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SedimenTerra

Abstract:

In 2017, after the Gloria Storm in Spain, farmers on the Delta del Ebro (East of Spain) asked for one thing: sediments. They are the third natural resource used worldwide after water and air. Mainly present in construction, they are also exploited to manufacture chips, solar panels or satellite and represent the soil on which we cultivate, and we live. However, recent studies highlight the lack of sediment monitoring despite its importance. SedimenTerra is an assessment tool using satellites to forecast sediment deposition, identify hotspots (areas at risk because of a lack or a surplus of sediment), and propose management plans.

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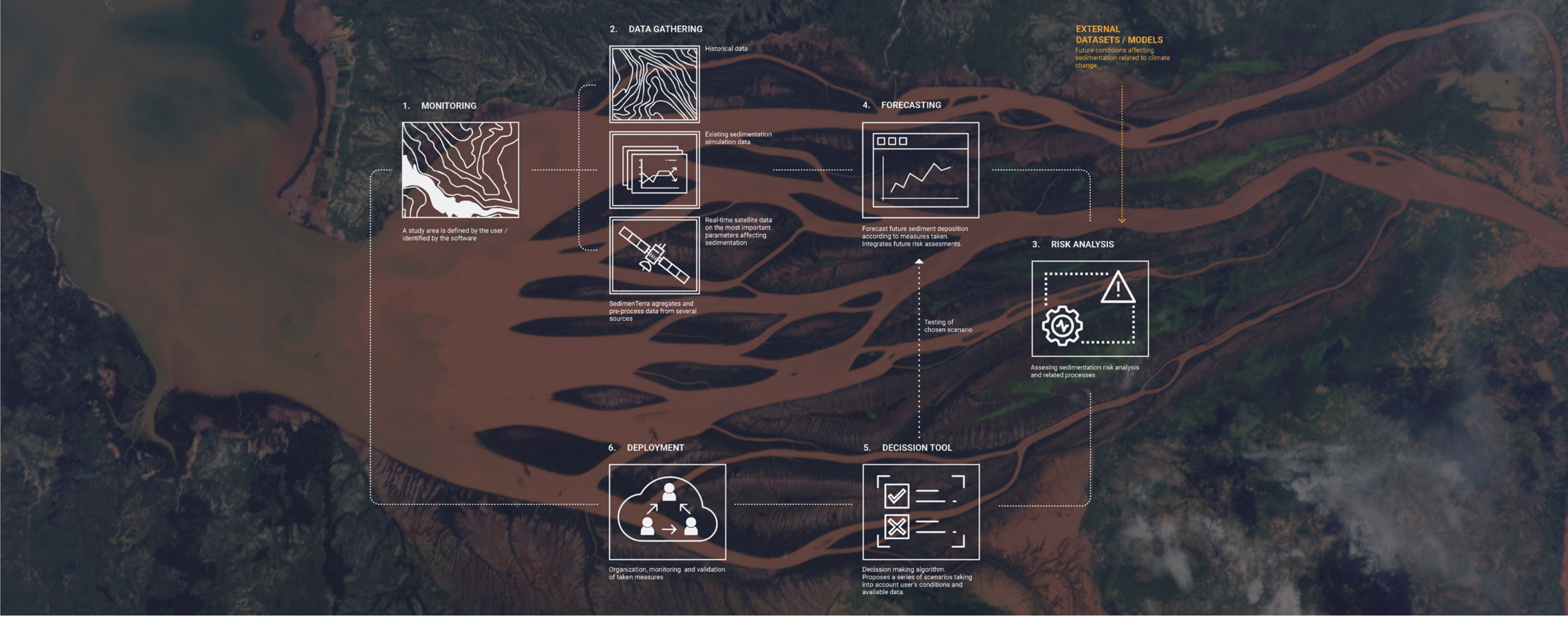

SedimenTerra

Space-Enabled local sediment management for large basins

Contents

Abstract

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1. Problem : state of the arts

Complete overview

1.1. Sediment problematic

On the surface, rocks are transformed into sediments, undergoing weathering, erosion, and transportation through, water flows, wind, ice melting...

