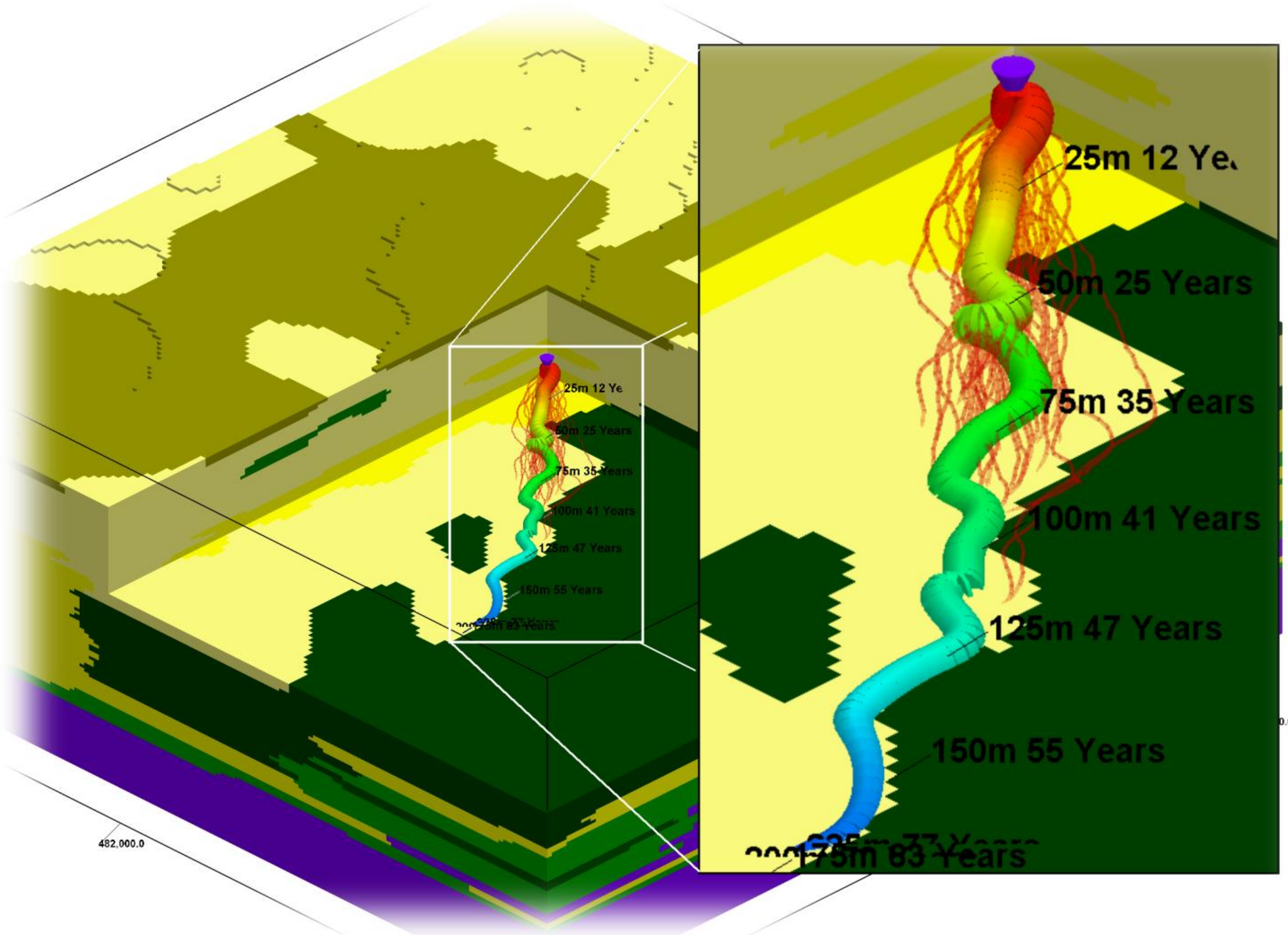
FlowPath Simulator

10/02/24/JPR



The *FlowPath* program simulates groundwater or fluid flow through geological models. It uses hydraulic conductivity data (indicating how easily fluids move through materials) to generate flow paths in a 3D model. The program supports both isotropic (uniform flow) and anisotropic (directionally varying flow) conditions. Because all supported migration is either lateral or downward, the program is limited to unconfined aquifers and/or vadose zones.

Key Features:

1. **Hydraulic Conductivity Input Models**: The software reads both horizontal and vertical hydraulic conductivity models to define fluid movement. If the vertical model is disabled, the program assumes that the media is isotropic.

2. **Flow Path Calculation**: The program calculates the most likely flow path based on local hydraulic gradients. In areas with homogeneous regions of identical hydraulic conductivities, it uses a regional gradient and slight randomization to continue path generation.

3. **Stochastic Paths**: Users can generate multiple potential flow paths to account for uncertainties, offering a range of outcomes.

4. **Most-Probable Path**: Based on the stochastic paths, the program generates a single “*Most-Probable*" flow path by analyzing their spatial distributions.

5. **Time-Based Annotation**: Flow transit times are calculated along the *Most-Probable* flow path, helping users understand the speed of fluid or contaminant movement.

6. **3D Visualization**: Results are visualized in the *RockWorks* 3D tool, allowing integration with other geological diagrams, such as lithology models, surface models, and borehole logs.

The *FlowPath* program is useful for hydrologists, geologists, and environmental engineers looking to model subsurface fluid dynamics. It provides a view of possible and most-probable fluid movement, aiding in tasks such as contamination tracking, water resource management, and environmental assessments.

How it Works

This program models the flow of groundwater based on the hydraulic conductivities of geologic units. It takes input from horizontal hydraulic conductivity (HK) and optionally, vertical hydraulic conductivity (VK) models that define the permeabilities for different rock and/or soil types.

Starting at a user-specified point, the program will calculate flow pathways, either stochastically (introducing variability) or deterministically (the most probable path). These paths are influenced by the local hydraulic properties defined within the hydraulic conductivity models as well as a broader, user-specified regional gradient. The software can handle anisotropic models (where horizontal and vertical permeability differ) or simpler isotropic models.

