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

PhD Yearbook | 2020

DOCTORAL PROGRAM IN ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING

Chair:
Prof. Riccardo Barzaghi

The Doctorate in Environmental and Infrastructure Engineering has been operating since the academic year 2008/2009. The program introduces doctoral students to the world of research on key theoretical and technological elements associated with water, environment, hydraulic and transportation infrastructures, geology, as well as geomatics.
In this context, the program is grounded on environmental, civil, and industrial applications where water is the primary unifying element. The doctorate program is characterized by a strong inter- and multi- disciplinary structure and is organized according to the following key thematic areas.

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 and wastewater treatment technologies (including disposal/reuse of wastewater, sludge management and disposal, anaerobic digestion processes; management and planning of environmental resources (including water quality modelling, knowledge-based decision support systems); solid wastes management (including Life Cycle Assessment of energy and resource recovery initiatives); phenomenology of the atmospheric environment and treatment of gaseous emissions; contaminated soils and their remediation.
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.
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.

DOCTORAL PROGRAM BOARD

Riccardo Barzaghi	Mario Grosso	Federica Migliaccio
Manuela Antonelli	Alberto Guadagnini	Monica Papini
Gianfranco Becciu	Giovanni Lonati	Alessio Radice
Barbara Betti	Laura Longoni	Monica Riva
Daniele Bocchiola	Stefano Malavasi	Maria Cristina Rulli
Maurizio Crispino	Francesca Malpei	Emanuele Toraldo
Carlo De Michele	Marco Mancini	Giovanna Venuti

ADVISORY BOARD

Sanchez-Vila Xavier	Universitat Politècnica del Catalunya - Barcelonatech, Barcelona (Spain)
Ackerer Philippe	Université de Strasbourg (France)
Ruffo Paolo	ENI, Milano (Italy)
Burlando Paolo	ETH, Zurigo (Switzerland)
Sansalone John J.	Florida University (USA)
Marino Carlo	ARPA Lombardia
Bortone Giuseppe	ARPA Emilia-Romagna
Losa Massimo	Università di Pisa
Marti Urs	SwissTopo, Berne (Switzerland)
Dermanis Athanasios	Aristoteles University, Thessaloniki (Greece)
Radicioni Fabio	Università di Perugia, Perugia (Italy)

SCHOLARSHIP SPONSORS

Metropolitana Milanese	Pibiviesse	Ricerche sul Sistema Energetico - RSE
Lario Reti S.p.A.	European Space Agency	Agenzia Spaziale Italiana
ENI	EURAC	Goodyear - LIST
Fondazione Cariplo	Banca d'Italia	Regione Lombardia – ENEA
CAP Holding S.p.A.	Acque Bresciane	Geolog Technologies s.r.l.
Bracco Imaging s.r.l.	ERSAF – Ente Regionale per i Servizi all'Agricoltura e alle Foreste	

DECISION SUPPORT SYSTEM FOR HYDRAULIC RISK MANAGEMENT OF A RIVER BRIDGE

Gianluca Crotti - Supervisor: Prof. Francesco Ballio

Tutor: Prof. Stefano Malavasi

A number of river bridges collapses worldwide every year during flood events, due to combination of actions including traffic loads, water and wind load, river bed degradation, accumulation of debris. Statistics of bridge collapse in several countries around the world indicate hydraulic processes as the main triggering cause: the bed level variations and local scour around bridge foundations are predominant factors.
A comparative analysis of some national building and maintenance codes over the last 20 years reveals that, with respect to the past, recent codes provide more explicit and punctual indications to designers and managers on how to evaluate and take into consideration the interactions between the river system and the structure. Evolution of codes is expected to grant higher level of safety for bridges. However, it also makes several existing structures to be no more compliant with the new standards; considering the increase of the nominal traffic and wind loads in the last sixty years and the modification of reference hydraulic hazard scenarios due to climate change. Considering that it is not economically feasible to construct all bridges to resist all conceivable floods, or to install scour countermeasures at all existing bridges to ensure absolute invulnerability from scour damage, some risks of failure from future floods may have to be accepted. How can we manage a bridge that is no more compliant with the new standards? While one might regretfully accept the possibility of a bridge failure, failure-induced casualties must be instead avoided. To handle this situation there are, basically, three ways: (i) to rebuild the bridge, (ii) to reinforce the bridge to increase its resistance and so respecting the new standards or (iii) to use a monitoring system and associated procedures to manage the structure anytime. Depending on the specific case it is also possible to combine different strategies. The last one considers real time management of river bridges as a non-structural risk mitigation measure, alternative (or in addition) to the standard structural countermeasures. The implementation of such a Decision Support System (DSS) is the key scope of this thesis. More specifically, we propose a DSS, based on a monitoring infrastructure, which helps the bridge managers decide whether a bridge should be partially or totally closed to traffic due to a forecast of particularly harsh environmental conditions which may lead the structure to operate out of its safe operational zone. Bridge management may not prevent the damage of the structure but should avoid casualties. Such a strategy is consistent with the indications of the Eurocode EN 1990 which states (clause 2.2) that “the measures to prevent potential causes of failure and/or reduce their consequences may, in appropriate circumstances, be interchanged to a limited extent provided that the required reliability levels are maintained.”

The specific case study under discussion is a road bridge across the Po river, Italy. The structure, built in the sixties, is relatively well preserved; however, traffic and wind nominal loads are now larger than the design values and there is historical evidence of strong variation of the river bed elevation at the bridge cross-section, which was not originally accounted for. Analysis of past events and the simulation of possible future scenarios show that a proper management protocol of closure of traffic on the bridge, based on indications from a monitoring system, allows for adequate safety with respect to casualties without significant impact of the functionality onto the infrastructure. A peculiar feature of present proposal is that the monitoring system is focussed on the evaluation of the environmental actions on the structure rather than on the health state of the structure itself. Such a choice is in this case necessary, as warning based on variation of properties of the structure (a classic Structural Health Monitoring, SHM) would not give sufficient lead time to perform the actions that are necessary for bridge closure. With respect to a structural pier reinforcement, the non-structural strategy here adopted is advantageous in that: (i) it is less expensive, (ii) through a continuous monitoring it provides a deeper knowledge of the environmental actions on the structure, (iii) it is more flexible and adaptable to future changes of the environmental scenarios. The necessity of a technological system and a management plan for guaranteeing the required safety constitutes the obvious drawback of the proposed solution. From this point of view, time becomes the most important parameter to control. Knowing the stress state of the structure anytime (now and in a forecasted evolution), thanks to the monitoring system we can develop procedures to manage the bridge from normalcy to emergencies (floods) possibly arriving at its closure.
Basically, the DSS dataflow has to answer at least three questions. (i) “Is now the bridge in safety condition?”: we need a real time monitoring system together with a structural model to evaluate the stress state of the structure anytime, also computing a safety coefficient of the bridge. (ii) “How much time do we have before the potential bridge collapse?”: we need a scenario forecasting to understand the evolution, in time, of the safety coefficient. (iii) “How can we manage a bridge anytime?”: we need an emergency procedures according to the scenario forecasting to manage the structure for every safety coefficient time evolution leading to the complete closure of the bridge.
Regardless of the structure to manage, the DSS is composed by five conceptual blocks: (i) a real time monitoring system focusing on the evaluation of the environmental actions on the structure; (ii) a data analysis tool to evaluate the reliability and validation of the data; (iii) a structural model to determine how far the structure is from collapse; (iv) a forecasting scenario to indicate how much time is left to exit from the safe operational domain of the structure and (v) procedures to manage the structure from the normalcy to the emergency state.
The methodology is presented with reference to the field case of a bridge over the river Po (Italy); its generalization to a larger variety of conditions is also discussed.

