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DOCTORAL PROGRAM IN WATER ENGINEERING

Chair:
Prof. Alberto Guadagnini

The Doctoral Programme in Water Engineering is coordinated by the Department of Hydraulic, Environmental, Infrastructures, and Surveying Engineering (DIIAR). It offers technical/scientific curricula geared to the design, planning and management of sustainable development strategies related to the interactions between human life and environment in all aspect involving water. The programme is focused on topics associated with land protection, assessment and prevention of hydrologic, hydrogeologic and hydraulic risks; assessment of contaminant fluxes through the environment; river hydraulics and infrastructures; management of water resources, aquatic ecosystems and technological industrial networks involving water; climate change effects on water resources partitioning. Students are actively involved into national and international research projects, with Academic Institutions and/or other private/ public agencies.

Objectives and methods

The program aims at training students for a variety of careers in research, teaching and high-technology, related to theoretical and operational aspects above identified. Beginning of research activity is harmonized to the students' background and abilities. Dissertation research topics are original and innovative and are proposed at the cutting edge of the field of interest. The following general areas constitute the backbone of the educational and research programme: fluid mechanics and fluid-structure interactions; river hydraulics and hydraulic risk management; groundwater flow and transport processes; hydrological extremes; integrated water resources management; land surface processes.
Fundamental fluid-mechanics is crucial in understanding physical processes observable in environmental and/or geophysical applications. Theoretical and applied aspects are tackled and strongly integrated within the programme. Main development axes therefore include the analysis of advanced methods for fluid-dynamic measurements (e.g., image analysis technologies) and direct assessment and modeling of fluid-structure interactions.
River hydraulics and sediment mechanics are naturally related to the concept of hydraulic risk and its management. They involve concepts leading to optimization of land protection approaches and technologies. Key educational and research objectives include river hydraulics and scour processes, hyper-concentrated flow, modeling of flooding processes and hydraulic risk assessment and management. Flood processes are typically analyzed in the context of risk assessment, upon considering methodological aspects related to the quantification of the risk components, with particular focus on vulnerability. The Programme has a strong and active interaction with other Departments and Doctoral Programmes of the Politecnico di Milano, mainly involved in territorial planning activities.
In the context of groundwater flow and transport processes, the main objective is to understand the mechanisms governing processes of flow and transport of passive and reactive contaminants within the subsoil to provide the bases for management and development of technological tools to mitigate the impacts of contaminant fluxes on the water system. Emphasis is devoted to process understanding and modeling of the key flow and geochemical processes occurring in natural heterogeneous aquifers.
In the area of hydrological extremes, main activities include data assimilation and data fusion of rainfall observations from multiple sensors (e.g., rain-gauge network, radar telemeter and satellite - active and passive microwaves) aimed at reducing uncertainty in real-time prediction of precipitation. Information is then integrated within mathematical modeling of major hydrological processes, including rainfall storms, droughts and flash floods, debris flows, firefloods, soil slips, woody debris and snow avalanches.
Aspects related to the Integrated Water Resources Management paradigm have been integrated in all activities, to provide the student with proper perspectives in planning and managing water resource systems.
In this framework, excellent level classes deal with novel statistical estimation techniques for extreme values of hydrologic phenomena, uncertainty analysis in extreme value estimates, analysis and modeling of time and space-time random fields, mainly addressing combined scaling in time and space, and effects of non-stationarities. These courses are harmonically integrated with basic fluid-mechanics, hydraulic and hydrology programs as well as with advanced classes in groundwater, urban hydrology, hydraulic measurements, computational fluid mechanics, thermo-fluid-dynamics.
As such, the contents of the Doctoral Programme are envisioned to address the needs of:

- setting the basis for understanding the factors governing a variety of key physical processes, to achieve increased modelling and predictive capability;

- integrating methods and tools of observation, measure and representation, in order to extend spatial scales of observation and degree of space-time resolution of observable quantities;
- creating a bridge across science, technology and planning actions, in order to establish settings and operational rules for an integration of water and socio-economic policies, within a pragmatic framework of realization and modulation of structural actions, typical of civil and environmental engineering techniques, together with non-structural actions, typically associated with civil protection and land-use planning strategies.

Due to the nature of the research lines, interdisciplinary expertise is required, together with a strong level of integration. These include knowledge and understanding of hydrological, hydraulic, hydrogeological and hydro-geo-chemical processes and aspects, as well as strong analytical and numerical modeling abilities, together with field and laboratory-based expertise. These competencies are currently present in the Faculty Board of the Programme.

