MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING | URBAN PLANNING, DESIGN AND POLICY | AEROSPACE ENGINEERING | ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING | ARCHITECTURAL, URBAN AND INTERIOR DESIGN | BIOENGINEERING | DATA ANALYTICS AND DECISION SCIENCES | DESIGN | ELECTRICAL ENGINEERING | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | MANAGEMENT ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING

PhD Yearbook | 2025

DOCTORAL PROGRAM IN ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING

Chair:
Prof. Monica Riva

The Doctoral Program in Environmental and Infrastructure Engineering has been operating since the academic year 2008/2009. The program is dedicated to exploring crucial theoretical and technological aspects related to water, the environment, hydraulic and transportation infrastructures, geology, and geomatics. In this context, the program is grounded on environmental, civil, and industrial applications where water is the primary unifying element. The doctoral program stands out with its remarkable inter- multi- and trans-disciplinary structure, fostering a comprehensive approach to research. It is carefully designed around the following three key thematic areas, collectively providing a comprehensive platform for advanced research and expertise in the field of Environmental and Infrastructure Engineering.

Area 01. **Water Science and Engineering**. This area delves into the realm of hydrology and water resources, with emphasis on the main physical processes of the hydrological cycle, water and energy budgets. It also includes the study of hydrological hazards and strategies for their mitigation, hydrological extremes, floods, droughts and precipitation, early warning operative systems, snow avalanching and flood risk; hydraulic networks engineering; and coastal engineering.

Area 02. **Transport infrastructures and Geosciences**. This area focuses on the dynamic interactions between transport networks and regional, national and international territories. Sustainable development, including dynamics of development and their relations with infrastructure systems, is a key aspect. Technological innovation, including methods and indicators for performance characterization of infrastructure construction and maintenance techniques, is also explored. Furthermore, this area encompasses research on hydrogeological risk, landslide hazard; water resources identification and management, and pollution problems.

Area 03. **Environmental and Hydraulic Engineering and Geomatics.** Research in this area covers a wide range of topics. It encompasses water and wastewater treatment technologies, including disposal and reuse of wastewater, efficient sludge management and anaerobic digestion processes. Management and planning of environmental resources, such as water quality modeling and knowledge-based decision support systems, are also explored. Solid waste management, including evaluating energy and resource recovery initiatives through Life Cycle Assessment, is another focus. Other subjects covered in this area are computational and experimental fluid dynamics, fluid-structure interactions; river hydraulics; sediment mechanics; hydraulic risk assessment and management; flow and transport processes in porous systems; hydraulic networks, hydro-energy; oil and gas development and applications, physical geodesy and satellite geodesy; positioning and navigation; surface surveying; digital photogrammetry and image analysis; remote sensing; geographic information systems; cultural heritage reconstruction and archiving.

The doctoral program has been designed to address the intricate and diverse research questions surrounding the complex interplay between the water sphere and the key evolving anthropogenic activities responding to the needs of modern society. PhD students will be skilled in an interdisciplinary and multi-sectoral environment and will gain excellent communication, management and research skills. They will acquire a set of skills and a knowledge base that are transferable to a range of real-world challenges related to ecosystem services. These skills open up significant opportunities for PhD candidates in academia, as well as in private and public organizations. Career perspectives include opportunities at Universities, Research Centers, public bodies and Authorities, as well as private companies / industry. Small and medium size enterprises (SMEs) which cannot afford the development of an in-house specific know-how program may also require such highly professional profiles to guarantee critical innovation and competitiveness.

LABORATORIES

An integral component of the Doctoral Programme is the presence of our state-of-the-art Laboratories. These encompass various domains, including the laboratory of (i) Hydraulics "Gaudenzio Fantoli", (ii) Environmental Engineering, (iii) Geodetic and Photogrammetric measurements, (iv) Applied Geophysics measurements, (iv) Transport Infrastructures. These laboratories, linked to the strategic issues characteristic of the different territorial areas, are an indispensable and valuable tool for the development and implementation of research activities of our PhD candidates. The Department's Laboratories are also headed by experimental platforms allocated for logistical needs at industries, plants, research centers, and experimental sites. Additionally, our doctoral program provides access to computational infrastructures dedicated to software development and to interdepartmental laboratories, such as GEOLAB (Geomatics and Earth Observation Lab), SoLINano-LAB (Solid-Liquid Interface Nanomicroscopy and Spectroscopy Lab) and CFDHub@Polimi (Computational Fluid Dynamics Lab). These laboratories and computational resources not only enhance the research capabilities of our doctoral students, but also facilitate inter- and cross-disciplinary collaborations, enabling our students to make significant contributions in their respective fields and to address complex challenges in their research activities.

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COMBINING MATERIAL FLOW ANALYSIS AND LIFE CYCLE ASSESSMENT OF THE EUROPEAN PLASTIC VALUE CHAIN - UNVEILING HOTSPOTS AND SOLUTIONS TOWARDS INCREASED CIRCULARITY AND SUSTAINABILITY

Andrea Martino Amadei - Supervisor: Lucia Rigamonti

Plastics' versatility, durability, lightweight nature, and cost-effectiveness have contributed to an increasingly widespread use of plastics in the European Union (EU) economy. This is however causing environmental and health challenges, particularly regarding plastic pollution, littering, and greenhouse gases (GHG). Such challenges require further efforts to increase plastic recycling and proper waste management within the EU, as evidence suggests that a significant amount of plastic waste is still being mismanaged. In response to this wide array of multifaceted challenges, the EU has implemented a range of policies, including, among others, the European Green Deal, the EU Plastics Strategy and the Single Use Plastic Directive. Further, at the international level, the EU is involved in high ambition coalitions to end plastic pollution via a 'global plastics treaty' ending plastic pollution by 2040.
To safeguard and support EU competitiveness and to meet ambitious EU policies targets, an in-depth analysis of the EU plastic value chain is crucial. Consequently, Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) methodologies (and their combination) were thoroughly explored in the present PhD thesis. In particular, this PhD presents a series of analyses devoted to highlight the key methodological challenges and main results towards the development of a full eagle-eyes ("snapshot") overview of the flow and environmental impacts associated with the whole EU27 2019 plastic value chain across several impact categories (beyond the sole Climate Change impact). The analysis assessed the full EU plastic value chain, from production to end-of-life, including estimates for less-known flows and sectors, as detailed in Figure 1.
Results of the sector-specific top-down MFAs highlighted the role of packaging as the most important sector among those assessed, contributing to 33% of the total plastic consumption (around 45Mt). Of the total amount of post-consumer waste being generated (around 29Mt) only 38% was separately collected, with a significant fraction (13%) being mismanaged. The 4.5Mt of recycled plastics produced and consumed in the EU27 territory led to an end-of-life recycling rate not higher than 17%. Losses of plastics (micro-/macro-plastics) mostly occurred during the use phase (39% of the total 2.1Mt of plastic lost along the value chain).

LCA findings of the study (calculated according to the Environmental Footprint (EF) method) revealed that the total Climate Change impacts of the EU plastic value chain amounted to 279 Mt CO_2 eq. Production and manufacturing stages account for a significant share of more than 56% of the Climate Change impacts. The packaging sector contributed on average to around 30% of the total impacts across the various impact categories assessed, resulting in the most impactful among sectors. Sensitivity scenarios exploring the effect of shifts in plastic flows in the whole value chain impacts provided interesting results related to the interlinkages between plastics' life cycle stages. Only ambitious scenarios (exploring the effects of a hypothetical high recovery and efficient plastic value chain) could provide relevant impacts' reductions, in the order of -16% for instance for the Single Score (an aggregated index summarizing all 16 impact categories of the EF method). To further push impacts' reductions, these scenarios should be coupled with a reduction in plastic production, that would guarantee savings in the Climate Change impact category as high as -28% (when the production is reduced by 10Mt). When assessing the effects of alternative and cleaner electricity and thermal mixes, results indicated how a substitution with cleaner mixes would result in an overall reduction of both production and manufacturing impacts. These shifts would however also influence the performance of the incineration life cycle stage as the substituted energy mixes considers the increase in the share of renewables.
When LCA results are monetized via monetary valuation coefficients, the costs range associated with monetized impacts would be in the range of 73 bln€$_{2019}$ (minimum) and 190 bln€$_{2019}$ (maximum). If such results are compared with the total costs of the EU plastic value chain (estimated at 284 bln€$_{2019}$), they would represent a share in the range of 26-67%. Therefore, to account for the externalities' costs associated with the environmental impacts of the EU plastic value chain, a total of 73-190 bln€$_{2019}$ should be internalized on top of the estimated costs.
Despite a growing interest in analysing plastic flows, comprehensive EU-level studies detailing such flows at the granular level of multiple sectors/polymers along the whole value chain are currently lacking, especially those including estimates on losses, mismanaged waste, and recycled plastics' fate. Better sector-/polymer-specific data for less-explored sectors (such as textiles, fishing, and healthcare) coupled with in-depth knowledge of recycled plastics' fate should in fact be explored.
Another key finding is that plastic production and products manufacturing are both of paramount importance in terms of impacts of the EU plastic value chain. These two life cycle stages accounted for more than half of the total Climate Change impact of the EU value chain, especially because of the high impacts of virgin polymers production.
When looking at the life cycle assessment results, the importance of addressing impact categories beyond Climate Change has been recognized. In fact, greenhouse gases emissions are the sole focus of most literature studies available to date about the EU value chain impacts. Analysis going beyond Climate Change should not be underestimated. For instance, the comparative performance of recycling activities and incineration with energy recovery activities might diverge when analysing different impact categories. Further, exploring a wider number of impacts categories could more easily accommodate improvements such as the inclusions of new characterization factors (that could be relevant for instance to tackle microplastics impacts).
An improvement and rethinking of the value chain is mandatory and should be driven by an up-to-date knowledge of all its many hotspots. The findings of this study could prove useful to decision-makers and researchers alike as they enable the identification of hotspots and priorities of the EU plastic value chain in need of refined and up-to-date data. The need of investigating further the flows and impacts of EU plastic is a fundamental step in view of fulfilling EU ambitions to overcome the ever-growing plastic pollution issues, to lower the plastics environmental impacts and to boost its circularity. The findings of this study could also prove useful to researchers seeking estimates and information on the EU plastic value chain, with granular details on flows and associated impacts.

