resolutions.

Fig. 13. Results showing 3D Map of Ouchy



Source: Fluss

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