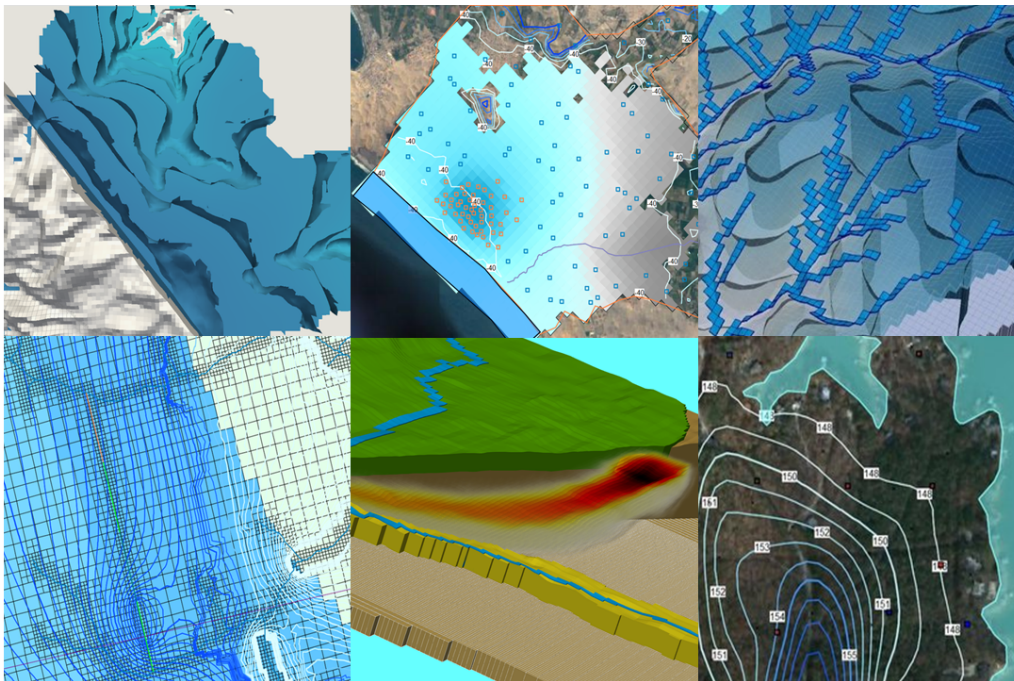




Diploma in Applied Groundwater Modeling with MODFLOW and Model Muse



v. 1.1

February - July 2023



Diploma in Applied Groundwater Modeling with MODFLOW and Model Muse

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1. Description

We have designed a complete program on MODFLOW with Model Muse that ranges from the essential topics in flow and transport modeling to applied cases of regional modeling, infrastructure projects, and seawater intrusion. MODFLOW with Model Muse is a recent open-source software that provides various tools for simulating the groundwater flow regime in different environments.

A numerical groundwater flow model can be the most efficient and effective tool to understand the groundwater flow regimen and to obtain practical information about relationships between the geological environment and surface flow. There needs to be more than a code for groundwater modeling; it is necessary to know both the modeling platform and the physical processes we want to reproduce, and in this particular case, the water dynamics of the hydrogeological system. This program will cover basic, intermediate and advanced topics such as manual/automatic calibration.

2. Objectives

The student will reach the following objectives based on a hands-on learning approach through understanding simple to complex concepts:

- Learning the Model Muse environment and tools for modeling with MODFLOW.
- Developing criteria for conceptualization, grid design and selection of boundary conditions.
- Designing strategies for data collection, model construction, calibration and analysis.
- Analyzing the water balance model and exporting model data to other platforms.
- Performing manual and automated calibrations.



3. Content

The diploma is divided into seven modules, described below.

