Boundary Condition Module

by Thomas Reimann, Eileen Poeter, and Eve L. Kuniansky

Booklet with Instructions and Exercises

for https://gwp-boundary-conditions-analysis.streamlit.app/

About this material:

This booklet compiles all instructions and exercises from the **Boundary Condition Module** into a single printable document. It is intended for users who prefer to work with a printed companion while using the interactive Streamlit module. Having the material in front of you can eventually support a more focused workflow, make it convenient to follow the individual steps, and allow space for taking notes while doing the investigations and exercises.

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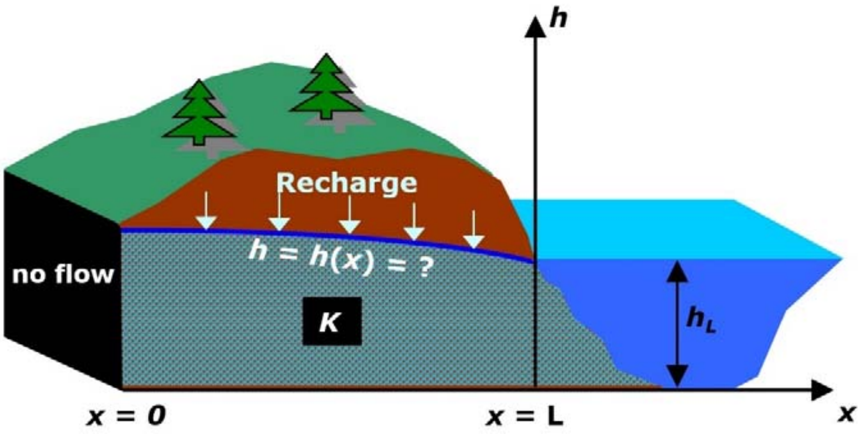

Figure: Schematic sketch of Scenario 1

Getting Started with the Interactive Plot Instructions for **Scenario 1**: Exploring Model Behavior and *Q*-*h* Relationships

Use the interactive tools in **Scenario 1** to investigate how model parameters and boundary conditions affect hydraulic head distributions and boundary flows. Follow the steps below to explore key relationships and system behavior.

1. Modify Model Parameters

- Open the INPUT CONTROLS and click "Click to Modify Model Parameters".
- Begin with increasing (or decreasing) the Recharge rate.
- Observe how the hydraulic head distribution changes throughout the domain.
- Next, adjust the Hydraulic Conductivity (K):
  - ▼ Lower values result in steeper gradients due to the reduced transmissivity (As K is decreased: for positive recharge, heads rise and for negative recharge heads decline).
  - ▲ Higher values result in lower gradients due to increased transmissivity (As K is increased: for positive recharge, heads decline and for negative recharge heads rise).
  - Proceed with a higher hydraulic conductivity and note the changes in head profiles.

2. Activate and Explore the *Q*-*h* Plot

- Navigate to the INPUT CONTROLS and click "Click for the *Q*-*h* plot".
- Select the No-flow *Q*-*h* plot for display.

- The red dot in the *Q*-*h* plot represents the flow and head at the location of the dot in the model shown in the upper figure.
- With the No-flow *Q*-*h* plot selected, this point corresponds to the no-flow boundary on the left and updates as parameter values are changed.
- The black line shows how Q_{in} varies as head at the no-flow boundary varies from 140 to 160 m. The flow is always zero because it is a no flow boundary.

3. Analyze Parameter Sensitivity

- Vary the recharge and observe how the red dot shifts vertically:
    - For the No-Flow Boundary, the flow remains constant at zero, while the head adjusts with changing parameters. When using relatively high hydraulic conductivity, the calculated head at the boundary does not substantially change.
    - Lower the hydraulic conductivity and again observe the effect on head and the red dot location.

4. Explore Head-dependent (River) Boundaries

- Return to the INPUT CONTROLS, activate the Head-dependent flux boundary, and then activate the *Q*-*h* plot for the Head-dependent flux Boundary.
- While the Head-dependent flux Boundary is active:
    - Adjust Recharge and note how both hydraulic head and flow change.
    - Modify the Head-dependent flux Conductance (*the units of the conductance are m²/s, this is explained in the **RIV** section of the module.*): Observe the head changes in the model and the different appearance of the ***Q-h*** plot. This demonstrates some characteristics of head-dependent boundaries. The next step considers the application of these boundary conditions.

5. Understand the Role of Head-Dependent Boundaries in Applied Groundwater Modelling

Head-dependent boundaries (such as River, General Head, or Drain boundaries) are commonly used to simulate interactions between an aquifer and external systems, where the flow across the boundary is not fixed, but governed by a conductance term and the difference in between the groundwater head calculated at the boundary and the boundary elevation or head of the external system (*this is explained more in the sections **GHB, RIV, DRN** of this module*).