WATER INDIRECT REUSE: FROM AN UNPLANNED RISK TO A PLANNED RESOURCE

Riccardo Delli Compagni - Supervisors: Manuela Antonelli

Reuse of reclaimed wastewater (RWW) in agriculture has recently received increasing attention as a possible solution to water scarcity in many parts of the world. However, RWW can still contains a large variety of contaminants of emerging concern (CECs), which can seep into the soil and enter into the food chain through uptake of edible plants, posing a risk to the environment and human health. Quantification of the risk consists of understanding the level of exposure concentrations with respect to safety thresholds derived from ecotoxicological studies. Historically, determination of exposure concentrations depended essentially on measurements. However, the monitoring of thousands of CECs in different environmental compartments is unfeasible (both economically and physically). Moreover, measurements are discontinuous in-time, site/person-specific and do not allow extrapolating contamination levels to others systems. Developing of reliable modelling tools can help to overcome these challenges.

The purpose of this PhD thesis is to contribute to filling the knowledge gaps in the field of risk assessment related to spread of CECs in RWW reuse systems. Specifically, the thesis aims at developing a modelling framework capable of supporting policy-makers to assess the environmental and human health risk of current and future water reuse management strategies. Moreover, the framework is indented for the planning of measuring campaigns to collect samples with high representativeness in order to allow a proper evaluation of compliance with current and forthcoming standards. In this work, the RWW reuse system was considered as made of 5 elements: (i) CECs sources (e.g. cities, industries, hospitals), (ii) combined sewer network, (iii) conventional wastewater treatment plant (WWTP), (iv) surface water and (v) irrigation system. Within this framework, dynamic deterministic conceptual models (both lump and distributed), have been combined with advanced statistical methods (i.e. cluster analysis, uncertainty analysis, stochastic generators, etc.) to make the best use of heterogeneous data sources (e.g. georeferenced information, sales data, etc.) to predict CECs exposure concentrations in target environmental compartments (surface water and edible plant organs). Risk assessment was mainly investigated due to: discharge of treated and untreated wastewater (during rain events) into receiving water system (i.e. environmental risk) and, (ii) human consumption of contaminated edible plants irrigated with RWW (i.e. human health risk).

The fate of down-the-drain CECs (e.g. pharmaceutical active compounds - PhACs, personal care products, etc.) from emission sources to the WWTP was first investigated. Within this context, a new systematic approach, combining GIS-based information and a Gaussian mixture model, was developed to identify the optimal structure of a multi-catchment conceptual model to simulate the fate of CECs in large urban catchments. The approach was tested in a catchment located in a highly urbanized Italian city and model performance compared against a traditional single-catchment conceptual model. Results showed that the multi-catchment model allows for a successful simulation of dry weather flow patterns and for an improved simulation of CECs fate compared to the classical single-catchment model.
Secondly, an existing micropollutants fate model library (IUWS_MP) was extended to simulate the fate of PhACs with different properties across the whole Integrated Urban Wastewater and Stormwater systems (IUWS – drainage systems, wastewater treatment plants, receiving water bodies). Extensions included specific PhACs fate processes (deconjugation) and a consumption-excretion model to allow simulation of seldom monitored PhAC fractions (e.g. metabolites and fractions entrapped within the faecal matter) along the whole system, thus refining fate and risk assessment in RWW system. PhACs process descriptions was based on simple equations (e.g. first-order kinetics rates to describe deconjugation) and easily retrievable input-parameters (e.g. inherent chemical-physical properties, consumption data, etc.) to minimize the need of data collection for model calibration (except for validation). Model predictions were tested in two different real case studies (i.e. Italian and Danish ones) under dry-weather conditions for 5 highly-consumed PhACs (i.e. carbamazepine, diclofenac, ibuprofen, furosemide and paracetamol). Predictions showed good agreements with measurements at various comparison points (e.g. WWTP inlet and outlet). Possible model implications included: (i) identification of potential environmental risks due to non-compliance of PhACs with existing or proposed environmental quality standards at the WWTP/sewer outlet and (ii) evaluation of the effects of different control strategies in reducing risks for the aquatic environment.

Then, the fate of PhACs under wet weather conditions was assessed to: (i) evaluate the impact of combined sewer overflows (CSOs) on surface water streams and (ii) identify optimal sampling strategies (i.e. type of composite, frequency and duration) to sample CSO concentration as much representative as possible. Specifically, a dynamic distributed model was coupled with stochastic PhAC loads generator to make the best use of census and georeferenced data (e.g. number of people per household, age and sex, house location) as proxy variables of unknown/confidential information (e.g., location of the person taking a certain drug, prescribed posology) to simulate realistic PhACs dynamics in sewer systems. Model prediction capabilities were tested in a small Swiss catchment where high-frequency measurements for diclofenac were available during wet-weather conditions. Results showed a proper match between model predictions and measurements.
The model was then used to predict diclofenac concentrations at the CSO location during different rain events. Results highlighted that diclofenac concentrations can exceed the quality standard (i.e. the chronic standard was used since an acute standard is not available yet) in the sewage flow discharging to the water stream, posing a risk for the environment. Simulations also showed that flow-proportional mode with a high sampling frequency (2-5 minutes) is the most appropriate way to capture most of the diclofenac load passing through the CSO structure.

Lastly, the extended IUWS_MP was coupled with a dynamic plant uptake model to predict the fate of CECs beyond wastewater treatments. The modelled system included a discharge channel and cultivation area where four different types of crops were irrigated with RWW. The model showed capability and flexibility in describing the fate of 13 CECs (clarithromycin, sulfamethoxazole, diclofenac, ibuprofen, paracetamol, carbamazepine, furosemide, 17α-ethinylestradiol, 17β-estradiol, estrone, perfluorooctanoic acid, perfluorooctane sulfonate and triclosan), covering a wide range of physicochemical properties, across different compartments and over long-time intervals. Model predictions were generally verified with measured data, thus allowing for the evaluation of ecological and human health risk. A negligible risk was predicted for most CECs, while sulfamethoxazole and 17α-ethinylestradiol exhibited the highest risk for consumers. Model predictions identified conventional wastewater treatments as an efficient barrier to reduce the overall risk of simulated CECs, although further reduction can be obtained by adopting more efficient irrigation practices.

