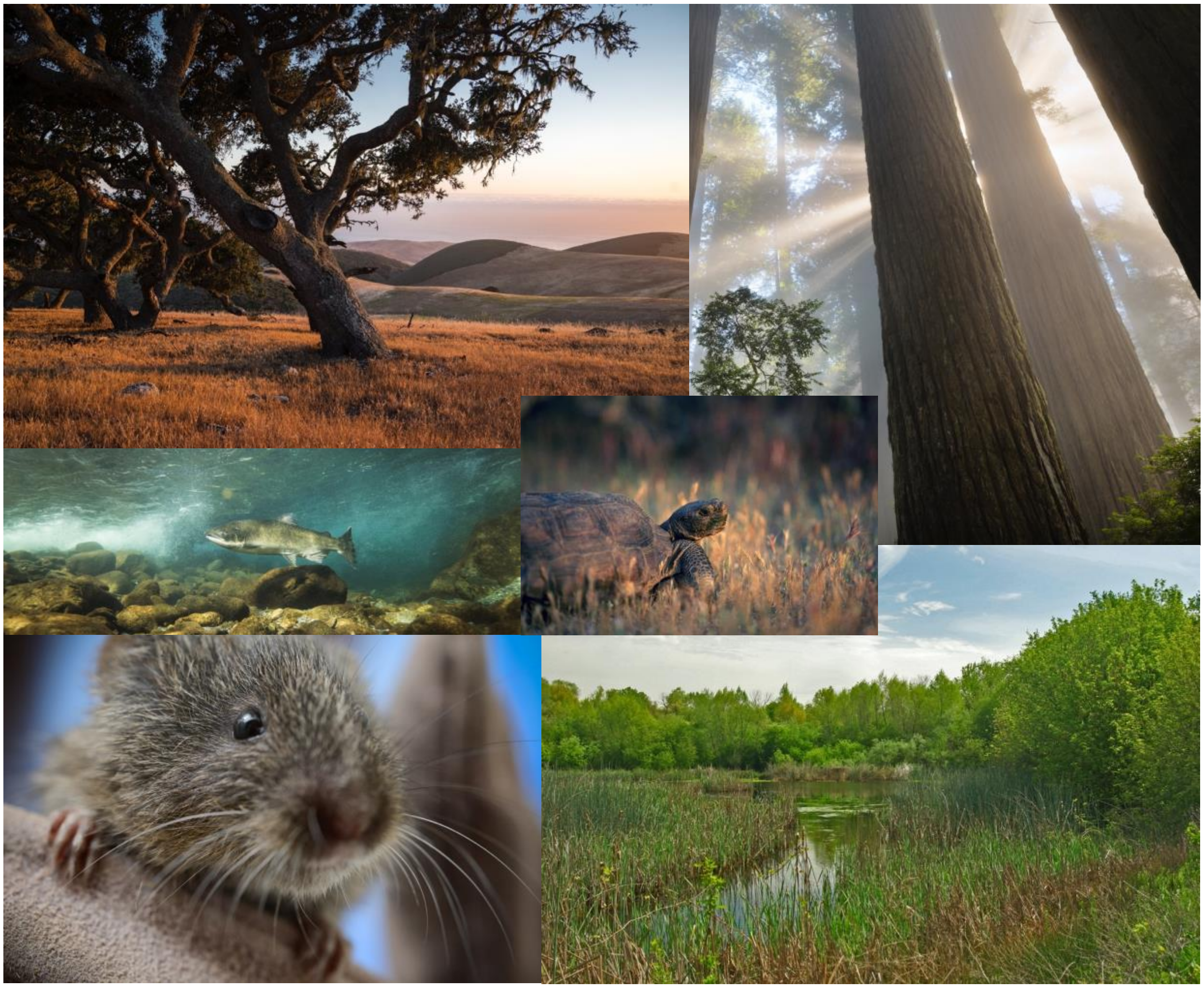
Groundwater Thresholds for Ecosystems

A Guide for Practitioners



Originally published September 2020
Updated December 2020

The Nature Conservancy

The Nature Conservancy is a global non-profit conservation organization whose mission is to conserve the lands and waters on which all life depends.

This publication was developed by the Global Groundwater Group (G3) at The Nature Conservancy (TNC). The G3 was formed in 2018 to network and leverage ongoing efforts across TNC business units to protect groundwater dependent ecosystems (GDEs) and enhance water security for people. The intent of this document is to present a practicable approach for protecting GDEs during groundwater allocation decisions and project planning that can be applied to varying levels of data availability, ongoing hydrologic and ecological monitoring, and future uncertainty.

The authors would like to thank the following individuals for their contributions and review: Allison Aldous, Zach Freed, Jeanette Howard, Eloise Kendy, Sally Liu, Sandi Matsumoto, and Meg White. Illustrations for Figures 1 and 3 were prepared by Rachel Strader.

Authors

Melissa M. Rohde
Groundwater Scientist
The Nature Conservancy of California
melissa.rohde@tnc.org

Laurel Saito
Nevada Water Program Director
The Nature Conservancy of Nevada
laurel.saito@tnc.org

Ryan Smith
Freshwater Ecologist
The Nature Conservancy of Texas
ryan_smith@tnc.org

Recommended Citation

Rohde MM, Saito L, Smith R. 2020. Groundwater Thresholds for Ecosystems: A Guide for Practitioners. Global Groundwater Group, The Nature Conservancy.

Front Page Caption and Photo Credit:
Oak trees: ©Bill Marr, The Nature Conservancy; Redwoods: ©Patrick McDonald, The Nature Conservancy; Chinook salmon: ©Kevin Arnold, The Nature Conservancy; Desert tortoise: ©California Department of Fish and Wildlife; Amargosa vole: ©Don Preisler, University of California Davis; Cosumnes River Preserve: ©Simon Williams, The Nature Conservancy

OVERVIEW

How and when to use this document

The purpose of this document is to provide guidance on quantifying groundwater conditions that are protective of groundwater dependent ecosystems (GDEs). Quantitative groundwater thresholds and objectives are intended to protect GDEs when evaluating new water project proposals (e.g., new wells, water transfers, etc.), developing regional and local water management plans, or meeting legal requirements such as the Endangered Species Act. In this document, we highlight five steps to quantify what groundwater levels are needed to avoid adverse impacts from groundwater use on GDEs. This document focuses on quantifying critical thresholds for ecosystems but does not cover setting triggers for actions to protect ecosystems from reaching those thresholds. Although not the focus of this document, the guidance could also be useful for informing methods to set environmental criteria for groundwater-related activities, such as managed aquifer recharge and water funds.

This document is grounded in the precautionary principle (‘do no harm’) and the mitigation hierarchy (‘first avoid, then minimize, and lastly mitigate’; Kiesecker et al. 2010). Hence, these guidelines are designed to assist the groundwater extractor or regional planning body to ensure that groundwater extraction is not causing or will not cause adverse impacts to local ecosystems.

Given the inherent uncertainty and data gaps that commonly exist at the hydrologic and ecologic interface, this document provides a practical approach based on best available science within an adaptive management framework. This approach relies on routine monitoring to inform decisions and refine thresholds and objectives, as needed. As more data are gathered and thresholds are evaluated, the framework can be iterated in a learning-by-doing approach. It also deals with uncertainty and data gaps by applying risk management and provides a range of approaches for different logistical or financial resources. While adaptive management is a practical approach for dealing with uncertainty, we advocate that strong due diligence (e.g., data collection, modelling, monitoring) is taken to minimize uncertainty as much as possible around the potential impacts to GDEs. A conservative approach that errs on the side of caution can help prevent irreversible damage to GDEs, such as the loss of species or habitat.

What are GDEs?

Groundwater dependent ecosystems (GDEs) are species and ecological communities that rely on groundwater for some or all of their water needs. Groundwater reliance within GDEs varies by species or ecologic communities and is either direct (e.g., phreatophytes relying on groundwater via roots) or indirect (e.g., riparian birds relying on groundwater-dependent vegetation). GDEs vary across the landscape -- from mountains across river valleys to coastal wetlands – with groundwater sustaining upland vegetation, streams, springs, and seeps. If the connection to groundwater is lost as a result of drought or unsustainable groundwater use, then water in GDEs can become depleted. Because groundwater provides a perennial water supply for GDEs, they serve as an important refuge during dry summers and droughts and are often associated with rare and endemic species. GDEs also benefit human well-being by providing water storage, water purification, soil preservation, carbon sequestration, flood risk reduction, and recreational opportunities (Aldous and Bach 2014; Brown et al. 2011; Rohde et al. 2018). For more information on GDEs visit: www.GroundwaterResourceHub.org.

Why is groundwater depletion a threat for groundwater dependent ecosystems?

Groundwater is an important part of the global water cycle, comprising 99% of liquid freshwater, and therefore a critical resource for both people and nature. Globally, an estimated 2.5 billion people rely on groundwater for their basic needs (IWRA 2017). In the United States, 50 percent of the population relies on groundwater for drinking water (Tarbuck and Lutgens 2005), and it is also widely used for irrigated agriculture and industry (Barlow and Leake 2012; Brown et al. 2011). In addition, groundwater provides a buffering capacity and resilience to our water supply during the dry season and droughts, and it moderates temperature and water quality for rivers, wetlands, and springs (Brown et al. 2011; Eamus et al. 2006; Gleeson and Richter 2017; Womble et al. 2018).

There are many threats to the long-term sustainability of groundwater, including groundwater depletion due to groundwater use, deteriorated water quality, and climatic changes that alter recharge rates. When groundwater pumping occurs, water levels decrease at the well, forming a cone-shaped depression that pulls in surrounding water to fill the void (Figure 1). The intensity and timing of the pumping, along with subsurface characteristics such as geology and direction of groundwater flow, will dictate how far the declining water level will extend out from the well along the cone of depression. Declines in water level due to groundwater pumping can disconnect plant roots from groundwater, as well as reduce streamflow in nearby rivers and springs by pulling water out of surface water features into the ground (Figure 1). Multiple wells tapping the same aquifer year-round for municipal use or seasonally for agricultural use amplify the impact, leading to chronic lowering of local and regional groundwater levels and complete disconnection of groundwater to streams and ecosystems.