The use of these boundaries can be considered in two fundamentally different ways depending on the modeling context, first:

a) During Model Calibration or Model Setup: One might have field data indicating the groundwater discharge to the river (for example $1.6x10^{-5}$ m^3/s per meter length of river). Given that the river (head-dependent flux boundary) is the only outlet of the model, the recharge rate can be calculated by dividing the discharge by the surface area of the model (2500 m by 1 m). Then, the hydraulic conductivity and conductance can be adjusted until the model heads match the measured field heads.

To explore this behavior:

- Set the boundary on the right side of the model to a specified head.
- Set the recharge to a value of (approximately) 200 mm/yr.
- Use the toggle to show the ***Q-h*** plot of the specified head boundary (on the right side). The blue dot represents the outflow at the boundary.
- Modify the hydraulic conductivity and the recharge to see how the Q-h plot reacts (focus on the blue dot that represents the head and flow at the boundary).
- Reset the recharge to a value of (approximately) 200 mm/yr.
- Now toggle in the middle section of the INPUT CONTROLS for the Head-dependent flux BC. Make sure that the ***Q-h*** plot for the Head-dependent flux boundary is active. The magenta-dot represents the outflow and head at the boundary.
- Assess the difference between the Specified head and the Head-dependent flux boundary by setting and resetting the Head-dependent flux BC toggle and study the ***Q-h*** plot with the value of aquifer hydraulic conductivity set higher than the conductance of the head-dependent flux boundary. The flow, which is solely a function of the recharge, is identical but the head at the boundary is increased if the Head-dependent flux BC is active AND the conductance value is less than the aquifer hydraulic conductivity (the same would be the case for other head-dependent boundary conditions like **GHB** or **DRN**). If the conductance is higher than the aquifer hydraulic conductivity, then including the riverbed does not change the heads in the system. If the conductance is much lower than the aquifer hydraulic conductivity, then there is a steep gradient between the aquifer head calculated at the boundary and the Head-dependent flux boundary (river) stage.
- It is useful to experiment with values of conductance C_B and observe how the heads in the model and the ***Q–h*** relationship change.

A second way to use the Head-dependent flux (river) boundary:

b) Once the Model is Calibrated such that the values of Recharge and Conductance are no longer adjusted: If other outlets are added to the system (e.g., abstraction wells, drains) the heads in the model will be a result of all the model boundary conditions and parameter values. In consequence, the previously calibrated, and then specified, conductance will control how much of the recharge flows to the Head-dependent flux boundary. The discharge will also depend on the location and properties of the other outlets. Such cases are discussed in the **GHB**, **RIV**, and **DRN** sections of this module. Further instructions for exploring the influence of boundary conditions are provided in those sections.

Introduction General Instructions Scenario 2

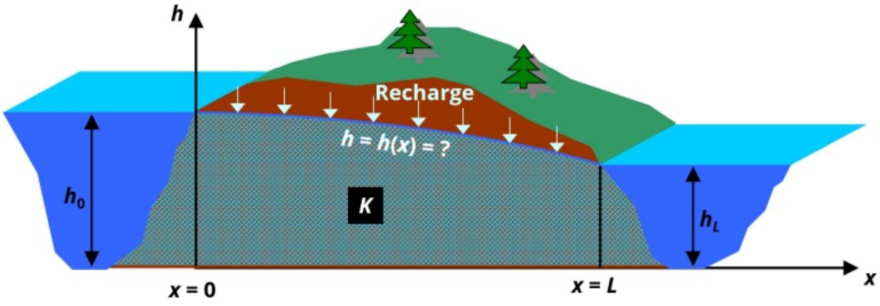

Figure: Schematic sketch of Scenario 2

Getting Started with the Interactive Plot Instructions for **Scenario 2**: Recharge, Groundwater Divide, and Boundary Flow Response

Scenario 2 allows you to explore the development of a groundwater divide under recharge conditions, and to investigate how hydraulic conductivity, boundary elevations, and model parameters influence both flow dynamics and *Q*-*h* relationships.

1. Modify Model Parameters

- Click "Modify Model Parameters" in the Control Panel to begin.
- Increase the Recharge:
  - A red vertical line will appear in the plot, marking the location of the groundwater divide.
  - Green arrows will appear in the plot, indicating the direction and magnitude of recharge.
  - Adjust the Hydraulic Conductivity:
    - ▼ Lower values create steeper gradients and form a distinct "groundwater mound".
    - Use a very low hydraulic conductivity to clearly visualize this effect.

