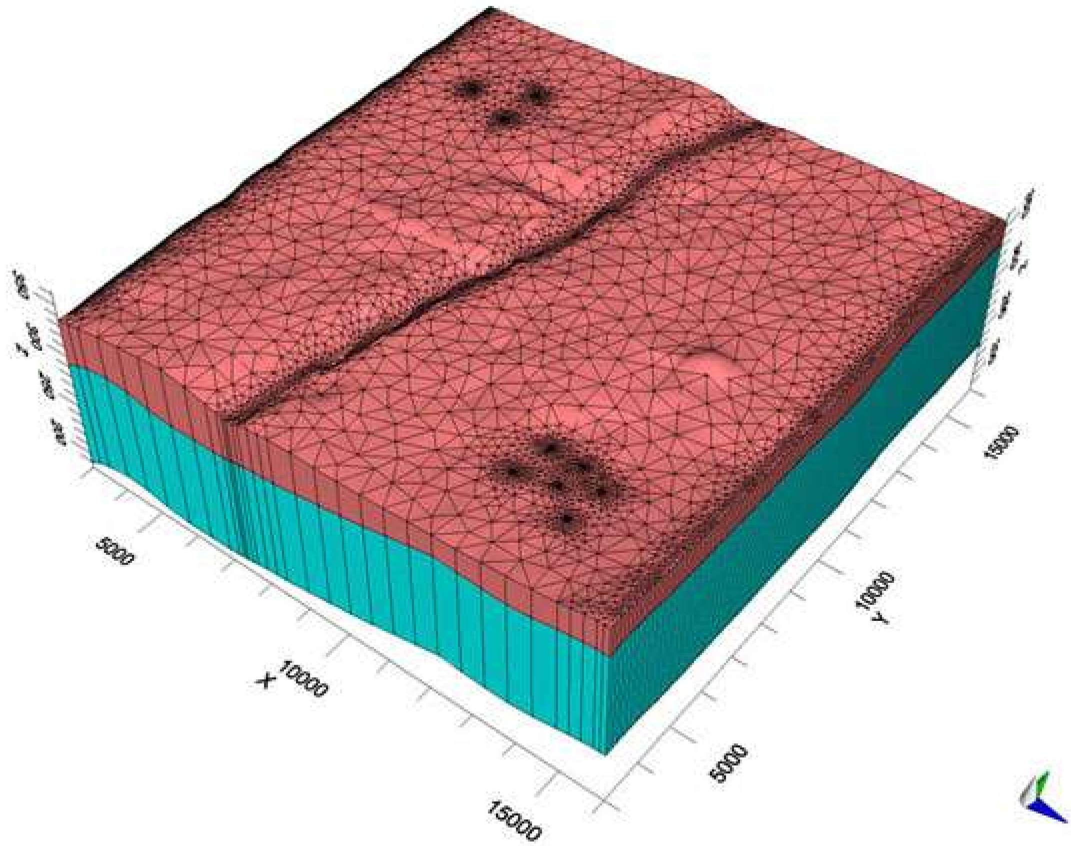
# MODFLOW-USG (UnStructured Grids): A Game Changer for Groundwater Modeling




A preview of the new MODFLOW-USG (UnStructured Grids) was unveiled by Sorab Panday and Chris Langevin at last year's MODFLOW and More Conference. Since then, the excitement around this new program has been building, and we have received numerous inquiries from Visual MODFLOW Flex users. So, what is MODFLOW-USG, and how is it different from conventional MODFLOW? We interviewed Sorab Panday, one of the co-authors of the code, to learn a little more about the program and its features.

## What is MODFLOW-USG?

MODFLOW-USG is a version of the groundwater flow code MODFLOW that uses Un-Structured Grids. An unstructured grid provides flexibility to a MODFLOW simulation by enabling use of triangular, rectangular or other polygon shaped geometries individually or in combination, to appropriately discretize the domain. This is in contrast to traditional MODFLOW which uses structured, rectilinear grids. An unstructured grid paradigm further allows 3D, 2D, and 1D cell combinations to include other flow processes such as discrete fracture networks into the groundwater flow model.