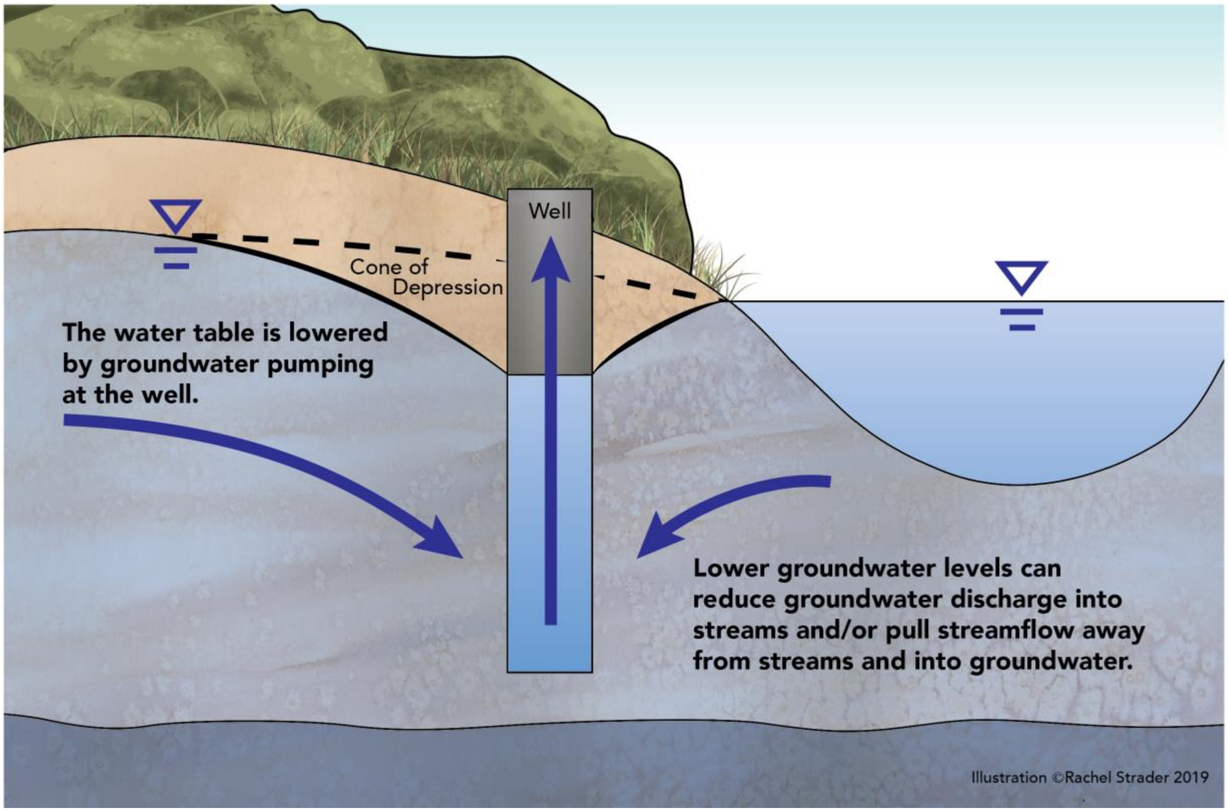


Figure 1. Example of cone of depression due to groundwater pumping. Adapted from Gleeson and Richter (2017).


Sulphur Hot Springs, Nevada
© Janel Johnson,
Nevada Division of Natural Heritage

While both water quantity and quality conditions can impact GDEs, **this document focuses on establishing groundwater quantity thresholds to prevent adverse impacts to GDEs resulting from groundwater declines due to well pumping, altered surface-groundwater interactions, or climate change.** Examples of these adverse impacts include disconnection of vegetation from access to groundwater, declines or cessation in spring flow, and alteration of timing and quantity of groundwater inputs to GDEs. Reduced access to water for plants and animals due to groundwater depletion can jeopardize their persistence, viability, and function. See Appendix I for summary of impacts on vegetation due to changes in groundwater levels. Because groundwater processes and impacts occur across a wide range of spatial and temporal scales (Gleeson et al. 2012; McMahon et al. 2011), setting guidelines for the protection and restoration of GDEs can be challenging, yet attainable.

What is a threshold?

An ecologic **threshold** is a point of irreversible transition from a "stable" state of ecosystem structure and function to an unacceptable or undesirable state (Figure 2; Chambers et al. 2004; Groffman et al. 2006; Moritz et al. 2013). For example, in the context of establishing groundwater level thresholds that are protective of GDEs, a threshold can be defined as groundwater levels that correspond to a hydrologic state that is beyond the acceptable range of variation for ecologic targets within a GDE, resulting in the impairment of key functional traits (e.g., reproduction, survival, growth) that mark a transition towards an undesirable state (e.g., decline in health or resiliency of an ecosystem). Groundwater thresholds can be defined in terms of magnitude, timing, frequency, duration, or rate-of-change, depending on the relevancy of these factors in the viability and resiliency of the GDE (Kath et al. 2018).

For practical purposes, an acceptable range of variation and groundwater threshold are best established for an ecologic target that can indicate whether changes are occurring to GDEs (Figure 2). An **ecologic target** is a species or natural community that can be used to focus a conservation effort and measure effectiveness (Parrish et al. 2003). For example, springsnails would be an ideal ecologic target for defining thresholds within a spring ecosystem, since springsnails entirely rely on groundwater and would cease to exist if spring flow declined beyond a certain amount. Because it is often challenging to directly monitor ecologic targets due to spatial and temporal variability as well as economic and time limitations, hydrologic indicators are more ideal for setting thresholds and monitoring GDEs. **Hydrologic indicators** are distinct and measurable parameters within an ecosystem that can be used to quantify thresholds, such as spring flow in the above springsnail example. A good indicator should be measurable (i.e., able to be recorded and analyzed), clear (i.e., conveys the same meaning to all people), and sensitive (i.e., responsive to changes in condition or item being measured) (TNC 2007). Because many GDEs have a lagged response to reduced access to groundwater and recovery time from impact can be very long (Barlow and Leake 2012; Eamus et al. 2006) it also is often important to have sentinel indicators between withdrawals points and GDEs (Noordujin et al. 2019).

The use of hydrologic indicators requires an understanding of the relationship between groundwater decline and ecologic responses. All ecologic targets will have an acceptable range of variation in response to groundwater due to their physiological and adaptive capacity to deal with water stress. While some targets may respond with a discernable “tipping point” after which ecologic condition rapidly deteriorates, other ecologic targets may respond more gradually, with incremental declines in the ecologic condition as groundwater discharge declines. Avoidance of the “tipping point” threshold may be a clear management goal for certain GDEs, but the establishment of management targets requires the quantification of an acceptable range of variation for the ecologic target. Such management targets and associated triggers are likely to be somewhere between the acceptable range of variation and the avoidance thresholds (i.e., in the “recoverable range”), but are not addressed in this document.

At what scale can thresholds be established?

Groundwater processes and ecosystem responses can occur at a wide range of spatial and temporal scales. These guidelines are suitable for establishing thresholds at two different GDE spatial scales. First are discrete GDEs, such as individual springs, gaining river reaches, wetlands, and terrestrial vegetation, which are the primary focus of this document. Second are groups of GDEs (e.g., all springs of a particular type supported by discharge from one continuous aquifer within the same ecoregion), where data may be collected at one or a few of the GDEs, but are intended to represent conditions at all other GDEs, assuming local hydrogeologic and ecologic conditions are similar.

Temporally, these guidelines apply at time scales of days to decades. Groundwater pumping immediately affects groundwater tables but impacts to GDEs may take months or years to develop (Kath et al. 2018).

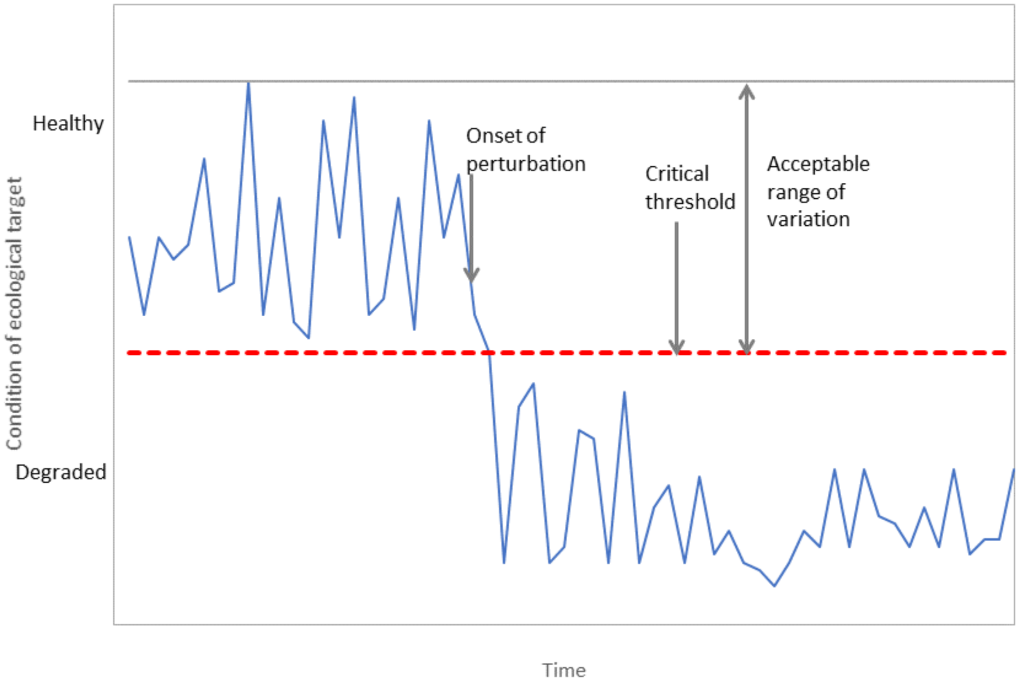


Figure 2. Illustration of acceptable range of variation for ecological targets. The critical threshold indicates when the ecological target has moved to a new state that may not be recoverable or only at high cost. Adapted from TNC (2007).

THE FRAMEWORK

This guidance provides a process to quantify an acceptable range of conditions and thresholds using hydrologic indicators to avoid adverse impacts from groundwater use on GDEs. This framework is structured to answer the following five key questions:

1. What is the conservation objective?
2. How does groundwater support the ecosystem, and on what temporal and spatial scales?
3. How does human groundwater use negatively impact the ecosystem?
4. What hydrologic indicators can be used to monitor impacts to target species within the ecosystem?
5. What groundwater levels are necessary to maintain or enhance the ecosystem?

Table 1 provides two examples for the outputs of Steps 1 through 5 for ecologic targets within a GDE that are either directly or indirectly reliant on groundwater.

Table 1. Example summary outputs of Steps 1-5 for ecologic targets within a GDE that are either directly or indirectly reliant on groundwater.

Guidance Component	Directly Reliant	Indirectly Reliant
Conservation Goal	Sustain or enhance natural habitats that rely on groundwater	Protect endangered species dependent on groundwater-fed habitat
Ecological Target	Springsnails	Southwestern willow flycatcher
Key Ecologic Attribute	Springsnail habitat in a spring	Riparian forest and willow (*Salix* spp.) habitat for southwestern willow flycatcher
Hydrologic Indicator	Spring flow	Groundwater levels
Hydrologic Goal	Spring discharge or water level in summer months (driest time of year)	Groundwater levels are close to willow roots
Ecologic Responses	Acceptable Range: Springsnail populations are stable over water year types Threshold: Springsnail population growth rate is below replacement.	Acceptable Range: Willow growth and reproduction are maintained over water year types. Threshold: Willow sapling recruitment is decreased.
Acceptable Range of Variation	5-50 cfs (cubic feet per second) throughout the year	1-2 m depth below ground surface
Threshold	5 cfs in summer months	2 m depth below ground surface

Step 1. State the Conservation Objective

There are many reasons why it may be necessary to define groundwater thresholds and acceptable ranges of variation for ecosystems. It is assumed that a process has been applied through collaboration, an agency mandate, or other means to develop the conservation objective for which groundwater thresholds for ecosystems are needed. Examples of conservation objectives include the desire to:

- quantify how much groundwater a GDE needs to balance human and ecosystem needs,
- improve ecosystem resilience to climate change,
- protect endangered species or critical habitats dependent on groundwater,
- sustain or enhance natural habitat areas that rely on groundwater,
- prevent proposed land development projects or well installations from impacting nearby ecosystems, and
- protect important ecosystem services (e.g., commercial fishing industry, recreational uses of habitat areas, crop production) that are supported by groundwater.