2. Investigate Flow and Divide Behavior

- The plot dynamically shows flow values across the boundaries. A negative Q indicates outflow at the boundary and a positive value indicates inflow.
- Click the middle tab in the INPUT CONTROLS to access Boundary Condition Parameters.
- Modify the elevation of the left specified head boundary:

  - ▲ Increasing the left head: Shifts the groundwater divide to the left. This also increases the hydraulic gradient and flow at the right boundary. The flow at the boundary increases because the area (between the divide and the right boundary) that collects recharge is larger.
  - If the flow magnitude at the left boundary becomes greater than $3x10^{-5}$ m^3/s, use the toggle to increase the Q axis range.
  - ▼ Decreasing the left head: Moves the divide to the right. Accordingly, reduces the contributing recharge area to the right boundary and lowers outflow.
  - Using a high ▲ head on the left coupled with a low ▼ recharge rate and a high ▲ hydraulic conductivity results in flow through the aquifer from left to right at a rate higher than the inflowing recharge and there is no flow divide within the model.

3. Explore the *Q-h* Plot Dynamics

- Activate the *Q-h* Plot for the right specified head boundary:
  - A blue dot in the main plot highlights the boundary condition point.
  - The *Q-h* plot shows this as a blue dot at a fixed head of 150 m.
  - As you adjust the left specified head, observe how the blue dot moves:
    - ▲ When the left head increases, the groundwater divide moves to the left and more recharge flows to the right boundary → the blue dot moves down, indicating higher outflow.
    - ▼ When the left head decreases, the contributing area shrinks → the blue dot moves up, indicating reduced flow.

4. Run Comparative Experiments

- Switch between the different *Q-h* plots to track how other boundaries behave.
- Vary the following parameters to better understand interactions:
  - Recharge
  - Hydraulic Conductivity
  - Left Boundary Head

GHB Boundary Condition Instructions

Getting Started with the Interactive Plot

Before starting the exercise, it is helpful to follow these steps to explore GHB behavior (you may want to use the toggle switch to allow number rather than slider input):

1. Start with H_B = 8 m, h_{gw} = 10 m, and C_B = 1x10⁻² m²/s

- Vary **groundwater head** h_{gw} and observe how **flow** Q_B changes in magnitude and direction.
- Use the slider to vary $\boldsymbol{C_B}$ and notice how the **slope of the $\boldsymbol{Q}$–$\boldsymbol{h}$ curve** changes.
- Toggle "Compute conductance" then enter values for K, A_B, and L_B to calculate $C_B = \frac{KA_B}{L_B}$ and notice how the **slope of the Q–h curve** changes.

2. Consider the Role of Head-Dependent Boundaries in Applied Groundwater Modeling

Depending on the modeling objective, head-dependent boundaries like GHB can be considered in two different ways, delineated under (a) and (b) here.

a) During Model Calibration or Setup: Assume that the discharge is known from field data (so the recharge is determined by dividing the discharge by the surface area of the model) and the general head boundary is the only outlet of the model. Then, given head values in the groundwater system, the values of hydraulic conductivity and GHB conductance can be calibrated. **This situation is discussed in the introduction** and can be accessed by clicking on the **Introduction button** on the left menu, then scrolling down and choosing **Show the interactive plot for Scenario 1**, then scrolling down below the plot to open the **Instructions** and finally **scrolling down to Step 5a**.

b) After the model is calibrated such that the hydraulic conductivity, recharge, and riverbed conductance are specified: If other outlets are added to the system (e.g., abstraction wells, drains) the heads in the model will be a result of all the model boundary conditions and parameter values. In consequence, the previously calibrated, and then specified, conductance will control how much of the recharge flows to the **GHB** boundary. The discharge will also depend on the location and properties of the other outlets. Here we investigate this behavior for the **General Head Boundary GHB**. Other head dependent boundaries like **RIV** and **DRN** follow similar principles.

The subsequent exercise is designed to help you build intuition for how GHB parameters control flow. Feel free to further investigate the interactive plot on your own.

GHB Boundary Condition Exercise

Expected Learning Outcomes: Completion of this exercise helps you to accomplish the following.

- Understand how GHB flux is driven by head difference and conductance.
- Interpret Q–h plots in relation to hydrogeologic behavior.
- Develop the ability to use this application for conceptual testing and scenario analysis.

Instructions - Use the interactive GHB plot as follows:

1. Start with H_B = 8 m, h_{gw} = 10 m, and C_B = 1x10^{-2} m^2/s

- Vary the groundwater head (h_{gw}) from **5 m to 15 m**
- Observe and describe how the flux (Q) changes
- Record:
  - The sign of the flux for different h_{gw} values
  - The value of Q when h_{gw} = H_B

2. Conductance Effect

- Start with H_B = 8 m, h_{gw} = 10 m, and C_B = 1x10^{-2} m^2/s
- Choose three different conductance values (e.g., **3x10^{-2}, 3x10^{-3}, and 3x10^{-4} m^2/s**)
  - Cycle through the 3 conductance values a couple of times, noting the influence of conductance on the slope of the line and flow conditions
- Choose one conductance value (e.g., **3x10^{-3} m^2/s**) and three values of H_B with increased and decreased values (e.g., **5, 9, and 20 m**)
  - Cycle through the 3 H_B values a couple of times, noting the influence of conductance on the slope of the line and flow conditions

