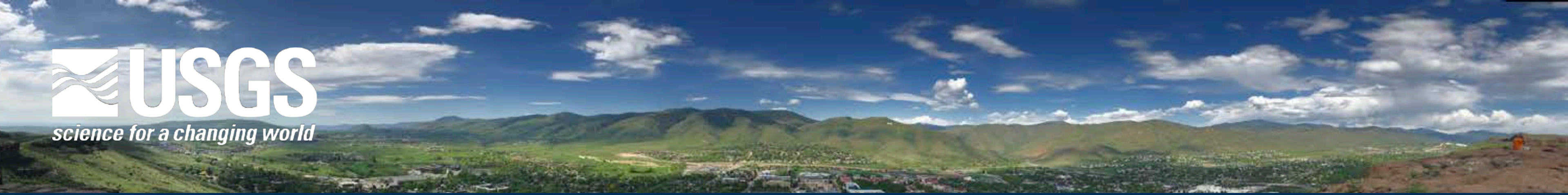


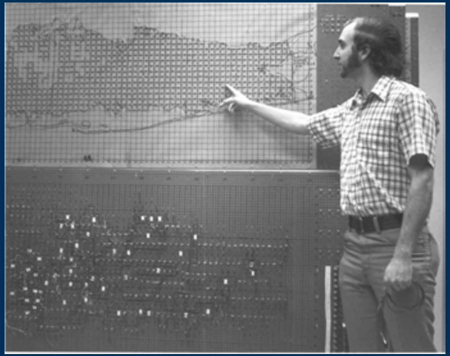
Advances in Modeling Groundwater Flow and Transport with MODFLOW

Presenter: Christian D. Langevin

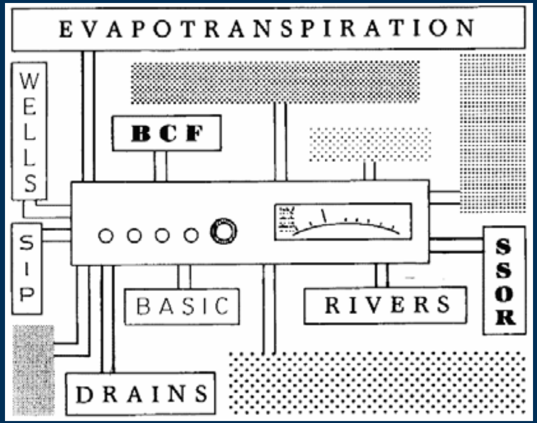
Contributors: Alden Provost, Sorab Panday, Joseph Hughes, Martijn Russcher, Jeremy White, and Eric Morway

EPA CLU-IN Webinar, February 3, 2021

U.S. Department of the Interior
U.S. Geological Survey



BACKGROUND



USGS

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA. 22092

In Reply Refer To:
Mail Stop 413

January 26, 1979

MEMORANDUM TO THE RECORD

From: Deputy Assistant Chief Hydrologist for Research

Subject: New Generation of Ground-Water Models

In a meeting in Denver, January 19, we agreed to the development of a new generation of ground-water computer codes. This new generation of programs will be designed to be:

1. *machine independent, insofar as possible, specifically* ... *ini-computers; and*

2. *flexible in concept, design, and utilization.*

Flexibility dictates that a series of modules be developed which can be put together as needed to form the basic program. The modules will be developed in such a way that they are basically compatible and yet independent of each other. Such a concept will allow much needed flexibility for modeling particular problems.

First priority is being given to developing ... two or three-dimensional finite difference code for flow which will include options for two-dimensional transport, as well as parameter identification.

A number of the key modules for the basic program were identified and the responsibility assigned for their development. We agreed:

Flow-Finite Differe...

Module

Basic 2D and 3D Fo...
Parameter Estimati...
Transport Without ...
Unsaturated Flow
Leakage
Influence Functions — Papadopulos

One Hundred Years of Earth Science in the Public Service

Transport with Density and Energy

Module	Responsibility
Basic 2D and 3D Formulation	Mercer, Faust

The code will be written and maintained in the structured programming language FLECS. Target dates for completing the tasks were set:

Task	Target
Operational Flow Code	September 1979
Documented (Teachable Flow Code)	January 1980
Published Basic Modules (TWRI)	1980.

John D. Bredehoeft

Copy to: ACH/R&TC
ACH/SP&DM
ACH/O
RH, NR, SR, CR, WR
GW Branch
R. Wolff
R. Cooley
S. Larson
D. Posson
D. Grove

"… modules … are basically compatible and yet independent of each other."

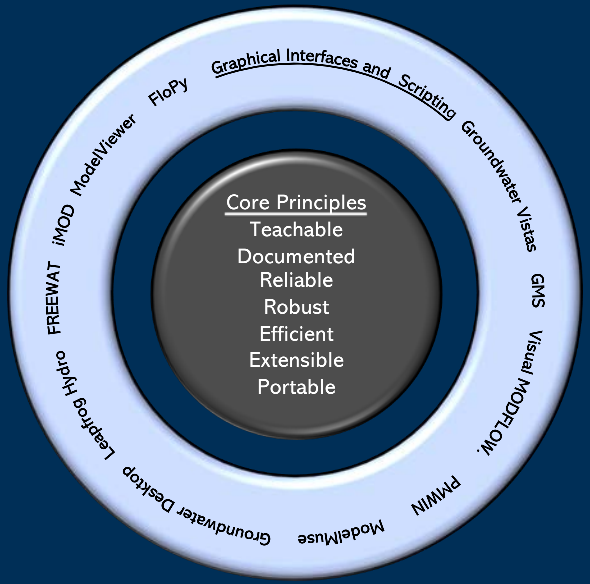
MODFLOW Philosophy

Core Principles

Teachable
Documented
Reliable
Robust
Efficient
Extensible
Portable

USGS

MODFLOW Support Environment



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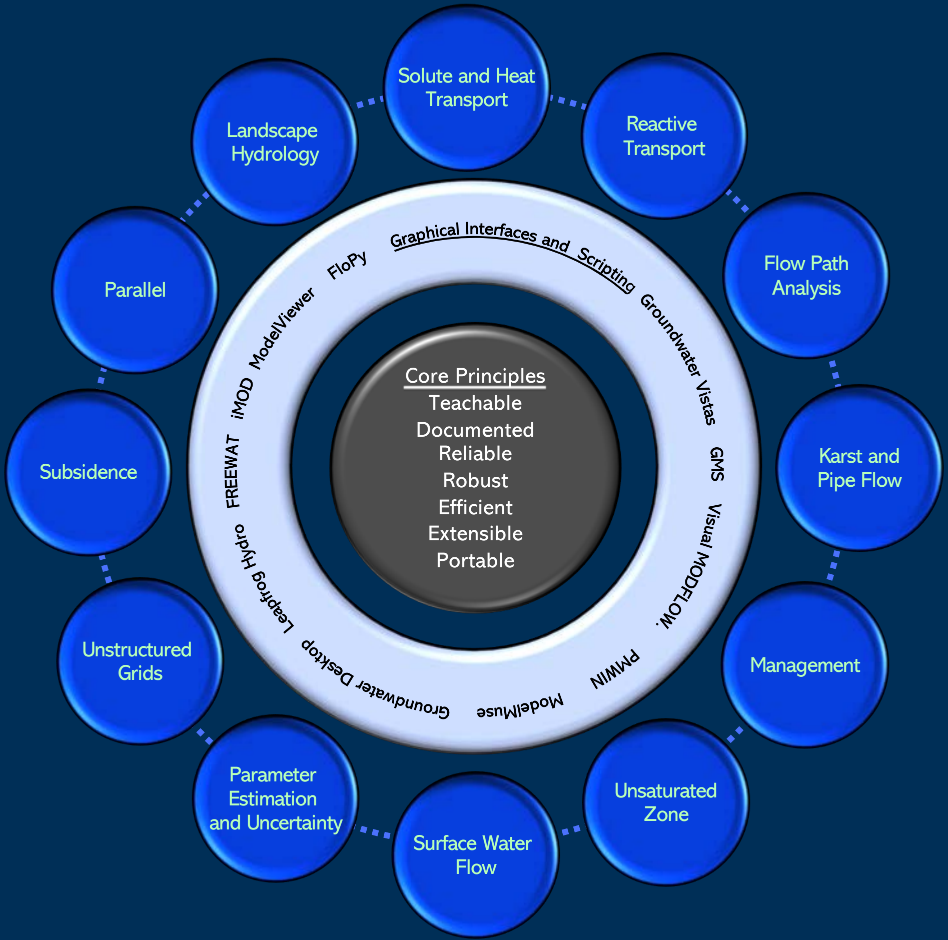

Core Principles
Teachable
Documented
Reliable
Robust
Efficient
Extensible
Portable
Graphical Interfaces and Scripting
Groundwater Vistas
GMS
Visual MODFLOW
PMWIN
ModelMuse
Groundwater Desktop
Leapfrog Hydro
FREEWAT
iMOD
ModelViewer
FloPy
Solute and Heat Transport
Reactive Transport
Flow Path Analysis
Karst and Pipe Flow
Management
Unsaturated Zone
Surface Water Flow
Parameter Estimation and Uncertainty
Unstructured Grids
Subsidence
Parallel
Landscape Hydrology

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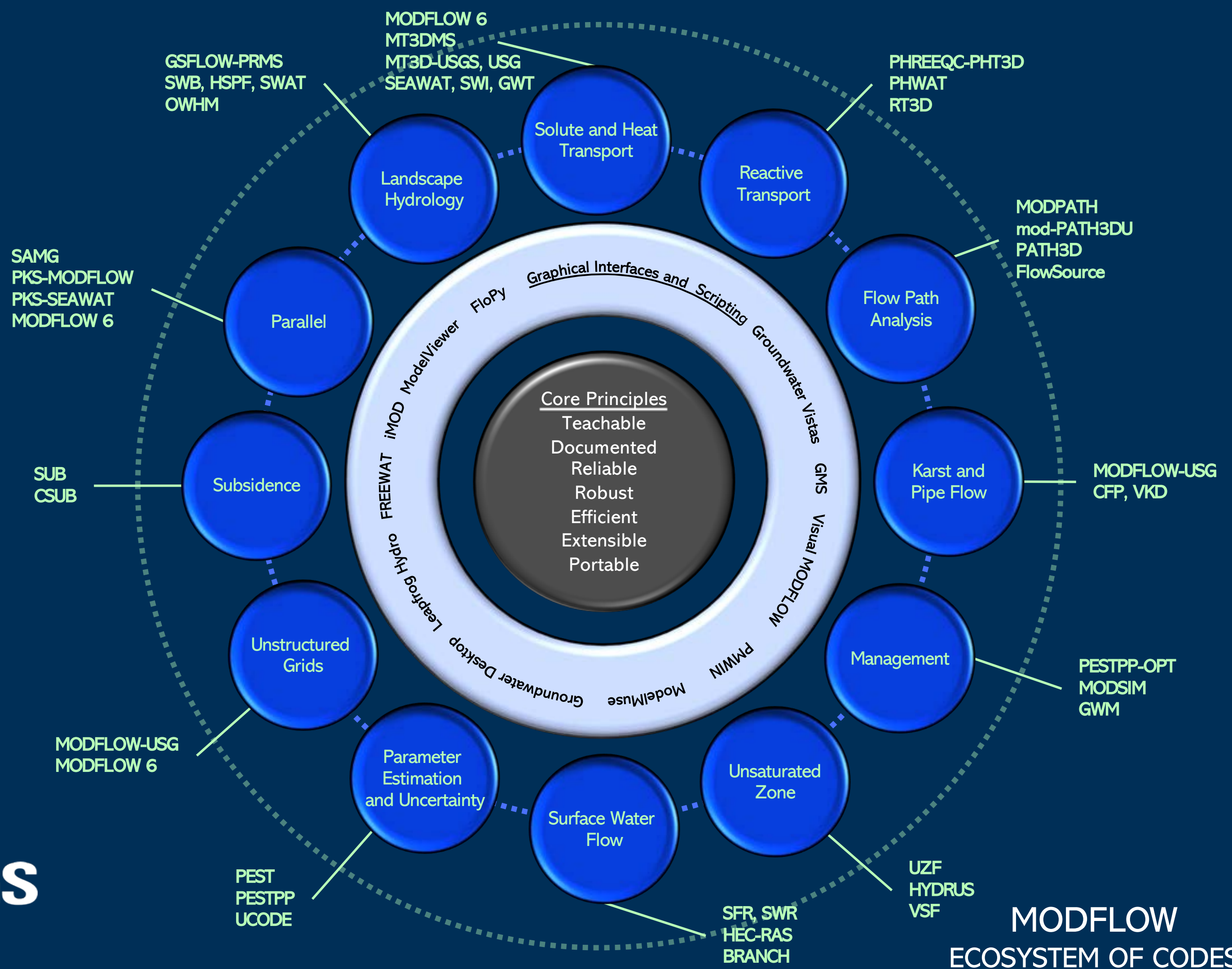


USGS

MODFLOW
ECOSYSTEM OF CODES

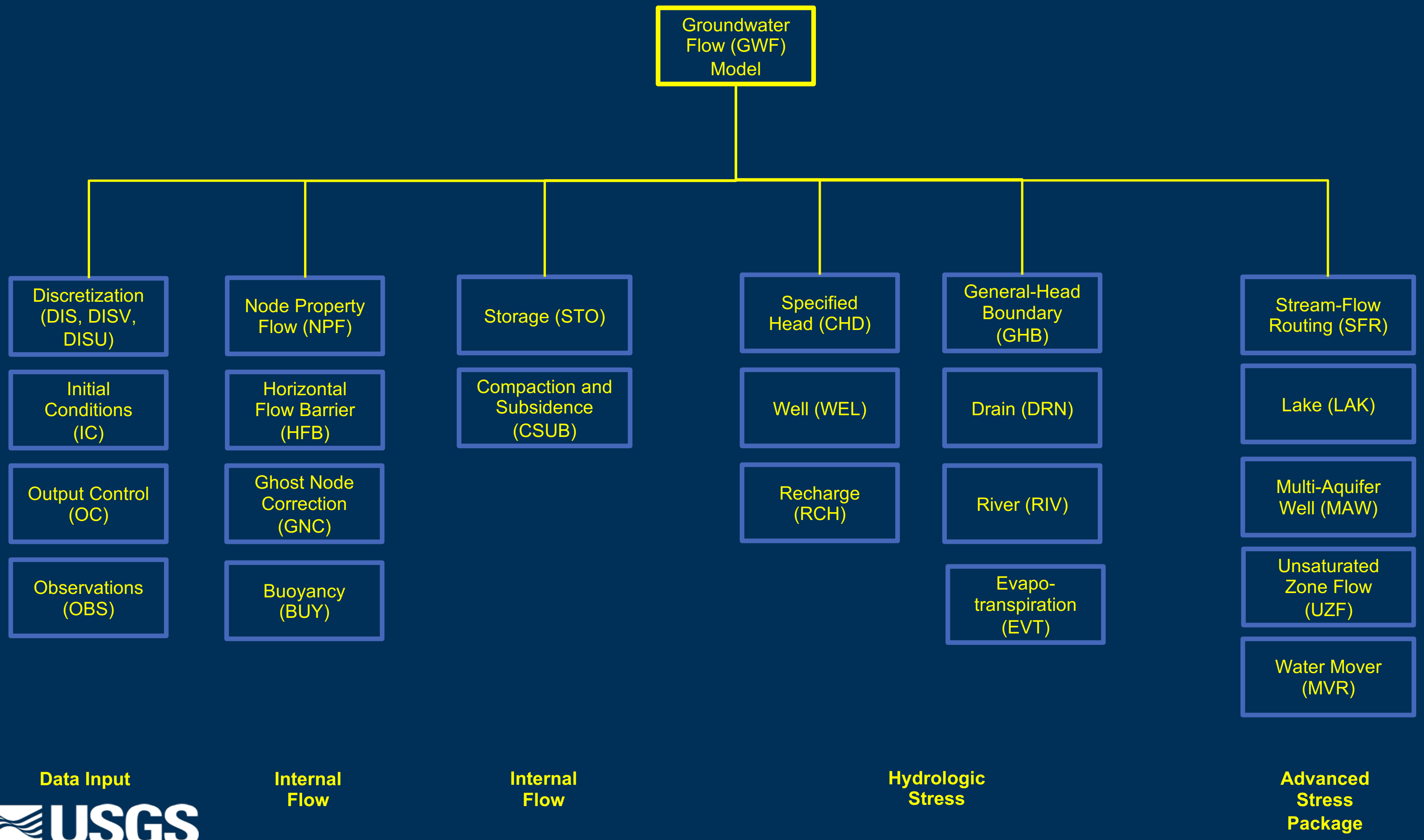
WHAT'S NEW?

USGS

Active Development

- MODFLOW 6
  - Groundwater Flow (GWF) Model (released Aug 2017)
  - Compaction and Subsidence (CSUB) Package (released Dec 2019)
  - Groundwater Transport (GWT) Model (released Oct 2020)
  - Coupled Variable-Density Flow and Transport (released Oct 2020)
  - MODFLOW API (released Jun 2020)
- Related Programs
  - FloPy
  - MODPATH
  - MT3D-USGS

USGS

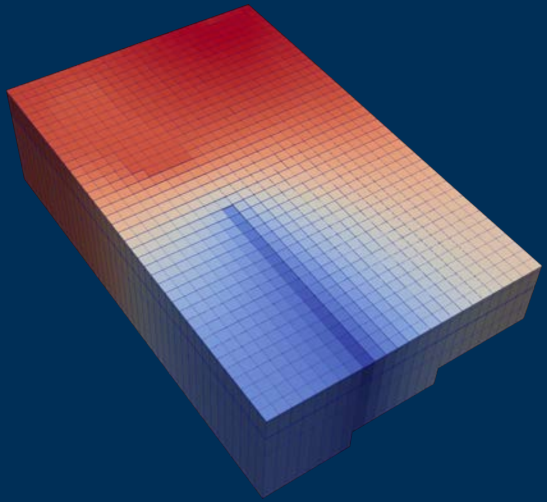

Groundwater Flow (GWF) Model
Discretization (DIS, DISV, DISU)
Initial Conditions (IC)
Output Control (OC)
Observations (OBS)
Node Property Flow (NPF)
Horizontal Flow Barrier (HFB)
Ghost Node Correction (GNC)
Buoyancy (BUY)
Storage (STO)
Compaction and Subsidence (CSUB)
Specified Head (CHD)
Well (WEL)
Recharge (RCH)
General-Head Boundary (GHB)
Drain (DRN)
River (RIV)
Evapo-transpiration (EVT)
Stream-Flow Routing (SFR)
Lake (LAK)
Multi-Aquifer Well (MAW)
Unsaturated Zone Flow (UZF)
Water Mover (MVR)
Data Input
Internal Flow
Internal Flow
Hydrologic Stress
Advanced Stress Package

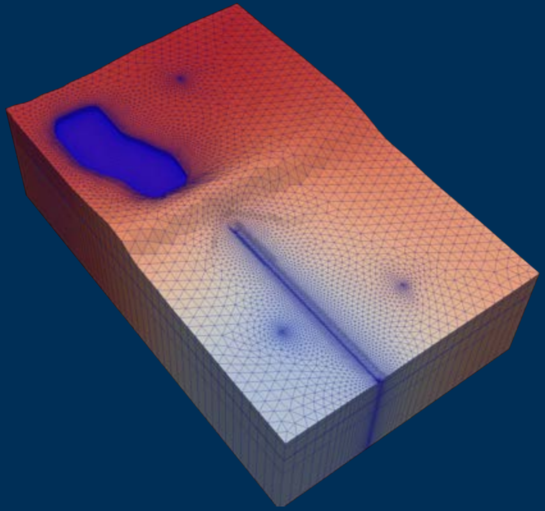
USGS

Regular or Unstructured Grids

3 Discretization Approaches

- Regular MODFLOW grid (DIS)
- Discretization by Vertices (DISV)
- Generalized Unstructured (DISU)





