Space for Sustainability Award

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SEA from Space

Coastal Management via Satellites: Strategic Planning in Response to Global Sea Level Rises

Rising global sea levels are already having an extremely damaging effect on local communities, human infrastructure, and the economy. The negative social and economic repercussions of this is only expected to worsen, meaning that effective coastal management strategies are critical. This project proposes the development of a new tool which acts as a strategic decision-support system for coastal management. The tool will make use of satellite data to characterise shoreline pressures and impacts in terms of future flood potential and coastal erosion, with a view of generating a solution for the most applicable and cost-effective coastal management strategy for different shorelines. These results can then be used to inform Shoreline Management Plans.

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1. Overview of Problem

Sea levels are rising at an alarming rate, which is having a devastating effect on many coastal habitats and putting many other low-lying settlements at serious risk. This is caused primarily by two factors related to global warming: the added water from melting of ice sheets and glaciers as well as the expansion of seawater as it warms. As can be seen in Figure 1, the global sea level has risen by an average of 3.3mm per year since 1993, as observed by satellites [1,2,3]. Looking further ahead, the National Oceanic and Atmospheric Administration (NOAA) reports that global sea levels are very likely to rise at least 0.3m above 2000 levels by 2100, even on a low-emissions pathway. On future pathways with the highest GHG emission projections, this could be as high as 2.5m [4].

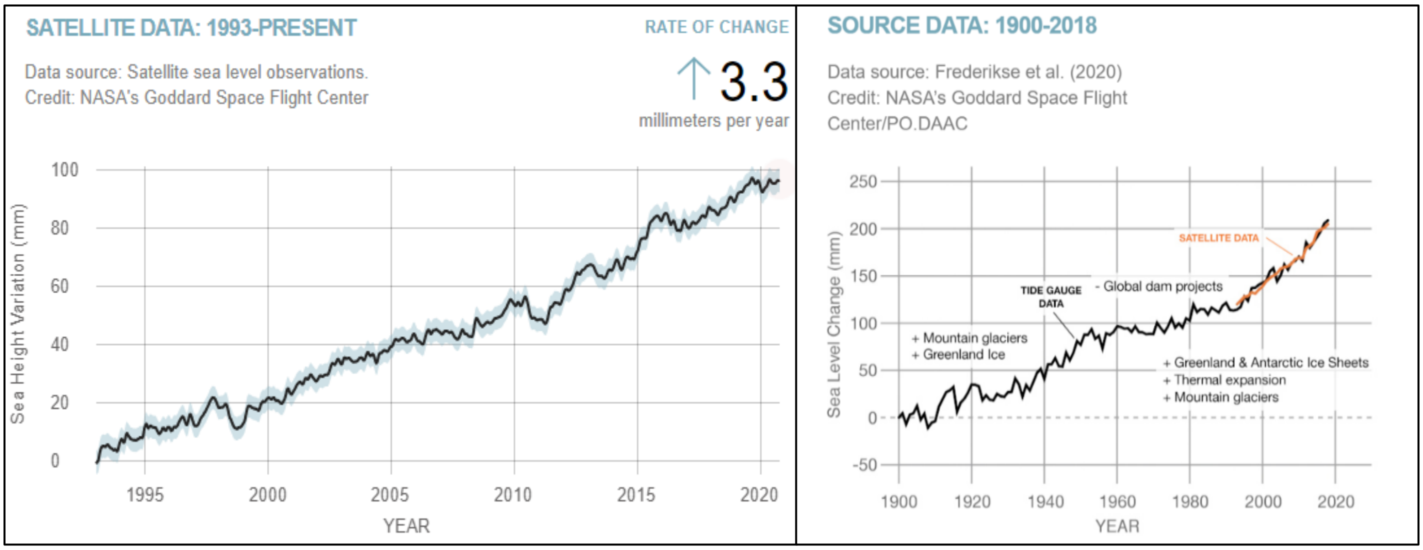

Figure 1: Global sea level since 1993 as observed by satellites [1,2,3]

As such, adapting to this challenge is of critical importance to society, particularly as the European Commission estimates that annual damages from coastal flooding in the EU and UK could increase sharply from €1.4 billion today to almost €1.6 trillion by 2100, with 3.9 million people exposed to coastal flooding every year [5].

2. Current Coastal Management Strategies

Coastal management strategies are a critical method of defence against flooding and erosion. Four main management coastal management strategies can be used to respond to changes in sea levels and protect coastlines:

- **Hold the line:** intervene with hard or soft engineering options to prevent flooding or coastal erosion.
- **Advance the line:** build new defences further out into the sea to reduce stress on current defences and extend the coastline.
- **Managed retreat:** realign the coast via controlled flooding of low-lying coastal areas.
- **No active intervention:** permit natural systems to modify the coastline as they are currently operating.