Perspectives

The current structure and contents of the interdisciplinary curricula offered by the Doctoral Programme in Water Engineering aim at providing appropriate skills to a variety of profiles. These include (and are not only limited to) research and development divisions of Engineering firms and Consortia for Land and Environment Agencies; industry and public/private companies devoted to management of technological networks and public service utilities, mainly in the institutional framework of management of the integral water cycle; technology innovation and development divisions of agencies / companies devoted to production, installation and management of networks of measurement instrumentation, and remote sensing for hydro-meteo-marine monitoring; public services of monitoring and environmental protection, Authorities and Agencies devoted to planning and monitoring of land and environment development, national and regional technical divisions, both at the Italian and international level; national and international Research Centers and Institutions; international Agencies at the level of the European Union and supra-nations Organizations. The experience of more than hundred of Graduates in Water Engineering, during 23 cycles of Doctoral Programme at the Politecnico di Milano established in 1985, clearly elucidates the capability of our Graduates to fit these key areas of modern engineering.

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ENERGY WATER BALANCE AND LAND SURFACE TEMPERATURE FROM SATELLITE DATA FOR EVAPOTRANSPIRATION CONTROL

Chiara Corbari

This thesis has as main objective the improvement of the synergic use of hydrologic modelling and remote sensing data for real time water management: flood forecast and parsimonious irrigation systems at different spatial and temporal scale.
In this framework three main issues have been investigated:

- **a.** an innovative approach for energy water balance computation based on thermodynamic equilibrium for a synergic use of hydrological model with remote sensing and ground data
- **b.** the relationship between land surface temperature and soil moisture and their spatial properties
- **c.** the representativeness of fluxes observed with an eddy covariance station.

The innovative approach of solving the energy and mass balance between soil surface, vegetation and shallow atmospheric layers (point a) was developed for local as large scale use. In particular the energy budget is solved looking for the representative thermodynamic equilibrium temperature (RET) defined as the land surface temperature (LST) that closes the energy balance equation due to the fact that any fluxes depend on land surface temperature. So using this approach, soil moisture is linked to the latent heat flux and then to LST. The RET thermodynamic approach solves most of the problems of the actual evapotranspiration (ET) and soil moisture computation. In fact it permits to avoid computing the effective evapotranspiration as an empirical fraction of the potential one. This approach is included into the FEST-EWB (Flash–flood Event–based Spatially–distributed rainfall–runoff Transformation- Energy Water Balance) model that is a distributed hydrological energy water balance model that it is developed starting from the FEST-WB and the event based models FEST98 and FEST04. This model computes the main processes of the hydrological cycle, such as evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow and snow dynamic.
This thermodynamic approach, based on the representative thermodynamic equilibrium temperature, was tested at several spatial scales, from field scale (10 ha), in Landriano, Moscazzano (Italy) and Bondville (USA), agricultural district (1000 ha) in Barrax (Spain) to river basin scale in the Upper Po river basin (Italy) (300000 ha), using as control data energy fluxes from eddy covariance stations and thermal infrared data from satellite, airborne and ground measurements.
Comparisons of satellite LST and RET from the hydrological model seemed to be an affordable way to control fluxes and the relative mass and energy balance in any pixel of the distributed model with the double result of a) providing complementary monitoring points respect to the traditional discharge data and b) assessing the use of land surface temperature satellite data for an operative model control. The possibility given by this approach to compare in a quantitative way the land surface temperature observed from satellites and the representative thermodynamic equilibrium temperature computed from model offers a contribution to the scientific debate about the possibility of driving distributed hydrological model from satellite data.
Spatial and temporal variation of soil moisture and land surface temperature data are analysed (point b) obtaining an improvement of the well known inverse relationship between soil moisture and land surface temperature when the thermodynamic approach is used.
The hydrological model performed well for the whole period of observation at the different spatial scales and was able to accurately predict energy fluxes and land surface temperature spatial and temporal distribution in comparison to in situ thermal infrared radiometric measurements, high resolution images and energy fluxes from eddy correlation tower.
The representativeness of land surface temperature for a distributed hydrological energy water balance model is analysed considering thermal data with different spatial scale from radiometer on board different satellites such as SEVIRI (Meteosat Second Generation satellite) with a temporal resolution of 15 minutes and at the latitude of the study areas (45° N) with a spatial resolution of 3.1 Km, MODIS (TERRA satellite) which overpasses the same area two times per day with a spatial resolution in the thermal infrared of 1 Km and ASTER (TERRA satellite) which is available every 16 days but with a spatial resolution of 90 m in the TIR, from radiometer on airborne, such as AHS (airborne hyperspectral scanner) with a spatial resolution of 3 m and from ground measurements.
In this thesis the capability of the model and of the images at high spatial resolution to correctly catch the diurnal strong spatial variability of the area with high LST standard deviation was shown. On the contrary coarser satellite images are able to detect only the mean land surface temperature value. Instead during night time, MODIS spatial resolution seems to be sufficient to represent the lower LST spatial variability of the fields showing the same statistics of higher resolution images from AHS and from the hydrological energy water balance model. This observation highlights the role of operative satellite that can be used in an assimilation process into hydrological energy balance model.
Similar results on the capability to catch the field spatial variability of evapotranspiration can be observed from ET values estimated from the hydrological energy water balance model and directly from AHS images both characterized by a good agreement also when a strong evapotranspiration field variance is presence, while the MODIS images do not retrieve even the mean ET values.
Fluxes data from eddy covariance station were discussed in order to understand the reliability and representatives of observed fluxes (point c). The use of energy data to validate land surface models requires that the conservation of energy balance closure is satisfied; but usually this condition is not verified when measuring energy with an eddy correlation station. The closure of the energy budget is analysed trying to give an overview of the different source of errors, such as the storage terms, the aggregation time period, the instruments source area and the meaning of turbulent measures respect to stable or unstable atmospheric conditions. In this work a different way to improve the energy balance closure of the observed data is investigated through the energy water balance model FEST-EWB.