The conservation objective should be time-bound and specify the geographic scope to inform what groundwater thresholds and acceptable conditions are necessary. Objectives that are SMART (Specific, Measurable, Achievable, Relevant, and Time-bound) are more likely to succeed.

Dolan Creek, Texas
©Ryan Smith, The Nature Conservancy

Step 2. Build an Ecohydrologic Conceptual Model

An ecohydrologic conceptual model provides an understanding of the general physical and biological characteristics related to what is known about the hydrology, land use, geology and geologic structure, water quality, and ecology. This step generates a representation of the system that identifies the ecologic target(s) and can serve as an important communication tool for expert opinion and stakeholder outreach. The ecohydrologic conceptual model can be a simple hand-drawn figure that indicates fluxes and stressors to the system. Figure 3 illustrates the type of system for which some data may be available, with identified fluxes and stressors drawn on the system.

To create an ecohydrologic conceptual model for the GDE of interest, answer the following questions:

1. What are the surficial landscape features of the GDE (e.g., slope, terrain, surface water features, land cover)?
2. How is groundwater expressed across time and space? What are the hydrological fluxes in and out of the system (see Appendix II for a list of guiding questions on how to identify the hydrological components of the system)?
3. What are the ecologic targets (e.g., the focal species, habitats, and ecosystems with biological or legal significance)?
4. What are the known or likely stressors in the system (e.g., surface water diversions, groundwater pumping, land development/disturbance, pests, invasive species)?
5. What are the data gaps and knowledge uncertainties?

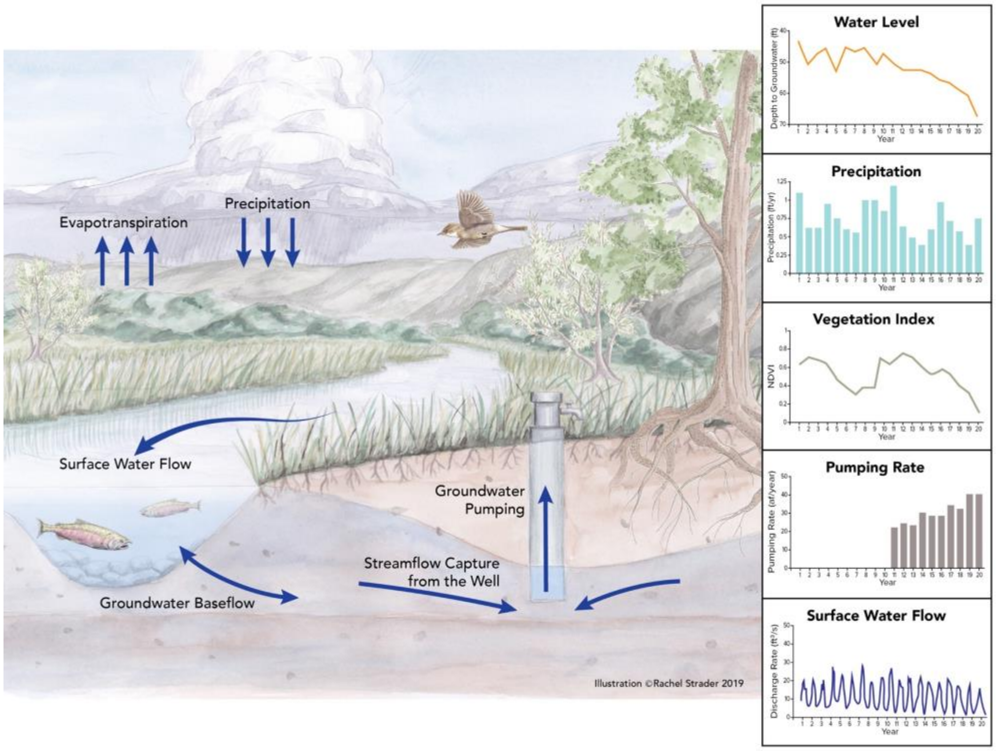


Figure 3. Example of generalized ecohydrologic conceptual model showing fluxes and stressors to the groundwater system. Charts show hypothetical time series data for water levels, precipitation, vegetation, pumping rates, and surface flows.

STEP 3. Identify Potential Cause-and-Effect Relationships and Define the Groundwater Threat

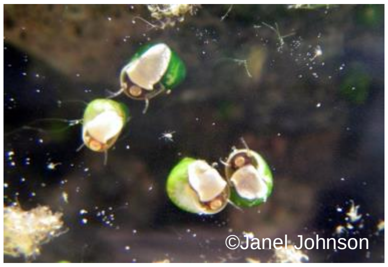
Ecosystems have many stressors; however, determining groundwater thresholds relies on a clear understanding of the cause-and-effect relationships between groundwater and ecosystems. The output of this step is a list of potential cause-and-effect chains between groundwater and the ecologic targets identified in Step 2 (Figure 4).

Figure 4. Generalized cause-and-effect chain

Cause-and-effect chains vary based on how the ecologic targets rely on groundwater, which can fall under two categories:

Direct Reliance – Species or ecologic communities that directly rely on groundwater for some or all of their water needs. Examples include aquatic species inhabiting spring ecosystems and entirely reliant on groundwater, phreatophytes relying on groundwater via rooting networks during the dry season, and anadromous fish relying on groundwater baseflow into streams for juvenile rearing and migration.

Example cause-and-effect chains for species directly reliant on groundwater:



©Janel Johnson

groundwater level declines diminish spring flow → springsnails lose necessary flow, wetted habitat, and water quality → springsnail population crashes

©Simon Williams

groundwater levels decline → phreatophytes lose access to groundwater →ecosystem transitions to weedy, fire-prone vegetation

©Pacific Northwest National Laboratory

groundwater levels decline cause decreasing baseflow → salmon lose spawning habitat → salmon population crashes

Indirect Reliance - Species or populations that indirectly rely on groundwater to satisfy habitat and forage needs. Examples include riparian birds (e.g., southwestern willow flycatcher) that depend on specific groundwater-dependent vegetation (e.g., willow, cottonwood) and upland species (e.g., sage-grouse) that depend on mesic wet meadows that are often fed by groundwater.

Example cause-and-effect chain for species indirectly reliant on groundwater:


©Kelly Colgan Azar

groundwater levels decline → willow (*Salix* spp.) roots lose access to groundwater → willow trees die off and southwestern willow flycatcher birds (a listed species) loses habitat


©Joe Kiesecker

groundwater levels decline → mesic wet meadows lose access to groundwater and dry out → decline in insect food source for sage-grouse chicks results in population decline


Guadalupe River, Texas
©Ryan Smith, The Nature Conservancy

STEP 4. Select Appropriate Hydrologic Indicators to Monitor and Assess Targets

The output of Step 4 is a set of hydrologic indicators that can be used to monitor the alteration in hydrologic connection for the ecologic target identified in the cause-and-effect chains developed in Step 3. These indicators should measure how the ecologic target responds to changes in groundwater levels or fluxes at appropriate spatial and temporal scales.

To select the appropriate hydrologic indicators, we recommend first identifying at least one key ecologic attribute for each ecologic target. **Key ecologic attributes** are defined as aspects of an ecologic target's biology or ecology that, if missing or altered, would lead to the loss of that target over time (Parrish et al. 2003; TNC 2007). The key ecologic attribute could be related to a target's size (e.g., area or abundance), condition (e.g., biological composition, structure, or biotic interactions), or landscape context (e.g., disturbance, connectivity, or resources) (TNC 2007). For example, a key ecologic attribute for springsnails might be habitat of sufficient water quality (e.g., temperature range).

Identify a set of hydrologic indicators by creating an inventory of available, missing, or insufficient data (see Appendix III), which will then be used to select the best indicator(s). The best indicators are those for which data are available and balance logistical and financial considerations, and which can indicate trends towards thresholds. For example, we may prioritize indicators for monitoring based on the risks associated with adverse impacts to various ecologic targets, how probable groundwater conditions are to change from baseline conditions, and the ecologic value of the GDE. If ecologic risks are high (e.g., groundwater conditions are likely to deviate from baseline conditions and ecologic targets have special or protected status), then selecting an indicator that can be quantified with more accurate methodology that provides more certainty should be prioritized.

Spring in Texas
©Ryan Smith, The Nature Conservancy

STEP 5. Quantify Acceptable Range of Variation and Groundwater Threshold

Hot Creek Pool, Nevada
©Janel Johnson,
Nevada Division of Natural Heritage

Once hydrologic indicators have been identified from Step 4, the next step is to quantify an acceptable range of variation and a groundwater threshold. This is done by tracking how the ecologic target responds to fluctuations in the hydrologic connection to groundwater over time and space. Most hydrologic indicators can be determined and monitored using a range of methodologies, with tradeoffs between time, costs, accuracy (and uncertainty), and expertise required. Appendix IV provides a table of methodologies that can be used to quantify acceptable ranges of variation or thresholds for various hydrologic indicators, along with the associated pros and cons.

Ideally, hydrologic data for the selected indicators should be paired with biologic data to empirically establish the threshold. However, in some cases if long-term hydrologic data exist, it is possible to infer a groundwater threshold initially using hydrologic data and expert opinion. For example, if a biological expert deems an ecologic target (e.g., phreatophyte oak species) to be in a relatively healthy condition (e.g., sapling recruitment and succession are occurring), and late-summer groundwater levels (the selected hydrologic indicator) in the GDE fluctuate between 5 and 10 m (15 to 30 feet) over wet and dry years, then it can be inferred that this is the acceptable range of variation (Figure 5a). Based on this acceptable range of variation, along with expert opinion of maximum rooting depths and a scientific literature review, an initial groundwater threshold can be established (e.g., the baseline low or 25th percentile of the range) until more data and analyses are obtained. Alternatively, if the hydrologic data indicate a rate of change in the baseline with corresponding effects observed for the oaks (e.g., lack of understory or crown dieback), then it could be inferred that a threshold has been passed (Figure 5b). Both examples are contingent upon baseline groundwater level data remaining steady over multiple years (and wet, average, and dry years) and that the data are not capturing a long-term declining trend (Figure 5c).

