IN PARTNERSHIP WITH:
CNRS
Université Rennes 1

Activity Report 2013

Project-Team SAGE

Simulations and Algorithms on Grids for Environment

IN COLLABORATION WITH: Institut de recherche en informatique et systèmes aléatoires (IRISA)

RESEARCH CENTER
Rennes - Bretagne-Atlantique

THEME
Earth, Environmental and Energy Sciences

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Project-Team SAGE

Keywords: Environment, Stochastic Models, Numerical Methods, High Performance Computing, Numerical Software Platform

Creation of the Project-Team: 2004 December 06.

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2. Overall Objectives

2.1. Main research areas

Numerical models are very useful for environmental applications. Several difficulties must be handled simultaneously, in a multidisciplinary context. For example, in geophysics, media are highly heterogeneous and only few data are available. Stochastic models are thus necessary. Some computational domains are complex 3D geometries, requiring adapted space discretization. Equations modeling flow and transport are transient, requiring also adapted time discretization. Moreover, these equations can be coupled together or with other equations in a global nonlinear system. These large-scale models are very time and memory consuming. High performance computing is thus required to run these types of scientific simulations. Supercomputers and clusters are quite powerful, provided that the numerical models are written with a parallel paradigm.

The team SAGE undertakes research on environmental applications and high performance computing and deals with two subjects:

1. numerical algorithms, involving parallel and grid computing,
2. numerical models applied to hydrogeology and physics.

These two subjects are highly interconnected: the first topic aims at designing numerical algorithms, which lead to high efficiency on parallel and grid architectures; these algorithms are applied to geophysical models.

Moreover, the team SAGE, in collaboration with other partners, develops the software platform H2OLab for groundwater numerical simulations in heterogeneous subsurface.

2.2. Highlights of the Year

Year 2013 was declared Mathematics of the Planet Earth by UNESCO. In relation with this domain, the team Sage participated in the prospective think tank "MATHématiqueS en INteractions pour la TERRE" (ANR project) and in various popularization actions:

- the french blog "un jour une brève". See http://mpt2013.fr/.
- the TDC journal "les mathématiques de la terre" (no 1062, october 2013),
- papers on the website Interstices. See http://www.interstices.info.
- panels and conferences for scholars.

3. Research Program

3.1. Numerical algorithms and high performance computing

Linear algebra is at the kernel of most scientific applications, in particular in physical or chemical engineering. For example, steady-state flow simulations in porous media are discretized in space and lead to a large sparse linear system. The target size is 10^7 in 2D and 10^{10} in 3D. For transient models such as diffusion, the objective is to solve about 10^4 linear systems for each simulation. Memory requirements are of the order of Giga-bytes in 2D and Tera-bytes in 3D. CPU times are of the order of several hours to several days. Several methods and solvers exist for large sparse linear systems. They can be divided into three classes: direct, iterative or semi-iterative. Direct methods are highly efficient but require a large memory space and a rapidly increasing computational time. Iterative methods of Krylov type require less memory but need a scalable preconditioner to remain competitive. Iterative methods of multigrid type are efficient and scalable, used by themselves or as preconditioners, with a linear complexity for elliptic or parabolic problems but they are not so efficient for hyperbolic problems. Semi-iterative methods such as subdomain methods are hybrid direct/iterative methods which can be good tradeoffs. The convergence of iterative and semi-iterative methods and the accuracy of the results depend on the condition number which can blow up at large scale. The objectives are to analyze the complexity of these different methods, to accelerate convergence of iterative methods, to measure and improve the efficiency on parallel architectures, to define criteria of choice.

In geophysics, a main concern is to solve inverse problems in order to fit the measured data with the model. Generally, this amounts to solve a linear or nonlinear least-squares problem. Complex models are in general coupled multi-physics models. For example, reactive transport couples advection-diffusion with chemistry. Here, the mathematical model is a set of nonlinear Partial Differential Algebraic Equations. At each timestep of an implicit scheme, a large nonlinear system of equations arise. The challenge is to solve efficiently and accurately these large nonlinear systems.

Approximation in Krylov subspace is in the core of the team activity since it provides efficient iterative solvers for linear systems and eigenvalue problems as well. The later are encountered in many fields and they include the singular value problem which is especially useful when solving ill posed inverse problems.

3.2. Numerical models applied to hydrogeology and physics

The team Sage is strongly involved in numerical models for hydrogeology and physics. There are many scientific challenges in the area of groundwater simulations. This interdisciplinary research is very fruitful with cross-fertilizing subjects. For example, high performance simulations were very helpful for finding out the asymptotic behaviour of the plume of solute transported by advection-dispersion. Numerical models are necessary to understand flow transfer in fractured media.

The team develops stochastic models for groundware simulations. Numerical models must then include Uncertainty Quantification methods, spatial and time discretization. Then, the discrete problems must be solved with efficient algorithms. The team develops parallel algorithms for complex numerical simulations and conducts performance analysis. Another challenge is to run multiparametric simulations. They can be multiple samples of a non intrusive Uncertainty Quantification method, or multiple samples of a stochastic method for inverse problems, or multiple samples for studying the sensitivity to a given model parameter. Thus these simulations are more or less independent and are well-suited to grid computing but each simulation requires powerful CPU and memory resources.

A strong commitment of the team is to develop the scientific software platform H2OLab for numerical simulations in heterogeneous hydrogeology.

4. Application Domains

4.1. Geophysics

The team has chosen a particular domain of application, which is geophysics. In this domain, many problems require solving large scale systems of equations, arising from the discretization of coupled models. Emphasis is put on hydrogeology, but the team also investigates geodesy, heat and mass transfer in soil, and granular materials. One of the objectives is to use high performance computing in order to tackle 3D large scale computational domains with complex physical models.

4.2. Hydrogeology

This is joint work with Geosciences Rennes at OSUR, Pprime at University of Poitiers and CDCSP at University of Lyon. It is also done in the context of the group Momas and Andra grant.

Many environmental studies rely on modelling geo-chemical and hydrodynamic processes. Some issues concern water resources, aquifer contamination, underground waste disposal, clean-up of former waste deposits, acid mine drainage remediation. Other issues, also related to energy, concern geothermy, unconventional gas, enhanced oil recovery, underground storage of CO2, underground storage of nuclear waste.

Simulation of contaminant transport in groundwater is a highly complex problem, governed by coupled linear or nonlinear PDAEs. Moreover, due to the lack of experimental data, stochastic models are used for dealing with heterogeneity. The main objective of the team is to design and to implement efficient and robust numerical models, including Uncertainty Quantification methods.

Recent research showed that rock solid masses are in general fractured and that fluids can percolate through networks of inter-connected fractures. Fractured media are by nature very heterogeneous and multi-scale, so that homogenisation approaches are not relevant. The team develops a numerical model for fluid flow and contaminant transport in three-dimensional porous fractured media.

An important output is the parallel scientific platform H2OLab, running on clusters, grids and machines available in supercomputing centers.