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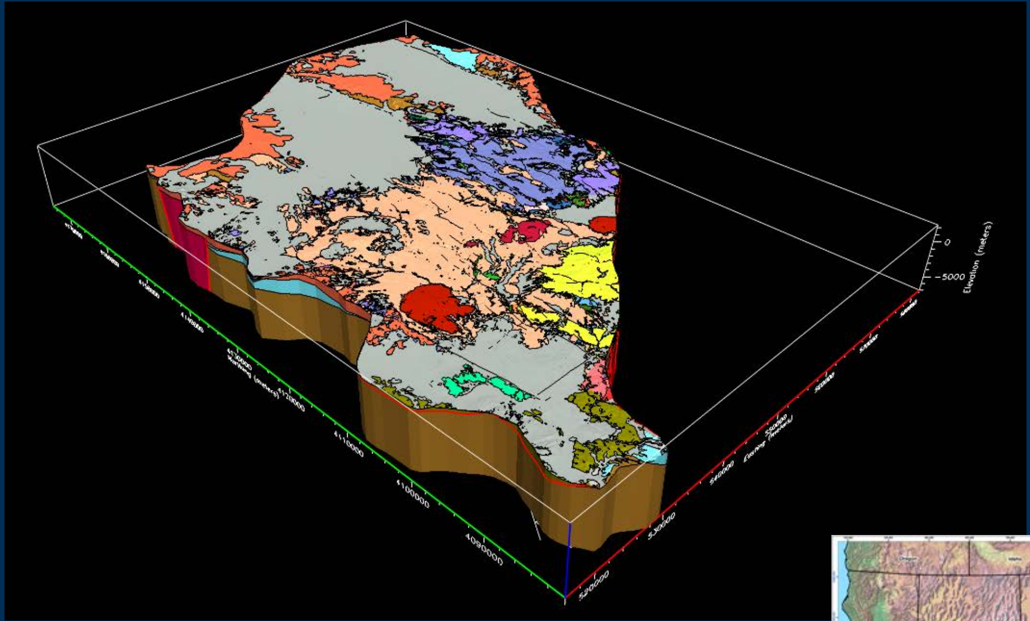
Pahute Mesa - Oasis Valley Example

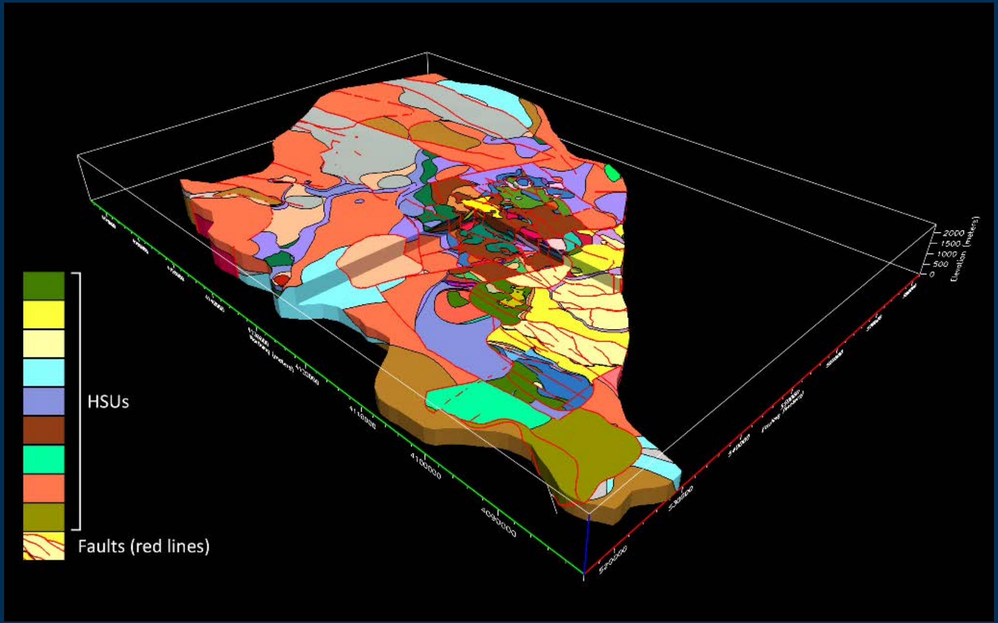
- Nevada National Security Site
- Navarro Research and Engineering Inc. funded by DOE
- Develop a groundwater flow model for scenario testing



USGS

Hydrostratigraphic Framework Model

- 77 hydrostratigraphic units
- 98 faults and structural features
- Convert Earthvision hydrostratigraphic model into a MODFLOW 6 GWF model



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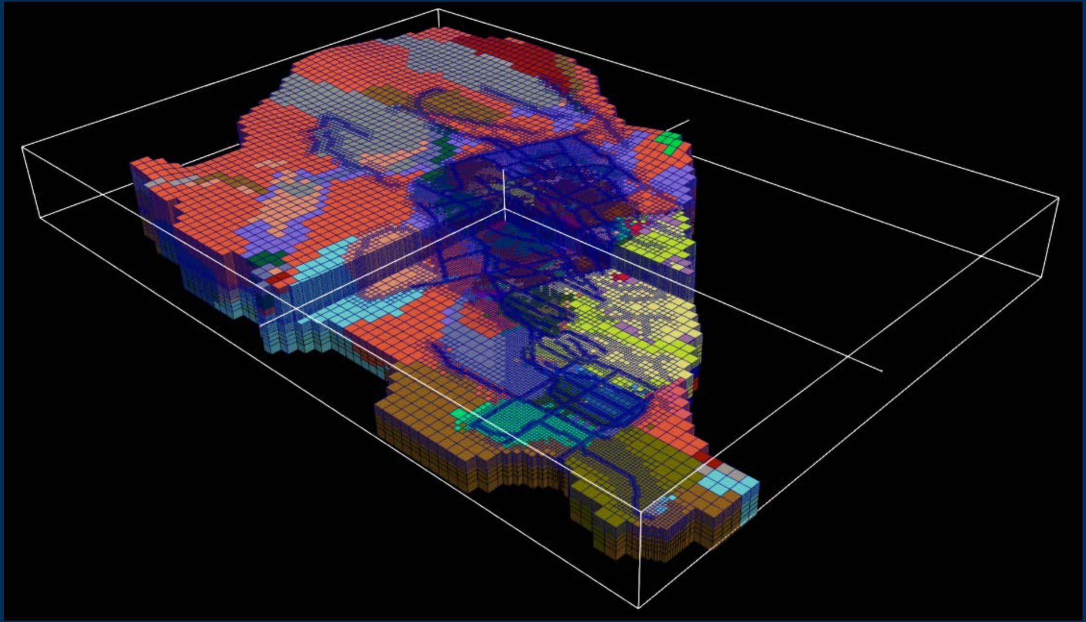
MODFLOW 6 Model

- Python and the FloPy Package used to convert Earthvision hydrostratigraphic model into MODFLOW 6 model



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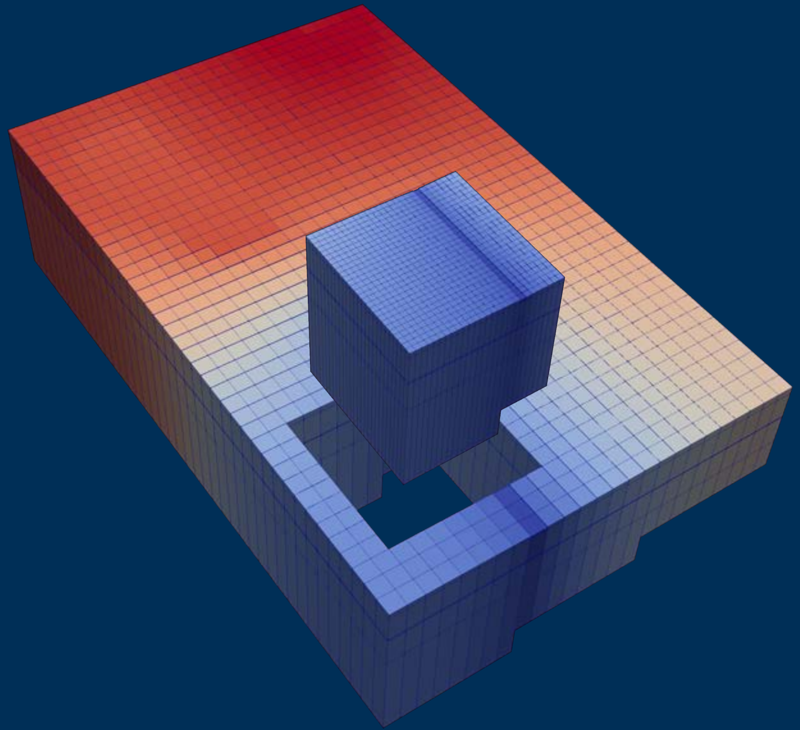
Multi-Model Coupling

- Any number of models can be included in a simulation
- Models coupled at matrix level
- Flexibility supports coupling of parent, child, grandchild models, stacked models or adjacent models



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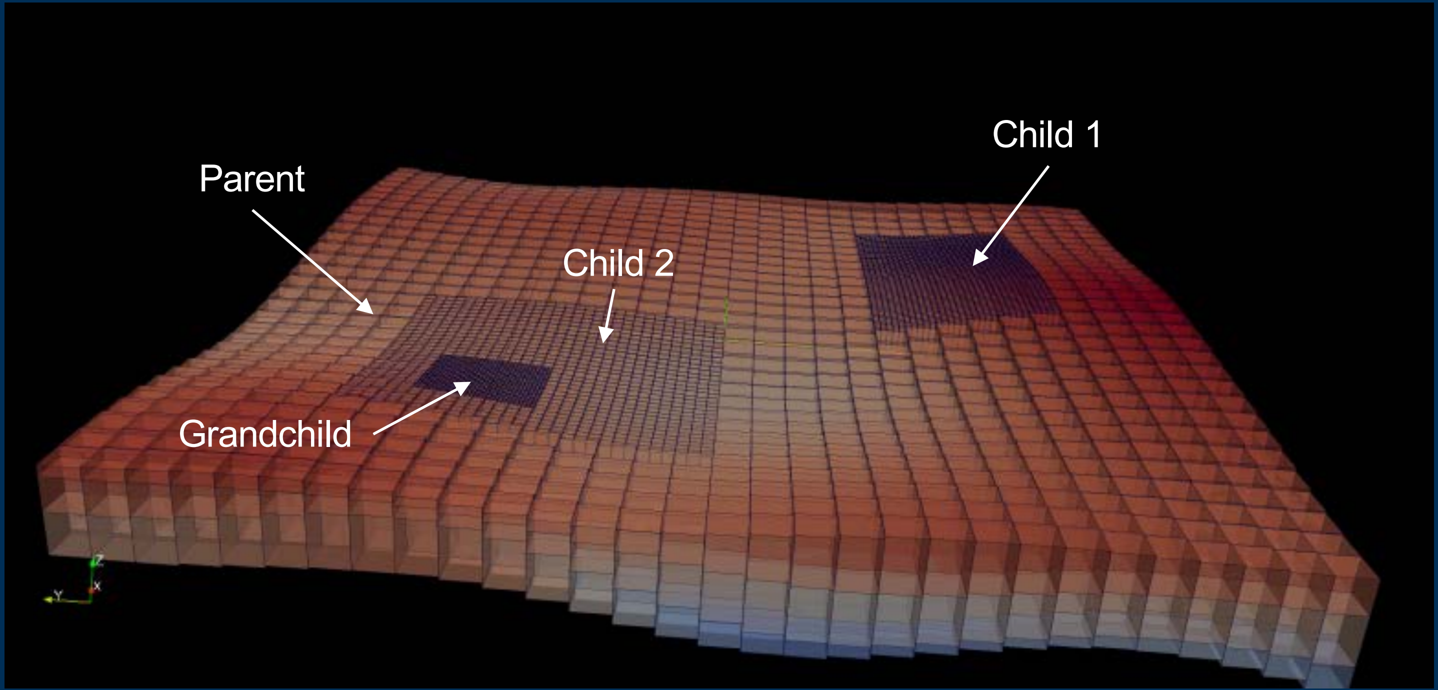
Nested Grids



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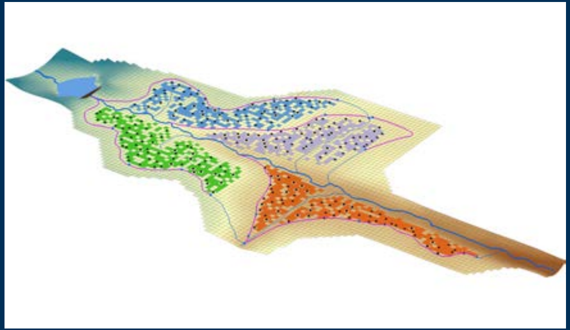
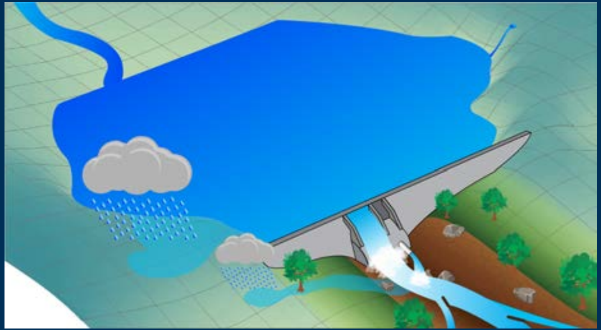
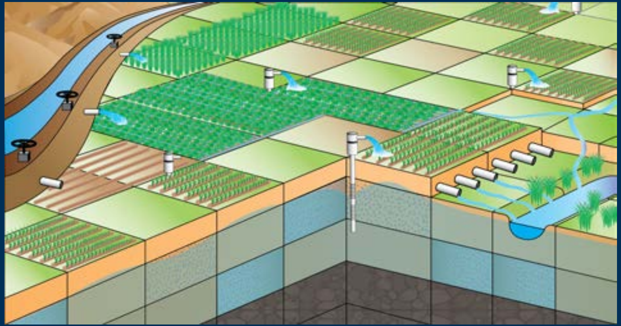
Water Mover

- Generalized package for transferring water from one MODFLOW package to another
- Water can be transferred from a “provider” to a “receiver” subject to simplified rules
- All transfers are tracked in a water budget

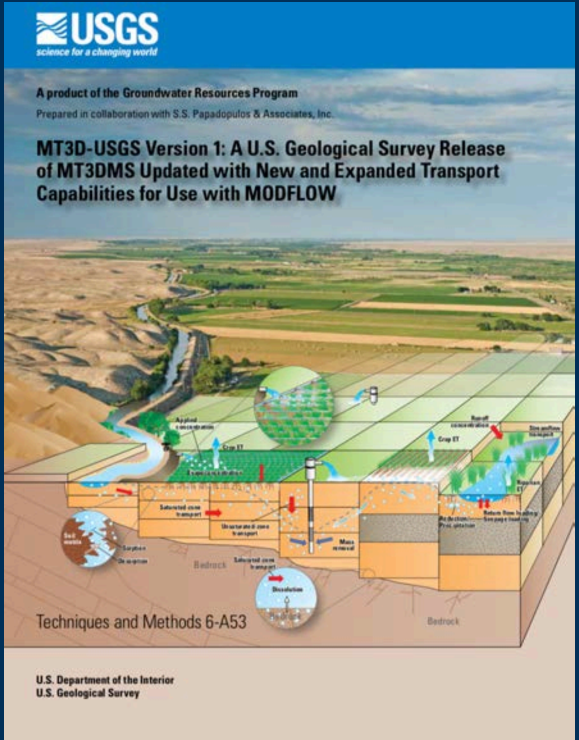






MODFLOW 6 GWF + MT3D-USGS

- MT3D-USGS developed and maintained in cooperation with S.S. Papadopulos & Associates Inc.
- Works with standard head and budget files produced by MODFLOW 6
- Regular MODFLOW grids



MODFLOW 6 Groundwater Transport Model

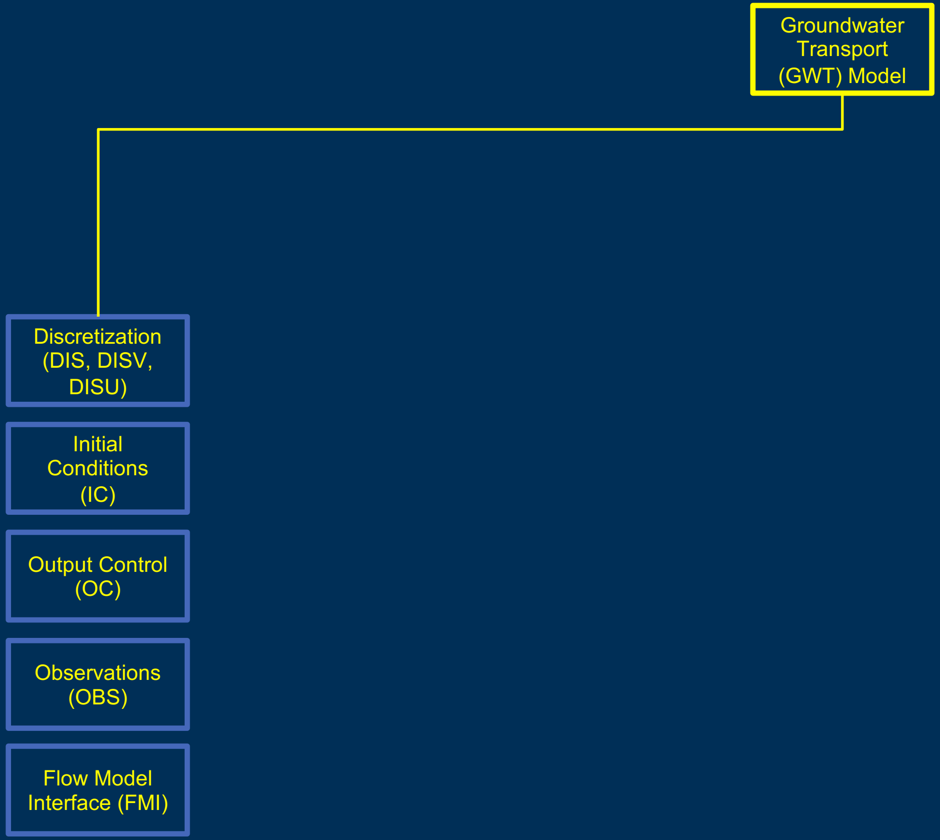
- First released October 2020
- New model type in MODFLOW 6
- Developed in collaboration with Sorab Panday, GSI Environmental Inc.
- Patterned after MT3D, USG-Transport, MODFLOW-GWT, SUTRA

$$\frac{\partial\left(S_w \theta C\right)}{\partial t} = -\nabla \cdot (qC) + \nabla \cdot \left(S_w \theta D \nabla C\right) + q_s' C_s + M_s - \lambda_1 \theta S_w C - \gamma_1 \theta S_w$$
$$- f_m \rho_b \frac{\partial\left(S_w \overline{C}\right)}{\partial t} - \lambda_2 f_m \rho_b S_w \overline{C} - \gamma_2 f_m \rho_b S_w - \sum_{im=1}^{nim} \zeta_{im} S_w \left(C - C_{im}\right)$$

USGS

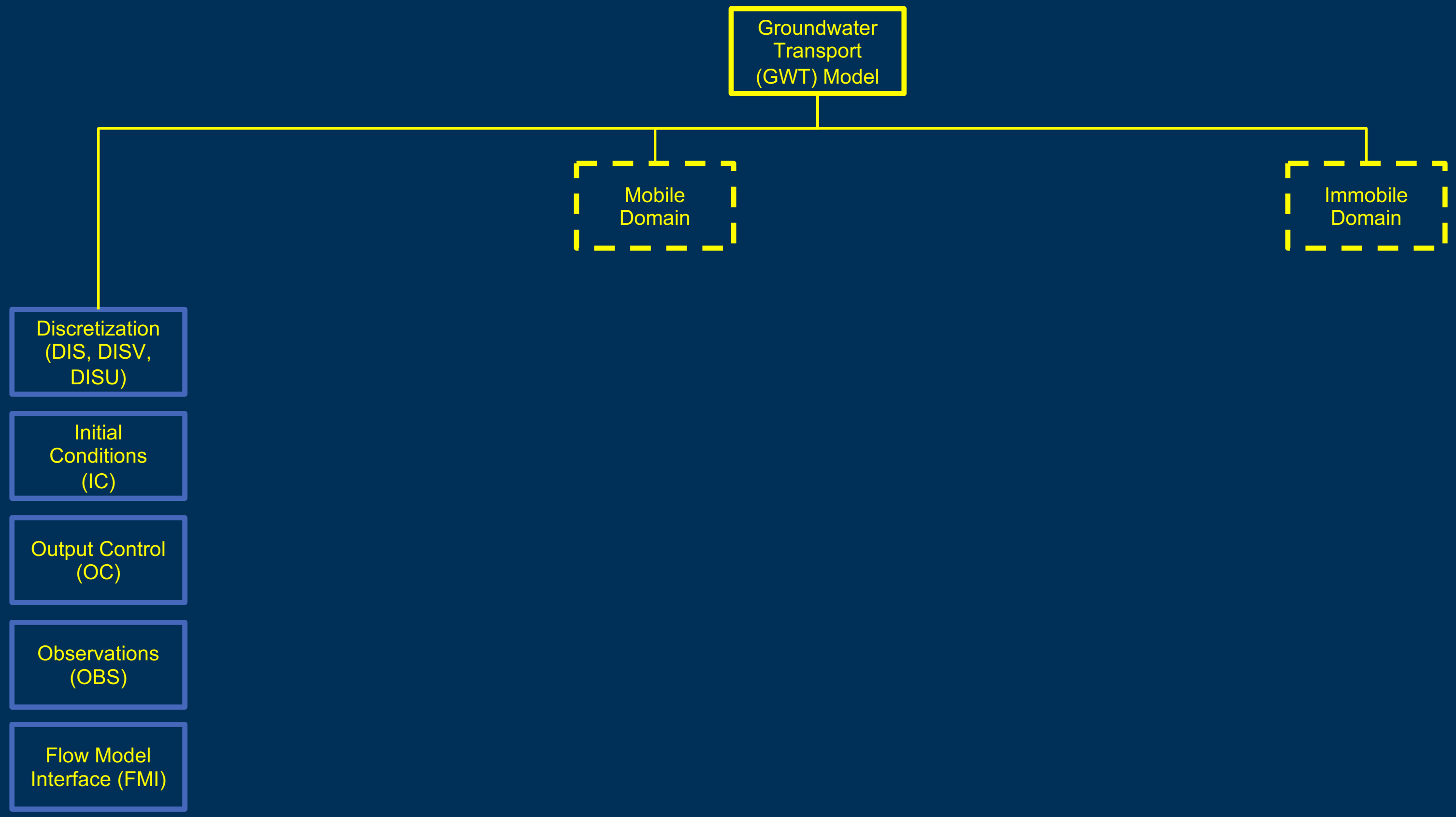
Groundwater Transport (GWT) Model

USGS



Data Input

USGS



Data Input

USGS

Groundwater Transport (GWT) Model

Mobile Domain

Immobile Domain

Discretization (DIS, DISV, DISU)

