Progetto di ricerca/Titolo assegno:

"Porous gravity currents in heterogeneous aquifers" - Protecting the aquatic environment from urban runoff pollution"- StopUP – CUP J33C22002080006

Descrizione breve delle attività di ricerca

This study will focus on the dynamics of Newtonian gravity currents (GCs) in porous media, with a particular emphasis on the role of geological heterogeneity and the uncertainty it introduces into predictions of current spreading. The research will be carried out in several steps, combining analytical theory, numerical modeling, and stochastic simulations.

The work will begin with the classical framework developed by Huppert and Woods (1995), which describes the propagation of GCs in homogeneous porous media using similarity solutions. These solutions, covering both instantaneous release (dam-break type) and constant injection cases, will serve as benchmarks for the study. They will be used to validate a numerical model developed in MODFLOW, ensuring that the code reproduces the sharp-interface behavior expected in homogeneous conditions before extending it to more complex settings.

Once the numerical framework is established, attention will shift to representing heterogeneity in the porous medium. Two statistical descriptions of hydraulic conductivity fields will be considered. The first will adopt Gaussian random fields, the conventional approach in hydrogeology, which provides mathematically convenient yet idealized descriptions of subsurface variability. The second will involve non-Gaussian probability fields, designed to capture more realistic geological structures such as stratification and layering that cannot be represented by Gaussian statistics alone.

To systematically explore the effect of heterogeneity, six simulation configurations will be defined. These will combine two flow regimes (instantaneous release and constant injection) with three levels of variance in the logarithm of hydraulic conductivity. For each configuration, 100 independent realizations of the conductivity field will be generated. The ensemble of simulations will then provide a basis for assessing variability in current profiles and identifying consistent trends.

The outputs of these ensembles will be processed to construct probability maps of current height and front position as a function of time. These probability distributions will make it possible to quantify uncertainty in the spreading of the current under different heterogeneity assumptions. Comparisons will be drawn between Gaussian and non-Gaussian fields and against the homogeneous solution, highlighting the extent to which deterministic models underestimate or misrepresent the influence of subsurface variability.

Through this structured approach, the study will provide new insights into how geological heterogeneity alters the propagation of gravity currents, both in terms of shape and advance rate. It will also establish a numerical framework capable of incorporating stochastic heterogeneity into GC modeling, paving the way for improved uncertainty quantification in practical applications. These applications include the long-term prediction of CO_2 plume migration during geological carbon storage, as well as the assessment of contaminant transport in aquifers.

Piano delle attività

The research activity will be focused on the development of the methods useful to address the specific goals described above and the application of these methods to the case study of CO2 intrusion in aquifers. The steps of the research activity are the following:

Step 1 – Benchmarking and Model Setup (Month 1–2)

- Revisit similarity solutions of Huppert & Woods (1995).
- Implement and validate a MODFLOW-based numerical code against homogeneous cases (instantaneous release and constant injection).
- Prepare baseline homogeneous simulations for later comparison.

Step 2 – Heterogeneity Representation (Month 2–3)

- Define hydraulic conductivity fields using Gaussian and non-Gaussian statistics.
- Generate realizations of heterogeneous fields with varying variance levels.
- Integrate stochastic fields into MODFLOW framework.

Step 3 – Numerical Simulations (Month 3–5)

- Run ensemble simulations (100 realizations per configuration) for all six scenarios.
- Collect outputs on current profiles, front positions, and height distributions.
- Ensure convergence and consistency checks across realizations.

Step 4 – Analysis and Probability Mapping (Month 5–6)

- Post-process results to construct probability maps of GC height and extent.
- Compare Gaussian vs. non-Gaussian heterogeneity outcomes with homogeneous benchmarks.
- Interpret implications for uncertainty quantification in CO_2 sequestration and contaminant transport.
- Prepare manuscript and presentation of findings.