# MDAG.com Internet Case Study 48

# The MDAG Dynamic ARD-Onset Simulator

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## Abstract

When should a minesite component containing potentially net-acid-generating material be declared acidic? Typically, this happens when ARD is detected flowing from the component. ARD flowing from a component can occur, obviously, when most material has become acidic. However, full-scale studies show ARD can still flow out when most material is net acid neutralizing and remains near neutral pH.

To explore and clarify this issue further, a relatively simple spreadsheet-based model was built, called the MDAG Dynamic ARD-Onset Simulator (DAOS). Based on user input in the Input Sheet, the output is shown graphically, with a time step of one week, in the Simulator Sheet. MDAG DAOS is based on the discrete-zone-mixing (DZM) model.

The DZM model of Morin and Hutt (2000) provided yes-no answers on whether ARD would flow from a minesite component at any point in the future. MDAG DAOS improves on the DZM model, by adding the passage of time to estimate a year when ARD would reach the underlying groundwater system and/or the surficial toe drain.

MDAG DAOS simulates the passage of time with visual displays of ARD onset, growth, and migration. ARD onset originates in net-acid-generating (NAG) zones after depletion of any effective Neutralization Potential (NP) in those zones.

When this effective NP is fully consumed, net acidity migrates downgradient (any combination of laterally and vertically), where it begins consuming effective NP in net-acid-neutralizing (NAN) zones. If effective NP in a NAN zone is fully consumed, that NAN cell becomes acidic, and any remaining Acid Potential (AP) releases net acidity to more downgradient cells. In this way, a "chain reaction" arises, which can accelerate the speeds at which the acidic plumes move towards the base or sides of a minesite component.

A trivial example is a single NAG layer at the top of an otherwise NAN waste-rock pile. In this case, strictly downward moving ARD would have to consume all underlying NP. The average Net Potential Ratio (NPR = effective NP/AP) gives a general, but not reliable, indication of whether this could happen. For example, one full-scale case study showed the ARD did not flow downward, but laterally, so that some ARD appeared on the side slope despite the overall NPR-based prediction of no ARD.

A more complicated example is a vertical stack of discrete NAG zones, with each separated vertically by NAN zones. Depending on the local NP:AP balance along the flowpath, ARD can flow from the minesite component despite most of the component remaining net acid neutralizing and near neutral pH. In other words, the component's NPR value (calculated two ways here) is irrelevant to whether ARD will flow out.

This MDAG Case Study contains a description of the DZM and DAOS models, the structure of DAOS, the required input for a DAOS simulation, the approach for running a simulation, and graphical examples of results. These examples include those discussed in the previous paragraphs, as well as others addressing channelling and internal low-permeability layers. Water tables, perched saturated zones, and submerged zones can also be added to a simulation. The MDAG DAOS spreadsheet can be downloaded free, as part of this MDAG Case Study.

# 1. Introduction

When should a minesite component containing potentially net-acid-generating material be declared acidic? Typically, this happens when ARD is detected flowing from the component. ARD flowing from a component can occur, obviously, when most of the material has become acidic. However, full-scale studies show ARD can still flow out when most material is net acid neutralizing and remains near neutral pH. This issue is examined in more detail here.

In 2000, Morin and Hutt (2000) presented a mathematical model for "discrete-zone mixing" (DZM) of distinct, individual masses of net-acid-generating (NAG) material within abundant net-acid-neutralizing (NAN) material. This was primarily developed for waste rock, but it would also apply to tailings where they are not well mixed and blended.

The potential for net acid generation and ARD is typically estimated with the Net Potential Ratio (NPR = Effective Neutralization Potential / Effective Acid Potential = NP/AP) . However, the DZM model showed that the NPR of a full-scale minesite component can be an unreliable indicator of whether any ARD would drain from the component. For example, an average NPR of 300:1 could still release some ARD, compared with NPR = 2:1 typical for small hand samples. This is an example of emergence in minesite drainage, where other factors become dominant as scale increases (e.g., Morin and Hutt, 2007; Morin, 2016a and 2016b).

The DZM model started with the recognition that each discrete zone of NAG material would eventually release a maximum amount of net acidity. To prevent any one internal drainage pathway from being acidic at the exit (outflow), each NAG zone must be separated from other NAG zones and from the discharge points by sufficient intervening NP.

If intervening NAN material has minimal excess NP, then relatively large distances ("L") of intervening NAN material are needed to provide the cumulative excess NP (Figure 1-1). If available NAN rock has high excess NP, then L between NAG zones can be low.

Due various physical and geochemical factors, water can move through a minesite component vertically or laterally, or more commonly with some combination of the two. For example, truck-traffic surfaces and large zones of finer-grained waste rock could cause mostly lateral flow in some portions of a waste-rock pile. Therefore, to be safe, the distances between a NAG zone and all underlying and laterally adjacent NAG zones should be equal to, or greater than, L (Figure 1-1).

If drainage patterns are known to be consistently vertically downwards, then the separation distances of L apply only to the next deeper zone directly beneath. Since this leads to L=0 in a lateral direction, it is synonymous with horizontal layering of NAG and NAN materials.

Based on discrete-zone mixing, Morin and Hutt (2000) found that the minimum allowable distance L between NAG zones can be calculated relatively easily. L basically reflects the local balances of NP to AP. Morin and Hutt (2000) presented an example of DZM modelling by using the input data in Table 1-1.

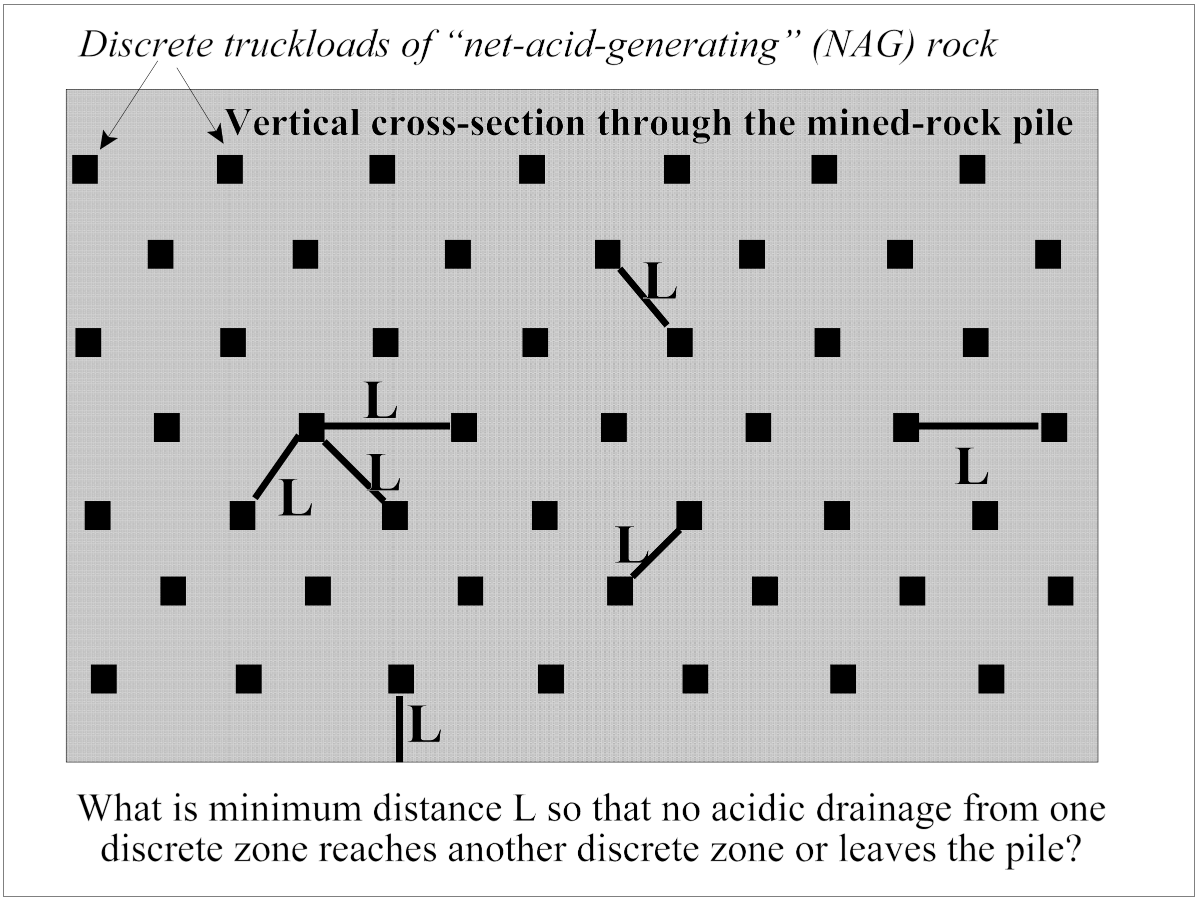


**Figure 1-1. Schematic vertical cross-section through a discrete-zone mine-rock pile, with discrete net-acid-generating (NAG) zones shown as black squares (from Morin and Hutt, 2000).**

**Table 1-1. An example of input parameters for the hypothetical design of a discrete-zone waste-rock dump (from Morin and Hutt, 2000)**

| Variable | Explanation | Selected Value |
|---|---|---|
| ReqNPR | Required site-specific NPR to ensure near-neutral pH indefinitely | 2.0 |
| DefNP | Net deficit of NP in NAG rock below ReqNPR | 141 t/1000 t |
| BDNAG | Bulk density of NAG rock | 1.7 t/$m^3$ |
| ExNP | Net excess of NP in NAN rock above ReqNPR | 31 t/1000 t |
| BDNAN | Bulk density of NAN rock | 1.7 t/$m^3$ |
| WtNAG | Weight of each discrete zone of NAG rock | 100 t |
| $X^2$ | Cross-section area of NAG rock perpendicular to water movement | 15.1 $m^2$ (each NAG zone assumed to be a cube) |
| CH | Channelling factor, indicating the proportion of the NAN rock and its NP in contact with acidic drainage | 0.1 |

The applicable equation for calculating the separating distance (L, Figure 1-1) between the discrete NAG zones was:

$$L = [DefNP * WtNAG * ReqNPR] / [ExNP * X^2 * BDNAN * CH] \quad (1)$$

For the example in Table 1-1, L was calculated as:

$$L = [141 \text{ t}/1000 \text{ t} * 100 \text{ t} * 2.0] / [31 \text{ t}/1000 \text{ t} * 15.1 \text{ m}^2 * 1.7 \text{ t/m}^3 * 0.1] \quad (2a)$$

$$L = 354 \text{ m} \quad (2b)$$

L is large in this example. The height of the pile would have to be at least 358 m (354 + 3.9 m) just so that one horizontal plane of NAG material could be placed at the top to safely ensure that no acidic drainage would reach the bottom. Obviously, the construction of such a high rock pile would be impossible at most minesites.