3. Realistic Scenarios

- Imagine a GHB represents a canal system connected to the groundwater system. The canal water level is 10 m.
- Assume the groundwater head starts at 8 m.
- Evaluate how much water would enter the groundwater system for:
  - A poorly connected canal (low conductance)
  - A well-connected canal (high conductance)
- Consider the implications of your findings for water management

RIV Boundary Condition Instructions

Getting Started with the Interactive Plot

Before starting the exercise, it is helpful to follow these steps to explore RIV behavior:

Start with H_{RIV} = 9 m, R_{bot} = 7 m, h_{gw} = 10 m, and C_{RIV} = 1x10⁻² m²/s

- Vary groundwater head h_{gw} and observe how the flow Q_{RIV} changes in magnitude and direction.
  - When $h_{gw} > H_{RIV}$, the groundwater discharges to the river (losing river).
  - When $h_{gw} < H_{RIV}$ but $h_{gw} > R_{bot}$, the river recharges the groundwater (gaining river).
  - When $h_{gw} < R_{bot}$, the river is not in direct contact with the groundwater. Flow through an unsaturated zone occurs, which is driven by the head gradient between river stage and river bottom. In this case, outflow from the river is constant and independent of h_{gw}.
- Use the slider to vary C_{RIV} and notice how the slope of the Q–h curve changes, with higher conductance resulting in more exchange of flow.
- Toggle "Compute conductance" then enter L_{RIV}, W_{RIV}, M_{RIV}, and K_v, to calculate $C_{RIV} = \frac{KL_{RIV}W_{RIV}}{M_{RIV}}$ and notice how the conductance value influences the Q–h relationship.
- Set $h_{gw} < R_{bot}$ and compute C_{RIV} directly. Investigate the effect of the river bottom elevation R_{bot} and riverbed thickness M_{RIV} on flow at the RIV boundary.

The subsequent exercise is designed to help you build intuition for how RIV parameters control flow. Feel free to further investigate the interactive plot on your own.

RIV Boundary Condition Exercise

Expected Learning Outcomes

Completion of this exercise helps you to:

- Understand how river–groundwater exchange is controlled by stage, groundwater head, bottom elevation, and conductance.
- Interpret *Q*–*h* plots in relation to gaining, losing, or inactive river segments.
- Identify conditions that limit or enable flow across the riverbed.
- Develop the ability to test and visualize river boundary behavior through scenario analysis.

Instructions Use the interactive RIV plot and complete the following steps:

1. Initial Exploration

- Set the **river head** (H_{RIV}) to **10 m** (remember that under INPUT CONTROLS, in the **"Modify Plot Controls"** drop-down menu, you can toggle to choose between slider or typed input to adjust the parameter values).
- Set the **river bottom elevation** (R_{bot}) to **9 m.**
- Vary the **groundwater head** (h_{gw}) from **8 m to 12 m** while observing and describing how the flow (Q_{riv}) changes. It is useful to expand the area below the graph that is labeled "Click here to show Parameters and Results". It is helpful to keep notes on the values you observe, so you may want to record the following items.

Record:

- Whether the river is gaining or losing in each case.
- The conditions where no flow occurs.
- The transition points between gaining/losing/inactive behavior.

2. Effect of Conductance

- Set H_{RIV} = 10 m and R_{bot} = 9 m
- Choose three different conductance values (e.g., **1x10^{-2}, 1x10^{-3}, and 1x10^{-4} m^2/s**)
    - o For each of the 3 conductance values view the plot Q_{RIV} vs h_{gw} while adjusting h_{gw} from 8 m to 12 m and note the influence of conductance on the slope of the line and the magnitude of flow. It is helpful to keep notes on the values you observe, so you may want to record the following items.

Record:

- Whether the river is gaining or losing in each case.
- Whether no flow occurs and, if so, for what conditions.
- Take note of transition points between gaining/losing/inactive behavior.

3. Realistic Scenarios: Recession Flow

- Imagine a river with stage H_{RIV} **decreasing** from **11 m** to **9 m** (e.g., during a dry spell)
- Set river bottom to **8.5 m**
- Groundwater head is fixed at **9.2 m**

Explore:

- How does the direction and magnitude of flow change as the river stage drops?
- How does the bottom elevation restrict or allow recharge?
- Discuss which condition (stage or bottom) dominates the system behavior

DRN Boundary Condition Instructions

Getting Started with the Interactive Plot

Before starting the exercise, it is helpful to follow these steps to explore DRN behavior:

1. Start with H_D = 8 m, h_{gw} = 10 m, and C_B = 1x10^{-2} m^2/s

- Vary **groundwater head** h_{gw} in steps between 6 and 12 m (if you prefer there is a toggle button under **Modify Plot Controls** that allows you to type in values instead of using the slider).
- Observe how the flow Q_D changes:
  - When $h_{gw} > H_D$, the groundwater drains, i.e. flow leaves the groundwater through the drain.
  - When $h_{gw} \leq H_D$, no flow occurs because the drain is inactive.