Rock cycle and sediment dynamics depend on natural phenomena but also human activities such as dams, coastal dikes, sand mining, and has consequences on human activities, like climate change and CO2 emissions, increasing weathering effect (powerful storm, acidic rains, floods, higher temperature...).

It is possible to observe those changes directly on Earth, through the years, but also from space with satellite imagery.

Facing an increasing consumption of resources, management plans are incresingly necessary in the world. One of the most implemented is water management (ether sewage, drinking water, or rivers...). However, all over the world, it is possible to encounter sediment-related problems. For example, in France, up to 50,000 households will be threatened by coastal erosion by the end of the century and their relocation could require an investment of up to 8 billion euros (Meyer-Hiliger, 2020). Also in France, Electricité de France (EDF), the biggest European energy distributor and producer cures an average of 200,000 m3 of sediment each year on its hydroelectric facilities. Elsewhere, islands in Indonesia are threatened by the extraction of sea sand for the construction industry in the rest of Asia.

Thus, after a water war, are we going to face a sediment war?

Sediment is not only a problem because of the lack of resources but also because of surplus. For example, in rivers, important sedimentation reduces the water depth and changes

Figure 1: Hydrological and sediment processes at the mouth of the Douro (SedNet, F. Veloso Gomes, 2006

the shape of the riverbed. Then, it can limit river transport but also, during heavy rainfall, create floods because rivers reduce their flow capacity. Moreover, excess of sediments in reservoirs of hydraulic dams also reduces energy production.

To curb the effect of excess or lack of sediments, important human, technical and financial resources are required. For instance, dredgings are made regularly. For reference, in Australia, dredging operations are estimated between $6 and $20 per cubic meter (Australian government, 2005). In the Danube, one of the most important rivers in Europe, maintenance dredging accounts for more than 300,000 m3 per year (European Conference of Ministers of Transport, 2006). For coastal areas, in addition to beach nourishment, relocation is a solution undertaken with important human and financial consequences.

1.2. Current solutions

According to the working group on the Analysis and Monitoring of Priority Substances, there is a real lack of sediment management (AMPS subgroup on sediment monitoring, 2004), even though the stakes are enormous and are becoming critical with the resources decreasing and the increasing number of stakeholders using sediments.

Currently, the existing European sediment regulations mainly concern the dredging and the management of polluted sediments resulting from dredging. At the European level, the WFD (Water Framework Directive) sets the scope to integrated management of sediments to the river basin scale providing guidelines for assessments of contaminated sediments.

Other sediment management plans have already been carried out on rivers, especially those with dams for hydraulic criteria and efficiency of the structure or use of the waterbody.

Plus, through the Maritime Spatial Planning founded by EU, a Coastal Protection Management Plans for adapting coastal zones to climate change against erosion has been implemented (beach nourishment with sediment coming from external sources, reducing sediment losses through proper management of beach sediment...).

Despite a good framework now taking place in Europe, sediments are not considered at a large scale including the source of the problem, the transition places, and the impacted areas. For example, beach erosion comes partially from the important sand extraction and dams in the river.

Excess sediment in rivers requiring dredging and relocation of infrastructure (e.g. harbors) may be the result of heavy inland erosion due to deforestation and extreme climate (high heat followed by heavy rainfall).

In recent years, sediment management has become a concern for policy makers (Anger, 2018). Therefore sediment monitoring programs should also address the basic physicochemical properties of sediments as well as the geomorphological process within each river system, including operations in floodplains, wetlands and coastal zone.

SedNet is a European network aimed at incorporating sediment issues and knowledge into European strategies. However, the implementation of measures, their follow-up, and validation are steps that are still little examined and difficult to put into action.

1.3. Future challenges

Because sediments are transported from inland to the sea throughout rivers, it impacts various territories and management plans have to be implemented across administrative boundaries. In Europe for instance, the lack or surplus of sediment and the human activities impact almost all the water paths. For example, according to WWF sediment management is an issue of concern in the Danube. The Elbe, third-largest river of Central Europe (shared between Germany, the Czech Republic, Austria, and Poland - see Figure 2) has regular maintenance dredging necessary to ensure the required depths for navigation. Exploitation of the river (dams, sand extraction) has changed sediment balance of a large part of the Elbe. As a result, the degradation of the riverbed not only affects the water level and the stability of structures but also the functioning of groundwater-dependent ecosystems, such as floodplains, with irreversible effects.