Nevertheless, this example makes an important point, because the selected parameters are not unusual. The deficit of NP in NAG rock would have to be cut from 141 to less than a negligible 6 t/1000 t before more than one horizontal plane could be placed in a 30-meter-high dump. This corresponds to an NPR of 1.94, which is very close to ReqNPR = 2.0 to change a NAG zone into a NAN zone.

All this shows that discrete-zone mixing, as well as layering and blending, of a significant volume of NAG rock cannot normally be carried out with a high probability of success and a low risk of ARD. This is consistent with the general lack of detailed full-scale case studies characterizing successful mixing and layering. Put simply, the characteristics and volumes of NAG and NAN rock at many sulphide-bearing minesites are apparently not suitable for safe discrete-zone mixing. Morin and Hutt (2000) showed this could even be the case using nearly pure limestone as NAN material.

Where discrete NAG zones are separated by less than L, a “chain reaction” of accumulating net acidity arises along the flowpath. As a result, NP farther downgradient would be consumed earlier and faster by hydraulically connected upgradient NAG zones. However, Morin and Hutt (2000) did not place the DZM model in a temporal context. Thus, there was no consideration of the gradual development and growth of acidic flowpaths with passing time, only a yes-no final answer.

To resolve the missing feature of time, this case study on the MDAG Dynamic ARD-Onset Simulator looks at the DZM model in a temporal context. The objective of this MDAG Case Study is to keep the calculations relatively simple, like Equation 1, but add the passage of time with visual displays of ARD onset, growth, and migration. Microsoft Excel was chosen as the application within which to do this.

## 2. Details and Input Requirements of the MDAG Dynamic ARD-Onset Simulator (DAOS)

The objective of this MDAG Case Study is to simulate, through time, the appearance of ARD in discrete-zone mixing (DZM) discussed in Chapter 1 (e.g., Figure 1-1). This is done through visual displays of ARD onset, growth, and migration, using consecutive time stepping within an Excel spreadsheet. The resulting model is called the MDAG Dynamic ARD-Onset Simulator (DAOS).

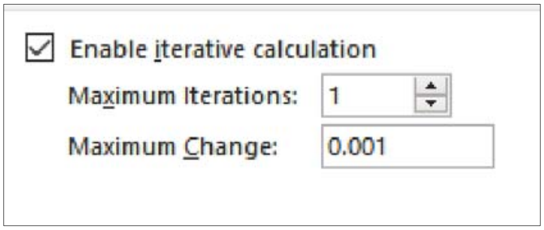
MDAG DAOS begins with a vertical cross-section through a minesite component. For Version 1.0, DAOS divides the vertical cross-section in a grid of 40 cells laterally by 20 cells vertically. Because simulations are based on unit weight, the cells can be viewed as any consistent size, but are nominally called 1 m by 1 m by 1 m. Cell size can increase up to the size of discrete NAG zones within a minesite component. If a NAG zone reflected a truckload of 200 tonnes, for example, all cell sizes would be enlarged up to 100 m$^3$ based on a bulk density of 2.0. In this case, each cell size as a cube would increase to about 4.6 m by 4.6 m by 4.6 m.

DAOS contains two sheets, Input and Simulator, which are actively linked. These are described in detail in the following subsections.

### 2.1 "Input" Sheet

Obviously, the "Input" Sheet in MDAG DAOS is where users enter input data for a particular simulation.

Before the input, it is important to ensure Excel allows iterations in MDAG DAOS. After opening DAOS, go to File|Options|Formulas, and ensure "Enable iterative calculation" is checked with a Maximum Iteration of 1 (Figure 2-1).



☑ Enable iterative calculation

Maximum Iterations: 1

Maximum Change: 0.001

**Figure 2-1. Important settings for using MDAG DAOS, found under File|Options|Formulas.**

After providing a unique name for the simulation, the Acid-Base Accounting (ABA), and the kinetic rates of acidity generation and of NP consumption, are entered, for both net-acid-generating (NAG) and net-acid-neutralizing (NAN) materials (Table 2-1).

Then, information is entered for any non-oxidizing cells in the event they are fully saturated, submerged, or flooded (Table 2-1). This is followed by input on the vertical and lateral movement of water and acidity. For both these inputs, on non-oxidizing cells and water/acidity migration, data are entered into 40x20 input grids, discussed next.

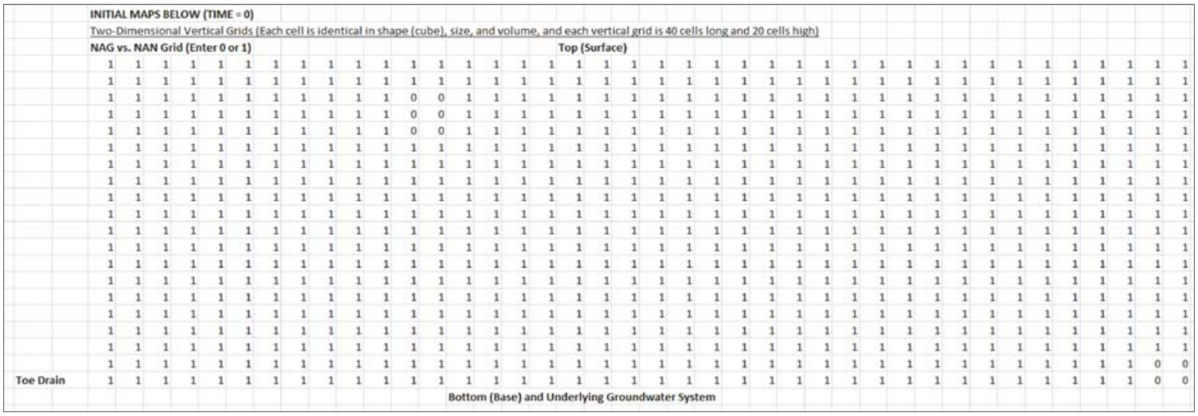
There are five input grids that must be filled (Table 2-1): NAG vs. NAN Grid, NP Grid, AP Grid, Non-Oxidizing Grid, and Vertical-Downward-Flow-Proportion Grid. The first grid, NAG vs. NAN Grid (e.g., Figure 2-2), requires users to specify whether a cell, row, or column is net acid generating (=0) or net acid neutralizing (=1). Based on this first grid and ABA-input values, the second and third grids are filled by DAOS. Nevertheless, any cell, row, or column can be overridden by entering another value in these grids.

## Table 2-1. Input information for running the MDAG Dynamic ARD-Onset Simulator (DAOS)

| Parameter or Grid | Details and Data Entry |
|---|---|
| Name of This Simulation | entered manually by user |
| *For both net-acid-generating (NAG) and net-acid-neutralizing (NAN) materials* | |
| Effective Neutralization Potential (NP, wt-ppt CaCO3 such as t CaCO3/1000 t) | entered manually by user |
| Equivalent Pyrite Content (%S) | entered manually by user |
| Acid Potential (AP, wt-ppt CaCO3 such as t CaCO3/1000 t) | calculated by DAOS, based on the previous parameter |
| Effective Net Potential Ratio | calculated by DAOS, based on the previous three parameters |
| Rate of Acidity Generation for NAG/NAN Rock (mg CaCO3/kg/wk) | entered manually by user |
| Ratio of Rate of NP Consumption / Rate of Acid Generation (NPR Criterion) | entered manually by user |
| Rate of NP Consumption for NAG/NAN Rock (mg CaCO3/kg/wk) | calculated by DAOS, based on the previous two parameters |
| Channelling Ratio of (% of net acidity transported downgradient) to: (% of downgradient NP exposed to this migrating acidity)[1] | entered manually by user (any value greater or less than 1.0; default = 1.0) |
| Adjusted Rate of Acidity Release for NAG/NAN Rock When Acidic (mg CaCO3/kg/wk) | calculated by DAOS, based on previous parameter multiplied by Rate of Acidity Generation, or entered manually by user |
| Internal acidity generated by NAG/NAN rock decreases its Effective NP until zero | note to user |
| Effective NP in NAG/NAN rock is consumed first by internal acid generation and second by any inflowing acidity | note to user |
| *Fully Saturated, Submerged, or Flooded Cell* | |
| These cells will be simulated by setting the cell's AP (Acid Potential) to zero | note to user |
| These cells are still open to acidity migration vertically and/or laterally | note to user |
| Saturated, Non-Oxidizing Cell (=0) | entered manually by user in the Non-Oxidizing Grid (see below) |
| Oxidizing Cell (=1) | entered manually by user in the Non-Oxidizing Grid (see below) |
| % of Cells Specified Here as Non-Oxidizing | calculated by DAOS, based on the Non-Oxidizing Grid (see below) |