Module 1: Groundwater Modeling using MODFLOW 6 and Model Muse

This course develops the main functions and applications of the latest version of the MODFLOW 6 groundwater modeling code through the ModelMuse interface, both developed by the United States Geological Survey (USGS). These versions of MODFLOW and Model Muse include innovative tools for constructing and simulating hydrogeological models, mainly highlighting the incorporation of the discretization option for discretized vertices grids (DISV).

Session 1: Introduction to MODFLOW 6

The student will develop a basic model to familiarize themselves with the construction and simulation of a steady state MODFLOW 6 model and the visualization of hydraulic heads in Model Muse. This session will include:

- The definition of a model grid.
- Setting the aquifer type (confined or unconfined) and the hydraulic parameters.
- Setting boundary conditions: RCH, RIV and WEL.
- Visualizing the results and the water balance.

Session 2: DISV Package and quadtree refinements

This session focuses on implementing a model with DISV (Discretization by Vertices) grid, a new feature incorporated in ModelMuse by the name of refined quadtree grid. The topics covered in the session are:

- Constructing a steady-state model with quadtree refinement.
- Defining boundary conditions representing a lake as a constant-head, a river and wells with different pumping rates.
- Model completion and water balance analysis.
- Visualizing groundwater level.



Session 3: Advanced packages

Session 3 includes an exercise focused on modeling the dynamics of the groundwater-related advanced stress packages like multi-aquifer wells (MAW) and stream-flow routing (SFR). The topics covered are:

- Constructing a model with advanced packages: MAW (Multi-Aquifer Well) and SFR (Stream Flow Routing).
- Adding a lake as a constant head boundary.
- Simulating a transient mode.

Session 4: Particle tracking

Session 4 develops two examples of particle tracking with Modpath7 to see the movement of particles coming from a source. The session will cover two parts, as follows:

Part 1:

- Configuring MODPATH in a steady-state model with quadtree refinement.
- Forward and backward particle tracking simulation applied to a model with general-head boundary conditions and wells.

Part 2:

- Configuring MODPATH in a transient-state model.
- Forward and backward particle tracking simulation applied to a model with wells with different pumping rates and a river that interacts with a nearby well.

Session 5: Three-dimensional anisotropy

This session configures XT3D, which enables a total 3d anisotropy in MODFLOW 6 models, applied through angles in a 3D model. The session will cover two parts, described below:

Part 1:

- Creating a model in steady-state with three-dimensional anisotropy applied in 2 axes that create whirls.
- Inserting wells pumping and injecting water in different layers.

Part 2:

- Three-dimensional steady-state simulation with quadtree refinement and three-dimensional anisotropy distributed in 2 axes of the grid.



Session 6: River-aquifer interaction modeling on a quadtree mesh with Modflow 6

In this session, we will create a groundwater model with river interaction using several boundary conditions, hydraulic parameters and temporal and spatial discretization techniques described below:

- Creating a quadtree mesh from shapefiles
- Assigning boundary conditions: RIV, WEL, GHB, RCH
- Defining solver parameters for DISV models.



Module 2: Contaminant Transport Modeling using MODFLOW and MT3D

Once we have covered the flow models in Modflow, we will develop exercises focused on the construction and simulation of solute transport in groundwater flow systems that have evolved rapidly in recent years, driven by the increased interest in knowledge of aquifer pollution. The MT3D package, implemented by MODFLOW, provides a tool for synthesizing these processes, evaluating their interactions and testing the effectiveness of groundwater remediation measures.

Session 1: Two-dimensional transport in a diagonal flow field

This session will develop a solution for the 2D transport of a solute injected continuously from a point source in a steady state flow field at a certain angle. The session will cover:

- Setting up MT3D options and migratory species.
- Defining regional flow based on vertex interpolation.
- Representing flow contours and concentrations over time.

Session 2: Transport modeling with observation points

Session 2 offers a solution for the 2D transport model of a solute injected continuously from a point source in a steady state flow field. The topics covered are:

- Defining flow and transport modeling options.
- Inserting observation points.
- Creating interactive animation of the contaminant plume.