To overcome all these problems, we must act. However, the solutions applied are often corrective and urgent rather than preventive and anticipatory. It costs more to react in an emergency and is less effective. It was felt that the EU should not only fund problem identification, but also problem-solving processes (Report on the SedNet Round Table Discussion, 2006).

Figure 2: main European rivers

In addition, sediments are a resource shared between several states or even continents. Through erosion, especially on rivers and coasts, sediments are transported from one country to another. Therefore, any action taken by one country on its river can impact its downstream neighbor. We should therefore shift from a national approach to a global vision, i.e. European or even international point of view.

Sediment issues should be discussed between different Directorate Generals in Brussels, like for instance DG Environment, DG Transport and DG Health (Report on the SedNet Round Table Discussion, 2006). A systematic approach that can be used throughout Europe is very much needed (Brils, 2008). There is a need for a scientific approach and practical experiences on the different ways of looking at sediment management at the scale of a river basin: from inland to the sea.

On another note, erosion, and lack of sand input lead to beaches and even entire islands' loss. This phenomenon is even more pronounced with climate change causing greater erosion, speacly in European islands.

The Douro river crossing Spain and Portugal is a great example of the effect of sediments. Indeed, sediment extraction activities and dams implemented on the river have led to an increase in the river depth by several meters. The sand spit has retreated inwards by 750 m since 1854. Subsequently, the estuary banks have been increasingly affected by waves (see Figure 1).

2. Project Idea

SedimenTerra a sediment management tool

2.1. Idea overview

As seen above, sediment is a highly exploited resource indispensable for human life. Poor management of sediments can lead to (i) loss of habitats (particularly in coastal and river areas), (ii) strong degradation of agricultural production, or (iii) critical issues in manufacturing, whether in construction, energy production and even spatial application such as satellites.
SedimenTerra is a complete solution combining different technologies to provide adequate sediment management while taking into account future climatic, urban and agricultural evolutions. This tool allows to track, map, and analyze sediment path in order to create management plans focused on sediment resources.

As sediments are part of the large cycle of rocks on Earth and can move via erosion (through wind, rivers, rain, ice melting or seas), it is necessary to see the problem on a large scale: from satellites. This macro observation facilitates the analysis of sediment evolution and the proposition to overcome the lack or surplus of sediment in a given territory.

The first phase of the SedimenTerra management tool will be to track sediments in a chosen area with different methods combined. Tracking will be made largely by remote sensing but other data impacting weathering and erosion (such as sea-level rise, climate change, or future urban planning) will also be collected in order to map and forecast sediment distribution at a present time and in the future (from weeks ahead to hundreds of years ahead).

The second phase gathers several solutions to analyze and manage sediments through time. Different tools will be combined in a model and various simulations will be run in order to create sediment management plans scenarios depending on level of risk, costs, timing, specific urban rules... For each simulation, a forecast will be made and analyze to have a clear picture of the new sediment evolution on the studied area.

2.3. Applicability

The table below summarizes a non exhaustive list of sediment uses, the impact of surplus or lack of sediment in different areas and stakeholders directly involved by those issues.

Person, systems or activity involved	Surplus of sediment	Lack of sediment	Use of Sediment
Agriculture	Floods and saline intrusion due to the reduction of river depth		organic sediments used as fertilizer
Transport	Reduction of river depth		
Biodiversity and tourism	Reef destruction and loss of biodiversity		
Construction industry			raw meterial, cement, concrete, beach nourishment
Local authorities, coastal residents, Tourism		Beach erosion	
Local authorities, residents, tourism	Floods on the riversides due to the reduction of river depth		
Local authorities, fishery	Biodiversity degradation, turbidity and obstruction of channel		
Electricity production	obstruction of waterbody, disminution of water storage capacity and electricity production		
Local authorities, residents, agriculture		Inland erosion and field disparition	

Figure 3: Sediment uses

The sectors depending on sediments, like construction industry or agriculture, are key activities for economic growth and development. With floods, saline intrusion and erosion agriculture is one of the most exposed activities. The loss of farmland will have an negative impact on the economy and food supply. With no proper and global regulation, construction industry will continue to increase an unequal distribution of resources. Finally, human will be directly impacted through relocation and destruction of habitat.
With those challenges, we already have to face and we will continue to face important human and financial losses without a sediment management plan to curb the crisis linked to sediment.