Initial Conditions (IC)

Output Control (OC)

Observations (OBS)

Flow Model Interface (FMI)

Data Input

General Features

- Works with DIS, DISV, and DISU model grids
- Supports active ”dry cells” from Newton flow formulation
- Current implementation uses implicit formulation for all transport terms
- Flow and transport grids must be the same

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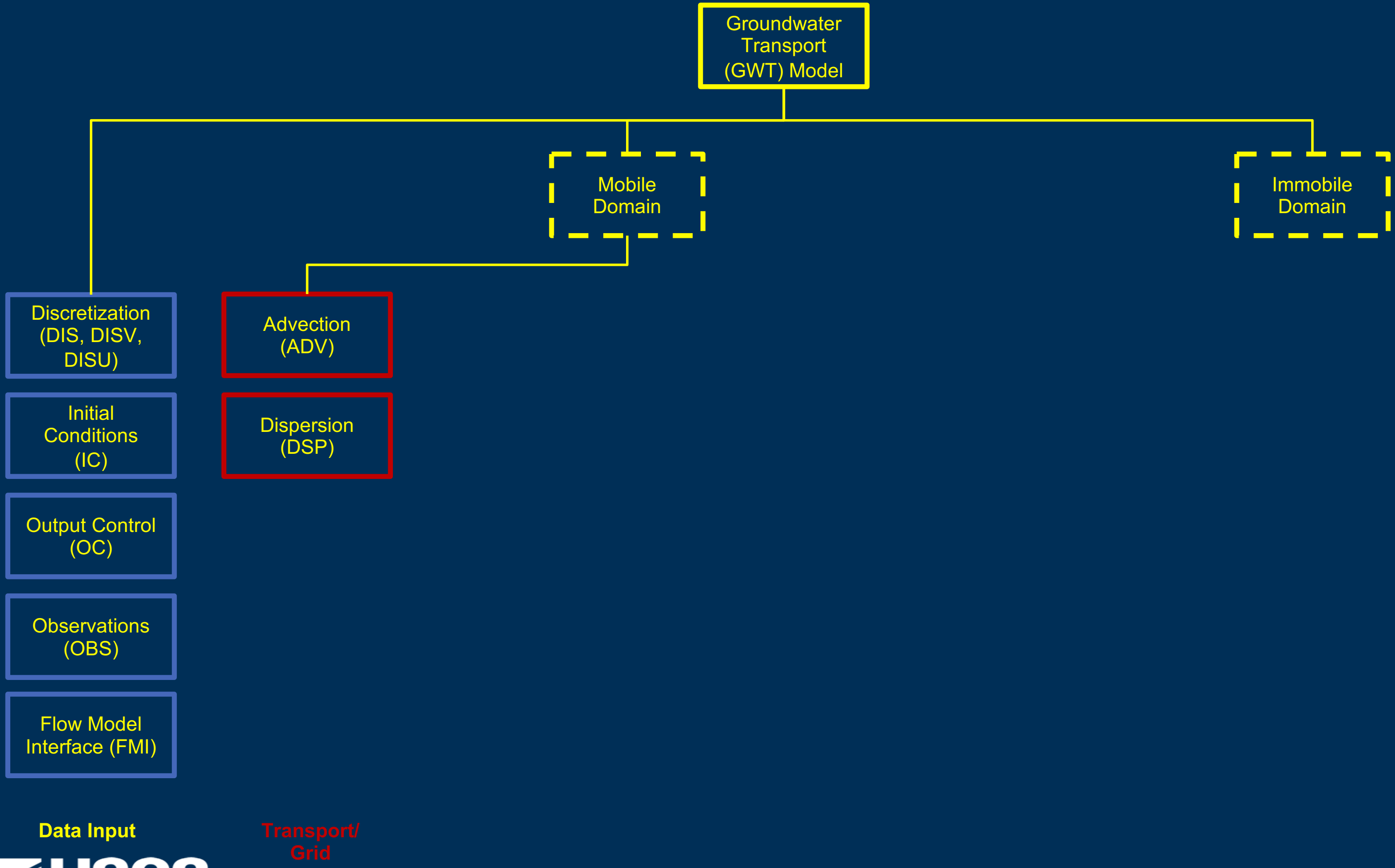
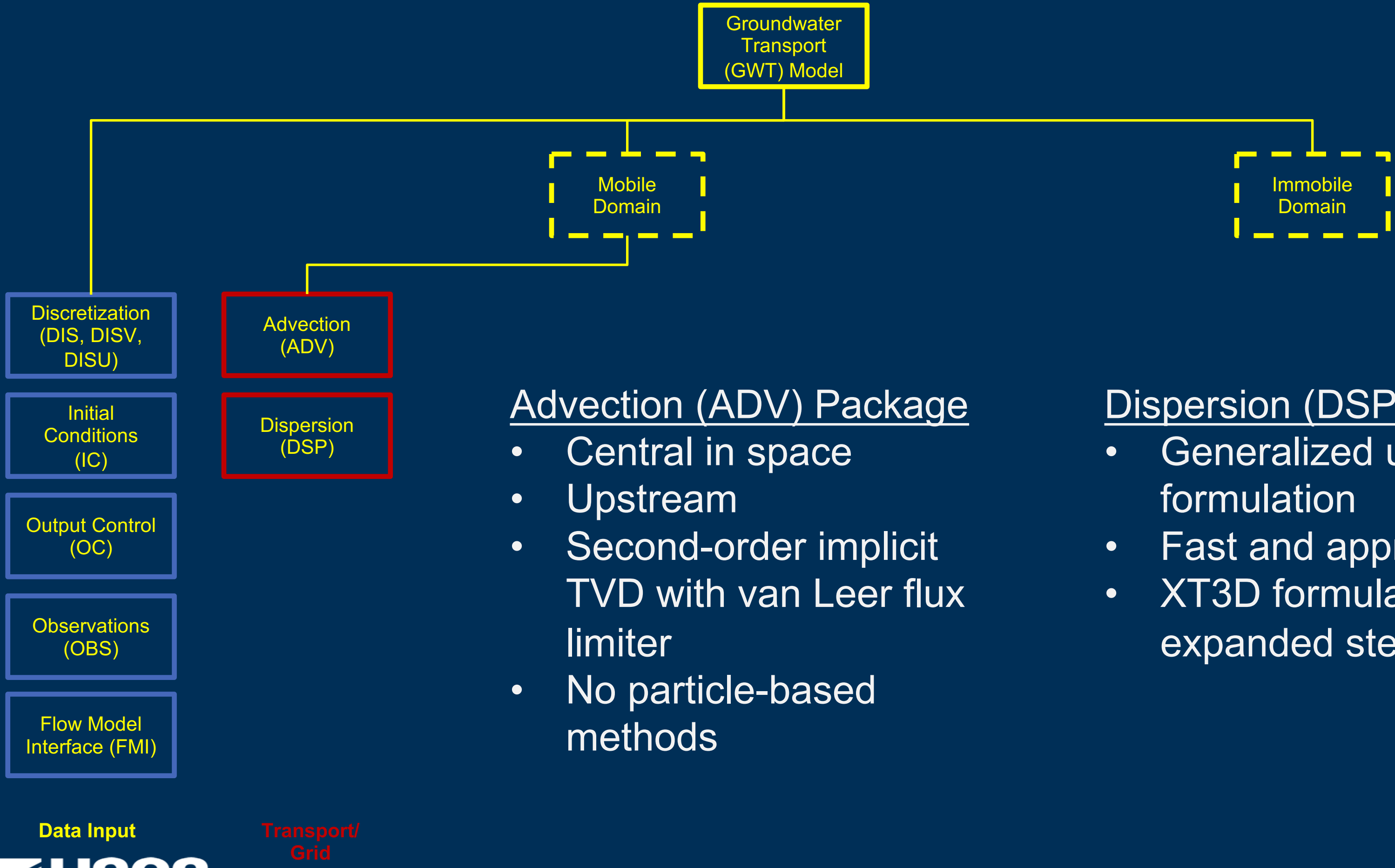


Groundwater Transport (GWT) Model
Mobile Domain
Immobile Domain
Discretization (DIS, DISV, DISU)
Initial Conditions (IC)
Output Control (OC)
Observations (OBS)
Flow Model Interface (FMI)
Advection (ADV)
Dispersion (DSP)
Data Input
Transport/ Grid



Advection (ADV) Package

- Central in space
- Upstream
- Second-order implicit TVD with van Leer flux limiter
- No particle-based methods

Dispersion (DSP) Package

- Generalized unstructured formulation
- Fast and approximate, or
- XT3D formulation with expanded stencil

Groundwater Transport (GWT) Model

Mobile Domain

Immobile Domain

Discretization (DIS, DISV, DISU)

Initial Conditions (IC)

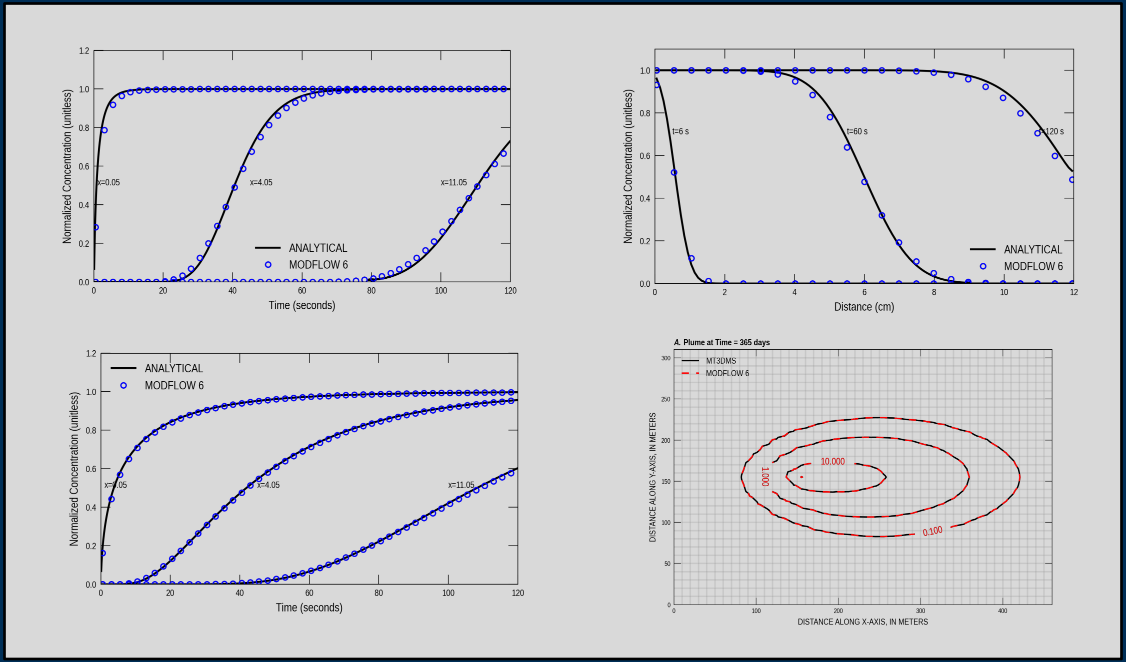
Output Control (OC)

Observations (OBS)

Flow Model Interface (FMI)

Advection (ADV)

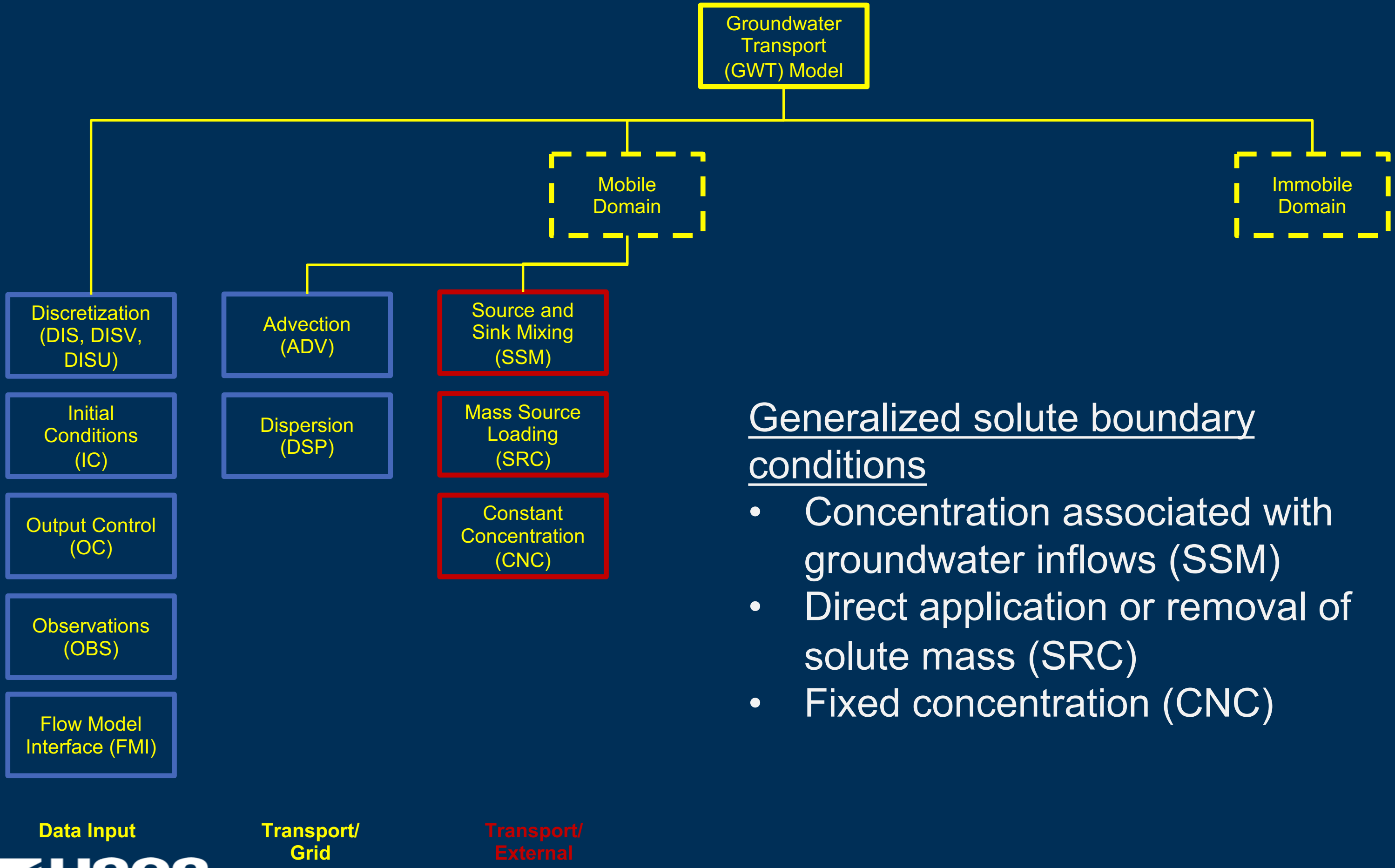
Dispersion (DSP)



Data Input

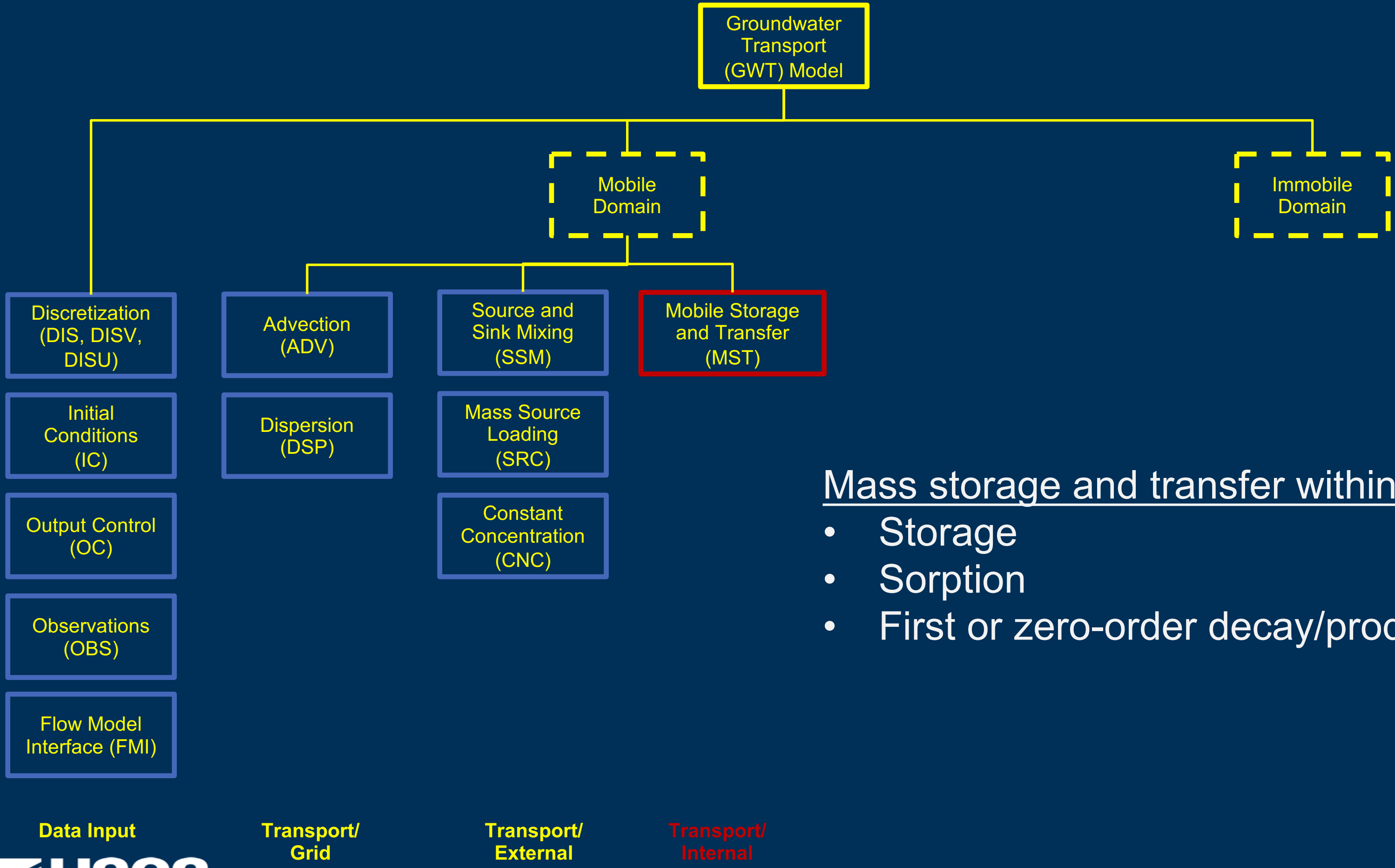
Transport/ Grid

USGS



Generalized solute boundary conditions

- Concentration associated with groundwater inflows (SSM)
- Direct application or removal of solute mass (SRC)
- Fixed concentration (CNC)



<u>Mass storage and transfer within a cell</u>

- Storage
- Sorption
- First or zero-order decay/production

USGS

Groundwater Transport (GWT) Model

- Mobile Domain
  - Advection (ADV)
  - Dispersion (DSP)
  - Source and Sink Mixing (SSM)
  - Mass Source Loading (SRC)
  - Constant Concentration (CNC)
  - Mobile Storage and Transfer (MST)
- Immobile Domain

Discretization (DIS, DISV, DISU)

Initial Conditions (IC)

Output Control (OC)

Observations (OBS)

Flow Model Interface (FMI)