In other words, the flowpaths run down-gradient. If a path gets "stuck", the program uses the regional gradient to get un-stuck. If that fails, the program picks a random direction to move.

<u>Input Options</u>

Input Model Type: Defines whether input is from a lithology, stratigraphy model, or separate HK and VK models.

Lithology Model: The specified lithology model will be converted to temporary horizontal hydraulic conductivity (HK) and vertical hydraulic conductivity (VK) models by using the HK and VK values within the *LithoTypes* table (Figure 1). This eliminates a step that would otherwise involve using the *Lithology → Anisotropic K* program.

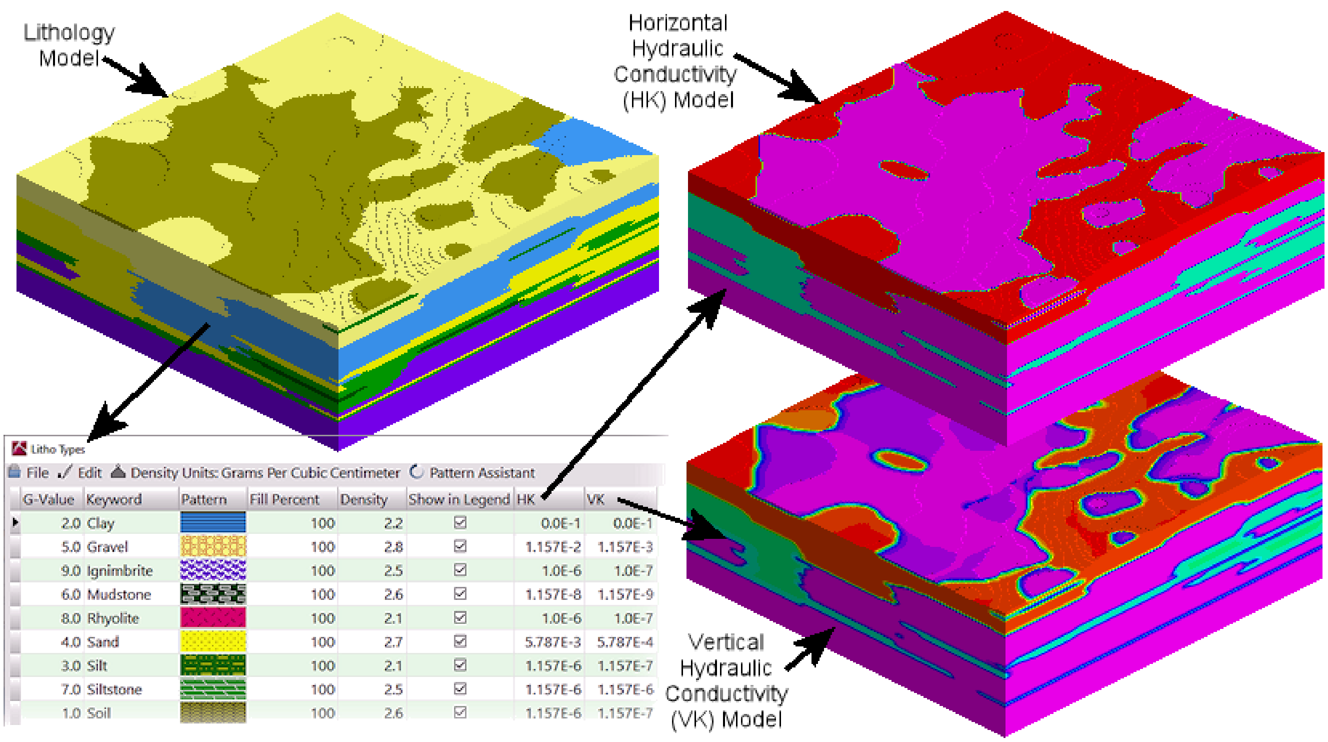


Figure 1

Stratigraphy Model: The specified stratigraphy will be converted to temporary horizontal hydraulic conductivity (HK) and vertical hydraulic conductivity (VK) models by using the HK and VK values within the Strata*Types* table.

Hydraulic Conductivity Models: This option will use, as input, a block model consisting of horizontal hydraulic conductivity values and (as an option) a block model consisting of vertical hydraulic conductivity values. If a vertical block model is not used, the program will consider the model to be isotropic.

Starting Point Coordinates

X & Y: Horizontal coordinates for starting point of flowpath simulation.

Z (Elevation): Vertical coordinate for starting point of flowpath simulation.

Automatic: Flowpath simulation will start at the highest, non-null voxel that corresponds to the XY starting point coordinates.

Grid Z: Flowpath simulation will start at the z-value within a specified grid model (Figure 2) that corresponds with the XY starting points coordinates. The intent here is to allow the user to start the simulation at the top of an aquifer.