| Parameter or Grid | Details and Data Entry |
|---|---|
| *Vertical and Lateral Movement of Water and Acidity* | |
| Proportion of Acidity Release Moving Downward | entered manually by user in the Vertical-Downward-Flow-Proportion Grid (see below), ≤ 1.0 |
| Proportion of Acidity Release Moving Left | calculated by DAOS, 1.0 minus previous parameter |
| *Input Grids (40 cells long by 20 cells high)* | |
| NAG vs. NAN Grid | enter 0 for NAG or 1 for NAN |
| NP Grid | calculated by DAOS, based on input data and the previous grid, or manually overridden by cell, row, or column |
| AP Grid | calculated by DAOS, or manually overridden by cell, row, or column |
| Non-Oxidizing Grid | specified by DAOS as 1, or manually overridden by cell, row, or column; 0 = saturated, non-oxidizing cell, 1 = oxidizing cell |
| Vertical-Downward-Flow-Proportion Grid | calculated by DAOS based on input, or manually overridden by cell, row, or column; 1 = vertical-downward flow only, 0 = lateral flow to the left only, 0.8 = 80% vertical flow and 20% lateral flow to the left, etc. |
| *Calculated Net Potential Ratios* | |
| [SUM(NP/AP)] by Cell | calculated by DAOS, based on input data and grids |
| [SUM(NP) for All Cells]/[SUM(AP) for All Cells] | calculated by DAOS, based on input data and grids |
| % of Cells Specified as Net Acid Generating | calculated by DAOS, based on NAG vs. NAN Grid |

[1] This “channelling” factor represents many physical and geochemical factors that result in less than 100% of particle surfaces in a cell being rinsed regular by infiltration; simplistically it can be thought of as the percentage of surfaces rinsed regularly in NAG materials divided by the percentages of surfaces rinsed regularly in downgradient NAN material; this is discussed further in Section 3.1.



INITIAL MAPS BELOW (TIME = 0)

Two-Dimensional Vertical Grids (Each cell is identical in shape (cube), size, and volume, and each vertical grid is 40 cells long and 20 cells high)

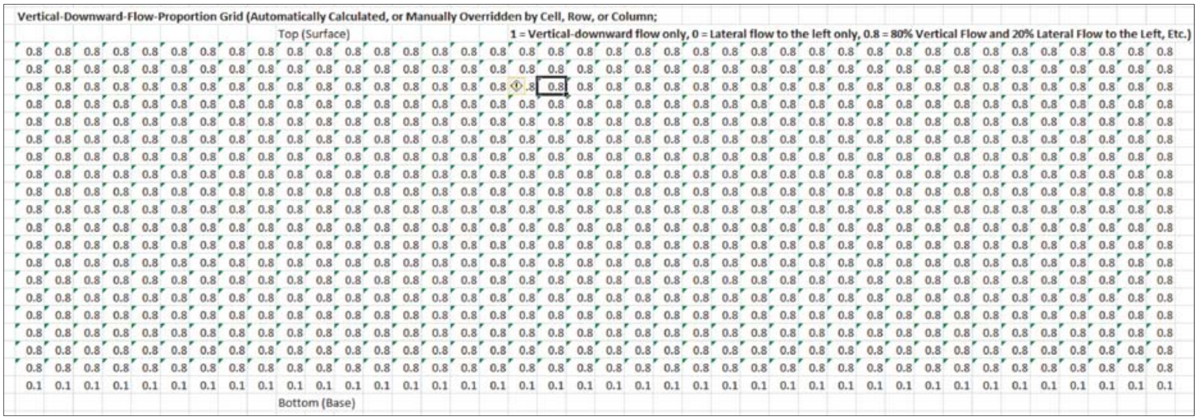
NAG vs. NAN Grid (Enter 0 or 1)

Top (Surface)

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| Toe Drain | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |

Bottom (Base) and Underlying Groundwater System

**Figure 2-2. A completed example of the first input grid, the NAG vs. NAN Grid, where 0 represents a NAG cell and 1 represents a NAN cell..**



Vertical-Downward-Flow-Proportion Grid (Automatically Calculated, or Manually Overridden by Cell, Row, or Column;

Top (Surface)

1 = Vertical-downward flow only, 0 = Lateral flow to the left only, 0.8 = 80% Vertical Flow and 20% Lateral Flow to the Left, Etc.)

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | .8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

Bottom (Base)

**Figure 2-3. A completed example of the fifth grid, the Vertical-Downward-Flow-Proportion Grid, with values of 0.8 indicating 80% of water and any net acidity moves downward from that cell and 20% moves to the left; the bottom row reflects relatively impermeable ground and thus 90% of flow and any net acidity moves towards the left and the Toe Drain.**

The fourth grid, Non-Oxidizing Grid, requires users to specify whether a cell, row, or column is non-oxidizing (=0) or oxidizing and thus generating internal acidity by sulphide oxidation (=1). DAOS initially specifies all cells as oxidizing, but this can be overridden by cell, row, or column.

The fifth and last grid, Vertical-Downward-Flow-Proportion Grid, determines the movement of any net acidity from an acidic cell to the next cell. When this happens, ongoing acidity migration could make the adjacent cells become acidic, and then the oxidation of their remaining sulphide adds to the net acidity passed to the next adjacent cells. This is the "chain reaction" discussed in Chapter 1 above.

Based on user-entered data, DAOS fills this fifth grid with the single, entered input value. This value is the proportion of flow and net acidity moving downward (between zero and one), with the remainder flowing laterally to the left (e.g., Figure 2-3). Nevertheless, as with all other input grids, this can be overridden by cell, row, or column. For example, in Figure 2-3, the underlying ground beneath the vertical cross-section was relatively impermeable. Thus, values in the lowest row cause

90% of water and any net acidity to move to the left, while only 10% moves downward into the underlying groundwater system. Following the same approach, a low-permeability layer (row) can be created higher in the grid (the minesite component), as illustrated in Section 3.2.

## 2.2 "Simulator" Sheet

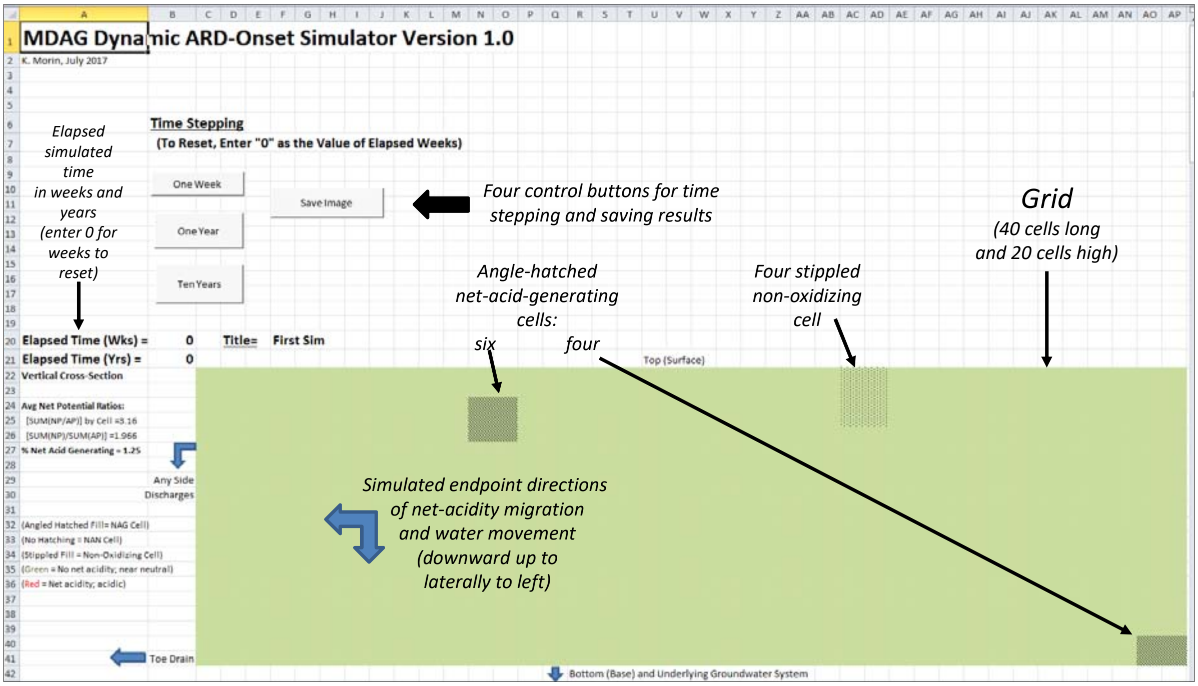
The Simulator Sheet animates the vertical and lateral migration of any net acidity through time, based on information entered on the Input Sheet and its input grids (Section 2.1). MDAG DAOS uses a time step of one week, and this cannot be changed.

*Security Alert - Macros.* To accelerate and ease time stepping in simulations, four "buttons" appear on the sheet: One Week (to advance the simulation by one week), One Year, Ten Years, and Save Image (Figure 2-4). Each button executes a macro, as explained in Appendix A. If you have security concerns over running macros, you can run MDAG DAOS manually, but as explained in Appendix A this would be a slow process, week by week by week, 52 times just for one year.

Although there are many grids lower down on the Simulator Sheet, these should not be altered as they contain weekly calculations and updates to ongoing simulations. Only the uppermost 42 rows are important for results and output (Figure 2-4).