FLOW MANAGEMENT AND ENERGY HARVESTING WITH THE GREENVALVESYSTEM

Giacomo Ferrarese - Supervisor: Stefano Malavasi

Control valves are used in civil and industrial plants to control discharge and pressures in pipelines. The process through which valves are able to control the fluid dynamic parameters is flow throttling that consists in the dissipation of a certain amount of energy.
In the last years' new frontiers of water management opened the way to innovative solutions that are able to improve the efficiency of plants both from the energetic and functional points of view. In this context the GreenValveSystem project takes place.
The core topic of the research is the development of the GreenValveSystem (GVS), an innovative control valve, based on a patent by Politecnico di Milano, designed to control the flow whereas recovering part of the energy dissipated in the process. The concept at the basis of the system is the creation of a control valve with additional functionalities that opens the way to innovative plant management strategies and improves plant efficiency. Part of the energy harvested is used to feed the instrumentations required for valve positioning according to defined, but remotely tunable, logics and to monitor and record data about the main parameters of the flow and of the system functioning. The data collected is then sent by an integrated communication system to a database for query. A scheme of the system can be seen in Figure 1 where the different styles of arrows indicate the different kinds of flows between the components.

A first section of the study regarded the evaluation of the energy dissipated in the throttling processes using the data of some examples from civil and industrial environments. For example, the data from a refinery and that of some district heating plants are considered for the calculation showing the total amount of energy dissipated. The standard energy recovery solutions, like PAT and micro turbines like cross-flow, are introduced and a threshold for their application is discussed in the end of the first section. Data both from bibliography and real plants are used to discuss the theme. Particular attention is given to the energy dissipated in civil environment and in particular through the pressure reducing valves used in aqueducts. These devices are particularly interesting for the application of the device under study for many reasons. The first is that often that kind of valves are installed in locations where the connection to the electric grid is not simple, making the availability of energy on site very advantageous. The second one is that the nodes in which a control valve is installed need usually to be monitored. Features that are specific of the device under study.

During PhD years the valve has been designed starting from starting from a patent of Politecnico di Milano and from a first prototype produced in the laboratory of hydraulic of the Politecnico di Milano (LIF), then developed, with the support of a valve manufacturer, to a prototype that has the requirements for the installation on real plant. Multiple kind of tests have been performed in the laboratory to verify the effectiveness of several aspects of the prototype that are the energy recovery, both mechanical and electrical performances, the quality of pressure control, the effectiveness of the control logic, the hydraulic characteristics such as cavitation aspects and flow capacity. The results of the tests are used to optimize some components of the valve. Particular attention is given to the quality of pressure control guaranteed by the system. After the phase of design and test four prototypes have been produced by a valve manufacturer and three have been installed in field. The installations were put in place in three different networks with different regulation requirements. The system worked in the field as stand-alone device, able to be remotely controlled and to supply monitoring data at the frequency of 1Hz. Through a direct comparison between pressure data of the pipeline before and after the installation was possible to verify that, in the cases studied, the GVS is able to increase the accuracy of the pressure regulation with respect to the installed PRV. In Figure 2 the regulated pressure of one of the field cases, is compared before and after the installation of the prototype.

The data collected has been stored on a database and an application to control in real time the state of the valve and the historical of the data is available at www.gvsmonitor.com. Using the data collected detailed information on the functioning of the valve in a real environment are available and have been used to verify the good performance of the system.

The functionalities added to the control process include the possibility to have local available energy, the possibility to remotely control the device, the possibility to change the working conditions or even to close the valve, the availability of a monitoring system able to collect the data of pressures and flow rate with a frequency of 1Hz without connection to the electric grid. All these new features enable new applications and new management methods for water distribution network.

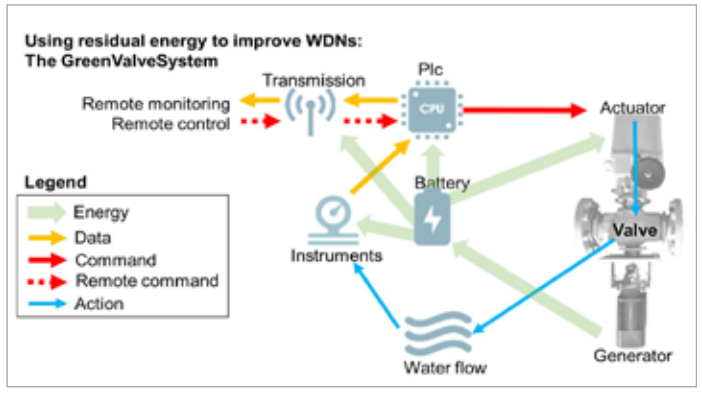

Fig. 1 - Functioning scheme of the prototype

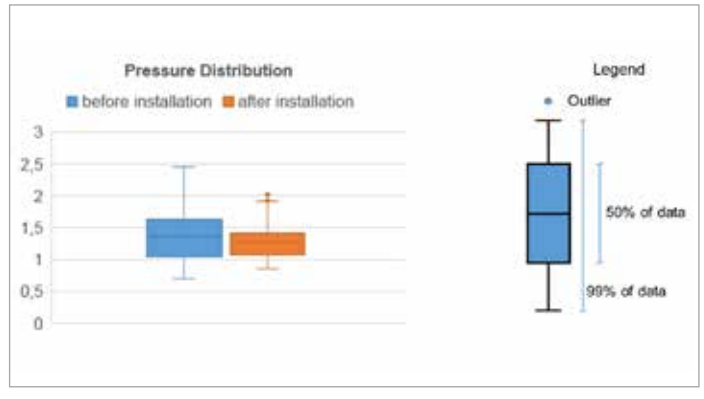

Fig. 2 - Pressure regulation quality before and after the installation on plant.

USING FREE AND OPEN SOURCE SOFTWARE FOR MULTIDIMENSIONAL VISUALIZATION AND PROCESSING OF BIG OPEN URBAN GEOSPATIAL DATA ON THE WEB

Candan Eylül Kilsedar - Supervisor: Prof. Maria Antonia Brovelli

Big data have become a significant area of study for both researchers and practitioners, as they have a great potential to benefit humanity in various domains, including climate change, disease surveillance, disaster response, and monitoring infrastructure. Assuming 80% of data possess a geographic reference, handling big geospatial data is a challenge worth undertaking in terms of storing, managing, processing, analyzing, and visualizing them. Improving the quality of the methods for handling big geospatial data improves the quality of the applications that employ such data and as a result, the decisions made using the applications. This research aims to develop innovative Geographic Information System (GIS) tools that employ various big geospatial datasets, built on the existing tools for handling big geospatial data, to understand several urban dynamics better and as a result, to manage natural resources in urban areas and urban infrastructures more effectively.

