Chair:
Prof. Alberto Guadagnini

DOCTORAL PROGRAM IN ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING

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 five key thematic areas.

1. *Hydraulic Engineering*, where major research themes include: fluid mechanics; fluid-structure interactions; hydraulic measurements; 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.
2. *Hydrology, hydraulic structures, water resources and coastal engineering*, where the main research topics include: hydrology and water resources, with emphasis on the main physical processes of the hydrological cycle, water and energy budgets; hydrogeological hazard and mitigation strategies, including hydrological extremes, floods, droughts and precipitation, early warning operative systems, snow avalanching and flood risk; hydraulic networks engineering; and coastal engineering.
3. *Environmental technologies*, with focus on: water supply technology and treatment, (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 and sludge management; phenomenology of the atmospheric environment and treatment of gaseous emissions; contaminated soils and their remediation.
4. *Transport infrastructures and geology*, with focus on: transport networks, including functional interactions with regional, national and international territory; sustainable development, in terms of dynamics of development and its relations with the infrastructure system; technological innovation, including methods and indicators for performance characterization of infrastructure construction and maintenance techniques; hydrogeological risk, landslide hazard; water resources identification and management, pollution problems.

5. *Geomatics*, with focus on: physical geodesy and satellite geodesy; positioning and navigation; surface surveying with optical or other sensors, such as SAR, LIDAR; digital photogrammetry and image analysis; remote sensing; geographic information systems; cultural heritage reconstruction and archiving.

The curriculum of PhD students has been tailored to the general and specific research questions associated with the multifaceted interactions between the water sphere and the key evolving anthropogenic activities responding to the needs of modern society.

Typical 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.

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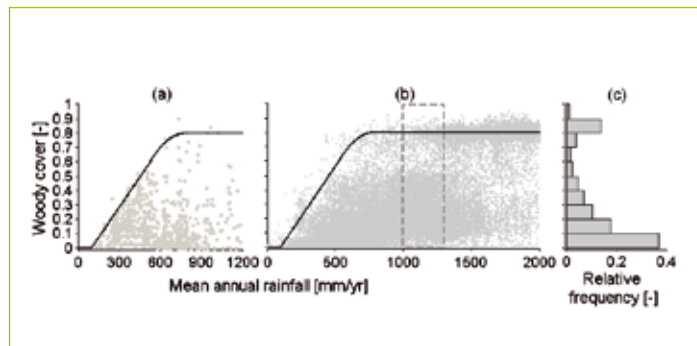| ADVISORY BOARD	
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DYNAMICS OF TROPICAL AND SUBTROPICAL VEGETATION: FROM AN EQUILIBRIUM TO A NON-EQUILIBRIUM MODELLING APPROACH

Francesco Accatino - Supervisor: **Carlo De Michele**

ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING

Tropical vegetation systems exhibit complex dynamics, characterized by transitions between different biomes (grasslands, savannas, or forests) under the influence of a number of factors (such as climate, fire, and herbivory). Many of these systems are rangelands, managed agroecosystems with prescribed fire and grazing/browsing pressure, and give an important contribution to world's meat production, sustaining millions of people. Understanding the dynamics of these ecosystems and the roles of the different determinants is fundamental for predicting the effects of climate change scenarios and for planning sustainable management strategies.

From the analysis of dataset collected on continental (Fig. 1a) or global scale with MODIS observations (Fig. 1b), two main issues emerge. The first issue is that there exists a mean annual cover threshold (650 ± 134 mm/yr) separating two main behaviors of woody vegetation. Below the threshold the maximum woody cover allowed by climate conditions increases linearly with mean annual rainfall. Biomes where trees and grass coexist are allowed because tree cover is limited by climate conditions. Above the threshold, the maximum woody

1. Data of mean annual rainfall vs woody cover coming from field measurements in the African continent (a) and MODIS observations in the tropical and subtropical areas (b) The histogram in panel (c) represents the relative frequency distribution of the woody cover in the rectangle of panel (b)

cover saturates at about 80% (forest) and is not dependent on mean annual rainfall. Biomes like savanna or grasslands can still be found because fires lower tree cover. The second issue is that above the threshold the woody cover is bimodal (see the histogram in Fig. 1c made from with the data in the dashed rectangle of Fig. 1b). This was considered as a proof that there are two alternative stable states in tropical and subtropical vegetation, one with low woody cover (savanna) and one for high woody cover (forest).

I compare two space-implicit approaches for modelling tropical vegetation dynamics, the *equilibrium* and the *non-equilibrium* approach. According to the *equilibrium* approach, vegetation reaches a stable

steady state, whereas according to the *non-equilibrium* approach, vegetation is continuously changing in response of disturbances such as fires and herbivory. I build two models, one for each approach, and I apply them, or slightly modified versions, to different problems, highlighting the different implications, and ultimately demonstrating that the *non-equilibrium* model can give a more complete and general description of tropical vegetation dynamics.

The *equilibrium* model describes vegetation dynamics through a deterministic differential equation system. Fire is a parameter of the system, in line with other deterministic differential equation models in literature. The bifurcation

analysis shows that for low fire frequency savanna can be obtained at low rainfall values because water scarcity limits tree cover, for high fire frequency savanna can be obtained also at high rainfall values, but they are an alternative stable state to forests. This implies that a change in mean annual rainfall, grazing or browsing pressure can provoke abrupt (catastrophic) savanna – forest transitions.

The *non-equilibrium* model is time-discrete, in each time step it may follow different dynamics depending on whether a fire occurs or not. Each year, the probability of fire depends on the state of the system, i.e., the more grass is in the ecosystem, the more the ecosystem is likely to burn, as grass provides fuel load. Overall, the model is a random switch between two different dynamics, each of them characterized by a stable steady state. Nevertheless the global dynamics are non-equilibrial, as in general the system does not stay in a steady state permanently. According to this model, fire is an emergent property rather than an *a priori* determined parameter. Using the model with measured parameters referred to different *Acacia* species in presence or in absence of browsers, it is possible to demonstrate that the presence of browsers could

increase fire frequency as a consequence of lowered tree cover. The global *non-equilibrium* trajectories, for certain parameter combination, show the same bimodality showed by data (Fig. 1c). Nevertheless, the implications of bistability are profoundly different from the *equilibrium* paradigm. The system can visit both steady states not because of catastrophic transitions provoked by changes in parameters, rather for its own dynamics. This view does not imply that woody cover data (Fig.1) are necessarily at the steady state, they rather represent snapshots of a variable system, which is a less strict and more realistic hypothesis.

Equilibrium and *non-equilibrium* paradigms have implication also on rangeland management. According to the *equilibrium* paradigm, the rancher needs to bring the system to a favorable steady state. Under a *non-equilibrium* paradigm, it is acknowledged that a steady state may not exist, and, if it exists, the rancher may be interested in maintaining the system within certain boundaries, not necessarily including the steady state. With a modified version of the *non-equilibrium* model I apply the viability theory to define the sustainable management strategies, defining for each

state of the system robustness against rainfall stochasticity and management adaptability. The results show that the states where management is more adaptable have intermediate values of trees and grasses, as long as the rancher's herd can adjust its feeding behavior along a wide range of grazing/browsing ratio (mixed herd).

Finally I build a spatially explicit version of the *non-equilibrium* model. In this model trees are represented as individuals and they modify the density of grass around themselves (facilitation or hampering). The spreading of fire in the spatial domain is simulated for each time step, and the number and spatial patterns of trees are observed. The model is run with different there different types of trees classified according to their strategy to cope with fire. The main conclusion is that space plays an important role in tropical and subtropical vegetation dynamics. In fact even the most vulnerable trees can deplete fire from the ecosystem with spatial strategies such as clumping.

EXPERIMENTAL INVESTIGATION ON MECHANICAL, VOLUMETRIC AND FUNCTIONAL PROPERTIES OF PERVIOUS CONCRETE: MIX DESIGN OPTIMIZATION FOR ROAD PAVEMENTS

Alessandra Bonicelli - Supervisors: **Filippo Giustozzi**

ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING

Pervious concrete aims at being a sustainable and eco-efficient paving material. A lot of studies have indeed been conducted on pervious concrete pavements (PCP) during the last decade but technical standards and rigorous construction specifications are still missing. Pervious concrete consists of coarse aggregate in a gap-graded size distribution curve, cement, water, and eventually admixtures. The limited presence of fine aggregate creates a particular structure of interconnected voids that allows water to percolate within the concrete matrix. Void content typically ranges between 15 % and 35 % of the concrete total volume depending upon the strength and permeability requirements of each particular application. The high void content guarantees the notable drainability features. A viscous cement paste (cement, water, and admixtures) is then used to prevent segregation and to bond the aggregates; water/cement ratio usually ranges between 0.2-0.4, while cement/aggregate ratio is usually 0.18-0.23. As pointed out by various studies compaction represents a crucial point to be assessed in laboratory as well as in situ to achieve both strength and drainability features in the final product. Preparing samples, or constructing a full scale pervious concrete pavements,

using different compaction methods and energies results in a widespread range of void content-drainability, and resistance properties. In addition, lab compaction needs to be calibrated according to real in situ construction conditions to foresee future mechanical performance and durability. To date, several compaction methods are reported to be used on site depending on countries' best practices. As a consequence, a significant inconsistency is commonly observed within results gathered in the laboratory according to the standard compaction methods (mainly Marshall and gyratory compaction). Too much compaction effort closes up the mix, thus resulting in poor drainability but generally high resistance, and vice versa. Proper compaction has been proven to be essential for increasing the strength and durability of the pavement but timing of compaction, weight of the rollers, and number of passes can vary among different applications and thus have to be correctly assessed. Moreover, finding out an accurate correlation between in situ and lab compaction is essential to provide useful information to contractors and therefore obtain comparable results. The present study investigated on the effects of compaction energy

on functional and mechanical properties of pervious concrete mixes characterized by different water contents. In this phase fourteen different mixtures were tested. Variations in w/c ratio, paste content and three compaction energies were applied for the specimen preparation. Fixed average values of the most common admixtures were also used. ITS and total void content were evaluated after 7 days of curing. In addition the Elastic Modulus was calculated. In the second phase of this study, three mixes were deepr investigated in order to define the compaction level able to balance between resistance and drainability capabilities in order to adopt PCP mixes on mid-high volume roads while preserving the primary feature of the material, drainability. ITS, void content, density, stiffness and drainability capacity were also evaluated. It has been also demonstrated that adding a small amount of fibers to pervious concrete mixes leads to enhancements in strength, freeze-thaw resistance, and porosity. In this study, five types of fibers were selected for a specific aggregate gradation while varying the compaction energy and modifying the mixture characteristics (water/cement ratio). After defining the characteristics of the mix components (aggregate testing,

paste evaluation, and content optimization of admixtures), pervious concrete specimens were prepared in the laboratory. The analysis was initially focused on three base-mixtures, which were characterized by three different mix proportions (water/cement ratio) without including reinforcing fibers. Since it does not exist a unique laying and compaction procedure for in situ applications, compaction energy was introduced as a further variable to be considered in the study. In particular, four levels of compaction energy were applied to specimens. For each one of the base-mixtures five types of fibers were tested in order to measure the mechanical characteristics (strength and stiffness and Cantabro abrasion resistance) the functional properties (drainability and superficial friction) and the volumetric characteristics (density and effective void content) of the mix. The main goal was to find a compromise between the strength of the material, which would be adequate to support medium-to-high traffic loading, and its ability to let the water percolate through the pavement structure and reach the soil beneath. Last part of lab analysis, in order to find out a way to increase the mechanical properties of the material was to test some amount of fine

sand in substitution to two different portions of aggregates. A sand, characterized by finess modulus of 2.9 was added to three base mixes in the proportion of 5% and 10% of the total aggregate weight. Indirect Tensile Strength (ITS), stiffness modulus, Cantabro index, BPN, void content, density and permeability coefficient of pervious concrete specimens were evaluated. Another aspect of this work was the simulation and modeling of pervious concrete pavement structures. Several pavement structures were modeled applying the multielastic theory, in order to indentify stresses and strains within the pavement layers. Materials properties were also modified during the modeling phase; in particular, the Elastic Modulus value was set according to the results obtained in the lab in order to simulate different stiffness, Poisson's ratio was instead kept constant for all the simulations. Three pavement structures, characterized by a pervious layer and an unbound granular foundation layer were modeled. In addition, two pavement structures characterized by having a cement bound foundation layer were also evaluated.
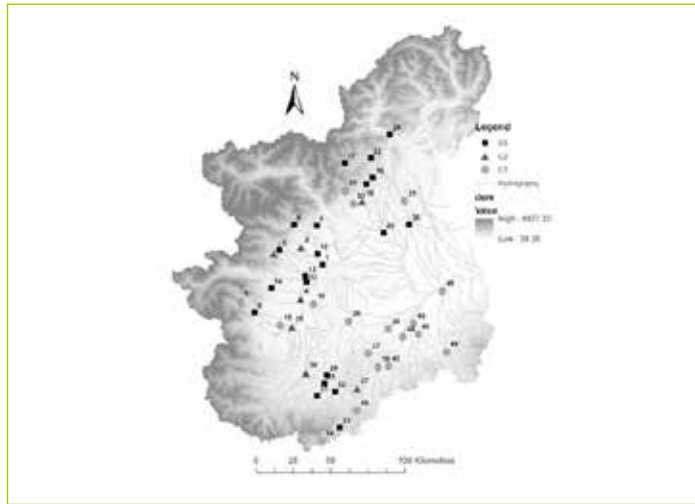
INSIGHT INTO HYDROLOGIC SYSTEM COMPLEXITY THROUGH CATCHMENTCLASSIFICATION FRAMEWORK

Laura Anna Boscarello - Supervisor: **Giovanni Ravazzani**

ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING

The need for simplification in hydrological modelling is present in the literature since some time ago and has lead in the last years to the development of catchment classification studies, with the objective of identifying similarities between catchments as a basis to transfer information and improve knowledge of hydrologic systems.

