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The Doctorate in Environmental and Infrastructure Engineering has been operating since the academic year 2008/2009. The program introduces doctoral students to the world of research on key theoretical and technological elements associated with water, environment, hydraulic and transportation infrastructures, geology, as well as geomatics.
In this context, the program is grounded on environmental, civil, and industrial applications where water is the primary unifying element. The doctorate program is characterized by a strong inter- and multi- disciplinary structure and is organized according to the following key thematic areas.
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3. *Environmental technologies*, with focus on: water and wastewater treatment technologies (including disposal/reuse of wastewater, sludge management and disposal, anaerobic digestion processes; management and planning of environmental resources (including water quality modelling, knowledge-based decision support systems); solid wastes management (including Life Cycle Assessment of energy and resource recovery initiatives); phenomenology of the atmospheric environment and treatment of gaseous emissions; contaminated soils and their remediation.
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HYDROGEOLOGICAL HAZARDS EVALUATION UNDER CLIMATE CHANGE SCENARIOS: AN APPLICATION OF THE CRHYME MODEL (CLIMATIC RAINFALL HYDROGEOLOGICAL MODELLING EXPERIMENT).

Andrea Abbate - Supervisor: Prof. Laura Longoni

This thesis work presents the development of a new model called CRHyME for the evaluation of the hazards related to the phenomena of geo-hydrological instability. CRHyME (Climatic Rainfall Hydrogeological Modelling Experiment) represents an extension of the classic hydrological models that simulate inflows-outflows at the basin scale. It is a physically based and spatially distributed model in which a series of routines have been integrated allowing to describe and simulate the phenomena of geo-hydrological instability such as the triggering of shallow landslides as well as debris flows, the erosion of river basins and the sediment transport into the river. Generally, these phenomena are decoupled with respect to the hydrological simulation while in CRHyME they are evaluated simultaneously through a multi-hazard approach.

The CRHyME model is part of a geo-hydrological modelling chain. CRHyME was written in Python language, using the PCRaster libraries and takes inspiration from the PCR-GLOWB-2 model. This distributed model has been implemented on a global scale to study the effects of climate change on the availability of water resources. CRHyME has been completely rewritten to work at a higher spatial resolution using the worldwide databases available for the reconstruction of the spatial data necessary for the assessment of geo-hydrological hazards. The use of these general databases allows their implementation in any type of existing river basin.

The thesis work aimed to reconstruct the effects of future climate evolution on the local territory through the use of CRHyME. One of the main novelties of the model concerns the possibility of directly assimilating the outputs of climate models, such as precipitation and temperature data from the NETCDF file format that is commonly used for climatic simulation but less adopted in the hydrological field. In this regard, CRHyME has been tested on some case studies located in Italian basins. In particular, two rather extended areas, Valtellina and Emilia, were considered for the calibration and validation procedures of the model thanks also to the availability of literature data concerning geo-hydrological instability phenomena. In particular, CHRyME can: 1 reconstruct the surface runoff at the hydrometric stations located at the outlets of the basins, 2. estimate the solid transport at some hydropower reservoirs compared to the reference data, and 3. evaluate the triggering of shallow landslides and debris flows compared to those recorded in the literature. In addition, two other case studies were proposed: the Caldone river in Lecco (Lombardy) and the Chiosina river in Calenzano (Tuscany). These additional cases aimed to test the versatility of the model with respect to the variation in the spatial and temporal resolution of the initial data.

After the calibration and validation, CRHyME was applied to conduct future climate simulations considering three different models proposed by EURO-CORDEX program. Firstly, the implementation involved a pre-processing of temperature and precipitation climate data through downscaling procedures to bring the initial resolution of ≈ 12 km to the reference ones of 90 m used by spatial data. Subsequently, the simulations were carried out considering the scenario of maximum radiative forcing RCP (Representative Concentration Pathway) = 8.5 and were organized in two phases: a first run on the historical period 1986-2005 and a second run on the future 2006-2075. The historical period was used as a reference to evaluate the trends in the future. In this regard, a series of key parameters related to the phenomena of geo-hydrological instability produced by the CRHyME model was analyzed. Several variables were investigated such as maximum daily precipitations, the mean temperature, the maximum daily water discharges, the annual sediment yield, and the maximum daily number of triggered shallow landslide and debris flow movements. Statistical tests on means and variance were applied to the data series to highlight possible future tendencies in comparison to the reference period. The results have shown a general intensity increase in the geo-hydrological cycle, especially across the Alpine region. In particular, for the Alpine region future trends indicate a general increase in geo-hydrological instabilities while in the Apennine region it is less evident with important differences depending on the investigated areas. Similar results were also assessed from the analysis of the outliers that represent the extremes of the sample distributions, which are projected to increase in the future decades. This evidence is a confirmation of the studies conducted by the IPCC. For the first time, the latest report on the state of the climate, the Sixth Assessment Report (AR6), has included some considerations about the possible effects on the geo-hydrological processes caused by climate change.

The propagation of uncertainty in this type of model is certainly important and to be taken into account given its articulation. In fact, the numerous assumptions adopted to deal with the usage and customization of the initial data and with the routines selected to simulate the various geo-hydrological processes. While the reconstruction of the surface hydrological balance is quite robust thanks to the greater amount of available reference data and models describing the phenomena involved, the approximations increase significantly concerning the reconstruction of the groundwater cycle and in the evaluation of geo-hydrological instability processes such as the triggering of surface landslides and debris flow, erosion and solid transport in the riverbed. In this context, CRHyME has been tested in the different case studies demonstrating on the one hand good results which do not significantly reduce the uncertainties inherent in the quantification of these processes. The scarcity of reference data for calibration, the extreme variability of the parameters necessary for slope stability assessment and for identifying the triggering condition of solid transport limit the validity of a single deterministic solution. In this regard, possible simulations using Montecarlo-type methods, already implemented by other software that deals with similar problems, could in the future be a reasonable solution to treat the results obtained by the model probabilistically. The first attempt in this direction was already implemented through the sensitivity analyses conducted on friction angle, particle size and water content of the soil in the calibration phase of CRHyME.
The development of CRHyME starting from the Python language, its validation of the historical data and its use for climate change scenarios are the activities carried out in this thesis work. Building a general model that touches on all aspects of this topic is a challenge where climate change scenarios add further complexity. However, CRHyME, together with PCR-GLOWB-2, represents one of the first attempts to integrate different disciplines such as meteorology, climatology, hydrology, geology, computer science and numerical calculation in a transversal way for interpreting and simulating geo-hydrological processes.

MODELING SOLUTE TRANSPORT AND MIXING IN POROUS MEDIA UNDER TURBULENT FLOW CONDITIONS: APPLICATION TO THE HYPORHEIC ZONE

Elisa Baioni – Supervisors: Prof. Alberto Guadagnini, Prof. Giovanni Michele Porta, Prof. Mohaddeseh Mousavi Nezhad

The thesis proposes a modeling approach to quantify the solute transport and mixing in porous media under turbulent flow conditions. The study is motivated by the significant implications of solute transport processes in the hyporheic zone (see Fig. 1 (a)) to the natural attenuation of pollutants and the lack of a complete model for predicting the complex phenomena characterizing such environment. The work comprises two main sections: (i) the assessment of solute diffusion under a turbulent flow close to a sediment-free flow interface representative of solute transport and chemical mixing in the hyporheic zone, and (ii) the development and testing of the modeling approach.

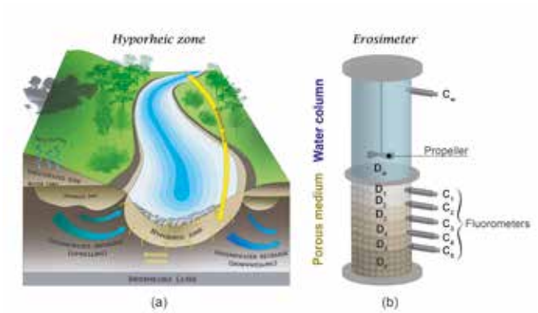

Fig. 1
Scheme of the hyporheic zone (a) and the experimental set-up (erosimeter) (b)

The first part of the thesis tackles the quantification of the vertical variation of the effective diffusion coefficient under a turbulent flow in a porous medium across the sediment-water interface (see Fig. 1 (b)) representative of solute transport and mixing in the hyporheic zone. Recent experimental results show an exponential reduction of the diffusion coefficient with depth below the exchange interface. This work expands these recent results by estimating the uncertainty associated with the spatially variable diffusion coefficients for different combinations of (a) the sediment grain size and (b) the turbulence level at the water-sediment interface. A Bayesian inverse method implemented through an acceptance/rejection algorithm is employed to obtain the depth-resolved posterior probability distributions of the effective diffusion coefficient. The results in Fig. 2 display a vertical exponential decay of the diffusion coefficient only in a limited range of dimensionless depths and provide quantitative estimates of the uncertainty associated with spatially variable diffusion coefficients. The work shows that the sediment particle size has a larger impact than the bed shear velocity on the diffusion process.