Session 3: Contaminant injection on a multilayer model with mesh refinement

In Session 3, we will implement 3D modeling of a contamination plume over a multilayer aquifer for 100 days. The model mesh has been refined to represent contaminant concentrations better. The session will include:

- Specifying the transverse dispersivity ratio.
- Representing head contour and water balance analysis.
- Mesh refinement on the well and near the downgradient area.



Session 4: Two-dimensional vertical transport in a heterogeneous aquifer

The fourth session covers the flow and transport of solutes in a heterogeneous aquifer with two low hydraulic conductivity horizons. This session includes:

- A simulation of steady and transient states.
- Assigning the transmissivity, K_x and K_z parameters.
- Defining pollution areas as the contamination source.

Session 5: Two-dimensional flow simulation with remediation technique

Session 5 includes an example of a simulation of a contaminated site from a point source upstream and remediation pumping well as a plume retention measure. This session will cover:

- Identify the horizontal low hydraulic conductivity zone.
- Simulating the effectiveness of remediation pumping schema.
- Analyzing low K area impacts on transport migration.

Session 6: Simulation of impact from pit latrines on water wells

The final session of the module is a simulation of the impact of a group of pit latrines on a water well in Nigeria for 70 years. This session will cover:

- Set up the transport model and mobile species.
- Discretize the time for flow and transport.
- Simulate contaminant transport.



Module 3: Regional Modeling with Modflow and Model Muse

Regional groundwater modeling is an important task in strategic water management that the users can use to assess the current groundwater situation and predict future conditions. It is also frequently used to quantify recharge and discharge and evaluate aquifer parameters. This course presents the main functions and applications of MODFLOW for regional groundwater modeling, three basins with different aquifer settings and boundary conditions are used as case studies to demonstrate the use of these tools so that the participants learn how to build these models and analyze the results for future decision-making.

Session 01: Regional model I

This session focuses on creating a model to represent a regional groundwater model based on a basin, rivers and topography. We will also develop a comparison of the head observed and simulated. Here we include:

- The construction of a three-dimensional steady-state model with a basin that delimits the active zone placed throughout the extension of the grid.
- Using graphic objects and external shapefiles to apply to boundary conditions such as recharge, evapotranspiration, and rivers.
- Applying head observations and post-processing of results.

Session 02: Building a Regional model II

This exercise will cover the identification of model area, setting model layers, grid definition, vector data import, aquifer discretization, and boundary condition. This session covers:

- The definition of the model area and an active zone.
- The use of model layers and spatial discretization.
- Importing external data
- Assigning hydraulic parameters.

Session 3: Assigning boundary conditions for a Regional model II

We will continue developing the previous model since the assignment of boundary conditions and setting up the Zone Budget package on a regional groundwater flow model. Here we will cover:

- Apply the MODFLOW packages - DRN, RCH and EVT.



- Use graphical objects and external shapefiles to apply model parameters and boundary conditions.
- Set up the Zone Budget Package
- Simulate zone budgets with an analysis of the interaction in a zone specified.

Session 04: Analysis of water balance of model II and visualization results

This session is focused on defining different global variables according to the geological formation in the study zone. After the simulation, we will analyze the hydraulic heads and water balance using GW_Chart. Here we will cover:

- Assign an input of geology
- Use global variables to assign model parameters.
- Compare simulated - observed hydraulic heads.
- Analyze the groundwater balance with GW_Chart

Session 05: Regional model III construction

In this session, we will learn to define the grid, elevation, the type and vertical discretization of the aquifer, boundary conditions, rock type and hydraulic parameters, insert objects that represent recharge and evapotranspiration, import the extent of the model, baseflow, basins, lakes, rivers and visualize the geology of the area. This session covers:

- Building another regional model.
- Applying the MODFLOW packages - DRN, RCH, EVT, and GHB.
- Using global variables to assign model parameters.
- Using graphical objects and external shapefiles to apply model parameters and boundary conditions.
- Visualizing the model.