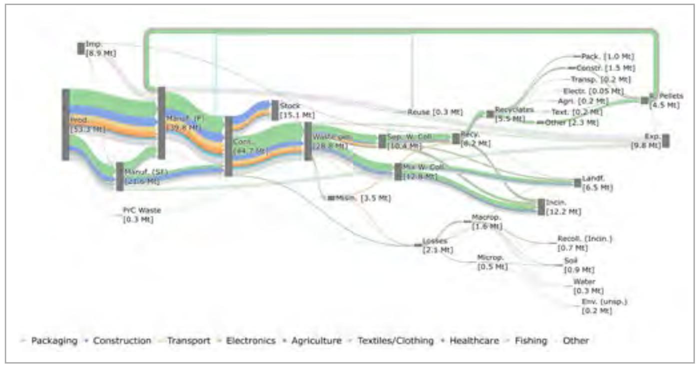

Fig. 1 - EU27 2019 MFA (Megatonnes [Mt]).

SOCIAL IMPACTS AND SUSTAINABILITY ANALYSIS OF EMERGING TECHNOLOGIES IN THE WASTE MANAGEMENT SECTOR

Giuseppe Cecere - Supervisor: Lucia Rigamonti

This study seeks to identify the primary challenges in applying Life Cycle Sustainability Assessment (LCSA) to emerging technologies within the waste management sector. LCSA is increasingly acknowledged as a structured framework for evaluating the environmental, economic, and social dimensions of products and services, facilitating a more systematic and integrated assessment of sustainability impacts. However, methodological challenges persist, particularly in the implementation of Social Life Cycle Assessment (S-LCA). The identification and selection of appropriate social subcategories remain a methodological challenge, affecting the reliability, consistency, and comparability of S-LCA applications in the waste management sector and in the assessment of emerging technologies.
The lack of standardized criteria and context-specific applications further complicate S-LCA results integration into sustainability assessments. To address these limitations, this research proposes a structured framework, aimed at enhancing objectivity and transparency in the selection of social topics for analysis. The framework is built upon three primary perspectives: technology experts, S-LCA specialists, and potentially affected stakeholders. The framework is initially applied within the waste management sector in Italy, complemented by insights from other European countries to contextualize social risks and sector-specific challenges.
The framework's applicability is further tested through a national case study in Spain, where it is implemented in the assessment of emerging plastic and food waste recovery technologies for composite material production.
Furthermore, this research examines the challenges related to the integration of S-LCA findings within LCSA.
A survey conducted among experts in the field identifies critical methodological gaps, challenges, and opportunities for advancing S-LCA in the broader context of LCSA.
The insights from this study contribute to the refinement of LCSA methodologies, supporting more robust sustainability assessments and fostering the strategic implementation of emerging waste management technologies.

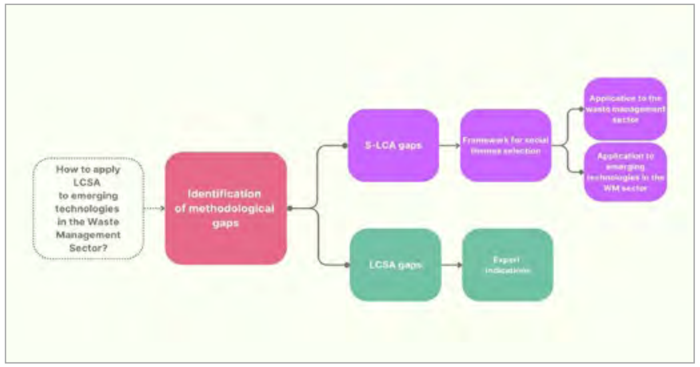

Fig. 1

A FRAMEWORK FOR URBAN GROUND-LEVEL NO2 ESTIMATION USING SENTINEL-5P, CLIMATE REANALYSIS DATA AND MACHINE LEARNING

Jesus Rodrigo Cedeno Jimenez - Supervisor: Maria Antonia Brovelli

This thesis presents a novel integration of satellite-based observations and Machine Learning (ML) techniques to estimate ground-level Nitrogen Dioxide (NO_2) concentrations, an environmental pollutant with negative health implications. The research comprises three interconnected studies that collectively contribute to the field of Geomatics Engineering. They offer innovative approaches to air quality monitoring, particularly in regions lacking ground sensor networks. This work addresses a critical environmental and health issue and contributes to the United Nations (UN) Sustainable Development Goals (SDGs) related to health, well-being, and clean energy.

The first study introduces a method combining ground meteorological measurements with satellite observations from the Sentinel-5P mission to estimate ground-level NO_2 concentrations in the Metropolitan City of Milan (MCM). This work uses state-of-the-art Machine Learning (ML) models, linear regression, and feature selection algorithms. Results demonstrated a significant reduction in Normalised Root Mean Square Error (NRMSE) by 55% compared to models relying solely on satellite data. This breakthrough provides a feasible alternative to traditional ground sensor measurements, especially for Low- and Middle-Income Countries (LMICs) where such infrastructure is scarce.

The second phase of this project expands the scope by incorporating a broader set of earth observation data and advanced ML models to refine ground-level NO_2 estimation accuracy. This phase critically evaluates the impact of relying solely on satellite data and reanalysis environmental variables from the ERA5 dataset. Additionally, in this phase we estimate ground-level NO_2 at point locations, and no longer as an average measurement for the whole MCM. The results of this study demonstrate that the proposed ML model is a promising tool for estimating ground-level NO2 concentrations using Sentinel- 5P satellite data and ERA5 reanalysis meteorological variables for the MCM. The model can be used to monitor air quality and to support public health and environmental management, especially in regions where direct ground-level NO2 measurements are not available. By using globally available data sources, future work will propose and test a model that can be used in most parts of the world, emphasizing LMICs' atmospheric NO2 ground-level concentration estimation.

The third phase of this project, shifts the geographical focus to the Metropolitan Area of Mexico City (MAMC), a metropolis known for its air quality challenges. Also, we introduce a comparative analysis with TimeGPT, a cutting-edge generative temporal model. This phase tests the adaptability and scalability of the developed models to different urban contexts and its ability to capture temporal dynamics and dependencies in air pollution data. This phase confirms the efficacy of combining ML with remote sensing data to estimate ground-level atmospheric NO2 concentrations. Our model provides a scalable and cost-effective solution for monitoring air quality, particularly in urban areas with significant pollution challenges. The insights gained from this can inform the development of more effective air quality management strategies and contribute to the broader efforts of mitigating the adverse health and environmental impacts of atmospheric pollution. Future phases should focus on further refining the model and exploring its application to other pollutants and regions to enhance our understanding of urban air quality dynamics and support global efforts in combating air pollution.

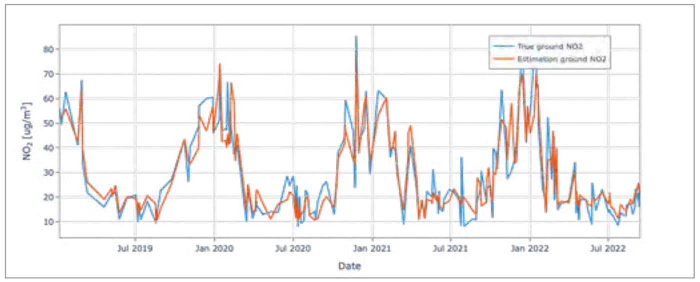

Fig. 1

Throughout the thesis, the logical flow from conceptual framework to empirical application highlights a systematic progression in tackling air quality monitoring's complex challenges. By analysing the results across different contexts and modelling techniques, this work reveals insights into the spatial-temporal variability of NO_2 and the potential of ML in environmental sciences. The interconnection of the three phases demonstrates the importance of satellite data and ML for atmospheric pollution monitoring. The research findings highlight the potential of this approach to make a meaningful impact on public health and environmental protection.