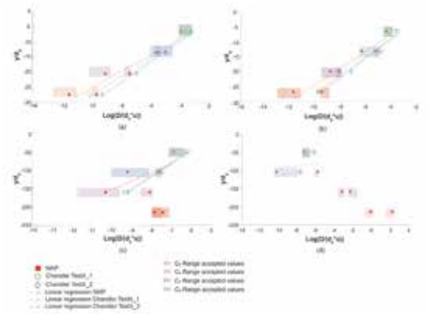

Fig. 2
Summary of the acceptance/rejection stochastic calibration results for all experimental tests: (a) Test 1, (b) Test 2, (c) Test 3, (d) Test 4, and the corresponding regression fits

The second part concerns the development and testing of the modeling approach implemented by combining (a) the Skew Brownian Motion (SBM) model, predicting the solute particles' behavior across media with spatially variable diffusivity, and (b) the Parameterized scalar profile (PSP) mixing model, quantifying the temporal evolution of chemical concentration due to turbulent mixing. The approach addresses the spatial variability of the diffusion coefficient and yields predictions of the solute concentration probability density function (see Fig. 3). The model is applied to a system constituted by a porous medium underlying a clear water column where turbulent flow is generated. A rigorous sensitivity analysis is performed to evaluate the influence of model parameters on solute concentrations and mixing, the latter being quantified in terms of the scalar dissipation rate. The study highlights that the vertical exponential decay of the diffusion coefficient has a marked influence on solute mixing and transport.
The model can be extended to the reactive solute transport.

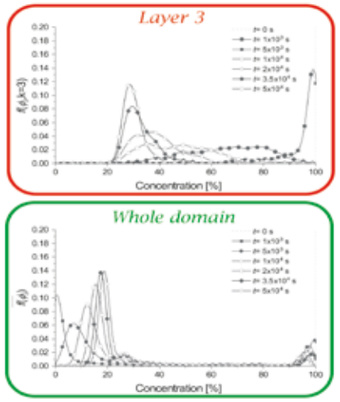

Fig. 3
Time-dynamics of the probability density of concentration values predicted by the implemented Lagrangian model in Layer 3 and the whole domain

MONITORING ALPINE CRYOSPHERE WITH EARTH OBSERVATION DATA

Riccardo Barella - Supervisor: Prof. Marco Gianinetto

The thesis covers the topic of Alpine cryosphere monitoring using earth observation data. Alpine cryosphere is mainly composed by two elements, glaciers and snow cover. These elements are an essential part of the hydrological cycle in the Alps, contributing to the delayed run off of precipitation, and they guarantee water availability through their seasonal melting. Water coming from the melting of the cryosphere's elements has an important follow up on many fields, e.g. the human consumption, the agriculture and the hydro-power production. Alpine cryosphere is a delicate environmental system, and small changes in air temperature and precipitation dynamics can have a relevant effect on it. For example glaciers are recognized as sentinels of climate change, and the magnitude of their retreat is the most evident effect of global warming. Snow accumulation and melting dynamics are changing as well, even if the change is not so evident and clear as the glacier shrinkage, but still influencing human activities related to it. The increased speed of glacier changes observed in the last years requires a more frequent update of the glacier inventories than in the past; however, the high human supervision required by the state-of-the-art techniques is discouraging their systematic application over large areas. All these aspects are deeply analyzed in the introductive first chapter of the thesis. As a response to this need in the second chapter of the thesis is proposed a novel approach to exploit the large volume of data provided by Copernicus Sentinel missions for detecting glacier outlines, including debris-covered glaciers. In detail the method exploits the Sentinel-1 and Sentinel-2 multi-temporal images to build a composite image representing the conditions during the yearly maximum ablation period. The Sentinel-2 multispectral images are classified with a support vector machine (SVM) and composed to a mosaic that represents the information of the maximum glacier ablation. At the same time, the Sentinel-1 time series are exploited to build a multitemporal interferometric coherence composite that represents all the snow covered and glaciated areas together with all the moving surfaces. The application of automatic methods for glacier mapping requires accurate and dense time series of thematic maps. In the third chapter we investigate the possibility to use SAR images regularly acquired by Sentinel-1 mitigate the inability of Sentinel-2 to retrieve information in cloud-covered sky. When available, the information provided by Sentinel-2 can be exploited to improve the accuracy on the Sentinel-1 glacier mapping. The classification performance using polarimetric SAR data is in fact lower than the one of multispectral optical data. The proposed approach for classifying Sentinel-1 images is based on a Hidden Markov Model (HMM), where the impossible class transitions within an ablation season are used to generate the transition probability matrix of the HMM. The HMM emission probability matrix is estimated through Support Vector Machine (SVM) and Platt scaling. The Viterbi algorithm is then used to perform the inference step. We tested our approach by forming a Virtual Constellation (VC) composed by the Sentinel-1 and Sentinel-2 images acquired over the glaciers.The classification of ice and snow in SAR images still represent a challenging topic, mainly because of the lack of knowledge in modeling the interaction between the microwaves and the snowpack. One of the main parameters that influence the backscatter of the snow, toghether with the wetness, is the surface roughness. In the fourth chapter of the thesis is presented a system for snow roughness measurement. The system is based on the coregistration of the digital photos taken at the panel on the field with a reference scaled image of the panel. In detail, the coregistration process is done by applying homography, of which parameters are estimated exploiting automatic key-points matching. In the end, in the last chapter, is deeper investigated the topic of subpixel snow retrieval in optical multispectral images. In fact providing reliable maps of snow cover in challenging atmospheric and illumination condition is still an open issue, especially in mountain areas. If these effects are not well corrected by applying the proper corrections, the state of the art method, based on spectral indices or linear multispectral unmixing, generally fail. To overcome this limit in the thesis it is proposed an unsupervised approach for collecting "snow" and "snow free" endmembers, for training a machine learning model that overfits each scene. The results are evaluated using a snow maps derived by very high resolution images acquired in challenging situations of fractional snow cover and low sun elevation over the Alps.

TECHNO-ECONOMIC ASSESSMENT OF A PROCESS TO REMOVE CO_2 FROM THE ATMOSPHERE

Beatriz Beccari Barreto – Supervisor: Prof. Stefano Caserini

According to the latest IPCC reports, Carbon Dioxide Removal (CDR) technologies are required to limit global warming to "well below 2 °C", as the objective of the Paris Agreement. The present PhD thesis studies a CRD process developed in the framework of the Desarc-Maresanus research project, a combination of bioenergy and carbon capture and storage and ocean liming. A techno-economic analysis has been developed, assessing costs and CO_2 penalty of the process in four different contexts (Brazil, China, Netherlands, and United States). An uncertain analysis based on the Monte Carlo method implemented in the program MATLAB has been done, using 11 varying parameters. The total cost of CO_2 removal is assessed between 45 and 180 USD/tonCO_2, a range similar to other assessments of CO_2 removal cost available in the literature.

The countries where the cost is higher are the Netherlands and USA, because of higher limestone cost, biomass cost, and storage and transportation of CO_2 cost.

Since the capture and storage of CO_2 emissions generated from the calcination of limestone is an essential point for a convenient CO_2 balance of the process, an analysis of different types of storage available has been realized with different methodologies. For the traditional Carbon Capture and Storage (CCS), already at a high stage of development, a detailed literature review of the cost has been done considering 762 papers published in the scientific literature from 2018 to 2020. The cost of carbon avoided (the extra cost for the plant to do the capture and storage of a certain amount of CO_2) that has a range from 50 to 100 USD/tonCO_2, which is competitive with the current EU-ETS Carbon Prices, around 70-90 €/tonCO_2. Since the development of the traditional geological storage faces many difficulties, the PhD thesis has evaluated an alternative CO_2 storage method proposed in the literature, the Buffered Accelerated Weathering of Limestone (BAWL), that allow the storage of carbon in the form of bicarbonate in the deep ocean. The cost of CO_2 storage with BAWL is assessed in the range 100-450 €/tonCO_2 for an Italian location, including the cost of CO_2 capture from a steam methane reforming flue gas. The uncertainty analysis based on Monte Carlo method shows that the most relevant parameters are pipeline cost, electricity cost and limestone cost. Although further research is needed to evaluate all the techno-economic and environmental aspects of the CDR process and CO_2 storage option considered, the present work provides information that could be of interest for the analysis of the role of CDR technologies in climate mitigation strategies.

INNOVATIVE SUSTAINABLE LOW-ENERGY TECHNOLOGIES FOR CONTAMINATED SITES

Gabriele Beretta - Supervisor: Prof. Elena Sezenna

The economic and social development have carried impacts on human health, water and soil quality. Reducing the negative impacts through appropriate remedial measures and interventions is needed. The innovative in situ clean up technologies that have been tested for heavy metals and hydrocarbons proved hopeful results (economic and time saving). Following the indications of the European Community, which requires "targeted, proportionate and sustainable approaches to face environmental quality issue", the work focuses on the study of sustainable in situ technologies for soil and groundwater decontamination by reducing the use of energy and natural resources and by avoiding long-term changes of subsurface conditions.

The research activity was directed toward different technologies, with the goal of decontaminating heterogeneous unsaturated or saturated soils, highly polluted by Total Petroleum Hydrocarbons (TPHs), Polycyclic Aromatics Hydrocarbons (PAHs), and heavy metals (Arsenic, Lead, Zinc, Copper, and Chromium).