In my research activity, I analysed 46 basins of the Upper Po territory, Figure 1, by calculating a lot of characteristics indices; these basins have been classified from two different point of view: from one hand, for each catchment six hydrological signatures (runoff coefficient, baseflow index, streamflow elasticity, median flow, ten percentile flow and slope of the flow duration curve) has been calculated, so that we can have a description of the hydrological behaviour of the catchments; from the other hand, all the basins have been classified also with fifteen climatic, physiographic, and soil usage-type characteristics. The main question is: how long the second classification scheme is useful to identify group of hydrologically similar catchments and so convenient to characterize also ungauged basins?

The methodology used for classification purpose is the cluster analysis, in particular a

1. Map showing the location of the 46 catchments, subdivided in the three hydrological classes, C1, C2, and C3. For each station: hourly discharge, temperature, precipitation and radiation data were available from 2000 to 2009.

two level approach has been used: first clustering with Self Organizing Maps, that is a type of artificial neural network and unsupervised learning algorithm, and then with hierarchical clustering method that allows to build a clustering tree, dendrogram, useful to interpret data structure and to determine the number of cluster. The number of cluster identified in this case is three. The results obtained from the two different classification scheme were compared through a contingency table and the degree of overlap was 68.5%, this means that in 68.5% cases the second classification

well explains the results of the hydrological one. This work would not be a propose for a universal classification system, but tries to discover the potential of catchment classification method in a relatively restricted area, in order also to improve knowledge about the possibility of extrapolation of information up – or downstream along a river network, useful for distributed hydrological models calibration.

Starting from the results gained at this point, my research activity focused on some applications that use operatively classification results: improve estimation of regionalization models for

flow duration curves, analyse different formulation for the computation of concentration time, improve and make efficient the calibration process of a distributed hydrological model. The first application examines the estimation of regional model for flow duration curves, FDC; FDC's were estimated using log-normal distribution. The two parameters describing the distribution were estimated through stepwise multiple linear regression. The estimation of parametersdone bytaking advantage of classification, so by building a different regionalization model for each hydrological class, allowed to improve considerably the results in term of estimation of flow duration curves.

Concerning the estimation of time of concentration, sixteen equations present in literature and widely used in Italy and in USA, were compared with the observed time of concentration, computed from the data. In this case, the subdivision in hydrologically similar catchments doesn't improve the estimate of time of concentration, but the main conclusion remains that time of concentration is a an extremely variable and difficult to evaluate parameter. Furthermore, a new equation to estimate time of concentration, was implemented using stepwise multiple linear regression and

fitted on the observed data. The advantage of this equation is that produces good results and all the parameters are easily obtainable from a DTM.

The last investigated point concern the distributed hydrological model. To calibrate a distributed model, several are the steps to do before reaching good results. First of all, after doing an accurate sensitivity analysis of the model, is crucial to define a rigorous parameterization process, so to reduce over-parameterization: we proceeded by assigning specific values to all parameters, obtained from soil usage and attributable to a physical range of variation. Each cell of the basin has its own value, but the process of calibration is implemented so that each parameter is corrected by an equal multiplicative correction factor, so to reduce substantially the numbers of parameters to be calibrated. The calibration was done with a trial and error approach. Two different components of the hydrological models were calibrated: the snow model, calibrated by using MODIS images and the soil processes, calibrated by comparison of observed and simulated discharge. In the analysed data set, there are several nested basins; in this case the classification scheme retrieved

before can help the user in the calibration process, because it was verified that if basins are nested, so geographically close and member of the same class, then using only one series of streamflow to calibrate the model allows to obtain good results in all basins considered; on the contrary, it was verified that if basins are nested, but member of different classes, then it is fundamental using all the streamflow series available to obtain good results.This approach proved to be useful in finding information about the differences or similarity present in nested, spatially close, catchments and the need of taking or not into account more information than the only ones about the biggest catchment, especially for distributed hydrological models calibration.

INTEGRATED MONITORING SYSTEM AND LOW COST INSTRUMENT

Valentina Buttolo - Supervisors: **Francesco Guerra**

Integrated monitoring system are used to verify the evolution of deformations in both existing and new structures. The value of deformations are usually compared to a threshold of concern and to a threshold of alarm, after which project activities to limit and contain strains must be initiated.
The first part of the thesis deals with the integrated monitoring of an under construction structure, an ungrounded park in Mestre. "Integrated" is here to be intended as the coexistence of different types of survey techniques and methods that complete and integrate each other in order to validate the data obtained in different ways. The second part of the thesis illustrates the development of a new instrument system that can be used alongside some tools and methodologies adopted in the integrated monitoring system. Given the size of the excavation to be done, it was necessary to define a plan for monitoring the possible deformations on two tall buildings facing north and south of the project area, as well as on the structure itself. The data, obtained from different independent measurement systems, have been used to control one the others. Through the structural analysis, significant points to be monitored were identified, both

on the two buildings and on the structure itself. It was also taken into account the possibility of a real-time control on the measurement system and on some parameters to perform changes if necessary.
The system allows the monitoring of the structural efficiency in the construction phase and even during the life of the structure. The performed controls are geodetic and topographic controls of the new and old buildings, the acquisition of the stress/strain tensors, inclinometers on some part of the structure and piezometers within and outside the excavations. The thesis deals in particular with the classical topographic measurements and automatic measurements with inclinometers.
The topographic techniques adopted are geometric leveling of high precisions and the survey of some significant points on the structure and on the buildings. The former allows the determination of any vertical displacement on the two tall buildings. Most of the points showed a negative trend, in particular during the excavation of the unground part of the parking, then they almost return to the initial value, after the critical phase of the excavation. The points surveyed during the construction were placed both on the buildings and on the

structure itself. The points on the buildings were determinate using the method of intersection from two points inside the building site. All the topographic surveys were carried out with a total station Leica TCA 2003. With the three dimensional coordinates of the points, the distance between corresponding target were calculated, and this value have been compared in different subsequent acquisitions that occurred before and after the excavations. The difference on the calculated distances are between 0.2 and 1 cm. This difference is due in large part to the lack of precision of the type of target used and to their placement on the paneling of the building, which are more subject to deformations according to climate changes. The coordinates of the points on the structure were determinate using a topographic network inside the building site. The points were placed during the foundation of the unground part of the parking, in the panels of the containing walls. The distance between corresponding points were calculated through the 3d distance formula, starting from the coordinates of any point, using a software developed in Delphi 7, which calculate the distance and the standard deviation on the result. The value of the distance acquired in different

subsequent acquisition have been compared and correlate to the observed environmental parameteres. In fact, these distance measurements are indirect, as they are derived from angular observations and cannot be directly related with temperature, humidity and barometric pressure. Those parameters do not directly affect the measurement, but the structure itself; this deformation is then read by the calculation of relative distance of the points. The last acquisition system is made of 3 inclinometers biaxial in the 4 walls of the structure, to measure changes in the inclination with respect to the vertical axe. They allow continuous acquisition: every 2 hours the slope value is record, send to a server and display through a software platform. The data obtained from this system were confronted with the topographic survey on the structure: in this sense the monitoring is intended to be integrated, as the different results are used to confirm the others.
The second part of the thesis focuses on the idea to combine the direct measure of the distance with the continuous monitoring, by the developing of an instrument prototype. The components, both hardware and software have been studied, as well as a small processing on the data acquired.
The hardware part is Arduino, an open source framework that enables rapid prototyping and is composed of a hardware platform for physical computing, bases on a printed circuit board that integrates a microcontroller pin connected to the input/output ports, a voltage regulator

and a USB interface that allows communication with computer. To the board were connected 2 sensors that measure environmental parameters, one for the acquisition of temperature and relative humidity values and one for barometric pressure value. The other hardware component is a Leica Disto D8, which allows continuous measurements, has stated accuracy of ± 1.00 mm and can be connect via Bluetooth to the computer. It is modified to be powered directly from the mains, by using a power supply.
There have been several attempts of communications between the system components, trying especially to decode the command strings that the computer sends to the distance sensor for the acquisition and recording of the data, in order to write a software or a procedure that commands at the same time the Disto and the Arduino system. The Leica system is particularly closed and it was not possible to make the two components of the prototype to dialogue: this problem has been solved with the use of multiple software, which, when properly configured, permitted the simultaneous recording of the values to be captured.
AutoHotKey, a free and open source utility controls the distance sensor in order to acquire data at the desired frequency. With another routine this data is sent to a MySQL database. The Arduino board is connected to the sensors for temperature, humidity and pressure and it sends via serial a string that contains the three values of the variables. A sketch

developed in Processing, a programming language based on Java, links the value of the distance with the environmental parameters and it adds, at the top of the string with the values, the date and time of the acquired data and records the whole string in another page of the database. This software allows setting alert thresholds with the automatic delivery of email or sms when overcome. The values of distance, temperature, pressure and humidity are record on a web page updated in real time where they can be visualized, downloaded and exported. In another web page, the graphics of the trends distance/environmental parameters are display.
The last part of the thesis focuses on the treatment of data derived from continuous systems. The first test is on the hypothesis of normal distribution of distance measurement. From this test emerges the need to perform some data snooping on the acquired set of measurements, in order to calibrate the system. The instrumental precision of the laser rangefinder was tested by confront with a topographic survey of the same distance. The distance and the precision (described by the standard deviation) obtained from the rangefinder are comparable to the topographic ones. Other tests have been carried out on the correlation between environmental parameters and distance measurements.

MERGING LOCAL DTMS: HELI-DEM PROJECT, PROBLEMS AND SOLUTIONS

Laura Carcano - Supervisor: **Biagi Ludovico, Giorgio Aldo**

Official cartographic bases in Europe include Digital Terrain Models (DTMs); in recent years, different countries and regions have produced their own DTMs. Since unique and strict rules did not exist, the different available DTMs are characterized by different resolutions and accuracies and are georeferenced in different reference frames. Moreover, in some cases the elevation data are not consistent at the borders between countries or regions. HELI-DEM (HELvetia-Italy Digital Elevation Model) project aims at developing a unique DTM for the alpine area between Lombardy and Piedmont Italian regions and Ticino and Grisons Swiss cantons. The unified DTM will be produced validating and integrating various available elevation data for the involved regions.