2. Experiment with Different Conductance Values

- With $h_{gw} > H_D$, use the slider to vary C_D and notice how the **slope of the Q–h curve** changes — higher conductance leads to stronger response of outflow to head differences.

These steps help you build intuition for how DRN parameters govern flow — especially the **threshold behavior** and **linear relationship** between head difference and outflow. Feel free to further investigate the interactive plot on your own.

DRN Boundary Condition Exercise

Expected Learning Outcomes

Completion of this exercise helps you to:

- Understand how drain–groundwater interaction is controlled by groundwater head, drain elevation, and conductance.
- Interpret the boundary characteristics with a Q–h plot.
- Recognize the threshold behavior of the DRN package and its role as a one-way boundary.
- Evaluate how conductance controls the rate of drainage when groundwater head is above a threshold elevation.
- Analyze realistic scenarios (e.g., excavation of a building foundation) and the implications for boundary fluxes.

Instructions

Use the interactive DRN plot to complete the following steps:

1. Initial Exploration (hint: there is a toggle button under Modify Plot Controls that allows you to type in values instead of using the slider)

- Start with H_D = 8 m, h_{gw} = 10 m, and C_B = 1x10^{-2} m^2/s
- Vary the groundwater head (h_{gw}) from 8 m to 12 m and observe how the flow (Q_D) responds to changes in head

Make a record of:

- The threshold value at which the drain becomes active
- The linearity of the Q–h relationship once the threshold is exceeded
- Drain flow when groundwater head is less than the drain elevation

2. Effect of Conductance

- Start with H_D = 8 m, h_{gw} = 10 m, and C_B = 1x10^{-2} m^2/s
- Choose three different conductance values (e.g., 1x10^{-2}, 1x10^{-3}, and 1x10^{-4} m^2/s)
    - For each of the 3 conductance values view the plot Q_D vs h_{gw} while adjusting h_{gw} from 6 m to 12 m and note the influence of conductance on the slope of the line and the magnitude of flow.

3. Realistic Scenario: Excavating a building foundation

- Fix the groundwater head at 10.3 m
- In 1-m steps, vary drain elevation from 9.3 m to 6.3 m, and make note of the flow rate to the drain
- Consider this as a simplified representation of increasing inflow that needs to be collected and routed away from a construction site. A similar process might be used at a larger scale for an open pit mine.

Explore:

- How does flow to the drain change as the excavation deepens?
- What would the construction company have to do to address the inflow?
- What would reduce the inflow?
- How might conductance be decreased on excavation walls?
- How might surrounding groundwater heads be lowered?

MNW Boundary Condition Plot 1 Instructions

Getting Started

Before starting the exercise, it is helpful to follow these steps to familiarize yourself with MNW:

1. To start exploring, enter a value of 3 for A, B, C, and P to represent a well with significant losses

- The default is **Q-target** mode with $Q = -0.5$ m³/s
- Observe the drawdown between h_{gw} and h_{well}
- Modify the withdrawal rate to investigate the response in the interactive plot. A higher withdrawal rate causes more head decline in the well.

2. Switch to H-target

- Toggle to **H-target** mode and Q will be reset to the default -0.5 m³/s
- Vary drawdown Δh from 0.5 to 8.0 m
- Observe how Q responds to increasing drawdown. The relationship is the same but now setting h_{well} produces the related value of Q, instead of setting Q to obtain the value of h_{well}.

3. Compare Parameter Sets

- Toggle to **modify CWC parameters** and the default values will be shown
- Assuming the first set of values is still 3 for A, B, C, and P
- Now, in the CWC menu, toggle to define a **second parameter set** and try a less restrictive case (if you prefer there is a toggle button under **Modify Plot Controls** that allows you to type in values instead of using the slider):
    - e.g., $A = 1.0$, $B = 0.2$, $C = 2.0$, $P = 2.5$
- Compare the resulting Q–Δh relationships.

Use the plot orientation toggle for alternate layouts.