## What are the driving forces behind developing MODFLOW-USG?

MODFLOW is the most popular finite-difference flow modeling code worldwide; however it has limitations for grid geometry and refinement. In recent years, finite element codes have been growing in popularity, with their ability to accommodate complex geology and local refinement around wells and boundaries. We wanted to advance

MODFLOW's capabilities in this regard, to fulfill the current needs of groundwater modelers. We however selected the finite volume approach to provide this flexibility.

## What are the benefits of a finite volume approach?

Finite volume discretizations provide a higher level of gridding flexibility than finite difference formulations but are just as easy to understand and implement into the MODFLOW framework. They also provide mass-conserved, robust and efficient solutions without the computationally intensive numerical integration, elemental assembly schemes, and expanded matrix connectivity associated with finite element methods. Also, various grid cell geometries can be readily implemented individually or in combination without requiring a catalogue of various element shapes to be coded into the program. In this regard, a finite volume approach offers more flexibility than a finite element approach.

## What types of grids can you design with MODFLOW-USG?

The finite volume formulation allows us to utilize any cell geometry: triangles, rectangles, and regular higher-order polygons are recommended. The finite volume formulation also allows use of nested grids. The grid is limited to a prismatic shape in the vertical direction; however, each grid layer can have a different level of nesting compared to other layers. Sub-nesting of layers (i.e., nesting grids in the vertical direction) is also possible to allow for pinched layers or displaced geologic formations.

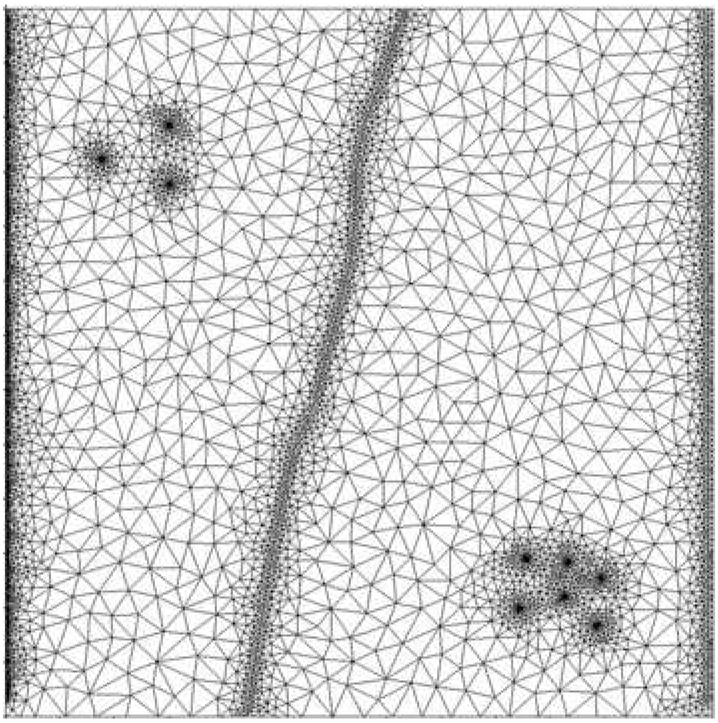


*Figure 1: Illustration of an unstructured grid using triangles, with refinement around wells and a river/stream*

You can build nested grids in any area of the model domain, both horizontally and vertically. For example, you can locally refine the grid around a well field, individual wells, or polyline/polygon features that represent flow boundaries (rivers, lakes, streams, etc.) or geological features (see Figure below). Each layer can have a different nesting structure, the refinement does not need to span through all layers of the model domain. Therefore you can control the nesting to be only around specific layers such as around well screens or surface water-groundwater interactions in the uppermost layer(s). The benefit is greater detail and accuracy around the areas of interest, without sacrificing model run times and stability.