To achieve the aim, different DTMs have been acquired. At low resolution: the official regional Lombardy (20 m planimetric resolution, georeferenced in Roma40) and Piedmont (50 m, ETRF89) DTMs and a national Swiss DTM (30 m, ETRF89). At medium/high resolution: a LiDAR DTM (5 m, ETRF89) which covers the whole Piedmont region and a LiDAR DTM (PST-A DTM) which covers only the river basins of Lombardy and Piedmont with a planimetric resolution of 1 m.

This PhD thesis is completely framed in HELI-DEM. Before merging the available DTMs, a validation of the input data has been performed in three steps: low resolutions (LR) DTMs have been cross validate in their overlaps, then they have been validated by HR (high resolution) DTMs; a final check has been made by geodetic techniques. General statistics are consistent with the nominal accuracies. In particular the validation of LR DTMs by HR DTMs has provided almost everywhere excellent results and the global statistics are significantly better than the nominal accuracies. Some sparse local anomalies are present. Therefore geodetic data have been used to point wise validate input DTMs where these anomalous behaviors have been highlighted by previous checks. This has been performed both by using existing geodetic monographs and by ad hoc surveyed areas by GNSS RTK technique. The comparisons confirm the accuracy of HR data and the presence of few local anomalies in LR DTMs. As an example, in Figure 1 the differences between PST-A DTM and RTK GNSS points surveyed in the Adda River Valley are shown: the 99% of the points present differences smaller than 10 cm.
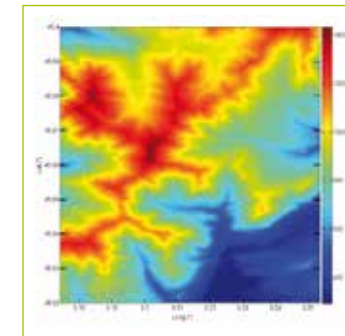

1. Differences between the LiDAR PST-A DTM and some RTK GNSS points surveyed in the Adda River Valley.

Different procedures can be adopted to produce a unified output DTM from different original elevation data. In general, three independent operations are necessary: alignment of the available DTMs to a common reference frame, interpolation of the DTMs on the output grid and merging of the interpolated elevations between two or more DTMs, where they overlap. The order in which the operations are performed depends on the adopted procedure. Three different procedures have been studied and implemented, named 1.A, 1.B and 2. Methods 1.A and 1.B are similar because the alignment of the available input DTMs to the final output reference frame is performed as first operation. The two procedures differ in the order of the operations of merging

and interpolation: in 1.A the input DTMs are independently interpolated on the output grid and then the results are merged by averaged their overlaps; in 1.B the DTMs are unified into a unique dataset that is interpolated on the output grid. Method 2 acts in an opposite way: the nodes of the output grid are back-transformed from the final reference frame to each reference frame of the input DTMs; then each input DTM, still gridded, is interpolated on the back-transformed nodes of the final grid; finally the individual estimated elevations are merged and averaged. Inside the HELI-DEM project and for its final purpose the two procedures 1.A and 1.B have been compared. Since method 1.A produces better results, it has been adopted to produce the final DTM. In particular a bicubic polynomial model has been used to interpolate the DTMs on the final grid. When the bad configuration of the input points produce an unstable system, different regularization approaches have been compared.
Following the selected procedure, the final product of the HELI-DEM project (called HD1 DTM) has been created through the merging of the low and medium resolution available data. The output grid is in ETRF2000 geographical

coordinates, covers the alpine area contained in the geographic rectangle with boundaries λ=7.80°E, λ=10.70°E in longitude, φ=45.10°N, φ=46.70°N in latitude and has a spatial resolution of 2×10-4degrees, about 15m in longitude and 22m in latitude. It is composed of 8000 rows and 14500 columns, for a total of 116M nodes (Figure 2).

2. Portion of HD1unified DTM

After the conclusion of the project, also method 2 has been studied and implemented. The new method has been tested on HELI-DEM data and a new unified DTM has been created and compared to the official HELI-DEM product. This solution seems to be optimal because does not bring to unstable systems and does not requires regularization methods. PST-A DTM has been then used

to correct HD1 DTM where it exists. Corrections had to be implemented by avoiding sharp discontinuities: therefore, the HR input DTMs have been resampled on HD1 grid nodes, then the differences (corrections) with respect to LR DTMs have been computed and a low pass filter has been applied to the corrections; finally the filtered model has been added to HD1. The result of this correction has been called HD2.
All the produced datasets have already been published by an open access geoservice (www. helidemdataserver.como.polimi. it).

UNCONVENTIONAL MEDIA CHARACTERIZATION FOR THE REMOVAL OF HEAVY METALS FROM WATER

Arianna Catenacci - Supervisor: **Manuela Antonelli**

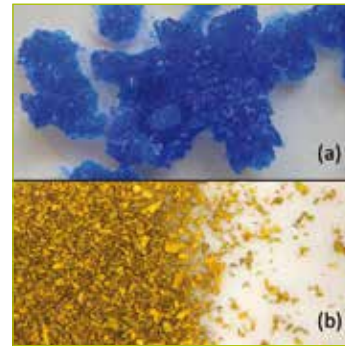ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING

1. Aim of the research

Heavy metals and metalloids have severe implications on environmental and human health: according to the World Health Organization, Cr, Ni, Cu, Pb, Hg and Zn are those of most immediate concern. Due to the increasing diffusion and variety of heavy metals in natural water supplies, more restrictive legal limits were recently defined. Specifically-designed technologies are required to support conventional processes, (chemical precipitation, coagulation/flocculation, ion exchange, adsorption, membrane filtration) and improve removal efficiencies and selectivity to comply with new standards. In fact, conventional treatments lack specificity, resulting in several disadvantages mainly related to low affinity and selectivity and long equilibrium times: such conditions often increase costs. Since much attention is to be focused on innovative water treatment technologies, new/unconventional media for the removal of micropollutants are today of great interest in the research world.
In this background, two granular media for the removal of heavy metals from water were tested at laboratory scale (Fig. 1): PolyAmidoAmine Hydrogels (PAAH) and KDF®55 Granular Brass Media (KGBM). They both remove heavy metals from water, by using two different mechanisms: hydrogels create complex bonds between active groups and heavy metal, while brass media, through a redox reaction, exchange electrons with contaminants, changing them into harmless components. Since few information concerning their removal abilities are provided in literature, an experimental plan for a first screening has been designed and implemented on both PAAH and KGBM, thus including kinetics, isotherms, selectivity tests and experiments for the assessment of the influence of different water constituents. Aimed at both the description of the solute removal process and the achievement of information for the selection and design of water treatment processes, by using a strategy that couples the microscopic and the macroscopic world, two main features were studied:
1. the chemical reactions occurring among solute and media, useful to define the field of application (type and form of contaminants) and to evaluate the influence of water characteristics (pH, interferences) on metal removal efficiency;
2. the diffusion processes involved in the removal of solutes, in order to study the influence of process parameters (initial concentrations, dose

of media) and to identify and improve suitable process units.

2. Experimental plan

PAAH are synthetic polymers designed by the Department of Organic and Industrial Chemistry (Università degli Studi di Milano, IT) and characterized by the presence of amido and tertiary amine groups along the macromolecular chain. The high structural versatility of PAAH offers interesting opportunities for designing media devoted to the removal of specific contaminants; however, no engineering applications in this field have been reported so far. Two samples of PAAH, termed MBA/EDA and MBA/CYS, were synthesized and supplied as powder (d<1mm) and grains (1mm<d<2mm). After an initial physical characterization, kinetics, isotherms and selectivity tests were performed at different doses and initial solute concentrations for two metals: copper, Cu(II) tested on both structures, and hexavalent chromium, Cr(VI) tested only on MBA/EDA since no significant removal has been observed for MBA/CYS. The two ions were selected because their opposite charges are supposed to involve different active groups along the chains. In order to gain information about the chemical reactions involved, the influence of pH was also investigated. KDF Fluid Treatment Inc. manufactures (MI, USA) provided the KGBM, an high-purity copper-zinc formulation. Unlike PAAH, KGBM is currently used in a variety of treatment units both at the Point-of-Entry (POE) and Point-of-Use (POU) applications. Kinetics of Cu removal were performed in order to define the influence of water characteristics on redox reactions. Since water constituents can create Cu-complexes that decrease the percentage of Cu dissolved in water as divalent ion, directly available for redox reactions, the pH and the presence of different types and amounts of dissolved inorganic (hydroxides and carbonates) and organic (EDTA, humic and fulvic acids and Natural Organic Matter) compounds were investigated.

3. Results and conclusions

Experimental results allow to quantify process rates, amounts of solute removed, influencing parameters and interference mechanisms. As for PAAH, MBA/EDA structure, besides its considerable volume expansion, proved to be more suitable because of its affinity towards both anion and cation, faster kinetic rates and easier synthesis process. Unlike the starting solute concentration that shows scarce influence on results (range: 16-64 µM), the pH and the dose of PAAH determine the removal process. In regards to KGBM, the pH, the form of contaminants and the presence of other compounds dissolved in water, all influence the removal rates of Cu and the process of brass corrosion, quantified by the amount of Zn released into water.
Moving from a macroscopic to a microscopic interpretation of data, by using specific models and statistical techniques for data analysis, a first description of the chemical/physical processes characterizing the two media has been attempted, thus generating new, interesting and unknown issues valuable to achieve a more detailed understanding of the media itself. As for PAAH, both tested structures remove similar amounts of solutes but MBA/EDA is faster than MBA/CYS:

the interpretation of kinetics and isotherm data with specific models suggests that the removal process involves the entire volume of particles and the diffusion of ions inside pores: because of the presence of both macro- and micro- pores, MBA/CYS acts slower if compared to MBA/EDA that, when in water, greatly opens its molecular chains thus promoting the diffusion of solutes through the pores towards active groups. Differences in the removal abilities of Cu(II) and Cr(VI) are to be ascribed to steric or charge interferences that determine the diffusion of ions: an in-depth analysis would allow to include in the diffusion model not only the properties of hydrogels (pore size, expansion degree) but also the characteristics of solutes (charge and dimensions of ions). As for KGBM, redox reactions occurring at the microscopic scale partially explain the entire process. A statistical analysis on data, the stepwise multiple regression, contributed, on the one hand to verify the occurrence of other possible reactions; on the other hand to identify further constituents and range of concentrations to be tested, aimed at defining the relationship existing between Cu removal and Zn release and creating a descriptive model of KGBM and its behavior in aqueous solutions.

CONNECTIONS AMONG IMAGES, TEXTS AND MAPS

Valentina Dante - Supervisor: **Luigi Mussio**

All the several disciplines concerning survey constituted in a single science with the foundation of geodesy and cartography. Over more than four centuries, they both contributed to the development of major branches of applied mathematics: 3D space geometry, calculus, statistics, and treatment of spatial observations.

After the second half of the twentieth century, information technologies made new observations available, while data had very different quality and size of databases grew, requiring the use of new methodologies and procedures for data analysis.

Within this picture, geometry, mathematical analysis and discrete mathematics show some limits which prevent the construction of robust models that Statistics could easily handle. In fact, there is now the need for the complete automation of procedures for both management and processing of data: size of available databases requires considerable computing power and should undergo a drastic downsizing, in order to allow a manual analysis or processing. Naturally, then, the technique developed and searched the most effective solution for calculation automation: in particular, some operational problems are substantially solved yet, by the use of dedicated software.

The primary focus of this thesis is to develop further strategies of elaboration, looking for analysis simplification by increasing the effectiveness of the automation: the aim is to reduce the number of computational steps, which actually force the use of extremely sophisticated software and hardware.

We applied some principles of Linguistics, finding new processing strategies for geomatic analysis (study of information contained in maps and images).

We demonstrated that the centring (matching) required for databases comparison can be successfully improved by using:
· the analysis of the connections, where the high probability of intersections is taken as a parameter of recognition reliability,
· and direct comparisons between the structures of the graphs.

Starting from the contrast between the rationalist approach and the empirical point of view, we are looking for integrated tools of abstract rules and statistical modules: so this is a new science, the so-called Human Computer Sciences, or Knowledge Engineering. The main goal of this modern discipline is image processing, assisted by machine learning and robot vision. However, the linguistic competence computer technology can simulate is not yet comparable to that in humans, mainly for two reasons: there's a technical limit to feigning and even the understanding of language processing is incomplete up to now.