The developed framework has demonstrated its capability to accurately estimate ground-level NO2 concentrations, achieving an NRMSE of 55.92% and an R2 of 0.76 in the MCM, and a mean NRMSE of 84.47% in the MAMC. The research also highlighted the critical role of meteorological factors, such as temperature and wind speed, in influencing NO2 levels.

The contributions of this dissertation to the field of Geomatics Engineering extend beyond the development of an atmospheric NO2 ground-level model. One of the key contributions is the development of a scalable and efficient framework that integrates satellite observations with ground meteorological data. This framework is not limited to the estimation of NO2 concentrations; it has the potential to be extended to other atmospheric pollutants such as particulate matter (PM2.5) and O3. The versatility of this framework offers a powerful tool for environmental monitoring, capable of providing accurate and localised pollutant estimates that can inform public health strategies and regulatory policies.

In addition to the technical advancements, this dissertation contributes to the broader understanding of ML applications in Geomatics Engineering. The successful application and optimization of machine learning techniques in this research demonstrate that when these models are properly calibrated and validated, they can significantly enhance the accuracy of pollutant concentration estimates. This finding is particularly relevant in the context of environmental monitoring, where the ability to accurately predict pollutant levels is critical for assessing public health risks and developing effective mitigation strategies.

Looking ahead, this research opens doors for future investigations. The framework's potential for application in other regions and other pollutants presents promising opportunities. Integrating additional data sources, such as traffic patterns and land use information, could further enhance the model's predictive capabilities. Improvements in satellite technology and machine learning algorithms offer promising avenues for refining and expanding the scope of this research.

This dissertation has successfully addressed the challenge of accurate and accessible air quality monitoring. By integrating satellite technology with machine learning, we have provided a novel, scalable, and efficient framework for estimating ground-level air pollutants. By providing a robust, scalable, and adaptable framework, this research lays the groundwork for future contributions in the accurate estimation of air pollutants, contributing to better informed decision-making processes aimed at improving air quality and safeguarding public health.

MULTI-SCALE AND MULTI-TEMPORAL PHOTOGRAMMETRY FOR ALPINE GLACIER MONITORING

Francesco Ioli - Supervisor: Livio Pinto

Co-Supervisor: Francesco Nex

The climate crisis has led to an acceleration in glacier retreat and volume loss worldwide. Understanding these changes is essential for assessing climate impacts, predicting future trends, and mitigating related hazards. In the European Alps, where glaciers have long been viewed as both natural wonders and vital water resources, the consequences of ice mass loss are especially critical. Alpine glaciers influence local hydrology, contribute to tourism economies, and, if destabilized, can trigger catastrophic events such as ice avalanches and debris flows. As such, understanding glacier dynamics is essential for both scientific inquiry and hazard mitigation. This thesis comprehensively investigates multi-scale and multi-temporal photogrammetry for monitoring alpine glaciers, focusing on the debris-covered Belvedere Glacier in the Italian Alps (Fig. 1). Historically, glacier monitoring has relied on ground-based surveys and remote sensing from satellites. While satellite imagery offers large-scale views, its limitations in spatial and temporal resolution have necessitated the development of complementary techniques. This thesis proposes that photogrammetry—a method for obtaining three-dimensional measurements from photographs—can bridge the gap between historical records and modern high-resolution monitoring. By integrating archival aerial imagery, Unmanned Aerial Vehicle (UAV) surveys, and innovative terrestrial low-cost camera systems, this research establishes a multi-faceted approach to glacier monitoring that is both robust and adaptable to various field conditions.

The historical aerial image analysis reconstructs glacier evolution over the past 50 years, revealing periods of advance, surge events, and recent retreat. This long-term perspective is critical for understanding past glacier behavior and provides a reference for assessing contemporary changes. Complementing this, high-resolution UAV surveys (2015–2023) capture seasonal and inter-annual variations in glacier surface geometry, volume loss, and flow dynamics. Using Structure-from-Motion and Digital Image Correlation (DIC) techniques, this component enables the extraction of precise glacier velocity fields and volume variation estimates at sub-decimeter accuracy. This combination of data made it possible to derive geodetic mass balance of the Belvedere Glacier between 1977 and 2023, by considering periods longer than 5 years for volume differencing and assuming a constant ice density of 850 ± 60 kg m^{-3} (Fig. 2). Recognizing the inherently non-linear nature of glacier dynamics, this thesis presents a low-cost stereoscopic system built with homemade time-lapse cameras controlled by microcontrollers for deriving daily 3D models of the glacier terminal lobe by photogrammetry. An automated workflow, powered by state-of-the-art deep learning feature matching algorithms, overcomes

Fig. 1 - Picture and map of the debris-covered Belvedere Glacier (Italian Alps), used as study site for this thesis.

the challenges posed by the wide baselines of the stereo cameras and has resulted in the derivation of daily 3D displacements and glacier melt. The automated workflow extracts daily displacement maps and ice volume changes, allowing for an unprecedented high-frequency analysis of glacier dynamics. This dataset is further correlated with meteorological variables such as air temperature, demonstrating a strong link between short-term climate fluctuations and glacier behavior (Fig. 3).
Beyond the methodological contributions, this study emphasizes open science and data accessibility, making all datasets—including point clouds, orthophotos, and digital surface models (DSMs) publicly available. Moreover, the ICEpy4D and Deep-Image-Matching software tools developed as part of this research are released as open-source on GitHub, ensuring the wider scientific community can benefit from and build upon these methodologies.

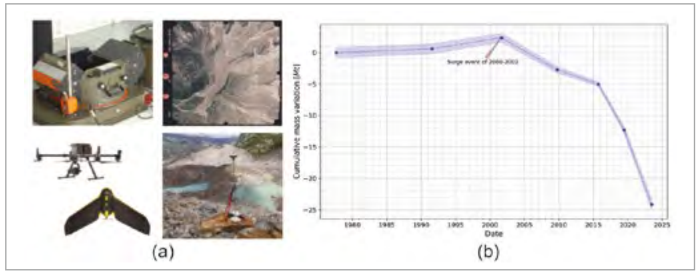

Fig. 2 - (a) Pictures of the instruments and images used to derive geodetic mass balance of the Belvedere Glacier by historical aerial photogrammetry and in-situ UAV surveys; (b) Estimated cumulative ice mass variations (in megatonnes) between 1977 and 2023.

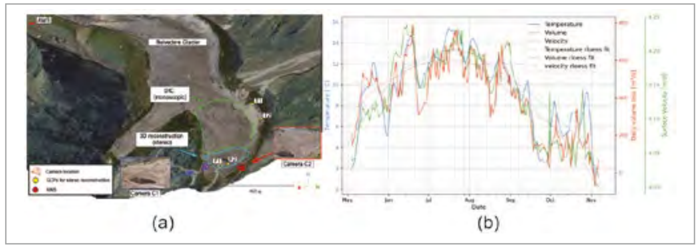

Fig. 3 - (a) Study site and setup for daily glacier monitoring using time-lapse cameras. The 3D stereo reconstruction focuses on the terminal ice cliff (dashed blue), while monoscopic DIC tracks movement in the north lobe (dashed green). (b) Time series of daily ice loss at the glacier terminus, compared with surface velocity and 5-day smooth air temperature.

The findings of this research highlight the power of photogrammetry as a scalable, cost-effective, and high-resolution approach to glacier monitoring. The ability to integrate long-term historical analysis with modern UAV surveys and daily imaging provides a multi-scale perspective on glacier evolution, essential for both scientific research and practical hazard assessment. The methodologies developed here have the potential to be generalized to other glaciers and remote sensing applications, aiding in climate change studies, natural hazard mitigation, and future advancements in cryosphere monitoring and photogrammetric techniques.

STRUCTURAL HETEROGENEITY AND PERMEABILITY OF POROUS MEDIA

Wenqiao Jiao - Supervisors: Alberto Guadagnini, Pietro De Anna

Co-Supervisor: Martina Siena

The structural properties of a porous system (like soil, aquifers, but also filtration systems or biological tissues) control the way it can host fluid transfer. In particular the medium intrinsic permeability quantifies the relationship between average fluid velocity, moving across a porous system, and the pressure difference necessary to produce it. For spatially homogeneous systems there are models to predict the medium permeability from its macroscopic features (i.e. porosity and average grain size). The work summarized in this thesis investigates the long standing problem of determining the permeability of porous system characterized by a complex structure. The common challenge of all heterogeneous porous media is their multi-scale nature, associated to the wide range sizes and shapes their pores can have. For instance, the pore size of an individual sample can span between a few microns to a few millimeters. The thesis is organized in an introduction, 3 research chapters and a conclusion.

In the first research chapter, I present a model to characterize the intrinsic permeability of porous media with variable pore sizes. To validate this model, I designed and performed microfluidic experiments with several porous structure of random (but controlled) pore size distribution. While traditional models cannot predict the permeability of heterogeneous porous structures, my model can. It explicitly embeds the spatial variability of pore sizes through a conceptualization of the system as a collection of smaller-scale porous media arranged in series.