The GIS tools developed enable geospatial data visualization, query, and processing via a geoportal that is available on the Web. Integration of heterogeneous datasets, both in terms of context and format and technologies in the same geoportal poses technical challenges that were tackled to produce the geoportal.

Furthermore, the multidimensional vector and raster geospatial data (x/y/z and x/y/t) were challenging to handle both due to their multidimensional nature and large sizes. Multidimensional big vector and raster geospatial data visualization and processing on the Web is a well-recognized challenge in the literature.

The geoportal is available on the Web so that access to it is independent of users' operating system. Moreover, open standards to ensure the interoperability of the geoportal were adopted. Furthermore, Free and Open Source Software (FOSS) and open data were used for developing the geoportal, as they diminish the barriers to access and use geospatial software and data. The geoportal is composed of four dynamic and interactive virtual globes that represent four applications. NASA Web WorldWind and CesiumJS were utilized for creating the virtual globes. Below, a summary of the applications that are designed to respond to the challenges listed above is given.

In the first and second applications, 3D vector data were visualized. In the first application, NASA Web WorldWind and 3D OpenStreetMap (OSM) Plugin Application Programming Interface (API) for NASA Web WorldWind that I developed were used to create triangle meshes for the 3D visualization of buildings to decrease the time spent for rendering and painting using the data of one of the most prominent Volunteered Geographic Information (VGI) projects, OSM. The API enables initiating a geodatabase query using a Graphical User Interface (GUI), geovisualization of the response to the query, and the manipulation of geovisualization parameters. In the second application, 3D vector data of buildings in CityGML format were utilized. CityGML data were converted to tiled KML/COLLADA/glTF data using 3DCityDB Importer/Exporter. The tiled data were visualized employing the 3DCityDB-Web-Map-Client that extends CesiumJS. A virtual 3D city model can be used for various application areas, such as noise propagation simulation and mapping, energy-related assessments of buildings, indoor navigation, disaster management, and homeland security. In this work, virtual 3D city models in CityGML format were used for flood simulation (see Figure 1).

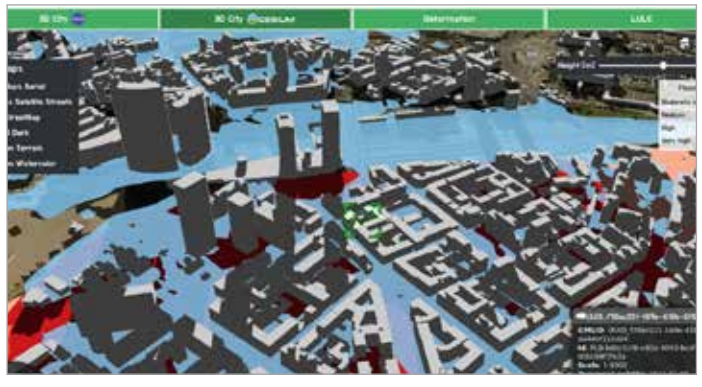

Fig. 1 - Flood simulation in Milan with a flood risk map and the visualization of CityGML data on a virtual globe created using CesiumJS

In the third and fourth applications, 3D raster data were visualized. Web Map Tile Service (WMTS) was used for big raster data visualization. WMTS achieves visualization of big raster data by tiling and indexing. For adding a time dimension to the raster data, the ImageMosaic data store of GeoServer was used. The tiles were created using GeoWebCache (GWC) integrated into GeoServer. GWC was also used for storing the tiles served through WMTS to decrease the access time to them. For the visualization of the ImageMosaic, which represents spatio-temporal data, animation using the animation and timeline widgets of CesiumJS was employed, as interactive animations can be used for the visual exploration of spatio-temporal data.

The third application employed ground deformation data and the fourth application employed Land Use and Land Cover (LULC) data. The raster data used for ground deformation animation were obtained through summarization of the raw data to avoid information overload in the visualization. In the fourth application, additionally, multidimensional raster data can be processed using the Web Coverage Processing Service (WCPS) implementation of rasdaman by making a query using the GUI (see Figure 2). rasdaman uses parallel computing and tiling and indexing to accelerate data processing. Additionally, VGI was placed on the raster imagery, which brings together informal data with formal maps. Finally, mean deformation velocity maps and VGI can be queried. The response to the queries is visualized as a text or plot.

Fig. 2 - Processing of the drawn area of GlobeLand30 that calculates the amount of change of permanent snow and ice cover from 2000 to 2010