## 2.3 Running a Simulation

After all input information is entered on the Input Sheet, a simulation starts by ensuring 0 (zero) is entered for Elapsed Time (Wks) in the Simulator Sheet (Figure 2-4). The simulation then proceeds week by week (e.g., Figures 2-5 to 2-8). At any pause in the simulation, pressing the Save Image


MDAG Dynamic ARD-Onset Simulator Version 1.0
K. Morin, July 2017

Time Stepping
(To Reset, Enter "0" as the Value of Elapsed Weeks)

Elapsed Time (Wks) = 0 Title= First Sim
Elapsed Time (Yrs) = 0
Vertical Cross-Section

Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =3.16
[SUM(NP)/SUM(AP)] =1.966
% Net Acid Generating = 1.25

(Angled Hatched Fill= NAG Cell)
(No Hatching = NAN Cell)
(Stippled Fill = Non-Oxidizing Cell)
(Green = No net acidity; near neutral)
(Red = Net acidity; acidic)

**Figure 2-4. A view of the important portion of the Simulation Sheet, showing examples of various input conditions and the control buttons to run a simulation.**

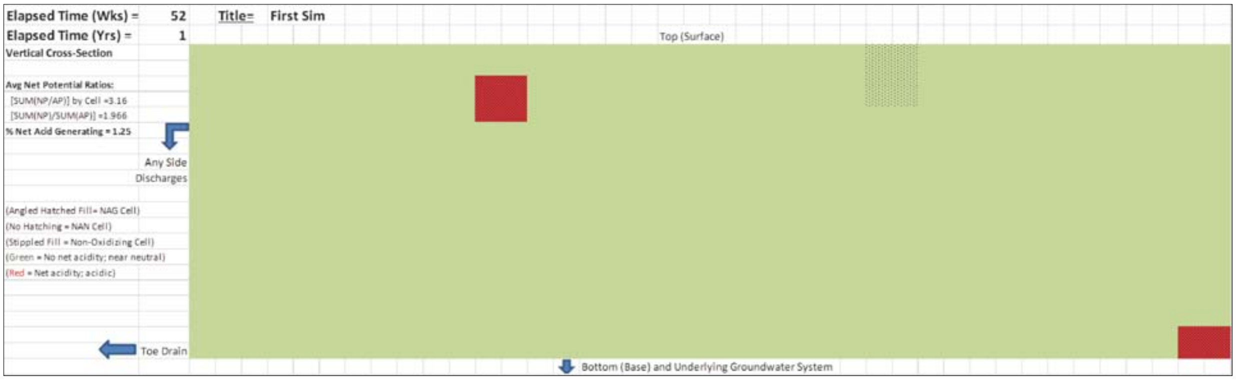
button will save the graphical result as a PNG file, in the folder containing the DAOS spreadsheet, using the simulation name and week number in the file name. Note: previous PNG files with the exact same file name will be automatically replaced without warning.

As shown in Figure 2-5, the NAG cells have become acidic (red-filled cells) within a year, which is eventually expected of NAG material, and the NAN cells have remained near neutral (green-filled cells). After five years (Figure 2-6), the acidic NAG cells have generated and released sufficient net acidity that NP in adjacent underlying NAN cells has been consumed and they too have become acidic. These now-acidic NAN cells, if still containing any AP, become net acid generating themselves, releasing additional acidity to adjacent cells.

After 15 years (Figure 2-7), the acidic plumes moving downward and laterally to the left have grown larger. By Year 60 (Figure 2-8), the downward and basal lateral acidic plumes have merged, and accelerated their rate of movement towards the effluent exit at the toe drain to the left.

If/when the basal acidic plume reaches the toe drain, the minesite component would be declared "acidic" and releasing ARD, but only after many decades, perhaps after the minesite closed. This declaration would be made, despite most cells still being near neutral, and despite several cells releasing ARD within a few years. Such a scenario can explain the distributions of thousands of near-neutral and acidic rinse pHs in a full-scale waste-rock pile releasing ARD, discussed in MDAG Case Study 47 (Morin, 2017). However, this is notably different from full-scale case studies where NP remained present, but was unreactive, due to processes like secondary-mineral encapsulation, as discussed in MDAG Case Study 31 (e.g., Morin and Hutt, 2008).

Furthermore, this scenario depicted in Figures 2-5 to 2-8 is generally consistent with various geochemical and monitoring "zones", in which flowpaths with variable solid-phase and aqueous chemistries are homogenized downgradient as flowpaths merge (Figure 2-9). Figure 2-9 depicts a more detailed and realistic scenario for minesite components (Morin and Hutt, 2007; Morin, 2015), but the MDAG Dynamic ARD-Onset Simulator remains relatively simple to illustrate general findings about ARD onset and internal migration.



Elapsed Time (Wks) = 52
Title= First Sim
Elapsed Time (Yrs) = 1
Vertical Cross-Section

Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =3.16
[SUM(NP)/SUM(AP)] =1.966
% Net Acid Generating = 1.25

(Angled Hatched Fill= NAG Cell)
(No Hatching = NAN Cell)
(Stippled Fill = Non-Oxidizing Cell)
(Green = No net acidity; near neutral)
(Red = Net acidity; acidic)

**Figure 2-5. In this example, the originally near-neutral NAG cells (Figure 2-4) have become acidic within a year; because the lower right cells are now acidic, some ARD has entered the underlying groundwater system.**

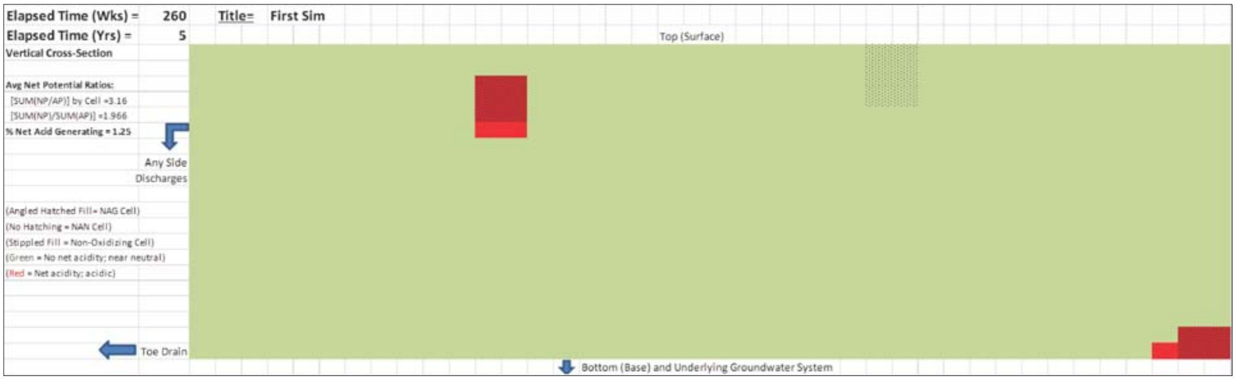


**Figure 2-6. After five years, the acidic NAG cells have generated and released sufficient net acidity that NP in adjacent NAN cells has been consumed and they too have become acidic; these NAN cells, if any AP is left, become net acid generating themselves, and release additional acidity to adjacent cells.**

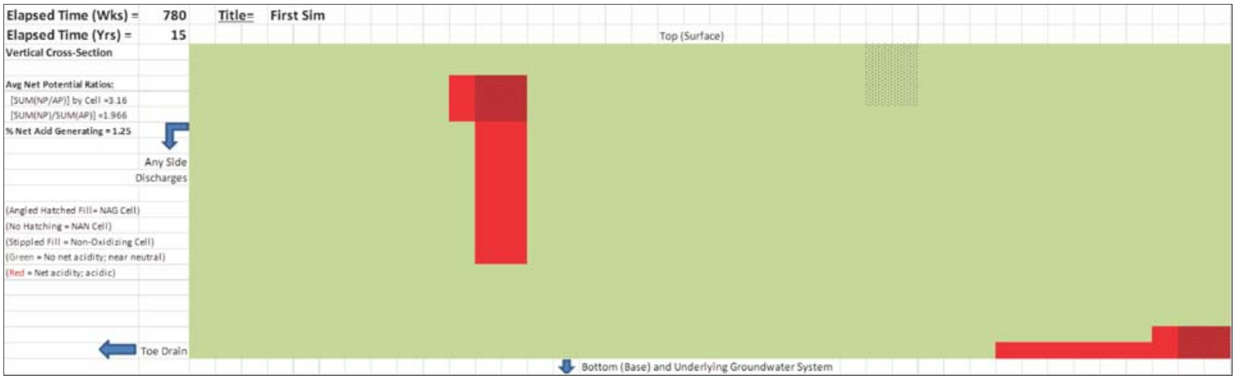


**Figure 2-7. After 15 years, the acidic plumes moving downward and laterally to the left grow larger.**

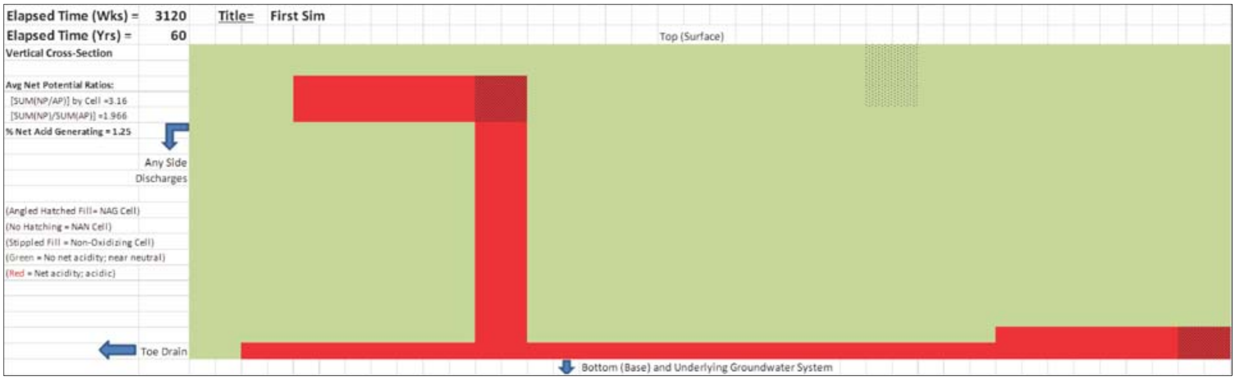


**Figure 2-8. After 60 years, the basal acidic plume has merged with the wider, vertical acidic plume, has reached the underlying groundwater system long ago, and has almost reached the toe drain to the left; another acidic plume higher in the minesite component is approaching the side slope.**