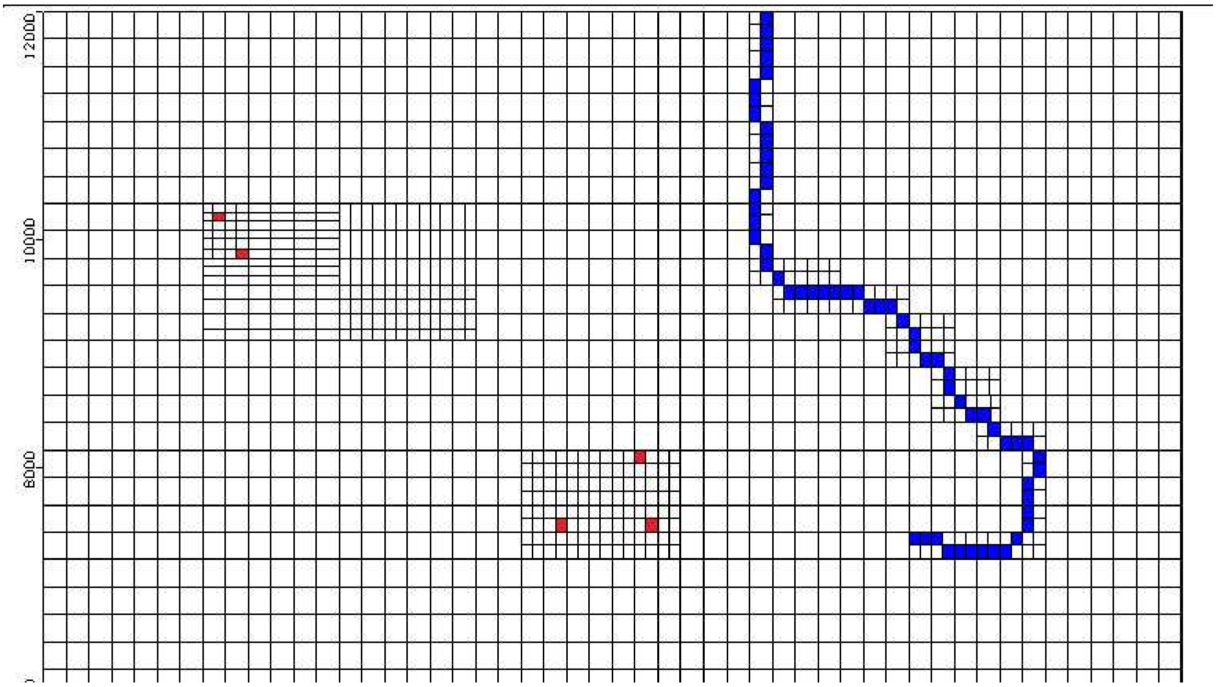



*Figure 2: Illustration of nested grids around wells and local refinement around a river boundary*

Vertically nested grids, or sub-layering, can also be designed around isolated lenses or pockets of materials or a discontinuity within a larger unit (see Figure below). The layers do not need to extend across the entire model domain. This will allow you to better represent complex geological formations, without sacrificing model run times and stability.