5. Software and Platforms

5.1. Hydrogeology

5.1.1. H2OLab

Participants: Thomas Dufaud, Jocelyne Erhel [correspondant], Grégoire Lecourt, Aurélien Le Gentil, Géraldine Pichot.

The software platform H2OLab is devoted to stochastic simulations of groundwater flow and contaminant transport in highly heterogeneous porous and fractured geological media. It contains a database which is interfaced through the web portal H2OWeb. It contains also software modules which can be used through the interface H2OGuilde. The platform H2OLab is an essential tool for the dissemination of scientific results. Currently, software and database are shared by the partners of the h2mno4 project (see 8.2.1). Software integrated in the platform and registered at APP are GW-UTIL, GW-NUM, PARADIS, MP-FRAC.

See also the web page http://h2olab.inria.fr.

5.1.2. GW-UTIL

Participants: Jocelyne Erhel, Grégoire Lecourt, Aurélien Le Gentil, Géraldine Pichot [correspondant].

- Version: version 1.0, May 2008
- APP: registered
- Programming language: C++
- See also: http://h2olab.inria.fr.
- Abstract: The software GW-UTIL allows to discretize PDE for flow and transport in aquifers and to deal with stochastic models. It contains a set of utilitary modules for geometry, input, output, random numbers, visualization, parallel computing, numerical algorithms, etc. A package is devoted to launch applications.
- Current work: refactoring.

5.1.3. GW-NUM

Participants: Thomas Dufaud, Jocelyne Erhel, Grégoire Lecourt, Aurélien Le Gentil, Géraldine Pichot [correspondant].

- Version: version 1.0, May 2008
- APP: registered
- Programming language: C++
- See also: http://h2olab.inria.fr.
- Abstract: The software GW-NUM is a set of generic modules to discretize PDE of flow and transport in 2D computational domains in order to deal with stochastic models. Methods for flow simulations are either Finite Volume on structured meshes or Mixed Finite Element with unstructured meshes. Method for transport simulations is a particle tracker for advection and a random walker for diffusion. Uncertainty Quantification method is Monte-Carlo. For flow computations, the involved linear system is solved by external software devoted to sparse matrices.
- Current work: refactoring.

5.1.4. MP-FRAC

Participants: Thomas Dufaud, Jocelyne Erhel, Aurélien Le Gentil, Géraldine Pichot [correspondant].

- Version: version 1.0, May 2008
- APP: registered
- Programming language: C++
- See also: http://h2olab.inria.fr.
- Abstract: The software MP-FRAC aims at modelling and simulating numerically flow in a fractured aquifer. The physical domain is a network of fractures, either deterministic or stochastic, with a permeability field either deterministic or stochastic. The software computes the velocity field in the aquifer, by assuming that the medium is saturated and that flow is steady-state. Physical equations are stochastic PDEs, handled by a Monte-Carlo method. This non intrusive approach generates a set of random samples, which are used for simulations. Then, the software analyzes statistically the flow in the stochastic case. The objective is to characterize hydraulic properties in Discrete Fracture Networks. The software MP-FRAC handles a simulation corresponding to one sample, whereas Monte-Carlo method is implemented in a generic way by the software GW-NUM. The software is specific of the physical model (Discrete Fracture Network) and of the application (steady-state flow). Generic numerical methods to discretize PDE are implemented in the software GW-NUM.
- Current work: refactoring and design of libraries.

5.1.5. PARADIS

Participants: Jocelyne Erhel, Grégoire Lecourt, Aurélien Le Gentil, Géraldine Pichot [correspondant].

- Version: version 1.0, May 2008
- APP: registered
- Programming language: C++
- See also: http://h2olab.inria.fr/.
- Abstract: The software PARADIS aims at modelling and simulating numerically flow in a porous aquifer and transport by convection-diffusion of an inert solute. The porous medium is heterogeneous, with a stochastic or deterministic permeability field. A first step computes the velocity filed in the aquifer, by assuming that the medium is saturated and that flow is steady-state. A second step computes the distribution of solute concentration, by assuming a transport by convection and by molecular diffusion. Physical equations are stochastic PDEs, handled by a Monte-Carlo method and discretized by numerical methods. This non intrusive approach generates a set of random samples, which are used for simulations. Then, the software analyzes statistically the flow in the stochastic case. The objectives are to determine asymptotic laws of transport, to characterize pre-asymptotic behavior and to define global laws.

  The software PARADIS handles a simulation corresponding to one sample, whereas Monte-Carlo method is implemented in a generic way by the software GW-NUM. The software is specific of the physical model (heterogeneous porous medium) and of the application (steady-state flow then transport with macro-dispersion). Generic numerical methods to discretize PDE are implemented in the software GW-NUM.
- Current work: refactoring and design of libraries.

5.1.6. GRT3D

Participants: Édouard Canot, Jocelyne Erhel [correspondant], Souhila Sabit.

- Version: version 1.0, April 2011
- APP: registered
- Programming language: C
- Abstract: Reactive transport modeling has become an essential tool for understanding complex environmental problems. It is an important issue for MoMaS partners (see section 8.2.7), in particular Andra (see section 7.1). We have developed a method coupling transport and chemistry, based on a method of lines such that spatial discretization leads to a semi-discrete system of algebraic differential equations (DAE system). The main advantage is to use a complex DAE solver, which controls simultaneously the timestep and the convergence of Newton algorithm. The approach SIA uses a fixed-point method to solve the nonlinear system at each timestep, whereas the approach SNIA uses an explicit scheme.

  The software suite GRT3D has four executable modules:
  - SIA1D: Sequential Iterative Approach for 1D domains;
  - GDAE1D: Global DAE approach for 1D domains;
  - SNIA3D: Sequential Non Iterative Approach for 1D, 2D or 3D domains.
  - GDAE3D: Global DAE approach for 1D, 2D or 3D domains. This module has three variants: the original one with logarithms, an optimized one still with logarithms, an optimized one which does not use logarithms.
- Current work: extension of the chemistry module and parallelization.

5.1.7. SBM

Participant: Géraldine Pichot [correspondant].

- Version: version 1.0, November 2013
- Programming language: C
- Abstract: SBM (Skew Brownian Motion) is a code developed with A. Lejay (Inria, Nancy). This code allows exact or approximated simulations of the Skew Brownian Motion. This code is used for the simulation, with a Monte-Carlo approach, of a 1D diffusion process with a discontinuous diffusion coefficient. Several benchmark tests are also implemented.
- Current work: paper about benchmarking results.

5.2. High Performance Scientific Computing

5.2.1. PALMTREE

Participants: Lionel Lenôtre [correspondant], Géraldine Pichot.

- Version: version 1.0, November 2013
- Programming language: C++
- Abstract: We present an easy-to-use package for the parallelization of Lagrangian methods for partial differential equations. In addition to the reduction of computation time, the code aims at satisfying three properties:
  - simplicity: the user just has to add the algorithm governing the behaviour of the particles.
  - portability: the possibility to use the package with any compiler and OS.
  - action-replay: the ability of the package to replay a selected batch of particles.