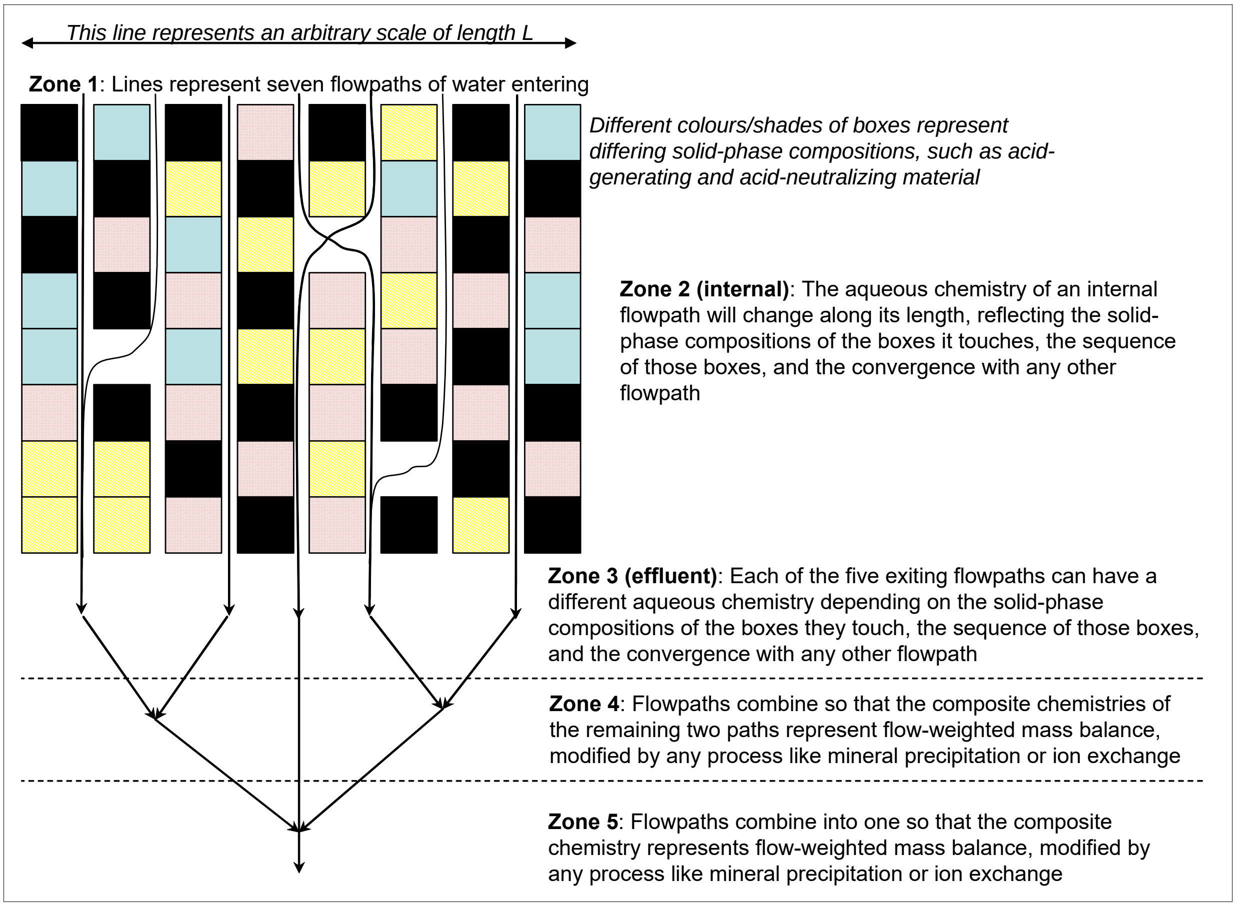


**Figure 2-9. Schematic diagram of adjoining blocks of differing geochemical composition, with flowpaths for water and air, showing Zones 4 and 5 as becoming spatially homogenized and thus not spatially discrete (from Morin and Hutt, 2007, and Morin, 2016 ).**

# 3. Examples and Observations on ARD Onset and Internal Migration, Using the MDAG Dynamic ARD-Onset Simulator (DAOS)

As explained in Chapter 1, Morin and Hutt (2000) created a simplified mathematical model for discrete-zone mixing (DZM) based on values of NP and AP from ABA, leading to a value for "L". L is the minimum required distance between any two, hydraulically connected, zones of net-acid-generating (NAG) material so that ARD does not migrate downgradient from one NAG zone to the next NAG zone.

If L is not maintained, there is a "chain reaction" of accumulating and migrating acidity that can eventually cause ARD to exit the minesite component into underlying groundwater systems and/or lateral surface drainages. An example was discussed in Section 2.3, which showed that defining the release of ARD based on monitoring outside a minesite component (Zones 3 to 5 in Figure 2-9) can miss the important facts such as:
(1) ARD may be migrating through a component for decades before the outflow becomes acidic, and
(2) outflow of ARD can happen despite most material remaining near neutral.

This chapter looks at additional examples that lead to interesting observations.

## 3.1 The Original Discrete-Zone-Mixing Model, the DAOS Channelling Factor, and Horizontal Rows of NAG Cells

As discussed in Chapter 1, the original, simple DZM model was based on net excess of NP in NAN material and net deficit of NP in NAG material (Table 1-1), to provide a yes-no answer on whether ARD could flow from a minesite component. To place this into a temporal model, the MDAG Dynamic ARD-Onset Simulator (DAOS) expanded the required input (Table 2-1). For example, the net deficit of NP in NAG material is now calculated in DAOS based on user-entered values of effective NP and sulphur.

On the other hand, MDAG DAOS reduced some input. For example, bulk density and weights of individual zones are no longer needed, because calculations are made on a unit-weight basis. This means that grid cells discussed in Chapter 2 can be any consistent size, are nominally considered 1 m by 1 m by 1 m, and can be enlarged up to the size of discrete NAG zones in a minesite component.

To simulate the original DZM example with DAOS, NAG material has %S = 3 and effective NP = 47 t/1000 t, and NAN material has 1%S and effective NP = 94 t/1000 t.

The rate of NP consumption is twice that of acidity generation for this example. However, no rates were originally specified, because that approach was time independent and provide end-of-time yes-no predictions. For MDAG DAOS, any rate can be specified: the faster the rate, the faster the ARD will spread through the grid. Therefore, to speed up the simulations, but not change the final outcome, acidity-generation rates for NAG and NAN material were taken as relatively fast rates of 1000 mg CaCO3/kg/wk and a slow rate of 100 mg/kg/wk, respectively, based on data in the International Kinetic Database[1].

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[1] http://www.mdag.com/ikd.html

The channelling factor in the DZM model (CH, Table 1-1) was 0.1 for the original example. In MDAG DAOS, this is replaced by the Channelling Ratio (Table 2-1) representing the ratio of (% of net acidity transported downgradient) to: (% of downgradient NP exposed to this migrating acidity). Simplistically, it can be thought of as the percentage of surfaces rinsed regularly in NAG materials divided by the percentages of surfaces rinsed regularly in downgradient NAN material. It is essentially the reciprocal of CH (Channelling Ratio = 1/CH). Because NAG materials can oxidize and break apart quickly compared with NAN materials, the value of the Channelling Ratio should often be ≥ 1.0, but values less than 1.0 are possible.

A value of 1.0 for the DAOS Channelling Ratio means that the percentage of net acidity transported from a cell upon becoming acidic is equal to the percentage of downgradient NP encountering this migrating acidity (not absolute amounts, but percentages of input values). A value of 10, as used in the original DZM example means that 100% of net acidity encounters only 10% of downgradient acidity, allowing the acidic plume to migrate faster. Put another way, a value greater than 1.0 “hides” some downgradient NP from the migrating acidity, whereas a value less than 1.0 “hides” some acid generation from the downgradient NP.

This MDAG DAOS simulation, using the original DZM approach, considers a horizontal NAG layer across the entire length of the grid, one row down from the top. All cells can oxidize, and all water and acidity migration is 95% downward until the bottom row where 95% moves to the left.

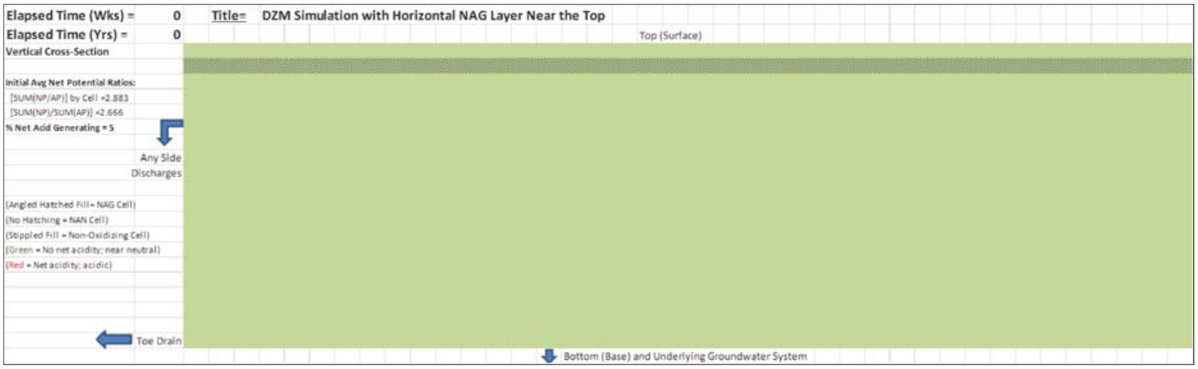
With the original Channelling Ratio of 10, the high-up NAG row and all NAN rows to the bottom become acidic in about 3 years (Figure 3-1 and 3-2), accompanied by ARD outflow into the underlying groundwater system and the toe drain. In fact, any Channelling Ratio greater than about 4 with this dataset will lead to ARD outflow.