In this regard, Shoreline Management Plans (SMPs) provide broad, large-scale assessments on the risks of coastal processes and describe which coastal management option is most applicable to a given stretch of shoreline. The main objective of an SMP is to promote a strategic, long-term approach to coastal defence in an area by managing the risks of marine flooding and coastal erosion. During the development of the SMP, it is necessary to assess the level of risk posed by such processes and how this may alter in the future (e.g., as a consequence of climate change). In this context, the term 'risk' implies not just the probability and extent of flooding or loss of land through erosion, but also the consequences of such events in terms of risks to the public, damage to property etc. As such, SMPs consider not only coastal processes such as waves, tides, and sediment movements, but also the impact this has on coastal assets, including buildings, infrastructure, natural habitats, archaeology, and the historic environment. The provision of satellite data could play a vital role in the SMP process across Europe and beyond by enabling planners to make more informed decisions on the most appropriate coastal management strategies to deploy per stretch of coastline.

3. A Decision-Support System for Coastal Management

This project proposes the development of a new open-source software application capable of identifying areas of land that are most susceptible to flooding and coastal erosion given rising sea level projections. The tool will combine in-situ and satellite data to identify and characterise shoreline pressures and impacts. This data will then be fed into an optimisation algorithm to determine the most applicable and cost-effective coastal management strategies for a variety of different shorelines, taking into account proximity to settlements and critical infrastructure. In view of this, the proposed software application has four steps which are outlined in Figure 2 and described further below:

- **Step 1:** Develop a map-based application (which combines land elevation data with sea level rise scenario projections) to identify coastal areas most susceptible to flooding over a given time series.
- **Step 2:** Integrate in-situ and satellite data on shoreline characteristics and pressures to determine areas that are most susceptible to coastal erosion, accounting for sea level rise projections and land elevation.
- **Step 3:** Based on the above steps, use an optimisation algorithm to determine which coastal management strategy is best-suited to a given shoreline, considering trade-offs and proximity to community infrastructure.
- **Step 4:** Synthesise findings as part of a Shoreline Management Plan.

Figure 2: A decision-support system for coastal management

Consequently, the new tool is proposed to improve present solutions, boosting the planning and execution of coastal defences in the view of rising sea levels. Given that satellite surveys are capable of providing near-continuous coverage of shorelines, this enables a data-driven approach for coastal management and provides planners with a greater oversight into coastal ecosystems. This data will be complimented by in-situ measurements, which will be used to calibrate and verify the accuracy of the modelling tool, as well as to fill-in any potential data gaps. Sentinel satellite data will be collected on a wide variety of coastal features due to its open-access nature, all of which will be collectively integrated as individual criteria points as part of the optimisation algorithm. The algorithm will then use these criteria points as a method for evaluation to determine an optimal solution when iteratively comparing the suitability of different coastal management strategies to particular shorelines. More details and a technical overview on the implementation of the proposed tool is provided below.

4. Implementation of Proposed Solution

Since a map-based application is proposed, it has been decided that geographic information system (GIS) mapping software will be used as the foundation for the tool's development. GIS is a conceptualised framework that allows users to capture, create, manage, analyse, and map spatial and geographic data. Accordingly, GIS mapping software has the ability to display and contrast many different kinds of data on a single map, which enables users to gain a better understanding into patterns and relationships. This makes it an ideal choice and particularly well-suited to the intended project scope. Based on this architecture, the four steps noted within Figure 2 for the development of the proposed software application will be discussed, with a graphical description of the planned user interface presented within the Annex A.

STEP ONE requires satellite data on topography and sea level rises to be input to the map-based software application. In terms of topography, a digital elevation map can be created based on land remote sensing data. Sentinel-2 is a large provider of such data as this is central to the European Commission's Copernicus programme. More specifically, Sentinel-2's multi-spectral instrument (MSI) allows for land height observations to be made along a 290-km orbital swath with a ground sampling distance of up to 10m/pixel [6,7]. The MSI measures the Earth's reflected radiance in 13 spectral bands from the visible to infrared portion of the electromagnetic spectrum, making it ideal for the proposed software application [6,7]. This should provide sufficient spatial resolution for identifying urban areas and places where there is evidence of human settlement or infrastructure, with future Sentinel and Copernicus satellites expected to add further precision. However, in the unlikely event that this proves to be insufficient, then alternative data sources could be sought from ground data or satellites with higher resolutions such as GeoEye-1 and Landsat-7. For monitoring sea level rises, the new Sentinel-6 is recommended as the baseline data provider due to its short revisit period (~10 days) and mm precision with regard to sea surface height [8,9]. Sentinel-6 uses a synthetic-aperture radar (SAR) altimeter to measure mean sea levels by bouncing radio wave pulses off the ocean surface and precisely timing how long those pulses take to travel back to the spacecraft [10]. As such, Sentinel-6 data will be collected over a variety of coastal regions, given that a recent study found that sea level rise along coastlines can exceed the global mean due to complex ocean dynamics nearer land [11]. This data will be combined with long-term data records of the sea state to assess changes over decades.