  The last property allows the user to replay and capture the whole sample path for selected particles of a batch. This feature is very useful for debugging and catching some relevant information.
- Current work: paper about performance results.

5.2.2. GPREMS

Participants: Édouard Canot, Jocelyne Erhel [correspondant].

- Version: version 1.0, May 2008
- APP: registered
- Programming language: C++
- See also: http://www.irisa.fr/sage/.
- Abstract: GPREMS implements a robust hybrid solver for large sparse linear systems that combines a Krylov subspace method as accelerator with a Schwarz-based preconditioner. This preconditioner uses an explicit formulation associated to one iteration of the multiplicative Schwarz method. The Newton-basis GMRES, which aims at expressing a good data parallelism between subdomains is used as accelerator.

5.2.3. DGMRES

Participant: Jocelyne Erhel [correspondant].

- Version: version 1.0, June 2011
- APP: distributed with the free software PETSC
- Programming language: C
- See also: http://www.irisa.fr/sage/.
- Abstract: DGMRES implements a preconditioner based on adaptive deflation, which can be used with any preconditioner for the GMRES algorithm.

5.2.4. AGMRES

Participant: Jocelyne Erhel [correspondant].

- Version: version 1.0, November 2011
- APP: distributed with the free software PETSC
- Programming language: C
- See also: http://www.irisa.fr/sage/.
- Abstract: AGMRES implements an augmented subspace approach, based on adaptive deflation, which can be used with any preconditioner for the GMRES algorithm. It also implements a Newton basis for enhancing parallelism.

5.2.5. PPAT

Participants: Édouard Canot [corresponding author], Bernard Philippe.

PPAT (Parallel PATh following software) is a parallel code, developed by D. Mezher, W. Najem (University of Saint-Joseph, Beirut, Lebanon) and B. Philippe. This tool can follow the contours of a functional from $\mathbb{C}$ to $\mathbb{R}^+$. The present version is adapted for determining the level curves of the function $f(z) = \sigma_{\min}(A - zI)$ which gives the pseudospectrum of matrix A.

The algorithm is reliable: it does not assume that the curve has a derivative everywhere. The process is proved to terminate even when taking into account roundoff errors. The structure of the code spawns many independent tasks which provide a good efficiency in the parallel runs.

The software can be downloaded under the GPL licence from: http://sourceforge.net/projects/ppat.

5.2.6. MUESLI

Participant: Édouard Canot [corresponding author].

Doing linear algebra with sparse and dense matrices is somehow difficult in scientific computing. Specific libraries do exist to deal with this area (*e.g.* BLAS and LAPACK for dense matrices, SPARSKIT for sparse ones) but their use is often awful and tedious, mainly because of the large number of arguments which must be used. Moreover, classical libraries do not provide dynamic allocation. Lastly, the two types of storage (sparse and dense) are so different that the user must know in advance the storage used in order to declare correctly the corresponding numerical arrays.

MUESLI is designed to help in dealing with such structures and it provides the convenience of coding in Fortran with a matrix-oriented syntax; its aim is therefore to speed-up development process and to enhance portability. It is a Fortran 95 library split in two modules: (i) FML (Fortran Muesli Library) contains all necessary material to numerically work with a dynamic array (dynamic in size, type and structure), called `mfArray`; (ii) FGL (Fortran Graphics Library) contains graphical routines (some are interactive) which use the `mfArray` objects.

MUESLI includes some parts of the following numerical libraries: Arpack, Slatec, SuiteSparse, Triangle, BLAS and LAPACK.

Linux is the platform which has been used for developing and testing MUESLI. Whereas the FML part (numerical computations) should work on any platform (*e.g.* Win32, Mac OS X, Unix), the FGL part is intended to be used only with X11 (*i.e.* under all UNIXes).

Last version of MUESLI is 2.6.6 (2012-08-29). More information can be found at: http://people.irisa.fr/Edouard.Canot/muesli

5.2.7. CANARD

Participant: Édouard Canot [corresponding author].

When dealing with non-linear free-surface flows, mixed Eulerian-Lagrangian methods have numerous advantages, because we can follow marker particles distributed on the free-surface and then compute with accuracy the surface position without the need of interpolation over a grid. Besides, if the liquid velocity is large enough, Navier-Stokes equations can be reduced to a Laplace equation, which is numerically solved by a Boundary Element Method (BEM); this latter method is very fast and efficient because computing occur only on the fluid boundary. This method has been applied to the spreading of a liquid drop impacting on a solid wall and to the droplet formation at a nozzle; applications take place, among others, in ink-jet printing processes.

The code used (CANARD) has been developped with Jean-Luc Achard (LEGI, Grenoble) for fifteen years and is used today mainly through collaborations with Carmen Georgescu at UPB (University Polytechnica of Bucarest, Romania), and with Alain Glière (CEA-LETI, Grenoble).

6. New Results

6.1. Parallel numerical algorithms

6.1.1. Parallel Adaptive GMRES with deflated restarting

Participant: Jocelyne Erhel.

Grants and projects: C2S@EXA 8.2.3, JLPC 8.4.4

Software: DGMRES, AGMRES, GPREMS.

Publications: [17], [26].

Abstract: The GMRES iterative method is widely used as a Krylov subspace technique for solving sparse linear systems when the coefficient matrix is nonsymmetric and indefinite. The Newton basis implementation has been proposed on distributed memory computers as an alternative to the classical approach with the Arnoldi process. The aim of our work here is to introduce a modification based on deflation techniques. This approach builds an augmented subspace in an adaptive way to accelerate the convergence of the restarted formulation. In our numerical experiments, we show the benefits of using this implementation with hybrid direct/iterative methods to solve large linear systems.

6.1.2. Hybrid algebraic solvers for CFD problems

Participant: Jocelyne Erhel.

Grants and projects: C2S@EXA 8.2.3, JLPC 8.4.4

Software: DGMRES, AGMRES, GPREMS.

Publications: [18].

Abstract: Sparse linear systems arise from design optimization in computational fluid dynamics. In this approach, a linearization of the discretized compressible Navier-Stokes equations is built, in order to evaluate the sensitivity of the entire flow with respect to each design parameter. The goal is to reduce the memory requirements and indirectly, the computational cost at different steps of this scheme. Numerical results are presented with industrial test cases to show the benefits of our methodology.

6.1.3. Algebraic multilevel preconditioning

Participant: Thomas Dufaud.

Grants: C2S@EXA 8.2.3

Publications: [51], [23], [24].

Conferences: [37], [24].

Abstract: The Schwarz domain decomposition method is a very attractive numerical method for parallel computing as it needs only to update the boundary conditions on the artificial interfaces generated by domain decomposition. Thus only local communications between the neighbouring sub-domains are required. We review the use of Aitken's acceleration applied to the Schwarz domain decomposition method.

6.1.4. Counting eigenvalues in domains of the complex field

Participant: Bernard Philippe.

Grants: momappli 8.4.2

Publications: [15], [28].