THE CANOPY RESISTANCE FOR THE DETERMINATION OF THE ACTUAL EVAPOTRANSPIRATION ON MAIZE CROP IN LOMBARDIA REGION

Olfa Gharsallah

The actual evapotranspiration can be considered equivalent to the water requirement of a crop, then under this form it is a critical aspect of the water resources management over the entire land surface of the globe. Therefore, a high degree of accuracy in the estimation of crop evapotranspiration may lead to important saving in water requirement in irrigated area.

The Food and Agriculture Organization (FAO, bulletin 56), proposed a methodology for computing crop evapotranspiration based on the use of the reference standard evapotranspiration ET0 and crop coefficient Kc, adopting the Penman-Monteith (PM) equation with constant canopy resistance r_c. The variables used to calculate this ET0 are usually measured above a reference grass through a standard agro-meteorological station. However, the fixed value of r_c retained by this model may causes tendency for the PM equation to underestimate or overestimate evapotranspiration. On the other hand, it has been widely demonstrated that an accurate estimation of crop actual evapotranspiration can be obtained if the PM model is directly applied to the crop. In other words, when the measurements of the input variables of the PM equation are carried out above the crop in object and when the canopy resistance is suitably estimated, then the values of the calculated actual evapotranspiration show a high degree of accuracy.

In order to provide more accurate estimation of evapotranspiration using the PM equation it is necessary to parameterize canopy resistance r_c as a primary factor in the evapotranspiration process.

The analysis carried out in the present work has yielded directly to the importance of the canopy resistance in the accurate estimation of the actual evapotranspiration in Lombardia region (North Italy).

In fact, the sensitivity analysis of Penman-Monteith evapotranspiration model to climate factors (available energy, vapour pressure deficit) and to aerodynamic and canopy resistances carried out in this present work showed that the canopy resistance has a very important role in the estimation of the evapotranspiration during all the day and through the whole crop growth season.

In fact, the available energy explains 50% of the daily ET variation, furthermore, the variation of the vapour pressure deficit explains 70% of the daily ET and finally the variation of the canopy resistance explains the 80% of ET variation.

Moreover, the canopy resistance r_c is strongly influenced by the available energy which is the actual deciding factor of the evapotranspiration, it decreases when the available energy increases if the crop is in well watered conditions. Also the vapour pressure deficit plays an important role on the early and late part of the day and, in general, canopy resistance decreases when it increases. However, the canopy resistance r_c increases with the increasing of r_a which means with the decrease of the wind speed. The aerodynamic resistance must be accurately modelled since it greatly influences the evapotranspiration when the wind speed is low.