Based on the acquisition of these data sources, the main output of the first step will be the production of a visual map which provides inundation depths (measured in metres) at locations globally, calculated by a flood-fill algorithm where satellite data will be used to constantly adjust sea level rise projections. The focus will extend beyond only coastal regions, also examining the flooding susceptibility of areas located near river estuaries. This should lead to the identification of potential 'red-flag' areas, which are defined as those most at risk of being inundated by flooding. The end-user can then choose to focus on particular locations according to their individual preferences or motivations such as proximity to urban settlements, critical infrastructure, available productive land, conservation areas with protected statuses, sites of special scientific interest, etc.

STEP TWO will integrate additional Sentinel satellite data on shoreline pressures and impacts across the identified red-flag areas to update the visual map with the potential influence of storm surges and coastal erosion. In terms of storm surges, this will require multi-spectral imaging to track the progress of storms and estimate their landfall location, altimeter measurements to provide near-real time information on changes in sea level height and the use of SAR instruments to determine maximum wave height/direction and wind speeds. However, it is understood that the Sentinel missions may not be able to measure short storm surges in specific locations due to the length of their revisit times. Where current or historic Sentinel product data is not available, alternative data could be extrapolated from existing numerical weather and ocean prediction models such as ESA's eSurge project on storm surge forecasting [12]. The use of such models within the proposed software application could provide greater insight into potential flooding events caused by storm surges, particularly as their magnitude can also generally relate to the strength of onshore winds, the local geometry of the coastline and the bathymetry of the offshore seabed. The discharge inputs can be combined with sea level rise projections and extrapolated to determine maximum flooding inundation extents. For coastal erosion, Sentinel-2's MSI can be used to search for evidence of erosion. In this regard, a library of spectral changes can be created to search for material loss or changes to the shape of the coastline over time, including evidence of high sediment deposition via plume concentrations. This change analysis can also be combined with sea level rise projections and extrapolated to predict probabilistic future coastal erosion patterns.

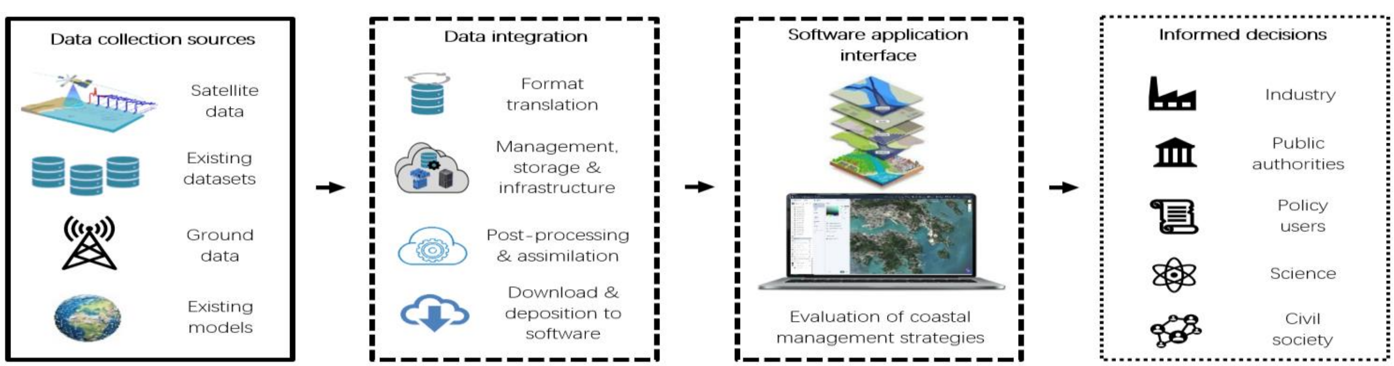

Figure 3: Process for converting the data products used within the software application into informed decisions

The purpose of obtaining this data on storm surges and coastal erosion is to integrate it as an optional feature of the flood-fill algorithm. Its use could provide users with more accurate information relating to risks associated with potential future flooding scenarios throughout the identified red-flag areas under study. Therefore, the data will be fed into the visual map to update it, taking into account shoreline characteristics, including sandy beaches, cliff faces and substrates. All of the suggested Sentinel data products mentioned within this paper are considered to of a high enough quality to create a fully-functional tool, with a sufficient level of detail provided. Additionally, given that these data products are freely available to the public, this means that the software can be created at low or no cost to users. The overall process for converting Sentinel data in its raw form into information which is understandable to stakeholders via assimilating and processing techniques has been outlined in Figure 3 above.