Conferences: [47], [48], [22].

Abstract: A procedure for counting the number of eigenvalues of a matrix in a region surrounded by a closed curve is presented. It is based on the application of the residual theorem. The quadrature is performed by evaluating the principal argument of the logarithm of a function. A strategy is proposed for selecting a path length that insures that the same branch of the logarithm is followed during the integration. Numerical tests are reported for matrices obtained from conventional matrix test sets.

6.1.5. Sliced-time computation method

Participant: Jocelyne Erhel.

Grants: MODNUM 8.4.5

Publications: [16], [25].

Abstract: We consider the mathematical framework of a sliced-time computation method for explosive solutions to systems of ordinary differential equations. We also derive an Adaptive Parallel-in-Time Method with application to a membrane problem.

6.1.6. Interacting particles systems

Participant: Lionel Lenôtre.

Grants: H2MNO4 8.2.1

Conferences: [31]

Abstract: We consider a variance reduction method for simulations with particles.

6.2. Numerical models and simulations applied to physics

6.2.1. Heat and mass transfer modeling in porous media

Participants: Édouard Canot, Salwa Mansour.

Grants: MODNUM 8.4.5, HYDRINV 8.4.7

Conferences: [33], [35],[44]

Abstract: The effective thermal conductivity is a key parameter for obtaining good simulations of heat transfer in wet porous media. It is very sensitive to the presence of liquid water, even in very small quantity. Moreover, during the evaporation of water, some changes of geometric configuration of the liquid meniscus lead to hysteresis behaviors. Micro-scale studies help us in understanding the global properties, via numerical simulations.

6.2.2. Heat transfer in soils applied to archaeological fires

Participants: Édouard Canot, Salwa Mansour.

Grants: MODNUM 8.4.5, ARPHYMAT 8.4.6

Conferences: [34], [36]

Abstract: In order to be validated, the numerical simulations of heat transfer at the surface of the soil are compared to experimental results, because of the complexity of the phenomenon and the great number of physical mechanisms involved. It appears that making good experiments is hard, not to mention the limitations and lacks of the Laloy and Massard method used to obtained the effective thermal conductivity of the granular material. The Laloy and Massard method have been slightly improved; besides a different, new experimental method, based on the mathematical properties of heat transfer, has been proposed.

6.2.3. Granular materials

Participant: Édouard Canot.

Publications: [19].

Abstract: Using the $\mu(I)$ continuum model recently proposed for dense granular flows, we study theoretically steady and fully developed granular flows in two configurations: a plane shear cell and a channel made of two parallel plates (Poiseuille configuration).

6.2.4. Geodesy

Participants: Amine Abdelmoula, Bernard Philippe.

Grants: LIRIMA-EPIC 8.4.3, joint Ph-D 8.4.9.

Publications: [12].

Thesis: Ph-D of Amine Abdelmoula, University of Rennes 1 and Tunis, defended in December 2013.

Abstract: We solve a geodetic inverse problem for the determination of a distribution of point masses (characterized by their intensities and positions), such that the potential generated by them best approximates a given potential field.

6.3. Models and simulations for flow and transport in porous media

6.3.1. Flow and transport in highly heterogeneous porous medium

Participants: Jean-Raynald de Dreuzy, Jocelyne Erhel, Géraldine Pichot.

Grants: H2MN04 8.2.1, H2OGuilde 8.2.4, HEMERA 8.2.2

Software: PARADIS, H2OLab

Publications: [13]

Abstract: Models of hydrogeology must deal with both heterogeneity and lack of data. We consider a flow and transport model for an inert solute. The conductivity is a random field following a stationary log normal distribution with an exponential or Gaussian covariance function, with a very small correlation length. The quantities of interest studied here are the expectation of the spatial mean velocity, the equivalent permeability and the macro spreading. In particular, the asymptotic behavior of the plume is characterized, leading to large simulation times, consequently to large physical domains. Uncertainty is dealt with a classical Monte Carlo method, which turns out to be very efficient, thanks to the ergodicity of the conductivity field and to the very large domain. These large scale simulations are achieved by means of high performance computing algorithms and tools.

6.3.2. Diffusion processes in porous media

Participants: Lionel Lenôtre, Géraldine Pichot.

Grants: H2MN04 8.2.1

Software: SBM 5.1.7, PALMTREE 5.2.1

Publications: [21]

Conferences: [41], [43], [42]

Abstract: We present some recent results about Monte Carlo simulations in media with interfaces. By nature, porous media are extremely heterogeneous. We consider a one-dimensional advection-diffusion equation with piecewise constant coefficients. Without drift term, the Skew Brownian Motion permits to develop several exact algorithms with constant time step. We aim at adding the drift term and dealing with higher dimensional problems.

6.3.3. Adaptive stochastic model for flow and transport with random data

Participants: Jocelyne Erhel, Mestapha Oumouni.

Grants: HYDRINV 8.4.7, joint Ph-D 8.4.8

Publications: [27].

Conferences: [46].

Thesis:[11].

Abstract: This work presents a development and an analysis of an effective approach for partial differential equation with random coefficients and data. We are interesting in the steady flow equation with stochastic input data.

A projection method in the one-dimensional case is presented to compute efficiently the average of the solution.

An anisotropic sparse grid collocation method is also used to solve the flow problem. First, we introduce an indicator of the error satisfying an upper bound of the error, it allows us to compute the anisotropy weights of the method. We demonstrate an improvement of the error estimation of the method which confirms the efficiency of the method compared with Monte Carlo and will be used to accelerate this method by the Richardson extrapolation technique.

We also present a numerical analysis of a probabilistic method to quantify the migration of a contaminant in random media. We consider the previous flow problem coupled with the advection-diffusion equation, where we are interested in the computation of the mean extension and the mean dispersion of the solute. The flow model is discretized by a mixed finite elements method and the concentration of the solute is the density of the solution of a stochastic differential equation, which is discretized by an Euler scheme. We present an explicit formula of the dispersion and optimal a priori error estimates.

6.3.4. Reactive transport

Participants: Édouard Canot, Jocelyne Erhel, Souhila Sabit.

Grants: H2MN04 8.2.1, ANDRA 7.1, MOMAS 8.2.7, C2SEXA 8.2.3

Software: GRT3D.

Publications: [52],[30].

Conferences: [20],[40],[50], [32].

Abstract: Numerical simulations are essential for studying the fate of contaminants in aquifers, for risk assessment and resources management. In this study, we deal with reactive transport models and show how a Newton method can be used efficiently. Numerical experiments illustrate the efficiency of a substitution technique. Moreover, it appears that using logarithms in the chemistry equations lead to ill conditioned matrices and increase the computational cost.

6.4. Models and simulations for flow in porous fractured media

6.4.1. Synthetic benchmark for modeling flow in 3D fractured media

Participants: Jean-Raynald de Dreuzy, Jocelyne Erhel, Géraldine Pichot.