The soil water status has, of course, great influence on the behaviour of the stomata: the canopy resistance increases when the soil water content decreases. The relationship between the canopy resistance and the soil water status was underlined by many authors and experiences.

For tall crops as maize almost the entire relative error in the estimation of the evapotranspiration is due to the canopy resistance modelling. So that, for r_c it is necessary to take into account all climatic, canopy and soil water content characteristics and simple models of canopy resistance usually do not work well.

In this work four mechanistic and semi empirical model of canopy resistance have been analysed in detail, among the most diffusion and known ones: Monteith; Jarvis; Katerji and Perrier; Todorovic.

A comparison between actual evapotranspiration values of maize crop estimated by these models and directly measured values by the eddy covariance method applied above the crop has been carried out during 2006 and 2008 at Landriano and Moscazzano experimental sites.

The results of the performance analysis of the above mentioned r_c models can be summarizes as following:

- Monteith model gives an overestimation at hourly and daily scale, because the values of LAI remain constant during growth and senescence stage, although r_c is variable during all the agriculture season from the development stage up to the senescence.
- The Jarvis multiplicative model overestimates at hourly and daily scale because it is very hard to determine with enough accuracy one of the most important input parameter: the value of the $r_{s,min}$. A large discussion around this minimal crop resistance value was treated in the literature. In fact, for example, it is difficult to decide if this minimal stomatal resistance should be taken at leaf scale or at canopy scale. Moreover, the Jarvis model does not take into account the interactions among climatic factors. The Jarvis model is one of the most famous approach to estimate bulk canopy resistance, however this procedure only includes the physiological and climatic components of r_c, and does not take in consideration the aerodynamic component which is so important mainly in the case of tall crops like maize.
- The Katerji-Perrier model seems to work well for maize crop, both at hourly and daily scale. We have also to add that Katerji and Perrier model achieved a good results in the determination of the canopy resistance in many other cases and crops like soybean, sweet sorghum and on six other irrigated crops under Mediterranean climate conditions (Reference grass, soybean, grain sorghum, sunflower, Tomato, sweet sorghum). The good accuracy reached during all those cases showed that the model worked well, but it needs to be calibrated for each crop. However, the calibration is only crop dependent and it is not site dependent.
- Todorovic Model overestimates a lot the crop evapotranspiration both at hourly and daily scale, it doesn't require any calibration but the problem is that it takes into account the vapour pressure deficit D and only marginally the aerodynamic resistance r_a and the available energy A, and it's ignore totally the soil water status which is a fundamental factor in the estimation of the actual evapotranspiration mainly in the Mediterranean region.

Hence, the results of the present work confirming many other in the literature, demonstrates that the calculation of crop evapotranspiration by direct method (r_c modelled) is more accurate than the use of the indirect method (FAO method) using a constant canopy resistance.

The intermediate calculation of the reference evapotranspiration ET0 and the crop coefficient Kc necessary in the calculations generate significant errors in both ET0 and Kc. We showed that it overestimates more than 46% the maize evapotranspiration in the present case.

The possibility to carry out the indirect calculation of ET by means of measurements in a standard agro-meteorological is the main advantages of this method. However, the need of the local determination of ET0 and the calibration of Kc deprives this approach of its main advantages.

The direct methods of calculating ET are increasingly considered as suitable tools for determining the actual crop evapotranspiration. The main obstacle to the routine use of this kind of models is the need to determine certain micrometeorological variables above the crop (Rn, D, r_a …). Thus, further research is necessary to make the direct method for estimating actual crop evapotranspiration more attractive from the practical point of view. For example, by establishing functional relationships among climatic variables measured on a standard reference grass and the same variables above the crops in object, in order to make possible the estimation of evapotranspiration with the use of PM model under its direct form.