STEP THREE applies an algorithm to determine the optimal coastal management strategy for a given shoreline. To achieve this, land use classification of remote sensing imagery must take place [13]. As such, a range of different land cover classes will be created within the software application. The user must then identify and allocate these land use types within the specific red-flag area under study. To reduce the work-hours required, semi-supervised or supervised classification techniques could be applied, including Artificial Neural Network (ANN) methods or spectral-slope-based techniques that look at spectral range. This approach will enable a trade-off analysis to be conducted, based on the land-cover composition and shoreline characteristics. In this regard, the most applicable coastal management strategy will be determine using an optimisation algorithm which is based on:

(a) Expected benefits: Environmental rebuts, social desirability and economic sustainability of implementation (value/m^2).

(b) Damage costs: Spatial distribution of unmitigated damage based on infrastructure proximity and land productivity (€/m^2).

(c) Ease of implementation: Technical feasibility to implement/maintain strategy (features analysis based on satellite data).

(d) Motivation / urgency: Potential flooding exposure based on population density per area (people/km^2).

(e) Expected cost: Cost of strategy implementation to protect affected area (€/m^2).

(f) Risk assessment: Risk matrix calculation based on job hazard analysis (likelihood x severity).

(g) Implementation time: Project timespan based on industry averages (estimated duration/m^2).

(h) Term to payoff: Estimated payback time (expected cost/cost of not implementing the option).

The optimisation algorithm will split these points into a list of positive and negative criteria, where (a) to (d) are positive and (e) to (h) are negative. Each criteria point can then be scored according to their metric value outlined above, using a scale of one to ten (where one is low and ten is high). The scoring method to be used within the algorithm will be developed based on perceived maximum and minimum thresholds for each criteria point, using uniformed intervals. This threshold has yet to be determined for each point but will likely be developed with consultation from industry-experts, assuming that this project is pursued further (see Section 5). Nonetheless, after this step, the total score for each list will be calculated based on the sum of values. Each list will then be compared to one another, with the difference in score calculated as the final result. Therefore, based on this method, it is foreseen that the coastal management strategy with the highest score will be put forward as the most applicable for that given shoreline. An example of this process is provided within Table 1 below.

Table 1: Example of a trade-off analysis between coastal management strategies for a hypothetical shoreline

Hold the Line *(+14)*

Positive criteria	Score	Negative criteria	Score
Expected benefits	9	Expected cost	6
Damage costs	9	Risk assessment	6
Ease of implementation	8	Implementation time	4
Motivation / urgency	9	Term to payoff	5
Total	**35**	**Total**	**21**

Advance the Line *(+9)*

Positive criteria	Score	Negative criteria	Score
Expected benefit	9	Expected cost	6
Damage costs	9	Risk assessment	3
Ease of implementation	6	Implementation time	8
Motivation / urgency	9	Term to payoff	7
Total	**33**	**Total**	**24**

Managed Retreat *(-2)*

Positive criteria	Score	Negative criteria	Score
Expected benefits	3	Expected cost	7
Damage costs	9	Risk assessment	9
Ease of implementation	5	Implementation time	3
Motivation / urgency	9	Term to payoff	9
Total	**26**	**Total**	**28**

No Active Intervention *(-8)*

Positive criteria	Score	Negative criteria	Score
Expected benefit	2	Expected cost	10
Damage costs	9	Risk assessment	10
Ease of implementation	4	Implementation time	2
Motivation / urgency	9	Term to payoff	10
Total	**24**	**Total**	**32**

It should be noted that all of the data contained within the above table has been randomly generated to aid in the explanation of the algorithm results and does not represent accurate data or values. However, as can be seen through this example, the most appropriate option for the given hypothetical coastline is 'hold the line' based on the scoring. Within the proposed application tool, this information would be mapped visually, including pop-out quantitative information. The tool will also allow users to change the preference settings (including the alteration of thresholds and weightings), with the option of adding to or deleting the predefined criteria points. The reason for this is because it is recognised that the weighting of criteria points within the algorithm adds subjectivity to the analysis whilst any missing/inaccurate data could obscure algorithm results.