SUSTAINABILITY ASSESSMENT OF ELECTRIC MOBILITY

Benedetta Marmiroli - Supervisors: Prof. Dotelli, Prof. Messagie

Transportation is the backbone of capitalistic society, and transport of goods and people absolves to several functions. Our wellness depends on goods and people movements, and in particular on private transport.
The demand for transport is directly related to the households' income: the higher the income, the higher the vehicle kilometre travelled. And vice versa. There has been a close statistical correlation between the growth of Gross Domestic Product and growth in transport, both passenger and freight. Growth in per-capita income levels has had a positive effect on the ownership and use of private vehicles, tending to increase reliance on private vehicles to meet mobility demand, particularly in emerging economies. If present transport policies do not undergo significant changes, CO_2 emission from transport will increase around 2/3 between 2015 and 2050. Electric mobility has the ability to detach transportation and fuel consumption if policies in matter of transportation and electricity generation are taken, thus solving the main problem of the transportation sectors. Policy makers must take decisive action now to put transport on a sustainable path.
The transition to a sustainable transport sector requires a framework able to quantify and define metrics in order to achieve this sustainability. In order to do so, a combination of Life Cycle Assessment tool and Energy System Analysis has been built to define a framework to assess transition to electric mobility. Life Cycle Assessment has proved to be the right tool to have a comprehensive picture of environmental problem.
The system boundary of the electric mobility has been detailed in order to include all the aspects of the transport sector in the analysis: the vehicle production and use, the infrastructure and the energy carrier used to propel the vehicle (1).
The thesis is structured following the three axes of mobility presented in Figure 1. In chapter 1, the Life Cycle Assessment of three identical vehicles equipped with different powertrains is analysed. The analysis presented in this chapter stemmed from the limits of the comparisons between electric vehicles and traditional mobility found in the literature: differences in system boundaries, vehicles properties and functions, make the comparison unfair and not clear. Thanks to the collaboration with an Italian car manufacturer, it was possible to address the gap found in the literature studying the production system of a light commercial vehicle with three different powertrains (Compressed Natural Gas, Electric engine, Diesel). The vehicles are produced in the same plant and the differences between them are due only to the different powertrain and related components. The peculiarity of this system allowed to even out comparison inequalities that usually originates in LCA studies comparing traditional and electric vehicles. The results of this analysis show a higher impact in the production phase of the electric version of the LCV, with a relevant contribution from the battery. However, the analysis indicates that the lower impact in the use phase compensate for the higher impact of the production.
In chapter 3 the hurdles of the infrastructure required for the shift to a widespread adoption of electric mobility are addressed. In particular, the effects of the introduction of a cutting-edge technology like the on-road dynamic charging are analysed. The on-road dynamic charging technology could be seen as a possible solution to push the widespread adoption of the electric vehicles. Due to the greater complexity of this system the analysis cannot be limited at the vehicle itself, but it requires an evaluation of the entire system and the definition of scenarios in which this technology could be profitable. The first part of the work was the definition of scenarios for the implementation of this technology. The second part was the drafting of guidelines for the application of the LCA methodology to such a complex system. Based on the definition of scenarios set in the first deliverable and on the data collected by the partner of the project, the impact related to construction and implementation of the infrastructure for the Dynamic charging adoption has been assessed.
In chapter 4 the role played by electricity generation in Life cycle assessment of electric mobility is addressed, through an extensive literature search, and a meta-analysis of the data available is performed in order to get meaningful insights from pervious researches. The analysis shows that Life Cycle Assessments on electric mobility are providing a plethora of diverging results. 44 articles published from 2008 to 2018 have been investigated in order to find the extent and the reason behind this deviation. The first hurdle can be found in the goal definition, followed by the modelling choice, as both are generally incomplete and inconsistent. These gaps influence the choices made in the Life Cycle Inventory (LCI) stage, particularly regarding the selection of the electricity mix. A statistical regression is made with results available in the literature. It emerges that, despite the wide-ranging scopes and the numerous variables in the assessments, the electricity mix's carbon intensity can explain 70% of the variability of the results. This encourages a shared framework to drive practitioners in the execution of the assessment and policy makers in the interpretation of the results.
When it comes to evaluating the effect of a transition to electric mobility drawing the attention to the vehicle level can be misleading. In order to have a deep understanding of the phenomenon stopping at a vehicle level it is not enough to evaluate electric mobility. As mentioned in chapter 3, the dimension of the analysis should be at fleet level/ scenario level, when the aim is to inform the decision makers on the effect of shifting to electric mobility. In this case the entangled system transport-power generation has to be included in the analysis. In order to do so, explorative scenarios, evaluated with the use of ESA tools has been identified as the correct solution.
In chapter 5, as a proof of concept, the Italian energy and transportation systems at 2030 has been analysed under different EV and Renewable Energy sources penetration scenarios, using the ESA tool EnergyPLAN.
The results obtained showed environmental benefit of shifting to electric mobility - compared with the business as usual - that a classical LCA structure at vehicle scale would have not detected. In particular, the role played by the introduction of a massive amount of EVs in the power system allows to reduce GHG emissions not only because of the use of more efficient motors but also because of the synergies of electricity demand from EVs and intermittent sources.

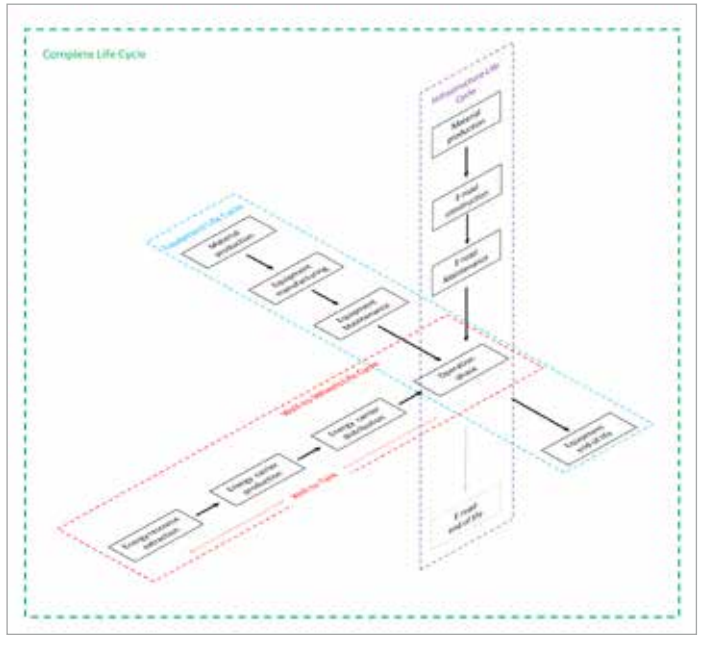

Fig. 1 - System boundary of the electric mobility

IN SITU TECHNOLOGIES FOR THE TREATMENT OF HEXAVALENT CHROMIUM

Andrea Filippo Mastorgio - Supervisor: Prof. Elena Sezenna

Chromium is one of the most frequently used metal contaminants. Its hexavalent form Cr(VI), which is exploited in many industrial activities, is a known human carcinogen and, being water-soluble in the full pH range, represents a major threat to groundwater resources. Many polluted sites show extensive Cr(VI) plumes in groundwater.
The traditional approach to Cr(VI) remediation by contaminated soil excavation and off-site disposal and groundwater remediation through the "Pump and Treat" method is still the selected option at most sites, even new in situ technologies have been developed in recent decades up to full scale and nowadays accounts for many field applications. These technologies include chemical-physical removal processes through electrokinetic and soil flushing, chemical reduction with iron or sulfur-based reagents, or bio-induced reduction with registered brand reagents. Due to the complex behavior of chromium in the environment and to its interaction with numerous chemical species in the subsurface, careful evaluations of site-specific conditions and maybe specific tests are required for selecting the best approach to site remediation.
In the first part of this thesis, a thorough review of existing literature on the environmental behavior of chromium and available technologies made it possible to identify significant scenarios of Cr(VI) contamination and feasible approaches to Cr(VI) remediation in the different contexts, leading to the definition of selection criteria for preliminary assessment of potential exclusion of some technologies. The main factors that influence to the choice include: i) pH (5-7; 7-9), ii) Cr(VI) concentration (below/above 100 mg/kg unsaturated soil or 10 mg/l in groundwater), iii) iron availability in the soil (above/below 1 g_{Fe}/kg) and iv) soil heterogeneity (variation in hydraulic conductivity or intrinsic permeability within or more than 2 orders of magnitude).
The experimental part of the work aimed to investigate in situ bioremediation, and the remedial option with the greatest potential for combining efficiency and sustainability, both in terms of costs and environmental impacts.
Microorganisms, thanks to their adaptability and metabolic versatility, are capable of not relying solely on various toxic compounds for carbon or energy sources, but also of adopting different detoxification strategies in order to adapt and survive in contaminated environments.
Biological activity in the subsurface can be stimulated to ensure, proper environmental conditions (e.g. neutral pH, electron acceptors availability, ...), by means of external supplies of substrates, nutrients and electron acceptors. Experimental activities investigated:

Bio-induced reduction, relying on the injection of rapidly biodegradable organic substrates to promote reducing conditions into the aquifer, viable for Cr(VI) reduction.
Bioelectrochemical systems (BESs), taking advantage of the ability of several microrganisms to make use of solid electrodes as electron acceptors or donors to carry out their own metabolic reactions.