SedimenTerra was created first to encourage and help local and low cost innovation of person directly impacted by the lack or the surplus of sediments. In addition and in order to create an application at a river basin scale, this management tool will serve local, national and politico-economic authorities such as EU to follow sediment evaluation, determine and encourage hyperlocal solutions with technical and financial support.

Thus, good sediment management implemented from inland to the sea, through rivers and water bodies will not only reduce the state investment but will provide security for all sediment user or person impacted by the evolution of sediment.

3. Implementation
Gradual implementation, building up capabilities while having real impact

SedimenTerra relies on the integration of existing technologies to deliver sediment monitoring, forecasting and decission support (see Figure 4). To reduce development complexity, a series of modules with specific tasks have been defined:

3.1 Monitoring
A study carried out in the lagoon of New Caledonia highlighted the reliability of satellite remote sensing in determining the concentration of suspended matter in the water. The comparison between satellite data and measurements carried out in situ shows an uncertainty rate of less than 20% (IRD - M. Guillaume, 2005). Remote sensing, by indicating the variations in colour of the ocean water, makes it possible to draw up a map of this turbidity (see Figure 4).

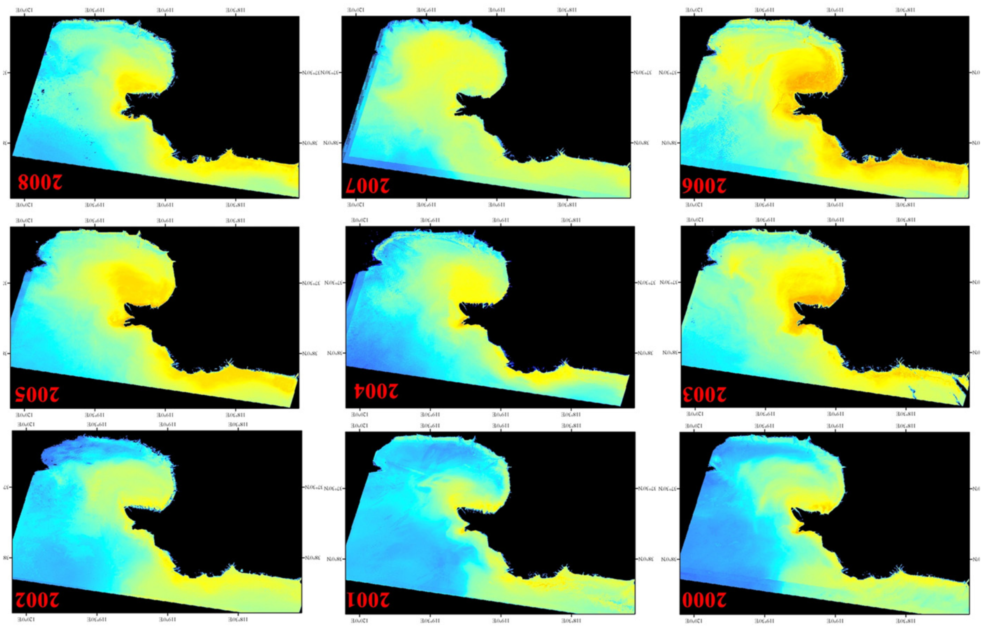
Figure 4: Suspended sediment concentration in Yellow River Stuary from (Zhang, P, 2014)

For this purpose, sensors, on board the satellites, essentially use the measurement of electromagnetic radiation emitted or reflected by objects. Optical radiometers operating in the visible/near infrared (VNIR) and short wave infrared spectral range record the reflectance of the sea surface. The processing of these data allows the quantification of certain characteristics of surface waters, in particular the content of suspended matter (turbidity).

In addition, the use of satellite images provides a global view of the study area, which is difficult to obtain using in situ prospecting means. The repeatability of observations from space (few days) makes it possible to study the spatio-temporal evolution of the phenomena observed. This information is particularly useful for the observation of sediments before and after major disasters such as fires or hurricanes.