STEP FOUR is concerned with tool outputs and their application. In this regard, the system will enable users to extract the information generated on different shorelines in raster or vector format (including csv or xlsx for the background data), allowing decision-makers to write a summary on the model findings and integrate this as part of a SMP (see Figure 4). This information can be in relation to any (or all) of the data contained within the tool, including optimal coastal management strategies for different shorelines. However, it should be understood that the suggested coastal management strategy generated by this tool may not necessarily be approved of at stakeholder/scoping meetings, which is a key part of the SMP process. This is not considered to be a major hinderance, as the system is intended to act as a decision-support tool rather than a decision-making tool. In this regard, its purpose is to provide a better understanding of coastal flood risk and mitigation, thereby facilitating informed decisions rather than making them directly. Additionally, due to the keen political interest in developing coastal management strategies, it is also suspected that the system could also promote the development of larger Integrated Coastal Management Plans.

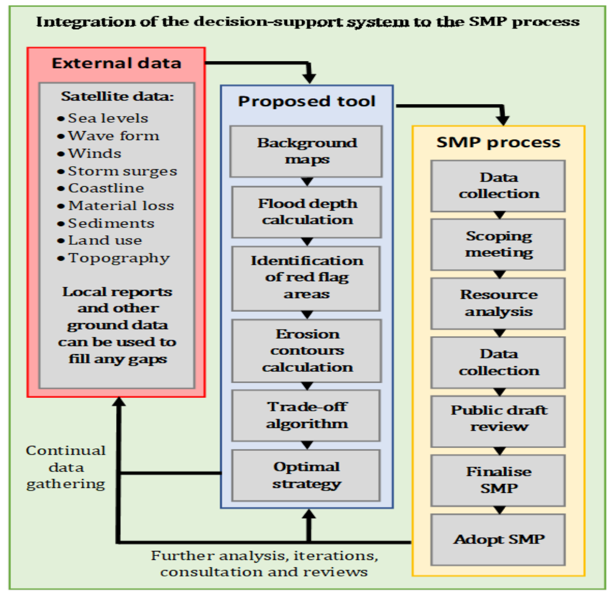

Figure 4: Expected inputs to the SMP process

5. Pilot Study Selection: Dumfries & Galloway

Dumfries & Galloway is one of 32 local council authority areas of Scotland and is located in the Western Southern Uplands. It is predominantly a rural region with small, sparsely populated communities scattered throughout it, connected by critical infrastructure. However, Dumfries and Galloway has several low-lying coastal areas which are at serious risk of flooding as sea levels continue to rise (as depicted in Figures 5 and 6). This presents a major challenge on how the provision of essential social services can be maintained across an increasingly fragmented landscape. As such, the local council are currently looking to investigate a range of coastal management strategies, including the possibility of implementing managed retreats for areas that are going to be too difficult and/or costly to save from rising sea levels.

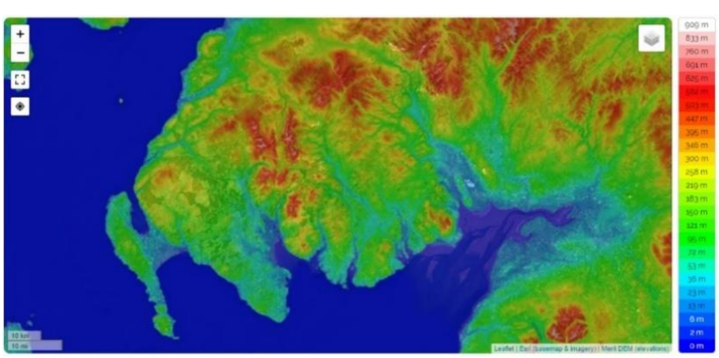

Figure 5: Topography and land elevation map of the Dumfries & Galloway coastline with a clear and distinct presence of low-lying coastal areas [14]

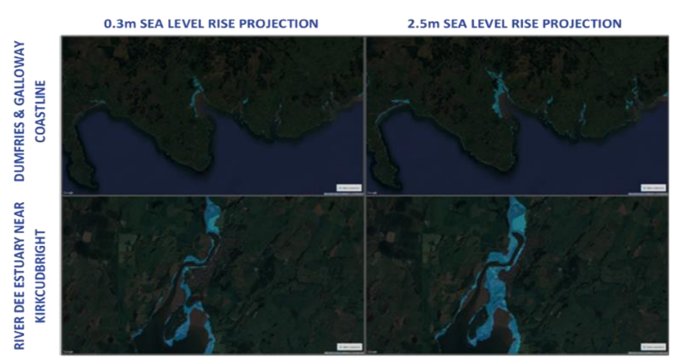

Figure 6: Flooding potential around the Dumfries & Galloway coastline, focussing on the River Dee estuary near Kirkcudbright (adapted from [15])