The second research chapter is devoted to the exploration biofilm growth in porous media. In the first part of this chapter I present a study on how microbial biofilm takes place and affects flow within porous environments characterized by variable pore size. Through systematic microfluidic experimentation and time-lapse microscopy, I show that biofilm development (by individual bacterial cells division), influenced by flow velocity and nutrient availability, significantly alters the macroscopic structure by reducing the individual pores, eventually leading to localized clogging which changes the permeability. The interplay between biofilm accumulation and flow conditions results in dynamic permeability variations, which are captured through a predictive model, that I developed, which accurately reflects biofilm-induced clogging over time.

The second part of this chapter investigates the biochemical mechanisms that govern bacterial behavior within porous media characterized by grains with different shape (instead of different size). I explored how flow-mediated interactions allow the bacterium *Escherichia coli* sp. to colonize a porous structure that is composed of heterogeneous dead-end pores (DEPs, or single grain cavities) and connecting percolating channels, i.e. transmitting pores (TPs, space among grains), mimicking the structured surface of mammalian guts or some soil structures.

In presence of flow, gradients of the quorum sensing (QS) signaling molecule autoinducer-2 (AI-2), secreted by the cells, themselves promote *E. coli* chemotactic accumulation in the DEPs. This results in hot-spots of accumulation where Quorum Sensing happens, triggering rapid growth and mechanical evasion of biomass from nutrients and oxygen depleted DEPs.

The last research chapter investigates the impact of rocks microscopic-scale dissolution process on their structural heterogeneity and, thus, macroscopic permeability. The investigation is carried out via i) two-dimensional numerical

simulations and ii) microfluidics experiments designed to directly visualize the individual dissolution of grains, while monitoring the overall, macroscopic, system permeability. I observe how the structure of a porous system changes due to dissolution and I show that the model proposed in the second chapter captures the effect of these dynamical changes on the system permeability.

In conclusion, I developed theoretical models and experimental tools to investigate how the spatially variable (heterogeneous) structure of a porous system controls fluid transfer (permeability) and how, in turn, flow-driven processes (like biofilm growth or rock dissolution) modify the porous structure and, thus, its permeability.

A METHODOLOGY TO PREDICT COASTAL-RIVER PLUMES COUPLING REMOTE SENSING IMAGES AND NUMERICAL MODELLING

Antonia Menzione - Supervisor: Marco Mancini

The study of river mouth interaction with the coastlines addresses interconnected issues such as coastal sediment dynamics, salt wedge intrusion, and nutrient flow, as evidenced by extensive scientific literature. Over the years, numerous numerical models have been developed to simulate these processes and predict their evolution. These models serve as virtual laboratories in engineering, enabling the design and assessment of engineering structures to regulate hydrodynamic processes. Despite technical and scientific interest, calibrating river mouth interaction hydrodynamic models lacks observational data due to spatial and temporal data characteristics. To address this, the study explores the use of satellite as tools to support the hydrodynamic modeling. The focus is on detecting suspended sediment plumes at river mouths after flood events, serving as a closer representation of the numerically generated flow field by hydrodynamic models in river-sea interaction. This work analyses two case studies located in Italy, along the coasts of the Adriatic Sea basin, where following extreme events it is possible to observe large quantities of suspended solids from satellites, which drag along not only water and sediments but also organic materials and pollutants. The first results show a good correspondence between the model outputs and satellite images during flood events. In particular, the option to implement a 3D hydrodynamic module shows promising results and a good detail in the estimation of the magnitudes related to such events. The development of such a methodology allows to make predictions on the dispersion of such plumes and to predict in advance the turbidity and concentration of coastal waters, in support of users such as bathers, users of the primary sector and other stakeholders who use the mouth areas.
The numerical modeling approach is now widespread in the field of hydraulic and coastal engineering. Numerical models, in fact, are one of the main tools for studies on sediment dynamics (in complex coastal waters and estuarine areas) and represent a virtual laboratory that allows modeling and studying various hydrodynamic and morphological phenomena.
In this work the model implemented is TELEMAC.
The TELEMAC-MASCARET open system is a suite of finite element computer programs owned by the Laboratoire National d'Hydraulique et Environnement (LNHE), part of the R&D group of Électricité de France. Currently managed by a consortium of other consultants and research institutes, further information can be found on their website (www. opentelemac.org).

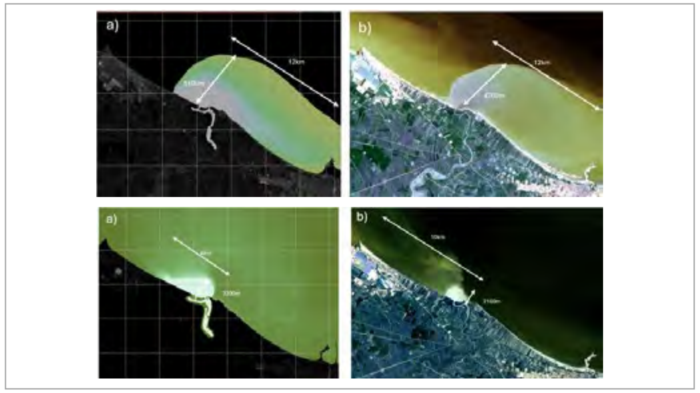

Fig. 1 - The images represent a 3D modeling results compered with the remote sensing images for 2 events for the case study of the Ofanto River (South of Italy). Both analyze the dispersion of the plume of suspended solids, once for the same event in March 2021 and another for an event in which the plume propagated in the opposite direction of the Decembre 2019.

HIGH-RESOLUTION UAV REMOTE SENSING FOR COMPLEX AQUATIC ENVIRONMENTS: FROM PLANNING TO DATA PROCESSING

Erika Piaser – Supervisor: Giovanna Sona

Co-Supervisor: Paolo Villa

The global decline of wetlands and inland water ecosystems, driven by human disturbance and climate change, is leading to severe ecological deterioration and the loss of essential ecosystem services. As a key functional component of these ecosystems, aquatic vegetation is heavily impacted by habitat degradation and loss, factors that reduce biodiversity and disrupt connected ecological processes. Given its ecological significance, monitoring aquatic vegetation dynamics is important for assessing ecosystem health, understanding its response to environmental stressors and aiding restoration strategies to mitigate further degradation.

Advancements in remote sensing, particularly for Unmanned Aerial Vehicles (UAV) equipped with hyperspectral sensors, provide valuable tools with unprecedent spatial and spectral resolutions.

However, their application in aquatic ecosystems remains underexplored, due to challenges and limitations posed by the presence of water.

The aim of this thesis is to identify potential radiometric and geometric distorting factors that affect UAV hyperspectral imaging in aquatic environments, and to develop effective methods to mitigate these issues. By addressing challenges such as water surface reflection, variable light conditions, and the need of high resolution Digital Surface Model (DSM) for image ortho-projection, this research seeks to enhance both data accuracy and reliability.

Dealing with radiometric distortions, we investigated how illumination conditions and angular configurations during UAV flights contribute to potential distortions in reflectance-based quantities (Chapter 2). Overcast sky was found to reduce spectral reflectance in highly reflective bands, particularly for floating plants. Overall, this effect lowers Spectral Indices (SI) values compared to clear sky, with lower impacts on the Normalized Difference Vegetation Index (NDVI), which was found to be less sensitive to illumination conditions. Findings on angular configurations revealed that, low values of Sun Zenith Angle (SZA) and Relative Azimuth Angle (RAA) caused spectral anisotropy in the visible, with increasing reflectance in specific image regions depending on plant functional types (**Figure 1)**. Floating plants showed increased reflectance towards forward direction, similar to open water, while emergent vegetation reflected more in backward direction, consistent with common patterns in terrestrial vegetation. Again, among tested SIs, NDVI remained the most stable to sun-target-sensor angular configuration changes.

Building on these findings, we performed an empirical experiment focused on mitigating biases from angular configuration during UAV flights (Chapter 3).

We found that lateral sun (low RAA) and high angles above the horizon (high SZA), caused higher spectral distortions in

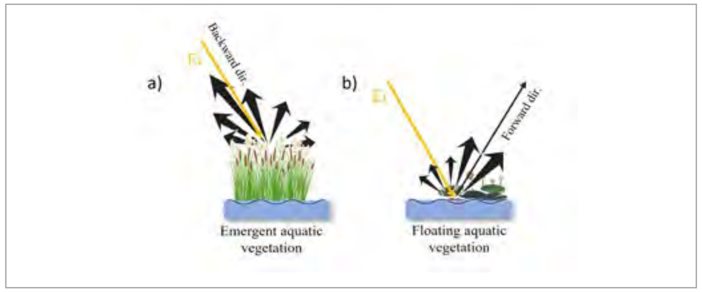

Fig. 1 - Main incident energy (Ei) reflection mechanisms according to plant functional types: mainly a) backward reflection for emergent species and b) near-specular reflection for floating species.

the image, confirming results of the previous chapter. For floating vegetation, spectral anisotropy occurred at both leaf and canopy scale, influenced by water near-specular reflection, acting as a canopy background or droplets on planophile leaves. In contrast, emergent vegetation showed increased reflectance in backward direction only at canopy level, attributed to shadow-hiding effect commonly seen in terrestrial canopies. Furthermore, UAV flights conducted at different times revealed that, transitioning to a sun azimuth consistent with flight direction (RAA ~ 90°) or flying under a higher SZA (> 60°), gradually reduced reflectance anisotropy, minimizing significant spectral biases and providing recommendations for operational protocols.