Grants: GEOFRAC 8.2.5, FRACINI 8.1.1

Software: MPFRAC

Publications: [14]

Abstract: Intensity and localization of flows in fractured media have promoted the development of a large range of different modeling approaches including Discrete Fracture Networks, pipe networks and equivalent continuous media. While benchmarked usually within site studies, we propose an alternative numerical benchmark based on highly-resolved Discrete Fracture Networks (DFNs) and on a stochastic approach. Test cases are built on fractures of different lengths, orientations, aspect ratios and hydraulic apertures, issuing the broad ranges of topological structures and hydraulic properties classically observed. We present 18 DFN cases, with 10 random simulations by case.

6.4.2. Robust numerical methods for solving flow in stochastic fracture networks

Participants: Jean-Raynald de Dreuzy, Jocelyne Erhel, Géraldine Pichot.

Grants: GEOFRAC 8.2.5, FRACINI 8.1.1

Software: MPFRAC, H2OLab.

Publications: [29].

Conferences: [49].

Abstract: In this work, flow in Discrete Fracture Networks (DFN) is solved using a Mortar Mixed Hybrid Finite Element Method. To solve large linear systems derived from a nonconforming discretization of stochastic fractured networks, a Balancing Domain Decomposition is used. Tests on three stochastically generated DFN are proposed to show the ability of the iterative solver SIDNUR to solve the flow problem.

6.4.3. Flow in complex 3D geological fractured porous media

Participants: Jean-Raynald de Dreuzy, Thomas Dufaud, Jocelyne Erhel, Géraldine Pichot.

Grants: GEOFRAC 8.2.5, FRACINI 8.1.1

Software: MPFRAC, H2OLab

Conferences: [38], [39]

Abstract: Taking into account water and solute exchanges between porous and fractured media is of great interest in geological applications. The coupled porous-fractured flow equations and their discretization by a Mixed Hybrid Finite Element Method are presented as well as the derived linear system. An appropriate mesh generation is proposed to deal with the complexity involved by randomly generated fracture networks. Numerical experiments are shown, that provide flow fields for forthcoming transport simulations.

7. Bilateral Contracts and Grants with Industry

7.1. ANDRA: Numerical methods for reactive transport

Participants: Édouard Canot, Jocelyne Erhel, Souhila Sabit.

Title: Numerical methods for reactive transport.
Time: October 2010-October 2013
Partner: ANDRA Coordination: J. Erhel, with G. Pépin (ANDRA)

Abstract: It is quite challenging to develop a numerical model for deep storage of nuclear waste. The time interval is very large (several thousands years), models are coupled and simulations must be accurate enough to be used for risk assessment. In most cases, chemistry must be included in models of deep geological storage. We have developed an efficient global method coupling transport and chemistry by a Newton-type algorithm. See sections 6.3.4, 4.2, 8.2.7, 5.1.6.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Brittany council: FRACINI project

Participants: Jean-Raynald de Dreuzy, Jocelyne Erhel, Géraldine Pichot.

Contract with Brittany council
Duration: one year from December 2013.
Title: European initiative towards models and numerical methods for simulations in fractured-porous geological media.
Coordination: Géraldine Pichot.
Partners: Geosciences Rennes.
Web page: http://www.irisa.fr/sage/
Abstract: FRACINI is an initiative funded by the Région Bretagne. It aims at gathering researchers from the European community working on models and numerical methods for simulations in fractured-porous media. Two international workshops will be organized in 2014. The overall objective of these workshops is to end up with a submission of a proposal in response to the Future and Emerging Technology (FET) call of H2020 Funding.

8.2. National Initiatives

8.2.1. ANR-MN: H2MNO4 project

Participants: Édouard Canot, Jocelyne Erhel, Grégoire Lecourt, Aurélien Le Gentil, Lionel Lenôtre, Géraldine Pichot, Souhila Sabit.

Contract with ANR, program Modèles Numériques
Duration: four years from November 2012.
Title: Original Optimized Object Oriented Numerical Model for Heterogeneous Hydrogeology.
Coordination: Jocelyne Erhel and Géraldine Pichot, with Fabienne Cuyollaa.
Partners: Geosciences Rennes, University of Poitiers, University of Lyon 1, Andra, Itasca.
International collaborations: University of San Diego (USA), UPC, Barcelona (Spain)
Web page: http://h2mno4.inria.fr/
Abstract: The project H2MNO4 develops numerical models for reactive transport in heterogeneous media. It defines six mathematical and computational challenges and three applications for environmental problems with societal impact (see 6.3, 5.1.1).

8.2.2. Inria Project Lab: HEMERA project

Participants: Jocelyne Erhel, Géraldine Pichot.

Title: Hemera - developing large scale parallel and distributed experiments
Duration: September 2010 - July 2014
Coordination: C. Perez, Avalon team.
Partners: 22 Inria teams.
Webpage: http://www.grid5000.fr/mediawiki/index.php/Hemera
Abstract: Hemera is an Inria Project Lab, started in 2010, that aims at demonstrating ambitious up-scaling techniques for large scale distributed computing by carrying out several dimensioning experiments on the Grid'5000 infrastructure, at animating the scientific community around Grid'5000 and at enlarging the Grid'5000 community by helping newcomers to make use of Grid'5000.

The team Sage is the leader of the Scientific Challenge Hydro: Multi-parametric intensive stochastic simulations for hydrogeology. The objective is to run multiparametric large scale simulations (see 6.3).

8.2.3. Inria Project Lab: C2S@EXA project

Participants: Édouard Canot, Thomas Dufaud, Jocelyne Erhel, Géraldine Pichot, Souhila Sabit.

Title: C2S@EXA - Computer and Computational Scienecs at Exascale
Duration: from January 2012.
Coordination: S. Lanteri, Nachos team.
Partners: Inria teams working on HPC; external partners: ANDRA and CEA.
Webpage: http://www-sop.inria.fr/c2s_at_exa/
Abstract: The C2S@Exa Inria Project Lab is concerned with the development of numerical modeling methodologies that fully exploit the processing capabilities of modern massively parallel architectures in the context of a number of selected applications related to important scientific and technological challenges for the quality and the security of life in our society (see 6.1, 6.3, 6.4). The team participated in several workshops.

8.2.4. Inria Technological development actions: H2OGuilde project

Participants: Jocelyne Erhel, Aurélien Le Gentil, Grégoire Lecourt, Géraldine Pichot.

Title: H2OGuilde - Graphical User Interface and Library Development for H2OLab platform
Duration: October 2011 - October 2013.
Coordination: J. Erhel and G. Pichot.
Partner: Charles Deltel, SED Inria Rennes
Webpage: http://www.irisa.fr/sage/
Abstract: The project H2OGuilde aims at developing an interface for the platform H2OLab and at designing software libraries with a large academic diffusion (see 5.1.1,5.1.5, 5.1.4).

8.2.5. Inria Collaborative Research Action: GEOFRAC project

Participants: Thomas Dufaud, Jocelyne Erhel, Géraldine Pichot.