The surface suspended sediment concentration can be monitored and assessed using the Copernicus Programme and especially Sentinel-2, Sentinel - 2A and Sentinel-2B (the last two increase frequent revisits and high mission availability). An atmospheric correction algorithm can be developed for retrieving the water-leaving radiance from the remotely sensed data. The radiance is used together with the retrieval model to calculate the suspended sediment concentration.

The use of satellites also makes it possible to monitor other phenomena that impact sedimentation such as :

- waves, currents and sea level rise that may increase coastal erosion (thanks to Copernicus Sentinel-3 and Copernicus Sentinel-6)
- maritime traffic in order to monitor sand extraction (thanks to Copernicus Sentinel-2)
- fires and deforestation that may increase inland erosion (thanks to Copernicus Sentinel-2 and Copernicus Sentinel-3)
- Sea and land temperatures that may increase weathering (thanks to Copernicus Sentinel-3)

3.2 Detailed data gathering
Data-driven models need large amounts of data from various years to reach high accuracy. Data sources for sediment transport are often not open to public and very heterogeneous. Moreover, sediment monitoring stations shall be constructed and operated in a way that the monitoring of suspended sediments is possible throughout the whole year and that the measurement results can be considered as representative for the section of the river.
In the other hand, satellite data is more consistent and over 30 years of it are now fully available.
However, successfull models will need a combination of both, state owned in site measures and large scale data (Zhang, P et al., 2014). Pre-processing such heterogeneous dataset will require the implementation of data science algortihms that can handle it in a consistent way.

3.3 Forecasting
Sediment forecasting is a complex task, that has been assessed in several ways. Mathematical and numerical models have been widely used in sediment forecasting with good accuracies but high computing costs, the availability of such predictions for larger areas remains difficult. In the other hand, data-driven models use machine learning techniques to generate accurate and relatively fast models (Pereira, F. et al., 2019). Both approaches are combined in the so-called hybrid models, which can benefit greatly from remote sensing data and satellite imagery. In fact these models can establish complex relationships between heterogeneous input data (river flow, climate, land use, etc) to deliver accurate forecast.

3.4 Risk Analysis
The Risk analysis module will process information from forecasting models to elaborate automatic reports on present and future risks related to sedimentation dynamics. It aims

to provide decision makers clear and accurate data that can be easily shared and understood.
This data will be provided in form of technical reports including info-graphics, maps with risk areas, maps and figures with opportunity areas, ecological, social and economic assessments and other useful information varying regarding the specific conditions of the study case.

3.5 Decision tool

Decision making in the case of sediment management face two major challenges: the large scale of intervention area and the amount and nature of projects to coordinate.
An ecological, social and economical evaluation of projects to be implemented is key for decision makers to proactively engage in implementing green infrastructure. However, the lack of information or knowledge about the processes governing sedimentation can stop investment. For that reason a system of adaptation metrics, investment frameworks and cost benefit analysis are planned to make part of the tool.
For a first release, the financing framework and cost benefit analysis from Ihobe (see Figure 5) is chosen, along with adaptation metrics from The Global Comision in Adaptation.
Finally the tool will be iterated over modelling modules giving the opportunity to stakeholders to test several scenarios, evaluate costs and benefits and take informed decissions (Publicwiki, 2020).

3.6 Deployment

One of the pillars of SedimenTerra is to use satellite technology to foster community awareness, participation and decision in the sedimentation management plans. For this reason one of the modules will be dedicated to deploying a system of data exchange and communication between decision makers and actors in the field, either for monitoring tasks (like sending sediment levels), warnings (sending messages to the whole network) or coordination (organizing the implementation, upgrades, etc). This is key in making the whole process successful, a river system depends on the upstream, so do the people that contribute to its management and efficient communication is essential.