Dealing with potential geometric distortions in UAV hyperspectral data, we introduced AQUA-LIDAR, a novel approach for high-resolution DSM reconstruction using Light Detection and Ranging (LiDAR) data, as ancillary input for hyperspectral data ortho-projection (Chapter 4). The method used LiDAR derived features for mapping water pixel collected nadirally by the sensor, extract the corresponding elevation values, and used the information to fill DSM gaps over off-nadir water classified pixels. The approach demonstrated superior accuracy in DSM elevation reconstruction, outperforming available open-source products (**Figure 2**), especially in preserving boundaries between water and fine-scale natural or anthropogenic elements, and providing valuable solution for real-world scenarios. Finally, in the last chapter (Chapter 5), we examined possible arising georeferencing errors, using AQUA-LIDAR DSM or a horizontal surface (simulating low topography variations of wetlands) for hyperspectral imagery ortho-projection. The analysis highlighted that the platform's tilt (roll angle) and flight altitude were primary sources of potential geometric distortion. Additionally, terrain topography and scan direction interactions also contributed to geometric inaccuracies, even in predominantly flat areas.

This thesis investigates potential distortions in UAV hyperspectral data for aquatic ecosystems, focusing on radiometric and geometric accuracy. Beyond identifying key issues, it proposes mitigation strategies and operational guidance for optimal data acquisition and processing.

Additionally, this work establishes a foundation for future research to enhance wetland monitoring and conservation efforts.

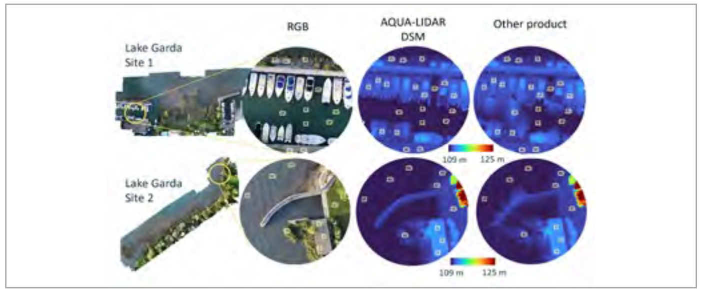

Fig. 2 - Comparative analysis between AQUA-LIDAR DSM and a DSM produced with an open-source software in Lake Garda sites. High resolution RGB imagery is included to support visualization.

GEOAI FOR RESILIENT URBAN DEVELOPMENT: A MACHINE LEARNING FRAMEWORK FOR MODELLING AND MAPPING ENVIRONMENTAL HAZARD SUSCEPTIBILITY AND SIMULATION OF NATURE-BASED SOLUTIONS

Angelly de Jesus Pugliese Viloria - Supervisor: Maria Antonia Brovelli

A general machine learning framework for modelling and mapping the susceptibility towards urban environmental hazards was proposed based on an extensive literature review; the framework encompasses a holistic approach that includes data collection from multiple data sources, pre-processing and harmonisation, Machine Learning (ML) models, interpretation, and further model application. To model the behaviour of hazards, it utilises historical hazard occurrences and related conditioning factors, e.g., meteorological or land cover. This framework serves as a basis to characterise the spatial behaviour of multiple urban environmental hazards. The production of hazard susceptibility maps for an area of interest is undertaken by evaluating the generated models on unseen locations.
The proposed framework is showcased by modelling three environmental hazards in the city of Milan, Italy: air pollution, Urban Heat Island (UHI), and floods. A novel and robust technical workflow was produced to model each hazard, encompassing its multiple data sources, models, and the final production of susceptibility maps. The data sources include discrete data from in-situ stations, authoritative rasters, and satellite imagery. The trained models include state-of-the-art ML models such as Artificial Neural Networks (ANN), XGBoost, Random Forest (RF), Support Vector Machine (SVM), among others. Multiple pieces of software were developed and integrated to encompass the modelling of multiple hazards based on multiple data sources and the testing of multiple models.
The air pollution susceptibility was modelled as the likelihood of surpassing a pollution concentration limit based on governmental directives. The specific modelled pollutants were $PM_{2.5}$, PM_{10}, SO_2, O_3, and NO_2 relying on pollutant concentration measurements from an in-situ stations network maintained by the local environmental agency, ARPA Lombardia. The conditioning factors were the land cover, digital terrain model, distance to water, distance to main roads, and meteorological measurements from in-situ stations, specifically, temperature, relative humidity, global radiation, precipitation, wind velocity, and wind direction. The air pollution susceptibility maps were produced per month based on the monthly average meteorological conditions considering the seasonal behaviour of the multiple pollutants' concentration and sparsity of the target data. See the $PM_{2.5}$ susceptibility map in January in figure 1. Moreover, the results were interpreted using explainable artificial intelligence.
The UHI susceptibility was modelled by leveraging Land Surface Temperature (LST) derived from Landsat-8, and it is referred to as Surface UHI (SUHI). The SUHI was modelled as the likelihood of a location to surpass the reference LST; which is defined as the average temperature in forest and agricultural areas. The SUHI was modelled during summer using an ANN model conditioned by the LST, land cover, building height, population density, and derived spectral indices. The SUHI susceptibility map was produced based on the average conditions of the last years, see figure 2.
Furthermore, the SUHI intensity was modelled; it is defined as the difference LST of a location with respect to the reference LST. The conditioning factors to model the SUHI intensity were the same as the ones used to model the SUHI, except for the LST. The reason to exclude LST from the SUHI intensity model was to enable the prediction of the expected LST difference independently of the LST fluctuations in time.
The flood susceptibility was modelled using the historical flood occurrences provided by the local authority, Regione Lombardia. The flood occurrences consisted of polygons which delimitate the extent of a flood in a particular year. On the other hand, the flood conditioning factors were topological (digital elevation model, slope, and aspect), geology, hydrological (water distance, stream power index, topographic wetness index), land cover, and others. Moreover, different models were tested to evaluate their accuracies including RF, ANN, SVM, and Logistic Regression. The flood susceptibility map was produced with the best performant model, RF. See figure 3.
Additionally, a further application of the models was studied. In the context of Nature-based Solutions (NbS) and their usage for the potential mitigation of environmental hazards, multiple studies have measured the cooling effects of urban vegetation, e.g., green roofs and parks. Therefore, the SUHI intensity model was leveraged to measure the cooling effect of simulated land cover changes that introduce urban vegetation, i.e., mocking a vegetation pixel by changing the land cover class and related spectral indices. Two cases were tested to showcase the potential use of the model insights by urban planning experts. Specifically, the addition of green roofs in the residential buildings of a neighbourhood and the enlargement of current urban vegetation cores, which resulted in an average cooling effect of 5K and 1K, respectively.
In conclusion, the proposed machine learning framework provides a robust and scalable approach to modelling and mapping urban environmental hazards, integrating diverse data sources, advanced ML techniques, and explainable AI for enhanced interpretability. By successfully applying this framework to air pollution, UHI, and flood susceptibility in Milan, it demonstrates its adaptability to different hazard types and its capacity to generate actionable insights. Furthermore, the extension of the framework to assess the impact of NbS highlights its potential for supporting sustainable urban planning and climate resilience strategies. Future research could expand its applicability to other cities and hazards, refine predictive capabilities through additional data sources, and further explore NbS interventions for hazard mitigation.

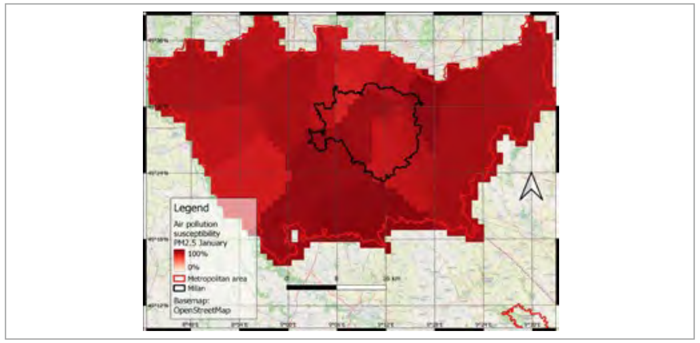

Fig. 1 - $PM_{2.5}$ susceptibility map in January in the metropolitan city of Milan.

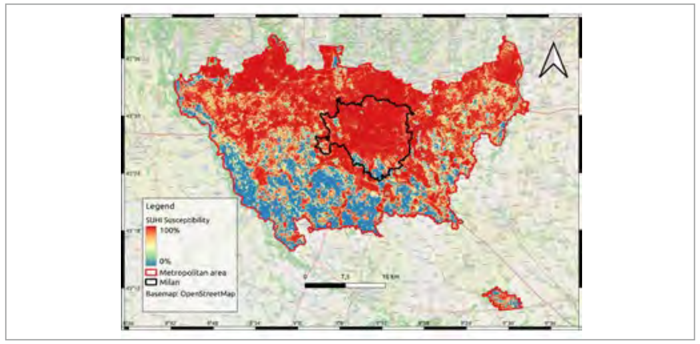

Fig. 2 - Surface urban heat island susceptibility map in the metropolitan city of Milan.