Title: GEOFRAC
Duration: June 2011-June 2013.
Coordinator: J. Erhel and G. Pichot.
Partners: Pomdapi and Gamma3 Inria teams, Géosciences Rennes.
Webpage: http://www.irisa.fr/sage/geofrac/
Abstract: In the last twenty years, the interest of geological fractured rocks has been renewed by a variety of energy-related applications, such as carbonate oil reservoirs, geothermic energy production, geological storage of high level nuclear waste, geological sequestration of CO2. Fractures are highly permeable pathways within a less pervious but more porous medium generally called matrix. The discrete modeling of fractures faces at least two challenging numerical issues. First, the fracture and matrix phases have very different hydraulic properties. Permeability is at least two orders of magnitude larger in the fractures than in the matrix. Second, the fracture structure complexity yield intricate geometrical configurations difficult to mesh. We propose to address these limitations by developing new numerical methods (see 6.4, 5.1.1).

8.2.6. GENCI: project on advanced linear solvers

Participants: Édouard Canot, Jocelyne Erhel, Grégoire Lecourt, Lionel Lenôtre, Géraldine Pichot.

Title: Scalabilité de méthodes numériques pour l'hydrogéologie
Duration: 2012
Coordination: J. Erhel and G. Pichot.
Webpage: http://www.genci.fr/
Abstract: To run large scale simulations, we defined a project, based on the software H2OLab, SBM, PALMTREE and GRT3D. We obtained and used computing time on machines located at GENCI supercomputing centers. (see 6.1, 6.3).

8.2.7. GNR MOMAS: project on reactive transport

Participants: Jocelyne Erhel, Souhila Sabit.

Webpage: https://www.ljll.math.upmc.fr/cances/gdrmomas/

The working group MOMAS includes many partners from CNRS, Inria, universities, CEA, ANDRA, EDF and BRGM. It covers many subjects related to mathematical modeling and numerical simulations for nuclear waste disposal problems (see 6.3, 6.4). The team participated in workshops.

8.3. European Initiatives

8.3.1. FP7: EXA2CT project

Title: EXascale Algorithms and Advanced Computational Techniques
Instrument: Specific Targeted Research Project
Duration: September 2013 - August 2016
Coordinator: S. Ashby, IMEC, Belgium
Partners: 10 partners
Inria contact: Luc Giraud
Web page: https://projects.imec.be/exa2ct/
Abstract: The goal of this project is to develop novel algorithms and programming models to tackle what will otherwise be a series of major obstacles to using a crucial component of many scientific codes at exascale, namely solvers and their constituents. The results of this work will be combined in running programs that demonstrate the application-targeted use of these algorithms and programming models in the form of proto-applications.

8.3.2. Collaborations with Major European Organizations

UPC: Universitat Politècnica de Catalunya-UPC, Institute of Environmental Assessment and Water Research (Spain)
numerical simulations in hydrogeology, reactive transport in heterogeneous media, upscaling, scientific software platform (see 5.1.1, 6.3.1, 6.4).
UFZ: Helmholtz Centre for Environmental Research-UFZ, Hydrogeology group (Germany)
numerical simulations in hydrogeology, flow in porous fractured media, scientific software platform
HPCLab: University of Patras, High Performance Information Systems Laboratory (Greece)
cooperation with B. Philippe in writing a book, and in common research on low rank approximations of matrix functions.
ERCIM: working group on numerical algorithms, high performance computing.

8.4. International Initiatives

8.4.1. Informal International Partners

University of Kent (USA)
Krylov methods
University of Purdue (USA)
High Performance Scientific Computing
University of San Diego (USA)
Hydrogeology

8.4.2. LIRIMA laboratory: momappli team (Cameroon)

Participant: Bernard Philippe.

Program: Laboratoire International de Recherche en Informatique et Mathématiques Appliquées
Title: Modélisation Mathématique et Applications
Inria principal investigator: Bernard Philippe
International Partner (Institution - Laboratory - Researcher): University of Yaounde, Cameroon - Norbert Noutchegueme
Duration: 2010-2013
See also: http://www.lirima.uninet.cm/index.php/recherche/equipes-de-recherche/momappli
Abstract: The team deals with high performance scientific computing, with a focus on reliable tools for localizing eigenvalues of large sparse matrices (see 6.1.4).

8.4.3. LIRIMA laboratory: EPIC team (Tunisia)

Participants: Amine Abdelmoula, Jocelyne Erhel, Sinda Khalfallah, Bernard Philippe.

Program: Laboratoire International de Recherche en Informatique et Mathématiques Appliquées

Title: Problèmes Inverses et Contrôle

Inria principal investigator: Houssem Haddar, Defi team

International Partner (Institution - Laboratory - Researcher): ENIT, University of Tunis, Tunisia - LAMSIN - Amel ben Abda

Duration: 2011-2013

See also: http://www.lirima.uninet.cm/index.php/recherche/equipes-de-recherche/epic

Abstract: The team deals with nonlinear and inverse problems.

8.4.4. Joint Laboratory for Petascale Computing (USA)

Participant: Jocelyne Erhel.

Program: Joint Laboratory for Petascale Computing

Inria principal investigator: Franck Cappello and Laura Grigori, Grand Large team

International Partner (Institution - Laboratory - Researcher): University of Illinois at Urbana-Champaign, USA - Marc Snir and Bill Gropp

Duration: 2011-2013

See also: http://jointlab.ncsa.illinois.edu/

Abstract: The team works on deflation methods and their integration into the software PETSc (see 6.1.1); the team works also on domain decomposition methods (see 6.4.2).

8.4.5. CEDRE program: MODNUM project (Lebanon)

Participants: Édouard Canot, Jocelyne Erhel, Bernard Philippe.

Program: CEDRE Lebanon

Title: Modélisation numérique pour des applications libanaises

Inria principal investigator: Jocelyne Erhel and Bernard Philippe

International Partner (Institution - Laboratory - Researcher): American University of Beirut (Lebanon)

Duration: Jan 2012 - Dec 2013

Abstract: the project deals with numerical parallel algorithms and with applications to archaeology.

8.4.6. ECOS Sud (Argentina): ARPHYMAT project

Participant: Édouard Canot.

Program: COFECUB

Title: Processus de formation et transformation de structures de combustion archéologique

Inria principal investigator: Édouard CANOT

International Partner (Institution - Laboratory - Researcher): University of Buenos Aires (Argentina)

Duration: Jan 2012 - Dec 2014

Abstract: the project concerns numerical simulations of prehistoric fires and comparison with archaeological data in South America.

8.4.7. Inria Euromediterranean: HYDRINV project

Participants: Édouard Canot, Jocelyne Erhel, Sinda Khalfallah, Bernard Philippe.