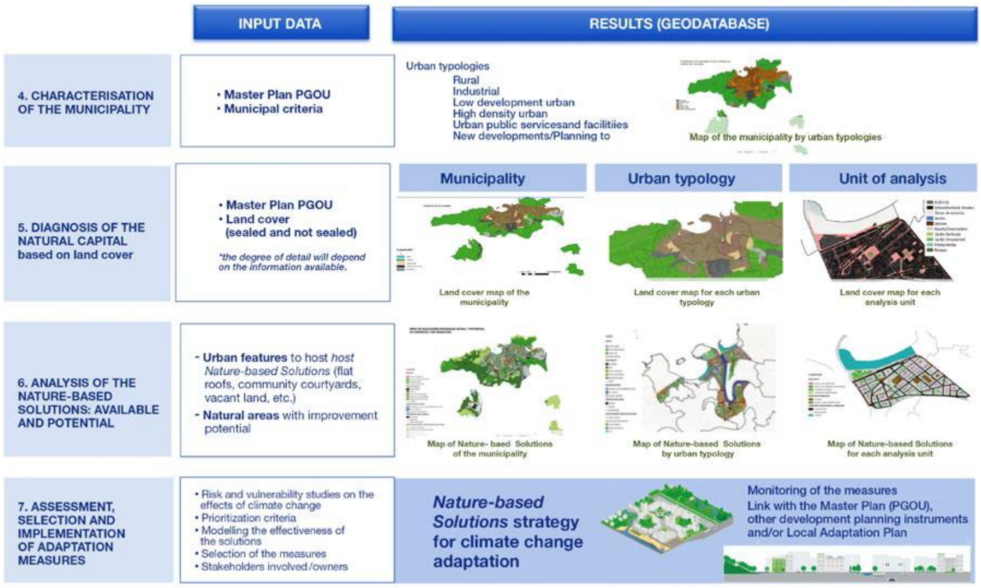

Figure 5: Decission framework BwN solutions (IHOBE, 2017)

3.7 Short term implementation

SedimenTerra relies on the integration of several technologies to be fully operative. This is a relatively long process requiring participation from multiple actors. For this reason, development and deploying of the technology will be spread in time, organized into two major releases and with continuous updates (see Figure 6).
Monitoring and Deployment modules will be released first, using satellite technology to asses main sedimentation causes, establishing an operative network and providing a system of alerts. This will enable prototype projects to flourish that will participate in the calibration of models.
In a second stage modelling and decision tools will be implemented: first as a simpler version using static, rule-based models, then evolving to more complex data-driven satellite-enabled models.

	Inputs	Technology	Outputs	Validation	Space-enabled?
Monitoring	- Satellite data	- Computer vision - Remote sensing	- Analysis reports - Alerts	- On site reports	- Fully driven by satellite technology
Data gathering	- ESA and other Space agencies repositories - In site data - Governmental data	- Databases with consistent and homogeneous datasets (type Open Earth) - Data pre-processing algorithms	- Collection of pre-processed datasets ready to model	- Only reliable sources	- Part of data coming from space sources (land cover, deforestation, water occurence,
Forecasting	- Pre-processed data from previous module	- Large scale models - Detailed Morphodynamic models (1D,2D,3D) - Data-driven models - Hybrid models	- Forecast on a series of data impacting sediment dynamics (sediment concentration, water flow, ...)	- Model validation by forecasting past known data	- Same as Data Gathering - Models are faster when feeded with satellit data
Risk Analysis	- Forecasted data	- Autmatic Risk assesment reports	- Hotspot areas - Infographics - Alert reports	- Validation from past extreme events	- Same as data gathering
Decision	- Risk analysis - External data - Community participation	- Montecarlo cost benefit analysis - Financial models - Planning	- Feasability reports - Consultation + Planning documents		
Deployment	- Data exchange	- Database - Web/Mobile applications	- Implementation reports		

Short term (0-2 years) — Medium term (2-10 years) — Long term (10+ years)

Short term (0-2 years): Deployment (100%), Monitoring (100%), Decision (50%)
Medium term (2-10 years): Decision (100%), Data gathering, Forecasting, Risk analysis (50%)
Long term (10+ years): Data gathering, Forecasting, Risk analysis (100%)

Figure 6: Overview of each module of SedimenTerra (up) Implementation timeline (down)

4. Case Study: Betsiboka River (Madagascar)

Basemodel for space-enabled local sediment management

Figure 7: Left: Sediment (orange), deforestation (red), SLR (blue). Right: future management strategy

In order to illustrate basic capabilities and potential for SedimenTerra a prototype tool has been tested. Betsiboka Delta region (Madagascar), as one of the world's fastest changing coastlines has been chosen as case study, where main sedimentation drivers are analysed and an alternative local management plan is proposed:

4.1 Deforestation

Since the end of the 20th century, deforestation rate has accelerated increasing soil erosion. Satellite-based data from (WFW, 2020) reveals that forest cover decreased at 2% rate per year.