To overcome the challenges posed by this kind of contamination, the following technologies were considered:
- Electrokinetics (EK) involves the application of a potential gradient or a low direct current (up to 1 A) across electrodes inserted into the contaminated soil. The main mechanisms occurring in the soil are: electroosmosis, electromigration, and electrophoresis. In the EK process, water electrolysis usually result in soil acidification/alkalization around anode/cathode, phenomenon that has to be properly contrasted. EK can handle mostly toxic metals, and can be scaled up to meet different site-specific requirements.

- Microbial electrochemical technologies (MET) benefit from the natural capacity of microorganisms to catalyze electrochemical reactions using solid electrodes as inexhaustible electron acceptors/donors. Therefore, they require little or no energy supply, and do not require the injection of chemicals into the soil. As other bioremediation techniques, MET can be a complementary remediation strategy to obtain effective and efficient removal at non-toxic pollutant concentrations.

The research carried out has focused on designing, planning and conducting lab-scale experiments, and realization of the remote control and monitoring system for the tests.
The laboratory tests were conducted with the aim of:
- to investigate the extent of the different phenomena under the different operational conditions;
- to evaluate the transport of contaminants in soil;
- to verify the effect on pH, electrical conductivity, redox potential, and temperature, under different operative conditions;
- to investigate the applicability of sequential operative conditions to optimize the remediation.

Furthermore, commercial software has been used to model the electrokinetic removal of arsenic and lead from contaminated soil. The model uses the finite element method for the solution of partial differential equations, through the construction of a discretization grid of the geometry of the modeled system. The use of "physical interfaces", allowed for the simulation of water electrolysis, electric potential, electromigration, electroosmosis and transport of contaminants.

Batch tests have been used for exploring the mobility of metals at different pH in soils polluted by metals. Leaching tests have been performed following standard procedure, using properly pH conditioned tap water as a leachant. The results of these tests highlighted metals in the experimental soils to be present in highly stable and not mobile forms, with a minimum leachability in water and only at extreme pH conditions. Desorption and recovery of metals were strongly affected by the high alkalinity and buffering capacity of the soil.

Enrichments of electroactive bacteria (EAB) aimed at the formation of an electroactive biofilm which was then used in the cathodic reduction tests of the contaminants. This acclimatization method involves the transfer of a mature bioanode of an MFC to the cathode chamber of a MET system. This operation allows reducing the time taken by the electroactive microorganisms to colonize the electrode.

Microbial electrochemical batch test in remediation perspective aimed to investigate the treatment of groundwater contaminated by sulphates, nitrates and Cr (VI). To stimulate the bioelectrochemical reduction of Cr(VI) in groundwater several possible applications of METs have been explored. To get closer to the real conditions of low organically loaded groundwater the only carbon source introduced into the system was the carbonates.

The Microbial electrochemical Cr(VI) reduction in continuous flow systems activities aimed to approach the microbial electrochemical remediation (MER) of Cr(VI) contaminated soil and groundwater. The implementation of two different configurations of METs operating in continuous flow for the bioelectrochemical removal of Cr(VI) from contaminated water and soils has been performed starting from the results obtained in microbial electrochemical batch tests. Concentrations of Cr (VI) tested approach those of real contaminated groundwater rather than those present in industrial wastewater treatment plants.

In conclusion, batch tests were crucial to investigate the limiting factors affecting the removal of the different types of pollutants under study, and allowed to design the suitable treatment and the operative conditions to obtain an effective degradation of organic contaminants and metal removal in the treated soil.

Further studies are needed to understand both the role of the indigenous soil microbial community in electrokinetic remediation and the effects of this technology on natural bio-pedologic mechanisms.

Numerical model simulations indicated electromigration has been the main electrokinetic transport mechanism for the removal of heavy metals from saturated soil. Further implementation of the numerical model might be considering the geochemical processes, contaminants distribution among phases and different degrees of soil saturation. The balanced calibration-validation of the model can provide a useful tool for designing tests (lab-scale or pilot-scale) and a support for identifying the best operative conditions for in situ electrokinetic remediations.

Relationship between the availability of substrate and the production of a potential difference indicates the development of a community of electroactive bacteria. The initial phase of EAB enrichment proved to be fundamental in improving the efficiency of bioelectrochemical reduction of Cr (VI), this approach could be considered in full-scale implementation also with other contaminants. Electroactive biofilm was proven to be essential for the removal of dissolved chromium. Community analyses suggest that *Moheibacter, Nitrobacter* and *Truepera* were selectively enriched in the biofilm of the polarized system. Bacteria belonging to the *Flavobacteriales, Nitrosomonadales* and *Rhizobiales* orders play a dominant role in electroactive communities enriched in POL −0.3 V. These results demonstrate that the bioelectrochemical removal of Cr (VI) can occur, even in the absence of organic carbon.

The configuration tested in continuous flow system has demonstrated the possibility of applying MET to the remediation of saturated contaminated soils and could be considered for a future scale-up of the technology and the implementation of remediation in situ.

Although bioelectrochemical treatment needs further studies (pilot-scale and field scale) also from an economic feasibility point of view, it can represent an innovative and sustainable approach for the removal of contaminants from soil and groundwater.

AVAL RISK. AVALANCHE RISK UNDER PRESENT AND PROSPECTIVE CLIMATE CHANGE

Giovanni Martino Bombelli – Supervisor: Prof. Daniele Bocchiola

The avalanche risk is a little perceived risk in general except in the winter period, but once the critical moment has passed, it is often quickly overshadowed or worse forgotten. This is very serious because if we consider the statistics reported by the Meteomont Service of the Carabinieri and by AINEVA, there are on average 20 victims per year and 60 people are involved on average. Instead in the European context EAWS estimates that snow avalanches claim an average of 100 lives in Europe every year.

Thus, the snow avalanche risk and the hazard component must be considered in the same way as all the other hazards originating from calamitous events governed by urban planning instruments: in fact, avalanches, due to the size and forces that characterize them, can represent a potentially very destructive threat. An emblematic case is that of Rigopiano where risk of snow avalanches hit the headlines in Winter 2017 when a 10^5 m^3 snow mass hit and destroyed the Rigopiano Resort Hotel in Abruzzo. The event caused 29 casualties, and the investigation to assess responsibilities are undergoing.

The occurrence of such events may indicate that climate change under global warming is a modifying hazard in the mountain, especially concerning snowfalls, and avalanches. And not only skiers, and mountain users are affected during open air activity, but houses and touristic structures built within avalanche prone areas can be destroyed given the tremendous impact pressures during such events.

This research has as objective the investigation of snow avalanches hazard and its mapping, under present and future climate condition under climate change, little investigated and yet tremendously important in the Alps.

In this work an avalanche model Poli-Aval-2D was elaborated and presented, able to describe avalanche flow, based on solving of shallow water equations. The model so elaborated can also consider the interaction of snow avalanches with vegetation, and snow entrainment along the track. The model, with the different components described before, was applied for the Rigopiano Avalanche case with reasonable result within a poorly monitored area as this case also compared to models present in literature. The model was able to describe the historical event and starting from the parameters obtained, the hazard mapping procedure was applied to which a study on the uncertainty of the estimate was provided.

Also, a model for the snow gliding model and the application on a case study was presented here. An important topic in the snow dynamics literature because snow gliding is a complex phenomenon to predict and to model, and very important because it drives snowpack dynamics in the pre-avalanching phase. The physically based model was set up and applied to the avalanche site called "Torrent des Marais - Mont de La Saxe" in Aosta Valley, displaying a good capacity of the model to reproduce time patterns, and final displacement of the snowpack.

To analyze the possible effect of climate change it was presented an application of the Poli-Aval-2D model coupled with the Poli-Snow model to simulate a long term simulation of the avalanche regime from avalanche release to deposition, driven by meteorological conditions. Using future projected snow conditions, it is possible to estimate the future possible extent of avalanche hazard zones, under different climate scenarios, using a time continuous simulation for the Vallecetta Valley avalanche site in Valtellina Valley in Lombardy Region.

The results show that there will not be a disappearance of the avalanche hazard in general but only, in the most climatically severe scenarios, SSP3 7.0 and SSP5 8.5, a possible retreat of the areas subject to avalanche hazard.

A methodology and the theoretical background for specific approach to avalanche triggering, and release simulation and stablishing strong relationships between weather conditions and avalanche days using a logistic regression was used to explain event occurrence or non-occurrence from a series of variables, in this case the weather data. Therefore, since this statistical tool was found effective in describing the link between avalanche events and the meteorological situation, it was decided to apply it to two avalanche areas of the central Alps, the Alta Valtellina region, and the Davos region to study the climatic change effect on the avalanche hazard.

The reported results show that the occurrence of events does not disappear except in the late spring months when the increase in temperatures leads to an early melting of the snowpack. Otherwise, if we consider the winter season, for less severe climatic scenarios, SSP1 2.6 and SSP2 4.5, there is an increase in the number of events, especially those of a smaller size.

And finally, an application of the regional approach to the Alpine region of Lombardy, based on the available data is to provide a distribution suitable for the evaluation of the snowfall extremes for a defined return period, on a regional basis. In this way, a methodology is proposed that can be applied by policy makers to practical cases in which hazard mapping is required.