With a Channelling Ratio of 1.0 instead of 4-10, the NAG row still quickly becomes acidic. However, now the NAN cells take much longer to become acidic due to more available downgradient NP. In fact, the acidic plume only moves downwards one row until virtually all AP is consumed (Figure 3-3). As a result, no ARD reaches the basal exit points (but side discharges are possible) with a Ratio less than about 4 for this dataset. However, this is only because the NAG layer is near the top, with abundant intervening NP.

If the NAG layer is placed near the bottom (Figure 3-4), there is ARD outflow even with a Channelling Ratio of 1.0 (Figure 3-5). This occurred despite the average NPR values of 2.7-2.9 for this grid.

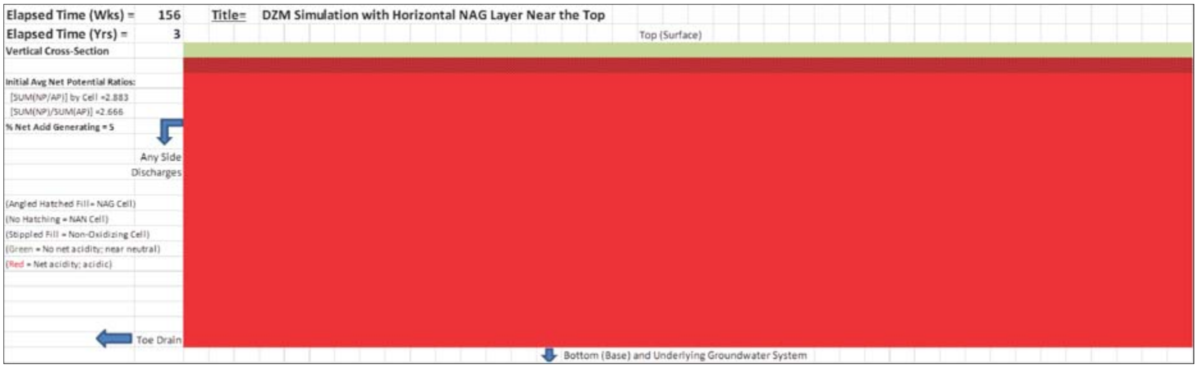
## 3.2 Partial Low-Permeability Layers

Values in the Vertical-Downward-Flow-Proportion Grid can be adjusted close to zero to create a low-permeability (low-K) layer that extends across part of the profile. A low-K layer placed in the right half of the grid, just beneath the NAG layer, slows slightly the downward migration of ARD on the left side (Figure 3-6). The overlying NAG layer releases sufficient acidity, even if proportionally minor, to turn this layer and underlying cells acidic relatively quickly.



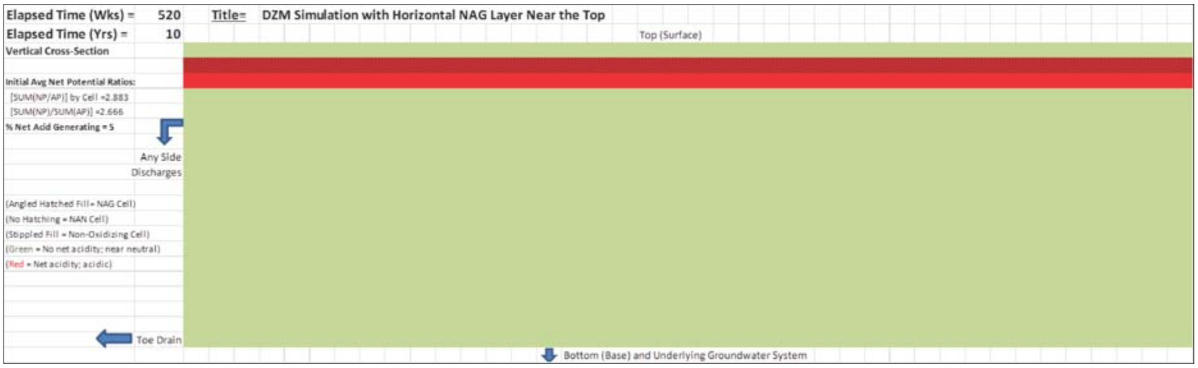
Elapsed Time (Wks) = 0
Elapsed Time (Yrs) = 0
Title= DZM Simulation with Horizontal NAG Layer Near the Top
Initial Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =2.883
[SUM(NP)/SUM(AP)] =2.666
% Net Acid Generating = 5

**Figure 3-1. Simulation of a high, laterally continuous NAG layer, with input parameters matching those of the original example for discrete-zone mixing - Week 0.**



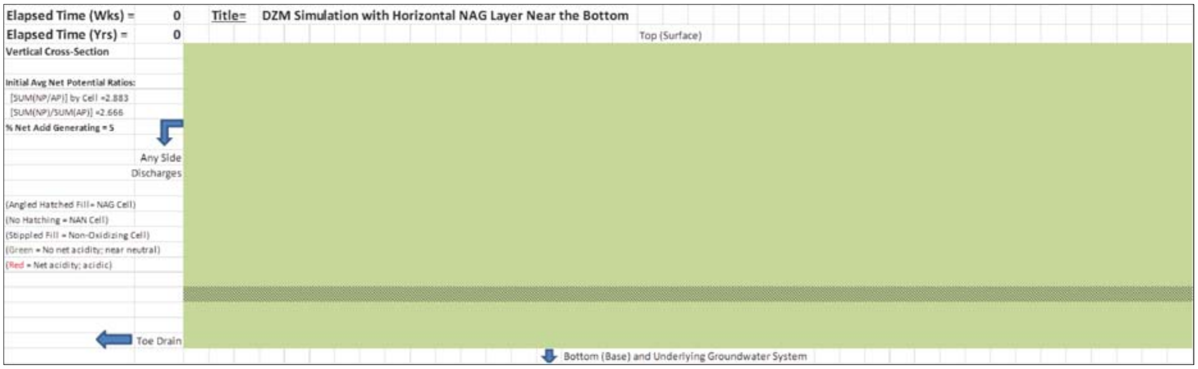
Elapsed Time (Wks) = 156
Elapsed Time (Yrs) = 3
Title= DZM Simulation with Horizontal NAG Layer Near the Top
Initial Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =2.883
[SUM(NP)/SUM(AP)] =2.666
% Net Acid Generating = 5

**Figure 3-2. Simulation of a high, laterally continuous NAG layer, with input parameters matching those of the original example for discrete-zone mixing - Week 156; showing the entire vertical cross-section at and below the NAG layer has become acidic and an outflow of ARD has occurred.**



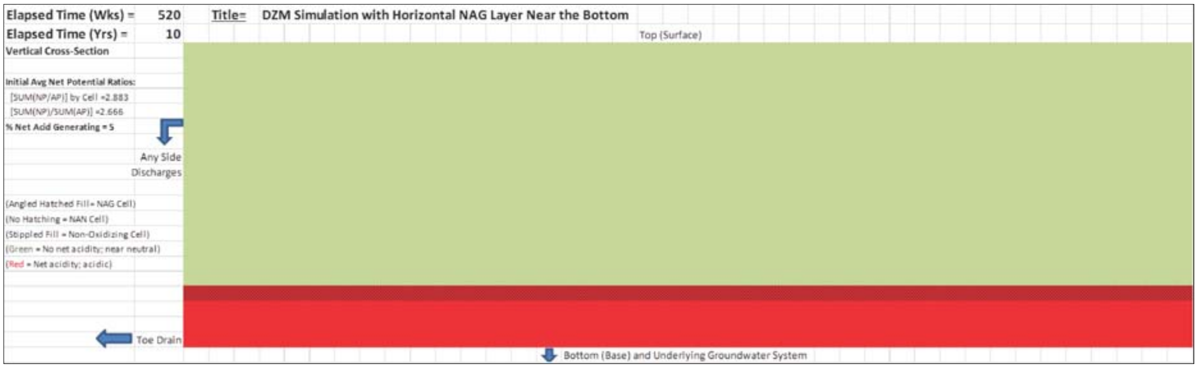
Elapsed Time (Wks) = 520
Elapsed Time (Yrs) = 10
Title= DZM Simulation with Horizontal NAG Layer Near the Top
Initial Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =2.883
[SUM(NP)/SUM(AP)] =2.666
% Net Acid Generating = 5

**Figure 3-3. Simulation of a high, laterally continuous NAG layer, with input parameters matching those of the original example for discrete-zone mixing, except a Channelling Factor of 1.0 - Week 520, showing (1) only the NAN row directly below the NAG layer has become acidic, (2) no outflow of ARD has occurred unless side discharges are possible, and (3) all AP is consumed so no more acidity can be generated.**