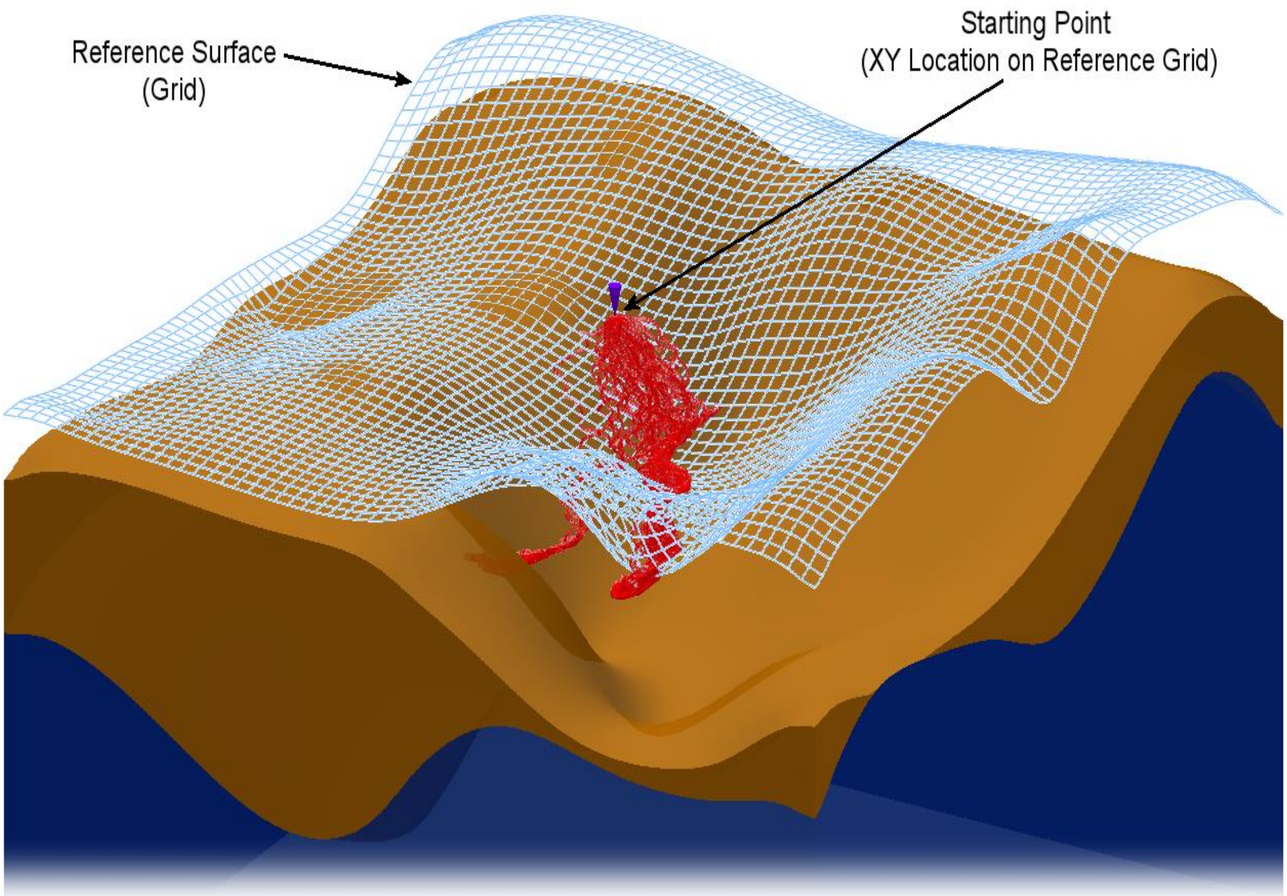


Figure 2

Other: Use this option to start the flowpath simulation at any location within the input model(s).

Simulations: Defines the number of stochastic simulations to run (Figure 3). The "most probable" flowpath (described below) is based on the all of the stochastic simulations. Consequently, larger numbers of simulations can be used to increase the confidence in the results.

