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5.4. HYDROGEOLOGICAL MODEL: MARTHE CODE

5.4.1. The MARTHE software

MARTHE software is designed to address underground hydrodynamic problems in various context of groundwater management, civil works, environments, and mining operation. It has the possibility to simulate 3D advective and dispersive flow with solute transport under steady or transient state conditions with multilayer aquifer[3].

The finite-difference based MARTHE software (French acronym for: Modélisation d'Aquifères par maillage Rectangulaire en régime Transitoire pour la simulation Hydrodynamique des Ecoulements) developed by BRGM enables to perform three-dimensional simulations of groundwater flow, mass, and energy transport in porous media.

It can model hydrosystems by integrating groundwater flow, hydro-climatic budgets, and surface-water flow. The underlying schemes can be simple or complex (unsaturated flow, multiphase flow, density-dependent fluid flow, consideration of vegetation, aquifer-river interactions, etc.). The implementation of the different functionalities is described by Thiéry in related reports and publications.

The software uses a numerical finite difference scheme using irregular parallelepiped or rectangular meshes. This can represent complex multi-layer aquifer systems, with bevelled layers and the occurrence of free surfaces in any layer. MARTHE addresses modelling of regional multi-layer systems covering several thousand square kilometres, as well as local scale modelling of porous media systems down to few cubic centimetres, with millimetre-size cells.

It computes pollutant and energy flows and transport in porous environments and can represent them in two or three dimensions. The code is based on the finite volumes method and incorporates:

- ***Standard hydraulic features****:*
  - 2D (plan, vertical cross-section, axisymmetric) or 3D grids.
  - Single- or multi-layer aquifer systems (stacked aquifers that may be separated by semi-permeable layers).
  - Unconfined, semi-confined, or confined aquifers under steady-state or transient conditions.

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[3] Thiéry, D. (1990) – Software MARTHE. Modelling of Aquifers with a Rectangular Grid in Transient state for Hydrodynamic Calculations of Heads and Flows. Release 4.3. Rap. BRGM 4S/EAU R 32548; Thiéry, D. (2010a) – Modélisation des Ecoulements Souterrains en Milieu Poreux avec MARTHE. in Traité d'hydraulique environnementale – Volume 9 – Logiciels d'ingénierie du cycle de l'eau. Tanguy J.M. (Ed.) - Éditions Hermès - Lavoisier. Chapitre 4 pp. 77-94. ISBN 978-2-7462-2339-4.; Thiéry, D. (2010b) – Hydrogeologic Models. in "Mathematical Models Volume 2, chapter 4, pp. 71-92 • Environmental Hydraulics Series". Tanguy J.M. (Ed.) – Wiley/ISTE London. ISBN: 978-1-84821-154-4.; Thiéry, D. (2010c) – Reservoir Models in Hydrogeology. in "Mathematical Models Volume 2, chapter 13, pp. 409-418 • Environmental Hydraulics Series". Tanguy J.M. (Ed.) – Wiley/ISTE London. ISBN: 978-1-84821-154-4.; Thiéry, D. (2010d) – Groundwater Flow Modeling in Porous Media Using MARTHE. in "Modeling Software Volume 5, Chapter 4, pp. 45-60 • Environmental Hydraulics Series". Tanguy J.M. (Ed.) –Wiley/ISTE London. ISBN: 978-1-84821-157-5.; Thiéry D. (2020a) – Code de calcul MARTHE v7.8 - Modélisation 3D des écoulements et des transferts dans les hydrosystèmes - Notice d'utilisation. Rapport BRGM/RP-69541-FR, 333 p., 158 fig.; Thiéry, D. (2020b) – Didacticiel du code de calcul MARTHE v7.8 - Exploration des fonctionnalités de modélisation des écoulements et des transferts dans les hydrosystèmes. Rapport BRGM/RP-69542-FR. 381 p., 256 fig.; Thiéry, D. (2020c) – MARTHE v7.8 - Analyse des écarts de simulation ; Exportations de fichiers de résultats en « shapefiles ». Rapport BRGM/RP-69210-FR. 38 p., 27 fig.