Program: Euromediterranean 3+3

Title: Direct and inverse problems in subsurface flow and transport

Coordination: H. ben Ameur, ENIT, Tunisia and J. Jaffré, Inria, Paris

Inria-Rennes principal investigator: Jocelyne Erhel

International Partners (Institution - Laboratory - Researcher):

Université Ibn Tofail - Faculté des Sciences de Kénitra (Morocco) - Laboratoire Interdisciplinaire en Ressources Naturelles et en Environnement - Zoubida Mghazli

Ecole Nationale d'Ingénieurs de Tunis (Tunisia) - Laboratoire de Modélisation en Hydraulique et Environnement - Rachida Bouhlila

Universidad de Sevilla (Spain) - Department Ecuaciones Diferenciales y Anâlisis Numérico - Tomas Chacon Rebollo

Universitat Politècnica de Catalunya (Spain) - Department of Geotechnical Engineering and Geo-Sciences - Xavier Sànchez Vila

University Centre of KHEMIS MILIANA (Algeria) - Laboratoire de l'Energie et des Systèmes Intelligents - Mohammed Hachama

Ecole Mohammadia d'Ingénieurs (Morocco) - LERMA - Rajae Aboulaich

Ecole Nationale d'Ingénieurs de Tunis (Tunisia) - Laboratoire de Modélisation Mathématique et Numérique dans les Sciences de l'Ingénieur - Hend Ben Ameur

Duration: Jan 2012 - Dec 2015

The management of water resources is a problem of great importance in all countries, and is particularly acute around the Mediterranean sea. The goal is to find a reasonable balance between these resources and demand while preserving the quality of water. Towards this goal it is essential to understand and simulate flow and transport in the subsurface. The science corresponding to this topic is hydrogeology. Since models become more and more complicated and quantitative answers must be given, numerical modeling become more and more sophisticated and mathematicians must also be involved. This project brings together hydrogeologists and mathematicians from France, Spain, Algeria, Morocco and Tunisia in order to develop, analyze, and validate numerical methods for several problems arising from modeling flow and transport in the subsurface. The emphasis is put on direct nonlinear problems (air-water flow, density driven flow related to salinization, transport with chemistry) and on inverse problems.

8.4.8. Joint supervision of M. Oumouni's PhD (Morroco)

Participants: Jocelyne Erhel, Mestapha Oumouni.

Program: International joint supervision of PhD agreement

Title: Méthodes numériques et leur analyse pour la résolution des équations de l'écoulement et de transport en milieux poreux hétérogènes et aléatoires

Inria principal investigator: Jocelyne Erhel

International Partner (Institution - Laboratory - Researcher): University Ibn Tofail - Faculté des Sciences de Kénitra (Morocco) - Zoubida Mghazli

Duration: Jan 2009 - June 2013

Abstract: see 6.3.3.

8.4.9. Joint supervision of A. Abdelmoula's PhD (Tunisia)

Participants: Amine Abdelmoula, Bernard Philippe.

Program: International joint supervision of PhD agreement

Title: Résolution de problèmes inverses en géodésie physique

Inria principal investigator: Bernard Philippe

International Partner (Institution - Laboratory - Researcher): Ecole Nationale d'Ingénieurs de Tunis - LAMSIN (Tunisia) - Maher Moakher

Duration: 2005 - 2013

Abstract: The objective is to compute a set of point-mass which generate an a priori given gravitational field (see 8.4.7, 8.4.3).

8.4.10. Joint supervision of S. Khalfallah's PhD (Tunisia)

Participants: Jocelyne Erhel, Sinda Khalfallah.

Program: International joint supervision of PhD agreement

Title: Contribution à l'analyse mathématique et numérique de quelques problèmes issus de l'hydrogéologie

Inria principal investigator: Jocelyne Erhel

International Partner (Institution - Laboratory - Researcher): Ecole Nationale d'Ingénieurs de Tunis - LAMSIN (Tunisia) - Amel ben Abda

Duration: 2010 - 2014

Abstract: The objective is to solve data completion problems applied to hydrogeology (see 8.4.7, 8.4.3).

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Emmanuel Kamgnia, University of Yaoundé, 2 months, March-April 2013
- Nabil Nassif, American University of Beirut, 3 weeks, July 2013, November 2013, December 2013
- Stratis Gallopoulos, Uiversity of Patras, 1 week, August 2013
- Ahmed Sameh, University of Purdue, 1 week, August 2013
- Mohamad Muhieddine, Libanese University, 2 weeks, June 2013
- Lamia Guellouz, University of Tunis, 1 week, December 2013

8.5.2. Internships (Joint supervision of Ph-D students

- Louis-Bernard Nguenang, University of Yaoundé, 4.5 months, March-July 2013
- Mestapha Oumouni, University of Kenitra, 3 months, March-June 2013
- Marwen ben Refifa, University of Tunis, 3 months, April-July 2013
- Salwa Mansour, Lebanese University, 7 months, Feb-Aug 2013

8.5.3. Visits to International Teams

- Édouard Canot, ENIT Tunis, Tunisia, 1 week, February 2013 (project HYDRINV)
- Jocelyne Erhel and Géraldine Pichot, UPC Barcelona, Spain, 1 week, April 2013 (project H2MNO4)
- Édouard Canot and Salwa Mansour and Bernard Philippe, Beirut, Lebanon, 1 week, May 2013 (project MODNUM)
- Édouard Canot, ANCBA Buenos Aires, Argentina, 2 weeks, November 2013 (project ARPHYMAT)
- Bernard Philippe, Yaoundé, Cameroon, 1 week, December 2013 (project MOMAPPLI)

9. Dissemination

9.1. Scientific Animation

9.1.1. Scientific committees of conferences

- J. Erhel is a member of the editorial board of the PARENG'2013 conference (Pecs, Hungary, March 2013).
- J. Erhel is a member of the scientific committee of the MAMERN'13 conference (Granada, Spain, April 2013).
- J. Erhel is a member of the scientific committee of the SMAI 2013 conference (Seignosse, France, May 2013).
- J. Erhel is a member of the international advisory committee of the parallel CFD conferences (Changsha, Hunan, China, May 2013).

9.1.2. Organization of workshops

- J. Erhel organized with E. Faou and T. Lelièvre the conference NASPDE (Rennes, September 2013).

9.1.3. Editorial Boards

- B. Philippe is one of the four chief-editors of the electronic journal ARIMA (revue Africaine de la Recherche en Informatique et Mathématiques Appliquées).
- B. Philippe is managing editor of the electronic journal ETNA (Electronic Transactions on Numerical Analysis).
- J. Erhel and G. Pichot are editors of the proceedings of Domain Decomposition XXI (LNCSE, Springer)
- J. Erhel is member of the editorial board of ETNA.
- J. Erhel is member of the editorial board of ESAIM:Proceedings.
- J. Erhel is member of the editorial board of Mathematics of Planet Earth 2013, un jour-une brève.
- J. Erhel is member of the wide consortium of the prospective think tank: MATHématiqueS en INteractions pour la TERRE (funded by ANR)

9.1.4. Steering committees

- J. Erhel is a member of the steering committee of the Réseau National des Systèmes Complexes.
- J. Erhel is the scientific coordinator of the website Interstices (since June 2012).
  See http://www.interstices.info.