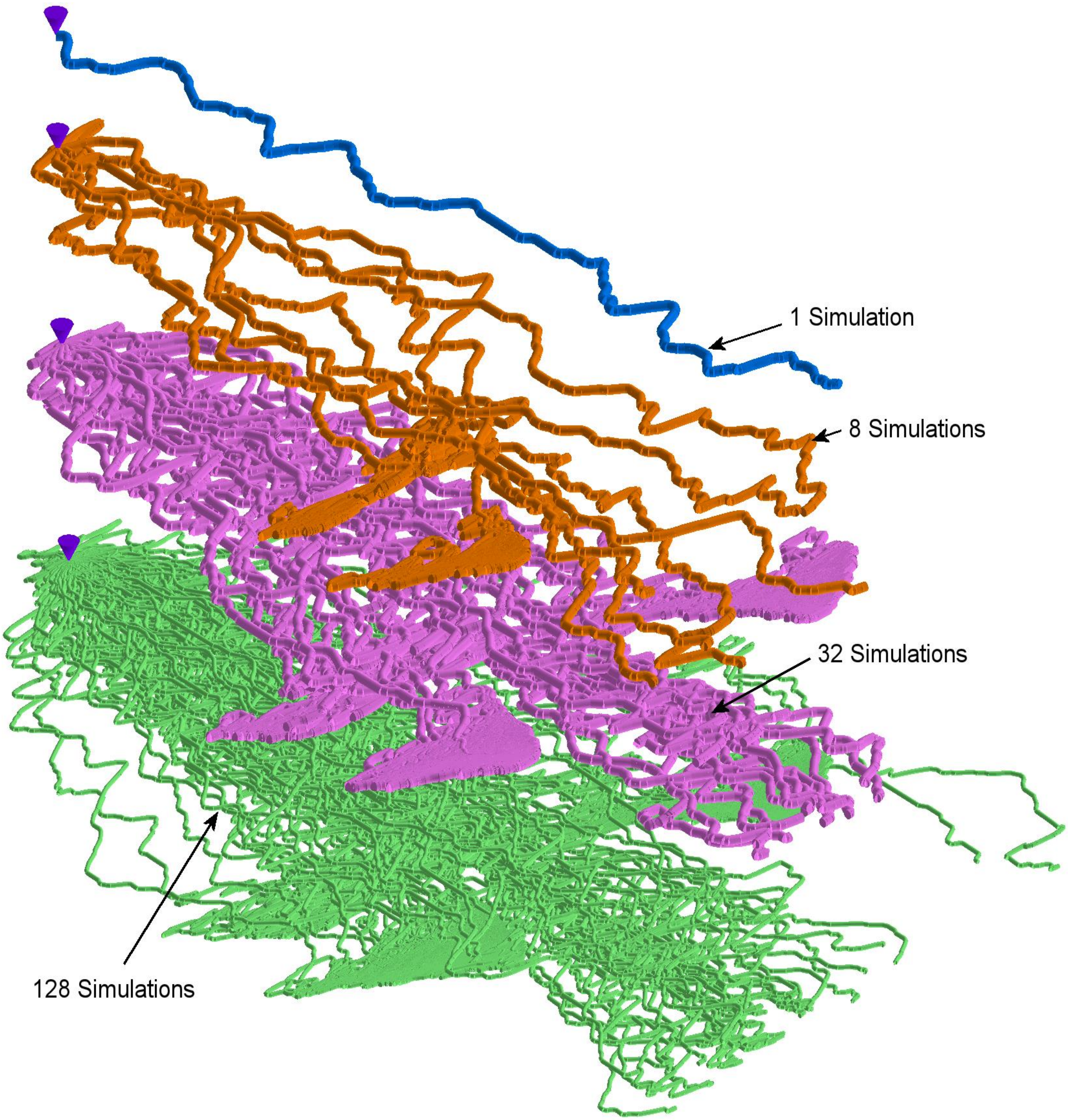


Figure 3

Maximum Points Per Simulation: Represents the upper limit on the number of points or vertices that can be created in a single flowpath. Each point represents a position in 3D space that the flow follows, based on the computed gradients and random perturbations. This variable acts as a safeguard to avoid endless flowpaths in cases where the algorithm may fail to reach a valid termination condition, such as reaching an impermeable zone or the boundaries of the model.

Smoothing: Number of smoothing passes to subject each flowpath path to in order to "de-kink" their appearance (Figure 4). The smoothing filtering algorithm is essentially a three-dimensional moving average.

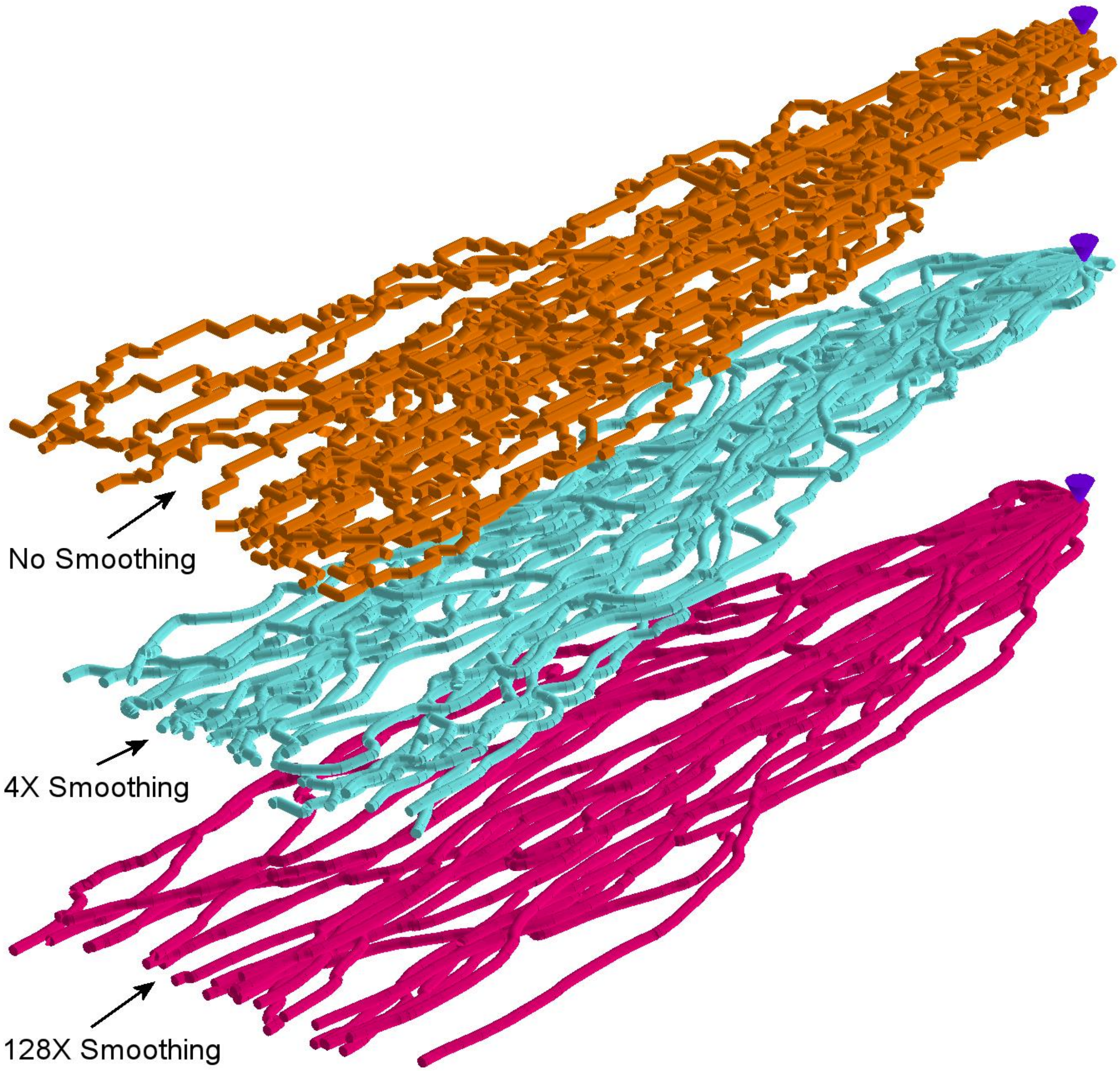


Figure 4

Variability: This setting determines the "Stochastic Strength" which refers to the degree of randomness or perturbation introduced into a system or model to simulate natural variations or uncertainties in its behavior. In the context of the flowpath algorithm, it controls how much random fluctuation or deviation is applied to the local flow direction, simulating the natural variability in groundwater flow due to small-scale heterogeneities or uncertainties that are not captured in the deterministic model. In essence, the Variability defines how much the flowpaths can "wander" from their calculated direction, simulating natural variability that arises from real-world imperfections or unknowns in the model. A value of zero will result in no variability (i.e., all of the flowpaths will fall upon the same line), whereas, a value of 1.0 will produced a moderate amount of variability. The flow direction will still generally follow the local and regional gradients, but with enough random deviation to create noticeable differences in the paths across multiple simulations. The randomness will be controlled, so the flowpaths won't stray too far from the intended direction. Higher variability settings will introduce significantly more perturbations leading to a wider range of possible flowpaths, with more pronounced scattering of paths.