A METHOD FOR GENERATION OF SPATIALLY DISTRIBUTED PRECIPITATION WITHIN CLIMATE CHANGE SCENARIOS

Bibiana Groppelli

The "Global warming" is tremendously impacting the climate of mountain areas in temperate regions and the water resource distribution therein. Hydrologists are therefore required to make accurate predictions of the impacts of climate change on the intensity, amount and variability of precipitation and their fallout upon streamflow regime. To this purpose, the lack of high-resolution spatial rainfall data has been one of the most prominent limiting factors in hydrological, meteorological, ecological and agricultural research insofar. The recent shift of our focus to deal with complex problems, such as water resources assessment and management, extreme rainfall effects and drought, soil water infiltration movement, stream flow dynamics and their interaction with groundwater, has displayed an increased deal of uncertainty due to the mismatch between the available and necessary data.
Moreover, emphasis on basin - and local - scale research, requires coupling of local climatic data and scenarios from climatic models to provide the climatic input for impact analysis upon water resources, hydrological extremes and on habitat of animal and vegetal species at a consistent scale.
General Circulation Models (hereon, GCMs) are physically based tools presently used in addressing climate change. GCMs deliver meteorological variables in a fine time resolution but in a usually coarse spatial grid (200-600 km). Although GCMs perform reasonably well in simulating synoptic atmospheric fields, they usually reproduce poorly the statistics of historical records at the spatial scales of interest in impact analyses and a proper tailoring is required for local use, before any accurate guess about hydrologic cycle can be ventured.
So-called "downscaling" techniques have subsequently emerged as a means of bridging the gap between what climate modellers are currently able to provide and what impact assessors require. However, downscaling in space and/or in time of outputs from climatic model requires appropriate data assimilation schemes which master the tremendous variability of precipitation in scales. The downscaling plays a major role in mountain areas, where snow precipitation is strongly controlled by topography, poorly represented in GCMs. These models do not provide adequate information at the smallest scales, where snow is playing a major role and the dynamics of habitat formation for several vegetal and animal species in played.
Most previous studies on the relationship between GCM precipitation and the corresponding streamflow used downscaling schemes that do not account for the intermittency and self-similarity properties of precipitation in space and time, but these are key features of precipitation field. Instead we used a class of methods that accounts for these properties, namely statistical downscaling via Stochastic Space Random Cascade approach, henceforth termed as SSRC. A considerable effort has been recently devoted towards multi scale data assimilation schemes using Scale Recursive Estimation (SRE) based upon the SSRC theory. This novel approach makes model estimation possible when information from multiple sources is available, this including imperfect (i.e. noisy) measurements from the real world. In the thesis, we originally used SRE approach to set up consistent use of SSRC for downscaling of GCMs output. Our case study area, namely the Oglio river (closed at Sarnico), is a basin in the Retiche Italian Alps. This basin is subject of a study carried out under the umbrella of the CARIPANDA project, funded by the Cariplo Foundation of Italy, and aiming to evaluate scenarios for water resources in the Adamello Natural Park of Italy, laid within the Oglio river watershed, in a window of 50 years or so (until 2060). Once the target area is selected, one needs to identify the GCM that best reproduces precipitation in the chosen study area. Four models are selected from among the available ones for this purpose, and their performance ranked by a back cast procedure based upon comparison against ground truth of monthly precipitation for the window 1990-2000 from 270 gauging stations in Northern Italy. Then we select Parallel Climate Model (PCM) by NCAR (The National Center for Atmospheric Research - USA) that resulted the more accurate GCM to depict the North – Italy climate, for setting up the downscaling procedure.
The method uses a data driven parameterization of a Stochastic Space Random Cascade model, which is calibrated for the first time in our knowledge against rain gauge data, more widely available worldwide than any other source, rather than against remotely sensed data. The SSRC approach explicitly accounts for multi-scale invariant properties and internal correlation structure of precipitation including spatial intermittency, thus yielding realistic precipitation fields.
Further, we originally used scale recursive estimation SRE approach coupled with the Expectation Maximization algorithm (EM) to set up consistent use of SSRC for downscaling of GCMs output. Seasonal parameters of the multiplicative cascade are accommodated by statistical distributions conditioned upon climatic forcing given by precipitation intensity, based on regression analysis. This novel approach made model estimation possible when information from multiple sources is available, this including observation from real world and GCM scenarios.
We set up a model, namely $Bias_{GAO}$, which allows correction of the bias between GCM's and rain gauge daily values of precipitation upon Oglio basin, so obtaining daily precipitation scenarios consistent with ground truth, including duration of wet and dry spells, and second order statistics of precipitation. Backcasting validation of the SSRC joint with $Bias_{GAO}$ approaches showed those are capable to acceptably depict statistics of past precipitation starting from control GCM scenarios, so providing ground for reliable future conjectures. This approach allows to develop likely projections of future downscaled precipitation scenarios, necessary for water budget pending climate change. We observed somewhat high variability of at site (*i.e.* cell) precipitation as given by the SSRC approach, however unlikely to considerably influence hydrological budget within the catchments. In the future, some adjustment may be introduced to deal with such issue.
The preliminary assessment of future precipitation upon the investigated area indicates highest average daily and yearly precipitation, together with an expected increase of the number of wet spells, particularly during spring and summer. We can preliminary use the proposed model to project realistic precipitation fields within this area, displaying considerable topographic variability, at a resolution which is viable for hydrological and ecological conjectures. In the thesis, also in view of relatively low average altitude of the gauge network, we dealt in practice with total precipitation. For prospective hydrological balance exercise we will need accounting for changing snowfall patterns, that we may depict using GCMs' projected temperatures against altitude.
In the future, we will also test use of the SSRC approach to downscale precipitation scenarios from other GCMs, aimed to provide an ensemble approach to precipitation scenarios, as required for more robust sensitivity analysis.
Eventually, the tentative use of the SSRC approach here provides encouraging results, and we are confident that this tool will be useful in short to evaluate hydrological and ecological implications of future modified rainfall regime upon this area, and possibly upon the wider Alpine region.