INFLUENCE OF THE COLLECTION EQUIPMENT ON ORGANIC WASTE TREATMENT: TECHNICAL AND ENVIRONMENTAL ANALYSES

Giovanni Dolci – Supervisor: Prof. Mario Grosso

The organic fraction, the most relevant among the separately collected materials in the municipal solid waste, is mainly composed of food waste, together with green waste. In addition, the amount of compostable bioplastics conferred within the organic waste has grown in recent years. The progressive increase in the use led to an increasing amount of compostable bioplastics that are becoming (and will be in perspective) a problem for the organic waste processing facilities, not originally designed for their treatment. The criticalities are first associated with the mechanical pre-treatments preceding the biological process: when subjected to size-based separation, most of the bioplastic products are discarded as residues, similarly to conventional plastics. This is particularly relevant in anaerobic digestion plants, where pre-treatments are often very intense. The problems associated with the management of discarded bioplastic items are amplified by the fact that, when removed, they show a drag effect on a non-negligible amount of food waste remaining adhered to them and not delivered to the anaerobic digestion.

Although the increasing amount of different bioplastic items, a relevant contribution is still constituted by the bags employed for the collection of food waste. The Italian collection systems of food waste from households are mainly based on the use of bioplastic bags, typically made with the Mater-Bi® polymer, compostable according to the UNI EN 13432:2002 standard. They can be either specifically sold for this purpose (dedicated) or bags used for the overall shop at the supermarkets (shopper) that can be reused for the food waste collection. Alongside, a less widespread type of paper bag, specifically designed for the food waste collection, is available on the market. It is made of recycled fibres and composed by a main bag and a cartonboard bottom to be inserted inside the main bag before its use.

Building up on the previous considerations, this research was carried out to analyse the environmental and energy performances of the treatment chain of the food waste collected from households, with a particular focus on the influence of the different types of collection bags.

In the first part of the study, the behaviour of the food waste during the household storage was examined. In detail, the weight loss of the food waste during the household storage was evaluated to assess how it is affected by the type of bags used for the collection. Bioplastic and paper collection bags showed a different behaviour, with the paper allowing for higher weight losses: +29% and +44% on average compared respectively to dedicated and shopper bags. In addition, paper bags allowed for a lower odour and leachate release during their use at the household, paving the way to a potential decrease of the frequency of food waste collection, thus reducing costs and environmental impacts.

Subsequently, the treatment stage was examined: assuming that operational problems associated to the management of bioplastics could be solved in the future, bioplastic collection bags must be compatible with biological processes. Accordingly, the assessment of the anaerobic degradability of the bags was the goal of the second part of the study. In detail, Biochemical Methane Potential (BMP) tests on bioplastic and paper bags were performed to evaluate their behaviour under anaerobic conditions. Subsequently, to better simulate the real operating conditions of full-scale digesters, collection bags were subjected to semi-continuous co-digestion tests with food waste. Mesophilic BMP tests showed a limited degradation of bioplastic bags compared to a good degradation of paper bags. As regards thermophilic conditions, BMP tests indicate a good degradability (>71%) of different commercial types of bioplastic bags. On the contrary, results of the semi-continuous co-digestion tests showed a reduced methane production from bioplastics, corresponding to a low anaerobic degradability (<27%), confirmed by the physical status of the undigested bag pieces. As regards the paper, very interesting perspectives are offered by the tested bag, since its anaerobic degradability in the semi-continuous co-digestion tests (82%) resulted even higher than that observed in the BMP tests (74%), suggesting a very good compatibility with the anaerobic digestion process.

Finally, the environmental performances of the overall management chain of the food waste collected from households were evaluated, by means of the life cycle assessment methodology, comparing two systems in which the collection bags are respectively made of bioplastic and paper. The potential impacts for the management of 1 kg of food waste generated at the household were evaluated. The assessment included the collection bags manufacturing and distribution, their use at the household, and the collection and treatment of the food waste by means of an anaerobic digestion process. Potential impacts were calculated by examining 16 midpoint impact categories. For the modelling, two different approaches were considered: the approach applied in the International Environmental Product Declaration (EPD) and the one of the Product Environmental Footprint (PEF) methodology. The results highlighted a beneficial influence associated with the use of recycled paper bags instead of bioplastic bags, in particular the dedicated ones; shopper bags are less impacting because they are used, as the first purpose, for carrying the grocery shopping. The benefits of the use of paper bags are associated to both the bag manufacturing (especially thanks to the use of recycled fibres) and the benefits in the anaerobic digestion treatment, since they are not discarded during pre-treatments, differently from bioplastic bags. Anyway, the methodological approach has a relevant influence on the comparison: the paper bag system achieves the highest environmental advantages with the EPD approach, while using the PEF entails a significant increase of the impacts because of the effect of partially considering the virgin paper production, in place of the use of recycled fibres.

According to the results of the whole study, summarised in Fig. 1, the increase of the use of paper collection bags in a current system characterised by bioplastic bags should be encouraged, showing several benefits in the management chain that allow for a general reduction of environmental impacts.

Fig. 1
Schematic overview of the research

FLOOD DAMAGE ASSESSMENT TO ECONOMIC ACTIVITIES IN THE ITALIAN CONTEXT

Marta Galliani – Supervisors: Prof. Francesco Ballio, Prof. Daniela Molinari

The study of flood impacts on the different sectors that compose the built environment and the society is crucial to implement actions of prevention, protection, and risk-aware planning. In such a context, the sector of businesses assumes a critical role, both for its importance for the welfare of the society and because of the high losses it suffers in case of inundations. Nevertheless, flood damage modelling to businesses is still a challenging task because of the high variability of activity types, the difficulty of standardisation, the paucity of information to characterise the enterprises and the low accuracy in observed damage data. Since the Italian territory suffers from the lack of a shared and validated methodology to assess damage to enterprises, this thesis took up the challenge to address this topic, with specific reference to direct damage and the Italian context. It undertook three alternatives to study the problem: the study of the transferability of a foreign model in Italy, the analysis of post-event observations from some Italian case studies and the implementation of a synthetic approach to develop damage functions for some activity categories. The first approach aimed at testing the validity and transferability of the French methodology for the estimation of flood damage to activities in France and in Italy. This exercise pointed out the paucity of information to validate the methodology and allowed to verify the actual availability of data to implement the method in the two countries, hence the transferability of the method. The second approach concerned the analysis about a thousand observed damage records regarding industrial and commercial activities retrieved from the local authorities after different flood events in Italy. Data analysis focused on searching information and relations between damage and activity type, activity dimension and water level. This study aimed at building knowledge about types and dimensions of impacts of flood events to economic activities in Italy. The third study aimed at developing damage models for structure and equipment of retail activities through a synthetic approach. It provided two main results. The first is the simplified version of the INSYDE model for assessing flood damage to the structure of civil buildings. The second is a detailed analysis of the composition and the assessment of value of the equipment of five retail businesses, i.e. pharmacies, clothing shops, tobacconists, supermarkets, restaurants. The results can support the identification of the more vulnerable elements within the business sector, orienting modellers' and decision makers' choices in risk assessment and be starting points for the development of a more comprehensive and complete method to assess damage to economic activities.

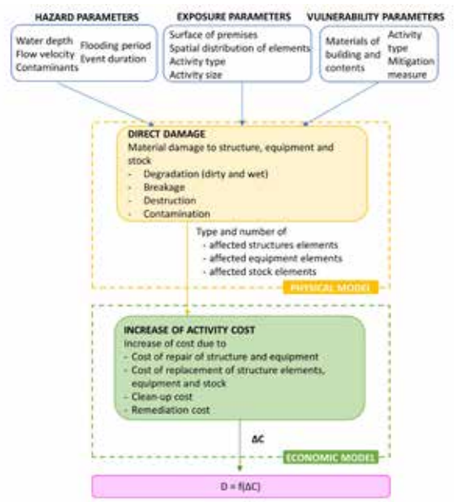

Fig. 1
Conceptual model of direct damage assessment to economic activities

INTEGRATION OF MACHINE LEARNING AND CITIZEN SCIENCE TO ADDRESS THE CHALLENGES OF PUBLIC ENGAGEMENT AND DATA VALIDATION

Maryam Lotfian - Supervisor: Prof. Maria Antonia Brovelli - Co-Supervisor: Prof. Jens Ingensand

In recent years, citizen science (CS)— the participation of members of the public in scientific projects — has grown significantly, owing to technological advancements. The two main challenges in CS projects are sustaining participation, and validating the quality of data collected by the participants. Since volunteers come from heterogeneous communities, the need for data validation methodologies in CS projects is of utmost importance. Today data validation in CS projects is mainly done by expert review. As CS projects are growing, the amount of data contributed to such projects is also increasing. Therefore, considering expert validation as the main approach for data quality assurance can have certain disadvantages. One disadvantage is that manual big data validation is time-intensive. The other disadvantage is that the time period between the point when the participants make contributions and the point when the data are verified by experts can be very long and can result in demotivating participants; since they either do not receive feedback or they may receive feedback months after their contribution. It is therefore important to search for ways to automate validation tasks in CS projects and consider expert verification for final flagged outliers. Accordingly, despite the studies that have been conducted to address the CS challenges, there is still a need for new approaches, one of which is the use of machine learning (ML) in CS projects.