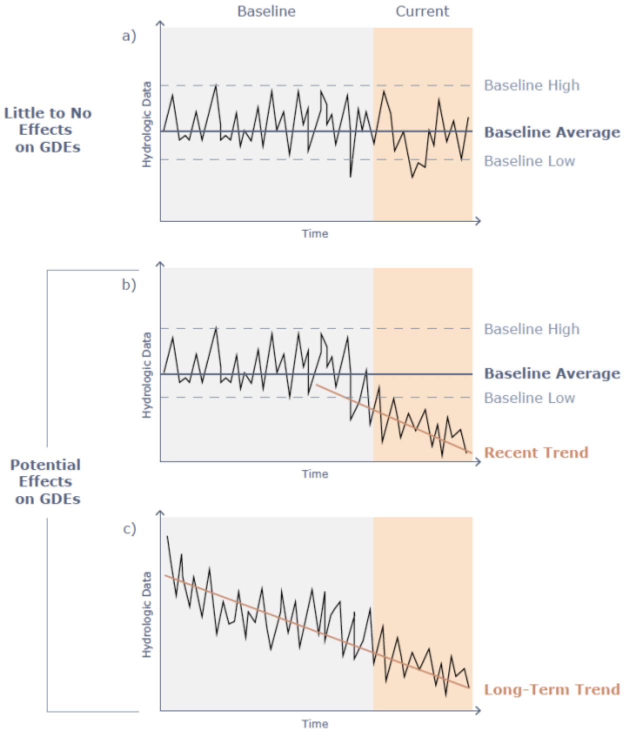


Figure 5. Using hydrologic data to infer an acceptable range of variation and groundwater threshold (Source: Rohde et al. 2018).

While the simplified approach described with Figure 5 may work for ongoing groundwater management efforts, it is not a sufficient approach for evaluating potential impacts from groundwater development projects on GDEs. Using the five steps outlined in this framework, three case study examples are provided in Appendix V to demonstrate how groundwater thresholds were determined for GDEs in Texas (USA).

ADDITIONAL CONSIDERATIONS

In addition to establishing thresholds and acceptable ranges of variation, it is critical to set triggers for action to avoid reaching thresholds, and to use a monitoring network to track how groundwater use in the basin is impacting GDEs. Setting triggers is beyond the scope of this document because it involves stakeholders and decision-makers that must balance multiple factors. In regard to monitoring, impacts to GDEs may take months or years to develop due to lagged groundwater responses, and those impacts can continue even after pumping stops (Barlow and Leake 2012). The lagged groundwater response thus requires a careful selection of groundwater monitoring wells outside the GDE to provide an early warning system of migrating impacts to inform appropriate management actions. For example, in the above springsnail example, monitoring spring flow at the spring itself would not allow for sufficient response time to prevent adverse impacts to the springsnails. Instead, monitoring thresholds should be situated outside the GDE closer to the groundwater withdrawal location to indicate whether groundwater is declining. Ideally, GDE thresholds should be used in groundwater models to simulate (1) whether or not proposed projects will cause adverse impacts to occur to GDEs, or (2) whether groundwater use in the basin are maintaining groundwater conditions within the acceptable range of variation to sustain GDEs.

REFERENCES

Aldous A, Bach L. 2014. Hydro-ecology of groundwater-dependent ecosystems: applying basic science to groundwater management. Hydrologic Sciences Journal 59(3-4): 530-544.

Barlow PM, Leake SA. 2012. Streamflow depletion by wells: Understanding and managing the effects of groundwater pumping on streamflow. US Geological Survey Circular 1376, Reston, VA. 84 p. Available at http://pubs.usgs.gov/circ/1376/. (accessed 9/4/18)

Brown J, Bach L, Aldous A, Wyers A, DeGagné J. 2011. Groundwater-dependent ecosystems in Oregon: an assessment of their distribution and associated threats. Frontiers in Ecology and the Environment 9(2): 97-102.

Chambers JC, Miller JR, Germanoski D, Weixelman DA. 2004. Process-based approaches for managing and restoring riparian ecosystems. Pp. 261-292 in Chambers JC, Miller JR, eds. Great Basin Riparian Ecosystems, Island Press, Washington, DC.

Eamus D, Froend R, Loomes R, Hose G, Murray B. 2006. A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. Australian Journal of Botany 54(2): 97-114.

Gleeson T, Alley WM, Allen DM, Sophocleous MA, Zhou Y, Taniguchi M, VanderSteen J. 2012. Towards sustainable groundwater use: setting long-term goals, backcasting, and managing adaptively. Ground Water 50(1): 19-26.

Gleeson T, Richter B. 2017. How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers. River Research and Applications 2017:1-10.

Groffman PM, Baron JS, Blett T, Gold AJ, Goodman I, Gunderson LH, Levinson BM, Palmer MA, Paerl HW, Peterson GD, Poff NL, Rejeski DW, Reynolds JF, Turner MG, Weathers KC, Wiens J. 2006. Ecological thresholds: the key to successful environmental management or an important concept with no practical application? Ecosystems 9:1-13.

IWRA. 2017. Policy Brief: Groundwater and Climate Change: Multi-level Law and Policy Perspectives. Water International, Number 8. 4 p.

Kath J, Boulton AJ, Harrison ET, Dyer FJ. 2018. A conceptual framework for ecological responses to groundwater regime alteration (FERGRA). Ecohydrology 11: e2010. https://doi.org/10.1002/eco.2010.

Kiesecker JM, Copeland H, Pocewicz A, McKenney B. 2010. Development by design: blending landscape-level planning with the mitigation hierarchy. Frontiers in Ecology and the Environment 8(5): 261-266.

McMahon PB, Plummer LN, Böhlke JK, Shapiro SD, Hinkle SR. 2011. A comparison of recharge rates in aquifers of the United States based on groundwater-age data. Hydrogeology Journal 19: 779-800.

Moritz MA, Hurteau MD, Suding KN, D'Antonio CM. 2013. Bounded ranges of variation as a framework for future conservation and fire management. Annals of the New York Academy of Sciences 1286:92-107.

Noordujin SL, Cook PG, Simmons CT, Richardson SB. 2019. Protecting groundwater levels and ecosystems with simple management approaches. Hydrogeology Journal 27:225-237. https://doi.org/10.1007/s10040-018-1849-4.

Parrish JD, Braun DP, Unnasch RS. 2003. Are we conserving what we say we are? Measuring ecological integrity within protected areas. BioScience 53(9):851-860.

Rohde MM, Matsumoto S, Howard J, Liu S, Riege L, Remson EJ. 2018. Groundwater Dependent Ecosystems under the Sustainable Groundwater Management Act: Guidance for Preparing Groundwater Sustainability Plans. The Nature Conservancy, San Francisco, CA.

Tarbuck EJ, Lutgens FK. 2005. Earth: An Introduction to Physical Geology, 8th Ed. Pearson Prentice Hall, Upper Saddle River, NJ.

[TNC] The Nature Conservancy. 2007. Conservation Action Planning Handbook: Developing Strategies, Taking Action and Measuring Success at Any Scale. The Nature Conservancy, Arlington, VA. Available at https://www.conservationgateway.org/Files/Pages/action-planning-cap-handb.aspx (Accessed 3/6/19)

Womble P, Perrone D, Jasechko S, Nelson RL, Szeptycki LF, Anderson RT, Gorelick SM. 2018. Indigenous communities, groundwater opportunities. Science 361(6401): 453-455.

Photo Credits

Page 10. “Moapa springsnails” ©Janel Johnson, Nevada Division of Natural Heritage

Page 10. “Lamoille Canyon, NV” ©Simon Williams, The Nature Conservancy

Page 10. "Chinook Salmon" by Pacific Northwest National Laboratory - PNNL is licensed with CC BY-NC-SA 2.0. To view a copy of this license, visit https://creativecommons.org/licenses/by-nc-sa/2.0/

Page 11. "Willow Flycatcher" by Kelly Colgan Azar is licensed with CC BY-ND 2.0. To view a copy of this license, visit https://creativecommons.org/licenses/by-nd/2.0/

Page 11. “Sage Grouse” ©Joe Kiesecker, The Nature Conservancy

APPENDICES

APPENDIX I

Summary of Recent Literature Relating Vegetation Response to Groundwater Availability (Adapted from Eamus et al. 2015)

Process/trait	Process Response	Change or Range in Depth to Groundwater (meters)	References
Leaf-scale Photosynthesis			
	Decreased	0 to 9	Horton et al. (2001)
Stomatal Conductance			
	Decreased	0 to 9	Horton et al. (2001)
	Decreased	0 and >1	Cooper et al. (2003)
	Stomatal resistance increased from 38.8 to 112.5	0 to > 3	Zunzunegui et al. (2000)
	Decreased	7 to 23	Gries et al. (2003)
	Decreased	2 to 4	Kochendorfer et al. (2011)
Canopy Conductance			
	Decreased	1.5 to > 5	Carter and White (2009)
	Decreased	2 to 4	Kochendorfer et al. (2011)
Leaf and Stem Water Potential			
	ψ_{pd} decrease from -0.5 to -1.7 MPa	0 to 9	Horton et al. (2001)
	ψ_{pd} decrease from 0.2 - 0.4 MPa to -0.4 – -0.8 MPa	0 and >1	Cooper et al. (2003)
	Decreased from -0.79 to -2.55 MPa	<2 to >20	Froend and Drake (2006)
	Decreased from -1.85 to -3.99 MPa	0 to 3	Zunzunegui et al. (2000)
	ψ_{midday} decreased	7 to 23	Groom et al. (2000)
	ψ_{midday} decreased during growing season	0 to .15	Devitt et al. (2011)
Transpiration Rate			
	Total ET decreased 32%	0.9 to 2.5	Cooper et al. (2006)
	ET decreased	2 to 4	Kochendorfer et al. (2011)
	Evaporation decreased from 966 to 484 mm	1.1 to 3.1	Gazal et al. (2006)
	Annual evaporation decreased	zero to 8	Ford et al. (2008)
Resistance to Xylem Embolism			
	Increased	1.5 to 30	Canham et al. (2009)
	PLC_{50} decreased from -1.07 to -3.24 MPa	<2 to >20	Froend and Drake (2006)
Growth Rate			
	Decreased	zero to >1	Scott et al. (1999)
	Decreased	7 to 23	Gries et al. (2003)
Leaf Area Index			

	Decreased from 3.5 to 1.0	1.5 to >5	Carter and White (2009)
	Decreased	n.d.	O'Grady et al. (2011)
	Decreased from 2.5 to 0.66	zero to 3	Zunzunegui et al. (2000)
	Decreased from 2.7 to 1.7	1.1 to 3.1	Gazal et al. (2006)
Huber Value (SWA/LA)			
	Increased from 3.3 to 4.7	1.1 to 3.1	Gazal et al. (2006)
	No change	1.5 to 30	Canham et al. (2009)
	Increased from 3.4 to 4.3 x 10^{-4}	1.5 to >5	Carter and White (2009)
Plant Density			
	Vascular species number decreased	n.d.	Zinko et al. (2005)
	Species composition changed	0.9 to 2.5	Cooper et al. (2006)
	Plant cover type changed	1.1 to 2.5	Merritt and Bateman (2012)
	Vegetation cover and diversity decreased	1 to 110	Lv et al. (2013)
NDVI			
	Decreased	1 to 110	Lv et al. (2013)
	Decreased	zero to 1.5	Aguilar et al. (2012)
	Decreased	1.8 to 3.5	Wang et al. (2011)
Crown Die-Back			
	Increased between <40% to >50%	zero to 9	Horton et al. (2001)
	Leaf loss 34%	zero and >1	Cooper et al. (2003)
Mortality			
	Increased	>2.2	Groom et al. (2000)
	Increased	zero to >1	Scott et al. (1999)
	Increased	0.4 to 5	González et al. (2012)

ψ_{pd} is the pre-dawn water potential

ψ_{midday} is the water potential at mid-day

PLC is the water potential corresponding to 50% loss of conductivity

n.d. no data available

APPENDIX II
Identifying Hydrologic Components in a System

These questions can help to understand the hydrologic components in the system of interest. Not all of this information may be available for a particular system.