THE MICROFLUIDICS OF BIOFILM FORMATION IN POROUS MEDIA

Alberto Leombruni

Understanding the microscale dynamics of flow and microbial populations in porous media is of critical importance for the water and nutrient cycles, affecting transformation of organic matter, water infiltration and evaporation, and nutrient availability to plant roots. At the same time, a full understanding of the coupling between fluid flow and biofilm growth might provide significant opportunities to improve the performance of industrial and environmental processes. The mining industry, for example, claims methods for microbially enhanced leaching of metals from ores and recovery of metals from solutions (biohydro-metallurgy). The petroleum industry is likewise interested in controlled biofilm accumulation to aid in enhanced oil recovery operations. In fact, deliberate plugging of high-permeability zones (to prevent injection water from reaching the production well) is valuable and can be accomplished by injecting cells and nutrients into the oil-bearing formation. Similarly, controlling biofilm accumulation is important to both injection and production well operation in order to avoid unwanted plugging near the well bore. Furthermore, an enhanced ability to bioengineer the coupling between subsurface flow and biofilm formation in porous media is valuable for the bioremediation of contaminated groundwater and soil through biotransformation of organic compounds.
Literature results suggest that growth enhancement of biofilms in soils might be a feasible technology for creating low-permeability waste containment barriers. In particular, the rate of biofilm growth is strongly influenced by mass-transport dynamics, including hydraulic conductivity and the detailed pore velocity distribution.
In addition, the reduction in hydraulic conductivity in porous media could contribute to provide solutions to other important engineering problems, including the confinement of polluted soils and the creation of waterproofing barriers. In all these cases, progress relies on an improved understanding of the coupling between porous media hydrodynamics and the formation and spatial distribution of biofilms.
Transport of flow through soil is strongly influenced by the presence of biofilms, which alter the paths of fluid as it creeps through pores in soil. In turn, the formation of biofilms is affected by fluid flow, as hydrodynamic shear and drag on biofilms affect their development and growth. Yet, little is known about the coupling between flow and biofilm formation in the porous media, thus my project focuses on an improved understanding of the coupling between porous media hydrodynamics and the formation and spatial distribution of biofilms, analyzing the development of biofilms in porous media and the associated reduction in hydraulic conductivity and contaminant transport. In my Ph.D research project, I have studied how cell motility, erosion by fluid shear, bacterial growth, nutrient diffusion, and porous media surface properties influence the biofilm dynamics using experimental laboratory microfluidic tests in porous media. The observation of experimental data allows understanding better the coupling process between the porous media hydrodynamics and the bacteria growth, exploring the physical mechanism of the biofilm formation according to the non linear link with the flow characteristics. The biofilm development on a support skeleton is the combined result of bacteria growth and their production of sticky polymeric substances. Before starting the experimental tests, we discussed the hydraulic problem proposed, analyzing the theoretical background of our research project and summarizing briefly some aspects of the art of modeling viscous flow about thin objects, such as a coin, filling a narrow gap between two parallel plates. We have observed the theoretical behavior of the flow among the poles of the synthetic porous media in the microchannels under low Reynolds number flow. In addition we have