The thesis project focuses on a possible new challenge of artificial intelligence, suggesting a theoretical proposal about image matching in the geomatic field: my study deals with the chance to integrate the concepts borrowed by liberal arts in the humanistic field, into the context of automated data. The final target is to measure the reliability of the rules of the Universal Grammar by Chomsky, integrated into the automatic reading of maps and images: we'll perform a syntactic recognition of comparison models among maps, images or 3D models, by using archetypes. Indeed, there is an analogy between the hierarchical structure (tree-shaped) of models and languages syntax: in fact, the combination rules-representations perfectly corresponds to the representation of syntactic structures in mind. Please note that:
· models are built by sub-models, just as words compose sentences;
· while sub-models consist of primitives, just as combinations of letters and syllables make up words.

Grammars are then defined as combination rules for objects primitives and they directly derive from the language that can describe the model. Given that a valid syntactic approach can successfully describe complex objects, I studied its expressive capacity through:
· analysis of the number of primitives in the chosen and adopted model. Naturally, a modest amount of atomic elements makes easier both computation, both management of an automated system;
· and analysis of rules, to be applied iteratively according to re-writing instructions.

Therefore, the best possible syntactic representation establishes an effective compromise between the number of existing relationships and the endless amount of primitives necessary for the model description, taking into account the technical constraints (the available computational power) and final result of the study.

Applications of the syntactic method for pattern recognition are several and refer to the use of different types of grammars: for example, this technique is used to analyse shapes of waves and boundaries (seismograms, electrocardiograms and electro-encephalograms). In the geomatic field, we could study the textures of digital images, or improve results in soil classification from satellite images: in fact, stochastic grammars can produce models for this kind of elaborations. With reference to the matching between images and maps, the aim of this thesis is to prove the bijective correspondence between an image and a text relevant to its description, of course considering that quality of correspondence depends on both image definition and text complexity. The text shall perfectly correspond to visible structures in the image, without referring to single objects: the key point is that such a text isn't a map.

This thesis walks through a brief description of the state of the art in image processing, with a short recall of cultural heritage due to Computer Science, Logic and Psychology. Then, it reports the principles of computer vision, while verifying eventual hints for automatic pattern recognition.

The second chapter deals with Linguistics, through the history of the study of language, until the formulation of the Universal Grammar and the theory of formal languages, by Chomsky. The third chapter analyse a case study, relevant to my experience in an image representation. I deal with further representations of a single image, taken by a common digital camera, aiming to a textual description that could be eventually traced back to the original scene. First of all, the picture is not widely recognizable, nor professional, in order to reduce the impact due to previous awareness of symbols and proportions. Then, there's an image description, with object-based structure, targeting to build a conceptual map that streamlines the further development of (semi) automatic software: it should offer interpretation and classification to representations, which shall be unambiguous and reliable as much as possible.

A drawing-skilled guy performed the reconstruction of the image: I evaluated results for his two tentative (unsupervised procedure and supervised one), then a rescaling really improved final likelihood assessment values.

My work ends with an evaluation of the overall reliability of the proposed procedure, while suggesting some hints in order to improve details and correctness of description. The thesis focuses on the cultural reasons of a possible choice, therefore clues are just an indication for other researchers – but of course they shall be taken into due account when an automatic system is under construction.

A computerized expert system, able to translate images into their textual descriptions, or to reconstruct an image representation starting with its text, is out of the scope of this thesis: the creation of software would have been too demanding for a single person, while it could have been completely useless in case the procedure cannot prove its reliability. Conversely, now that effectiveness of procedure seems to be proved, the automation could be an interesting field to explore, as an outcome of this thesis work.
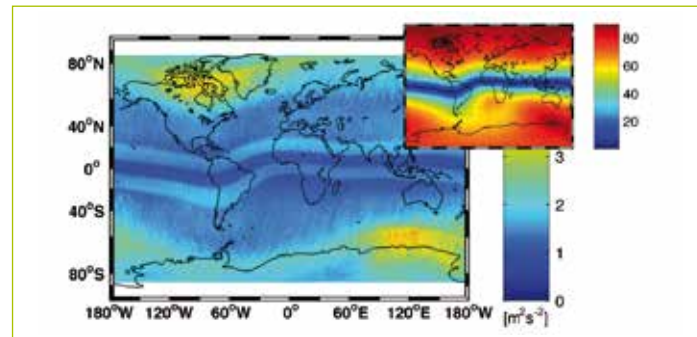
ADVANCED GOCE DATA PROCESSING FOR SPACE-WISE GRAVITY SOLUTION

Andrea Gatti - Supervisor: **Mirko Reguzzoni**

ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING

GOCE is the first satellite gradiometric mission of the European Space Agency (ESA). Launched on March 17, 2009 the spacecraft observed the gravity field of the Earth from about 250 km of altitude; its life in orbit ended on November 11, 2013 after finishing its fuel, reentering the atmosphere. The main goal of the mission is to estimate the Earth gravity field with an unprecedented accuracy and spatial resolution (about 1 ~ 2 cm of geoid error at 100 km resolution). The main instrument on board the satellite is a triaxial gradiometer complemented by a GPS receiver, while the first is able to detect small spatial variations in the field, the second instrument can be used to restore long wavelengths applying the technique of SST-hl (Satellite to Satellite Tracking in high-low mode).

In the framework of the GOCE data analysis three different approaches have been proposed. One of these is the so called space-wise approach (SPW): an iterative method based on collocation techniques able to exploit the gravitational field spatial correlation.

The basic idea of the space-wise approach to the satellite data analysis is to take advantage of the spatial correlation of the measurements, which is inherited by the spatial correlation of the gravitational
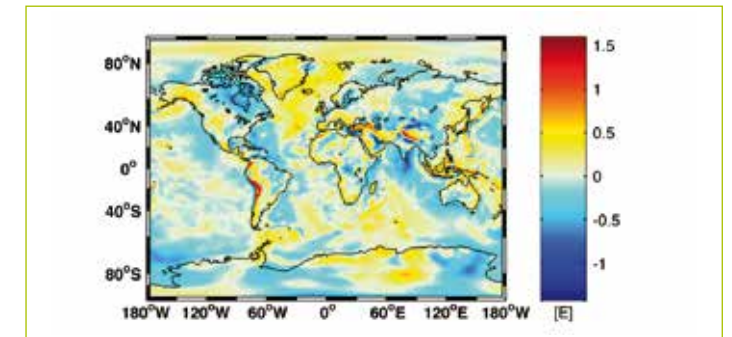

1. Estimated error of the SST-hl solution [m2s-2] showing the two tropical bands of higher variance, derived from the map of the Magnetic Inclination [deg].

potential, in order to filter the noise and predict the grids describing the geo-potential model. Theoretically, the best way to implement this approach is by applying a unique global collocation solution to all the observed data, assuming that the covariance function of the potential T is known. Unfortunately this method is unfeasible, because the number of observations is so huge that even with a machine able to process such amount of data, the time necessary to compute a valid solution would be too big. A way to process data based on a step-wise strategy has been chosen: first, an interpolation on a regular spherical grid at the mean satellite altitude based on SST data is applied to reduce the dataset, then a further improvement of the grid is done by using gradiometric

observations, from the gridded data, an algorithm of harmonic analysis can be used to extrapolate the coefficients of the field. Among all the different ways to implements gridding, it has been demonstrated by numerical tests that a technique based on least squares collocation (LSC) is preferable. For the same reason as above, a unique global collocation is unfeasible and therefore a local approach working on overlapped subsets is used. Gridding is the key of the space-wise approach; it allows connecting data, near in space, but far in time, reducing the effects of time-correlated noises. Moving from theory to practice, the space-wise approach must be adapted to consider the limitations of the mission, such as instrument noise, polar gaps, and transformation among the

reference systems involved. In 2009 the space-wise approach was implemented to work on two months of simulated data, after the arrival of the first valid observations, and the computation of a first solution it was clear that some issues would have to be addressed. Four were the main problems: scalability, poor data pre-processing, use of a priori solutions with GRACE, and over-smoothing. To be added to these, the estimation of potential resulting from the GPS tracking is prone to correlations with the Earth's magnetic field (Figure 1) that cause an incorrect reconstruction of the gravity signal with an error undetected by the instrumentations on board.

To bypass the original scalability limits, the software has been partially rewritten, optimizations in the parallelization and cache efficiency algorithms have been implemented. A tool to perform a supervised data pre-processing has been coded and used to process the whole dataset of the mission. The 2009 a-priori model which showed some unwanted GRACE data infiltrations has been substituted with a GOCE only one, made on a limited dataset of the mission through a sequence of global LSC updates on the coefficients of a the first solution. The spherical

2. Map of the second order radial derivatives of the anomalous potential computed at satellite altitude [Eötvös].

harmonics solutions created with SPW always showed an over regularization at high frequencies (over spherical harmonic degree 180), it was originally based on global degree variances, thus not allowing a local description of the data variability.

The work done in the past years has been focused on trying to solve this issue, gridding is now computed with one tailored collocation per each point of the grid to be estimated; the new grids such obtained by SPW have now a finer resolution (0.2x0.2 degree), and the currently applied regularization is calibrated on locally estimated empirical variances. Thanks to the big number of observations available it is now possible to compute fine solutions, unfortunately increasing the precision of them the SST-hl

part shows low accuracy due to undetected errors that are correlated with the inclination of the Earth magnetic field, these can be locally isolated and the frequencies affected can be also computed with gradiometric data. We designed a geographic mask to discriminate observations affected by the interference, increasing their estimated errors we force the gradiometric solution to apply a stronger correction over the isolated area. With local strategies, which can be further improved in the future, we are now able to produce grids of various functionals of the Earth's gravity field using only GOCE data (Figure 2).

HYDROLOGICAL MODELLING OF EXTENSIVE GREEN ROOFS IN TEMPERATE CLIMATES

Carlotta Lamera - Supervisor: **Gianfranco Becciu**

In the last decades the importance of stormwater management in urban areas has increased considerably, due to both urbanization extension and to a greater concern for environment pollution. Traditional stormwater control practices, based on the "all to the sewer" attitude, rely on conveyance to route stormwater runoff from urban impervious surfaces towards the nearby natural water bodies. In recent years, infiltration facilities are receiving an increasing attention, due to their particular efficiency in restoring a balance in hydrological cycle quite equal to quite pre-urbanization condition. In particular, such techniques are designed to capture, temporarily retain and infiltrate stormwater, promote evapotranspiration and harvest water at the source, encouraging in general evaporation, evapotranspiration, groundwater recharge and the re-use of stormwater.
Green roofs are emerging as an increasingly popular Sustainable Urban Drainage Systems technique for urban stormwater management. Indeed, they are able to operate hydrologic control over stormwater runoff: they allow a significant reduction of peak flows and runoff volumes collected by drainage system, with a consequent reduction of flooding events and pollution

masses discharges by Combined Sewer Overflows. Furthermore green roofs have a positive influence on the microclimate in urban areas by helping in lower urban air temperatures and mitigate the heat island effect. Last but not least, they have the advantage of improving the thermal insulation of buildings, with significant energy savings. Many studies suggest that green roofs can reduce stormwater runoff in comparison to conventional roofs with volume retention scores in the order of 40–80% of the total rainfall volume. From literature's data it is also evident that a decrease of 60–80% in runoff peak rates is to be expected from a green roof. However, the dynamic stormwater response of a green roof to precipitation events is highly variable and related to a particular set of climate conditions and changes with green roof design. The basic problem driving my PhD research is that green roofs differ from a natural environment as they are on top of a building and are not connected to the natural ground; therefore it is critical that soils can drain and retain water simultaneously and that they work even in very shallow systems. The growing medium used for green roofs is specifically engineered to provide the vegetation with nutrients, discharging any excess