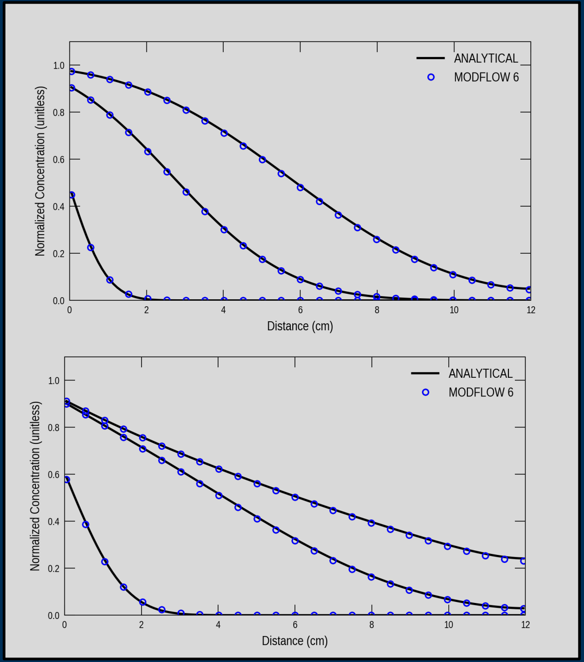
Data Input

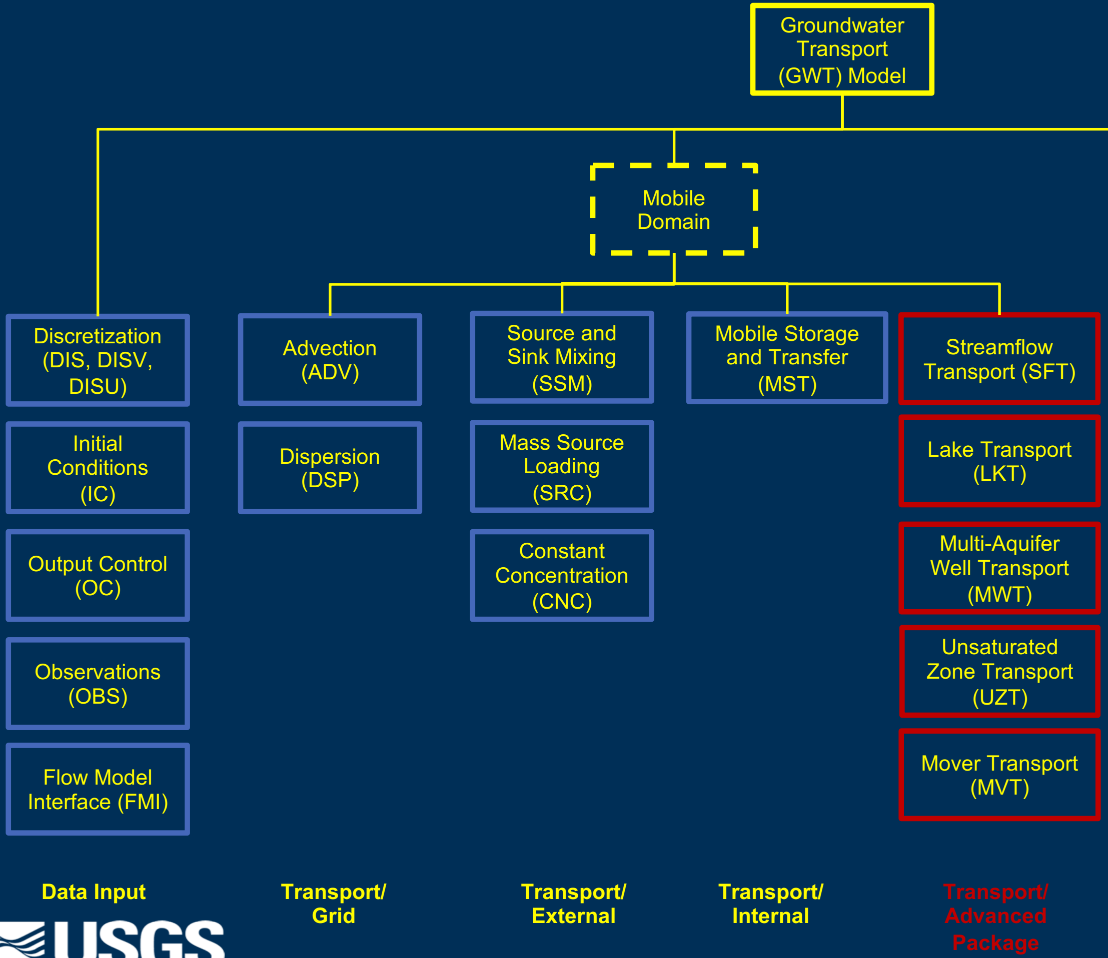
Transport/ Grid

Transport/ External

Transport/ Internal

USGS





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<u>Support for advanced flow packages</u>

- Simulate concentration in individual features (stream reaches, lakes, wells, unsaturated zone)
- Simulate mass transfer between flow packages
- Alternative to SSM

- Groundwater Transport (GWT) Model
  - Discretization (DIS, DISV, DISU)
  - Initial Conditions (IC)
  - Output Control (OC)
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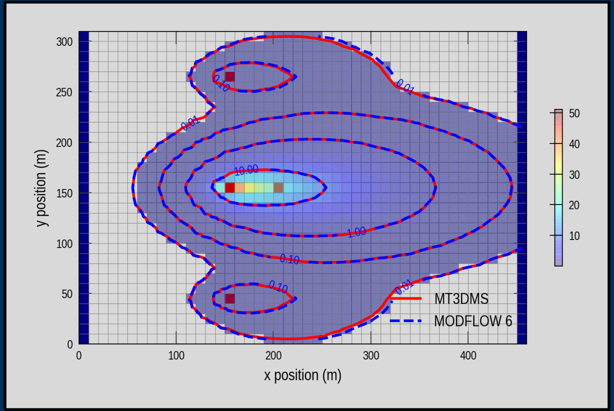
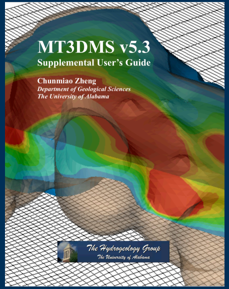
    - Streamflow Transport (SFT)
    - Lake Transport (LKT)
    - Multi-Aquifer Well Transport (MWT)
    - Unsaturated Zone Transport (UZT)
    - Mover Transport (MVT)
  - Immobile Domain

Data Input | **Transport/ Grid** | **Transport/ External** | **Transport/ Internal** | **Transport/ Advanced Package**





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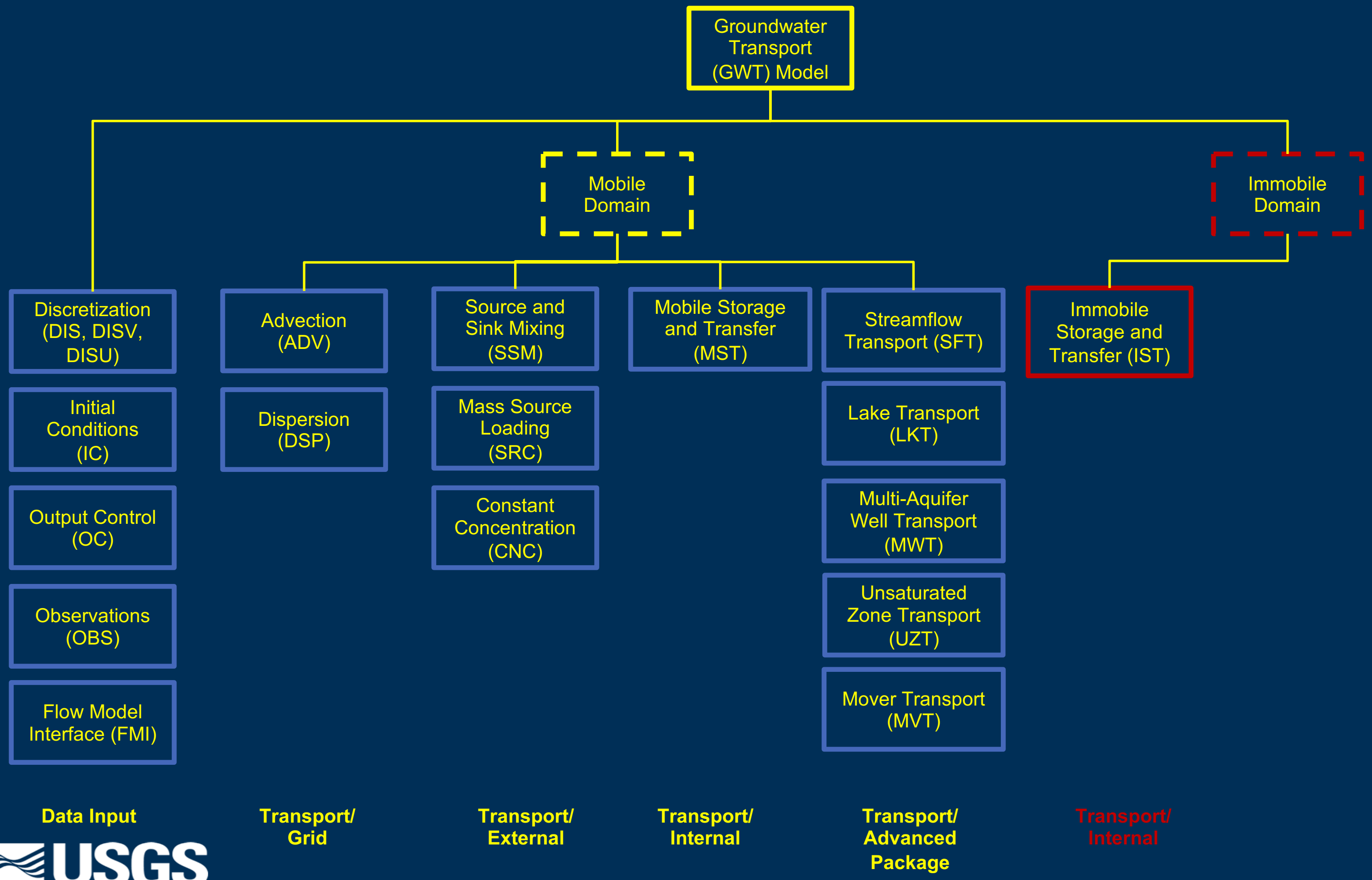
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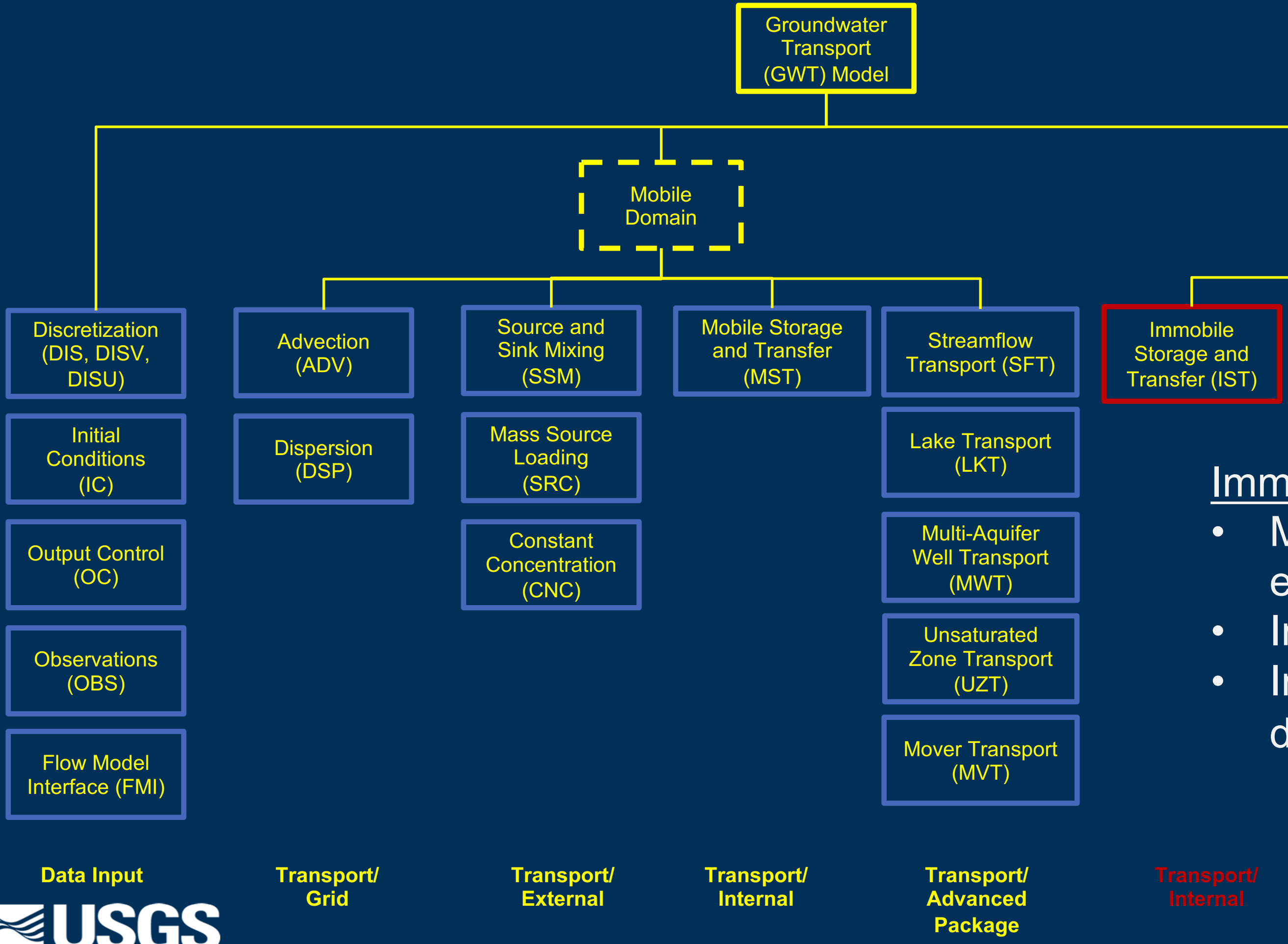
Immobile Storage and Transfer (IST)
Data Input
Transport/ Grid
Transport/ External
Transport/ Internal
Transport/ Advanced Package
Transport/ Internal



Immobile Domain

- Mobile-immobile exchange
- Immobile sorption
- Immobile decay/production

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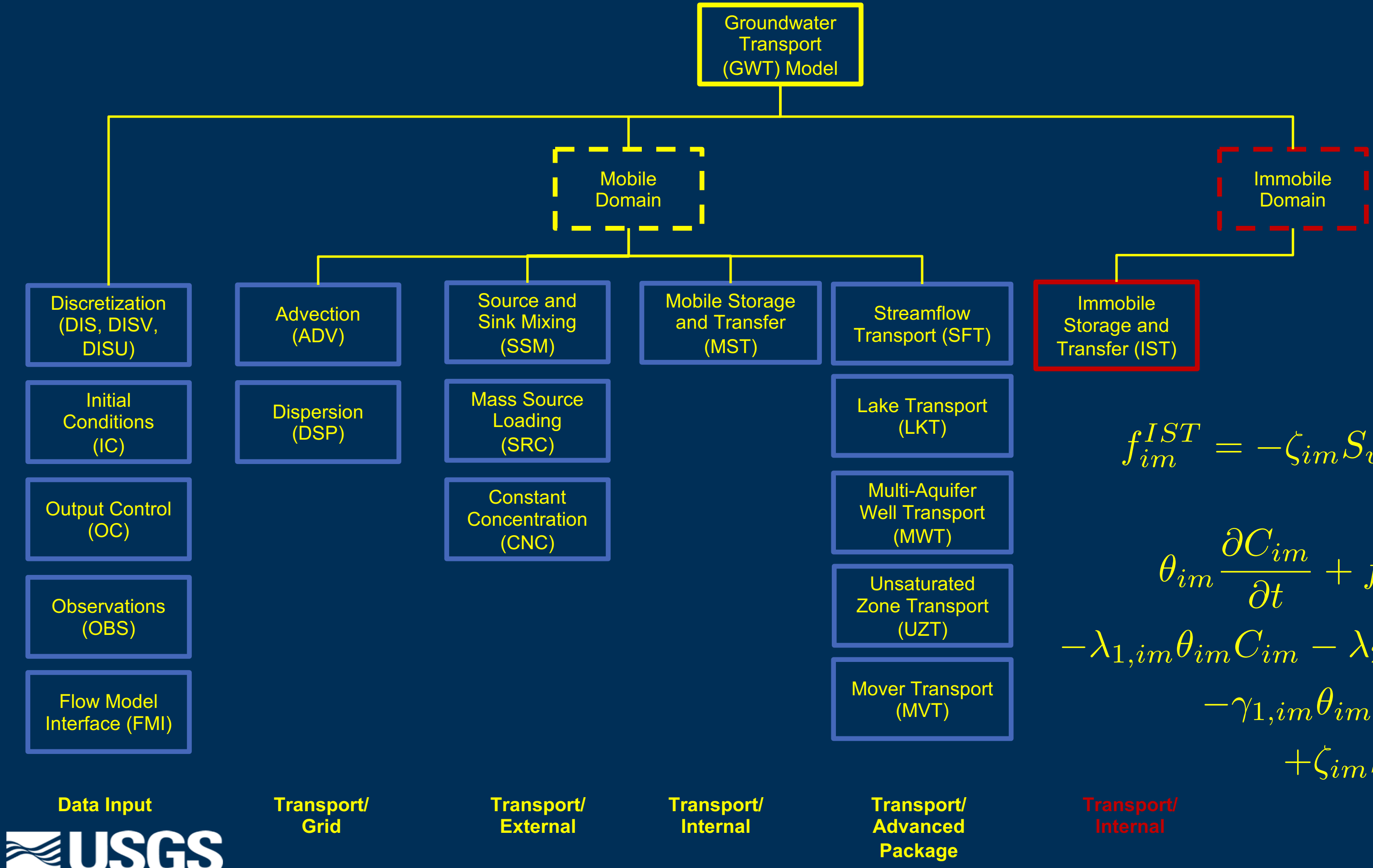
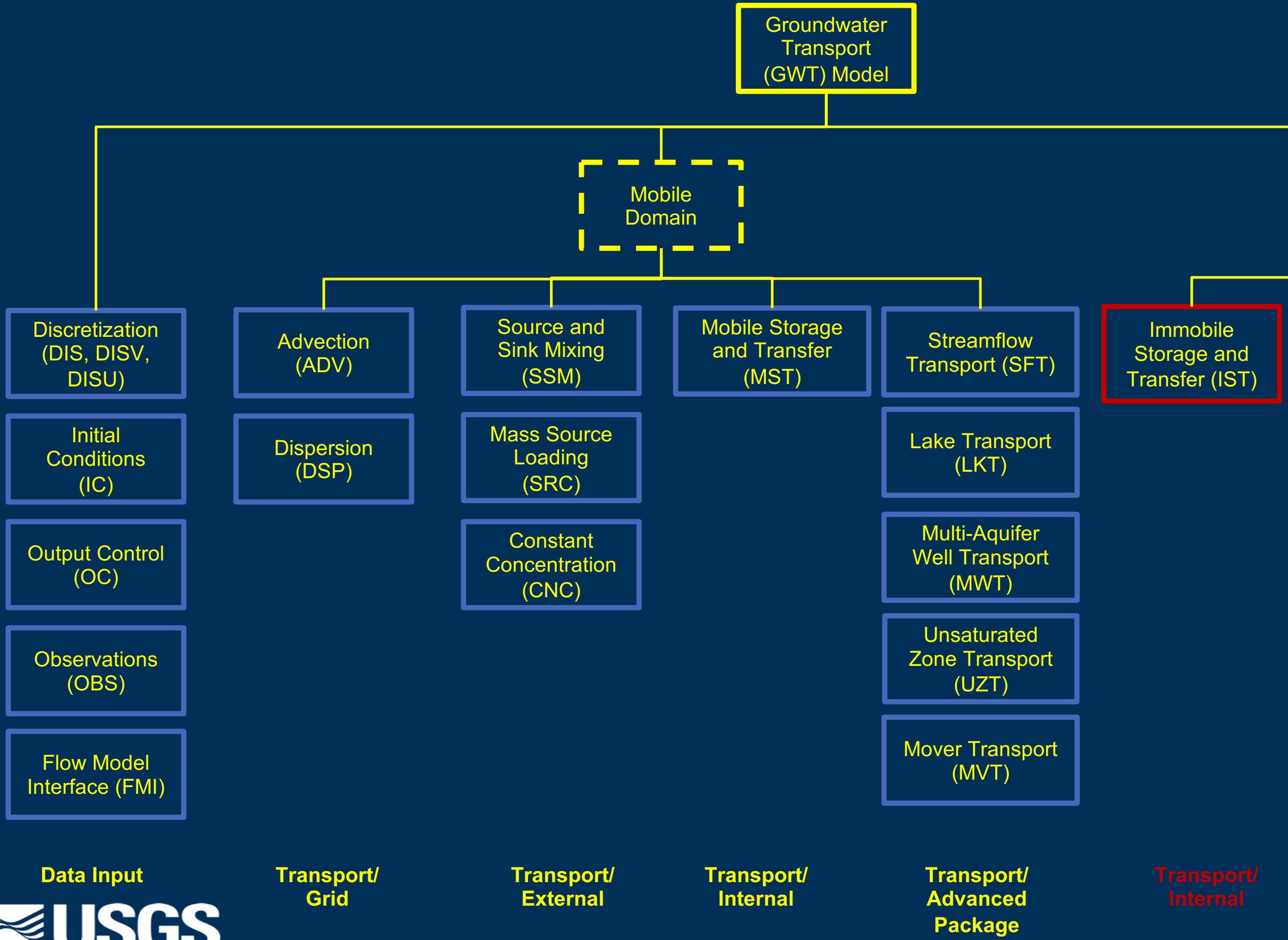


$$f_{im}^{IST} = -\zeta_{im} S_w \left(C - C_{im} \right)$$

$$\theta_{im} \frac{\partial C_{im}}{\partial t} + f_{im} \rho_b \frac{\partial \overline{C}_{im}}{\partial t} = -\lambda_{1,im} \theta_{im} C_{im} - \lambda_{2,im} f_{im} \rho_b \overline{C}_{im} - \gamma_{1,im} \theta_{im} - \gamma_{2,im} f_{im} \rho_b + \zeta_{im} S_w \left(C - C_{im} \right)$$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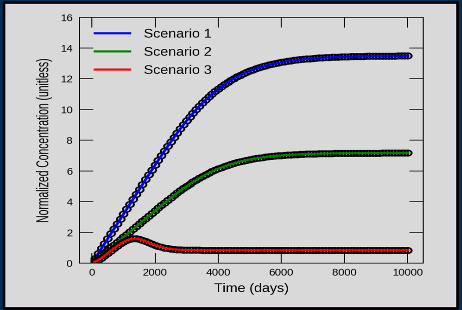
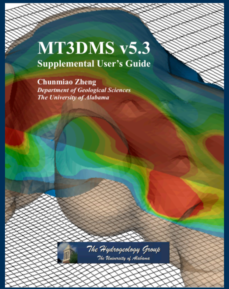
Transport/ Internal
Transport/ Advanced Package
Transport/ Internal