This aforementioned exercise will form the basis for the development of a new SMP for Dumfries & Galloway, replacing the current version which was originally produced in 2005. The main recommendation of the original plan was that new methods for data gathering on the rate of erosion or the frequency and extent of flooding events were essential [16]. It was also suggested that this could be supplemented by numerical modelling techniques to predict more severe events and the effects of an increased mean sea level. The new SMP is expected to take a minimum of two years to complete, and will provide an update on potential flooding, coastal erosion, and the most suitable coastal management strategies for the Solway coastline [17].

As such, the coastal management tool proposed by this project has high relevance to this process. It presents a modest method of evaluating shoreline pressures with a view of selecting the most appropriate coastal management strategies, concentrating on the areas that are most likely to require coastal defences due to rising sea levels. In this regard, a logical next step would be to develop the tool as part of a university-led initiative, with a view of applying it to Dumfries & Galloway as a use case. As a result, its implementation may lead to an overall better knowledge of coastal processes and associated risks along the Solway Firth, which would be extremely valuable to the new SMP and to those responsible for flood defence and coastal protection.

6. Challenges & Expected Results

This project has been proposed to protect the most vulnerable from future sea level rises and prevent costly infrastructure damage. The software application is expected to act as a strategic decision-support system for coastal management and feed into the development of future SMPs by providing a greater oversight into the prospect of future flooding and coastal erosion risks. Therefore, it is envisaged that the utilisation of the tool will enable planners to better prepare for the adverse impacts of global sea level rises through the identification of the most sustainable coastal management strategy in the:

- **Short-term:** 0-20 years.
- **Medium-term:** 20-50 years.
- **Long-term:** 50-100 years.

However, to determine whether the execution of this project is realistically achievable, the technical and operational feasibility should be evaluated. In this regard, a SWOT analysis was selected as the most appropriate strategic planning approach for this purpose, since it organises information into a logical order by examining both internal strengths/weaknesses and external opportunities/threats, thereby making it very easy to understand. The results of this SWOT analysis can be found below.

Table 2: SWOT analysis on the feasibility of the proposed decision-support system for coastal management

S	W
Accurate and reliable results, based on up-to-date information. Clear visual map presenting optimal coastal management strategies. Could be developed freely as an open-source application (proposed).	Weighting of criteria points within the algorithm adds subjectivity. Spatial resolution for some aspects may be insufficient (unlikely). Long development time and high computational power.
O	**T**
Future Sentinel and Copernicus satellites will add further precision. Keen political interests in developing coastal management strategies. Could be used as part of larger Integrated Coastal Management Plans.	Any missing/inaccurate data could obscure algorithm results. The potential cost of alternative data if a better resolution is required. Suggested strategies may not be approved of at stakeholder meetings.

Given the findings contained within the SWOT analysis, this project can be considered to be technically and operationally viable, within the defined constraints. Procedures to minimise internal weaknesses and external threats of the proposed tool have already been discussed within Section 4, with no insurmountable obstacles foreseen. As a result, this system has huge potential to contribute towards a more sustainable future, particularly as the project provides vital support to the attainment of several of the Sustainable Development Goals (SDGs) contained within the 2030 Agenda for Sustainable Development [18].

7. Impact on the Sustainable Development Goals

The SDGs and associated targets focus on a wide range of global issues, including coastal protection. Careful management of this essential global resource is a key feature of a sustainable future. In particular, this is vital for ensuring climate resilient and adaptable coastal development, particularly when considering the potential impact of climate change on coastal communities. As demonstrated by Schipper at al. [19], a total of 38 out of the 169 SDG targets are directly relevant to coastal management strategies and flood protection. Drawing upon this finding, 22 of those targets were deemed applicable to this project. These are outlined in Table 3 below, along with a short description on the connection between each target and this project.