water into the drainage layer, and releasing stored water back into the substrate. In this way, medium depth and porosity play an important role in stormwater retention and plant growth in a green roof.
Due to the lack of a good understanding about the hydraulic efficiency of each green roof's layer in rainwater management, a detailed analysis of the hydrological dynamics, connected with the green roof technical design is essential in order to obtain a full characterization of the hydrologic behavior of a green roof system and its effects on the urban water cycle components. The purpose of my PhD research is analyzing the soil-water dynamics through the different components of a green roof and modeling these processes though a detailed but clear conceptual model, based on green roof vertical soil water movement reproduction, in relation to climate forcing, basic technology components and geometric characteristics of green roof systems (thickness of the stratigraphy, soil layers and materials, vegetation typology). Though research has been published attempting to model green roof storm response as a time series, these models have generally been based on existing soil models (typically used to represent the processes

of infiltration in natural soils), requiring high levels of specific parameterization; our aim was to employ a model structure for handling soil water fluxes in each element, with a bare minimum of "tuning variables" but to retain the physical basis, and to adapt it to a soil characterized by a specific engineered stratigraphy, designed for extensive green roof systems in multilayer construction.
A multi-layer bucket model, which represents a good compromise between the difficulty of parameterization and accuracy in the description of the process of infiltration into the soil, has been applied to examine the hydrological response of a small-scale physical green roof system, under a temperate maritime climate, by varying the physical and geometric parameters that characterize the different components of the vegetated cover. In this model a single green roof is outlined as a system consisting of three individual module in series, subjected to different hydrologic and hydraulic processes; each layer works as a bucket and communicates with each other. A mass balance equation is applied to the whole system, taking into account the specific phenomena occurring in each module. The surface layer is represented by the vegetation module, where the evapotranspiration processes are modeled using the FAO56 Penman-Monteith Equation, proved to be the most robust tool for predicting ET for green roof experiments; the growing medium is the second module, which predicts the infiltration

and vertical percolation of water both through the unsaturated zone and from the saturated zone to the drainage layer, passing through the geotextile filter fabric. Finally the drainage layer, which usually consist of drainage plates, waffled plastic sheets that store water above and drain water below, is modelled as a storage. The modeling was performed following progressive steps of complexity in the outline of the green roof system, starting from a detailed representation of the hydrological fluxes which characterize the different layers of the system through a mass balance at event scale, and then switch to a modeling at seasonal scale, where the evapotranspiration component represents a critical process, in terms of percentage reduction of the volume drained.
The model is applied to two different case study, with different stratigraphy and climate conditions. As a case study for the calibration and validation, we analyzed at event scale a test roof located in Sheffield (UK), for which there are available experimental data of hydrological, hydraulic and climatic monitored continuously since 2006. In the first approach we didn't consider evapotranspiration; although it plays an important role in green roof working process for a long term, in the process of a single rainfall storm its value is minimal enough to be neglected. Results confirm the suitability of the model to describe the hydrologic response of the green roof during the observed rainfall events: the discharge hydrograph profile, volume and timing, predicted by the

model, matched experimental measurements rather good, as demonstrated by the model efficiency coefficients obtained both for the total discharged volume and the peak flow. The other case study is the green roof located on the department ABC building in Milan, where weather data are measured by a weather station positioned on the roof of an adjacent building. At event scale the volume reduction is relatively low; dominates the phenomenon of peak attenuation. At annual scale the simulations show that evapotranspiration component play a central role in terms of percentage reduction in the drained volume. Due to the high sensitivity of the hydrological response to a small variation of the system configuration, we provide finally a sensitivity analysis of hydrological benefits of the green roof at different soil and geometric parameters to test the model response, in terms of peak and volume reduction; this two variables corresponds to the measures associated to the potential environmental impact of the green roof: the degree of imperviousness exhibited by the green roof. This has allowed to draw some general guidelines useful in the design and construction of this type of drainage systems.

RISK ASSESSMENT OF UNDERWATER SOUND EMISSIONS: IMPACT FOR MARINE ENVIRONMENT

Caterina Lanfredi - Supervisor: **Arianna Azzellino**

Background

Human activities are exerting increasing environmental pressure on the oceans, threatening marine ecosystems and the sustainability of maritime activities. The health of global marine ecosystems is in serious decline, due to multiple stressors such as over-fishing, oil and gas extraction, pollution, incoming of invasive species, coastal and offshore development, and alteration due to climate change. Among these sources of impact to the marine environment, one of the must discussed and still poorly know pressure is the "human induced underwater noise". Oceans are becoming increasingly noisy especially in costal developed areas and in areas of intensive maritime traffic. Extremely loud underwater noise is generated by air-guns, widely used for geophysical explorations for oil and gas industry, and by high power sonars, either military or civil, used by ship traffic, and by shoreline and offshore construction developments for scientific purposes. The most powerful noise sources (i.e. air-guns, sonars, explosions and, in some cases, pile driving) are often characterized by short duration but may lead to direct injure of animals in the nearby of the source. On the other hand, general ship traffic, heavy industries on the coast, wind-farms and a variety of different human activities, although they do not produce such intense noise, their acoustic pollution is continuous over time and may affect large areas and entire populations. The awareness that underwater noise affects marine life, and marine mammals in particular (i.e. beaked whale), as the need for a regulatory system to mitigate such effects has raised over the past few years, mainly in the context of loud, low and mid frequency impulsive sounds activities such as military and seismic sonars. The most recent policy for the protection of the marine environment is Marine Strategy Framework Directive, MSDF (Directive 2008/56/EC adopted in June 2008). The EU Directive specifically mentions the problem of noise pollution and provides a legal framework for addressing this issue. The Directive represents the first international legal instrument to explicitly include man-made underwater noise within the definition of pollution (Article 3 (8)) and listed the underwater noise (Annex III, Table 2) among the indicative list of pressures and impacts. However, there is still a lack in the legislative framework and the implementation of the EU Directive is still at a very initial stage. To manage the impact that acoustic energy may have on the marine environment, and particularly on marine mammals, a quantification of the risks is needed.
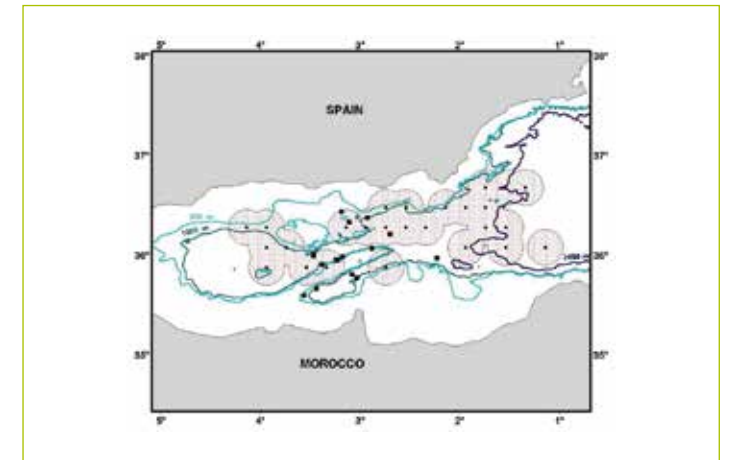
Objective of the Research:

Main scope of this research is to provide tools to support the management of underwater noise Specific aims of the PhD research were: 1) to study the environmental factors affecting the distribution of the species vulnerable to underwater noise; 2) The development of models to predict the environmental risk for Mediterranean vulnerable species ; 3)The validation of models developed and the evaluation of their transferability to different areas of the Mediterranean Sea; 4) The integration of acoustic propagation models of anthropogenic sound sources (e.g. ship traffic) with the distribution of vulnerable species; 5) The use of quantitative Marine Spatial Planning criteria to support the sustainable planning of conflicting human activities in the perspective of minimizing the overall marine environmental impacts.

Key Results

The distribution of vulnerable species was evaluated in two areas of the Mediterranean Sea: The Ligurian Sea and the Alboran Sea. Data on the distribution of marine mammals were collected through visual observation and acoustic detections. Data were analyzed using GIS software. Spatial information on both dynamic (i.e. dissolved oxygen, temperature, salinity, density) and static (i.e. depth and slope) environmental parameters has also been processed. This type of data constituted the calibration and evaluation set for these models. Both dynamic and static predictor provided significant results in predicting the presence of vulnerable species. However the static predictors provided a higher accuracy in model classification (80% vs 60%). Risk prediction maps were created based on model results (Fig. 1). The modeling of underwater noise has been developed by ARPAT in the area of the Ligurian Sea using shipping data from Automatic Identification System (AIS). Noise maps has been realized for the Ligurian Sea area. These maps were integrated with the distribution of vulnerable species by using the output of the habitat models developed in the Ligurian Sea area. Finally, a multi-criteria analysis was developed to identify the best location of marine renewable energy infrastructure (optimal siting) in the perspective of the Strategic Environmental Assessment. The raising interest in the exploitation of

2. Risk prediction map for the Alboran Sea area. Buffer zone represent area of high risk for vulnerable species to underwater sound. Beaked whale observations (one of the species most vulnerable to underwater noise) are shown as dark full squares. The 800 m, 1000 m and 2000 m depth contours are also shown.

offshore renewable energy sources (such as wind, wave and tidal energy) is expected to put additional pressures to the marine environment. These new developments will bring increased noise exposure, both during construction (e.g. pile driving) and operation. In this analysis a spatial planning approach was applied at a regional and a local scale. The environmental background was considered through set of multiple indicators (e.g. sea bottom topography and characteristics, marine biodiversity, presence of vulnerable species). Environmental indicators were aggregated into environmental impact indexes that constitute the basis for evaluating the site suitability for Marine Renewable Energy Installations (MREIs). Concurrently, areas of potential conflicts between the interests of MREI developers and commercial, recreational users were identified. Marine Spatial Planning offers good examples about how spatial planning has the potential to guide the transition from the single sector management toward the integrated management of sea uses.

INVERSION OF GEOPHYSICAL PARAMETERS FROM ENKFANALYSIS OVER SEMI-ARID REGIONS

Ju Hyoung Lee - Supervisor: **Marco Mancini**

As more and more satellites, specifically designed for hydrological monitoring,have beenrecently launched, the needs of satellite datautilization study are increasingly growing in the fields of hydrology, atmospheric science and geoscience.The development of inverse method is intended for such research needs. Main objective of this thesis is to propose the method inverting geophysical parameters from the measurements after filtering out the measurement errors, by means of data assimilation, specifically Ensemble Kalman Filter (EnKF).Significance of this method lies inovercoming the limitations of empirical formulations. The globally available satellite data-based inversion method appropriately addresses the characteristicsin the extreme climatic conditions misestimated by means ofempirical formulations. This thesis is organized as follows: EnKF was implemented withSurface Energy Balance System (SEBS)-retrieved sensible heat flux, and Synthetic Aperture Radar (SAR) and Soil Moisture and Ocean Salinity (SMOS)-retrieved surface soil moisture products. These EnKF analyses were further used as the reference data in the inverse method. The inversion of aerodynamic roughness in the SEBS model was first conducted

with the Tibet-Global energy and water cycle experimentAsian Monsoon Experiment (GAME) datasets. The inversion of soil hydraulic inputs in the Soil Vegetation Atmosphere Transfer (SVAT) model was implemented with the Tibet-GAME and Analyses Multidisciplinaires de la MoussonAfricaine(AMMA) datasets.

Prior to the implementation of the inverse method, it is required to filter out satellite errors via EnKF. The satellite errors are often very large. If the measurement is contaminated, then its errors can be propagated through the inverse method to the estimation of geophysical parameters.Two different EnKF schemes (i.e. stationary and sequential) were compared. Because the stationary ensemble-based Ensemble Optimal Interpolation (EnOI) scheme is a computationally cost-effective but suboptimal approach, this study suggested the two-step stationary EnKF scheme empirically defining the observation errors with L-band Microwave Emission of the Biosphere(L-MEB) radiative transfer model, in contrast to sequential EnKF assuming global constant *a priori* variance. A point-scale comparison results show that the two-step stationary EnKF scheme was

better matched with the field measurements at the AMMA sites than the original SMOS L3 data and sequential EnKF scheme. Its spatial average (brightness temperature scheme) was just comparable to the sequential EnKF, in contrast to other perturbation schemes. At a spatial scale, it mitigated the rainfall-induced run-off errors, vegetation attenuation and underestimations by aninappropriatedielectric constant model in dry sandy soils. It was suggested that the sequential EnKF scheme consuming a longer record of satellite data may not be required if the SMOS brightness temperature errors in EnOIare empirically adjusted at a pixel scale. The operational merit of the two-step stationary EnKF scheme lies within a short analysis time step due to one-time update and accordingly low computational cost, when compared with the Cumulative Distribution Functions (CDF) matching requiring a long record (usually, at least one year) of satellite data and the sequential EnKF scheme. Additionally, there is no need to assume a slow evolution or a global constant for the observation error parameter in the observation operator of EnKF or to define the length of the localising function for sampling errors.In contrast,

whenthe observation error is not processed with retrieval algorithms, the performance of EnKF was better than the EnOI. This experiment was carried out with the SAR datasets over the Tibetan Plateau.