Bio-induced reduction technology has already been used in full-scale remedial works, traditionally done using expensive trademark registered products. As alternative organic substrates, two different cheap food industry by-products (ultrafiltration permeate of cheese whey and waste from brewing processes) have been investigated in terms of removal of Cr(VI) from groundwater and of the kinetics of the process in lab-scale batch tests. Batch microcosms using 5 and 10 mg/L Cr(VI) initial concentration, two different soils, and 25% or 50% solid/liquid ratios were set up. Important removal of dissolved Cr(VI) was observed at the end of the total incubation time (approximately 40 days). Key factors to Cr(VI) removal in induced bioremediation are the initial concentration of Cr(VI) and the availability of Fe(II) for Cr(III) co-precipitation. Precipitation of the reduced chemical form is not instantaneous; stable redox potentials below -200 mV vs SHE were required to observe Cr(VI) reduction. Higher Cr(VI) abatements were observed in the soil with a higher total heterotrophic bacteria concentration (10^4 vs 10 CFU/$g_{d.w.}$).
The use of inexpensive by-products can be considered as a possible alternative to registered products for Cr(VI) bio-induced reduction, with interesting prospects in terms of limiting costs and environmental impacts. A peculiar limitation with by-products is the difficult definition of the appropriate dose to be used to suit to site-specific conditions. Doses that are too high can cause negative secondary effects in the aquifer and the accumulation of residues and metabolites, conversely, an insufficient supply produces a stall in Cr(VI) reduction. Furthermore, with bio-induced reduction, chromium precipitates throughout the contaminated area with no concrete chance of recovering the metal, which possibly undergoes partial re-oxidation with time.
BESs is an innovative technology, with only some positive laboratory experiences in soil/sediment treatment reported so far. Most of the available data refers to exposure to electrostatic fields or electrical fields generated by direct current, already exploited in electrokinetic processes. Most of the experiences available in literature on Cr(VI) treatment with BES have been focused on wastewater treatment combined with energy recovery in Microbial Fuel Cells (MFC). Such systems use Cr(VI) at the cathode as an effective electron acceptor of the electrons resulting from the oxidation of organic substances at the anode. The high chemical reduction potential of Cr(VI), especially at acidic pH, is responsible for energy production. In the case of groundwater, an external power supply is required due to a low concentration of oxidable organic matter and a pH typically around neutral value. The research activity focused on the design and development of lab-scale BESs to carry out Cr(VI) reduction tests. Lab-scale batch and continuous tests in microbial 3-electrode cells (M3Cs) were used to investigate Cr(VI) removal in polluted water at 1-2 mg/l Cr(VI). To run these systems an potentiostat was used that had been built in-house, to set the biocathode potential in the range -300 mV and +700 mV vs Standard Hydrogen Electrode (SHE). Abiotic and open-circuit controls were also set up, to discriminate i) purely electrochemical from biological reduction, and ii) compare bioelectrochemical to just biological reduction.
BESs, with properly set electrode potential, showed higher Cr(VI) removal efficiencies in comparison to purely electrochemical or biological processes. The fastest decrease in Cr(VI) concentration was observed in a test with a biocathode poised at -300 mV vs. SHE, that, after only six days' operation, showed a 7% residual chromium concentration. Microbial analysis, performed by 16S rRNA gene sequencing, made it possible to evaluate the selection in the systems of bacterial communities containing electro-active and/or Cr(VI) reducing/resistant bacteria. Known electro-active bacteria (EAB) were able to adapt; autotrophs like *Alcaligenaceae* appear to be favored. *Bradyrhizobiaceae, Trueperaceae* and *Flavobacteriaceae* were selectively enriched on the polarized cathode biofilm; the microbial consortium makes a contribution to high removal of chromium to the biocathode.

CLIMATE, WATER, ENERGY NEXUS: POTENTIAL IMPACTS ON HYDROLOGY AND HYDROPOWER PRODUCTION

Epari Ritesh Patro – Tutor & Supervisor: Prof. Carlo De Michele

In the present economic and technological conditions, hydropower has been the dominant source of renewable electricity generation component of the worldwide energy-mix. As one of the key sources of grid stability, flexibility and primary storage technology, hydropower needs to evolve and adapt to the challenges and opportunities dictated by the changing conditions. Evidently considering the greater reliance of hydropower on the hydrological cycle, effects of climate change dynamics cannot be neglected. Hydropower has three major uncertainties to address a) uncertainty in future hydropower generation due to climate change, b) influence on the future electricity mix due to variability in hydropower and vice-versa, and c) uncertainty of hydropower's future revenue.
Even though existing research have quantified these issues but there has been little research to examine them in a holistic manner.
Future perspectives of hydropower in a changing climate have been the subject of a fairly extensive body of literature, but most research has addressed either water supply or energy demand. Also, most research has focused on storage hydropower, a rather robust technology to climate variability due to the possibility of adapting storage management to variable streamflow patterns. Future perspectives of run-of-the-river (ROR) hydropower plants, which represent an important component of the energy market that have no regulation capacity, have been much less investigated. Sedimentation is a major problem for dam and reservoir management worldwide due to the associated economic and environmental consequences.
The interest of this research is also to understand varying impacts due changing scenarios on hydropower operating in different mode, one being storage type and other being run-of-the-river mode but situated in the same area. If the economic viability of hydropower projects is of concern, climate change may or may not be important. But in long term fluctuation in electricity prices must be accounted since it can have wider impact. Nevertheless, it should be remembered that, below a definite profitability level, hydropower is not sustainable and may jeopardize the energy supply security.
An inventive modelling approach was used to address the interest of this research by combining engineering (hydrology, hydraulics and sedimentation) and economics (revenue maximization and electricity prices evolution) to understand from interconnecting perspectives, as shown in graphical abstract (Fig.1). Basically, it simulates multiple hydrological scenarios, based on simulated multiple future electricity price and its seasonality for covering the sustainable functionality of hydropower. This PhD research applied the aforementioned methodology for case studies in Italy, Switzerland and as well as at a nation-wide scale of Italian hydropower evaluating until the end of this century. Findings have identified that run-of-the-river hydropower in Italy faces a median decrease of -3% across all basins and all scenarios. Results show that in catchments where the proportion of glacier area over the total area of the catchment ratio is currently greater than 10%, run-of-the-river hydropower is particularly exposed to medium-term impacts of climate change (through 2065). Hydropower operators will need to adapt to changing climate scenarios to preserve optimum productivity. Electricity price seasonality (and by extension the energy market as a whole) has thus the potential to significantly change conclusions drawn from water-supply simulations i.e. viability and profitability are deeply interconnected. It also emerged from the study that areas with higher erosion variances (positive and negative) are probable to amplify in the future, and their patterns will be restrained by future climate and land use. The increased knowledge about future hydrological conditions, improved hydrological simulations and good assessment of modelling uncertainty can assist in focusing on the management of water resources in an altered climate scenario.
This research supplements to literature pursuing to provide understandings for existing hydropower by integrating updated knowledge on hydrologic, hydraulics, and sedimentation processes to address the water management of impounded river basins through a holistic paradigm (Fig. 2). In particular, this thesis aims to assess the representation of hydropower in a more comprehensive manner than it has carried out before within the management model, addressing the following issues: 1) re-think of design scenarios of dams taking into account modified climate conditions, and considering not only the streamflow variable, but including also electricity prices and sediment; 2) update of dam operations in order to accommodate modified behaviour of climate forcing's and hydrologic variables, and modified needs; 3) illustrate some demonstrative case studies considering post-construction assessment of dam-reservoir systems; and 4) hydropower adaptability to volatility in fossil fuel prices and non-hydro renewable deployment.