AQUIFER CONDITIONS

1. What type(s) of aquifers (e.g., unconfined, confined, perched, semi-confined) underlie the GDE? What is known about the groundwater flow, residence time, and interactions between aquifers?
2. What is known about the lithology (e.g., clay, silt, sand, gravel) comprising the aquifer and unsaturated zone? What are the hydraulic properties (e.g., hydraulic conductivity, porosity, specific yield)?

WATER AVAILABILITY

1. How much consumptive water use occurs within the GDE?
2. What are the depths to groundwater within the GDE?
3. What are the seasonal (summer/winter), interannual (wet/dry/average years), or long-term trends in groundwater levels?
4. What is the spatial variability in groundwater levels within the GDE? If so, what is the general direction of flow and the cause of that flow?
5. For GDEs with water emerging at the Earth’s surface (e.g., natural runoff, urban stormwater runoff, treated wastewater effluent, springs, rivers),
    a. What is the spatial or temporal variability in the gaining and/or losing conditions of the surface water and groundwater interconnection?
    b. What are the main sources of surface water (e.g., natural runoff, urban stormwater runoff, treated wastewater effluent)? What are the timing and flow dynamics?
    c. Are there any seasonal (winter/summer), interannual (wet/dry/average years) or long-term trends in the flow hydrograph?
6. How may climate change impact future water availability in the GDE?

WATER QUALITY

1. Are there any known water quality issues (e.g., temperature, dissolved oxygen, nutrient, salinity, pH, etc.) with the groundwater?
2. Are there any known water quality issues (e.g., temperature, dissolved oxygen, nutrient, salinity, pH, etc.) with the main source of surface water?
3. Are there any known contaminant plumes in groundwater under the GDE?

HUMAN INFLUENCES

1. Is there any current or anticipated pumping from the aquifer that supports the GDE?
2. If the aquifer supporting the GDE is perched, has the underlying aquitard been compromised by well bores or other construction activities?
3. Is the aquifer supporting the GDE actively monitored or managed?
4. Is any of the surface water interconnected with groundwater supporting the GDE being diverted, regulated, or used for other beneficial uses and users? If so, what is the variability in the timing and flow?
5. Is there any anticipated land use change that could affect the GDE?

APPENDIX III
Sample Indicator Inventories

Complete one form for each conservation target and cause-effect chain (*example entries are in italics*)

Data availability: Indicate availability of data
H = high (fairly complete dataset of measure over time and space)
M = moderate (data available for measure with some gaps in time and space)
L = low (some data available for measure)
X = no data available
Knowledge certainty
H = high (little uncertainty in knowledge of measure)
M = moderate (medium level of uncertainty in knowledge of measure)
L = low (high uncertainty in knowledge of measure)
X = no knowledge of measure

Conservation goal:	*Sustain or enhance natural habitat areas that rely on groundwater*		
Ecological target or key ecological attribute:	*Springsnail habitat in a spring*		
Items in case-effect chain			
Groundwater Indicator	Description	Data availability	Knowledge certainty
Measure 1:	*Groundwater levels at site 1*	*M*	*M*
Measure 2:	*Groundwater levels at site 2*	*H*	*H*
Measure 3:			
Alteration in hydrologic connection	Description	Data availability	Knowledge certainty
Measure 1:	*Spring flow at site 1*	*L*	*L*
Measure 2:	*Streamflow at downstream site 2*	*H*	*H*
Measure 3:			
Habitat or species impacted	Description	Data availability	Knowledge certainty
Measure 1:	*Springsnail population numbers*	*L*	*L*
Measure 2:	*Spring habitat (i.e., water in spring) for springsnails*	*M*	*M*
Measure 3:			

APPENDIX IV

Methods for Quantifying Acceptable Range of Variation and Groundwater Thresholds

Method[a]	Assumptions	Data Needs	Uncertainty	Effort[b]	Cost[c]	Pros/Cons
Expert opinion	• Experts are knowledgeable	Low	High	🕒	$	Subjective, and can be questioned
Literature review	• Literature is science-based	Low	High	🕒	$	Relevant literature may not be available
Basic statistical approaches Baseline change detection, linear correlations, stress gradients, ordination, percent change approaches (e.g., % of flow)	• Data independence • No auto-correlation for time series (or it is addressed) • Adequate data are available	Med-High	Med	🕒🕒	$$	• Uncertainties due to large data gaps may exist • Some approaches do not handle small sample size, data that are not independent, or missing data
Statistical models General models (e.g., linear, logistic), functional linear models, Bayesian models, forest gradient models, information theory	• Normal or other statistical distribution • Data independence • No auto-correlation for time series (or it is addressed) • Adequate data are available	Med-High	Med	🕒🕒	$$-$$$	• Most models require large sample sizes • Can deal with missing data
Population/ecological models Population, life-history models	• Adequate understanding of life history, population dynamics • Relevance of model coefficients • Adequate data are available	Med-High	Low-Med	🕒-🕒🕒	$$-$$$	Transferability of models is highly uncertain
Spatially-explicit models Aquifer models, watershed models, hydraulics models	• Acceptable accuracy of model • Representativeness of selected model area • Adequate data are available	High	Low	🕒🕒-🕒🕒🕒	$$$	• Data requirements are high for well-calibrated models • Model outcomes can be sensitive to assumptions of inputs and parameters

[a] See brief descriptions below in Method Definitions
[b] Effort: 🕒 = less than 6 months for one person**,** 🕒🕒 = 6 months to two years for one or more people**,** 🕒🕒🕒 = more than two years for one or more people
[c] Cost: $ = less than $10,000, $$ = between $10,000 and $100,000, $$$ = greater than $100,000

Method Definitions:

Expert opinion – consultation with experts with technical knowledge of the relevant GDE including ecological indicators of its health and hydrologic metrics that drive ecosystem health. Experts can inform all steps in the process, with emphasis on definition of GDE thresholds based on their experience with GDEs of interest or similar GDEs.

Literature review – review of relevant literature for the GDE of interest, which may include available information specific to the site/region of interest or may include relevant information such as rules of thumb (e.g., % of flow thresholds) that can be reasonably assumed to be relevant to the GDE(s) of interest.

Basic statistical approaches –methods using statistical approaches to analyze and evaluate thresholds using empirical data from the GDE of interest. May include descriptive statistics (e.g., average baseline water level in monitoring wells), inferential statistics, or methods such as time series analysis (e.g., trend tests). Main distinction with the next category is that these methods do not develop predictive models, but only use descriptive or inferential statistics.

Statistical models –approaches using statistical methods to develop models describing the relationships between hydrologic metrics and ecological metrics and allowing prediction of ecological characteristics based on hydrologic metrics. This category may include a broad array of modeling approaches with different assumptions (e.g., underlying statistical distributions). Models will require empirical data from the GDE, though models from other GDEs may be transferred to the GDE of interest if the user assumes sufficient similarity of systems.

Population/ecological models – models that predict population (e.g., population size) or life history outcomes (e.g., recruitment) based on environmental conditions and other factors (e.g., species-specific coefficients). May be considered a subset of statistical models but differentiated here because of their greater ability to describe the processes regulating the ecological response.

Spatially-explicit models – spatial models that simulate physical or ecological conditions based on characteristics that can be spatially mapped. Examples include aquifer models (e.g., MODFLOW, FEFLOW), watershed models (e.g., HSPF, SWAT), and hydraulics models (e.g., HEC-RAS, PHABSIM). These models can then simulate management or other scenarios to evaluate changes in GDE conditions. These methods will often be combined with other models (e.g., basic statistics or statistical or population models) to define thresholds.

APPENDIX V
Example Framework Applications

We provide some examples of applications of the Groundwater Thresholds for Ecosystems Framework to groundwater dependent ecosystems in Texas.

Example 1 (High Data Availability)
EDWARDS AQUIFER

San Marcos River and Texas Wild Rice
©Edwards Aquifer Authority

The Edwards Aquifer in central Texas (Figure V.1) is an artesian aquifer formed in the karst of Cretaceous limestone that supplies water to more than two million people while supporting a diverse array of groundwater dependent ecosystems. Notably, the aquifer contains subterranean habitats and naturally discharges to springs such as Comal and San Marcos, which support eleven endangered species. Some of these species were a subject of a lawsuit that led to the creation of a management authority and initiated a period of intensive research that has informed a current Habitat Conservation Plan (Edwards Aquifer Authority, 2020). Components of this plan serve as the basis for the steps of our threshold framework as outlined below.

Figure V.1. Location of the Edwards Aquifer in central Texas. Shown are the drainage area contributing to the aquifer, its recharge zone and artesian zones from which the springs emanate. Source: Edwards Aquifer Authority.

STEP 1. State the Conservation Objective

The conservation objective aims to balance human use of the Edwards Aquifer with ecosystem water needs, especially by protecting endangered species (i.e., Texas wild-rice, fountain darter, and Comal Springs riffle beetle) and their critical habitats (i.e., San Marcos and Comal Springs) that are dependent on groundwater.

STEP 2. Build an Ecohydrologic Conceptual Model

A detailed ecohydrologic conceptual model is described in the Habitat Conservation Plan (Edwards Aquifer Authority, 2020). Figure V.2 provides a simplified model.