The first geophysical parameter inverted was aerodynamic roughness height. It is a key input required in various models such as land surface model, energy balance model or weather prediction model. Although theerrors in heat flux estimations are largely dependent on accurate optimization of this parameter, it remains uncertain, mostly because of non-linear relationship ofMonin-Obukhov Similarity (MOS) equationsand uncertainty in the vertical characterization of vegetation. Previous studies determined aerodynamic roughness using traditional wind profile method, remotely sensed vegetation index, minimization of cost function over MOS equations or linear regression. However, these are the complicated procedures presuming high accuracy for other related parameters embedded in MOS equations. In order to simplify a procedure and reduce the number of parameters in need, this study suggestedthe new approachinverting aerodynamic roughness height from EnKF-analyzed heat flux. To the best of knowledge, no previous study has applied EnKF to the estimation of aerodynamic roughness. The aerodynamic roughness height estimated by this approach was consistent with eddy covariance result and literature value. Consequently, this method rectified the

sensible heat overestimated and latent heat flux underestimated by the original SEBS model, demonstrating better heat flux estimation especially during the summer Monsoon period in the Tibetan Plateau. The advantage of this method is that this is time-variant over vegetation growth, not affected by the saturation problem of remotely sensed vegetation index, and useful even when eddy covariance data are absent in the fields.
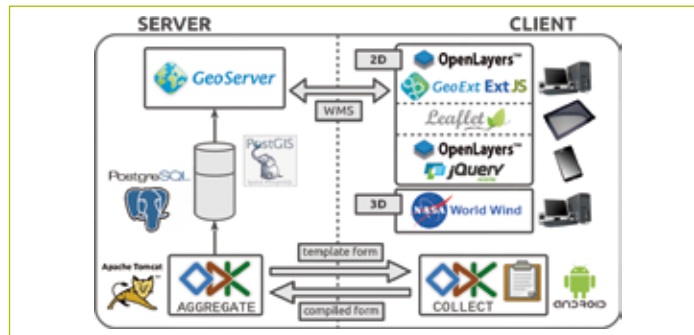
The inverse method was also applied for the soil hydraulic inputs of SVAT model. The performanceof SVAT model is largely constrained by uncertainties in spatially distributed soil and hydraulic information, which is mainly because any PTF estimating soil hydraulic properties is empirically defined. Accordingly, its applicability is limited. To overcome this limitation, this study suggested a new calibration of inverting soil hydraulic variables from EnKF-analyzed SAR and SMOSsurface soil moisture products. First, the inverse calibration was applied to the Tibet-GAME datasets. The results demonstrated that the calibrations of two soil hydraulic variables, soil surface variable C_1 and equilibrium soil moisture θ_{geq}, solved the misestimation problem due to the verticalhomogeneity assumption and empirical PTFs in the original SVAT scheme, and better demonstrated a non-linear relationship between surface and root zone soil moisture at a SAR spatial scale. It was also suggested that root zone soil moisture in highly stratified semi-arid soils

may not be linearly inferred from remotely sensed surface soil moisture.Secondly, this inversion calibration was also applied to the AMMA datasets representative of a single grid cell (0.25 degree) of SMOSimages. At a local scale, the results demonstrated that the mis-estimation of C_1 and θ_{geq} in dry and sandy soils were successfully solved after calibration, demonstrating a better agreement with field measurement of soil moisture profile than the SMOS data and un-calibrated SVAT scheme using FAO soil maps-based PTFs. On the meso-scale, the calibrated SVAT scheme appropriately captured a non-linear relationship between surface and root zone soil moisture, showing a typical dry climatic condition, in which dry surface was spatially consistent with the rainfall events, while wet root zone showed low correlations with surface soil moisture dynamics and rainfall events. In contrast, the un-calibrated SVAT model significantly overestimated surface soil moisture and rainfall effect. Accordingly, it was concluded that one of the key determinants for soil moisture profile is soil and hydraulic property. This approach suggests several operational merits in that there is no need to heavily rely on site-specifically defined empirical PTFs, and this can be applied even when model input is highly uncertain.

ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING

MULTI-DIMENSIONAL GEOWEB PLATFORMS FOR CITIZEN SCIENCE AND CIVIC ENGAGEMENT APPLICATIONS

Marco Minghini - Supervisor: **Prof. Maria Antonia Brovelli**
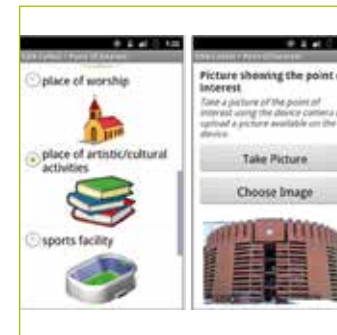
The way information is delivered and consumed on the Internet has known a tremendous revolution over the last decade, which often goes under the name of Web 2.0. This concept was coined to describe the global trends of exploiting the new Internet technologies to create, share and use information within participative applications. The notion of GeoWeb 2.0, the geographic extension of Web 2.0, denotes the corresponding technological shift in the management of spatial data over the Internet. Geographic information, whose access was traditionally held by mapping agencies according to a top-down paradigm, has become a prerogative of the single users, who are no longer mere consumers but can produce and share their own contents. Enhanced user interaction within GeoWeb 2.0 has made Web applications more and more similar to the desktop ones and accordingly new terms were coined. Neogeography was introduced as the "new geography" in which even common users can easily create their own Web mapping applications. The major expression of GeoWeb 2.0 is however Volunteered Geographic Information (VGI), i.e. the geographic version of crowdsourcing in which the single users (acting as sensors)

contribute local geographic information. Particularly interesting in the field of VGI is the so-called citizen science, i.e. the set of scientific activities featuring the voluntary participation of non-professional scientists. Finally the practice of Public Participation GIS (PPGIS), born in the mid-1990s, outlines the use of GIS to democratically involve the public community into decision-making processes. As a result of GeoWeb 2.0, PPGIS evolved into Web-based, shared platforms where users can publish and manage their own contents. A notable boost to this technological revolution was given by the massive spread of sensors, including those installed on current mobile devices and allowing e.g. to both register multimedia data (i.e. the camera) and georeference them (i.e. the GPS).

With all these premises, the work investigated the potential of creating a platform enabling citizen science and civic engagement applications, which: a) allow users to collect data on the field using common mobile devices (e.g. smartphones and tablets) and share them on the Web; b) provide not only a traditional 2D Web visualization, but also a 3D one through the use of virtual globe technology; and c) exclusively use Free and Open Source Software (FOSS), whose code openness enables a full customization of the products according to the needs. The basic developed architecture, structured in the server-side and the client-side and showing all the software used, is shown in Fig. 1. Its customization allowed to build four different applications (accessible from http://geomobile.como.

1. Basic architecture of the developed platform.

2. Screenshots of the Android application for reporting cultural points of interest (PoliCrowd).

3. Visualization and query of user-reported road pavement damages in a viewer for mobile devices.

polimi.it) allowing citizens to report: a) road pavement damages; b) tourist and cultural information (PoliCrowd project); c) architectural barriers; and d) water-related phenomena and points of interest (in collaboration with AdbPo – Po River basin Authority).

The information collected on the field using common mobile devices is managed by the Open Data Kit (ODK) toolkit, which in turn is composed of different modules (Build, Aggregate and Collect) responsible for the creation of the forms, the management of submissions and users, and the field-compilation of the forms from Android devices, respectively (see Fig. 2).

Citizen-collected georeferenced information is stored into a PostgreSQL database with

PostGIS spatial extension, which allows the geospatial server GeoServer to read and publish it on the Web using a standard Web Map Service (WMS) protocol. Several viewers were developed, which provide data visualization and query in 2D for both desktop computers (through OpenLayers, GeoExt and Ext JS libraries) and mobile devices enabling touch-screen commands (through OpenLayers and Leaflet libraries and jQuery mobile framework, see Fig. 3).

For the PoliCrowd project user interaction was also extended to the third dimension using the NASA World Wind virtual globe, available as a Java Software Development Kit and therefore fully customizable with specific functionalities. A real social platform was built in which registered users can benefit

from additional functionalities, e.g. enter comments and multimedia contents about the field-collected data; create customized data mash-ups by combining layers published from multiple data Web servers; and save their own 3D map projects. Both the layers added and the projects saved are stored in a catalogue and remain available for all the users of the platform.

Beyond the implementation of the described citizen science architecture, which demonstrated the applicability of FOSS for managing data from its gathering in situ to its Web publishing, some field tests were performed in order to evaluate the accuracy of GPS positioning from common mobile devices. The most meaningful results showed that: a) the accuracy value usually returned from the devices is reliable; b) the mobile device planimetric accuracy is in average better than ten meters; and c) accuracy values on the two planimetric coordinates are not in general dependent.

DATA ASSIMILATION FOR COMPLEX SUBSURFACE FLOW FIELDS

Marco Panzeri - Supervisor: **Monica Riva**

Proper modeling of subsurface flow and transport processes is key to the solution of a wide range of engineering and environmental problems. Relevant applications include, e.g., the supply of fresh water for civil and industrial activities, the remediation of contaminated aquifers or the protection of groundwater sources, the need for enhancing the recovery efficiency of hydrocarbon reservoirs to face the ever increasing demand for energy resources, the quantification of the risk linked to the geological disposals of nuclear wastes. Building a subsurface flow model requires defining the spatial distribution of the input parameters embedded in the underlying governing equations, such as permeability and porosity. Despite the key role played by these petrophysical properties when modeling aquifer and oil reservoirs, our knowledge of the way they are distributed within a domain of interest is scarce in practical applications and often characterized by a high degree of uncertainty.

A well-established approach to tackle this problem is to work within a stochastic framework, in which the permeability and the porosity fields are treated as random processes of space. An inverse and/or data assimilation modeling framework is then employed for conditioning these spatial distributions relying on either direct or surrogate measurements. Among the various available inversion (or data assimilation) techniques, we focus on the Ensemble Kalman Filter (EnKF) approach. EnKF is a data assimilation technique which is employed to incorporate data into physical system models sequentially and as soon as they are collected. EnKF is appropriate for large and nonlinear models of the kind required for realistic subsurface fluid flow simulations and has traditionally entailed the use of a (numerical) Monte Carlo (MC) approach to generate a collection of interdependent random model representations. Despite its increasing popularity, there are several drawbacks that undermine the range of scenarios under which EnKF is applicable. A critical factor is the size of the ensemble, i.e., the number of MC simulations employed for (ensemble) moment evaluation. Whereas to estimate mean and covariance accurately requires many simulations, working with large ensemble sizes and assessing MC convergence is computationally demanding. Another common problem is that EnKF performs optimally only if the system variables (i.e., model parameters and state variables) can be described by a joint Gaussian distribution. Modern reservoir models require to explicitly take into account the spatial distribution of facies, which can be defined as distinctive and non-overlapping units forming the internal architecture of the host rock system and which are associated with given attributes such as porosity, permeability, mineralogy. Demarcation of diverse facies in a reservoir model is usually accomplished through indicator functions. Due to the typically non Gaussian nature of the latter, use of EnKF to update complex reservoir models can be fraught with severe challenges.

The main objectives of this work are: (*a*) to couple EnKF with stochastic moment equations (MEs) of transient groundwater flow to circumvent and alleviate problems related to the finiteness of the ensemble employed in the traditional MC-based EnKF; and (*b*) to develop an assimilation algorithm that is conducive to conditioning on a set of measured production data the spatial distribution of lithofacies and of the associated petrophysical properties for a collection of hydrocarbon reservoirs.