Therefore, the objective of this thesis was to investigate the integration of ML and CS, as well as the role of this integration in addressing CS challenges. A comprehensive review conducted in this study of motivational factors in CS projects indicated that interest in learning about science and receiving feedback were strong motivations among participants in the majority of CS projects. Typically, experts verify the data and provide feedback to participants. However, due to large amounts of data, this manual data verification can be time-consuming. Thus, in this research, it was investigated how the integration of ML and CS can, on the one hand, automate and speed up the data validation process, and on the other hand, increase public engagement and sustain participation by giving real-time machine-generated informative feedback to the participants.

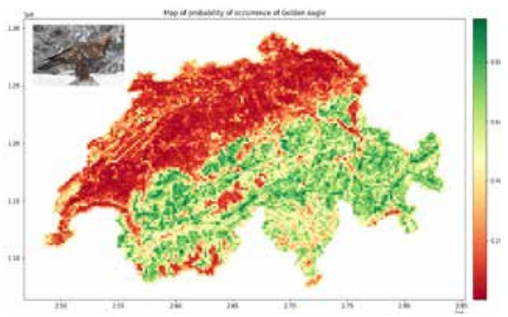

Fig. 1
Map of probability of occurrence of Golden Eagle species within Switzerland

To that end, a biodiversity CS project was implemented with the goal of collecting and automatically validating species observations as well as providing participants with real-time feedback. We implemented three types of automatic data validation in this application: date, image, and location validation, but the latter was the main focus. ML algorithms were trained to model species distribution using environmental variables (e.g., land cover, average elevation, NDVI) and bird species data within Switzerland from the eBird platform. Four algorithms of Naïve Bayesian, Random Forest (RF), Balanced RF, and Deep Neural Network were trained to generate species distribution models, but after accuracy assessment for all species, Balanced RF was chosen as the algorithm that performed better compared to the other three. Thus, the trained models from the chosen algorithm were used to validate new contributed observations based on the model prediction on the probability of observing a species in a specific location. Furthermore, volunteers were given real-time feedback on the likelihood of observing a species in a particular location, as well as species habitat characteristics. Finally, a user experiment was conducted, and the results indicated that participants with a higher number of contributions found the real-time feedback to be more useful in learning about biodiversity and stated that it increased their motivation to contribute to the project. Besides that, as a result of automatic data validation, only 10% of observations were flagged for expert verification, resulting in a faster validation process and improved data quality by combining human and machine power. Furthermore, based on the findings of the experiments and the discussions that followed, we made some recommendations for CS practitioners to consider before designing a new project or improving an existing one.

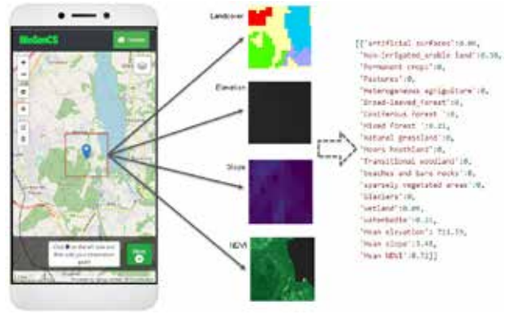

Fig. 2
Real-time extraction of environmental variables in a neighborhood of 1km around the location of an observation added by a participant

The future objective of this research is to focus more on the challenges of ML and CS integration, and to investigate how this integration can be applied in other CS fields besides biodiversity,

Fig. 3
Two examples of location feedback if probability of occurrence of species is higher (a) and lower (b) than 50%

ELECTRIFIED ROADS: STRUCTURAL PAVEMENT OPTIMIZATION AND METHOD OF IMPLEMENTATION IN URBAN NETWORK

Claudia Nodari - Supervisor: Prof. Emanuele Toraldo

European Commission report 2021 shows that, during 2019 in EU-27, transport sector produces 25.8% of the total Green House Gases (GHG) emissions. Road transport is responsible for 71.1% of the sector's emissions. As regard vehicles, cars account for the 60.6% of the road transport sector's emissions (11.2% of the total GHG emissions).
Due to high GHG emissions generated by road transport sector, Scientific Research investigates new solutions to increase environmental sustainability of road system. The electrification of vehicles is a possible solution, but it requires both new vehicles and proper charging infrastructure networks. Among the arising technology for electric mobility, contactless dynamic vehicle charging seems to overcome the current limitations of Battery Electric Vehicles (BEVs). The main BEV points of weakness are high initial cost, long charging time, limited diffusion of static charging stations, and range anxiety. In order to enable this type of vehicles charging, a proper infrastructure is required. Thus, traditional road (t-road) becomes electrified road (e-road) if it is able to provide electricity for BEVs.
The present study focuses on contactless dynamic vehicle charging, using Charging Unit (CU) embedded into the road pavement. These CUs are made of prefabricated cement concrete box, in which the electrical technologies are held. The available scientific papers assume the CU has a solid box; instead, in the current investigation, CU is considered as a box with a void for the electrical devices positioning. However, the CU has not to be detrimental for the pavement performances. This is the reason why this research studies the CU effect on pavement, comparing the results to the one obtained for t-road, using a 2D Finite Element Modelling (FEM) approach. This means e-roads are analysed in terms of structural behaviour, fatigue life and rutting resistance. Moreover, both shape and dimension of CU cavity are optimized. Therefore, several e-road cross-sectional geometries are analysed, by combining different CU cavity shape (one rectangle, two rectangles, four circles and six circles) and different CU concrete characteristics (C20/25, C30/37, and C40/50 according to EN 206-1). E-roads performances are evaluated in two steps. The first one describes e-road behaviour from a theoretical and numerical point of view. The second step is devoted to validating the achievements of the first one applying them to a real case study (Viale Forlanini in Milan). As a result of these analyses, interesting outcomes are obtained demonstrating that CU seems to be compatible with the structural performance of pavements.
Since it is not possible to electrify all roads at the same time (for economic reasons, construction aspects, etc.), the current study develops a simple, self-explanatory, repeatable, and adaptable method to identify which urban t-roads can be converted to e-roads. This method belongs to the so-called Multicriteria-Spatial Decision Support Systems (MC-SDSS), that are procedures useful for solving spatial problems through the integration of multicriteria analysis with a geo-referenced data management and analysis tool, such as GIS (Geographic Information System). This part of the research is divided into two sections. The first one describes the theoretical steps useful for the model implementation; the second one consists in the model application to a real case study (Comune di Milano). During the model implementation phase, an algorithm is developed to calculate a Feasibility Index (FI) based on numerous criteria (related to infrastructure/transport, society, and environment area). FI is a numerical score to be assigned to each road in relation to the feasibility of transforming a t-road into an e-road. FI varies from 0 (worst case) to 1 (best case, in which the road transformation is highly recommended). The obtained results show that this method is effective in identifying which urban t-roads can be electrified.

Keywords: Electrified road; Dynamic charging; Finite Element Modelling; Bituminous pavements; Multicriteria-Spatial Decision Support System (MC-SDSS); Geographic Information System (GIS).

MULTI-SOURCE AND MULTI-SCALE SATELLITE OBSERVATIONS FOR HYDROLOGICAL MODELLING AND IRRIGATION WATER MANAGEMENT

Nicola Paciolla - Supervisor: Prof. Chiara Corbari

Remote Sensing has known a consistent spread in use for agricultural purposes in recent years, although the relationship with in-situ correspondents and hydro-energetical modelling results is still being debated. Among the main variables in agricultural applications, Evapotranspiration (ET) plays a major role and its measuring complexity has prompted the development of numerous modelling formulations. This thesis work has focused on the improvement of hydrological modelling in agricultural applications, covering a wide variety of inter-connected themes, all linked to spatial heterogeneity and data source multiplicity.

Satellite Surface Soil Moisture (SSM) datasets have been analysed to determine their reliability in agricultural applications. A hydrological consistency algorithm has been developed, providing on average good consistency barely 60% of the time. The reason for these low values was explored, with generally-better performances during the irrigation season and with newer retrieval technologies. Extending the analysis to other satellite data, a high-density sensor network in a heterogeneous agricultural area has been used as a reference to determine the reliability of satellite observations, with surface temperature (LST) and Leaf Area Index showing good correspondences. SSM data, on the other hand, has shown weak feasibility for use in irrigation schemes. Thus, the optimal solution for improving irrigation and agricultural management would be a merging of on-ground information and satellite data.

Hydrological modelling is a robust way to improve, characterise and exploit the full potential of all input data and thus the second part of the thesis has focused on the FEST-EWB distributed energy-water balance model. Firstly, the model scale dependence has been investigated, with a multi-scale cross-analysis over a vineyard. Model accuracy with coarser data showed positive results, with a lower-than-one-third estimation error on ET, compared to roughly 10% errors from the aggregated model outputs. Another source of model uncertainty is the energetical heterogeneity in mixed soil-vegetation systems. A two-source version of FEST-EWB (FEST-2-EWB) has been developed to the purpose, separating the energy balances for the two components of any given pixel. The new model was tested over a dedicated innovative laboratory setting where it was possible to extract the Transpiration component from the total ET. Global performances were similar across both models, whereas Transpiration was portrayed quite closely by FEST-2-EWB, while FEST-EWB saw a consistent overestimation. A similar comparison was also performed in two open field cases, obtaining comparable results. Finally, the role of Aerodynamic Temperature in Sensible Heat formulation has been explored. A considerable dataset of EC measurements in a water-abundant and a quasi-arid location have been used to derive and compare it to LST. Notwithstanding temperature differences as high as 15-20°C, its integration into the model yielded only small gains in terms of Sensible and Latent Heat estimation.