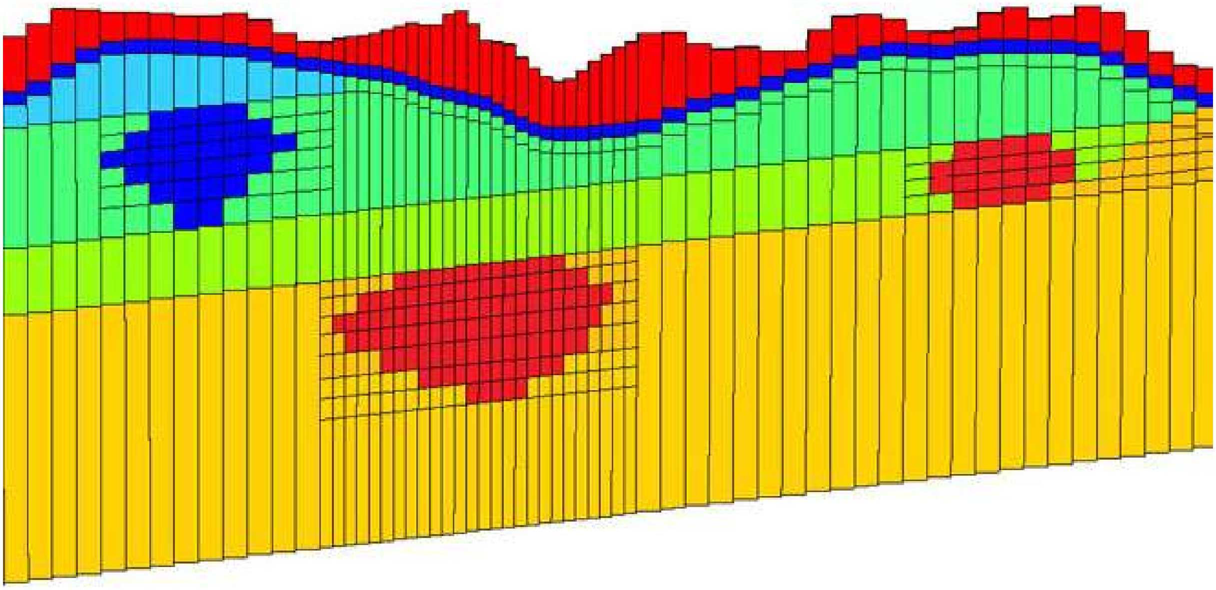


*Figure 3: Cross-section showing sub-layering to accommodate geological lenses/pockets, with cells rendered by hydraulic conductivity zone.*

## How are the MODFLOW-USG equations solved?

MODFLOW-USG incorporates the PCGU solver (White and Hughes, 2012) for the symmetric flow equation and the xMD solver (Ibaraki, 2011) for asymmetric matrices generated by use of Newton Raphson linearization using the upstream weighted formulation. This is the same solver used with MODFLOW-NWT.

## Is the input/output similar to MODFLOW-2005?

Essentially, the Input/Output formats for MODFLOW-USG follow those of MODFLOW-2005. The differences are due to the different grid structure. With MODFLOW-USG, we don't have layers, rows, and columns. Boundary condition nodes are identified within these packages by indexing the global node number instead of the structured layer, row and column classification used by MODFLOW-2005.

## What MODFLOW packages are supported?

The following "traditional" MODFLOW packages are supported in the first release:

- The BCF and LPF packages with all their options are supported.
- The upstream weighting (UPW) scheme and Newton-Raphson linearization methodology of MODFLOW-NWT is also supported.
- Constant Head (CHD)
- River (RIV)
- Recharge (RCH)
- Evapotranspiration (EVT)
- Flow and Head boundary (FHB)
- Well (WEL)
- Drain (DRN)
- General Head Boundary (GHB)
- Stream (STR7)
- Stream Flow Routing package with unsaturated flow beneath streams (SFR2)
- Stream-gage monitoring (GAGE)
- Lake (LAK3)
- Horizontal Flow Barrier (HFB)

## What other features are included with MODFLOW-USG?

- A new Connected Linear Network Package allows you to simulate features such as fractures, wells, conduits or channels within a 3-D groundwater flow domain. You can have conduits or networks of conduits, and these can be at any angle; they do not have to be only either horizontal or vertical. The groundwater interaction with conduit cells is via a leakage function or the Thiem solution to include sub-grid scale and well efficiency effects.
- A Ghost Node Correction (GNC) module is also introduced in MODFLOW-USG. It is used for providing higher order accuracy to irregular polygon grid geometries, nested grids, and conduits that are off-center from the porous matrix grid-block.
- The particle tracking codes MODPATH3D and PATH3D are being updated by their respective developers to support MODFLOW-USG.
- The developers of PEST are updating the PEST utilities to accommodate unstructured grids and the advantages they provide.
- MODFLOW-USG supports rectangular-grid models and is backward compatible to models developed for previous versions of MODFLOW with the above mentioned packages.

## What are some of the limitations for the first release and future developments?

- Contaminant transport currently is not supported, this is still in development.
- Density-dependent flow and transport will be developed once the transport routines are completed.
- Unsaturated zone flow packages (UZF or VSF) packages are not currently supported
- There are some limitations with vertical sub-discretization: LAK, SFR, SUB Packages currently do not support sub-discretization of layers that are included by these packages.
- The HUF package of MODFLOW-2005 is not supported.

End of Interview

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## VMOD Flex and MODFLOW-USG

Once MODFLOW-USG is released, we will start integrating this into the Visual MODFLOW Flex GUI. By following a conceptual modeling approach, and having flow boundaries and wells represented as grid independent points, polylines, and polygons, this will dramatically facilitate generation of the unstructured grid and locally refining the grid around these features. Complex geological elements are defined as conceptual volumes, representing pinchouts, discontinuities, and perched aquifers, lenses, etc. These objects can serve as inputs for defining the vertical layers, including generation of sub-layers, and populating the finite volumes with the appropriate parameter values. Stay tuned to this blog for more updates!

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## References:

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