Session 06: Simulation of a Regional model III

This session is focused on completing the properties of geological formations, adding piezometers and flows and adjusting parameters so that the match between the observed value and the simulated results is the best possible. Here we will cover:

- Insert piezometers in the model.
- Adjust parameters according to physical considerations.
- Compare observed and simulated data.
- Analyze water levels.
- Visualize and analyze the water balance of the calibrated model.



Module 4: Infrastructure Modeling

Infrastructure projects on the local, meso and regional scale can interact with shallow or deep groundwater flow regimes. There is a need to evaluate the potential impact of an infrastructure project for the engineering phase to design mitigation strategies and drainage schemas. This course covers three applied cases covering the groundwater impact simulation of trenches, tunnels and excavations.

Session 01: Modeling a trench excavation with flow barrier (HFB) in Modflow 6 on a quadtree mesh.

The first session covers a transient simulation of a trench excavation with a flow barrier in Modflow 6. The primary purpose of using an HFB is to prevent the extension of the depression cone to a VOC-contaminated site. This session includes:

- A Multi background image implementation.
- Defining a quadtree mesh from the trench alignment.
- Evaluating a depression cone extension pre and post-HFB.

Session 02: Transient Modflow 6 modeling of an infrastructure tunnel with quadtree refinement

The second session is an applied case for the transient simulation of a 4 km tunnel in stress periods of 1 year over a regional model. The model is constructed with Model Muse and Modflow 6 - DISV. Here we will cover:

- Define a cell/layer confinement in Modflow 6.
- Refine the quadtree on the tunnel path and stream networks.
- Perform a water balance analysis and head representation.

Session 03: Numerical Modeling of Construction Site Dewatering.

Session 3 is a transient groundwater flow simulation of a drainage schema for a building foundation. The model has multiple refinement layers to represent the depression cone better. This session will include:

- A horizontal flow barrier to decrease differential settlements.
- Coupled drainage techniques (drains + wells).
- An analysis of the drainage schema efficiency.

Module 5: Seawater Intrusion Modeling with Modflow, Model Muse and SWI2

The continuous exploitation of groundwater in coastal areas has intensified the phenomenon of salinization by inducing a salt wedge from the sea or deep saline horizons with a constant decrease in water quality. The SWI2 package is the latest release of the Seawater Intrusion (SWI) package for MODFLOW. This package allows simulating with MODFLOW vertically integrated three-dimensional variable-density groundwater flow and marine intrusion in coastal multi-aquifer systems. In this course, you will learn how to use Modflow and SWI to evaluate saline intrusion cases in contact with groundwater.

Session 01: Construction of Model I of saline intrusion in a coastal aquifer.

In this session, the construction of a coastal aquifer will be carried out, which will allow us to understand the different tools that the SWI 2 package has for the configuration of the flow model. This session covers:

- The construction of a georeferenced model in ModelMuse.
- The definition of transient temporal discretization.
- The implementation of historical well-log conditions.
- Post-processing the flow model in ModelMuse

Session 02: Model I simulation of saline intrusion in a coastal aquifer.

In this session, the construction of the previous model will be completed with the insertion of the boundary conditions. The simulation focused on exploitation over 45 years will be carried out to determine the state of the saline intrusion wedge. Here we will:

- Use SWI2 in ModelMuse.
- Add coupling of phases with variable density.
- Insert active surfaces depending on the phases.
- Post-process the three-dimensional model of intrusion with multiple wells in ModelMuse.



Session 03: Evaluation of a Model II of saline intrusion in a coastal aquifer.