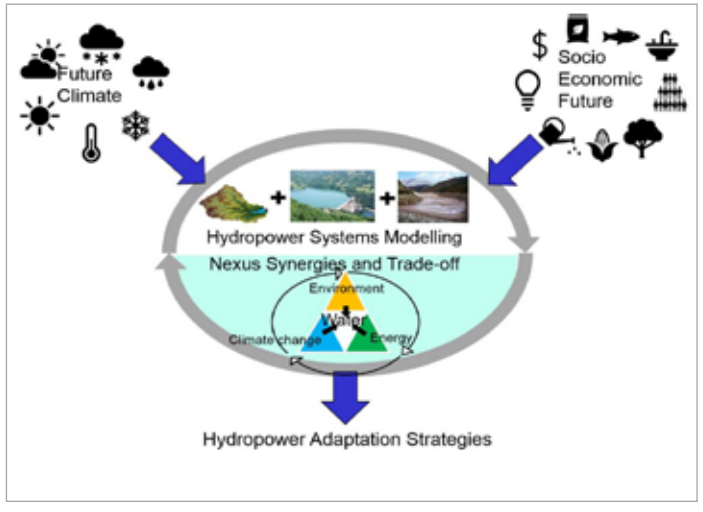

Fig. 1 - Graphical abstract of the research on hydropower future.

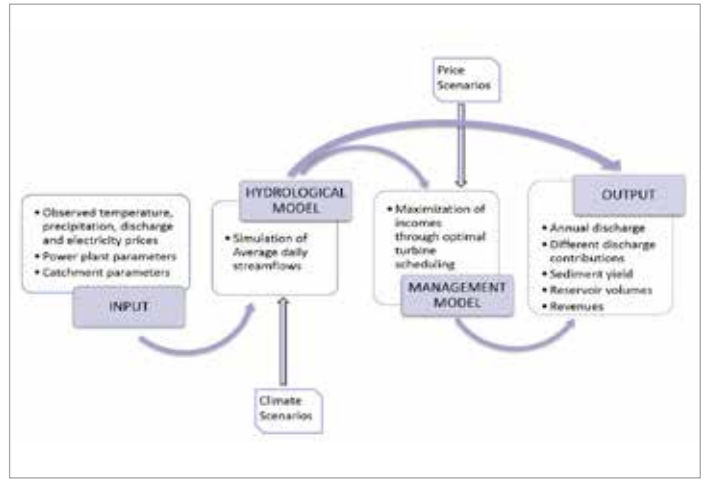

Fig. 2 - Flowchart of modelling framework adopted for hydropower modelling and future scenario generation.

UAV SURVEYS FOR CROP MONITORING AND MANAGEMENT IN PRECISION AGRICULTURE

Giulia Ronchetti - Supervisor: Giovanna Sona

Precision Agriculture (PA) can be generally defined as "*doing the right practice at the right location and time at the right intensity*". This requires a detailed description of the variability at field scale of soil and crop properties, in order to manage water and nutrients with variable rates, according to the actual irrigation and nutrient requirements. Fields are not treated homogeneously but are divided in management zones and the right treatments are provided separately within each zone. Benefits of PA are twofold: on one hand, saving the environment, by reducing the environmental impacts of agricultural practices and limiting the waste of natural resources, on the other hand, increasing farmers' incoming, by decreasing their inputs without affecting or even improving the quality of crop yield.
Fundamental in PA is the knowledge of the in-field spatial variability of soil and crop properties. Since the last four decades, Remote Sensing (RS) techniques have been widely adopted to collect spatial information on crops and soils. In particular, the introduction of Unmanned Aerial Vehicles (UAVs) as RS platforms has represented a revolution in collecting data in agricultural applications, dedicated to identifying within-field variations in agriculture and filling the gap between RS and terrestrial techniques. Using UAVs is a good compromise between the large coverage obtainable with remote platforms (mainly satellite and aircraft) and the accuracy of the terrestrial data. UAVs have introduced a new point of view for agricultural surveys, by allowing to acquire information closely from above, giving rise to several applications.
Despite all the efforts, a standardized workflow to perform successful UAV-based surveys for PA is still missing. Some practical and technical expertise are required to exploit the acquired data, thus preventing a wider use of UAV among farmers. The main challenges still refer to both data collection and data processing. This dissertation arises from these problems and tries to find solutions to some relevant issues still open, in order to encourage the spread of UAV surveys for PA applications. This thesis aims at proposing guidelines and defining best practices for performing effective UAV surveys in agriculture. Therefore, some critical aspects of UAV-based surveys are addressed in it, from sensors analysis to data exploitation, by means of four different case studies. In the first case, analysis of radiometric performances of a popular multispectral sensor is addressed, by comparing results that can be obtained following different elaboration strategies. The second case study focuses on the best practices of data acquisition and processing in order to obtain accurate products with a mass-market UAV equipped with a fisheye camera on a vineyard. Methodologies for detecting crop rows on UAV imagery are presented in the third study and then one of these methods has been used in the fourth case study, to produce site-specific management zones maps in a vineyard. The latter is a clear example of the potential of UAV surveys in PA, by combining UAV-based and ground-based measurements.
The illustrated case studies derive from real practical needs that occurred during the PhD period. Starting from these, it was possible to find solutions to the problems encountered and recommend guidelines for conducting UAV surveys in the agricultural sector.
A careful planning of the survey is relevant in any applications, together with proper choices during image processing. When working with multispectral sensors, radiometric calibration of data is required, anyhow it is recommended to assess accuracy of the calibration before using results, because significant radiometric distortions may be left. Radiometric errors are more evident on the edges of the acquired blocks. To reduce this effect, it is advisable to plan the survey of a wider area that includes the area under investigation. Semi-automatic processing methods must be used with awareness, knowing their limitations and weaknesses.
To facilitate the spread of UAV surveys in agriculture, it is worth knowing that mass market very-light UAV can also be used, even if equipped with fisheye cameras. Recent advancements in processing techniques compensate geometric distortions on images, leading to obtain high quality products. To optimize costs and times of the surveys, double grid flight configurations should be preferred to single direction flights, and placing any Ground Control Points (GCPs) inside the field would not affect quality of final results, as long as the minimum number of necessary points is reached and that they are well distributed all around the surveyed area.
Precision Agriculture applications require to derive specific information on crop canopy. Vegetation parameters can be easily extracted from products generated by means of UAV imagery processing, whether they are Digital Surface Model (DSM), natural colors orthophotos or Vegetation Indices maps. Different methods have been developed aiming at detecting vegetation canopy and differentiating from soil background. The performances of the methods are generally good but vary greatly according to the characteristics of the input data, the level of automation of the algorithm and the peculiarities of the analyzed crops. Compared to orchards and horticultural crops, the extraction of rows in vineyards presents the greatest challenges, due to the concurrent presence of bare soil, weeds and shadows in the inter-rows distance.
For responsible management of agronomic resources, the delineation of site-specific management zones can be improved by integrating soil electrical conductivity information derived from ground-based sensors with elevation, slope and crop vigor maps retrieved from UAV surveys.
To design and manage irrigation systems, it is required to collect information related to soil properties and topography, stable over the time, and time-dependent factors related to the crop development along the growing season, obtainable by means of very-high resolution UAV multispectral and thermal imagery.