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- Consideration of discontinuities such as surface water (lakes, gravel pits, etc.), local drying-up (and wetting) of (multi-layer) aquifer(s), aquifer-river interactions, springs, and water-tight walls (sheet piling, etc.).
- Automatic shut-down of pumping wells depending on the calculated hydraulic head (dewatering of the pumping screens).
- Detailed integration of drainage networks.
- Direct integration of hydro-climatic budgets.
- Horizontal and vertical anisotropy of the soils hydraulic conductivities.
- Tracking of forward and/or backward flow lines under steady-state or transient conditions.

o ***Hydrodispersive mass transport****:*

- Hydrodispersive migration of a solute in the aquifer and the unsaturated zone (UZ) by convection, diffusion, or hydrodynamic dispersion.
- Degradation of a solute through exponential decay over time (water-content and temperature functions).
- Chain degradation of several solutes.
- Invariant retarding factor or function of a linear partition coefficient (adsorption-desorption phenomena).
- Consideration of double porosity, with kinetics or in equilibrium.
- Freundlich or Langmuir isotherms.

o ***Unsaturated zone, Density, Temperature****:*

- Continuous modelling of both saturated and unsaturated zones.
- Density effects induced by salinity and/or temperature gradients.
- Temperature-dependent fluid Viscosity.

o ***Heat transport****:*

- Heat storage and recovery, migration of a thermal plume.
- Simulation of heat transport between geothermal doublet wells.
- Approximating thermal walls with the Vinsome (1980) analytical solution.

o ***Automatic model calibration, Optimization****:*

- Automatic calibration of model parameters along homogeneous zones or cell-by-cell calibration.
- Sensitivity analysis of the calibrated parameters.
- Analysis of the simulation variance. The "Analysis of simulation variance (Analyse des écarts de simulation").

o ***Geochemical reactions:*** MARTHE is coupled with two external geochemical modelling engines:

- The hydrogeochemical REACT model from the LBNL's TOUGHREACT code.

    - The hydrogeochemical modules of the USGS's PHREEQC code[4]. The physico-chemical interactions between the liquid phase and the porous matrix can be simulated at will with one of these coupled versions.

- ***Advanced features**:*
    - Drain or tunnel networks.
    - Transport with physico-chemical interactions between water, effluents, and porous matrix.
    - Two-phase flow: saltwater intrusion analysis, water and air, water and "oil".
    - Single-phase gas flow.
    - Development of vegetation in the root zone.
    - Simulation of vertical fractures by their equivalent transmissivity.

5.4.2. Objectives

Designing and applying hydrodynamic and hydrodispersive models for sustainable groundwater management has multiple benefits to stakeholders. Constructing and calibrating models improves understanding the critical processes that influence the water bodies (surface water and groundwater). The application of a model for testing the influence of projects and management actions on site conditions may provide a framework for stakeholders to screen and select appropriate strategies for the management of water resources and environment. Further on, model allow long-term predictions when it calculated forecasting effects resulting from the natural specific environment as climate change or human-related changes in water use[5].

5.4.3. Interest for MAR-SAT systems

Modelling tools of subsurface flow and hydrogeochemical reaction help to understand behaviour of pollutants in MAR/SAT systems. Groundwater modelling can provide the possibility to preview de feasibility of MAR system in regional context (geological, climate, flood-event frequency…) and give a tool to identify and optimise the choice for implementing MAR systems. Standard numerical models are able to simulate 3D adjective and dispersive flow of water and solute. It has been shown that the MARTHE model has a fairly complete packaged well adapted to MAR problems(ibid). The model will offer possibility to calculate watershed scale hydrodynamic flux with climate, water uses variations, water balance and will allow estimating groundwater table levels in contact with river levels, then determining the potential environmental impact on the estuary under different MAR options.

The set of groundwater monitoring probes (water level, salinity, and temperature) implemented at various distance from the MAR scheme could be taken as observation reference to design and calibrate the groundwater dynamic.

A specific document was written in English for the EVIBAN project to apply MARTHE code on MAR system particularly in coastal area[6].

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[4] Parkhurst, D.L., Appelo, C.A.J., 2013. Description of input and examples for PHREEQC version 3: a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations (Report No. 6-A43), Techniques and Methods. Reston, VA. https://doi.org/10.3133/tm6A43

[5] Kloppmann, W., Aharoni, A., Chikurel, H., Dillon, P., Gaus, I., Guttman, J., Kraitzer, T., Kremer, S., Masciopinto, C., Pavelic, P., Picot-Colbeaux, G., Pettenati, M., Miotlinski, K., 2012. Use of groundwater models for prediction and optimisation of the behaviour of MAR sites, in: Water Reclamation Technologies for Safe Managed Aquifer Recharge. pp. 311–349.

[6] Thiéry D. and Picot-Colbeaux, G. (2020) – Guidelines for MARTHE v7.8 computer code for hydro-systems modelling (English version). Report BRGM/RP-69660-FR, 246 p., 177 fig.

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The report "Tutorial for the WinMarthe v4.0" pre-processor, BRGM/RP-54652-EN[7] describes the WinMarthe preprocessor in more detail. Recent information on BRGM's MARTHE software is available on the dedicated website: http://marthe.brgm.fr/ in French and in English.

[7] Thiéry, D. (2007) – Tutorial for the WinMarthe v4.0 pre-processor. BRGM/RP-54652-EN, 89 p.,48 fig.