In this session, the construction and simulation of a model located in a coastal aquifer with intense exploitation of 50 high-performance wells for 60 years will be carried out. This session covers:

- A review of the geometry of the model / discretization.
- An evaluation of the types of aquifers and hydraulic parameters.
- The analysis of the temporal discretization of the model.
- Selecting parameters of the solver of flow and variable density.
- Simulating the model and analysis of the water balance.
- Visualizing the values of the Hydraulic Head, Water Table, and Saline Interface

Module 6: Modflow in Mining with Modflow and Model Muse.

Modeling groundwater inflows to pit and underground mines and assessing the impact of mining projects on the surrounding groundwater flow regime is vital for the planning and engineering of mining projects. Mine working interaction with the groundwater flow regime is a dynamic process that the user can model with standard MODFLOW packages implemented on Model Muse. This platform has high performance due to its "design by objects" that optimizes the conceptualization of boundary conditions and other model elements, reducing construction time and improving the interpretation of output data. This course covers the use of MODFLOW with Model Muse for numerical modeling of the groundwater flow impact from pit development, underground mines and seepage from water dumps and tailings storage facilities.

Session 01: Modeling underground mine inflows with MODFLOW

This session covers an applied numerical simulation of underground mine entrances covering transient model construction, simulation and water balance analysis. Several common steps in groundwater modeling are covered, such as importing vector and raster (elevation) spatial data, spatial and temporal discretization, setting hydraulic parameters, defining boundary conditions, running simulations, and exporting data. Here we will cover:

- Construct a model in a transient regime.
- Import vector data and elevations, refine the grid, discretize the aquifer, define space and times, and define boundary conditions.
- Define the water table.
- Assign hydraulic parameters, such as hydraulic conductivities of each layer.
- Simulate water inflow flows.
- Activate the ZONE BUDGET package
- Analyze the results with GW CHART

Session 02: Seepage flow modeling from mine dumps with Modflow and MT3DMS

This session covers the simulation of groundwater in the area of two mining dumps in an Andean basin and visualization of the formation of the contaminant plume. Here we will cover:



- Define the aquifer and boundary conditions (Recharge, Evapotranspiration, Drains and Constant head).
- Import grid data for defining a water table.
- Import a dump mine area.
- Set up the MT3DM package to define the contaminant species.
- Analyze the contaminant plume in the time.

Session 03: Construction of a tailings dam model I

This session shows the insertion procedure of the boundary conditions and main properties in a tailing dam model on steady-state conditions over a five-layer model. The session includes:

- Importing vector data for defining the extension model, leachates zone and tailings areas.
- Importing elevations.
- Defining the aquifer.
- Setting up hydraulic parameters.

Session 04: Simulation of seepage flow from a tailings dam model I

This session covers the insertion of boundary conditions and simulation of the seepage flow from tailings on the model, using the Newton solver in Modflow. The session covers:

- Defining boundary conditions such as recharge, evapotranspiration and regional flow.
- Assigning and visualizing the hydraulic conductivity in the tailing area.
- Setting up the properties of the NWT solver.
- Visualizing of the water table
- Analyzing of results

Session 05: Construction of the drainage pit model II

This session covers the construction of the pit drainage model that includes analyzing the spatial discretization, the temporal discretization, the definition of type confinement and analysis of the water table. Here we will cover:

- Insert grid refinements.
- Set up steady and transient temporal discretization.
- Define the types of boundary conditions required and their application by objects.
- Configure hydraulic parameters of the aquifers.



- Visualize the water table using the triangle method interpolation.

Session 06: Simulation of drainage pit model II

This session focuses on evaluating the hydrogeological regime according to the pit's progress throughout the mine's life. Here we will

- Import elevations according to the mine plan.
- Simulate the transient model in MODFLOW for pit drainage.
- Analyze the water table throughout the life of the mine.
- Perform detailed water balances and determine the cone of depression.

Module 7: Automatic and Manual Calibration with Modflow and Pest.