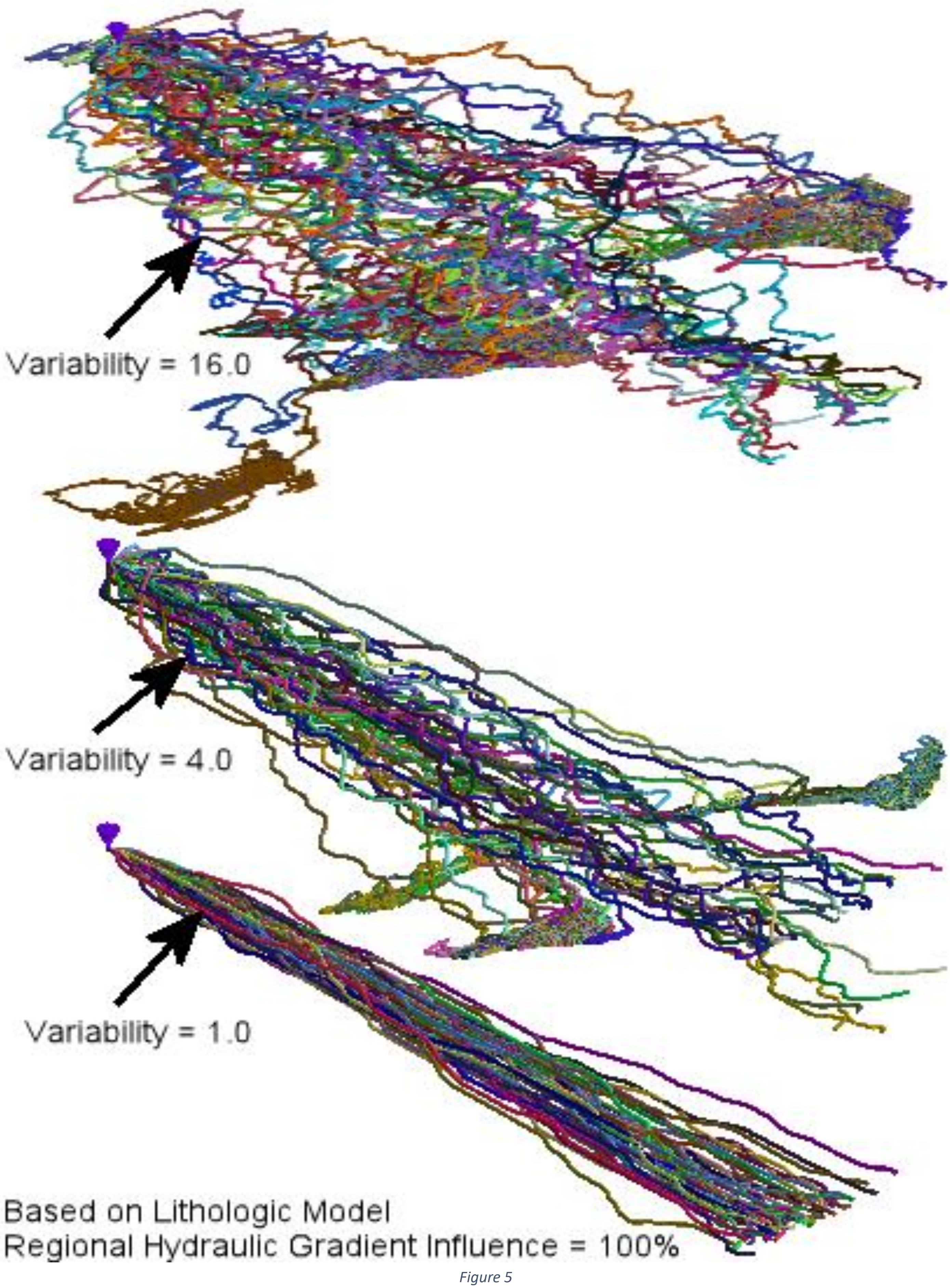

Variability = 16.0
Variability = 4.0
Variability = 1.0
Based on Lithologic Model
Regional Hydraulic Gradient Influence = 100%

Figure 5

Regional Hydraulic Gradient: The *FlowPath* program will blend the regional hydraulic gradient with the local conditions (local HK/VK gradients).

Dip Direction: Azimuth for regional flow direction.

Inclination: Dip or inclination angle of the regional gradient.

Influence: This defines the influence of the regional gradient in pathfinding. A value of zero will result in flowpaths that are controlled only by the HK/VK model values. The flow within homogeneous regions within these models will be determined randomly. Conversely, if the Regional Gradient Influence is set to 100, flowpaths will be determined solely by Regional Gradient. Ideally, a blended approach should be used. For example, if the Regional Gradient Influence is set to 60%, the program will behave as described within the following pseudocode;

1. Start new path & set "*Point*" to Starting Point.
2. Add *Point* to path.
3. If path has extended outside model or maximum number of allowed points within path has been exceeded then terminate path and exit.
4. Compute gradients from *Point* to neighboring HK/VK voxels within same plane or plane immediately below *Point*.
5. If there is one voxel that has a gradient greater than the other candidates, set *Point* to that voxel's midpoint & go to Step 2.
6. If there are multiple neighboring voxels that share the highest-gradient distinction, randomly select voxel from list of voxels with highest gradient & use its three-dimensional direction relative to *Point* to compute a Local Hydraulic Gradient. Set *Point* to location based on blend of Local Hydraulic Gradient (40%) with Regional Hydraulic Gradient (60%) and go to Step 2.
7. If immediately surrounding voxels are equal to the HK/VK voxel at *Point*, set *Point* to the midpoint of a neighboring voxel based on Regional Hydraulic Gradient unless HK/VK for this voxel is impermeable in which case set *Point* to the midpoint of an adjacent, permeable, randomly-chosen voxel and go to Step 2.

Conductivity Model Units

If Lithology or Stratigraphy models are being used as the input, the Conductivity Model Units should correspond to whatever units were used when creating the LithoTypes or StrataTypes tables. Otherwise, the results will be unpredictable.