4.2 Sedimentation

Betsiboka runs along 600 km before discharging at the Mozambique Channel. It is a major drain for sediments derived from the highlands of Central Madagascar to the sea (Raharimahefa, 2010). Soil losses observed along the Betsiboka have grown exponentially in the past 30 years. With soil erosion contributing about 3 600 t.km^(-2). a^(-1), Betsiboka River is among the largest recorded in the world (Chaperon et al., 1993). Landsat imagery was used to elaborate sedimentation maps.

4.3 Sea level rise

Madagascar's coastline is threatened by climate change, increasing storm surge and sea level rise. At the same time, coastal areas are more densely populated than the hinterland and considering Madagascar coastal length protecting the whole country will not be feasable. Sea level rise was forecasted using satellite-data of elevation model terrain and IPCC's avergae SLR height.

4.4 Proposed local management plan

Mainly due to deforestation and periods of high erosion, a large amount of sediment is found in the river and the estuary. At the same time, sea level rise and storms erode the coast, reducing beaches and coastal activities. Sediments flow freely to the ocean, while they are needed to cape with sea level rise. A new sediment management plan, reliying on local projects is proposed in order to reduce sedimentation effects and protecting the shoreline (see Figure 8):

1. Prevent erosion
The first step takes place in the highlands, where sediments are come from. The aim is to regulate sediment flow into the river to reach a normal flow rate. To do so, preventive and corrective measures have to be set up in order to limit deforestation and erosion processes.
2. Transport sediments
When the sediments are already in the river, the objective is to avoid accumulation on the riverbed by maintaining sufficient water depth to guarantee the sediment transportation and continue activities like navigation or ecological continuity.
3. Unlock sediments in delta
The third step is located on the Betsiboka estuary. Because of its particular shapes and the different current coming from the sea and the river, important accumulation areas of sediment are forming off the river mouth. Little islands are created with new vegetation growing on it. Similar to the second stage, the aim is to maintain sufficient water depth to guarantee the sediment transportation, continue activities like navigation or ecological continuity and avoid floods due to less storage capacity of the waterways.
4. Rise the coast with sediments
Once the sediments have reached the shoreline, it is important to slow their progression and use them to protect and enlarge the coastline. To do so, an underwater low-cost structure developed by MIT will be used on a large scale to create barrier islands. Wave energy creates sand accumulation around the structure. Powerful waves and current, like during a hurricane, will increase the sand accumulation effect. Over time the sand will grow into new islands. Those structures are large bladders made of biodegradable material that will be filled by sediments coming from the river. They will be placed underwater on strategic locations and with different shapes to optimize the sand redistribution and growing barrier islands.

Risk assesment and proposed strategy, elaborated using Google Earth Engine, are presented on Figure 7. Even though they are still in a very early development stage, they illustrate the need of a technological framework like SedimenTerra scale-up this process. Moreover, such a deployment of small scale interventions will need constant monitoring, making computer vision and satellite imagery the best options.

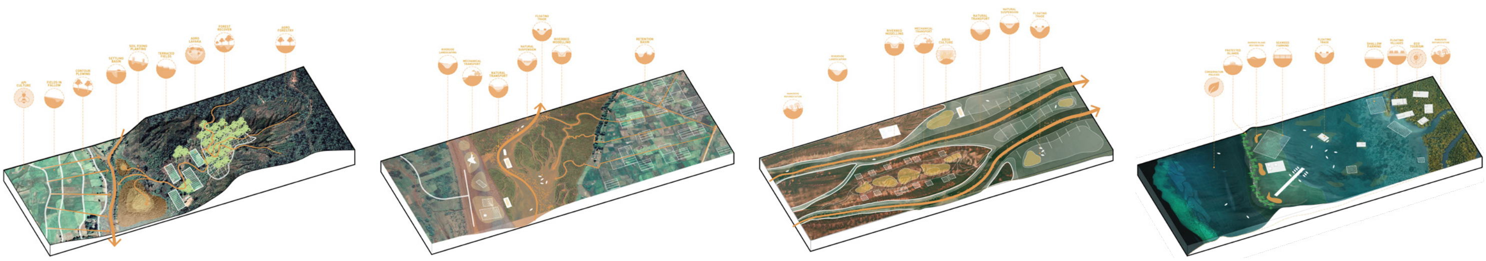

Figure 8: Possible projects for each area type: highlands, riverbed, delta, coast (left to right)