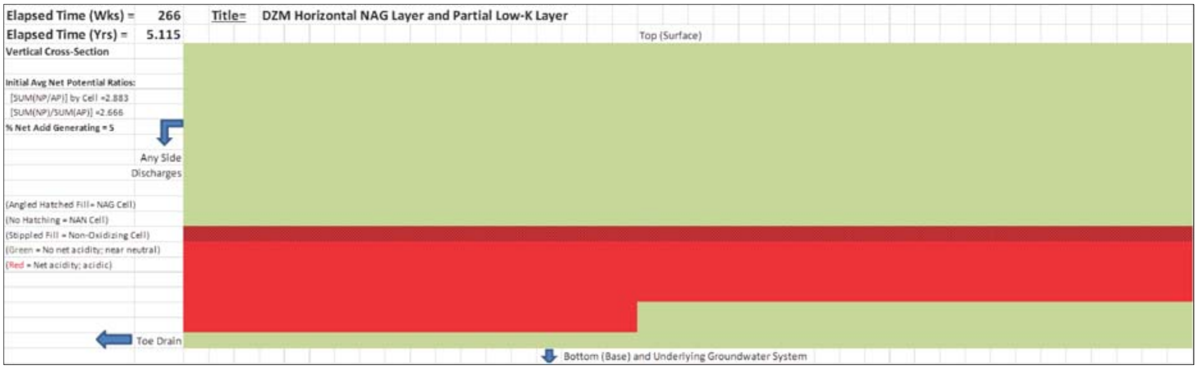
Elapsed Time (Wks) = 0
Elapsed Time (Yrs) = 0
Title= DZM Simulation with Horizontal NAG Layer Near the Bottom
Vertical Cross-Section
Initial Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =2.883
[SUM(NP)/SUM(AP)] =2.666
% Net Acid Generating = 5
(Angled Hatched Fill = NAG Cell)
(No Hatching = NAN Cell)
(Stippled Fill = Non-Oxidizing Cell)
(Green = No net acidity; near neutral)
(Red = Net acidity; acidic)

**Figure 3-4. Simulation of a low, laterally continuous NAG layer, with input parameters matching those of the original example for discrete-zone mixing, except a Channelling Factor of 1.0 - Week 0.**



Elapsed Time (Wks) = 520
Elapsed Time (Yrs) = 10
Title= DZM Simulation with Horizontal NAG Layer Near the Bottom
Vertical Cross-Section
Initial Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =2.883
[SUM(NP)/SUM(AP)] =2.666
% Net Acid Generating = 5
(Angled Hatched Fill = NAG Cell)
(No Hatching = NAN Cell)
(Stippled Fill = Non-Oxidizing Cell)
(Green = No net acidity; near neutral)
(Red = Net acidity; acidic)

**Figure 3-5. Simulation of a low, laterally continuous NAG layer, with input parameters matching those of the original example for discrete-zone mixing, except a Channelling Factor of 1.0 - Week 520; showing (unlike Figure 3-3) the vertical cross-section at and below the NAG layer has become acidic and an outflow of ARD has occurred despite average NPR values of 2.7-2.9.**



Elapsed Time (Wks) = 266
Elapsed Time (Yrs) = 5.115
Title= DZM Horizontal NAG Layer and Partial Low-K Layer
Vertical Cross-Section
Initial Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =2.883
[SUM(NP)/SUM(AP)] =2.666
% Net Acid Generating = 5
(Angled Hatched Fill = NAG Cell)
(No Hatching = NAN Cell)
(Stippled Fill = Non-Oxidizing Cell)
(Green = No net acidity; near neutral)
(Red = Net acidity; acidic)

**Figure 3-6. Simulation of a laterally continuous NAG layer, with a low-permeability NAN layer directly beneath the right half - Week 266; showing the NAN low-permeability layer has little effect on ARD migration (compare to Figure 3-7).**

However, when the right partial low-K layer is part of the NAG layer itself, then the initial migration of the right side is greatly delayed (Figure 3-7).

## 3.3 Discrete NAG Zones

While the preceding subsections were informative, they focussed on layers, particularly NAG layers extending across the entire length of the grid. In those situations, the predictions are more reflective of overall mass balances of NP and AP. If the NAG layer is high in the grid, the abundant underlying NP will slow or prevent ARD outflow at the base, but not necessarily for any side-slope discharges. If the NAG layer is low in the grid, less underlying NP will more likely allow ARD outflow.

In contrast, the DZM model (Chapter 1) was considered with discrete NAG zones distributed throughout minesite components. As a simple example, NAG cells occur vertically in a column, with each NAG cell separated vertically by two NAN cells (Figure 3-8). Less than 1% of the cells are NAG, and the grid average NPR is approximately 2.2.

The NAG cells quickly become acidic and turn the directly underlying NAN cells acidic also (Figure 3-9), which at the base means ARD has reached the underlying groundwater system.

However, most of the basal flow and basal acidity migration are directed laterally to the left in this simulation, and the NAN cells along the bottom sequentially become acidic (Figure 3-10). As the basal ARD plume approaches the toe drain (Figure 3-11), the minor lateral migration at each NAG cell higher in the grid turns the laterally adjacent cells acidic.

Finally, ARD appears at the toe drain (Figure 3-12). The minesite component is declared acidic and ARD-releasing. Yet, as Figure 3-12 shows, most of the material is NAN, most has remained near neutral in pH, and the average NPR was above 2.0.

Real examples of this can be seen in Morin and Hutt (1997a) and Morin (2017). Also, a forensic investigation found that Figure 3-12 explained Case Study 6 in Morin and Hutt (1997b). As a variation on Figure 3-12, the lateral migration of ARD to the side slope, rather than to the base and toe drain, explains Case Study 2 in Morin and Hutt (1997b).

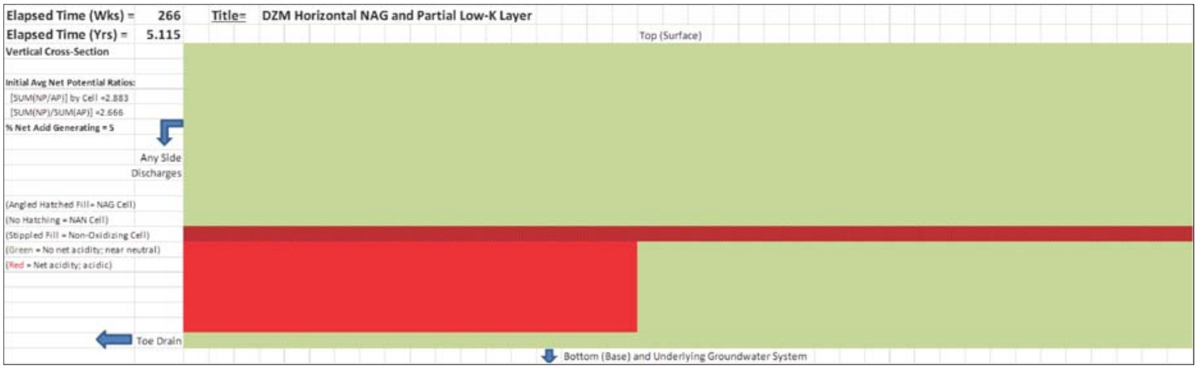


**Figure 3-7.** **Simulation of a laterally continuous NAG layer, with the right half also being a low-permeability layer - Week 266; showing the the combination of NAG and low permeability has a more significant effect on ARD migration (compare to Figure 3-6).**

**Figure 3-8.** **Simulation of a vertical stack of NAG cells, each separated by two NAN cells - Week 0.**

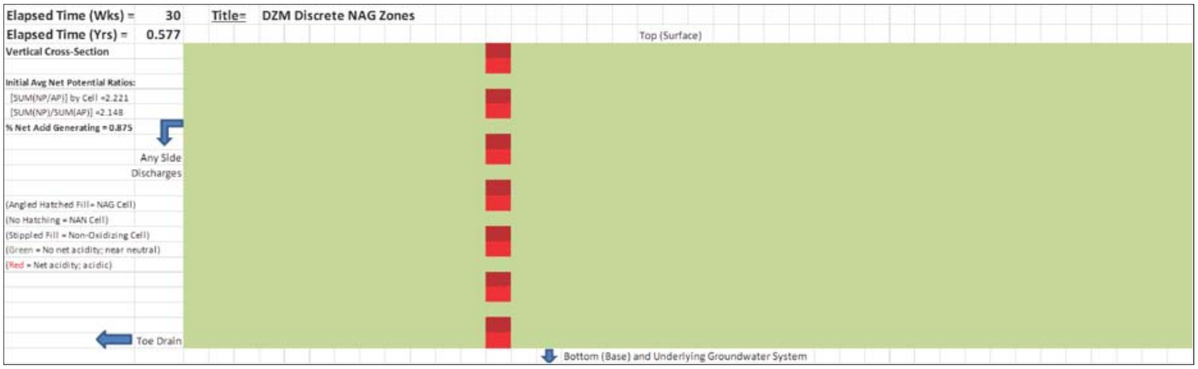
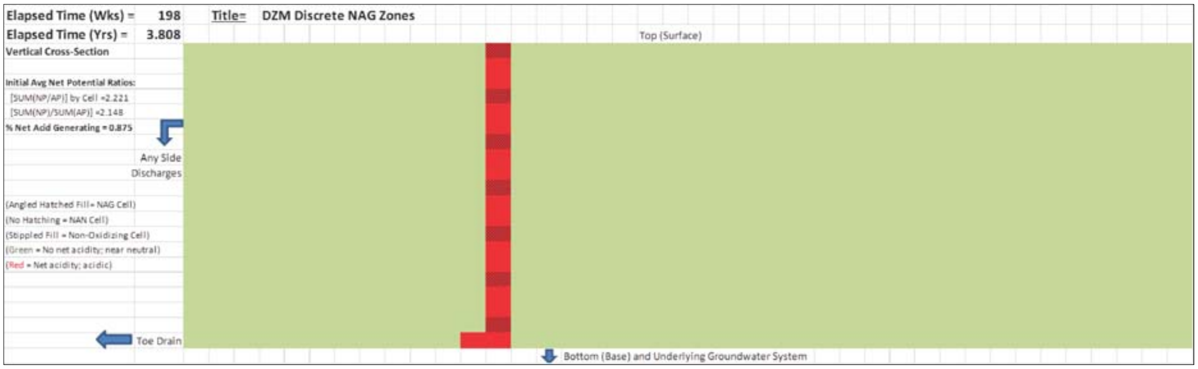
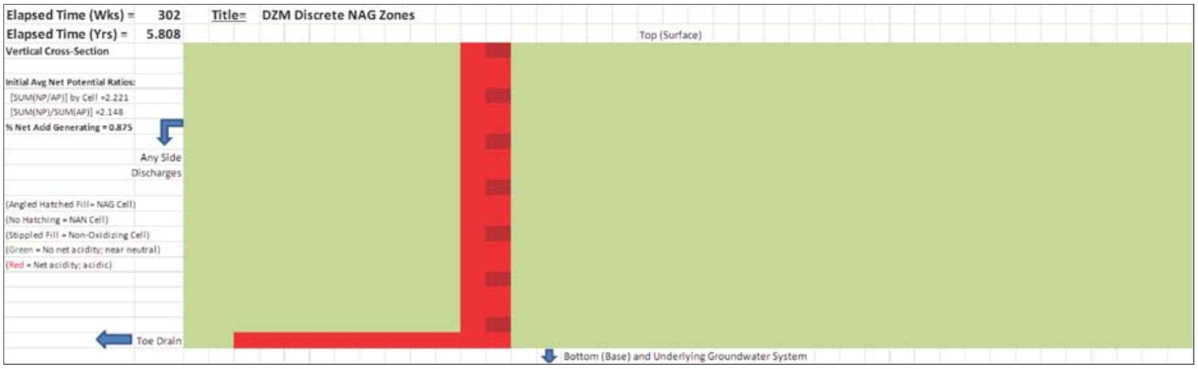