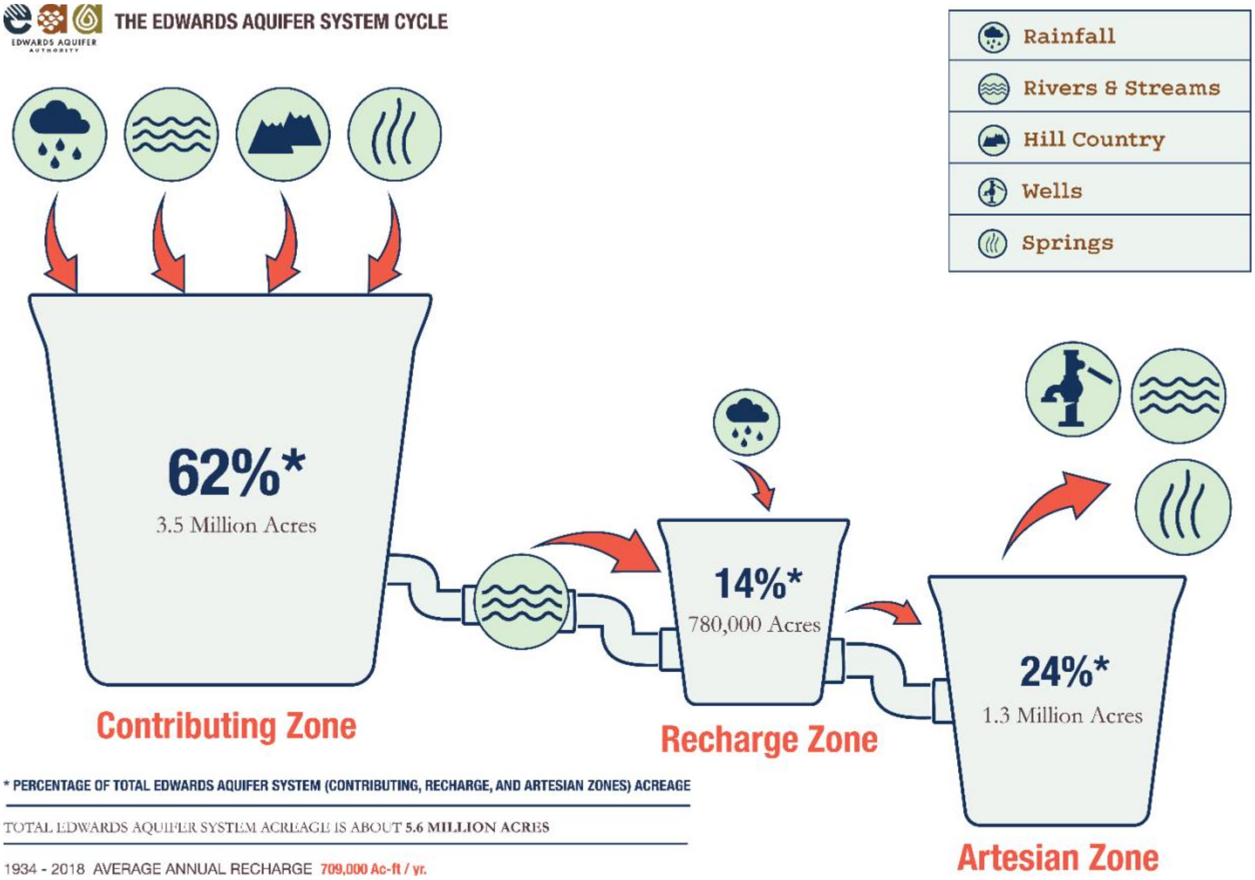
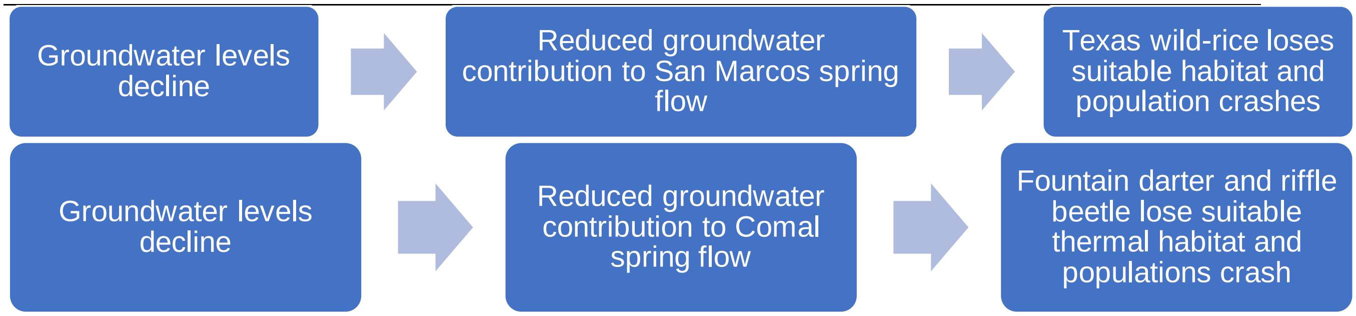


Figure V.2. A simplified ecologic conceptual model for the Edwards Aquifer.

STEP 3. Identify Potential Cause-and-Effect Relationships and Define the Groundwater Threat



For more details, see Habitat Conservation Plan [2].

STEP 4. Select Appropriate Hydrologic Indicators to Monitor and Assess Targets

For Texas wild-rice habitat, monitor San Marcos Springs spring flow based on relationship between spring flow and Texas wild-rice habitat (Figure V.3). Total flow of San Marcos Springs is measured as the flow of the San Marcos River downstream of the springs.

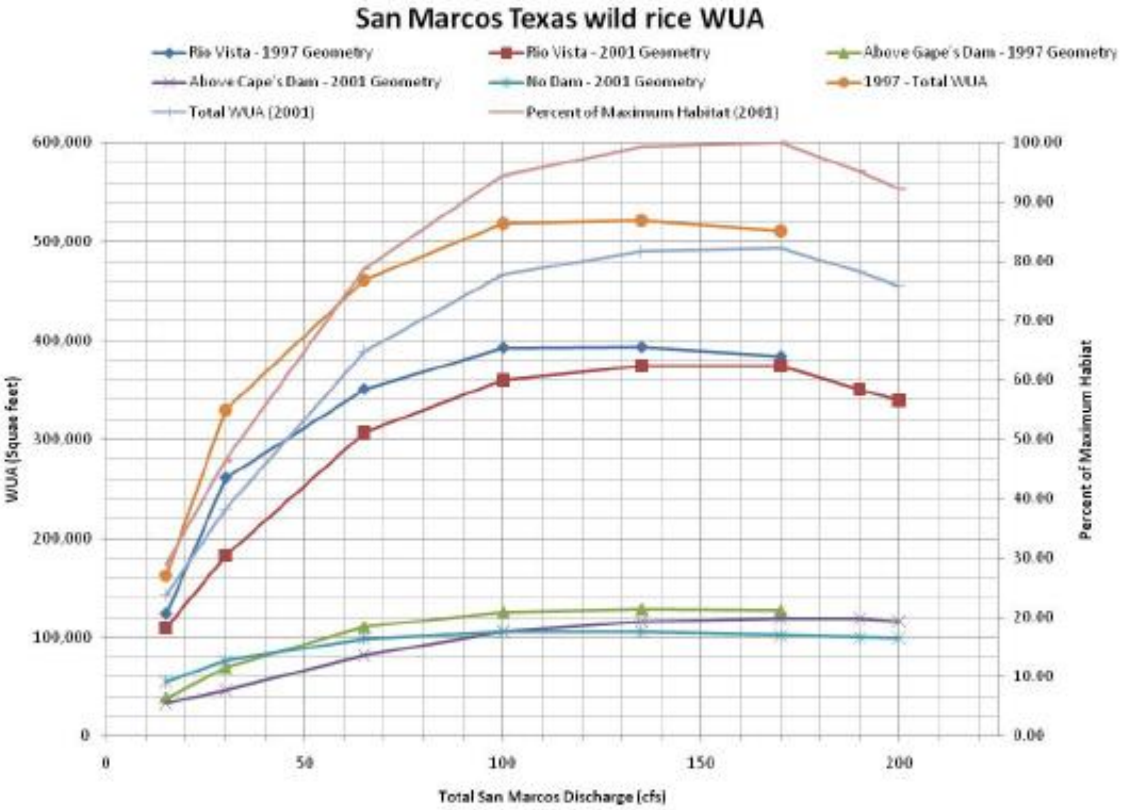


Figure V.3. Simulated Texas wild-rice available habitat ("weighted usable area" (WUA)) in sections of the San Marcos River based on 1997 channel geometries, 2001 channel geometries, and geometries based on assumed removal of Cape's Dam (No Dam). The total area based on 2001 geometry is also shown as a percent of the maximum habitat (Hardy, 2009).

For Comal Springs riffle beetle and fountain darter, monitor Comal Springs spring flow based on relationship between spring flow and thermal habitat for Comal Springs riffle beetle and fountain darter (Figure V.4). Total flow of Comal Springs is measured as the flow of the Comal River downstream of the springs.

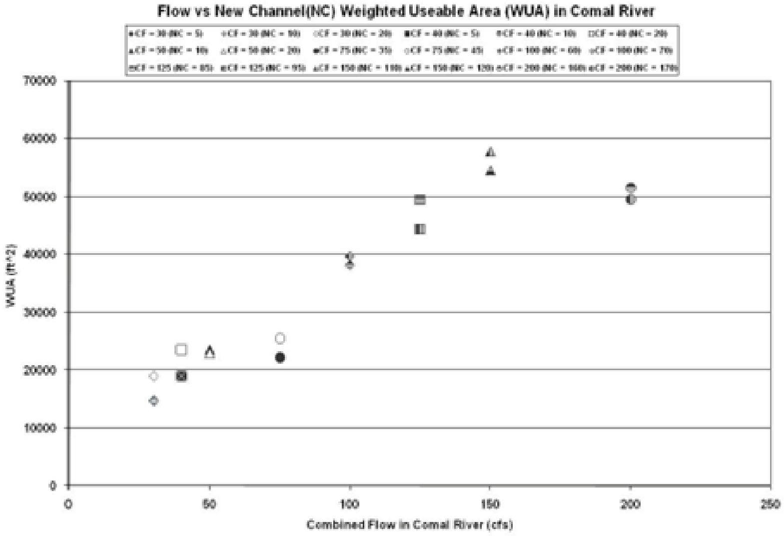


Figure V.4. Relationships between total Comal River discharge and simulated available habitat for fountain darters in the new channel [3].

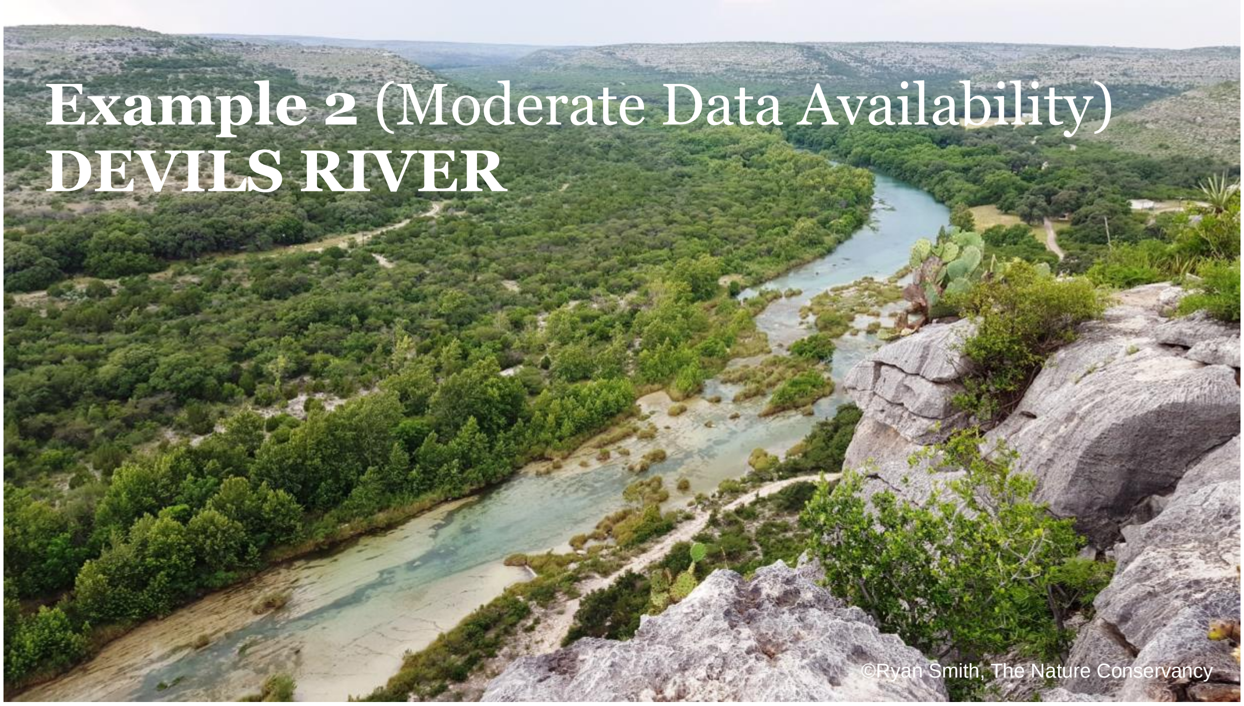
STEP 5. Quantify Acceptable Range of Variation and Groundwater Threshold

Multiple long-term ecological datasets have been analyzed to understand the relationships between spring flows and the ecological targets. Long-term monitoring datasets, statistical analyses, population modeling, and process-driven ecological models were used to determine acceptable ranges of variation and groundwater thresholds (Table V.1) (NAS 2018).