Otherwise, if separate HK and VK models are being used as input, the units used within these model(s) should be specified within this portion of the menu.

Output Options

Stochastic Flowpaths: Options to adjust the radii, color, and opacity of the quasi-random flowpaths. If the *Stochastic Flowpaths* option is disabled, they will still be generated – just not displayed. This is because they are used to generate the *Most-Probable Flowpath*.

Origin Symbol: If enabled, an inverted cone will be plotted such that it points to the starting point for the flowpath simulations. The radius, height, and color (Figure 6) for the origin cone symbol are adjustable.

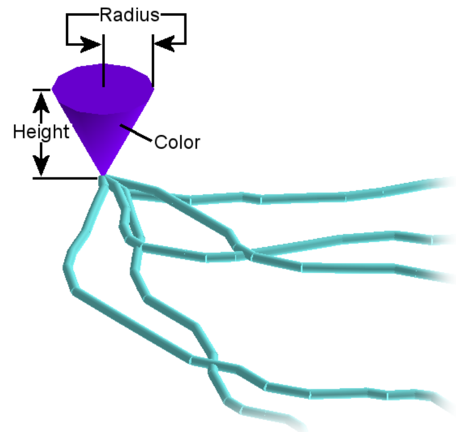


Figure 6

Regional Gradient Vector: If enabled, a vector arrow (Figure 7) will be plotted from the starting point to show the user-specified *Regional Gradient.*

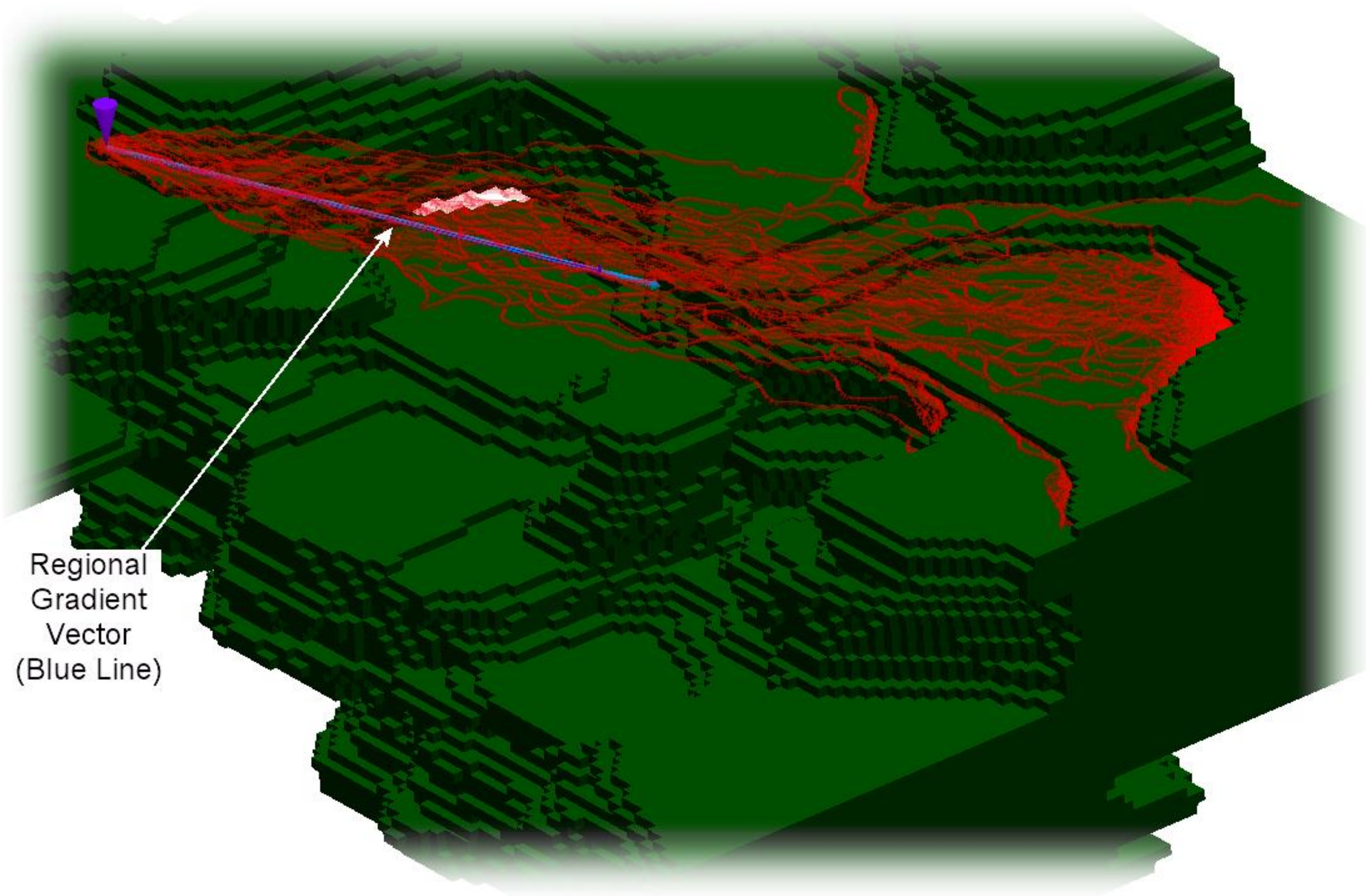


Figure 7

Most-Probable Flowpath: The Most-Probable Flowpath (Figure 8) is determined by averaging the stochastic flowpaths.