PROBABILISTIC SUBSURFACE CHARACTERIZATION FOR INDUSTRIAL APPLICATIONS THROUGH DATA DRIVEN APPROACHES AND MACHINE LEARNING ALGORITHMS

Selene Eliana Patani - Supervisor: Prof. Alberto Guadagnini

Subsurface systems are characterized by complex phenomena and intrinsic uncertainty. Even if literature information and data collection are not abundant and simple to plan due to acquisition issues, they confirm the heterogeneity which distinguishes these systems.

In the last decades, several models have been developed to assist interpretation of the evolutionary processes associated to subsurface systems. These tools are extremely important for modelers since they can simulate the entire scenario domains and give a general view of spatial distributions of target variables. Despite of this, these models suffer from some limitations which do not allow to take full advantage of the entire potentialities that they may offer.

This work aims at overcoming the main constraints detected by sedimentology experts regarding industrial application modeling, i.e.: *(a)* the large number of input parameters and their values, which are affected by uncertainty, *(b)* the high computational cost associated to simulations, *(c)* the ill posed problems with respect to available information and *(d)* the difficulty to incorporate calibration data and to conduct quantitative comparisons.

We propose here to overcome these limitations with the implementation of a general framework considering uncertainty of model parameters/inputs to assist model calibration, the latter step being performed in a probabilistic context. Our procedure is applied to three systems involving different time and spatial scales: *(i)* sedimentary basins, which are large-scale bodies where sediments are transported and accumulated across geologic time scales; *(ii)* sediment gravity flows responsible for distributing vast amounts of clastic sediments through water currents and where lithified accumulations of these deposits may, in time, become hydrocarbon reservoirs; *(iii)* naturally fractured reservoirs which play a crucial role in energy supply and where open fractures govern hydrocarbon production and reservoir permeability.

Considering as starting point model simulations, our procedure is built on data-driven analysis in order to perform quantitative assessments and to take full advantage of available information. This is carried out through machine learning and statistical algorithms, which allow to incorporate calibration data and to perform stochastic inverse modeling to provide compatible sets of solutions.

For each system considered, we are able to provide an integrated tool which helps experts with model interpretation. As regard sedimentary basins, we maximize the information content of data by providing alternative stratigraphic reconstructions within a time period considerably shorter with respect to traditional approaches. Considering gravity flow events, we provide sets of volumetric fractions at selected locations compatible with respect to available information content, considering also interpreted data sources. Finally, we offer fracture aperture estimations quantifying the impact of data measurement errors and then comparing results against a traditional tool employed for interpretation of fracture apertures in naturally fractured reservoirs.

DYNAMIC SOIL EROSION MODELLING WITH FUTURE SCENARIOS OF CLIMATE CHANGE

Francesco Niccolò Polinelli - Supervisor: Prof. Marco Gianinetto

Soil erosion is a natural process caused by the erosive forces of rainfall or precipitation runoff, which causes soil detachment or removal of rock materials. It is addressed as one of the main hydrological risks in the European union, and the Alps are one of the most prone areas to soil erosion, in Europe. It causes nutrients loss and exposes the environment to landslides, with negative impacts on agriculture, ecosystem and infrastructures. Several human activities and climate change induce environmental modifications which intensify the pressure on soils and increase their predisposition to water erosion. Therefore, understending soil erosion spatial patterns and temporal trends could provide important information for supporting government land use policies and strategies to reduce this underestimated natural hazard.

In this work the potential soil erosion rate is estimated by the D-RUSLE model under climate change and land use/land cover change scenarios, in the Alpine section of the Oglio river basin in North Italy. D-RUSLE is a modified version of the well-known RUSLE model that aims at providing more accurate estimates of the potential soil erosion. The classic RUSLE was modified to include the shielding effect of snow on soil erosion, with the integration of a model that describes separately the behaviour of rainfall and snow and, moreover, the temporal evolution of the land cover and its spatial distribution were estimated with the integration of Earth Observation data. Climate projections are obtained trough statistical spatio-temporal downscaling of 9 simulations among those available from CMIP5 protocol. Projection of land use/land cover have been obtained through a neural network algorithm trained with past land cover maps. The results show that the integration of satellite-derived data in D-RUSLE allow a better representation of soil erosion forcings, thus providing a more accurate erosion estimation to support government land use policies and strategies. Furthermore the results show two possible scenarios at 2100: if mean annual precipitation is unvaried and temperature increases of about 1.5-2 °C, almost 47\% of the area would experience a reduction in the mean annual erosion rate and only the 18\% would see an increase; If precipitation increases of about 8\% and temperature raises of about 4 °C, then almost the 16\% of the territory could expect an erosion rate decreases while the 72\% will see an increase.

To conclude the scalability of the model was tested, implementing it in a different area, the Dudh Koshi basin, in Nepal. The lower availabilty of data forced the implementation of machine learning algorithms to better optimize the parameters of the D-RUSLE model and its coefficients, in order to obtain realaiable results. The model proved to be scalable in a different area and the machine learning algorithm proved to be a useful tool to optimize the model parameters and integrate geographical with statistical data.

STOCHASTIC MODELLING AND GIS-BASED STATISTICAL ANALYSIS TO ASSESS GROUNDWATER POLLUTION IN URBAN AREAS

Licia Camilla Pollicino - Supervisor: Prof. Luca Alberti - Co-Supervisors: Prof. Loris Colombo, Prof. Marco Masetti

The growth of urban areas and related industrial districts, which has occurred in many regions throughout the world at a slow but steady rate for thousands of years, continues to impose a strong pressure on groundwater quality. It is widely recognised that one of the most serious problems of groundwater contamination are associated with urban areas characterised by a long history of industrial activities. Among the myriad of contamination sources and pollutants potentially responsible for groundwater quality deterioration, chlorinated solvents contamination arising for point sources and multiple-point sources represents one of the most serious threats for urban groundwater quality. While point sources can be managed and controlled with the conventional remedial strategies, multiple-point sources are difficult to identify and can make entire aquifers unsafe for human consumption by simply increasing contaminant concentrations to levels just beyond drinking water quality standards.
In the last decades, the valuable role of aquifers beneath urbanised centres has attracted an increasing worldwide attention and considerable progresses have been made in the field of urban groundwater. Nevertheless, meeting the escalating private, municipal, and industrial demand for water supplies while guaranteeing safe water levels remains a formidable challenge.
Today, the development of innovative and robust scientifically based methodologies as support tools for public authorities is recognised as the key to cope with this environmental issue.
In this study, a GIS-based statistical technique, called Weights of Evidence (WofE), and a stochastic approach, known as Null-Space Monte Carlo (NSMC), have been applied to assess PCE contamination due to point and multiple-point sources within the densely urbanised NW and NE sectors of the Milan Functional Urban Area. The joint use of these two methods together with the implementation of a new stochastic approach to address diffuse pollution have been firstly tested in two synthetic case studies and then in a real-world context. This allowed to accurately assess both the advantages and limitations of these approaches.
The WofE technique was found to be effective in mapping the hydrogeological and land use conditions that promote the migration of the pollutant towards the aquifer and in mapping the areas that are more likely to be affected by contamination. Differently from the knowledge-driven methods of aquifer vulnerability assessment, this Bayesian technique led to statistically (i.e., objectively) define the role of specific factors in conditioning the occurrence of the contamination and, above all, to identify the range of values of each predictor factor that are directly correlated with the pollution. The WofE method offered the possibility of combining different satellite and ground-based information concerning land use and hydrogeological variables in a GIS environment, incorporating it into a unique end-product that can be easily interpreted even by non-expert decision-makers.
The NSMC stochastic approach highlighted that the inclusion of the uncertainty associated with parameter estimation can significantly enhance the predictive power of a numerical model. Differently from most previous works, in this study, this stochastic approach investigated the uncertainty of a transport parameter (i.e., the solute mass discharge field) to predict the potential location of the multiple-point sources responsible for diffuse contamination. As a first step, the performance of the proposed methodology has been successfully verified starting from a synthetic case study. Then, the robustness of the new stochastic approach has been further tested by assessing PCE widespread pollution in the NW sector of the Milan Functional Urban Area. The analysis on multiple random realisations of the mass discharge field coupled with of the k-means Cluster Analysis proved to be effective in discriminating the potential source zones.
Although the proposed NSMC stochastic method offered new insights to the problem of groundwater diffuse pollution, the application of the inverse approach to solute transport models was found to be particularly complex. The extremely high computational burden incurred in inverse problems applied to transport models together with the uncertainty associated with the release history (e.g., start time, continuity, and duration of each source) and the evolution of the pollutant (e.g., biodegradation and natural attenuation processes) constitute important limitations to both the applicability of this approach over large areas and to its reliability.
In addressing the problem of urban aquifers pollution, the final predictive outputs derived from both the WofE and the NSMC stochastic approach can be used by decision-makers and public authorities as an advanced support tool to:

- gain key information on the potential source zones as well as on the hydrogeological and land use conditions that increase the probability of groundwater contamination;
- better discriminate and manage the areas that urgently require to be prioritised in terms of environmental monitoring to prevent any additional contamination of groundwater resources and avoid the further deterioration of the ones that are already contaminated;
- develop more adequate and rigorous policies and plan effective actions towards the containment and mitigation of the groundwater contamination problem in densely urbanised areas.