9.1.5. Inria, IRISA and University committees

- É. Canot is member of the CLHSCT (Commité Local Hygiène Sécurité Conditions de Travail), of Inria-Rennes, from September 2010.
- J. Erhel is member of the Comité Technique d'Etablissement Public of Inria.
- J. Erhel is member of Conseil d'Administration of Inria.
- J. Erhel is member of the working group of Inria Rennes on project management.
- J. Erhel participated in the panel during the workshop on HAL organized by the Universities of Rennes.
- G. Pichot is responsible for the domain "environment" at IRISA.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

- A. Abdelmoula is teaching assistant (permanent position) in computer science at the University of Tunis, Tunisia.
- S. Khalfallah is teaching assistant (permanent position since September 2012) in mathematics at the University of Kairouan, Tunisia.
- L. Lenôtre is teaching assistant (contrat doctoral avec mission d'enseignement) in mathematics at the University of Rennes 1.
- A. Le Gentil: Master M1; title: TP d'analyse, conception et programmation orientée objets; 26 hours; INSA, Rennes, France.
- J. Erhel: Master M2; title: Cours de modélisation et calcul scientifique; 12 hours; INSA, Rennes, France.
- É. Canot and G. Lecourt: Master M2; title: TP de modélisation et calcul scientifique; 12 hours each; INSA, Rennes, France.

9.2.2. Supervision

PhD: M. Oumouni, University of Rennes 1 and University of Kenitra, June 2013, co-advisors J. Erhel and Z. Mghazli.

PhD: A. Abdelmoula, University of Rennes 1 and University of Tunis, December 2013, co-advisors B. Philippe and M. Moakher.

PhD in progress: S. Khalfallah, University of Rennes 1 and University of Tunis, October 2009, co-advisors J. Erhel and A. ben Abda.

PhD in progress: L. Lenôtre, University of Rennes 1, October 2012, co-advisors A. Lejay (Inria Nancy) and G. Pichot, with J. Erhel.

PhD in progress: S. Mansour, University of Rennes 1 with LIU and AUB (Beiruth, Lebanon), January 2013, co-advisors É. Canot, M. Muhieddine and N. Nassif.

PhD in progress: L.-B. Nguenang, University of Yaounde 1, October 2011, advisors E. Kamgnia with B. Philippe.

PhD in progress: M. ben Refifa, University of Tunis, October 2013, advisors Rachida Bouhlila with J. Erhel and É. Canot.

PhD in progress: S. Sabit, University of Rennes 1, October 2010, advisors J. Erhel with É. Canot.

9.2.3. Juries

- HdR: O. Coulaud, University of Bordeaux, November 2013. Reviewer J. Erhel.
- PhD: R. Lago, University of Toulouse, Mathematics, June 2013. Examiner J. Erhel.
- PhD: C. Heinry, University of Paris 6, Mathematics, December 20123. Reviewer J. Erhel.

9.3. Popularization

- J. Erhel participated in the Inria workshop on scientific popularization, Paris, January 2013.
- J. Erhel participated in the Mathematics of Planet Earth Day at UNESCO, Paris, March 2013.
- J. Erhel gave a talk entitled "la terre se met aux maths", during the week of maths, at lycée Victor and Hélène Basch, Rennes, in March 2013 [59]. See http://www.irisa.fr/sage/jocelyne
- J. Erhel participated in the panel on "Observer et mesurer la terre", Rencontres CNRS Jeunes Sciences et Citoyens, Ile de France, March 2013 See http://www.scienceouverte.fr/Rencontres-CNRS-Jeunes-Sciences-et,413 and http://www.scienceouverte.fr/-Divers-voyages- [58]
- J. Erhel was invited to "congrès des jeunes chercheurs", at ISFEC Bretagne, Rennes, April 2013
- J. Erhel gave a talk with F. Tort (ENS Cachan) entitled "L'informatique, c'est pas pour les filles", at the salon "Educatec-Educatice", Paris, November 2013.

- J. Erhel coordinated with C. Leininger the journal TDC no 1062 "les mathématiques de la terre", october 2013. See http://www.cndp.fr/tdc/tous-les-numeros/les-mathematiques-de-la-terre.html
- B. Philippe wrote a review on TDC no 1062. See http://www.interstices.info.
- J. Erhel wrote a document entitled "sur les traces des polluants", in TDC no 1062 [57].
- J. Erhel wrote a paper entitled "Le Jour d'après : vers une réflexion sur les modèles climatiques ", in Interstices [56]
- J. Erhel wrote two texts in the blog mpt2013: "Henry Darcy et sa loi" [54] and "La diffusion, un moteur universel" [55].
- B. Philippe wrote a text in the blog mpt2013: "La terre a du potentiel" [61] See http://mpt2013.fr/.

10. Bibliography

Major publications by the team in recent years

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[5] M. CROUZEIX, B. PHILIPPE, M. SADKANE. *The Davidson Method*, in "SIAM, Journal on Scientific and Statistical Computing", 1994, vol. 15:1, pp. 62-76

[6] J.-R. DE DREUZY, A. BEAUDOIN, J. ERHEL. *Asymptotic dispersion in 2D heterogeneous porous media determined by parallel numerical simulations*, in "Water Resource Research", 2007, vol. 43, n^{o} W10439, doi:10.1029/2006WR005394

[7] J. ERHEL, S. RAULT. *Algorithme parallèle pour le calcul d'orbites : Parallélisation à travers le temps*, in "Technique et science informatiques", 2000, vol. 19, n^{o} 5

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[9] M. MUHIEDDINE, É. CANOT, R. J. MARCH, R. DELANNAY. *Coupling heat conduction and water-steam flow in a saturated porous medium*, in "International Journal for Numerical Methods in Engineering", 2011, vol. 85, n^{o} 11, pp. 1390-1414 [*DOI :* 10.1002/NME.3022], http://hal.inria.fr/inria-00540366/en

[10] Y. SAAD, M. YEUNG, J. ERHEL, F. GUYOMARC'H. *A deflated version of the Conjugate Gradient Algorithm*, in "SIAM Journal on Scientific Computing", 2000, vol. 21, n^{o} 5, pp. 1909-1926

Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] M. OUMOUNI. , *Analyse numérique de méthodes performantes pour les EDP stochastiques modélisant l'écoulement et le transport en milieux poreux*, Université Rennes 1 and université Ibn Tofaïl de Kenitra, June 2013, http://hal.inria.fr/tel-00904512

Articles in International Peer-Reviewed Journals

[12] A. ABDELMOULA, M. MOAKHER, B. PHILIPPE. *A Slepian framework for the inverse problem of equivalent gravitational potential generated by discrete point masses*, in "Inverse Problems in Science and Engineering", 2014, 19 p. , http://hal.inria.fr/hal-00919094

[13] A. BEAUDOIN, J.-R. DE DREUZY, J. ERHEL, G. PICHOT. *Convergence analysis of macrospreading in 3D heterogeneous porous media*, in "ESAIM: Proceedings", 2014, vol. 41, pp. 59-76, http://hal.inria.fr/hal-00904436

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