MNW Boundary Condition Plot 1 Exercise

Learning Objectives

This exercise is designed with the intent that, upon completion, you will be able to:

- Understand how the withdrawal–drawdown relationship is defined for MNW boundaries
- Explain the influence of CWC parameters (A, B, C, P)
- Differentiate between Q-target and H-target modes
- Compare well behavior for different types and magnitude of well loss

Tasks

1. Explore Q–Δh Relationship

- Set: $A = 3$, $B = 3$, $C = 1.0$, $P = 2.0$
- Use **Q-target** mode
- Vary Q from -0.01 to -0.5 m³/s
- Record where the curve steepens and explain the influence of the different parameters in CWC (A, B, C, and P)

2. Test Parameter Sensitivity

- Set: $A = 1$, $B = 1$, $C = 1.0$, $P = 2.0$
- Set $Q = -0.3$ m³/s in **Q-target** mode
- Enable the **second parameter set**
- Vary A, then systematically change B, C, and P (ultimately setting all values to 4) and compare responses
- Reflect on the role of linear versus nonlinear resistance.
    - Switch on/off the linear resistance by setting A and B to 0.
    - Switch on/off the nonlinear resistance by setting C to 0.
- Reflect on what parameter values would represent well-aging?

3. Reverse Analysis with H-target

- Switch to **H-target** and make sure to use the initial parameter set: $A = 4$, $B = 4$, $C = 4$, $P = 4$
- Set $\Delta h = 1, 3, 5, 7$ m

- Compare resulting Q values across different parameter sets (e.g., to reflect an aged well).
- At what Δh value does Q have a larger withdrawal rate than -0.2 m³/s? How much does well-aging affect efficiency?

Use this exploration to build deeper insight into how MNW wells behave under variable design conditions.

MNW Boundary Condition Plot 2 Instructions

Getting Started : Begin with the following steps to explore the MNW discharge–head relationship:

1. To start exploring, enter a value of 3 for A, B, C, and P to represent a well with significant losses

- The groundwater head is fixed at h_{gw} = 10 m in this plot

2. Explore Q-target Mode

- Toggle to **modify CWC parameters**
- Set the CWC parameter values to: A = 5.0, B = 5.0, C = 1.0, P = 2.0
- Adjust discharge Q in steps between -0.05 and -0.7 m³/s and observe the resulting well head h_{well} and increasing drawdown

3. Switch to H-target Mode

- Set the CWC parameter values to: A = 5.0, B = 5.0, C = 1.0, P = 2.0
- Adjust drawdown Δh in steps between 1.0 and 6.5 m and observe how discharge changes with increasing drawdown

4. Modify CWC Parameter Values

- For both Q-target Mode and H-target Mode:
  - Try different values for A, B, and P
  - Compare how the drawdown or flow response changes

Consider how your observations differ from the behavior of **DRN** and **RIV** boundaries (linear, head-dependent flow) and from **WEL** and **RCH** boundaries (fixed Q).

MNW Boundary Condition Plot 2 Exercise

Learning Objectives

This exercise is designed with the intent that, upon completion, you will be able to:

- Understand how MNW represents nonlinear resistance between groundwater and a well
- Interpret how discharge and drawdown change for different parameterizations
- Explain how MNW behavior differs from other boundary conditions (e.g., WEL, RCH, DRN, RIV)
- Identify cases where turbulence is dominant

Tasks

1. Well Head Response to Discharge

- Use **Q-target** mode
- Set: $A = 0.5$, $B = 0.05$, $C = 1.0$, $P = 2.0$
- Vary Q from -0.05 to -0.8 m³/s
- Record h_{well} and compute the drawdown: $\Delta h = h_{gw} - h_{well}$

2. Effect of Parameter Variation

- Starting with the CWC settings from step 1, for a few values of Q, make the following changes and note the drawdown
  - Double A
  - Double B
  - Double C
  - Increase P to 2.5 or 3.0
- Record how each change affects drawdown for a given Q
- Which parameters cause nonlinear increases in Q?

3. Explore H-target Mode

- Retaining the final settings for CWC from step 2, set drawdown to Δh = 2.0 m, then in a few steps, lower it to 0.5 m
  - Record how discharge changes (hint: when the Q value is out of the axis range as is the case for Δh = 2.0 m, the value of Q can be determined from the legend)

4. Conceptual Comparison

- When is the MNW behavior close to behaving like:
    - a constant Q source (WEL)?
    - a linear head-dependent boundary (RIV)?
- What role does the parameter P play in making an MNW boundary behave differently?

Reflect: What happens if you set $A = 0$? When is turbulence (nonlinear loss) dominant?