EFFECTS OF THE USE OF INNOVATIVE FUELS AND BIOFUELS ON THE REDUCTION OF AIR POLLUTION AND THE CLIMATE CHANGE

Stefano Puricelli - Supervisor: Prof. Mario Grosso - Co-supervisors: Prof. Maarten Messagie, Prof. Simone Casadei

The transport sector was responsible for more than 25% of the EU total greenhouse gas (GHG) emissions in 2017. 53% of these emissions came from the passenger cars and light-commercial vehicles segments. Biofuels, electric vehicles, and e-fuels are seen as the most promising options to limit these emissions in Europe. This thesis analysed the potential environmental impacts of using different blends of petrol and renewable components in comparison with a battery electric vehicle, for an average C-segment car. First of all, in order to understand the recent evolution of biofuels and their future perspective, a literature review was carried out on their production, use, legislation, and environmental impacts, for light-duty vehicles in Europe. In 2017, biofuels made up 4.5% of the energy consumption in the road transport and non-road mobile machinery. Biodiesel in 2018 accounted for 62% of the biofuels consumed in the EU, followed by bioethanol (17.5%), HVO (16.6%), upgraded biogas (1.7%), and bio-ETBE (1.1%). A review of 86 Life Cycle Assessments (LCA) published between 2013 and 2020 indicated that the climate change impact of biofuels is generally lower than that of diesel and petrol, with average emission savings depending on the type of biofuel: 70% for biohydrogen, 63% for upgraded biogas, 41% for biodiesel, between 54% and 7% for bioethanol (depending on the blend percentage, between 100% and 10%). An important issue identified is the limited consideration of the land use change (LUC) effects, which are seldom assessed and are of paramount importance. When it comes to non-GHG-related impact categories, in general biofuels perform similarly or worse than fossil fuels for most of them, except for ozone depletion, fossil resource and abiotic depletion. As a general indication, it is highly recommended to move towards biofuels generated from non-edible feedstocks, waste and by-products, which guarantee a lower risk of LUC.

The experimental part of the research consisted in testing a Euro 6d-TEMP GDI passenger car with four different fuels (Fuel A, B, C, and D) both in the laboratory and on the road. Bionaphtha, methanol, bioethanol, and bio-ETBE (ethyl tert-butyl ether) were selected as the most promising products to be blended with petrol, in order to reduce its carbon footprint. The exhaust emissions of Fuel B, C, and D were compared with those released using Fuel A, a reference commercial petrol containing a typical level of bio-ETBE (3.6%). Fuel B contained 8.1% bioethanol and 7.0% bionaphtha. Fuel C contained a high level of ether (21.8% of bio-ETBE). Fuel D contained a non-negligible level of alcohols (2.7% methanol and 4.8% bioethanol). The measurements included both regulated and non-regulated pollutants, as well as GHGs. All exhaust emissions of the tested fuels were compliant with Euro 6 standard (for WLTP, Worldwide harmonised Light vehicles Test Procedure) and with Not-To-Exceed limits (for RDE, Real Driving Emissions). Compared with the reference Fuel A in WLTP tests, Fuel B showed a statistically significant reduction in volumetric fuel consumption (-3.4% v/v), energy consumption (-6.4%), and CO_2 emissions (-6.9% m/m). Fuel C caused a decrease in energy consumption, CO emissions, and NO_2 emissions (-1.0%, -22.3% m/m, and -2.9% m/m, respectively), and an increase in NOx emissions (+50.7% m/m) and fuel consumption (+1.6% v/v). Finally, Fuel D showed a significant increase in NOx emissions (+48.1% m/m). The emission of total aldehydes, only measured and detectable during cold conditions of the WLTP cycle, remained in a low range of values (1.5-2.5 mg/km). Based on the performed tests, none of the fuels clearly showed any criticality as a whole for tailpipe emissions. With respect to the laboratory tests, the RDE runs (on-the-road tests) resulted in higher NOx and CO_2 emissions and fuel consumption for all fuels, while CO, THC, CH_4, and PN (Particles Number) emissions were lower. The percentage changes observed between laboratory and road tests were different, due to the different methodology and the intrinsic non-repeatability of the latter. Moreover, it was demonstrated how the emission factors resulting from the processing of raw measurements through a regulation-compliant software can significantly differ from those directly based on raw measurements.

Finally, an LCA study was performed to evaluate the environmental impacts of using the C-segment GDI Euro 6d-TEMP passenger car fed with the previously tested blends. The use of the internal combustion engine vehicle (ICEV) was also compared with the use of a C-segment battery electric vehicle (BEV). The system boundary included the production, use, maintenance, and end-of-life of the cars. The functional unit was defined as "driving 1 km in Europe with a C-segment car that fulfils the Euro 6d-TEMP standard". Several energy carriers were assessed: petrol, ETBE from isobutylene, bio-ETBE (from corn, sugar beet, wheat, and wheat straw), bionaphtha (from 80% palm oil and 20% used cooking oils), bioethanol (from corn, sugar beet, wheat, and wheat straw), methanol, biomethanol (from sewage sludge, manure, municipal organic waste, corn, and willow chips), e-methanol, and electricity. According to the methodology used in this study, all the evaluated biofuels achieved the minimum 50% threshold for "Well-To-Wheels" GHG emissions saving set by Directive 2018/2001, except bioethanol from corn and wheat and biomethanol from corn. For this reason, these three types of biofuel and the related bio-ETBEs were excluded from the later analysed blends and not included in the complete cradle-to-grave results. All the blends potentially guarantee a slight reduction in the impact on climate change. The cradle-to-grave GHG emission savings compared with the fossil reference ranged from 0.8 to 10.1%. The use of a car specifically designed to be fuelled by a blend containing higher percentage of renewable fuels would probably lower the impact. Fuel B (containing bionaphtha and ethanol) resulted the most promising blend. Bionaphtha contributed to the high GHG savings of Fuel B, thanks to its high biogenic carbon content (84.0% m/m) compared with those of bioethanol (52.2% m/m), biomethanol (37.5% m/m), and bio-ETBE (24.5% m/m). However, if an estimation of the LUC effects is included in the calculation, the use of palm oil for the production of bionaphtha nullifies the emissions savings. The shift to advanced feedstocks or the use of palm oil certified at low-indirect-LUC risk are the recommended ways to minimise the LUC. The BEV was found to release less cradle-to-grave GHG emissions compared with the ICEV (-40.8% with respect to the fossil reference Fuel A). Recharging with the cleanest electricity mix currently available in Europe, i.e., the one of Norway, allows for a further decrease down to -70%, while even with the dirtiest (Estonia) the impact of BEV does not exceed the one of the reference fossil fuel (-5%). Although the ICEV fuelled by the analysed fuel blends and the BEV potentially guarantee a reduction of the impact on climate change and fossil resources, for the other 14 impact categories the picture is mixed. All the options increase marine eutrophication, terrestrial eutrophication, and land use impacts. Fuel B, C, and D can assure a diminution of impact in ozone depletion, and ionising radiation, while the BEV just in ozone depletion. All the assessed fuels increased the impacts in particulate matter, freshwater ecotoxicity, and use of minerals and metals, while the BEV reduced these impacts. For the remaining impact categories, the picture was less straightforward.

COMPOUND WEATHER AND CLIMATE EVENTS: DEPENDENCE AND CAUSALITY ISSUES

Leila Rahimi - Supervisor: Prof. Carlo de Michele

Composition of multiple climate drivers or/and hazards characterizes compound weather and climate events. Understanding this kind of events needs to analyze the complex causal chain, which could cause extreme impacts. Estimation of the dependence between characteristics/drivers (random variables) of these kind of events, is in its infant step and of significant importance in the field of hydrology, meteorology and risk assessment. To do this estimation, the combination of multiple climate drivers have to be considered, because the composition of them could push an event to extreme levels by a factor of up to some points, compared with variables being independent. Specially spatial and temporal dependencies as main classes of dependencies are respectively considered to estimate the dependencies of random variables at the same time, and inter-temporal situation. In addition, complex interacted physical processes, cause weather/climate related extreme events in multiple temporal and spatial scales. When drivers combine the impacts of events intensify, especially when they occur in succession / simultaneous (such as drought and heat wave, heavy rainfall and saturated soils or global or regional synchronized floods or heatwaves). Local and short timescales of compound events are felt in different spatial and temporal scales, in addition climate change and local-scale changes are significant issues to how deal with and model non-stationarity of compound events. To model and analyze compound events, understanding the components of compound events is an essential critical issue. Compound events may have modulators, drivers, hazards and impacts. Hazards do not need to be extreme in statistical senses to make an extreme impact. Generally, compound events are distinguished in four classes: 1) Preconditioned, 2) Multivariate, 3) Spatially Compounding and 4) Temporally Compounding, but it is not always easy to identify a strict bound to fit a compound event in a specific class. Separation of each type of compound events is a challenging issue.