5. Expected results
From SDGs perspective

5.1 General results
SedimenTerra will be directly influenced by targets and feedback set from decision makers and users, thus, expected results may differ regarding implementation time, scale, situation and actors involved.
Globally, the tool will provide relevant data and decision support to foster new proactive sediment management strategies in larger areas by:
1. Increasing available data and information related to sedimentation processes. Including, in the long term, an open global database to increase awareness and support further research developments.
2. Creating a technological framework fostering the implementation of small-scale and locally-managed projects reducing the need for large infrastructure investments.
3. Developing a channel for new local economies based on ecosystem services to flourish, positively impacting local communities.
4. Increasing knowledge to decision makers and financing entities to better evaluate nature-based solutions efficiency and foster its development.

5.2 Link to SDGs
Sediments, being the 3rd most used ressource on Earth, constitute a pilar of the Earth system. Local sediment management increases food and water securuty, prevents salt water infiltration and reduces floods. Moreover it is key in ecosystem functions, whether in forests or sea, altering sediment dynamics can hevaily impact nature. SedimenTerra contributes to monitor sediments and ensure ecological continuity.
Finally, by implementing hyperlocal measures, it promotes local jobs creation, and more widely a new economy managed at a small scale benefiting the inhabitants. As an example, Betsiboka case study uses the surplus of sediment that dykes the river (creating regular floods) to create barrier islands that will protect the coast from sea level rise, and particularly during hurricanes. By applying local measures to this management plan a local sediment economy will be created among the inhabitants inland, near the rivers and on the shoreline.

6. Future challenges
Risks and Opportunities

Satellite technology has a great potential, not only to gather information globally, but to coordinate and sustain sustainability actions throughout the world. However, there are a series of challenges SedimenTerra will face from the early stage where it is currently situated. A non-exhaustive list is:
6.1 Data, Models, Accuracy
As previously seen, the data needed for the models integrated into SedimenTerra is not homogeneous and completely consistent. Even though this challenge is addressed by any data-driven model, it is important to incorporate the infrastructure and methods needed to collect and treat satellite data in an efficient way.
6.2 Local singularities
One of SedimenTerra's pillars is the coordination with local actors and the public sector. Even deploying state of the arts technology, local singularities in political, economic and societal systems could jeopardize its effectiveness.
For this reason it is important for such a tool to include enough mechanisms to be adapted and customized by authorities and citizens. At the sale time, such an open source approach will lead to richer databases and better trained models enabling the tool to learn step by step.
6.3 Policy, Politics, Finance
Water is a global ressource and so are sediments. Climate change and human activities will impact sediment dynamics in major rivers, thus creating tensions between communities. Sediments are a key element to protect coasts against sea level rise in low-lying areas.
In the other hand, green infrastructure is a relatively new domain and its potential scale-up are still in progress, thus reducing financing opportunities. As previously discussed, SedimenTerra will be implemented gradually, increasing its capabilities and accuracy with time. In this process it will be crucial to build up a community of scientific, political and financial partners that will collaborate in the sediment management.

Figure 9: Impacted SDGs

Conclusion
SedimenTerra

Today's human pressure on sediment ressources is altering sediment cycles, often extracting larger amounts of sediment than naturally available. Under climate change, sediments are one of the most exposed resources. Tracking and managing sediments is a complex process that requires a global view and data collection in large areas.
SedimenTerra combines different innovations in terms of data satellite treatment, numerical models and artificial intelligence to address the problematics related to sediment fluctuation.
Thanks to its simplicity this solution can be used at different stages, scales (local or territorial) and a wide range of users (farmers, fishers, ecological organizations, local authorities, policymakers, or government).
Today's mass open space data combined with new hybrid computer vision models make space technical advances applicable to Earth challenges.

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