Scenario 1
Scenario 2
Scenario 3
Normalized Concentration (unitless)
Time (days)
0
2
4
6
8
10
12
14
16
2000
4000
6000
8000
10000


MT3DMS v5.3
Supplemental User's Guide
Chunmiao Zheng
Department of Geological Sciences
The University of Alabama
The Hydrogeology Group

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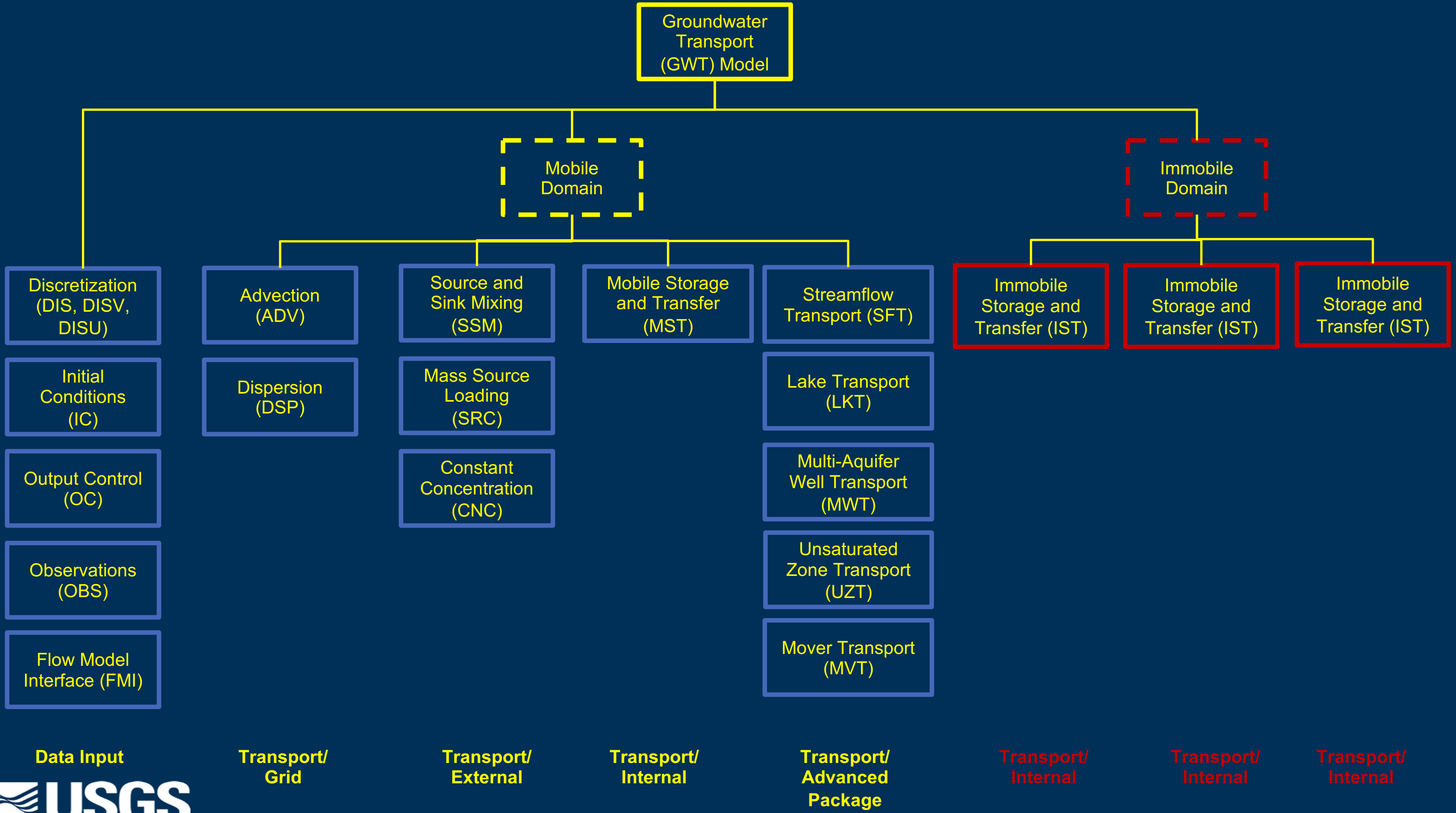
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Transport/ Internal

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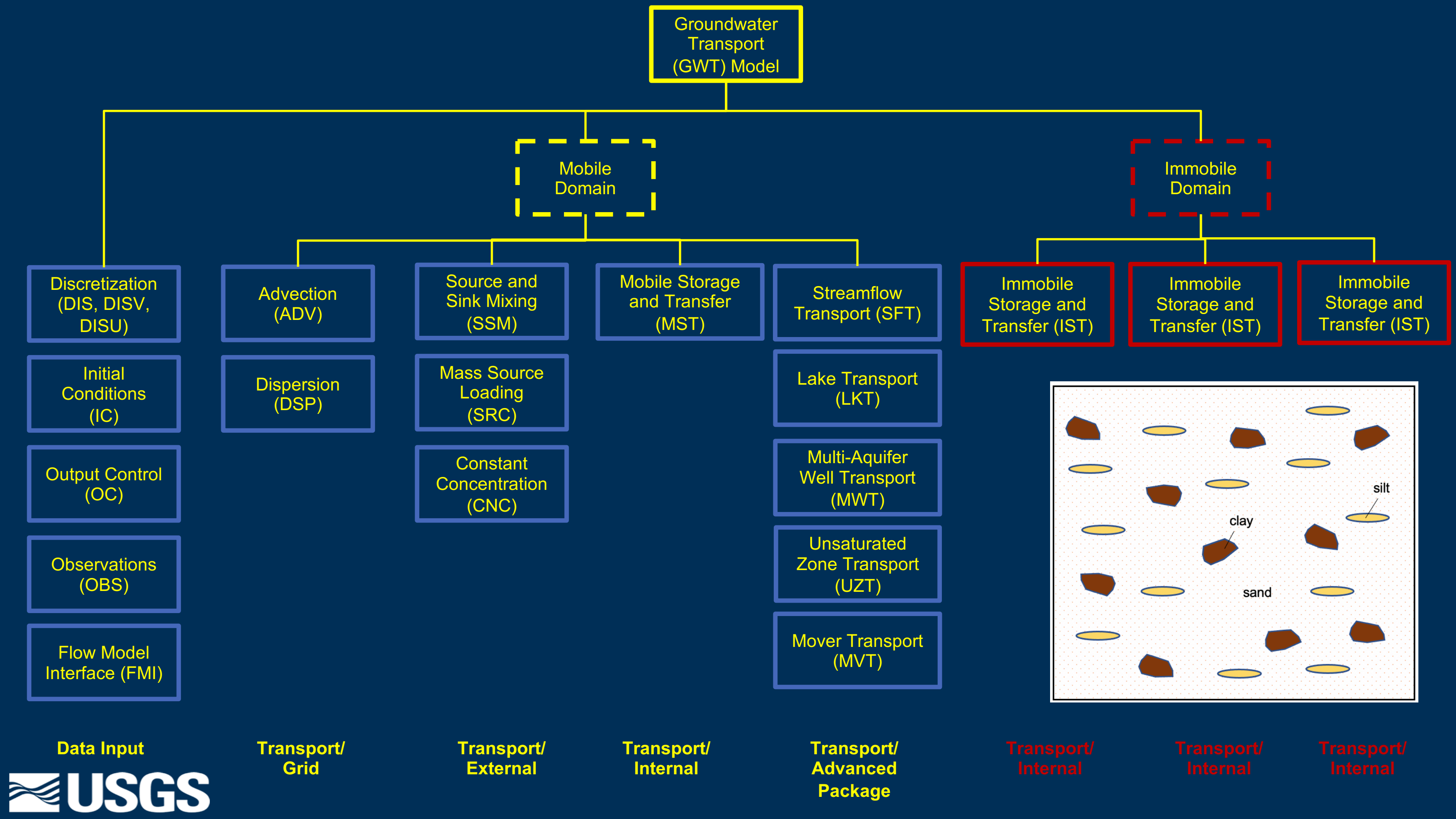

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Immobile Storage and Transfer (IST)
Immobile Storage and Transfer (IST)
Immobile Storage and Transfer (IST)
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clay
sand
Data Input
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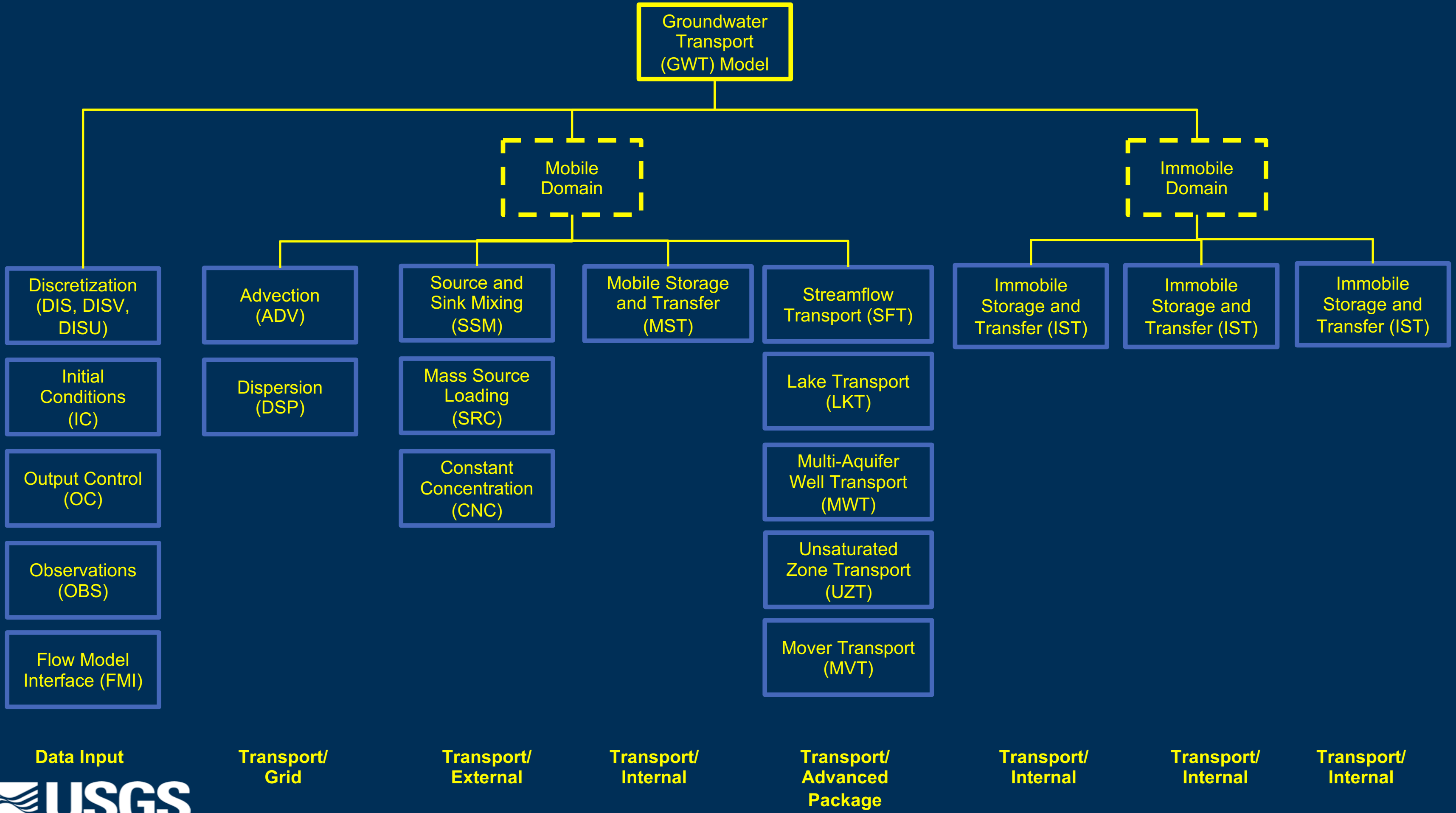
Transport/ External
Transport/ Internal
Transport/ Advanced Package
Transport/ Internal
Transport/ Internal
Transport/ Internal
USGS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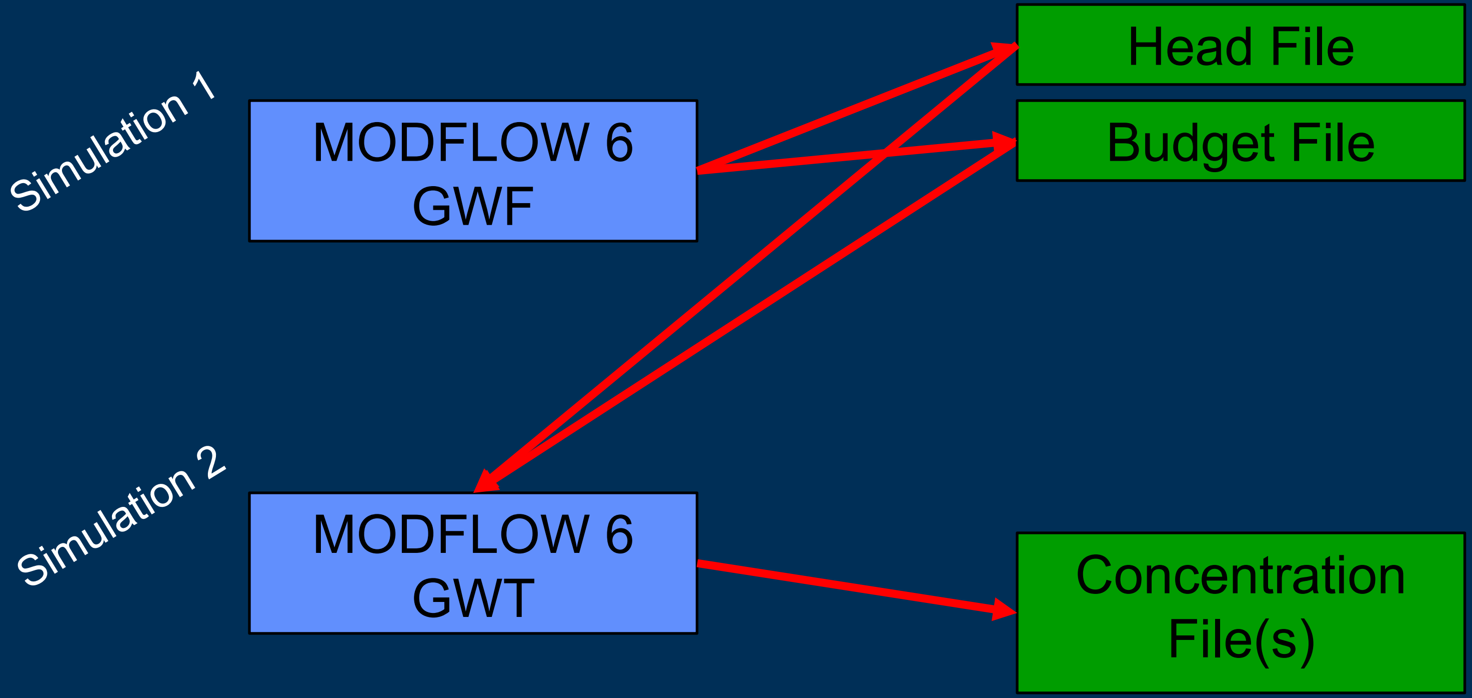
Streamflow Transport (SFT)
Lake Transport (LKT)
Multi-Aquifer Well Transport (MWT)
Unsaturated Zone Transport (UZT)
Mover Transport (MVT)
Immobile Storage and Transfer (IST)
Immobile Storage and Transfer (IST)
Immobile Storage and Transfer (IST)
Data Input
Transport/ Grid
Transport/ External
Transport/ Internal
Transport/ Advanced Package
Transport/ Internal
Transport/ Internal
Transport/ Internal

USGS

MODFLOW 6 GWF and GWT Approach (Option 1: Separate Simulations)



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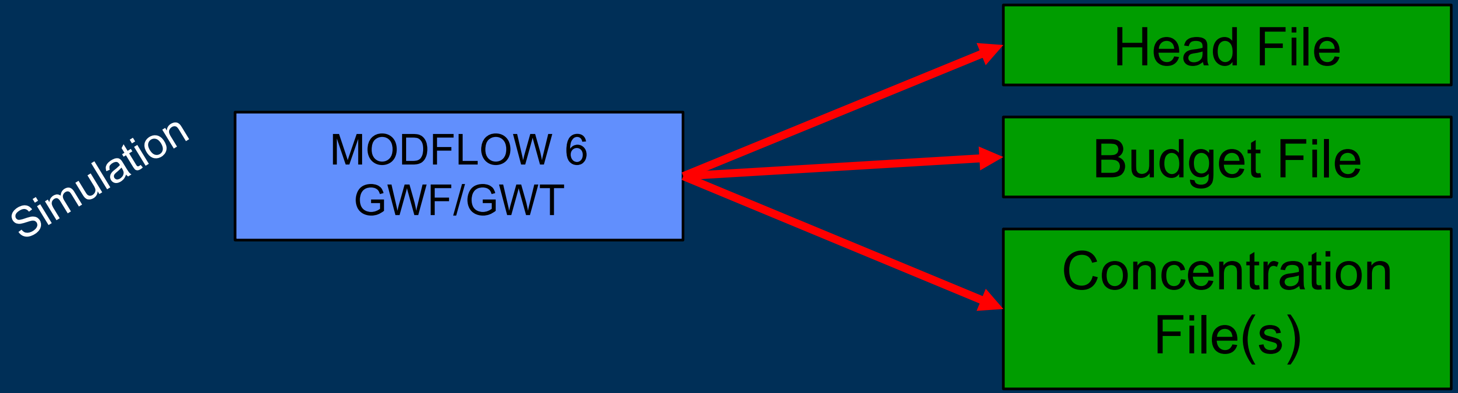
Can use different time-step lengths for GWT Model