In this study for each class of compound events a case study research has been done to detect and analyze multiple drivers. To consider a "Preconditioned Events", the effect of the rainfall intensity on the unsaturated (pre-existing condition) 3D corner slope under historical (1961-2005) and future (2006 and 2100) conditions (under climate change) has been investigated. To do this investigation two types of soil (clayey and sandy) have been considered. Rainfall caused an increment of pore water pressure _u in the unsaturated corner slope which led to a considerable reduction in the soil suction and the safety factor. By increasing the daily rainfall intensity, the slopes with high friction angle and low cohesion are more at risk, especially after increasing rainfall intensity under climate change, and safety factor of slopes reduced remarkable. This work is very useful to manage the infrastructure in downstream of slopes, also when climate change also in view.

In the "Multivariate class of compound events", the statistical dependence between flood peak Q, flood volume V and flood duration D has been investigated using a worldwide database of daily discharge. Results of this chapter shed light on the compound nature of flood events rainfall-driven, where the dependence between flood event characteristics (Q, V, D) emerges as a consequence of the relation of such characteristics to the rainfall input variables (I, W) that control the hydrographs. In addition, this result puts light also on the multivariate modeling of flood event characteristics (Q, V, D) stating that there is not a causal priority among these variables to be used in conditional analysis and modeling. From the modeling activity, on the U.S. sub-dataset, we obtained that the conceptual hydrological model is able to represent the observed dependencies between each couple of variables for rainfall-driven flood events, and for such events, the pairwise dependence of each couple is not causal, is of spurious kind, coming from the "Principle of Common Cause".

The third class of compound events, Spatially Compounding has been highlighted in United Kingdom (UK) catchments to extract the "Causes of dependence between extreme floods". The similarity of catchment characteristics and also climatology information help to deal with synchronization in specific time window between stations. We considered the co-occurrence of annual maxima, and then in a more general framework, introduced three dissimilarity indices: asynchrony index, climatological and hydrological dis-similarity indices. Asynchrony index represents the synchronized flood events that can be the result of meteorological reasons (heavy rain) or to hydrological reasons (snow melting). We considered the climatological dissimilarity index which accounts for the annual precipitation, and the hydrological index which takes in one several information about catchments characteristics. As well as these indices we considered also the distances of couple stations to the assessment of conditional statistical dependencies. These three indices are interrelated and have less dissimilarity for the near couples, and dependent-dissimilarity maps could help to more explanation of the dependence and independence between couples. This work could be done between different kind of climate regions for flood alerting. Finally for the last class of compound events, Temporal Compounding, sequences of different types of meteorological and hydrological droughts in snow-influenced catchments have been addressed. Three variables such as "Precipitation" (sum of Rainfall and Snowfall), "Rainfall", and "Runoff" (Snow melting as well as Rainfall-Runoff, estimated by HyS model in monthly scale to detect multi-temporal compound drought events from 1950-2015, have been considered. Detecting snow drought using SPI and SRI in preceding winter could make an alarm for SMI index in spring or summer. Using different indices as a complementary index of SPI, help to better deal with drought risk. It is notable that the distinction among the different types of compound classes is not easy. In this study I tried to make an effort in making clear this distinction.

A MODELLING FRAMEWORK FOR SLURRY EROSION PREDICTION THROUGH COMPUTATIONAL FLUID DYNAMICS SIMULATIONS

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Solid particle erosion is the physical process of material removal from a target surface caused by the mechanical interaction, typically in the form of collisions, with solid particles transported by a fluid. The term "slurry erosion" is often used when the carrier medium is a liquid, and this is definitely a serious concern in several applications involving pipeline system and hydraulic devices, as it is the cause of high economic costs due to performance deterioration and even sometimes, structural failure. Though extensive investigations on solid particle erosion in the past decades allow much better understandings on material removal mechanisms, it is still a challenge to provide a priori estimates of the wear resistance of plants and devices working in a slurry environment, which is essential for optimized design and scheduled maintenance. Laboratory testing of prototypes in studying slurry erosion comes with issues in terms of high economic costs, technical difficulties for accurate measurements, and scale-up of the laboratory data. Thanks to the advances in computational power, a rapid development in slurry erosion studies based on computer simulations has been witnessed in recent years. However, also this approach is not free from challenges, owing to the multi-physics and multi-scale nature of the slurry erosion process.

In a well-established methodology for the numerical simulation of slurry erosion, the transport of the solids is modelled using Computational Fluid Dynamics (CFD) models on the basis of the Eulerian-Lagrangian (EL) approach, and then erosion predictions can be made from converting the computed particles impact characteristics to the estimates of material removal. Several sources of uncertainty come into play in the simulation framework, reducing the confidence in erosive wear estimation. Probably, the most critical issue is the evaluation of material removal from the output of the EL model, which is the core of this thesis. Goal of this doctoral work is to improve the capability of CFD-based numerical simulation, which serves as a tool to produce quantitative prediction of slurry erosion. Particularly, efforts have been taken in addressing the three above mentioned sources of uncertainty (erosion model, particle size effects and particle shape effects), as well as developing a new modelling framework which improves the state-of-the-art. Workflow and main findings are as follows.

Erosion modelling approach
A CFD-experimental combined methodology has been recently proposed, which resides in the calibration of a case-specific erosion model by combining the eroded depth surface profile measured in a slurry erosion test (typically a wet direct impact test, W-DIT), with the particle impact characteristics, obtained from the simulation of the particle-laden flow in the same testing conditions. The goal of this method, here called SAER (abbreviation of the Surface Profile Aided ERosion prediction) approach, is to get an empirical erosion model which is case-specific for the conditions of the calibration tests and, thus, is suitable for slurry erosion predictions.

In this thesis, a methodology based on the SAER approach has been developed, improving a previous formulation by Mansouri (Wear 332-333, 2015). Initially, the prediction capability and accuracy of Mansouri's formulation was tested against widely used empirical erosion prediction correlations obtained from D-DITs, referring to several W-DIT results of in-house experimental tests and data from literature. It has been demonstrated that the SAER approach allowed for more accurate predictions compared to using existing empirical correlations, and that there was a scope for further improvement of Mansour's formulation.

Particle size effect
The effect of particle size can be identified in both steps of CFD-based slurry erosion prediction. On the one hand, the motion of particles is sensitive to particle size. For instance, large particles are more influenced by inertia, thus, in the W-DIT, they tend to deviate from the streamlines when approaching to the target material surface than small particles. Whereas drag will play a more important role in deciding the motion of small particles than inertia. This results in the change of the particle impact characteristics between large and small particles and, therefore, of the typical erosion pattern. On the other hand, the material removal associated to particles impingements is directly related to particle size, as a larger particle would produce more damage per unit particle mass compared to a smaller particle.

Two modelling improvements have been made for a more accurate treatment of finite particle size within the SAER framework. The first one is the consideration of particle finite-size at the stage of impact, that means, the particle impact characteristics are evaluated at a distance from the wall equal to half of its size, and this is also the position used to calculate the particle trajectory after rebound. Such approach represents an improvement over the traditional method that treats particle as a zero-volume, point source of momentum even at the stage of particle-wall collision. This finite-size treatment was integrated through UDF in Ansys Fluent for particle tracking, and it has been demonstrated that the particle impact characteristics were more physically calculated and, much more importantly, they were almost insensitive to the near-wall grid resolution. The second one is the introduction in the regression model of an empirical coefficient related with particle size, which takes the direct effect of particle size on material removal into account. The inclusion of treatments on particle size further increased the prediction capability of the SAER approach compared to the original formulation of Mansouri, as demonstrated by referring to in-house slurry jet impingement experiments, in which spherical glass beads were used as erodent.

Particle shape effect
Particle shape, as another important source of uncertainty, was also accounted for in an improved formulation of the SAER framework. The starting point is that, in describing the particle shape, two parameters come into play. The former is the particle shape factor (Ø), which quantifies the effect of particle shape on its motion in the particle-laden flow simulation. The latter is the particle shape coefficient (F_s) which, in the SAER regression model of Mansouri (*Wear*, 332-333, 2015) quantifies the direct effect of particle shape on material removal. It was argued that, since Ø and F_s are associated to the same physical feature of the particles, that is, their shape, they should not be treated as independent. Thus, it was decided to remove the explicit appearance of F_s in the SAER regression model. For natural sand particles, the shape of particles may be different for each individual particle and are very challenging or even impossible to accurately quantify. Thus, it was proposed to treat Ø as a calibration parameter in the SAER approach to determine the most appropriate value among those generically recommended in the literature (for instance, 0.66/0.76/0.86 for sand particles with sharp/semi-round/round shape). The consistency between particle impact characteristics from CFD simulations, which are affected by particle shape, and the eroded depth surface profile from experimental test, quantified by the accuracy of calibration and prediction capability from the calibrated function, was the criterion proposed to identify the most appropriate value of Ø).

In summary, a methodological approach based on SAER has been proposed for CFD-based numerical slurry erosion prediction. The results from several case studies referring to both in-house and published slurry impingement jet experiments demonstrate the improved prediction capability and reduced numerical uncertainty in slurry erosion calculation brought using this modelling framework.