We propose to circumvent the need for MC through a direct solution of nonlocal (integrodifferential) stochastic MEs that govern the space-time evolution of conditional ensemble means (statistical expectations) and covariances of hydraulic heads and fluxes. The purpose is to combine an approximate form of the stochastic MEs with EnKF in a way that allows sequential updating of parameters and system states without a need for computationally intensive MC analyses. We explore the resulting combined algorithm on synthetic problems of two-dimensional transient groundwater flow toward a well pumping water from a randomly heterogeneous confined aquifer subject to prescribed boundary conditions. We investigate the effect of the error variances linked to available log-conductivity data and the impact of assimilating hydraulic heads during the transient or the pseudo-steady state regime on the quality of the calibrated mean of log-conductivity and head fields as well as on the associated estimation variance. We also compare the performances and accuracies of our ME- and MC-based EnKF on synthetic problems differing from each other in the variance and (integral) autocorrelation scale of log-conductivity random fields. We analyze the impact of the number of realizations employed in the MC-based EnKF and the occurrence of filter inbreeding in the assimilations. We show that embedding MEs in the EnKF scheme allows for computationally efficient real time estimation of system states and model parameters avoiding the drawbacks which are commonly encountered in traditional MC-based applications of EnKF. Our results confirm that a few hundred MC simulations are not enough to overcome filter inbreeding issues, which have a negative impact on the quality of log-conductivity estimates as well as on the predicted heads and the associated estimation variances. Contrariwise, ME-based EnKF obviates the need for repeated simulations and is demonstrated to be free of inbreeding issues.

We further illustrate a novel data assimilation scheme conducive to updating both facies and petrophysical properties of a reservoir model set characterized by complex geology architecture. The spatial distribution of facies is treated by means of a Markov Mesh (MM) model coupled with a multi-grid approach, according to which geological patterns are initially reproduced at a coarse scale and are subsequently generated on grids with increasing resolution. This allows reproducing detailed facies geometries and spatial patterns distributed on multiple scales. The assimilation algorithm is developed within the context of a history matching procedure and is based on the integration of the MM model within the EnKF workflow. We test the methodology by way of a two-dimensional synthetic reservoir model in the presence of two distinct facies and representing a complex meandering channel system. We show that the proposed inversion scheme is conducive to an updated collection of facies and log-permeability fields which maintain the geological architecture displayed by the reference model, as opposed to the standard EnKF. We test the prediction ability of the realizations obtained through our procedure by means of two forecast scenarios, in which diverse flow configurations are considered following the latest assimilation time. In our first scenario, the same flow setting imposed in the course of the assimilation time is maintained also during the additional simulation period. A second study is performed by considering the presence of two additional wells that become operative after the assimilation period. The approaches tested yield a good estimation of the target production values during the first scenario, the predictions provided by standard EnKF being characterized by the highest degree of uncertainty. The performances of the two methodologies are markedly different when considering the second scenario where our proposed algorithm outperforms the standard EnKF by providing a superior match between the reference and the predicted production curves.

CHARACTERIZATION OF GROUNDWATER DYNAMICS IN RESPONSE TO FORCING TERMS UNDER UNCERTAINTY

Raul Perulero Serrano - Supervisor: **Monica Riva**

The current Ph.D. thesis has been developed under the umbrella of a European project (Framework 7), a former ITN (Initial Training Network) named IMVUL "Towards improved groundwater vulnerability assessment".

The aim pursued with this work is to improve our current knowledge in numerical modeling applied to hydrogeology, by means of conducting statistical analyses of the outcome of the procedures/ workflows adopted and the application of the results to real field case studies.

The project we carried out is mainly focused on the use and comparison of two geostatistical techniques to produce heterogeneous aquifer simulations in order to simulate the flow field induced by a mean hydraulic gradient superimposed to the effect of a pumping well in a real double aquifer system. A posed problem of the kind is relevant to hydrogeology practitioners, especially to those related to groundwater vulnerability and its characterization and/ or quantification. The actual system bears at surface level a natural and active springs' network which is threatened by anthropological activities such as water over abstraction, due

to excessive pumping effects for agricultural (mainly) and industrial purposes. We did combine a stochastic approach with the inclusion of real hard data (lithological input from available boreholes) to condition the aforementioned geostatistical simulations. We created a reality-based numerical model to study the impact of the hydro-facies generation scheme and the effect of competing hydraulic stresses over a given environmental target parameter of our choice: h (hydraulic heads). Subsequently/In a nutshell, the output of a study of the kind we propose could be used to further put thresholds or limits in water abstractions, in order to control hazardous drawdowns that could lead to the drying up of a springs' network fed by a confined aquifer.

In this dissertation, we perform a numerical Monte Carlo (MC) study based on a geological system whose heterogeneous structure mimics the one associated with an alluvial aquifer system located in northern Italy (Cremona province, Regione Lombardia) where abundant lithological and geological information are available. Our analysis considers a non-uniform flow scenario due to the superimposition of a base uniform (in the mean) flow
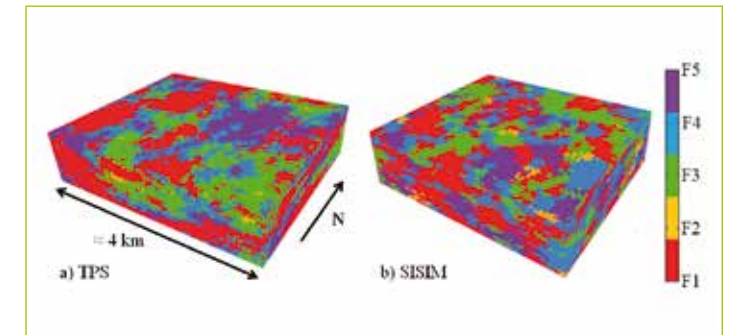
and the action of a pumping well. Field-scale available lithological data are analyzed to characterize prevalent litho-type categories and the associated geological contact rules. The simulation domain is modeled as a composite medium with randomly distributed hydro-facies, each associated with a given hydraulic conductivity. Collections of conditional Monte Carlo realizations (Figure 1) of the three-dimensional geo-materials distributions are generated by (i) a classical indicator-based approach (Sequential Indicator simulations) and (ii) the Truncated plurigaussian simulations (TPS) scheme, starting from available data which are employed as conditioning information. Afterwards we performed a statistical analysis (in terms of mean, variance, covariance function and probability distribution) of hydraulic heads as a function of (i) location in the domain and (ii) methodology of geological reconstruction of the system, highlighting the competing effect of the source term and boundary conditions. Since typical head observations are collected within screened boreholes, we explore the extent to which vertically averaging hydraulic heads can retain qualitative and quantitative information on the statistical behavior of point-wise head

values.
An ultimate purpose of this work would be presenting guidelines for practitioners when studying problems of the same kind like the one explored in our study.

The novelty of our study is rooted in the fact of investigating the relative impact of two different conceptualization and simulation techniques to characterize random hydro-facies spatial arrangement on the probabilistic distribution of hydraulic heads in three-dimensional aquifer systems under non-uniform mean flow conditions of the kind that is associated with large scale field. This analysis is intimately tied to Probabilistic Risk Assessment (PRA) procedures and constitutes one of the steps which can be adopted in modern PRA applications based on the idea of decomposing the full problem (that might comprise several uncertainty sources, including those associated with hydro-stratigraphic structure, aquifer recharge, boundary conditions, location and/or pumping/ injection rate of wells) into sets of basic events. History matching and inverse modeling are out of our scope in the present study.

Amongst the main findings we would like to highlight that

1. Selected realizations of hydro-facies distribution obtained by means of (a) TPS and (b) SISIM. Size of the represented blocks is 3.7 km × 4.3 km × 0.1 km: vertical exaggeration is set to 10× for ease of illustration.

hydraulic heads deduced from TPS-based flow simulations reveal larger variability than their equivalents evaluated by an SISIM-based modeling strategy. This can be seen as a consequence of setting geological contact rules, as considered within a TPS simulation scheme, which can lead to an increased variability in the internal architecture of hydro-facies distributions within a relatively large-scale aquifer model of the kind we consider.

Due to the enhanced degree of variability displayed within the collection of simulations and to the occurrence of long-tailed pdfs, reliance on a TPS scheme produces a broader range of possible drawdown values for the simulated groundwater system. As such, TPS-based results are associated with the

most conservative (in terms of high extreme values) drawdown estimates which can then be related to a given threshold probability of occurrence in the context of PRA protocols where the target environmental metric is the piezometric drawdown.

AUTOMATIC SEGMENTATION, CLASSIFICATION AND EXTRACTION OF REPEATED PATTERNS FOR BUILDING FAÇADES MODELLING

Mattia Previtali - Supervisor: **Raffaella Brumana**

Availability of realistic 3D building models is important in many applications. In urban planning the chance to explore 3D virtual reality world is much more efficient than the analysis of 2D maps. For public security, accurate 3D building models are indispensable to plan intervention strategies during emergencies. Virtual tourism may largely benefit from highly realistic city models.

The rapid development of terrestrial laser scanning devices allowed the acquisition of point clouds of urban environments in a relatively reduced time. With the considerable high point density and the explicit 3D coordinates of such point clouds, it is possible to recover both large structures and fine details of buildings. In addition, the increase of automation in acquisition stage and registration of laser scans, in conjunction with a reduction of the cost of instruments, extended to a larger number of operators the chance to use terrestrial laser scanners (TLS). This caused a great attention in generating as-built building models starting from laser scanning data. In many cases such models are generated by manual modelling of each building element. However, this is undoubtedly a rather time consuming and expensive procedure that limit a widespread dissemination of

building models. Automation in the reconstruction process is essential to speed up the processing. Indeed, only if a high degree of automation is maintained throughout the whole pipeline, from data acquisition to modelling, the economic sustainability of the model generation can be guaranteed. Automated approaches can bring advantages in term of speed, and thus the time needed to deliver the final model can be shortened in comparison with manual techniques. However, lack of automated approaches to understand the building structures captured in raw data is still underlined by different operators in the Architecture, Engineering, and Construction (AEC) domain.

This thesis introduces a new procedure aimed at the automated production of building façades models. This method is principally designed to generate as-built models of urban construction for thermal retrofitting. Indeed, energy efficient retrofitting of existing buildings, mainly the ones built in the period 1950 – 1975, is a key aspect for reaching the proposed energy consumption reduction targets fixed by national and international authorities. In this field, highly detailed as-built models of buildings are needed
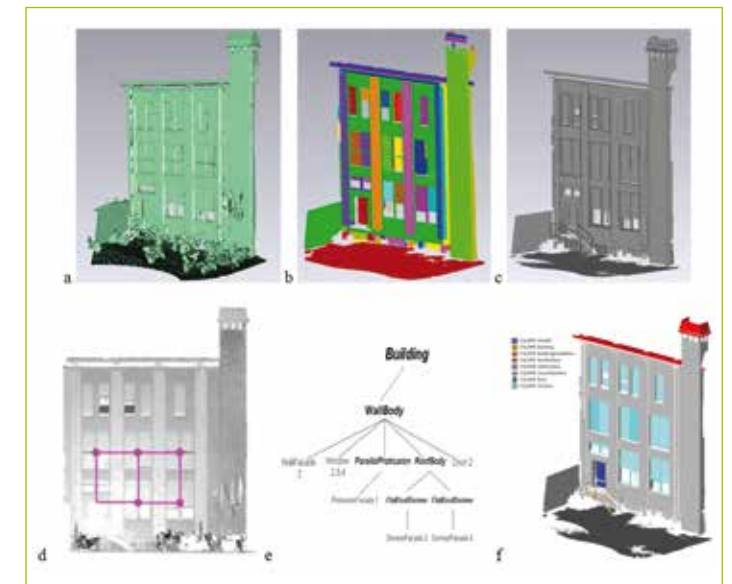
on one side for the thermal assessment, and on the other for producing executive drawings. The developed approach can be considered as a multi-step process in which the building model is iteratively estimated and refined starting from the raw point cloud.