**Figure 3-9.** **Simulation of a vertical stack of NAG cells, each separated by two NAN cells - Week 30; showing the onset of acidic conditions in the NAG cells and in the NAN directly beneath.**



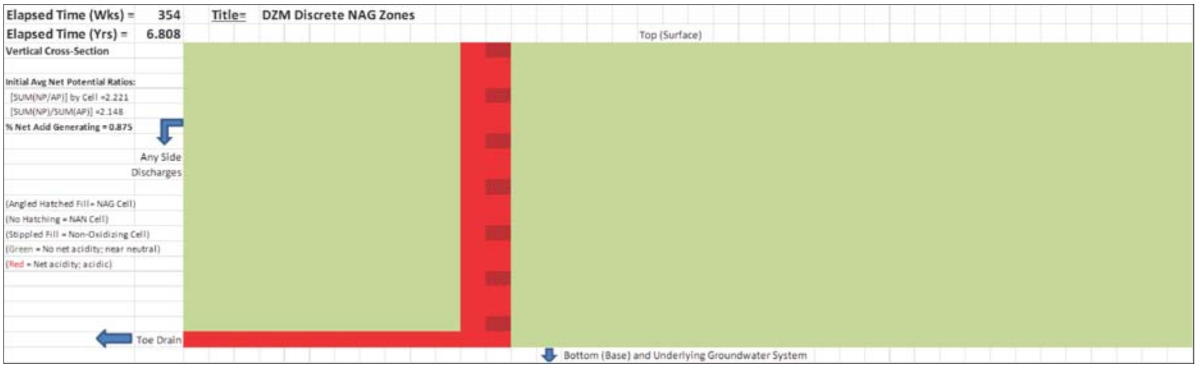
Elapsed Time (Wks) = 198
Elapsed Time (Yrs) = 3.808
Title= DZM Discrete NAG Zones
Vertical Cross-Section
Initial Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =2.221
[SUM(NP)/SUM(AP)] =2.148
% Net Acid Generating = 0.875
(Angled Hatched Fill = NAG Cell)
(No Hatching = NAN Cell)
(Stippled Fill = Non-Oxidizing Cell)
(Green = No net acidity; near neutral)
(Red = Net acidity; acidic)

**Figure 3-10. Simulation of a vertical stack of NAG cells, each separated by two NAN cells - Week 198; showing acidic conditions exist through the entire vertical stack and into the underlying groundwater system.**



Elapsed Time (Wks) = 302
Elapsed Time (Yrs) = 5.808
Title= DZM Discrete NAG Zones
Vertical Cross-Section
Initial Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =2.221
[SUM(NP)/SUM(AP)] =2.148
% Net Acid Generating = 0.875
(Angled Hatched Fill = NAG Cell)
(No Hatching = NAN Cell)
(Stippled Fill = Non-Oxidizing Cell)
(Green = No net acidity; near neutral)
(Red = Net acidity; acidic)

**Figure 3-11. Simulation of a vertical stack of NAG cells, each separated by two NAN cells - Week 302; showing ARD is migrating laterally along the base towards the toe drain, and NAN cells laterally adjacent to NAG cells higher in the profile have become acidic.**



Elapsed Time (Wks) = 354
Elapsed Time (Yrs) = 6.808
Title= DZM Discrete NAG Zones
Vertical Cross-Section
Initial Avg Net Potential Ratios:
[SUM(NP/AP)] by Cell =2.221
[SUM(NP)/SUM(AP)] =2.148
% Net Acid Generating = 0.875
(Angled Hatched Fill = NAG Cell)
(No Hatching = NAN Cell)
(Stippled Fill = Non-Oxidizing Cell)
(Green = No net acidity; near neutral)
(Red = Net acidity; acidic)

**Figure 3-12. Simulation of a vertical stack of NAG cells, each separated by two NAN cells - Week 354; showing has flowed out into the toe drain, and the minesite component is considered "acidic" despite most material still being near neutral and its NPR greater than 2.0.**

## 4. References

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Morin, K.A. 2016a. *Spectral Analysis of Drainage from Highly Reactive Geologic Materials*. Morwijk-MDAG Publishing, Surrey, Canada. ISBN 978-0-9952149-1-0, www.MDAG.com/spectral-book.html

Morin, K.A. 2016b. *Fractal 1/f temporal trends in minesite drainage from waste-rock dumps*. IN: 14th Experimental Chaos and Complexity Conference, May 16-19, Banff Center, Banff, Canada.

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Morin, K.A., and N.M. Hutt. 1997a. *Control of Acidic Drainage in Layered Waste Rock: Laboratory Studies and Field Monitoring*. Canadian MEND Report 2.37.3.

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# Appendix A. Code Listing of Macros in the MDAG Dynamic ARD-Onset Simulator Version 1.0

The MDAG Dynamic ARD-Onset Simulator Version 1.0 contains four macros: OneWeek, OneYear, TenYears, and ImageSave (see code listings below). These macros allow the simulator to work faster, by allowing you to "press" buttons in the simulator.

If you are concerned about macro security, you can still run the simulator, in manual mode, but it will take much longer. To run the simulator in manual mode without macros, the first three macros can be replaced by first typing 0 (zero) into Cell B20, the value for Elapsed Time (Wks), to start; then 1, then 2, then 3, etc. The simulator will not work if each Week is not entered sequentially. For example, entering 0 and then 52 will not make the simulator simulate one year, but only one week. The three macros simplify and accelerate the weekly time stepping.

The fourth macro, ImageSave, saves the graphical results at a particular time step and the input summary as a PNG file. To do this manually, highlight and copy to the clipboard the graphical results, then paste this into an appropriate graphics application for saving.

*[This macro increments the simulator by one time step, one week.]*

```
Sub OneWeek()
'
' OneWeek Macro
' Increment time step by one week
'
' Keyboard Shortcut: Ctrl+Shift+O
'
   Range("B20").Value = Range("B20") + 1
   Range("B20").Select
'   Calculate
End Sub
```

*[This macro increments the simulator by 52 consecutive time steps, one week each.]*

```
Sub OneYear()
'
' OneYear Macro
' Time step of one year
'
' Keyboard Shortcut: Ctrl+Shift+Y
'
   A = 1
   For A = 1 To 52
   Call OneWeek
   Next A
End Sub
```

*[This macro increments the simulator by 520 consecutive time steps, one week each.]*

```
Sub TenYears()
'
' TenYears Macro
' Time step of ten year
' Keyboard Shortcut: Ctrl+Shift+T
'
   A = 1
   For A = 1 To 520
   Call OneWeek
   Next A
End Sub
```

*[This macro saves the graphic result of the simulator at the current time step as a PNG file, using the simulation's name and current week in the filename, saved to the simulator's folder. Many thanks to the Microsoft community.]*

```
Sub ImageSave()
    Dim cb, sc, wks
    Dim rng As Range
    Dim sPath As String
    Dim sht As Worksheet
    Set sht = ThisWorkbook.ActiveSheet
    Set rng = sht.Range("A20:AP42")
    sPath = ThisWorkbook.Path & "\" & sht.Range("F20").Value & "-" & sht.Range("B20").Value & ".png"
    rng.CopyPicture Appearance:=xlScreen, Format:=xlPicture
    Set cb = rng.Parent.ChartObjects.Add(0, 0, 200, 200)
    Set sc = cb.Chart.SeriesCollection
    Do While sc.Count > 0
        sc(1).Delete
    Loop
    With cb
        .Height = rng.Height
        .Width = rng.Width
        .Chart.Paste
        .Chart.Export Filename:=sPath, Filtername:="PNG"
        .Delete
    End With
End Sub
```