Table V.1. Examples from the Edwards Aquifer in Texas of hydrologic indicator thresholds to avoid and acceptable ranges of hydrologic indicators to achieve for maintaining healthy GDEs.

Guidance Component	Directly Reliant GDE	Directly Reliant GDE
Conservation Goal	Sustain or enhance natural habitat areas that rely on groundwater for thermal habitat suitability	Sustain or enhance natural habitat areas that rely on groundwater
Ecological Target	Fountain darter, Comal Springs riffle beetle (Comal Springs)	Texas wild-rice (San Marcos Springs)
Key Ecologic Attribute	Fish and invertebrate habitat in spring-fed river	Wild-rice habitat in spring-fed river
Hydrologic Indicator	Spring flow (via flow-temperature relationship)	Spring flow and river baseflow (via flow-habitat relationship)
Hydrologic Goal	Spring flow in summer months (driest time of year)	Spring flow and river baseflow in summer months (driest time of year)
Ecologic Responses	Acceptable Range: Thermal conditions support strong fish and invert survival. Threshold: Thermal conditions allow reduced, but minimal fish and invert survival.	Acceptable Range: Habitat area for wild-rice prevalent. Threshold: Habitat area for wild-rice reduced, but minimal.
Acceptable Range	>140 cfs annual average flow	>140 cfs annual average flow
Threshold	45 cfs for no more than 6 months	45 cfs for no more than 6 months

Example 2 (Moderate Data Availability)
DEVILS RIVER



©Ryan Smith, The Nature Conservancy

The Devils River is situated at the interface of the Chihuahuan Desert and Edwards Plateau in central Texas (Figure V.5). The life blood of the river in inflow from the Edwards-Trinity Aquifer through several spring complexes. It is perhaps the most unaltered river in Texas and supports a unique and diverse ecosystem as well as important values such as rural quality of life, recreation and downstream water supply. TNC is working to develop science to inform the use of the Devils River as a benchmark for groundwater management.

Figure V.5. Location of the Devils River in central Texas**.**

STEP 1. State the Conservation Objective

The conservation objective is to define sustainable levels of groundwater development that can occur from the Edwards-Trinity Aquifer in the Devils River basin, Texas while protecting endangered species (i.e., Texas hornshell mussel and Devils River minnow) and the sensitive ecological elements (i.e., spring-dependent fishes) of the basin's groundwater dependent ecosystems.

STEP 2. Build an Ecohydrological Conceptual Model

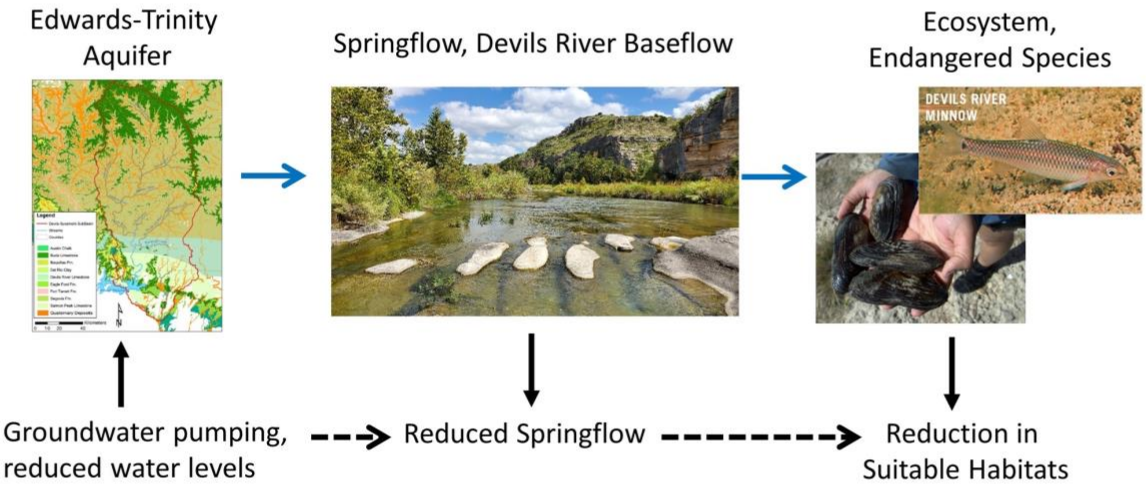
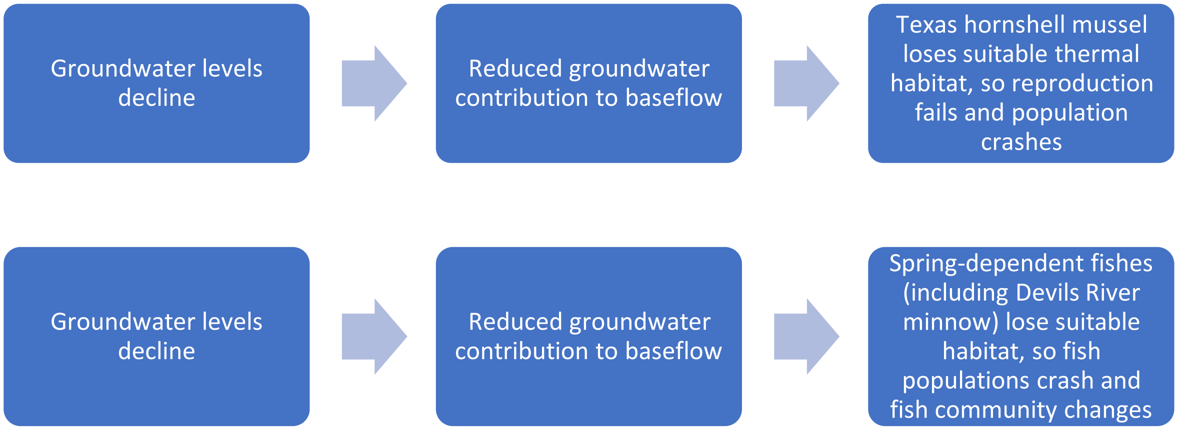


Figure V.5. Simple conceptual model for the Devils River.

STEP 3. Identify Potential Cause-and-Effect Relationships and Define the Groundwater Threat



STEP 4. Select Appropriate Hydrologic Indicators to Monitor and Assess Targets

For Texas hornshell mussel, monitor Devils River baseflow based on relationship between river flow and Texas hornshell mussel juvenile survival (Figure V.6). For Devils River minnow and spring-dependent fishes, monitor Devils River baseflow based on relationship between river flow and suitable habitat for Devils River minnow (Figure V.7).

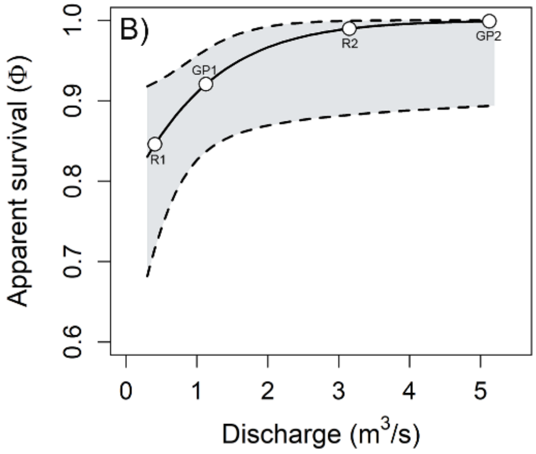


Figure V.6. Relationships between Devils River discharge and apparent survival of Texas hornshell mussel juveniles (Randklev, unpublished data).

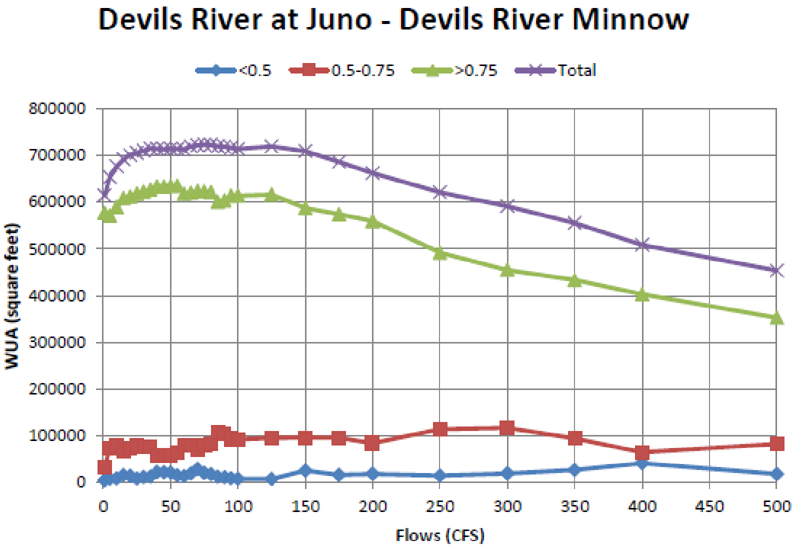


Figure V.7. Four ranges of weighted usable habitat area (WUA) quality (<0.5, 0.5-0.75, >075, and total) versus modeled flow (ft^3/s) for Devils River minnow at the Devils River near Juno (Upper Rio Grande Basin and Bay Expert Science Team, 2012).

STEP 5. Quantify Acceptable Range of Variation and Groundwater Threshold

The acceptable range and threshold values for the Devils River were defined using a combination of population and ecological models (Figure V.6) and spatially-explicit models (Figure V.7).

Table V.2. Examples from the Devils River in Texas of hydrologic indicator thresholds to avoid and acceptable ranges of hydrologic indicators to achieve for maintaining healthy GDEs

Guidance Component	Directly Reliant GDE	Directly Reliant GDE
Conservation Goal	Sustain or enhance natural habitat areas that rely on groundwater for thermal habitat suitability	Sustain or enhance natural habitat areas that rely on groundwater
Ecological Target	Texas hornshell mussel (federally endangered)	Spring-dependent threatened fishes including Devils River minnow
Key Ecological Attribute	Mussel habitat in spring-fed river	Fish habitat in spring-fed river
Hydrologic Indicator	River baseflow (via flow-temperature relationship)	River baseflow (via flow-habitat relationship)
Hydrologic Goal	River baseflow in summer months (driest time of year)	River baseflow in summer months (driest time of year)
Ecological Responses	Acceptable Range: Thermal conditions support strong Texas hornshell survival. Threshold: Thermal conditions allow reduced, but minimal Texas hornshell survival.	Acceptable Range: Habitat area for spring-dependent fishes prevalent. Threshold: Habitat area for spring-dependent fishes reduced, but minimal.
Acceptable Range	>50 cfs throughout the year	25-150 cfs throughout the year
Threshold	15 cfs in summer months	25 cfs in summer months

Example 3 (Low Data Availability)
DIAMOND Y SPRING PRESERVE

Diamond Y Spring, head spring pool
©Steven Gilbert, Jacquie Ferrato, TNC

Diamond Y Spring is located in the Chihuahuan Desert in west Texas. The spring emanates from a complex vertical groundwater interaction with at least two aquifers (Edwards-Trinity and Rustler) in a zone of heavy faulting. Spring flow supports a desert cienega system and spring run that provides habitat to seven endangered species including two springsnails (Diamond Y Springsnail, Gonzales Springsnail) endemic to the spring system and the Leon Springs Pupfish that now only occurs here. The surrounding area has been heavily developed for energy production and irrigated agriculture and both groundwater levels and spring flows have declined in recent years. TNC is working to develop spring flow targets for use in groundwater management.