The calibration of hydrogeological models can be defined as the procedure to adjust the hydraulic parameters of the model where the resulting hydraulic heads and flows are as close as possible to the observed values. Due to the complexities of hydraulic parameter distribution, model geometry, the conceptualization of boundary conditions, and other factors, the calibration procedure can be time-consuming and sometimes with limited success; however, there are tools implemented on Model Muse as PEST that speed up the process of calibration and uncertainty analysis in groundwater models. In this course, manual calibration will be developed using geospatial tools such as QGIS and Modflow with Model Muse for parameter adjustment. Automatic calibration cases will also be created using the PEST tool from Modflow with Model Muse.

Session 01: The applied case of hydrogeological conceptual modeling on a hillslope area with QGIS and Modflow with Model Muse.

This session focuses on reviewing and compiling data that allows us to understand the relationship between the flow of groundwater and the stability of a slope located in a study area on a hotspot of the US Landslide Inventory. This session covers:

- A review of spatial data such as geology, groundwater wells, topography and weather conditions in QGIS.
- The analysis of boundary conditions of the study area in QGIS.
- Visualizing the limit of the aquifer.
- Defining the grid and conditions of the aquifer layers in Modflow and Model Muse.

Session 02: Groundwater Modeling on a Hillslope Area - Model Construction

This session will continue with the construction of the numerical model from the configuration of the aquifer properties and boundary conditions to the simulation and visualization of the hydraulic heads. This session includes:

- The definition of boundary conditions, rock type and hydraulic parameters.
- The insertion of objects representing regional flow, sea, recharge, drainage and evapotranspiration.
- The insertion of 24 observation points using the HOB package.



- The simulation of the flow model and visualization of the values of hydraulic heads calculated and observed.

Session 03: Manual Calibration of a Groundwater Flow Model in MODFLOW 6 with Model Muse

In this session, the development of the previous model will be completed with the manual calibration that includes the adjustment of parameters so that the concordance between the observed data and the results of the model is the best possible. Here we will cover:

- Analyze hydraulic conductivity data.
- Analyze the recharge boundary conditions, drains, and evapotranspiration.
- Evaluate the influence of the increase or decrease of model parameters.
- Analyze and display the calibration statistics and comparison of hydraulic heads of the calibrated model.

Session 04: Basic PEST on a local scale model

This session includes an introductory example of PEST usage on groundwater model with two boundary conditions as parameters and heads as calibration observations. Here we will cover:

- Provide an overview of PEST implementation on Model Muse.
- Setup K and Recharge as PEST parameters.
- Obtain a PEST simulation and output analyses.

Session 05: Automatic calibration of MODFLOW 6 with Pest in heterogeneous media with two observation types

This session provides an example of a multilayered groundwater flow model that has a regional flow from a general head to an interpolated over vertex head with recharge and drain boundary conditions. Here we will cover:

- Implement four parameters of K and Conductivities.
- Setup head and flow as observations.
- Analyze the Pest results.

Session 06: Distributed parameter estimation using pilot points of a MODFLOW 6 - PEST peninsula model.

This session provides an applied example of the implementation of pilot points of PEST for the hydraulic conductivity on the peninsula groundwater flow model. We will include:



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- A PEST simulation with 20 observation points.
- A definition of distributed pilot points from a shapefile.
- The Hydraulic conductivity, GHB conductance and recharge rate as PEST parameters.



4. Trainer

Saul Montoya M.Sc. - Hydrogeologist - Numerical Modeler

Mr Montoya is a Civil Engineer who graduated from the Catholic University in Lima with postgraduate studies in Management and Engineering of Water Resources (WAREM Program) from Stuttgart University – Germany with a mention in Groundwater Engineering and Hydroinformatics. Mr Montoya has a solid analytical capacity for interpreting, conceptualising and modeling the surface and underground water cycle and their interaction. He is in charge of the numerical modeling for contaminant transport and remediation systems of contaminated sites. Inside his hydrological and hydrogeological investigations, Mr Montoya has developed a holistic comprehension of the water cycle, understanding and quantifying the primary hydrological dynamic process of precipitation, runoff, evaporation and recharge to the groundwater system.