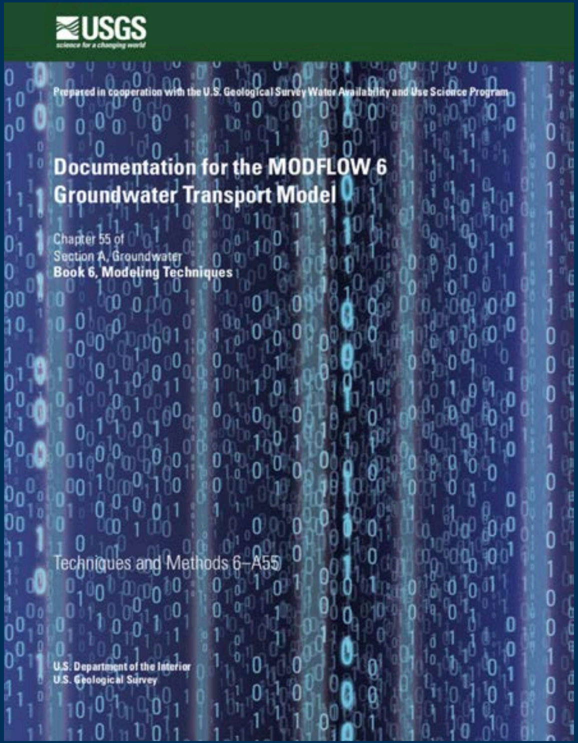
MODFLOW 6 GWF and GWT Approach (Option 2: Coupled Simulation)



Must use same time-step lengths for both models

Groundwater Transport Model Status

- Available now in MODFLOW 6
- Fully supported in FloPy
- Theory report is in review
- Limitations:
  - Represents a single species, BUT, can have any number of GWT Models
  - No transport across grids (yet)



In review

EXAMPLES

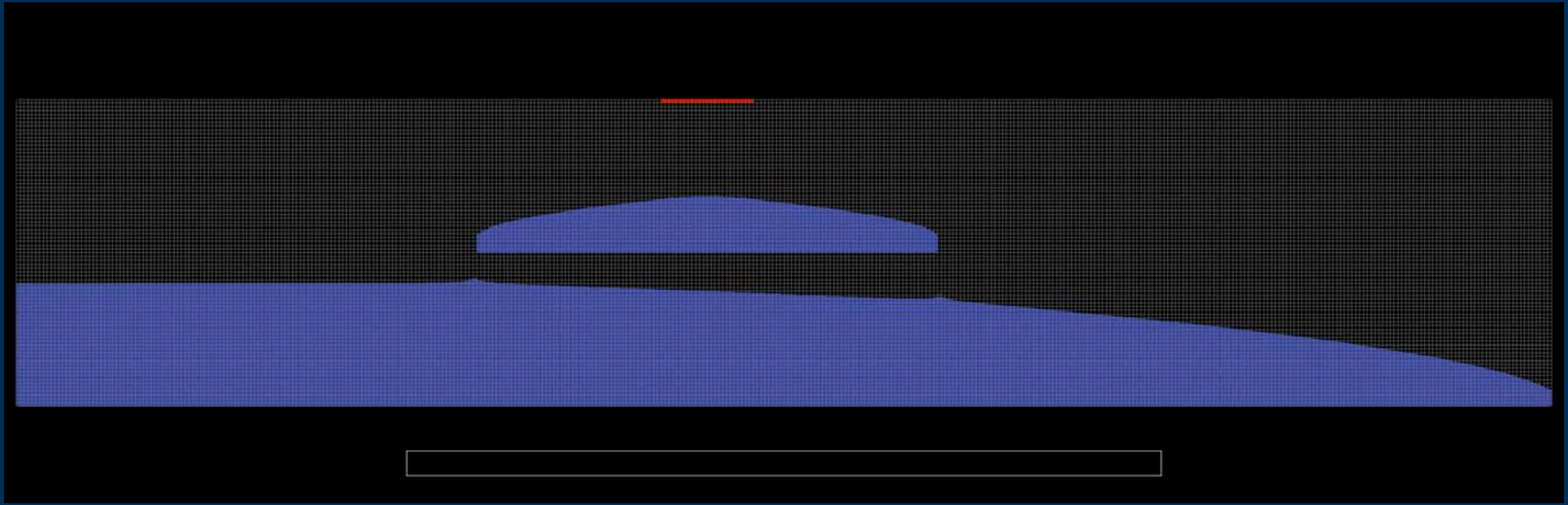
Newton Formulation for Water Table Aquifers

- Minimizes wetting and drying complications

USGS

Transport Solution for Perched Aquifers

- Instantaneous solute routing through the unsaturated zone



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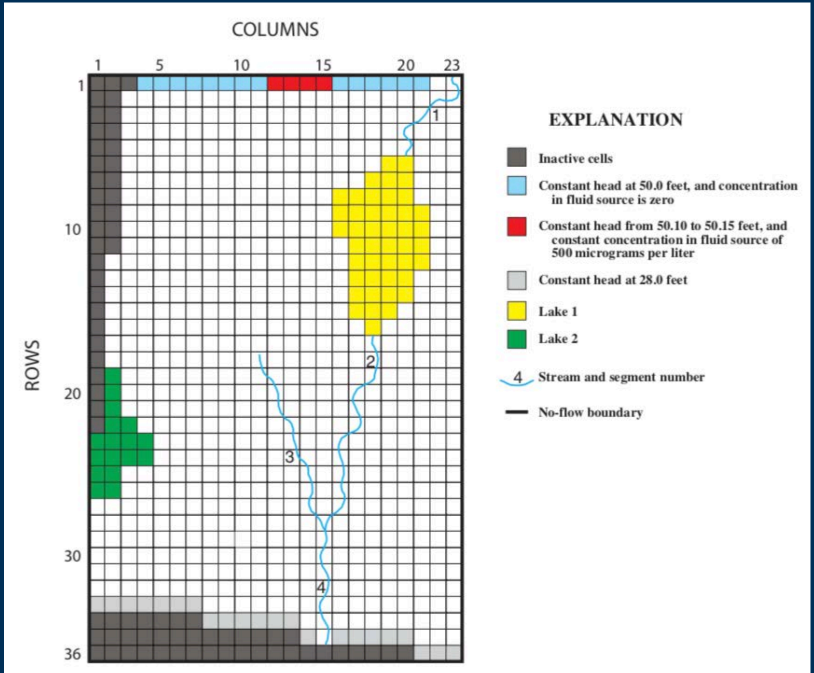
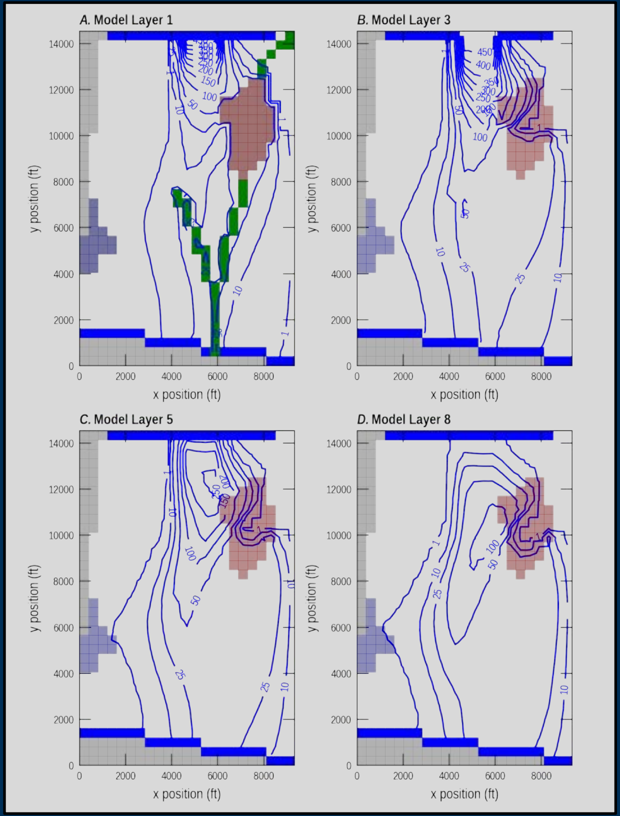
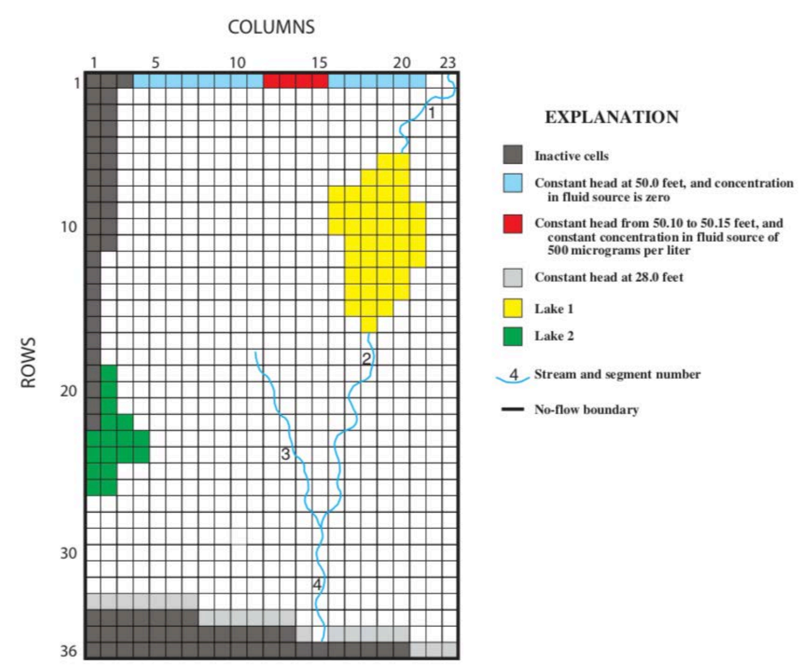
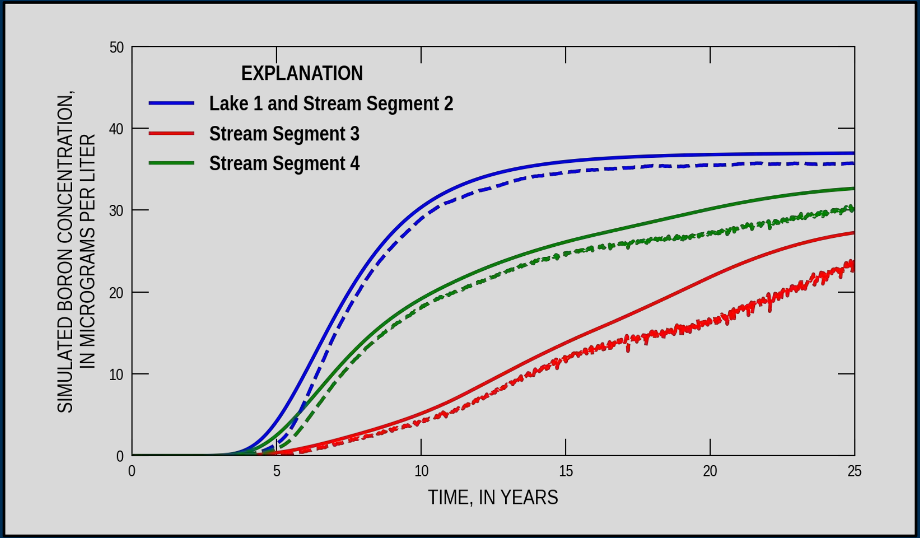
Advanced Packages and Water Mover





Surface and Groundwater Flow and Transport





Comparison between MODFLOW 6 (solid lines) and GWT (dashed lines)

Coupled Variable-Density Flow and Transport

- Run GWF and GWT in same simulation
- Turn on Buoyancy Package in GWF Model
- Represent salt as a chemical species

Groundwater

Hydraulic-Head Formulation for Density-Dependent Flow and Transport

by Christian D. Langevin[1], Sorab Panday[2,3], and Alden M. Provost[4]

Abstract

Density-dependent flow and transport solutions for coastal saltwater intrusion investigations, analyses of fluid injection into deep brines, and studies of convective fingering and instabilities of denser fluids moving through less dense fluids typically formulate the groundwater flow equation in terms of pressure or equivalent freshwater head. A formulation of the flow equation in terms of hydraulic head is presented here as an alternative. The hydraulic-head formulation can facilitate adaptation of existing constant-density groundwater flow codes to include density-driven flow by avoiding the need to convert between freshwater head and hydraulic head within the code and by incorporating density-dependent terms as a compartmentalized "correction" to constant-density calculations already performed by the code. The hydraulic-head formulation also accommodates complexities such as unconfined groundwater flow and Newton-Raphson solution schemes more readily than the freshwater-head formulation. Simulation results are presented for four example problems solved using an implementation of the hydraulic-head formulation in MODFLOW.

Introduction

Saltwater intrusion modeling codes such as SEAWAT (Guo and Langevin 2002; Langevin et al. 2003, 2008) formulate the density-dependent groundwater flow equation in terms of equivalent freshwater head (called simply freshwater head throughout the remainder of this paper). The freshwater-head formulation is easy to conceptualize, and the resulting generalized form of Darcy's Law, which relates specific discharge to the forces that drive flow, can be written as the sum of a freshwater-head term and a density-dependent term. The freshwater-head gradient is the sole driving force for horizontal flow; for vertical flow, the density-dependent term also contributes to the flux calculation. Once the freshwater-head formulation is solved for flow, the resulting fluxes are incorporated into a solute-transport model that solves for the distribution of solute concentration. However, the concentration distribution affects the fluid-density distribution, which in turn affects the groundwater flow field. Thus, the solution progresses in an iterative or time-lagged fashion, alternately updating and solving the variable-density flow equation and the solute-transport equation.

Although the freshwater-head formulation is conceptually appealing and convenient for calculating groundwater fluxes, some calculations in a groundwater model are best (or necessarily) performed using other types of head, such as hydraulic head. Thus, use of the freshwater-head formulation typically requires repeated conversion between freshwater head and another type of head within the modeling code. In modeling codes such as SEAWAT, hydraulic heads correspond to water-table elevations in unconfined model cells. Therefore, hydraulic heads (not freshwater heads) determine whether cells are confined, unconfined, or dry, or whether dry cells should rewet, and transmissivities computed in unconfined cells depend on hydraulic head. In codes that simulate variably saturated flow, moisture retention curves are expressed as functions of pressure head (hydraulic head minus elevation), not freshwater head. Also, in codes based on the freshwater-head formulation, prescribed-head and head-dependent boundary conditions ultimately need to be represented in terms of freshwater head. Therefore, either the user must calculate and specify approximate freshwater-head boundary values a priori in the model input, or a conversion from user-specified hydraulic-head values to freshwater heads must be performed within the code on every solution iteration to account for changes in density, which can destabilize the solution. Moreover, use of the freshwater-head formulation can render other

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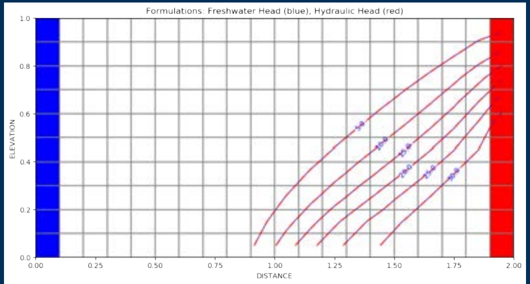
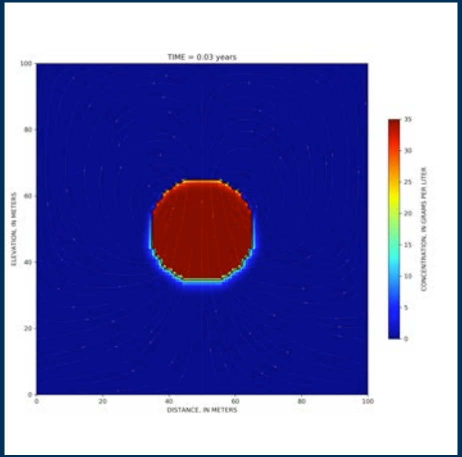
Received September 2019, accepted November 2019.

doi: 10.1111/gwat.12967





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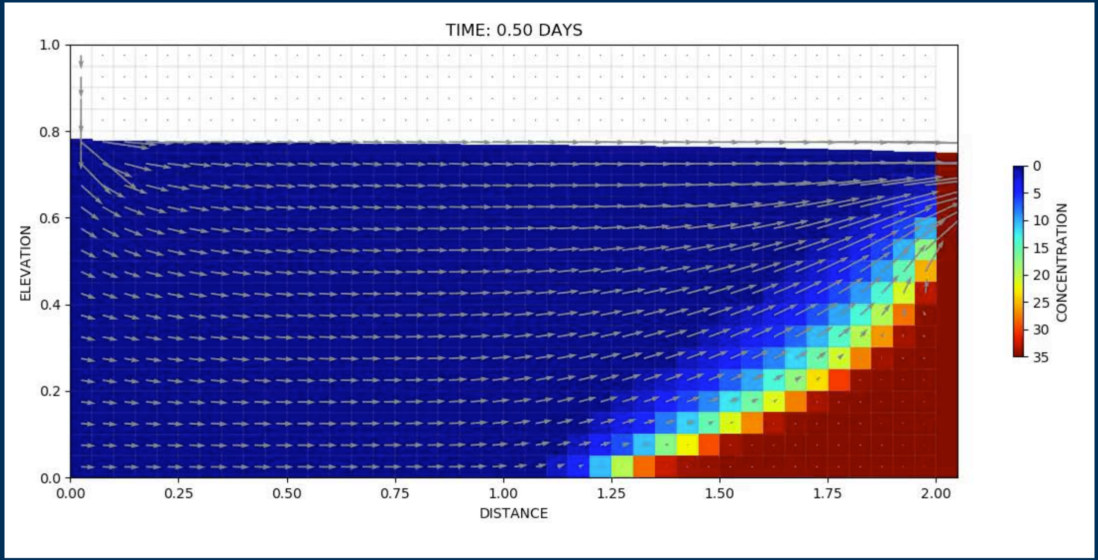
Coupled Flow and Transport Capabilities



Does MODFLOW 6 work with PEST?

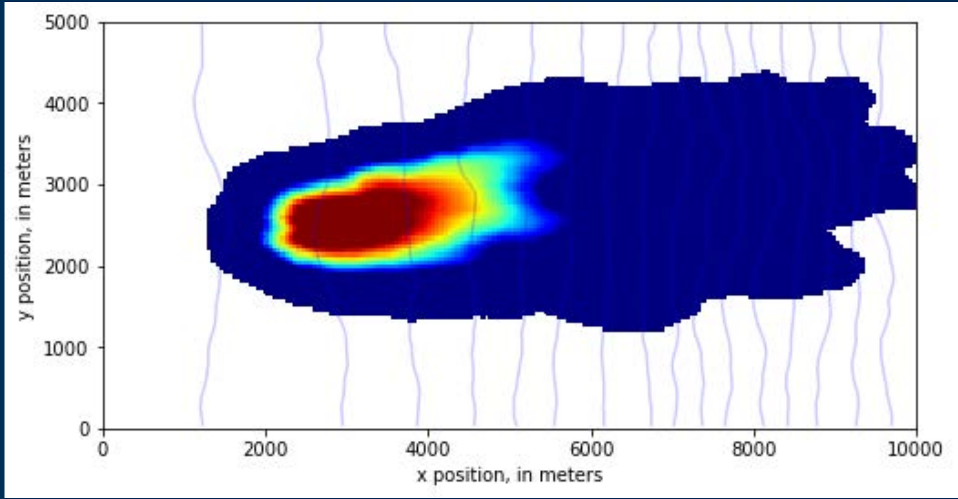
USGS

Does MODFLOW 6 work with PEST?

Of course!