verified how all the magnitudes that we apply in the micrometric scale to value the hydraulic conductivity Ksat are still representative of the magnitudes to value Ksat even if we consider the very small distance between the two parallel horizontal plats and thus a high shear stress between the flow and the horizontal plats. To verify this, first of all we analyzed the Hele-Shaw theory to observe the validity of the Navier-Stokes equation in our experiments. The micro-experimental framework and its microchannel dimensions was checked respect to the validity of Darcy hypothesis recalling the well known Hele-Shaw modeling theory and controlling the behavior of hydraulic conductivity respect to Reynolds number.
In the same chapter we also discussed the choice of natural soil and its statistical properties reproduction in the synthetic soil matrix used as porous media in the experiments. Then for each typology of porous media simulated (Loamy fine sand and fine sand) we evaluated the respective piezometric loss under different flow velocities, so to correlate the Reynolds number to the respective hydraulic conductivity. After the theoretical analysis, we focus on the development of biofilms in porous media and the analysis of the associated reduction in hydraulic conductivity, obtaining an improved understanding of the coupling between porous media hydrodynamics and the formation and spatial distribution of biofilms. During the experimental tests, we checked how several factors control biofilm formation and maintenance, including erosion by fluid shear, bacterial growth, nutrient diffusion, and surface properties. In particular, the surface is often topographically complex and allows heterogeneous microenvironments to develop. We studied how these processes influence biofilm dynamics for a synthetic porous media matrix in a patterned microfluidic channel. The matrix is composed of an array of cylinders of random diameter and position. The biofilm formation has been investigated for two different porous media matrixes and several hydraulic head boundary conditions. Laboratory observations show that biofilm formation experiences two main behaviors: firstly bacteria form a uniform clogging layer that travels as a front in the flow direction with a velocity of three orders of magnitude slower than the mean fluid velocity, then the layer breaks into a series of patches separated by preferential flow channels. We also analyzed the biofilm growth and its special distribution over time in term of Darcy saturated hydraulic conductivity. For all the simulated porous media, the main results show the importance of the microfluidic laboratory test for this investigation, the behavior of the biofilm formation in the porous media and the quantification of the main physical processes, the relationship between the porous media clogging and the Darcy saturated hydraulic conductivity, the analysis of the variation of the effective velocity field in the porous media after the clogging formation. We observed how the flow velocity strongly affects the biofilm formation in the porous media, thus how the biofilm formation affects the reduction of porosity and Ksat over time. In particular, for both the synthetic porous media, we have obtained similar experimental results. Increasing the flow rate injected into the microchannel, we have observed a decrease in attachment and development of biofilm on the grain surfaces (this causes an increase of the time needed to get a clogging formation in the porous media), a increase in porosity, an additional reduction in the hydraulic conductivity. So the formation of the biofilm clogging is slower for higher flow rates. This is understandable if we consider that a higher flow rate causes a higher shear stress and so a higher erosion of the biofilm. Consequently for higher flow rates we observed a stronger channelization that corresponds to bigger preferential flow channels in the biofilm formation, so more void space (higher porosity) and less biofilm.