Over the last nine years, Saul has developed two websites for knowledge sharing in water resources: www.qidahatari.com (Spanish) and www.hatarilabs.com (English), that have become relevant due to their applied tutorials on groundwater modeling, spatial analysis and computational fluid mechanics.



5. Methodology / Examination

Mode: Online with streaming - Synchronous

Some details about the diploma methodology:

- The manuals and files for the exercises will be delivered through our online platform.
- The course will be developed by video streaming with live support and interaction.
- Recorded **videos** will be available on our eLearning platform.
- There is online support for questions regarding the exercises developed through email and meetings.
- Video of the classes will be available for six months.

The exams and certification are organized as follows:

- The program has three exams that comprise the content of 2 courses.
- A digital certificate is available at the end of the program upon exam approval.
- To receive the digital certificate, you must submit the exams on the following date:
 - First exam before 31st March 2023,
 - Second exam before 31st May 2023.
 - Third exam before 31st July 2023.



6. Date and time

The course is offered in sessions of approximately 1.5 to 2 hours. All sessions start at 6 pm Central European Time (CET) - Amsterdam Time.

Module 1 - February 2023

- Week 1: Tuesday 07 and Thursday 09, 6 pm to 8 pm (Amsterdam Time).
- Week 2: Tuesday 14 and Thursday 16, 6 pm to 8 pm (Amsterdam Time).
- Week 3: Tuesday 21 and Thursday 23, 6 pm to 8 pm (Amsterdam Time).

Module 2 - March 2023

- Week 1: Tuesday 07 and Thursday 09, 6 pm to 8 pm (Amsterdam Time).
- Week 2: Tuesday 14 and Thursday 16, 6 pm to 8 pm (Amsterdam Time).
- Week 3: Tuesday 21 and Thursday 23, 6 pm to 8 pm (Amsterdam Time).

Module 3 - April and May 2023

- Week 1: Tuesday 18 and Thursday 20 April, 6 pm to 8 pm (Amsterdam Time).
- Week 2: Tuesday 25 and Thursday 27 April, 6 pm to 8 pm (Amsterdam Time).
- Week 3: Tuesday 02 and Thursday 04 May, 6 pm to 8 pm (Amsterdam Time).

Module 4 - May 2023

- Week 1: Tuesday 09 and Thursday 11, 6 pm to 8 pm (Amsterdam Time).
- Week 2: Tuesday 16, 6 pm to 8 pm (Amsterdam Time).

Module 5 - May 2023

- Week 1: Thursday 18 and Tuesday 23, 6 pm to 8 pm (Amsterdam Time).
- Week 2: Thursday 25, 6 pm to 8 pm (Amsterdam Time).

Module 6 - June 2023

- Week 1: Tuesday 06 and Thursday 08, 6 pm to 8 pm (Amsterdam Time).
- Week 2: Tuesday 13 and Thursday 15, 6 pm to 8 pm (Amsterdam Time).
- Week 3: Tuesday, 20 and Thursday, 22, 6 pm to 8 pm (Amsterdam Time).

Module 7 - July 2023

- Week 1: Tuesday 04 and Thursday 06, 6 pm to 8 pm (Amsterdam Time).
- Week 2: Tuesday 11 and Thursday 13, 6 pm to 8 pm (Amsterdam Time).
- Week 3: Tuesday 18 and Thursday 20, 6 pm to 8 pm (Amsterdam Time).



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7. Cost and payment method

The program cost is \$1500 US dollars or \$1320 US dollars before 20th December 2022.

Make your payment and register on this link:

<https://hatarilabs.com/ht-en/diploma-in-applied-groundwater-modeling-with-modflow-and-model-muse-06th-feb-to-20th-july-2023>