Optimal Plume Management

- Example from Jeremy White, INTERA Inc.
- Simple synthetic problem
- 50 m cells
- 10 km x 5 km x 1 layer
- 20 years of treatment



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INTERA
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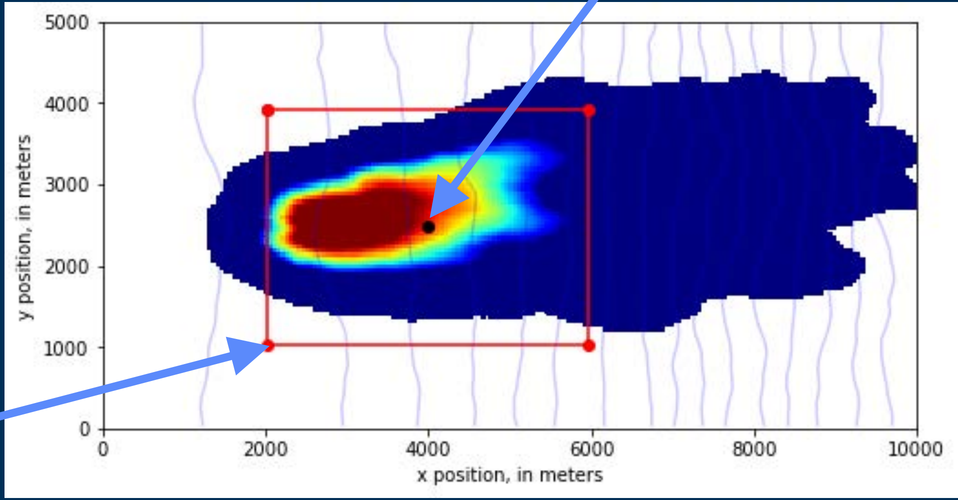
Optimal Plume Management

- **Standard 5-spot injector/extractor configuration**

Extractor



Injectors

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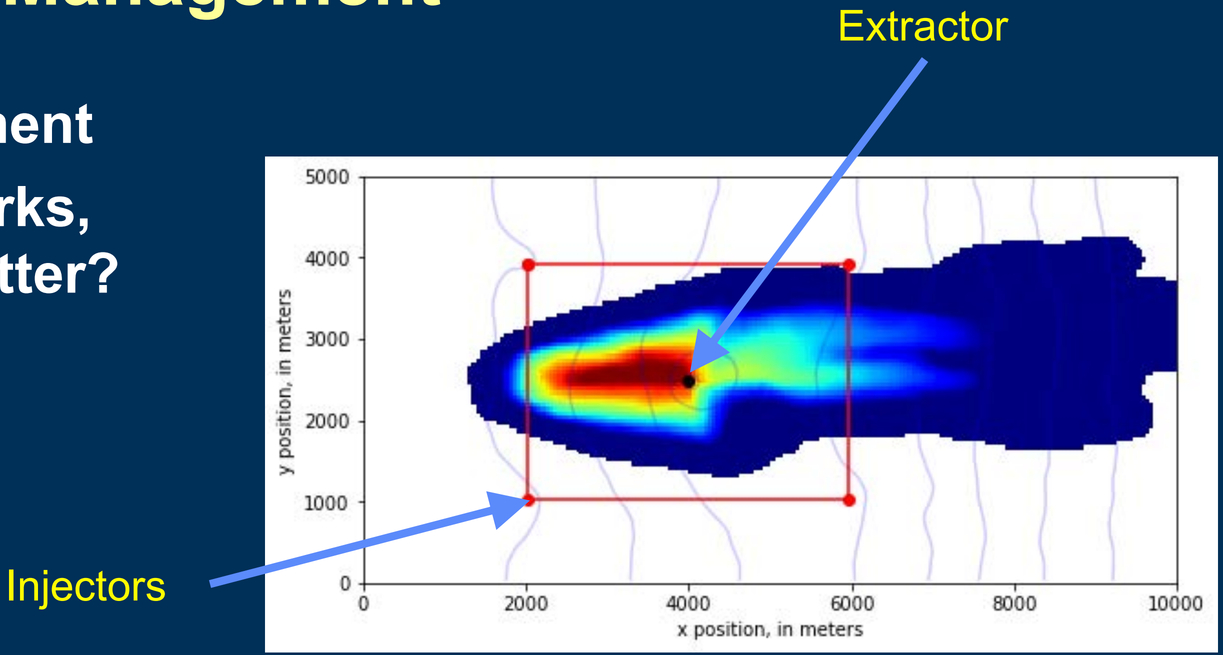
Optimal Plume Management

- 20 years of treatment
- Configuration works, but could it be better?



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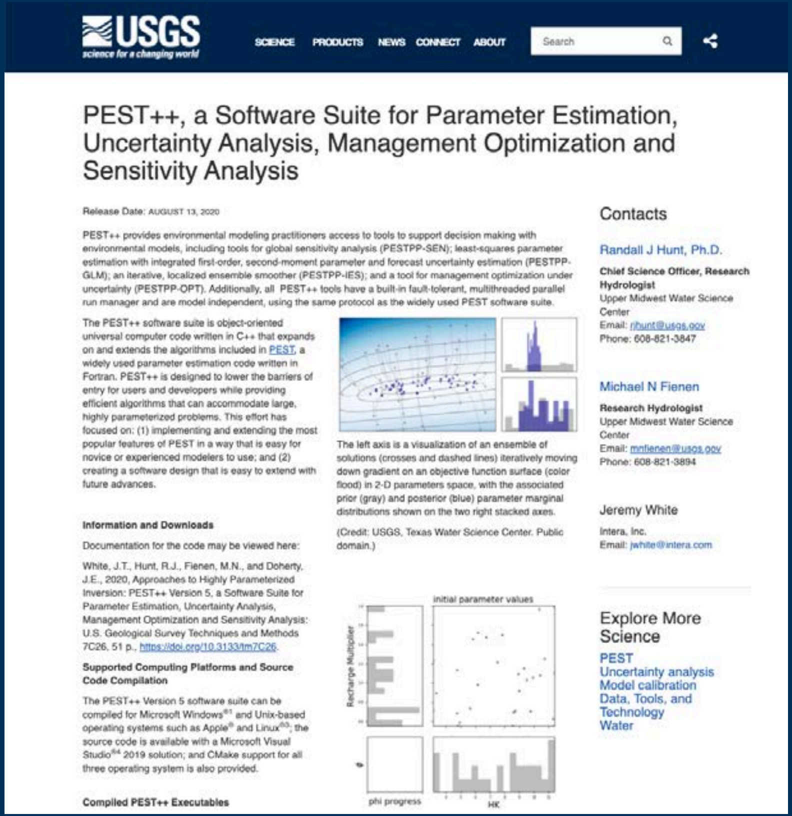
pestpp-mou (beta)

- Constrained multi-objective optimization under uncertainty within the PEST interface
  - Template files, instruction files, control files
- Treat "risk" (probability of success) as an objective
- Uses first-order second-moment or "stack"-based "chances"
  - Plays nicely with other PEST and PEST++ tools
- Fault-tolerant, model-independent, parallel run management



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PEST++, a Software Suite for Parameter Estimation, Uncertainty Analysis, Management Optimization and Sensitivity Analysis

Release Date: AUGUST 13, 2020

PEST++ provides environmental modeling practitioners access to tools to support decision making with environmental models, including tools for global sensitivity analysis (PESTPP-SEN); least-squares parameter estimation with integrated first-order, second-moment parameter and forecast uncertainty estimation (PESTPP-GLM); an iterative, localized ensemble smoother (PESTPP-IES); and a tool for management optimization under uncertainty (PESTPP-OPT). Additionally, all PEST++ tools have a built-in fault-tolerant, multithreaded parallel run manager and are model independent, using the same protocol as the widely used PEST software suite.

The PEST++ software suite is object-oriented universal computer code written in C++ that expands on and extends the algorithms included in PEST, a widely used parameter estimation code written in Fortran. PEST++ is designed to lower the barriers of entry for users and developers while providing efficient algorithms that can accommodate large, highly parameterized problems. This effort has focused on: (1) implementing and extending the most popular features of PEST in a way that is easy for novice or experienced modelers to use; and (2) creating a software design that is easy to extend with future advances.

The left axis is a visualization of an ensemble of solutions (crosses and dashed lines) iteratively moving down gradient on an objective function surface (color flood) in 2-D parameters space, with the associated prior (gray) and posterior (blue) parameter marginal distributions shown on the two right stacked axes.

(Credit: USGS, Texas Water Science Center. Public domain.)

Information and Downloads

Documentation for the code may be viewed here:

White, J.T., Hunt, R.J., Fienen, M.N., and Doherty, J.E., 2020, Approaches to Highly Parameterized Inversion: PEST++ Version 5, a Software Suite for Parameter Estimation, Uncertainty Analysis, Management Optimization and Sensitivity Analysis: U.S. Geological Survey Techniques and Methods 7C26, 51 p., https://doi.org/10.3133/tm7C26.

Supported Computing Platforms and Source Code Compilation

The PEST++ Version 5 software suite can be compiled for Microsoft Windows®1 and Unix-based operating systems such as Apple® and Linux®3; the source code is available with a Microsoft Visual Studio®4 2019 solution; and CMake support for all three operating system is also provided.

Compiled PEST++ Executables

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Email: jwhite@intera.com

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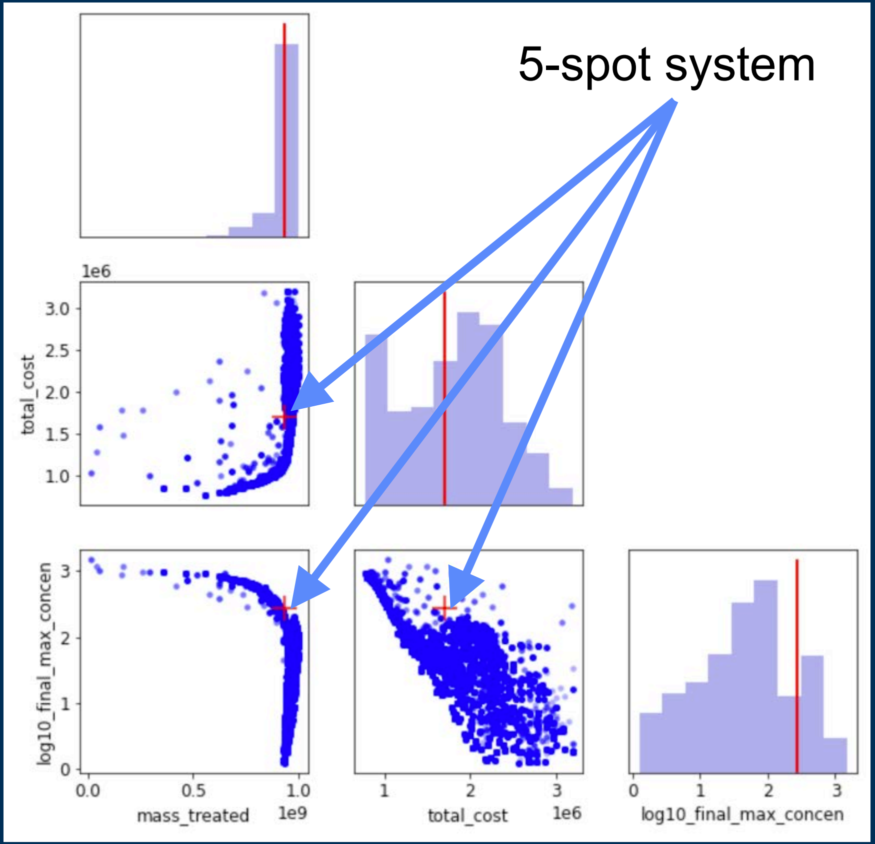
Mapping Tradeoff Between Objectives

- **Decision Variables**
  - Injector location
  - Extractor location
  - Extraction rate
  - Injector apportioning
- **Objectives**
  - Mass treated
  - Total cost (drilling + operation)
  - Final maximum concentration
- **Constraints**
  - Concentration at compliance point < 5-spot
  - Mass flux to downstream boundary < 5-spot



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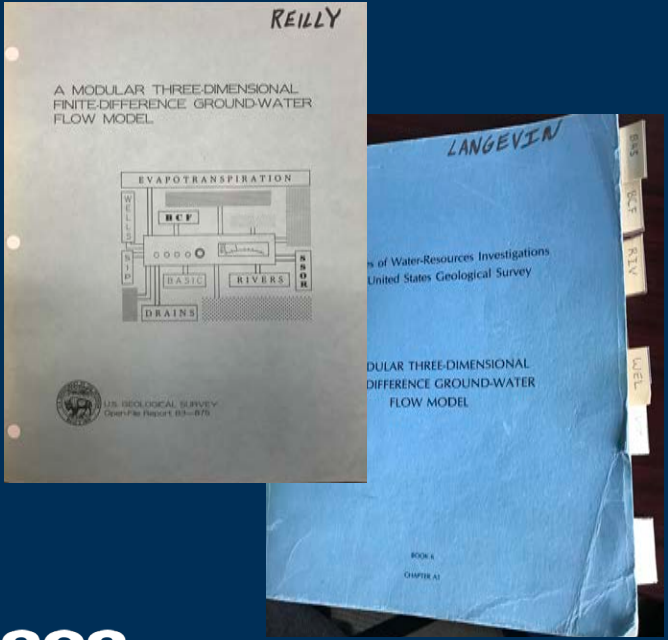
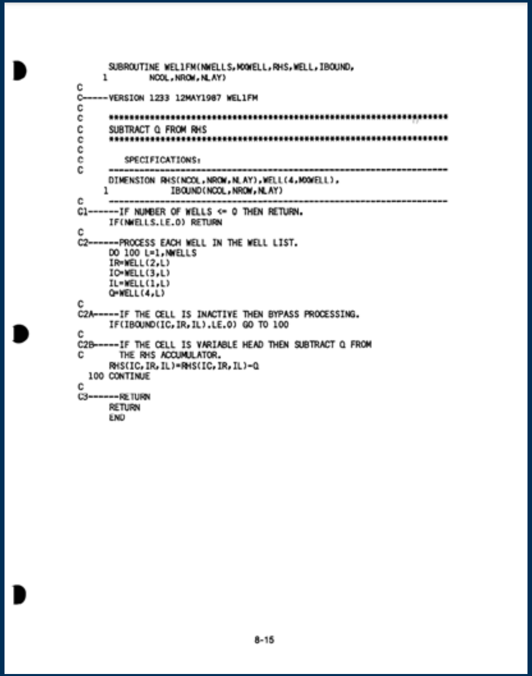
MODFLOW API

MODFLOW API

- **API = Application Programming Interface**





```
      SUBROUTINE WEL1FM(NWELLS,MXWELL,RHS,WELL,IBOUND,
     1        NCOL,NROW,NLAY)
C
C-----VERSION 1233 12MAY1987 WEL1FM
C
C     ******************************************************************
C     SUBTRACT Q FROM RHS
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION RHS(NCOL,NROW,NLAY),WELL(4,MXWELL),
     1          IBOUND(NCOL,NROW,NLAY)
C     ------------------------------------------------------------------
C1------IF NUMBER OF WELLS <= 0 THEN RETURN.
      IF(NWELLS.LE.0) RETURN
C
C2------PROCESS EACH WELL IN THE WELL LIST.
      DO 100 L=1,NWELLS
      IR=WELL(2,L)
      IC=WELL(3,L)
      IL=WELL(1,L)
      Q=WELL(4,L)
C
C2A-----IF THE CELL IS INACTIVE THEN BYPASS PROCESSING.
      IF(IBOUND(IC,IR,IL).LE.0) GO TO 100
C
C2B-----IF THE CELL IS VARIABLE HEAD THEN SUBTRACT Q FROM
C        THE RHS ACCUMULATOR.
      RHS(IC,IR,IL)=RHS(IC,IR,IL)-Q
  100 CONTINUE
C
C3------RETURN
      RETURN
      END
```

8-15

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API for MODFLOW 6

- Developed in collaboration with Martijn Russcher, Deltares
- Full control of MODFLOW while it's running
- Access to MODFLOW internal variables (as a copy or pointer)
- Three different levels of control
  - Between time steps
  - Within a time step
  - Within an iteration
- Well-defined interfaces based on Basic Model Interface (BMI) standard
- Uses identical code base as executable version

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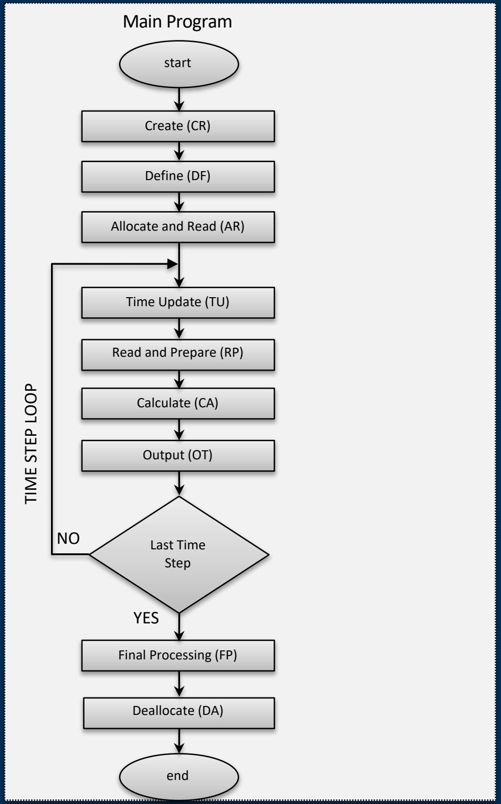
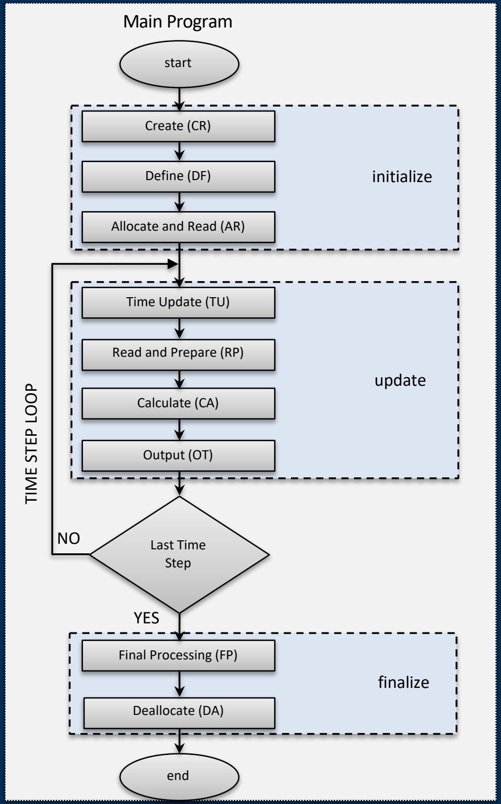
Deltares

MODFLOW API – Between Time Steps



MODFLOW API – Between Time Steps



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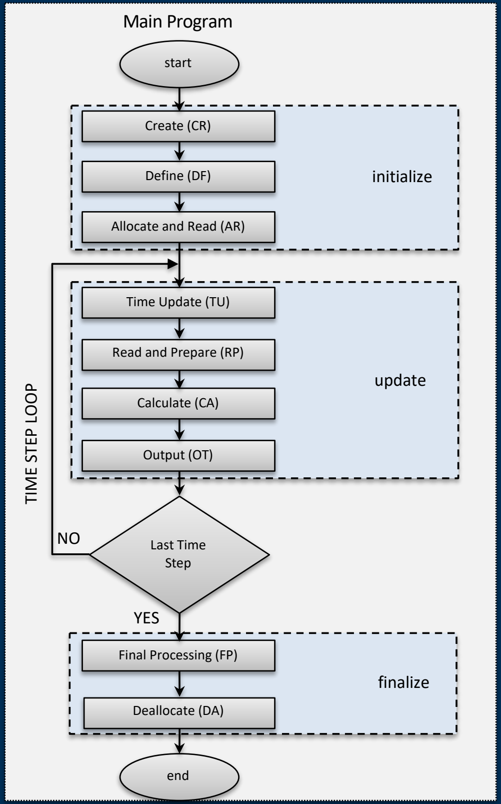
MODFLOW API – Between Time Steps




```
mf6 =  XmiWrapper(‘libmf6.dll’)
mf6.initialize(‘mfsim.nam’)
current_time = 0.
end_time = mf6.get_end_time()

while current_time < end_time:
  mf6.update()
  current_time = mf6.get_current_time()

mf6.finalize()
```

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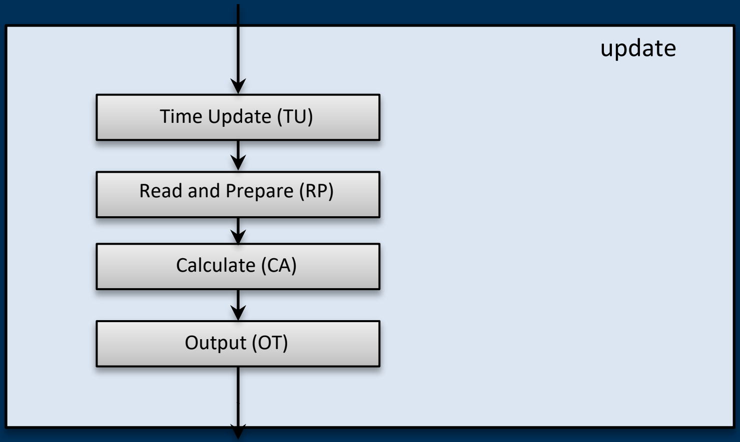
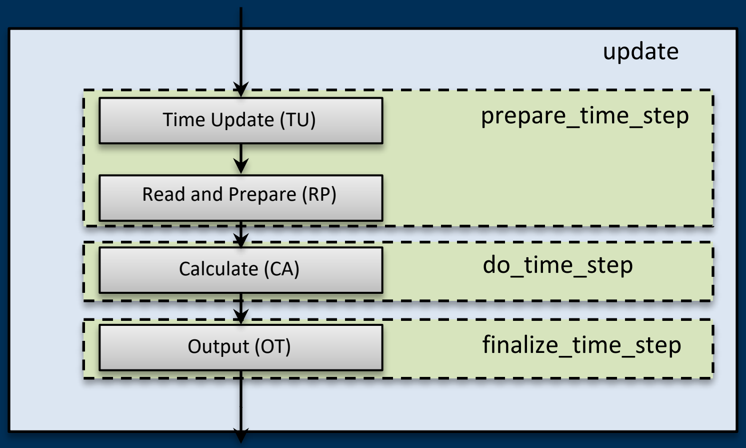
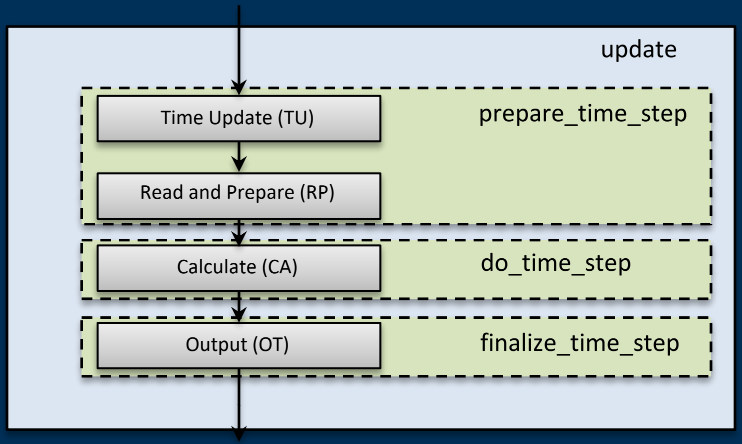
MODFLOW API – Within a Time Step