The presented methodology (Figure 1) first accomplishes the segmentation of the point cloud of a building façade into its planar elements. Then, starting from the identified planar clusters, façade break-lines are automatically extracted to be used later to generate a 3D vector model. During this step some priors on urban scenes like the prevalence of straight lines and orthogonal intersections are exploited to set additional constraints. Despite considerable effort, data obtained with range scanners usually may suffers from occlusions. However, building facades exhibit a high degree of self-similarity and redundancy. For this reason an algorithm was developed for the reconstruction of incomplete models with the help of high-level architectural objects and identification of repeated patterns in urban facades. The final product is a semantically enriched 3D model of the building façade that can be integrated to Building Information Model (BIM).

To demonstrate the reliability, precision and robustness of the method, several tests on different kinds of datasets are illustrated and discussed. The presented tests revealed that while reconstruction efficiency is improved by the developed approach, the geometric accuracy of derived models is also comparable to the one achievable by standard modelling process.

The obtained building models have several applications. In the last part of this dissertation integration of building models with thermal images is addressed in detail. In recent years this task has become quite popular, but actual approaches may not be able to provide accurate and rigorous results. A solution is proposed based on mapping of thermal data on the vector building model. The alignment of both data is obtained with a combined bundle adjustment of thermal and RGB images.

Finally, some of the algorithms developed for façade modelling are extended, and partially modified, to cope with new applications. In particular, the developed segmentation strategy is tested for scan registration of urban scenes which present the prevalence of some few basic geometric shapes. In these cases the identification of the same

1. Building façade at different processing steps: (a) row point cloud, (b) detected planar elements, (c) output vector model, (d) repeated pattern detected, (e) façade object classification, (f) final CityGML model with semantics.

planar features between scans is exploited to determine their registration parameters. A final extension of the developed algorithms concerns modelling of indoor environments. Indeed, automatic reconstruction of buildings exteriors share many problems with the issues associated with indoor reconstruction. However, indoor environments present generally a higher degree of clutter and occlusion than outdoors scenes. For this reason a tailored solution was developed.

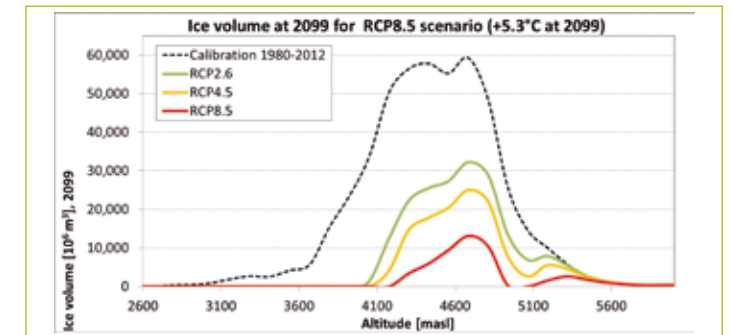# WATER RESOURCES FROM THE MOUNTAINS UNDER CLIMATE CHANGE: THE CASE OF THE UPPER INDUS BASIN

Andrea Soncini - Supervisor: **Daniele Bocchiola**

Overall glaciers world-wide, are shrinking as revealed by the time series of measured changes in glacier length, area, volume and mass. Current glacier extents are out of balance with current climatic conditions, indicating that glaciers will continue to shrink in the future even without further temperature increase. There is a need of a more accurate quantitative knowledge of the different mountain cryospheric components, especially glaciers, frozen ground and snow and of the amount of water stored inside, and of their current changes. Anyway changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, it is expected significant seasonal shifts of the hydrological cycle in the Alps and in other mountain regions worldwide will occur in the near future. Seasonal shift of hydrological fluxes may have fallout upon all uses of water, including availability for agriculture and the food chain, also under multiple re-use schemes, drinking water, hydropower, and ecosystems. Hydrogeological risk, including floods, storm driven landslides, avalanches, may increase under the modified hydrological cycle in mountain areas, where

environmental gradients are strongly enhanced. Integration of water quantity and water quality approaches, is extremely important to understand the societal and economical relevance of water modification under present and future climate change.

One of the mostly interesting and important area in the world respect high altitude water resources is the Hindukush-Karakorum-Himalaya region (HKH). The mountain regions of the Hindu Kush, Karakoram and Himalaya (HKH) are the "third pole" of our planet, and water from therein plays an essential role for agriculture, drinking purposes, and hydropower production. Dynamics of glaciers in Karakoram is complex, and in the last decades the area has experienced substantially unchanged ice cover against the noticeable loss observed worldwide (the "Karakoram anomaly") with stable or even positive ice mass balances and advancing glaciers. Assessment of future water resources and hydrological variability in this area is needed for impact studies of climate change, but the hydrology of these high altitude catchments is still poorly studied and little understood. This work focuses upon a particular watershed, the Shigar river closed at Shigar, with an area of about 7000 km2, nested within

the Upper Indus Basin (UIB) and fed by seasonal melt from two major glaciers (Baltoro and Biafo systems) at the toe of K2 peak, with an ice covered area of ca. 2100 km2. We used a set of hydrological, meteorological, and glaciological data gathered during three years of field campaigns (2011-2013). In particularly daily discharge data coming from two hydrometric stations we installed in the basin and debris thickness, ice and snow ablation data we collected on the Baltoro glacier. Using these data we set up a semi-distributed hydrological model, providing depiction of in stream flows, snow dynamics, and ice cover thickness and their changes in the next century. We also develop an ice-flow model to represent the glaciers dynamics due to the gravity force. We calibrate and validate each model components with observed data obtaining good results in depicting ice and snow dynamics also at high altitude where very few data and literature exists.We then used the model to assess changes of the hydrological cycle until the end of the twenty-first century, by way of downscaled precipitation and temperature projections provided by three state-of-the-art Global Climate Models used in the recent IPCC AR5 (EC-Earth, CCSM4 and ECHAM6) under the RCP2.6,

RCP4.5 and RCP8.5 scenarios. We investigated future (until 2099) ablation flows from the Shigar river. We highlighted the possible consequences of a warming climate upon the cryosphere, and water resources downstream. Our findings highlight in practice mostly increasing in stream flows (against the reference period 1980-2012) until the end of the century, with highest values at mid-century, and potentially decreasing thereon, when ice cover (and ice thickness) begins to decrease sensibly. In the future the ice volume stored at these altitude will decrease in the worst scenario (RCP8.5) of about 90% causing long dry period. Therefore, during the century flood hazard may increase, as much as hazards related to glaciers' down wasting (e.g. GLOFs, icefalls, crevasses), putting at stake local population, and tourists. The present approach profits of sparse data from several sources, and it is simple enough that portability to other catchments nearby should be reasonably feasible, pending availability of some basic information. Eventually, our contribution here seems of interest, as it provides a state of the art, reasonably well substantiated tool to provide conjectures about hydrological cycle of the investigated Shigar river, possibly representative

1. ice volume at different elevations at 2099 compared with actual situation

2. 1954-2013 photo comparison of the Baltoro glacier's snout. There are no evidence of changes.

for the area of Karakoram, and usable for policy makers and planners in the area. High altitude glacierized catchments as here are paradigmatic of glacierized areas within HKH, the third pole of the world, storing a tremendous amount of water to be delivered to populations downstream, and monitoring, assessing and projection of future dynamics here forward is

warranted, to aid taking actions for adaptation to climate change effects.

GRANULAR SHEAR FLOWS: CONSTITUTIVE MODELING AND NUMERICAL SIMULATIONS

Dalila Vescovi - Supervisor: **Diego Berzi**

In the recent past, the flow of granular materials has been the subject of many scientific works; this is due to the large number of natural phenomena involving solid particles flowing at high concentration, e.g., debris flows and landslides.
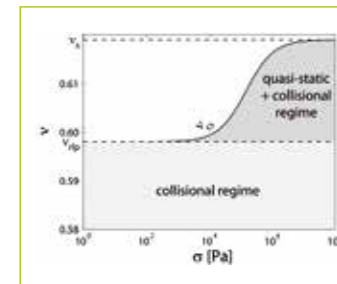
Granular materials are collections of discrete particles characterized by loss of energy whenever the particles interact. Due to their microscopic, discrete nature and their macroscopic behavior, granular materials are treated in both the frameworks of discontinuum and continuum mechanics.

In the realm of discontinuum mechanics, several numerical techniques have been developed, able to reproduce the single particle motions and to control the micro-mechanical properties of the grains. On the other hand, continuum mechanics models for granular flows solve the conservation equations of the whole medium. Although the balance laws are, somehow, easily deducible, the big challenge is the definition of the constitutive relations, which have to be able to capture the macroscopic behavior of the system, incorporating the microscale particle interaction dynamics.

At the microscale level, two possible dissipative mechanisms of interaction among grains are possible: enduring contacts among grains, which are involved in force chains, and inelastic collisions. When the first mechanism prevails, the material behaves like a solid (quasi-static regime). On the other hand, when the particles interact only through collisions, the material response can be assimilated to that of a gas (collisional regime). When the grains interact both through force chains and through collisions, the material is in the transition phase between the two extreme behaviors.

The aim of this work is to propose a theoretical, constitutive model for granular flows, able to deal with the phase transition, where both enduring contacts among particles involved in force chains and collisions are considered. In particular, the steady state condition of a granular material under shear is analyzed. The energy and the total stress are assumed to be the linear sum of a quasi-static and a collisional component, accounting, respectively, for the force chains and the collisions. The quasi-static and the collisional contribution are modeled in the context of the critical state theory of soil mechanics and the kinetic theory of granular gases, respectively. In the critical state theory, the granular material approaches a certain attractor state, independent of the initial arrangement, characterized by the capability of developing unlimited shear strains without any change in the concentration. In this context, the dominant role is played by the friction, which is supposed to support force chains. Also, the quasi-static component of the stress vanishes when the particle concentration is less than the random loose packing, which represents the lower limit for the existence of a disordered granular packing.

In the kinetic theory, the particles are assumed to interact through instantaneous, binary and uncorrelated collisions. A new state variable of the problem is introduced, the granular temperature, which accounts for the velocity fluctuations. The model has been extended to account for the decrease in the energy dissipation due to the existence of correlated motion among the particles and to deal with non-instantaneous collisions.

The proposed theory is applied to two configurations: simple shear flows and Couette flows. Simple shear flows are characterized by homogeneous shearing, then all the variables are constant along the flow field, except for the horizontal velocity which is linearly distributed. In such a simple case, at the steady state, under the usual assumptions of constant shear and normal stresses, the flux of energy is neglected, and an analytical solution can be obtained. According to this approach, the critical state can be interpreted as a particular steady state for which the granular temperature vanishes, as well as the shear rate. Also, a qualitative phase diagram has been drawn in the normal stress-concentration plane.

1. Phase diagram for steady, simple shear flow of inelastic spheres in the plane normal stress-concentration.

The theory has been proved to be capable of reproducing, qualitatively and quantitatively, numerical simulations on spheres taken from the literature, when the concentration is low and the rensponse of the material is dominated by collisions, in both the cases of frictionless and frictional particles. Furthermore, when deformations are very slow and the force chains play a relevant role, the model is able to qualitatively predict the characteristic features of simple shear flows.

In the conditions for which simple shear flows are well predicted, i.e., when using hard, frictionless particles, the theory is applied to the Couette flow configuration. In the Couette configuration, the granular material is sheared between two parallel planes, having infinite length, one at rest and the other moving at constant velocity. The granular material is an assembly of identical, frictionless spheres, and the inter-particle collisions are characterized by the coefficient of restitution (ratio of the relative velocity between two impending particles after and before a collision).

The walls are made bumpy by gluing particles in a regular array, and the bumpiness of the walls is defined in relation with the distance between the edges of two adjacent glued spheres. The resulting flow fields are non homogeneous and vary along the flow depth. In this case, the energy diffusion cannot be neglected, and the set of differential equations deriving from the proposed theory is numerically solved with appropriate boundary conditions. The influence of both the coefficient of restitution and the bumpiness of the walls on the flow variables has been investigated.

In order to make comparisons between the theory and the numerical results, 3D numerical simulations have been performed using the discrete element method (DEM). The simulations are carried out under the constant volume condition, and periodic boundary conditions are applied along the flow and the transversal direction. The theory is in very good agreement with the numerical results when using appropriate boundary conditions. A peculiar behavior has been highlighted by the simulations when using high bumpiness: some flowing particles get stuck in the gaps between wall spheres. This makes the bumpy walls disordered and more dissipative.