PHOTO-RESPIROMETRIC METHODS TO EVALUATE MICROALGAE-BACTERIA DYNAMICS – APPLICATIONS TO PHOTOBIOREACTORS MONITORING AND MODELLING

Simone Rossi - Supervisor: Prof. Elena Ficara

Tutor: Prof. Roberto Canziani

Nutrient removal from wastewater is crucial to preserve the equilibria of natural ecosystems by increasing anthropic pressures. On the other hand, the scarcity of natural resources is pushing agriculture and water industries to move from a linear to a circular approach in the management of nutrient resources. Within this context, the bioremediation of municipal/industrial wastewater in microalgae-based biorefineries are particularly interesting, due to the possibility of achieving important goals while treating gas, liquid and solid waste streams: i) reducing the energy requirement for the aerobic treatment of wastewaters by exploiting the photosynthetic oxygenation by microalgae, ii) recovering either wastewater nutrients (mainly N and P) and bioproducts (bioplastics, biofertilizers) or energy as biomethane from the digestion of algal biomass, and iii) capturing greenhouse gases such as CO_2 and other gaseous contaminants (H_2S, SO_X, NO_x) from polluted gas streams. Due to these reasons, the use of microalgae-bacteria consortia in wastewater treatment recently gained interest in the scientific community. However, a lack a knowledge of the complex interaction among phototrophic, autotrophic and heterotrophic microorganisms in these systems practically hinders the application of the process at full scale and only a few industrial applications of microalgae-based processes in wastewater treatment plants are available. Respirometry-based techniques have been historically applied to characterize conventional nutrient removal biotechnologies (mainly the activated sludge process) and the dependence of microalgal photosynthesis on light, temperature, nutrient concentrations and other parameters (photo-respirometry). Currently, only a few studies attempted to further characterize the complicated processes occurring in microalgae-bacteria systems by using photo-respirometry. In this work, the most important studies exploiting respirometric and photo-respirometric methods were reviewed, providing an extensive overview of experimental devices, protocols and potential applications of respirometry-based techniques which allowed defining the gaps and steps required toward effective and harmonized test procedures, experimental setup and operational conditions.

The main findings of the literature review process were used to design an appropriate respirometric apparatus and three standardized protocols, useful for monitoring and modelling the evolution of microalgae-bacteria systems: the *monitoring*, *model calibration* and *inhibition* protocols.

The *monitoring protocol* allowed to distinguish between the algal and nitrifying oxygen consumption rates in algae-bacteria consortia sampled from six cultivation systems fed with different types of wastewaters, thus constituting a rich dataset to which future studies should be compared. The cultivation systems analyzed ranged from conventional lab-scale photobioreactors, to pilot-scale high rate algal ponds and bubble-columns, to demonstrative-scale semi-closed photobiorectors. Wastewaters from different sources were tested, after selecting some the most suitable streams for microalgae cultivation: synthetic media, anaerobically digested municipal/piggery wastewaters, raw agro-zootechnical and runoff wastewaters. The obtained nitrification rates were in the range 0.8 to 44 mg O2 g TSS^{-1} h^{-1}, indicating that the occurrence of nitrification was strongly related to the influent type and to its nutrient concentrations. The *model calibration protocol* was defined to characterize the optimal cultivation conditions in a pilot-scale microalgae-bacteria system. The application of the protocol allowed to successfully identify optimal irradiance, pH, DO and temperature, in correspondence of which the photosynthesis and the respiratory activities were highest, and to identify minimum and maximum thresholds, for which the metabolic activities are stopped, with direct applications to microalgae-bacteria modelling. Model selection criteria were applied to select the best-fitting models among different options available in literature. The values returned from the parameter estimation process were comparable with similar literature cases, thus confirming the adequacy of the proposed protocol to evaluate optimal conditions for phototrophs growing in consortia with bacteria. The optimal irradiance, temperature and pH values for the photosynthetic rate were approximately 300 µE m^{-2} s^{-1}, 28 °C and 7.4, respectively. No photoinhibition effects on the microalgae-bacteria consortium were detected. Complete inhibition from dissolved oxygen was obtained at approximately 20 mg DO L^{-1} for both photosynthesis and respiration. Regarding the respiration rate, a similar optimal values were obtained for pH (7.8), but the maximum respiration rate was reached at higher temperatures (approximately 36 °C). In the *inhibition protocol*, the application of the standardized procedure allowed to successfully identify the effective concentration for free ammonia inducing 50% inhibition of the oxygen evolution rate (EC_{50}) in both green algae and cyanobacteria. Testing the activity reduction on both monocultures and mixed algae-bacteria cultures represents an innovative approach compared to available literature works, were the inhibition is generally assessed on pure cultures. The calculated inhibition thresholds ranged from approximately 11 to 30 mg NH_3 L^{-1} in cyanobacteria and from approximately 52 to 88 mg NH_3 L^{-1} in green microalgae, consistently with previous literature works.

On the overall, this thesis demonstrated that photo-respirometry is a suitable and promising technique to gain insights into oxygen dynamics in microalgae-bacteria systems. The definition of standardized protocols allowed to perform the experiments under comparable conditions and to minimize the experimental error. The standardization efforts were also aimed at identifying a set of guidelines for future photo-respirometric studies, in order to facilitate the spreading of this technique. Indeed, adopting the described set of protocols could be a very simple and effective tool for monitoring outdoor and/or indoor microalgae-bacteria photobioreactors treating industrial and municipal wastewaters and for the calibration of mathematical models describing their evolution. The application of the described methodology as routine monitoring procedure is expected to provide additional accuracy and reliability to algae-bacteria growth models, making them an even more reliable tool for the analysis and optimization of these bioprocesses.