ANISOTROPIC MESH ADAPTATION FOR SHALLOW WATER MODELING

Giovanni Michele Porta

The diffusion of two-dimensional modeling tools for large scale free surface flow phenomena is increasing in the hydraulic engineering community. Typical examples in this context concern simulation of flood wave propagation, analysis of flux distribution in large rivers, propagation of tidal waves in coastal areas, estuarine dynamics, lake circulation, dam-break modeling etc. These problems are usually characterized by large spatial scales in the horizontal plane directions and considerably smaller spatial scales in the vertical direction, so that a two dimensional modeling turns out to be appropriate. The reference model for these configurations is the two-dimensional Shallow Water Equation (SWE) system. The versatility of SWE model and the relevance of the connected problems from an engineering viewpoint pushed the development of ad hoc numerical methods. Thus a large variety of different numerical methodologies has been proposed in the literature. In this work the focus moves from the proposal of an improved approximation method to the optimization of the required computational effort, through the setting of an effective mesh adaptation method.
In general the purpose of a mesh adaptation method is to provide a computational mesh optimized with respect to some norm of the computational error. So the first step of a mesh adaptation strategy is to propose a reliable error indicator. Then the information given by the error indicator has to be transformed in an actual mesh, through a mesh adaptation procedure. Solution-adaptation procedures provide finally an essential link between the mesh adaptation and the numerical solver set for the problem at hand. These three blocks are the essential ingredients of the mesh adaptation method proposed in this work.
The mesh adaptation technique is here coupled with a solver for SWE based on a suitably stabilized finite element method. Such a scheme is chosen as it relies on a continuous finite element discretization. This is important for the formulation of the error estimator. In particular the continuous Galerkin finite element method is improved with suitable stabilizing streamline-diffusion and shock-capturing terms. The validation of the scheme is performed on two one-dimensional shallow water benchmark cases. The results show that the scheme is sufficiently reliable and efficient to be coupled with a mesh adaptation procedure. Moreover the method is suited to deal with highly stretched elements, provided that this occurrence is properly treated by setting a specific parameter in the stabilization and shock capturing term.
An automatically adaptive grid turns out to be a reliable tool in a real-scale SWE engineering analysis: the spatial scales of evolution may be different throughout the domain at a prescribed time, as well as they can change in space as time advances. This has been observed also in a number of previous literature studies. Our purpose here is to optimize as much as possible the gain derivable from a mesh adaptation method, hence we are particularly interested in generating anisotropic meshes. The adopted mesh adaptation method relies on an anisotropic recovery-based error estimator. The anisotropic estimator is derived just through gradient recovery techniques. In particular we start from the original recipe proposed in the literature by O.C. Zienkiewicz and J.Z. Zhu, which is slightly modified to better fit the chosen anisotropic framework. We provide here a first extensive application of this theoretical tool on a relevant application. Reliability and problem independence of the estimator were numerically assessed on diffusive and shallow water problems with known analytical solution.

This estimator is extremely flexible and can be applied to problems of different nature and dimensionality, provided that they are solved through a continuous finite element approximation. The estimator is computationally cheap and easy to implement, hence it is particularly suited to be included in an adaptive solver.
The information provided by the error estimator is used to generate an adapted mesh through a mesh adaptation procedure. Provided that a global tolerance is prescribed, the dimension, orientation of shape of the mesh elements are calculated applying the error equidistribution principle and solving a local optimization problem. Some additional control parameters are set to improve the performances of the method in particularly challenging simulations.
Several test cases are used to assess the performances of the proposed numerical techniques. In particular we rely on some standard benchmark test cases and on a real scale unsteady test case.
The gain obtained by using mesh adaptation technique can be measured in terms of the accuracy achieved with a certain number of elements, when the exact solution of the problem is known. We consider in this work two academic test cases with known analytical solution exhibiting different features. In such cases anisotropic meshes have a significative impact on the optimization process. In particular they are able to reduce the error measured in the H^1-seminorm by a factor 5-10 with respect to uniform meshes with a similar number of elements. Clearly the magnitude of such improvement depends on the problem at hand. This consideration suggests that in real scale applications the use of anisotropic meshes is more convenient when the physical process at hand exhibits directional features. This is confirmed by the analysis of the mesh topologies obtained for the two considered unsteady shallow water test cases.
Typical standard mesh generation process for a computational fluid dynamics simulation is characterized by the initial generation of an uniform isotropic mesh. Such mesh can be then manually refined or coarsened a priori, in light of preliminary considerations on the phenomenon at hand, or a posteriori, after first results are computed on a background uniform mesh. On the other hand a mesh adaptation method provides a gridding strategy, so that distribution of the elements in space is automatically afforded. We highlight in this work the advantages of using a mesh adaptation method by modeling a real-scale unsteady Shallow Water problem. In such a case, the mesh adaptation method identifies two kinds of mesh refinements: fixed mesh refinement areas, i.e., associated with a particular region of the domain, and moving mesh refinement areas, e.g., located in correspondence with moving wave fronts. If the first kind of mesh refinement could be performed through a manual a priori mesh refinement, the second can be achieved only by means of mesh adaptation or by a uniform refinement of the whole grid. Hence mesh adaptation turns out to be the only available choice to improve the accuracy on some particular solution features with limited computational costs, as convergence to local features of the solution can be significantly accelerated. The optimization of the mesh is even more effective, as we consider anisotropic meshes where elements are characterized by suitable orientation and shape.
The tuning of the parameters which control the mesh adaptation procedure is not straightforward: optimal calibration depends on the considered problem and on the required level of accuracy indeed. A priori this tuning has to be performed independently for each new problem. Anyway the obtained results show that the proposed mesh adaptation technique is sufficiently robust and can be easily controlled.
The results provided herein give a rigorous assessment of the reliability of all the proposed numerical techniques. Results are promising with a view to shallow water modeling of real challenging applications.

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