Table 3: Potential influence of this project on the Sustainable Development Goals

SDG	Target	Short Description
1	1.5	Disaster resilience
3	3.d	Early warning and risk reduction
6	6.6	Water quantity and quality
8	8.2	Economic productivity
9	9.1	Resilient infrastructure
9	9.5	Knowledge and innovation
11	11.5	Disaster risk reduction
11	11.a	Development planning
11	11.b	Holistic disaster risk management
12	12.8	Flood awareness
13	13.1	Resilience and adaptive capacity
13	13.2	Coastal erosion / accretion
13	13.3	Improved climate education
13	13.b	Effective planning
14	14.2	Biodiversity abundance
14	14.5	Coastal marine conservation
14	14.7	Small island development
14	14.a	Marine technology
14	14.c	Ocean conservation
15	15.8	Prevention of invasive alien species
16	16.7	Institutional capacity
17	17.17	Public-private partnerships

8. Conclusion

Rising sea levels are placing an increasing strain upon society and the economy. The new tool proposed as part of this project aims to inform SMPs by providing a greater oversight into coastal ecosystems. To do this, the tool makes use of Sentinel data products on shoreline pressures and impacts to determine appropriate coastal management strategies. The applied methodology has been presented in a clear and transparent manner, with the most important implications of the tool being summarised. Therefore, even if not all of the interested parties agree with the suggested strategy option generated by the tool, the basis for making that recommendation is clear. As a result, the implementation of this project is expected to improve European and global coastal management by providing planners with important information which will allow them to make more informed decisions relating to coastal erosion and flood mitigation. In turn, this will lead to better protection of coastal communities and assets by minimising the risk of damage to the furthest extent possible.

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References

[1] Beckley, B.D., Callahan, P.S., Hancock III, D.W., Mitchum, G.T. and Ray, R.D., 2017. 'On the "Cal-Mode" Correction to TOPEX Satellite Altimetry and Its Effect on the Global Mean Sea Level Time Series'. *Journal of Geophysical Research: Oceans*, 122(11), pp.8371-8384.

[2] Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V.W., Dangendorf, S., Hogarth, P., Zanna, L., Cheng, L. and Wu, Y.H., 2020. 'The causes of sea-level rise since 1900'. *Nature*, 584(7821), pp.393-397.

[3] National Aeronautics and Space Administration (NASA), 2020. *Sea Level | Vital Signs of the Planet*, NASA Global Climate Change, viewed 18 July 2021, <https://climate.nasa.gov/vital-signs/sea-level/>.

[4] Parris, A.S., Bromirski, P., Burkett, V., Cayan, D.R., Culver, M.E., Hall, J., Horton, R.M., Knuuti, K., Moss, R.H., Obeysekera, J. and Sallenger, A.H., 2012. *Global sea level rise scenarios for the United States National Climate Assessment*. NOAA Technical Report OAR CPO-1.

[5] Vousdoukas, M.I., Mentaschi, L., Hinkel, J., Ward, P.J., Mongelli, I., Ciscar, J.C. and Feyen, L., 2020. 'Economic motivation for raising coastal flood defenses in Europe'. *Nature communications, 11(1)*, pp.1-11.

[6] Ressl, C. and Pfeifer, N., 2018. 'Evaluation of the elevation model influence on the orthorectification of Sentinel-2 satellite images over Austria', *European Journal of Remote Sensing*, 51(1), pp. 693-709.

[7] European Space Agency, 2021. *Sentinel User Guides*, viewed 18 July 2021, <https://sentinels.copernicus.eu/>.

[8] European Space Agency Climate Office, 2020. *Coastal Observations Boosted By New Reference Satellite*, viewed 18 July 2021, <https://climate.esa.int/en/news-events/coastal-observations-boosted-new-reference-satellite/>.

[9] Rao, R., 2021. *The Sentinel 6 satellite is now tracking Earth's rising sea levels with unprecedented accuracy*, Space.com, viewed 18 July 2021, <https://www.space.com/sentinel-6-satellite-tracking-earth-sea-level-rise>.

[10] NASA Jet Propulsion Laboratory, 2021. *Sentinel-6: Spacecraft and Instruments*, viewed 18 July 2021, <https://www.jpl.nasa.gov/news/press_kits/sentinel-6/mission/spacecraft/>.

[11] European Space Agency, 2021. *New satellite data techniques reveal coastal sea-level rise*, viewed 18 July 2021, <https://www.esa.int/Applications/Observing_the_Earth/New_satellite_data_techniques_reveal_coastal_sea-level_rise>.

[12] Harwood, P., 2015. *DUE eSurge – Final Report*, Report D430_eSurge_FR, Version 1.0, February 2015.

[13] Prahl, B.F., Boettle, M., Costa, L., Kropp, J.P and Rybski, D., 2018. 'Data Descriptor: Damage and protection cost curves for coastal floods within the 600 largest European cities'. *Scientific Data*, 5, 180034 (2018).

[14] Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J.C., Sampson, C.C., Kanae, S., and Bates, P.D., 2017. 'A high-accuracy map of global terrain elevations'. *Geophysical Research Letters*, 44, pp. 5844-5853.