MNW Boundary Condition Plot 3 Instructions

Getting Started: Follow these steps to explore threshold-controlled withdrawal behavior in MNW (if you prefer there is a toggle button under **Modify Plot Controls** that allows you to type in values instead of using the slider):

1. Start by setting the following values

- $Q - target = -0.5$ m
- $h_{gw} = 10$ m
- Limiting head $h_{lim} = 5.0$ m
- CWC parameters: $A = 3$, $B = 3$, $C = 3$, and $P = 3$ to represent a well with significant losses

2. Step through values of Q

- Vary withdrawal rate Q from -0.1 to -0.9 m³/s
- Observe how h_{well} responds to withdrawal
- Identify where the well head h_{well} reaches the threshold head h_{lim}

3. Explore Threshold Activation

- Increase the withdrawal rate Q beyond the point where $h_{well} = h_{lim}$.
- Note that the current Q (represented by the dot in the plot) is automatically reduced to keep $h_{well} = h_{min}$

4. Explore Withdrawal Limits

- Set the limiting head h_{lim} to 5.0 m and the groundwater head h_{gw} to 15.0 m. Set the withdrawal rate to 0.5 m³/s. With these settings, the system is in proper operation.
- Toggle **Apply withdrawal thresholds** to automatically switch off/on the pump then the Q_{mn} and Q_{mx} will appear on the plot as solid and dashed black lines.
- Set Q_{mn} and Q_{mx} to -0.05 and -0.2 m³/s.
- Now, lower the groundwater head h_{gw} in steps down to 5.1 m. The groundwater head can be lowered by various mechanisms with the most common likely being withdrawal from neighboring wells.
- While lowering the groundwater head, observe how the adjusted withdrawal rate - represented by the dot in the plot - is affected.
- Once the groundwater head reaches 5.1 m, gradually raise the head back to 15.0 m and observe the adjusted withdrawal rate (dot in the plot).

5. Modify Parameters

- Try different values for A, B, C, and P
- Vary Q (Q-target), Δh (H-target), groundwater head h_{gw} and threshold head h_{lim}, and investigate the MNW behavior with the interactive plot.

This exercise facilitates understanding of how operational constraints (like prevention of water level dropping below a pump) interact with well head-loss to adjust the simulated flow rate so a model cannot represent more withdrawal of water than the well design will allow.

MNW Boundary Condition Plot 3 Exercise

Learning Objectives

This exercise is designed with the intent that, upon completion, you will be able to:

- Explain how threshold head limits influence MNW discharge behavior
- Identify the conditions for which withdrawal is reduced to protect wells
- Analyze how nonlinear head losses and operational limits combine to define feasible withdrawal rates
- Understand the role of Q_{mn} and Q_{mx} in the MNW implementation

Exercise Instructions

1. **Locate Threshold Activation Point**
   - Set: $A = 1$, $B = 1$, $C = 1$ $P = 1$, $h_{gw} = 10$ m, $h_{lim} = 7$ m
   - Increase Q from 0.2 to 1.0 m³/s
   - Identify the Q at which $h_{well} = h_{lim}$ — call this Q_{lim}
2. **Test Effect of Nonlinearity and Exponent P**
   - Starting again with: Q to 0.5 m³/s, $h_{gw} = 10$ m, $h_{lim} = 7$ m $A = 1$, $B = 1$, $C = 1$ $P = 1$
   - Increase C to 2 and repeat the test
   - Increase P to 2 and repeat the test
   - How does Q_{lim} change?
   - Is the threshold reached earlier or later?
   - Why does a higher P allow a higher flow rate?
3. **Apply Q_{mn} and Q_{mx} Limits**
   - Starting again with: Q to 0.5 m³/s, $h_{gw} = 10$ m, $h_{lim} = 7$ m $A = 1$, $B = 1$, $C = 1$ $P = 1$
   - Set Q_{mn} = 0.1 m³/s and Q_{mx} = 0.2 m³/s
   - Try to reach the value of Q_{mn} by lowering the groundwater head and take notice of the groundwater head when withdrawal stops.
   - Now, increase the groundwater head in steps up to 10.0 m and notice the value of groundwater head when withdrawal starts again. Consider why withdrawal stops and starts at different values of groundwater head.

- Double the parameter for linear well loss B and repeat the procedure. Quantify the changes in terms of groundwater heads for switching off/on the withdrawal.

Reflect: - When is the threshold head the limiting factor? - How do Q_{mn} and Q_{mx} affect the value of practical withdrawal? - How is this behavior affected by the value of CWC with respect to the individual processes that control CWC (aquifer loss, linear and nonlinear well loss).

This exploration prepares you to interpret MNW behavior in model calibration and design tasks.

MNW Boundary Condition Plot 4 Instructions

Getting Started: Follow these steps to explore threshold-controlled withdrawal behavior in MNW:

1. Start by setting the following values

- Limiting head $h_{lim} = 2.0$ m
- $h_{gw} = 10$ m
- CWC parameters: $A = 5.0$, $B = 5.0$, $C = 0$, $P = 2.0$

2. Step through values of h_{gw}

- Vary groundwater head h_{gw} from 10.0 to 19.0 m and observe how discharge Q responds to groundwater head changes.