MODFLOW API – Within a Time Step



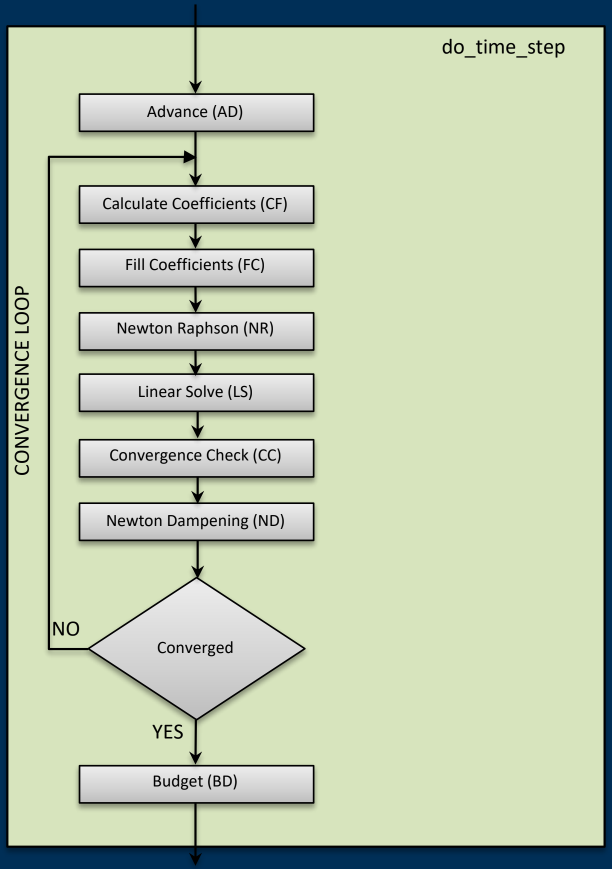
MODFLOW API – Within a Time Step



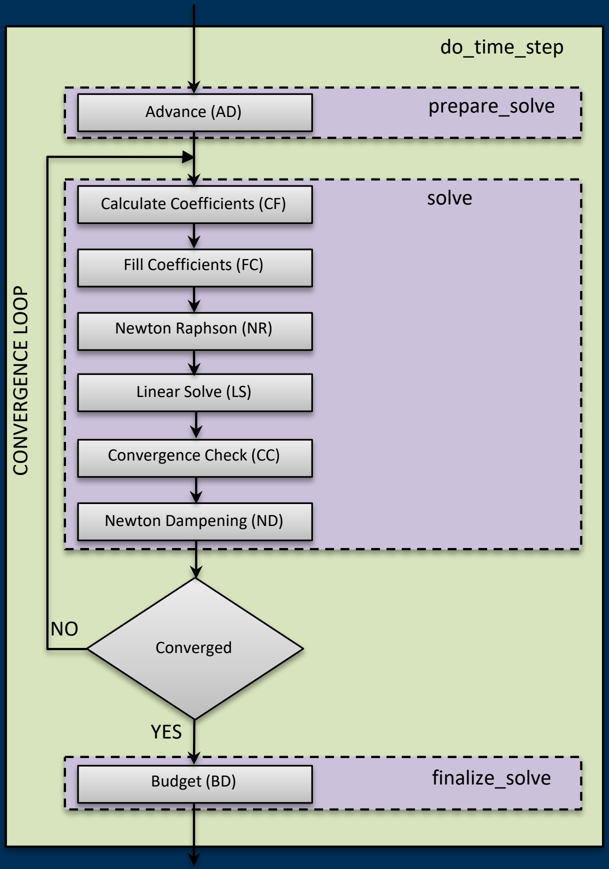

```
mf6 =  XmiWrapper('libmf6.dll')
mf6.initialize('mfsim.nam')
current_time = 0.
end_time = mf6.get_end_time()

while current_time < end_time:

  dt = mf6.get_time_step()
  mf6.prepare_time_step(dt)
  mf6.do_time_step()
  mf6.finalize_time_step()

  current_time = mf6.get_current_time()

mf6.finalize()
```

update

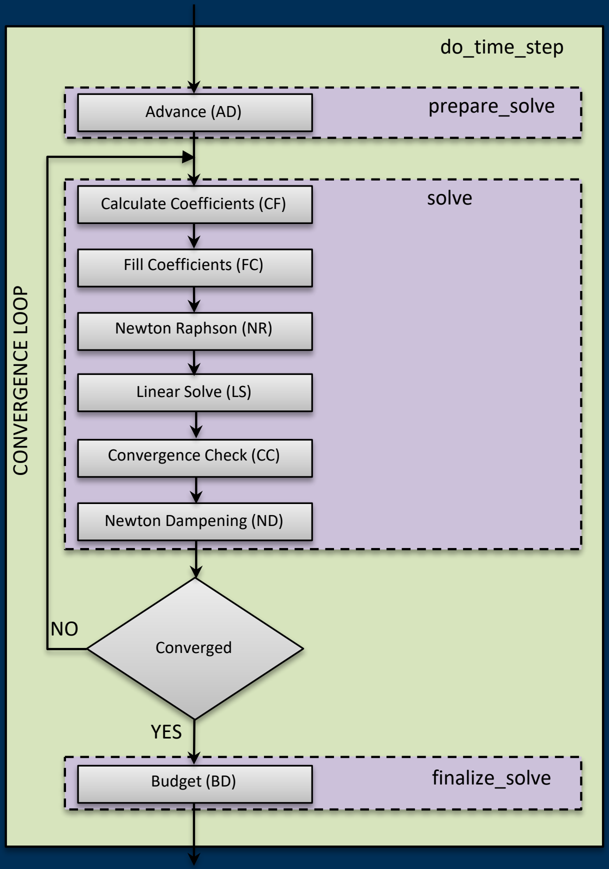
MODFLOW API – Within an Iteration



MODFLOW API – Within an Iteration



MODFLOW API – Within an Iteration




```
mf6 =  XmiWrapper('libmf6.dll')
mf6.initialize('mfsim.nam')
current_time = 0.
end_time = mf6.get_end_time()

while current_time < end_time:
  dt = mf6.get_time_step()
  mf6.prepare_time_step(dt)

  kiter = 0
  mf6.prepare_solve(1)
  while kiter < max_iter:
    has_converged = mf6.solve(1)
    if has_converged:
      break
  mf6.finalize_solve(1)

  mf6.finalize_time_step()
  current_time = mf6.get_current_time()

mf6.finalize()
```

do_time_step

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Why We're Excited about the API!

- Tight integration with other models
- Callable from other languages, such as Python; access to 3rd party tools
- Sensitivity analysis, adjoint state, parameter estimation, optimization, uncertainty analysis
- Alternative solvers (PETSc, …)
- Alternative data input (netCDF, database access, online services, …)
- MODFLOW can be customized by our users

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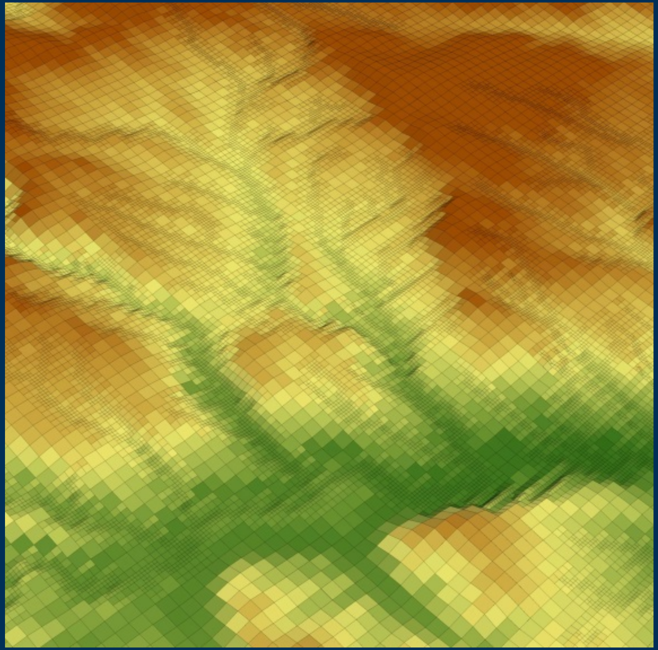

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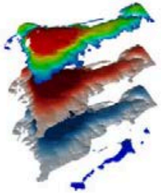
MODFLOW and Related Programs

Overview Publications Software

MODFLOW is the USGS's modular hydrologic model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. MODFLOW 6 is presently the core MODFLOW version distributed by the USGS. The previous core version, MODFLOW-2005, is actively maintained and supported as well.

Originally developed and released solely as a groundwater-flow simulation code when first published in 1984, MODFLOW's modular structure has provided a robust framework for integration of additional simulation capabilities that build on and enhance its original scope. The family of MODFLOW-related programs now includes capabilities to simulate coupled groundwater/surface-water systems, solute transport, variable-density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management.



MODFLOW Development Plans, July 20, 2020

The USGS Water Mission Area actively develops and supports the MODFLOW suite of programs. Ongoing efforts include providing maintenance and support for existing versions of MODFLOW such as MODFLOW 6, MODFLOW-2005, MODFLOW-NWT, MODFLOW-USG, MODPATH, MT3D-USGS, and related and supporting programs such as FloPy and PEST++. Current development efforts are focused on adding new capabilities to MODFLOW 6. These development efforts include:

Status - Active

Contacts

USGS MODFLOW Team

Email: modflow@usgs.gov

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variable-density flow
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Core Versions

- MODFLOW 6: current core version
- MODFLOW-2005: previous core version

MODFLOW Variants: Newer, specialized, or advanced versions of MODFLOW for use by experienced modelers

- MODFLOW-NWT: MODFLOW-NWT uses a Newton-Raphson formulation to improve solution of unconfined groundwater-flow problems.
- MODFLOW-USG: MODFLOW-USG uses an unstructured-grid approach to simulate groundwater flow and tightly coupled processes using a control volume finite-difference formulation.
- GSFLOW: GSFLOW is a coupled groundwater and surface-water flow model based on the USGS Precipitation-Runoff Modeling System (PRMS), MODFLOW-2005, and MODFLOW-NWT.
- GWM: The Groundwater Management (GWM) Process for MODFLOW-2000 and MODFLOW-2005 is used to simulate groundwater management

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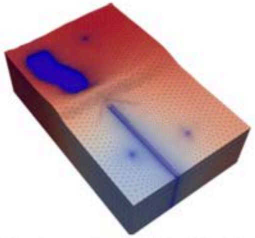
MODFLOW 6: USGS Modular Hydrologic Model

Release Date: OCTOBER 22, 2020

For over 30 years, the MODFLOW program has been widely used by academics, private consultants, and government scientists to accurately, reliably, and efficiently simulate groundwater flow. With time, growing interest in surface and groundwater interactions, local refinement with nested and unstructured grids, karst groundwater flow, solute transport, and saltwater intrusion, has led to the development of numerous MODFLOW versions. Although these MODFLOW versions are often based on the core MODFLOW version (previously MODFLOW-2005), there are often incompatibilities that restrict their use with other MODFLOW versions. In many cases, development of these alternative MODFLOW versions has been challenging due to the underlying program structure, which was designed for the simulation of a single groundwater flow model using a regular MODFLOW grid consisting of layers, rows, and columns.

Overview of MODFLOW 6

MODFLOW 6 is an object-oriented program and framework developed to provide a platform for supporting multiple models and multiple types of models within the same simulation. This version of MODFLOW is labeled with a "6" because it is the sixth core version of MODFLOW to be released by the USGS (previous core versions were released in 1984, 1988, 1996, 2000, and 2005). In the new design, any number of models can be included in a simulation. These models can be independent of one another with no interaction, they can exchange information with one another, or they can be tightly coupled at the matrix level by adding them to the same numerical solution. Transfer of information between models is isolated to exchange objects, which allow models to be developed and used independently of one another. Within this new framework, a regional-scale groundwater model may be coupled with multiple local-scale groundwater models. Or, a surface-water flow model could be coupled to multiple groundwater flow models. The framework naturally allows for future extensions to include the simulation of solute transport.



This figure shows a triangular grid in which the size of the triangular cells is reduced in areas with relatively large hydraulic gradients, such as around the shoreline of a lake, near pumping wells, and along a stream. This type of layered grid can be represented using the Discretization by Vertices (DISV) Package in MODFLOW 6.

Groundwater Flow (GWF) and Groundwater Transport (GWT) Models

MODFLOW 6 presently contains two types of hydrologic models, the **Groundwater Flow (GWF) Model and the Groundwater Transport (GWT) Model**. The GWF Model for MODFLOW 6 is based on a generalized control-

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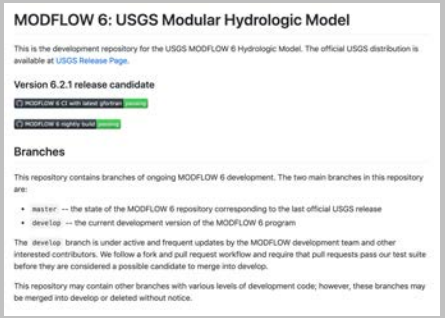
Additional Online Resources

Main Repository



MODFLOW 6: USGS Modular Hydrologic Model

This is the development repository for the USGS MODFLOW 6 Hydrologic Model. The official USGS distribution is available at USGS Release Page.

Version 6.2.1 release candidate

MODFLOW 6 CI with latest gfortran passing

MODFLOW 6 nightly build passing

Branches

This repository contains branches of ongoing MODFLOW 6 development. The two main branches in this repository are:

- `master` -- the state of the MODFLOW 6 repository corresponding to the last official USGS release
- `develop` -- the current development version of the MODFLOW 6 program

The `develop` branch is under active and frequent updates by the MODFLOW development team and other interested contributors. We follow a fork and pull request workflow and require that pull requests pass our test suite before they are considered a possible candidate to merge into develop.

This repository may contain other branches with various levels of development code; however, these branches may be merged into develop or deleted without notice.

FloPy

FloPy

a Python package to create, run, and post-process MODFLOW-based models

Version 3.3.3 — release candidate

build passing | codecov 72% | code quality A | docs passing

Install with conda | Anaconda Cloud 3.3.2 | pypi v3.3.2

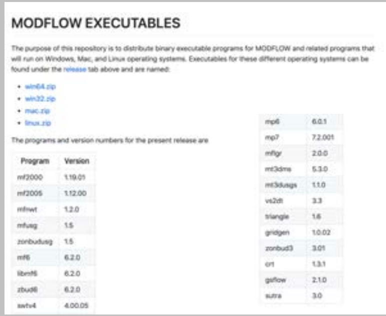
launch binder

Introduction

FloPy includes support for MODFLOW 6, MODFLOW-2005, MODFLOW-NWT, MODFLOW-USG, and MODFLOW-2000. Other supported MODFLOW-based models include MODPATH (version 6 and 7), MT3DMS, MT3D-USGS, and SEAWAT.

For general modeling issues, please consult a modeling forum, such as the MODFLOW Users Group. Other MODFLOW resources are listed in the MODFLOW Resources section.

Executables



MODFLOW EXECUTABLES

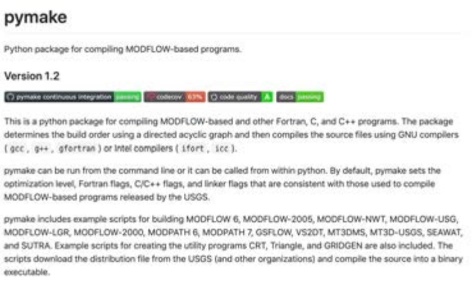
The purpose of this repository is to distribute binary executable programs for MODFLOW and related programs that will run on Windows, Mac, and Linux operating systems. Executables for these different operating systems can be found under the release tab above and are named:

- win64.zip
- win32.zip
- mac.zip
- linux.zip

The programs and version numbers for the present release are

Program	Version
mf2000	1.19.01
mf2005	1.12.00
mfnwt	1.2.0
mfusg	1.5
zonbudusg	1.5
mf6	6.2.0
libmf6	6.2.0
zbud6	6.2.0
swtv4	4.00.05
mp6	6.0.1
mp7	7.2.001
mflgr	2.0.0
mt3dms	5.3.0
mt3dusgs	1.1.0
vs2dt	3.3
triangle	1.6
gridgen	1.0.02
zonbud3	3.01
crt	1.3.1
gsflow	2.1.0
sutra	3.0

Pymake



pymake

Python package for compiling MODFLOW-based programs.

Version 1.2

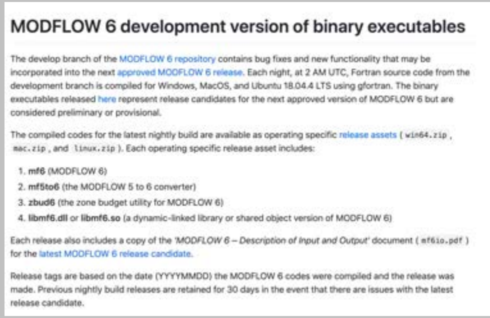
pymake continuous integration passing | codecov 63% | code quality A | docs passing

This is a python package for compiling MODFLOW-based and other Fortran, C, and C++ programs. The package determines the build order using a directed acyclic graph and then compiles the source files using GNU compilers (`gcc` , `g++` , `gfortran`) or Intel compilers (`ifort` , `icc`).

pymake can be run from the command line or it can be called from within python. By default, pymake sets the optimization level, Fortran flags, C/C++ flags, and linker flags that are consistent with those used to compile MODFLOW-based programs released by the USGS.

pymake includes example scripts for building MODFLOW 6, MODFLOW-2005, MODFLOW-NWT, MODFLOW-USG, MODFLOW-LGR, MODFLOW-2000, MODPATH 6, MODPATH 7, GSFLOW, VS2DT, MT3DMS, MT3D-USGS, SEAWAT, and SUTRA. Example scripts for creating the utility programs CRT, Triangle, and GRIDGEN are also included. The scripts download the distribution file from the USGS (and other organizations) and compile the source into a binary executable.

Nightly Build



MODFLOW 6 development version of binary executables

The develop branch of the MODFLOW 6 repository contains bug fixes and new functionality that may be incorporated into the next approved MODFLOW 6 release. Each night, at 2 AM UTC, Fortran source code from the development branch is compiled for Windows, MacOS, and Ubuntu 18.04.4 LTS using gfortran. The binary executables released here represent release candidates for the next approved version of MODFLOW 6 but are considered preliminary or provisional.

The compiled codes for the latest nightly build are available as operating specific release assets (`win64.zip` , `mac.zip` , and `linux.zip`). Each operating specific release asset includes:

1. **mf6** (MODFLOW 6)
2. **mf5to6** (the MODFLOW 5 to 6 converter)
3. **zbud6** (the zone budget utility for MODFLOW 6)
4. **libmf6.dll** or **libmf6.so** (a dynamic-linked library or shared object version of MODFLOW 6)

Each release also includes a copy of the *'MODFLOW 6 – Description of Input and Output'* document (`mf6io.pdf`) for the latest MODFLOW 6 release candidate.

Release tags are based on the date (YYYYMMDD) the MODFLOW 6 codes were compiled and the release was made. Previous nightly build releases are retained for 30 days in the event that there are issues with the latest release candidate.

Examples

Docs » MODFLOW 6 Example Problems

Edit on GitHub

MODFLOW 6 Example Problems

- Introduction
- MODFLOW 6 – Example problems
- MODFLOW 6 Examples - Jupyter Notebooks

Revision dc5c8128.

Built with Sphinx using a theme provided by Read the Docs.

CONCLUDING REMARKS

Summary

- MODFLOW 6 is presently the "core" MODFLOW
  - GWF Model
  - GWT Model
  - Coupled flow and transport
- New MODFLOW API
- Ongoing and planned efforts
  - Parallelization
  - Particle tracking
  - Time-variable properties (mining applications)
  - Adaptive time stepping, Richard's equation, heat transport, …

USGS

Any Questions?

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Or feel free to email me at
langevin@usgs.gov

Final Poll

We value your input! Please consider sending comments and recommendations.

USGS