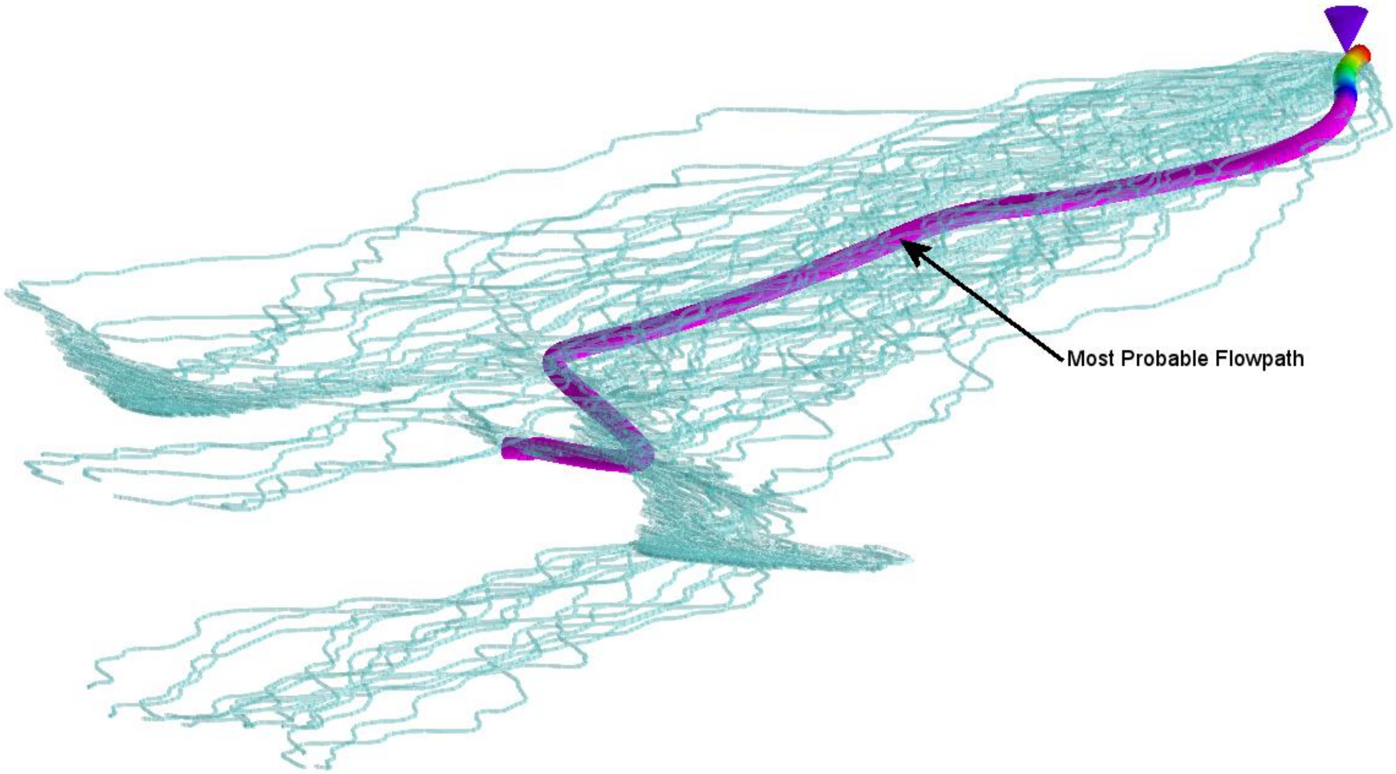


Figure 8

Time Labels: The optional time labels (Figure 9) are determined by computing the distances along the most-probable path and the conductivities of the voxels though which the path passes through.

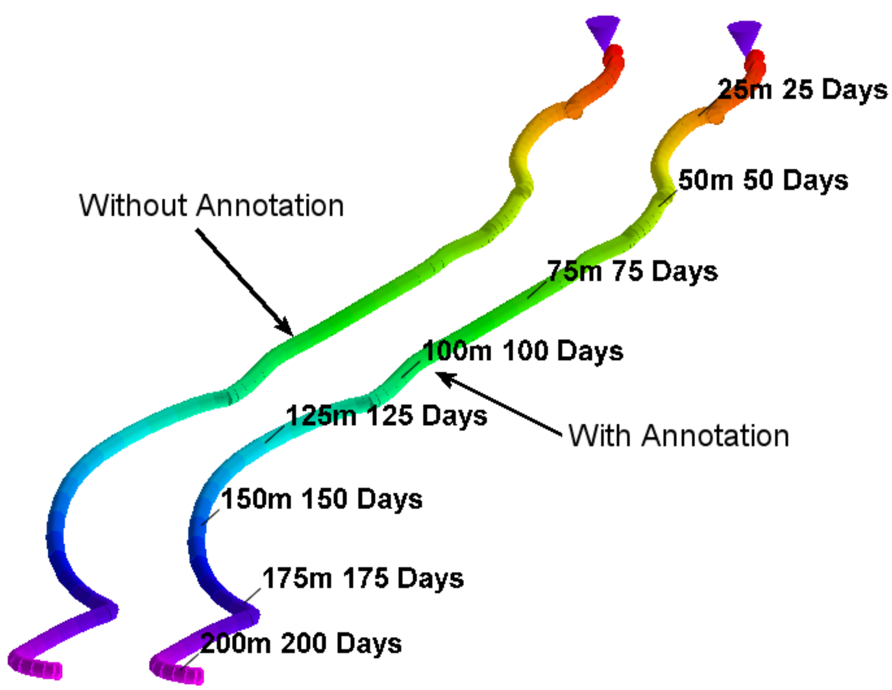


Figure 9

Time Units: The optional *Most-Probable Flowpath* annotation (Figure 10) can use a variety of time units.