3. Modify Parameters

- Adjust values of A, B, C, and P and observe how the shape of the ***Q-h*** plot responds.
- Vary groundwater head h_{gw} and the ratio of well-head/limiting-head h_{well}/h_{lim}, and investigate the MNW behavior for this ***Q-h*** plot with the interactive diagram.
- Identify the well head h_{well} and the groundwater head h_{gw} where the discharge becomes zero

Following these steps facilitates understanding of how the MNW package incorporates head targets and can be used to estimate well discharge.

MNW Boundary Condition Plot 4 Exercise

Learning Objectives

This exercise is designed with the intent that, upon completion, you will be able to:

- Explain how limiting the head influences MNW discharge behavior
- Analyze how nonlinear head losses and operational limits combine to define feasible withdrawal rates

Exercise Instructions

1. **Identify the outflow from an artesian flowing well**
    - Set: $A = 5$, $B = 5$, $C = 0.0$ $P = 1.0$, $h_{gw} = 15$ m, $h_{lim} = 5$ m
    - Identify the Q that flows out of the well
    - Quantify how Q changes when the groundwater head declines from 15 m to 12 m.
2. **Test Effect of Nonlinearity**
    - Set $h_{gw} = 18$ m and observe Q
    - then increase P to 3.5 and observe Q
    - Reset P = 1.0, set C = 3.0 and observe Q
    - then increase P to 3.5 again and observe Q
3. **Effect of linear losses**
    - Reset to: $A = 5$, $B = 5$, $C = 0.0$ $P = 1.0$, $h_{gw} = 15$ m, $h_{lim} = 5$ m
    - Double B (keep the others fixed)
    - Quantify how the discharge changes for Δh = 4.3 m.

Reflect:

- How does the MNW boundary behave in this exercise? What other boundary conditions presented in this module exhibit comparable behavior?
- How do linear and nonlinear losses shape the Q-h curve? What does this mean for the resulting outflow?

This exploration prepares you to interpret MNW behavior in model calibration and design tasks.

EVT Boundary Condition Instructions

Getting Started with the Interactive Plot

Before starting the exercise, it is helpful to follow these steps to understand how evapotranspiration (ET) interacts with the water table:

Start with *SURF* = 9 m, *EXDP* = 4 m, h_{gw} = 8 m, and *EVTR* = 2000 mm/yr

- Adjust the groundwater head in steps from h_{gw} ranging from 0.0 m to 10.0 m (if you prefer there is a toggle button under **Modify Plot Controls** that allows you to type in values instead of using the slider) and notice how Q_{ET} changes:
    - ET is zero below ***SURF*** - ***EXDP*** (which is equal to the expiration elevation shown on the graph)
    - ET increases linearly as h_{gw} rises above ***SURF*** - ***EXDP***
    - Maximum ET occurs when h_{gw} => ***SURF***

Start with *SURF* = 9 m, *EXDP* = 1 m, h_{gw} = 8 m, and *EVTR* = 2000 mm/yr, then analyze the influence of *EXDP*.

- Increase ***EXDP*** in steps and observe how the slope of the *Q*–*h* curve flattens and how Q_{ET} changes.

These steps build a foundation for the full exercise. Feel free to interactively explore additional parameter value combinations.

EVT Boundary Condition Exercise

Expected Learning Outcomes

Completion of this exercise helps you to:

- Understand the threshold-controlled behavior of the ET boundary condition
- Evaluate how extinction depth and surface elevation influence the rate of evapotranspiration
- Relate evapotranspiration losses to groundwater sustainability

Instructions

Use the interactive ET plot to complete the following steps:

1. **Initial Setup**
    - Start with h_{gw} = 8 m, ***SURF*** = 9 m, ***EXDP*** = 4 m, and ***EVTR*** = 730 mm/yr
    - View conditions by stepping through a range of groundwater heads from 3 m to 10 m

    Observe and record:

    - The head at which ET reaches its maximum value
    - The head at which ET drops to zero
    - The shape of the Q–h curve between these thresholds.
2. **Test Sensitivity to Extinction Depth**
    - Set ***SURF*** at 9 m and h_{gw} to 6 m
    - View conditions by stepping through ***EXDP*** from 1 to 5 m
    - For each value of ***EXDP***, observe the slope of the ET curve and the value of Q_{ET} for the groundwater head of 6 m
3. **Explore ET Surface Elevation Effects**
    - Set ***EXDP*** = 3 m and h_{gw} to 6 m
    - View results for ***SURF*** = 7 m, 8 m, 9 m, and 10 m
    - For each value of ***SURF***, observe the slope of the ET curve and the value of Q_{ET} for the groundwater head of 6 m
    - Observe how this shifts the entire ET response curve along the vertical axis

Reflect:

- When is groundwater significantly contributing to ET?

- What happens to ET when groundwater levels are low during droughts or due to pumping?
- How can extinction depth help represent different vegetation types or soil conditions?