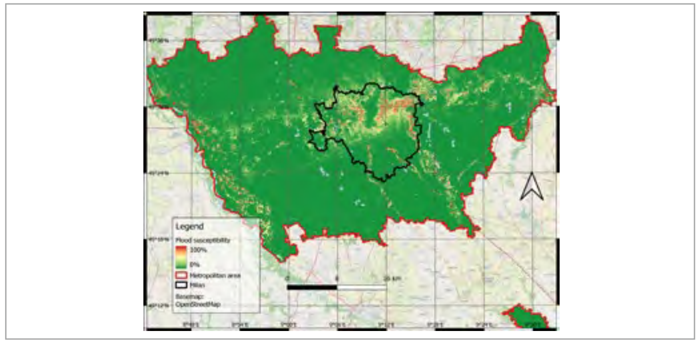

Fig. 3 - Flood susceptibility map in the metropolitan city of Milan.

SEDIMENT TRANSPORT: FROM AVERAGES TO FLUCTUATIONS

Daniel Rebai - Supervisor: Francesco Ballio

During my Ph.D., I dedicated my research to the study of sediment transport — the movement of granular particles, such as sand and gravel, carried by water and wind. This natural process plays a crucial role in shaping landscapes, influencing the formation and evolution of rivers, coastlines, and deltas. Beyond its geomorphological significance, sediment transport has far-reaching implications for various environmental and engineering concerns. It affects flood risks, impacts the stability and performance of hydraulic structures such as dams and levees, and plays a key role in determining water quality and ecological health. Since sediments often carried nutrients, contaminants, and pollutants, their movement could influence aquatic ecosystems. Understanding how sediments are transported is therefore essential for managing water resources, mitigating natural hazards, and protecting fragile environments.
This thesis specifically focused on bedload transport in rivers, examining its definition, measurement, and modelling, with the goal of improving our understanding and expanding current theoretical frameworks. Bedload transport referred to the movement of sediment particles that roll, slide, or saltate along the riverbed under the influence of flowing water.
In my analysis, I explored three different ways to express the solid flowrate of sediment, each providing different insights into the transport process. First, solid flowrate could be defined as the total volume of sediment crossing a specific line per unit width and per unit time interval. Second, it could be expressed as the product of an average particle activity—measured as the volume of moving particles per unit bed area—and an average velocity. Third, solid flowrate could be represented as the product of an average entrainment rate—the volume of particles lifted into motion per unit bed area and per unit time—and an averaged hop length, which described the distance travelled by a particle from the moment it began moving to when it came to rest.
Through a detailed theoretical and mathematical analysis, I demonstrated that these three definitions were different time and space averages of the same fundamental equation governing sediment flux. This equation described the local and instantaneous movement of sediment through a defined area and provided a unified framework for understanding bedload transport measurements.
Following this theoretical discussion, I dedicated the remainder of the thesis to an in-depth analysis of the second definition of solid flowrate. This choice was motivated by its practical applicability in both experimental and field studies, as well as its ability to reveal key relationships between sediment concentration, particle velocity, and transport dynamics. However, despite its advantages, I found that significant challenges remained in the accurate measurement of flowrate, concentration, and velocity, indicating that existing measurement techniques still required further development and refinement.
A critical issue in sediment transport research was determining how to distinguish between moving and still particles. Any statistical assessment of particle motion relied heavily on the definition of movement versus stillness, as different criteria could lead to different values of transport rates. To address this issue, I introduced and formalized definitions for three distinct particle states: stillness, 'transport,' and 'non-transport.' This classification scheme recognized that not all particle motions contributed equally to the overall sediment transport rate.
The transport state was characterized by a clear distinction between stream-wise and transverse particle velocity, meaning that particles in this state actively participated in the bedload transport process. In contrast, the non-transport state was associated with isotropic particle jiggling, a type of motion that did not significantly contribute to sediment movement along the riverbed. However, while these non-transported particles did not play a primary role in determining the mean bedload transport rate, their movement remained relevant for other key indicators of the sediment transport process, including the mean sediment concentration and the mean particle velocity. By distinguishing between these states, I provided a more precise framework for evaluating sediment motion and refining statistical models of transport dynamics.
In the final part of the thesis, I investigated how turbulence influenced sediment transport at the reach scale. Understanding the relationship between turbulent flow and sediment motion was essential for predicting transport rates under natural river conditions, where turbulence levels varied due to bed roughness, obstacles, and flow structures. To explore this problem, I conducted a series of controlled laboratory experiments in which I systematically modified turbulence levels within a flume using different arrays of cylinders. By altering the distribution and intensity of turbulent eddies, I was able to analyse how fluctuations in flow conditions affected sediment transport mechanisms.
Asynchronous measurements of fluid velocity, bed shear stress, and sediment motion allowed me to evaluate the combined effects of average flow and turbulent fluctuations on bedload transport. My findings revealed that, for a given bed shear stress, sediment flowrate, concentration, and velocity all increased with higher levels of turbulence. More specifically, I found that when modelling sediment flowrate, the influence of turbulence on sediment concentration was a first-order effect, meaning that it played a more significant role compared to its impact on particle velocity. This insight suggested that turbulence-driven variations in concentration were a dominant factor in determining overall transport rates, with important implications for sediment transport modelling in natural river systems.
By integrating theoretical analysis, conceptual refinement, and experimental validation, this thesis provided a deeper understanding of bedload transport in rivers. The findings contributed to advancing sediment transport research by clarifying key measurement challenges, refining definitions of transport states, and demonstrating the critical role of turbulence in determining sediment flowrate. These insights could be applied to improve sediment transport models, optimize hydraulic structure designs, and enhance environmental management strategies for river systems affected by erosion and sedimentation.

STOCHASTIC CHARACTERIZATION OF REACTIVE PROCESSES IN POROUS MEDIA

Chiara Recalcati - Supervisor: Alberto Guadagnini

The PhD thesis is keyed to exploring key elements of the nature of dissolution reactions taking place at the interface between a flowing fluid and minerals forming the solid matrix of natural porous media. These constitute the environment within which flow of water and transport of chemicals dissolved therein take place across the Earth subsurface. Mineral transformations induced by dissolution drive formation of preferential pathways across the Earth subsurface and are critical in a variety of engineering contexts, including risk assessment related to aquifer contamination, geogenic carbon storage through mineralization, or design of strategies for effective management of subsurface energy resources. Key research questions addressed in this thesis are related to (*a*) designing and executing original nanoscale imaging experiments enabling observations of dissolution reaction rates at their fundamental level and (*b*) providing an interpretation of the observed rates through original stochastic approaches capable of quantifying uncertainty. Doing so requires achieving a unique blend of fundamental experimental and theoretical advancements.

As an illustrative example, a geochemical system entailing dissolution of calcite under far-from-equilibrium conditions is considered. An original platform for sample preparation is designed to acquire absolute topographic measurements (referenced to an engineered non-reacted layer, see Fig. 1a). Imaging rests on *in situ* and real time Atomic Force Microscopy (AFM). Coupling the high horizontal resolution allowed by AFM with the tailored experimental procedure developed for the application of an inert mask on the crystal surface offers a completely novel framework for direct observation of absolute material fluxes and of the details of their spatial heterogeneity.

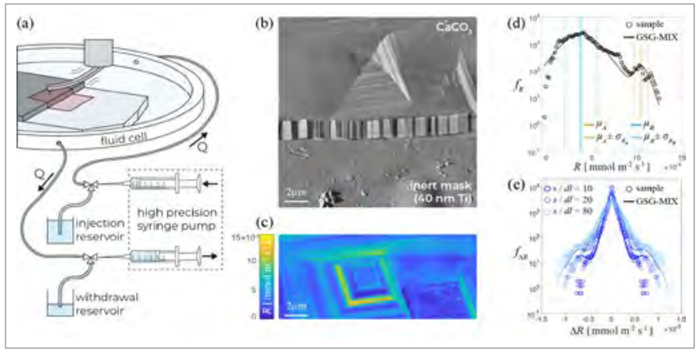

Fig. 1 - (a) Experimental platform enabling (nanoscale) absolute topography measurement of a crystal subject to reaction under continuous flow. (b) Exemplary AFM image of calcite subject to dissolution under far-from-equilibrium conditions and (c) ensuing dissolution rate map. Sample probability density of (d) dissolution rate, *R*, and (e) associated spatial increments, *ΔR*, evaluated at separations distance *s* / *dl* = 10, 20, 80 (*dl* = 19.5 nm being the measurement support). Modeling results according to the Generalized sub-Gaussian Mixture (GSG-MIX) model developed in the PhD thesis are juxtaposed to their sample counterparts.