[15] Climate Central, 2021. *Coastal Risk Screening Tool*, viewed 18 July 2021, <https://coastal.climatecentral.org/map/>.

[16] HR Wallingford, 2005. *Dumfries and Galloway Shoreline Management Plan*, Report EX 4963, Rev 2.0, June 2005.

[17] Dumfries & Galloway Council, 2021. *Dumfries & Galloway Shoreline Management Plan (SMP)*, viewed 18 July 2021, <https://www.dumgal.gov.uk/SMP>.

[18] United Nations General Assembly, 2015. *Transforming our world: the 2030 agenda for sustainable development*. A/RES/70/1, 25 September 2015.

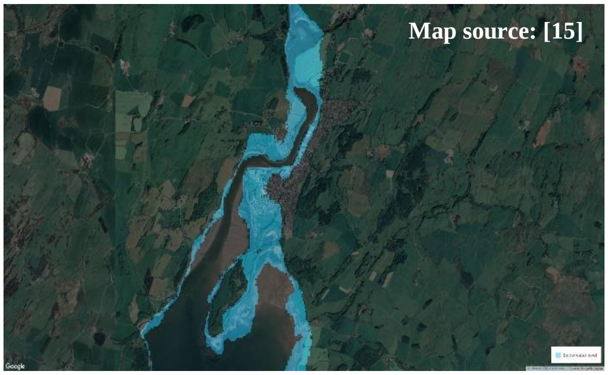
[19] Schipper, C.A., Dekker, G.G.J., de Visser, B., Bolman, B. and Lodder, Q., 2021. 'Characterization of SDGs towards Coastal Management: Sustainability Performance and Cross-Linking Consequences'. *Sustainability*, 13(3), 1560.

[20] National Library of Scotland, 2021. *HLAmap*, viewed 18 July 2021, <https://map.hlamap.org.uk/>.

[21] Hansom, J.D., Fitton, J.M., and Rennie, A.F., 2017. *Dynamic Coast – National Coastal Change Assessment: Cell 7 – Mull of Galloway to the Inner Solway Firth*, Report no. CRW2014/2, viewed 18 July 2021, <https://www.crew.ac.uk/sites/www.crew.ac.uk/files/sites/default/files/publication/NCCA%20-%20Cell%207%20-%20Mull%20of%20Galloway%20to%20the%20Inner%20Solway%20Firth.pdf>.

Annex A: Planned user interface – basic overview

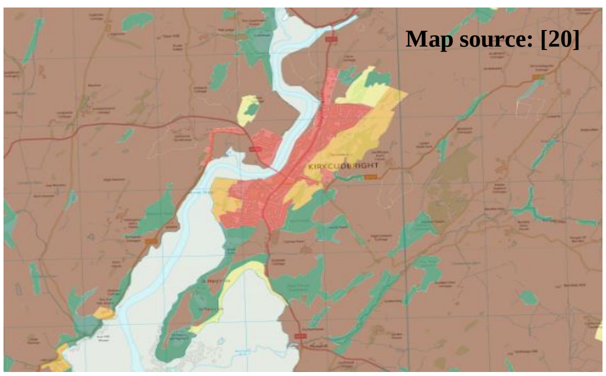
(a)



Below water with a 2.5m rise in sea level *(light blue)*

Figure (a): Satellite data on sea level rises and coastal erosion obtained during Step One and Step Two of the tool's framework will be used to generate a visual inundation map, based on different sea level rise scenarios. In this example, land below water with a 2.5m rise in sea levels can be seen for the Scottish town of Kirkcudbright along the River Dee estuary.

(b)



Meadow and permanent grass *(light green)*

Arable land including rotation grass *(brown)*

Heathland and moorland or rough hill pasture *(yellow)*

Forests and woodland *(dark green)*

Gardens *(purple)*

Urban areas *(red)*

n… Other land use classifications

Figure (b): Land use classification takes place based on the ANN method or spectral-slope-based techniques, as outlined in Step Three. Each land use classification has predefined criteria attached to it (which can be altered if desired), meaning that the user has only to define the land use types present in the area of study before the optimisation algorithm is run.

(c)

Hold the line *(blue and white)*

Advance the line *(pink and white)*

Managed retreat *(black and white)*

No active intervention *(purple and white)*

Figure (c): The optimisation algorithm indicates the optimal coastal management strategy for a given shoreline. This will be mapped as the sole entry within the software. However, the user can also choose to display all viable coastal management strategies (as is the case here). Pop-out quantitative information (in relation to the various criteria points presented within Section 4) can also be obtained by the user by hovering over each strategy. As part of Step Four, this can then be exported in many different formats, and used as a basis for informing SMPs.