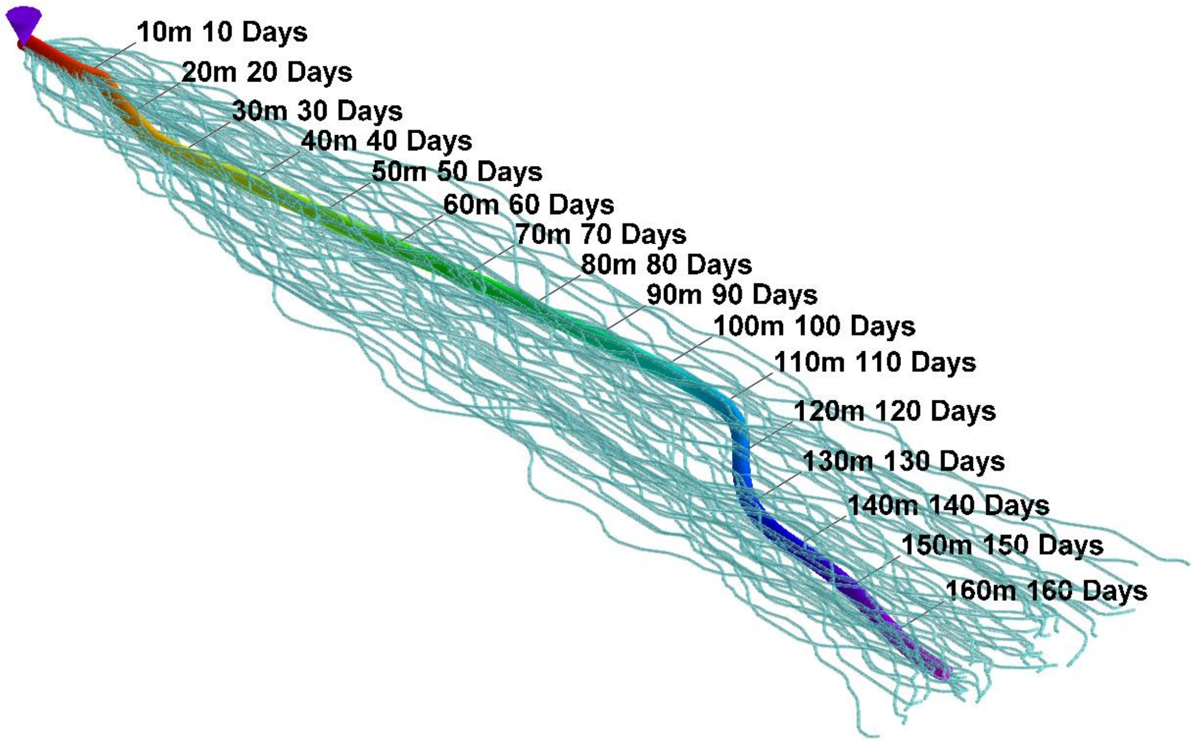


Figure 10

Case-Study

In this example (Figure 11), flowpaths are being blocked by an impermeable clay which is subsequently skirted by the flowpaths.

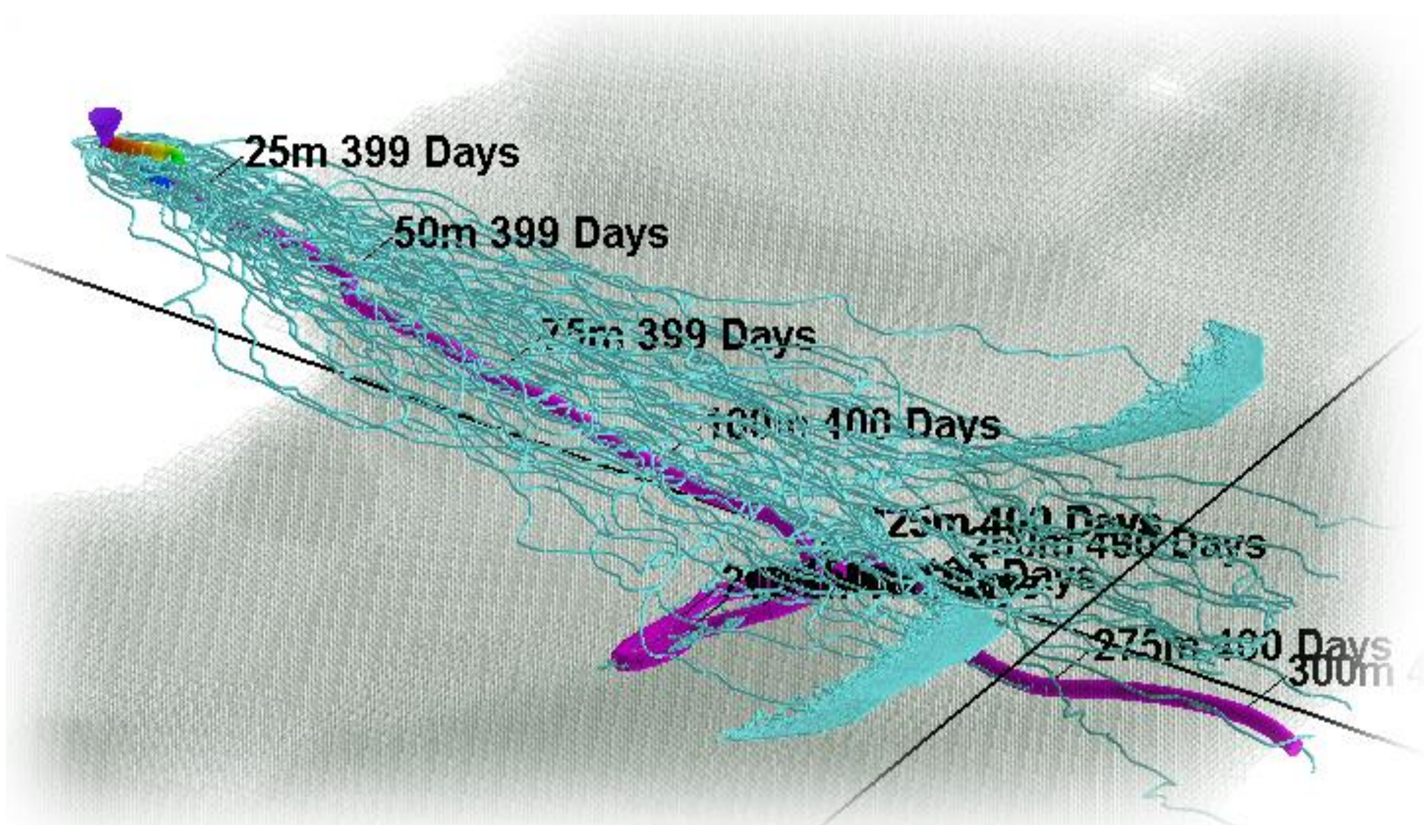


Figure 11