Various setups for fluid flow regulation are designed to experimentally resemble conditions typical of natural geologic systems. Static settings mimic processes associated with low velocity/stagnant regions within pores where reactions are driven by diffusion. Flow-through conditions are reproduced through a microfluidic setup. Such protocols provide a new generation of high-quality data. These can then be promptly employed for the evaluation of space-time distributions of rates. Such experimental observations document the diversity of local mechanisms contributing to the overall dissolution across the mineral-fluid interface (Fig. 1b).

These arise from an intrinsically uneven (and random) distribution of reactive sites due to natural defects at the mineral lattice level. The experiments document markedly heterogeneous spatial distributions of the ensuing reaction rates (Fig.1c). The latter are viewed as (spatially-correlated) random fields and modeled through a stochastic lens.

An original theoretical framework is developed for the analysis and interpretation of the experimental observations. It rests on joint assessment of probability distributions of a target variable and its spatial increments taken between locations separated by any given distance (or lag). Doing so ensures consistency between patterns of these two sets of data. Statistical traits observed for sample distributions are typical of a marked non-Gaussian behavior and include (*i*) the presence of multiple peaks and heavy tails (governing extreme values) in the distribution of rates and (*ii*) the occurrence of a dominant peak together with multiple secondary peaks in the distribution of increments (see, e.g., Figs. 1d-e). The relative importance of these peaks tends to vary with the lag at which increments are taken. This yields a stark and observable (for the first time at the nanoscale) scaling behavior of the probability density of increments. A general modeling framework inspired to geostatistics is developed to capture all of these statistical traits. We rely on a conceptual picture according to which the random field of reaction rates is viewed as a mixture of Generalized sub-Gaussian random fields. This significantly extends previous formulations, here recovered as specific instances.

Consistency of observations (Figs. 1b-c) with expected patterns associated with far-from-equilibrium conditions document the reliability of the designed experimental platforms. Modeling results document a striking agreement between sample probability densities and statistical moments of rates and associated spatial increments and their theoretical counterparts (Figs. 1d-e). Links between dissolution mechanisms and model parameters are analyzed.

The theoretical and experimental frameworks here developed imbue us with (*i*) experimental capabilities to identify nanoscale processes together with (*ii*) rigorous modeling tools capable of encapsulating dynamics of the fundamental mechanisms driving the evolution of mineral-fluid interfaces. This, in turn, yields fundamental insights into nanoscale patterns related to chemical weathering of minerals. These tools can benefit future studies aiming at transferring uncertainty linked to space-time distributions of dissolution rates to other spatial scales.

These experimental procedures and statistical frameworks are readily transferable to a variety of minerals to quantify rates and mechanisms governing chemical weathering thereof. As such, the methodologies and results of this PhD thesis impact on the way we observe, understand, and model heterogenous reaction kinetics of complex processes such as coupled dissolution-precipitation reactions taking place at solid-fluid interfaces. These underpin key environmentally relevant scenarios such as, e.g., geologic storage of CO2 or incorporation of heavy metals in natural geomaterials hosting groundwater resources.

EVALUATION OF THE IMPACT OF LAND COVER MAP RESOLUTION IN IDENTIFYING SUITABLE AREAS FOR NEW GROUND-MOUNTED PHOTOVOLTAIC INSTALLATIONS: A CASE STUDY FOR THE PROVINCE OF CUNEO

Lorenzo Stucchi - Supervisor: Maria Antonia Brovelli

The 2015 Paris Agreement and the new European Green Deal of 2019 have highlighted that the fight against climate change is closely dependent on expanding renewable energy production. The European Renewable Energy Directive (RED II) requires member states to identify actions that promote the development of renewable energy sources (RES), emphasizing the importance of environmental protection. In Italy, Legislative Decree 199 of 2021 has defined suitable areas for installing renewable energy plants. Identifying areas of greatest interest for photovoltaic installations is a topic of interest in the literature, with several studies conducted in Italy, particularly in Piedmont and Lazio. However, recent regulatory changes have necessitated a review of the methodologies used so far.

The approach presented starts from the current regulations to identify and determine the distribution of suitable areas across the territory. The methodology is fully repeatable and replicable, based entirely on open data and open-source software. This choice of replicability is driven by the interest of various entities in the topic and its developments. These entities will need to define the regulatory aspects to identify these areas according to the criteria established in the implementing decrees of Legislative Decree 199/2021. The suitable areas have been divided into four categories based on their regulatory definition in paragraph 8 of Article 20. For each category, a procedure has been defined to evaluate the effects of constraints on the areas. Additionally, an overall methodology has been established, which includes calculating all defined categories to avoid double counting for areas falling into multiple categories.

The most commonly used data were extracted from land cover maps. Two different maps were used to evaluate the results' dependence on the input data: the Corine Land Cover (CLC) and the high-resolution Land Cover Piemonte (LCP). The methodologies were tested in the Cuneo province area, a morphologically diverse region with a significant presence of installed photovoltaic plants.

The comparison of the two maps shows that the higher resolution of the LCP not only improves the delineation of areas but also their categorization. The calculation identified a suitable area of approximately 202,000 hectares in the study area. It was observed that the estimate does not vary significantly (difference of 0.02%) with the change of the land cover map in input. However, for some categories, the use of the Corine Land Cover provides a very partial estimate. Agricultural areas adjacent to industrial areas amount to 173,525 hectares with the LCP and only 13,207 hectares with the CLC, less than 8% of the areas identified with the higher-resolution map. Furthermore, external economic and technical factors were also found to be capable of removing potential surfaces identified as suitable but not subsequently utilized. Calculating slope and exposure divided the territory into ten different classes. The division was validated using data from existing plants in Italy, demonstrating its validity. The application of these classes shows that about 38% of the areas previously identified as suitable would not be used due to technical-economic limits. Thus, the estimate identifies about 124,300 hectares as suitable in the province of Cuneo. The results currently demonstrate a large availability of suitable areas if all classes identified by the regulations are included and considered. This availability could, therefore, limit suitability to only certain categories. However, in the absence of implementing decrees, which entities will be responsible for defining the regulations is not yet defined. Nonetheless, the created methodology can be freely used and tested to better identify the optimal combination of categories and constraints to better plan the development of RES in the territory.

It is important to remember that although some areas may be deemed suitable, they cannot be exploited due to technical-economic limits to the regulatory definitions. Therefore, it is necessary to include external criteria and factors to identify the surfaces better and obtain more accurate estimates.

A METHODOLOGY FOR LOCAL CLIMATE ZONE MAPPING AND URBAN HEAT ISLAND ANALYSIS USING HYPERSPECTRAL PRISMA IMAGERY

Alberto Vavassori - Supervisor: Maria Antonia Brovelli

The increasing frequency, intensity, and duration of heat waves, coupled with growing urbanisation, are intensifying the Urban Heat Island (UHI) effect in cities worldwide. Measuring this phenomenon and understanding its driving factors is essential for developing evidence-based mitigation and adaptation strategies. In the field of satellite remote sensing, multispectral and thermal infrared data are primarily exploited for this purpose. Although recently a large interest has developed in hyperspectral satellite data for environmental monitoring, which provides a more detailed description of the spectral properties of urban surfaces, the use of this kind of data in urban climatology has yet to be fully unfolded.

For this reason, this work aims to investigate the potential enhancement in urban climate research using hyperspectral satellite data, by exploiting the well-known Local Climate Zone (LCZ) model and multiple Earth Observation data and techniques. The focus is on the hyperspectral satellite imagery of the novel PRISMA mission owned by the Italian Space Agency (ASI). The thesis is organised around different case studies to address the research question and ultimately provide a comprehensive evaluation of the UHI phenomenon.

The first case study investigated the potential enhancement in LCZ classification using hyperspectral PRISMA data as opposed to multispectral Sentinel-2 images. It also proposed a hybrid Remote Sensing (RS) and Geographic Information System (GIS)-based method for LCZ mapping, consisting of the integration of satellite imagery with Urban Canopy Parameter (UCP) layers and Machine Learning techniques. The research disclosed an improvement in classification accuracy using PRISMA which can be mainly ascribable to the enhanced spectral separability of the LCZ classes offered by hyperspectral imagery. The integration of UCPs with spectral information led to a significant improvement in classification accuracy and reduced the confusion among built-up LCZ types. Furthermore, the proposed method outperformed the state-of-the-art LCZ Generator tool, with a significant increase in overall and class-specific accuracy metrics. Considering the LCZ maps relative to February and June 2023, a mean increase in overall accuracy of 5% and 16% was achieved using PRISMA compared to Sentinel-2 and the LCZ Generator, respectively. An example of LCZ obtained using PRISMA over Milan for June 2023 is depicted in Figure 1.

In the second case study, the relationship between the obtained LCZ maps and air temperature data was investigated and results were exploited to provide a quantitative evaluation of the UHI intensity, with a distinction between daytime and nighttime. Air temperature measurements were retrieved from the authoritative network of the Regional Agency for Environmental Protection (ARPA). A significant difference in nighttime air temperatures was observed between urban, built-up LCZ classes and suburban or natural LCZ types, confirming that the UHI effect is most pronounced after sunset. Daytime differences were notably lower, and in some cases, urban stations recorded slightly lower temperatures than stations in the countryside, due to the shadowing effect of buildings in the densely urban zones. We also quantified the UHI intensity as the difference of median nighttime temperature between Compact Mid-Rise and Low Plants LCZs, which turned out to be around 4.7°C in February and 2.5°C in June 2023.

A geostatistical analysis was also performed to identify hot and cold spots in the study area. For this purpose, crowdsourced air temperature data from citizen weather stations (Netatmo network) was integrated with authoritative ARPA data to enhance the spatial coverage of temperature observations. Considering the intrinsic limitations and multiple error sources characterising crowdsourced weather observations, an automated pre-processing pipeline was proposed and implemented. After data cleaning, the normalised 10th and 90th monthly temperature quantiles were computed for each station and used as weight attributes to calculate the Getis Ord Gi* and Anselin Local Moran's I indices. The spatial distribution of these indices highlighted a hot spot within the urban area of Milan when the 10th percentile is used as a weight attribute, confirming the stronger UHI effect during the nighttime.

Finally, the third case study provided insights into the effect of surface cover material's abundance and Land Surface Temperature (LST), thereby contributing to a more comprehensive understanding of the UHI effect. The fractional abundance of surface materials was derived through pan-sharpening and spectral unmixing of hyperspectral PRISMA imagery, and the correlation with summer LST distribution was assessed using Landsat 8 and 9 thermal infrared data. A regression-based spectral unmixing technique was used to compute the fractional abundance of surface materials. For the extraction of the endmembers, hyperspectral pan-sharpening was applied to achieve higher spatial resolution and thus enhance the possibility of selecting pure-material pixels from the images. The comparison between the obtained endmember fractional abundance and LST maps pointed out the cooling effect of natural surfaces, particularly vegetation, and the heating effect of artificial surfaces and bare soil. Interestingly, tall vegetation exhibited a higher cooling rate than grass. When the endmember fraction increases from low (0-25%) to high (75-95%) ranges, vegetation shows a decrease in LST up to 7.2°C (June 2023) while grass exhibits a decrease in LST up to 3.7°C (August 2023). Although these results require further investigation, they represent valuable pieces of evidence for addressing effective urban planning.

The research focuses on the Metropolitan City of Milan in Northern Italy. Nonetheless, it is entirely based on free and open-source data and software, allowing for easy scalability of the analyses to other geographical regions. The software tools developed in the thesis are released as open source for wider use and easily adaptable to other remote sensing-based monitoring applications.

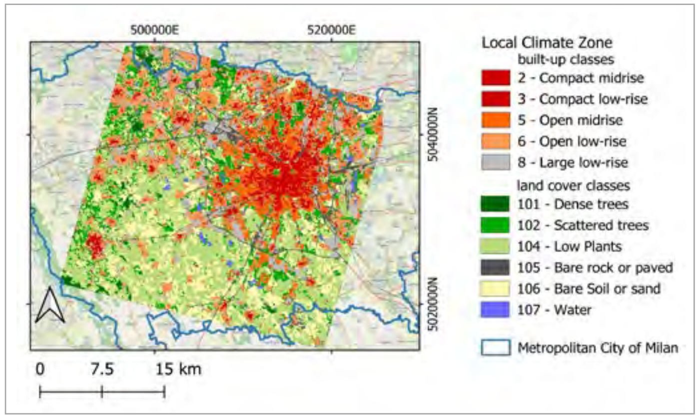

Fig. 1 - Local Climate Zone map computed using PRISMA imagery over Milan (Italy) for the 17th June 2023.

WATER AND MIGRATION: THE NEXUS BETWEEN WATER AVAILABILITY FOR FOOD AND LIVESTOCK PRODUCTION, HYDROCLIMATIC CHANGES, AND ENVIRONMENTAL MIGRATION

Sinafekesh Girma Wolde - Supervisor: Maria Cristina Rulli
Co-Supervisor: Paolo D'Odorico

Water is an essential natural resource for establishing and sustaining life, ecosystems, and economic development on earth. Despite humankind's rapid development and technological achievements, millions still lack access to food, energy, and water, and climate change exacerbates the pressure on limited natural resources. As a result, water governance is increasingly recognized as a critical factor in mitigating human-water problems and their socio-political consequences, including forced migration. When water access and quality deteriorate due to mismanagement or inadequate governance, communities may face heightened displacement risks, particularly in regions already grappling with environmental stressors like droughts, water scarcity, and food insecurity. Our study in the following chapters explores the nexus between water resources availability for food and livestock production, hydroclimatic changes, and environmental migration through a socio-hydrological framework that could be used to inform future water governance approaches addressing complex, multilayered and multicausal human-water problems focusing on East Africa. Communities in East Africa have been quite resilient against changes in rainfall patterns. However, when these changes spread to activate exacerbating factors, a holistic view of environmental drivers and their regional interactions is necessary. Our study focused on the crop and livestock production sectors to understand how water limitations associated with drought, agricultural water scarcity, and the consequent food insecurity can relate to environmental migration patterns. The nexus between these indicators and environmental migrations in the region plays an important role in shaping the response of farmers and agropastoralist communities, which account for roughly 80% of the population, to either adapt to the changing environment or depart. Environmental threats to shelter, livelihoods, and food security are often considered push factors for intra-African human migration. Research in this field is often fragmented into a myriad of case studies on specific subregions or events, thus preventing a more comprehensive understanding of the phenomenon. Our research begins with an introductory chapter overviewing some work on water governance and human-water problems. It focuses on the multidimensionality of water's nature in shaping sustainable development in all sectors by analyzing influential actors working to solve the problems for the past two decades. Then, we proceed to more specific works on the relationship between hydroclimatic changes and migration across a broader study area, Sub-Saharan Africa, and close examination of East Africa for specific mechanisms by which hydroclimatic factors influence migration trends in Somalia and Ethiopia. Despite the growing interest in environmental migrations observed in scholarly literature and the media, the nexus between hydroclimatic drivers and human displacement, conclusive empirical evidence of the relationship remains poorly investigated, particularly concerning the need for more comprehensive data and analyses to understand the specific mechanisms by which environmental factors influence migration decisions and patterns. Furthermore, the following chapters investigate the spatial interaction between the three indicators of the scarcity of water that highly influence East Africa's food and livestock production and primary internal displacement reasons: drought, agricultural water scarcity, and food insecurity. We draw insights from various sources of ground data from our study countries and combine them with remotely sensed climate data, multiple rounds of surveys on environmental migrants and internally displaced people, and socioeconomic development pathways (SSPs) from the Regional Climate Model. We used metanalysis, Qualitative Comparative Analysis, statistical correlation, multivariate spatial autocorrelation and clustering method, and agrohydrological and Persistence Index models to disentangle the complex multicausal phenomena of environmental migration and examine the multifaceted challenges posed by slow onset hydroclimatic extremes on environmental migration by taking account of the time lag of events exhibited before the people feel their effect. Understanding and predicting societal difficulties during global hydroclimatic and environmental changes is crucial, as well as the degree of susceptibility and the societal resilience to adapt and mitigate these changes. Therefore, in the end, we leveraged the above-mentioned methodological approaches to anticipate high-risk regions susceptible to future environmental migration or internal displacement based on climate change (RCP) and development scenarios (SSP). The results across these chapters show that the complex web of causal links is the main driver of environmental migration in Sub-Saharan Africa, while individual extreme or slow-onset events with high intensity and severity are very critical migration inducers. However, non-environmental underlying factors play a significant role by exposing the population to cumulative environmental changes and hindering their resilience. Multivariate spatial analysis and clustering provide the co-occurrence of scarcity of water indicators is found to be a statistically significant indicator and predictor of human displacement in the region. These results demonstrate that understanding and identifying areas prone to environmental migration flux depend highly on a cumulative driver approach that accounts for the persistence effect (slow onset events) rather than individual drivers. Overall, the research highlights that addressing the multifaceted layers of environmental migration drivers in East Africa requires integrating climate change and migration into policies across critical sectors like agriculture, water, livestock, forestry, and infrastructure to support adaptation.

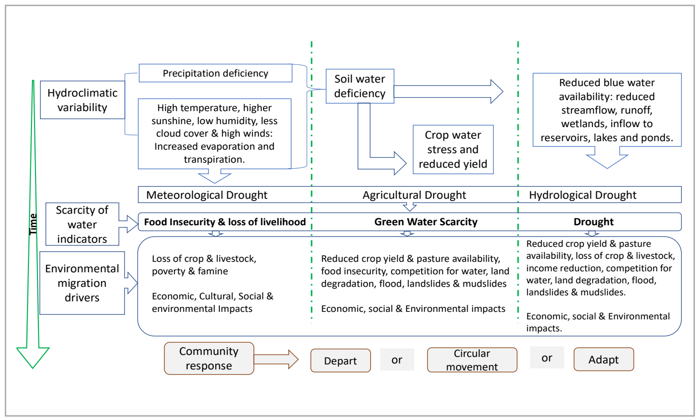

Fig. 1 - Aridity to exodus conceptual framework illustrates the cascading flow of hydroclimatic variability's effect on water availability and crop production, inducing Somalia's and Ethiopia's principal environmental migration drivers and the subsequent community response.