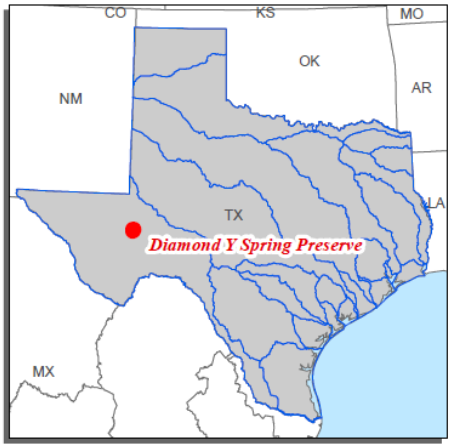


Figure V.8. Location of Diamond Y Spring in west Texas.

STEP 1. State the Conservation Objective

The conservation objective is to define sustainable levels of groundwater development that can occur from the Edwards-Trinity and Rustler aquifers in Pecos County, Texas while protecting endangered species (i.e., seven federally listed species including the Diamond Y and Gonzales springsnails and the Leon Spring pupfish) and the groundwater dependent ecosystems that support them.

STEP 2. Build an Ecohydrological Conceptual Model

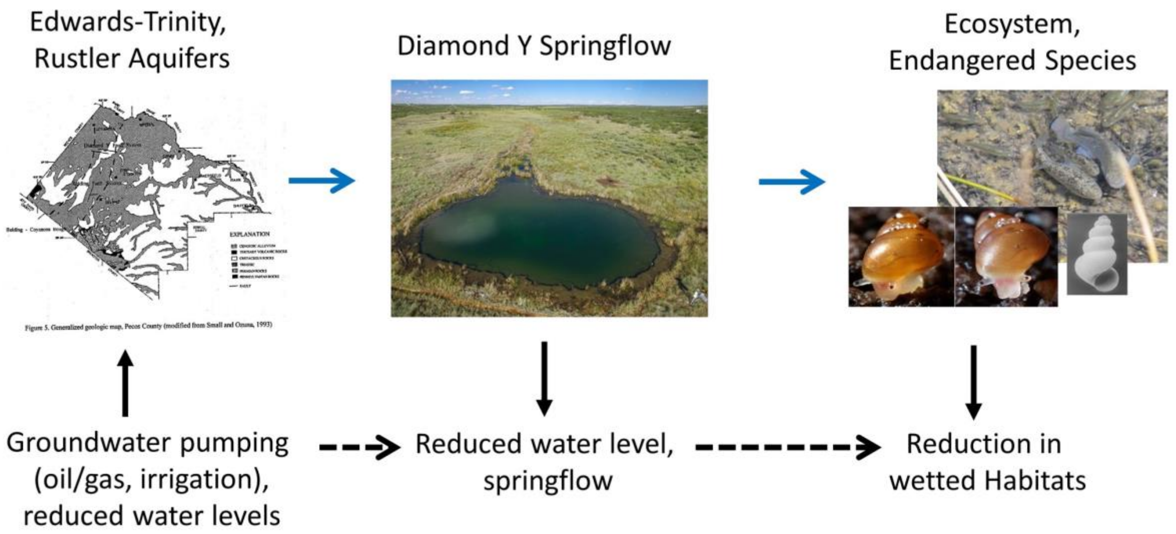
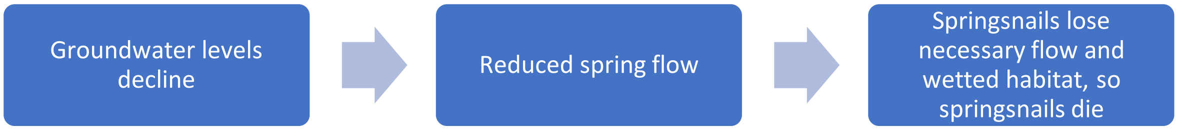


Figure V.9. Simple conceptual model for Diamond Y Spring system.

STEP 3. Identify Potential Cause-and-Effect Relationships and Define the Groundwater Threat



STEP 4. Select Appropriate Hydrologic Indicators to Monitor and Assess Targets

Monitor spring flow downstream from pool at head spring at Diamond Y Preserve and water level in the head spring pool, both of which are declining. While spring flow monitoring has been recently established and will be the long-term indicator, we currently rely on water level data in the head spring pool (Figure V.10). Average spring flow is around 1 cfs, and flow out of the head pool completely ceases at a water level of approximately 6.4 ft.

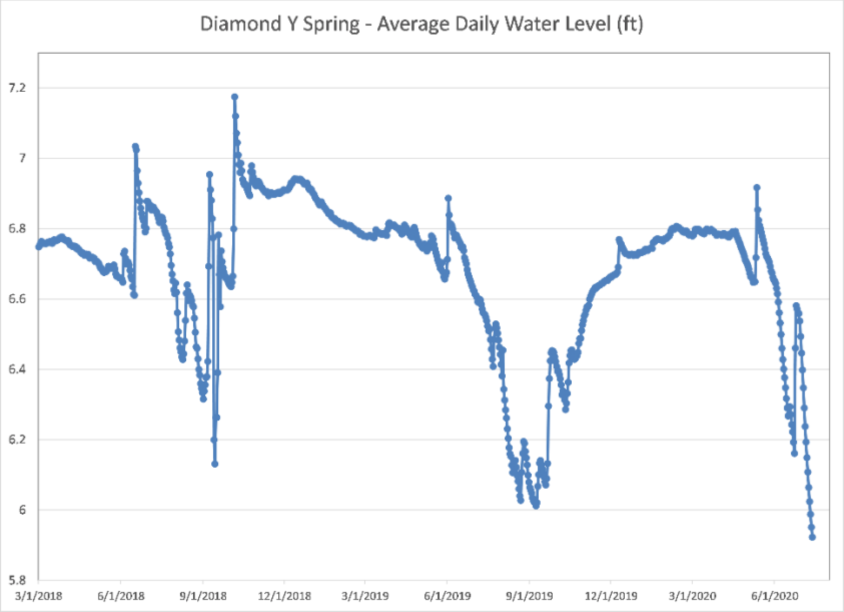


Figure V.10. Average daily water level (ft) (as arbitrary datum) in pool at head spring at Diamond Y Preserve.

STEP 5. Quantify Acceptable Range of Variation and Groundwater Threshold

The acceptable range and threshold values for Diamond Y Spring were defined using basic statistical approaches in which average springflow measurements and water level monitoring data were used to estimate the minimum flow needed to keep aquatic habitats wetted.

Table V.3. Examples from Diamond Y Spring in Texas of hydrologic indicator thresholds to avoid and acceptable ranges of hydrologic indicators to achieve for maintaining healthy GDEs

Guidance Component	Directly Reliant GDE
Conservation Goal	Sustain or enhance natural habitat areas that rely on groundwater
Ecological Target	Diamond Y Springsnail
Key Ecological Attribute	Wetted habitat below Diamond Y Spring pool
Hydrologic Indicator	Spring flow (water level as current proxy)
Hydrologic Goal	Maintain wetted habitat during dry summer months (July to September)
Ecological Responses	Acceptable Range: Spring flow is greater than zero Threshold: Spring flow is within 30% of average flow (1.5 cfs)
Acceptable Range	>1 cfs throughout the year
Threshold	1 cfs in summer months

APPENDIX REFERENCES

Aguilar C, Zinnert JC, José Polo M, Young DR. 2012. NDVI as an indicator for changes in water availability in woody vegetation. Ecological Indicators 23:290-300.

Canham CA, Froend RH, Stock WD. 2009. Water stress vulnerability of four Banksia species in contrasting ecohydrological habitats on the Gnangara Mound, Western Australia. Plant, Cell & Environment 32:64-72.

Carter JL, White DA. 2009. Plasticity in the Huber value contributes to homeostasis in leaf water relations of a mallee Eucalypt with variation to groundwater depth. Tree Physiology 29:1407-1418. doi:10.1093/treephys/tpp076.

Cooper DJ, D'Amico D, Scott M. 2003. Physiological and morphological response patterns of *Populus deltoides* to alluvial groundwater pumping. Environmental Management 31:215-226.

Cooper DG, Sanderson JS, Stannard DI, Groeneveld DP. 2006. Effects of long-term water table drawdown on evapotranspiration and vegetation in an arid region phreatophyte community. Journal of Hydrology 325: 21-34.

Devitt DA, Fenstermaker LF, Young MH, Conrad B, Baghzouz M, Bird BM. 2011. Evapotranspiration of mixed shrub communities in phreatophytic zones of the Great Basin region of Nevada (USA). Ecohydrology 4:807-822.

Eamus D, Zolfaghar S, Villalobos-Vega R, Cleverly J, Huete A. 2015. Groundwater-dependent ecosystems: recent insights from satellite and field-based studies. Hydrology and Earth System Sciences 19:4229-4256. DOI:10.5194/hess-19-4229-2015.

Edwards Aquifer Authority. 2020. Habitat Conservation Plan. Available at: https://www.edwardsaquifer.org/habitat-conservation-plan/ (accessed 09/25/20).

Ford CR, Mitchell RJ, Teskey RO.2008. Water table depth affects productivity, water use and response to nitrogen addition in a savvan system. Canadian Journal of Forest Research 38:2118-2127.

Froend RH, Drake PL. 2006. Defining phreatophyte response to reduced water availability: preliminary investigations on the use of xylem cavitation vulnerability in *Banksia* woodland species. Australian Journal of Botany 54:173-179.

Gazal RM, Scott RL, Goodrich DC, Williams DG. 2006. Controls on transpiration in a semiarid riparian cottonwood forest. Agricultural and Forest Meteorology 137:56-67.

González E, González-Sanchis M, Comín FA, Muller E. 2012. Hydrologic thresholds for riparian forest conservation in a regulated large Mediterranean river. River Research and Applications 28:71-80. DOI: 10.1002/rra.1436.

Gries D, Zeng F, Foetzki A, Arndt, SK, Bruelheide H, Thomas FM, Zhang X, Runge M. 2003. Growth and water regulations of *Tamarix ramosissima* and *Populus euphratica* on Taklamakan desert dunes in relation to depth to a permanent water table. Plant, Cell & Environment 26:725-736.

Groom BP, Froend RH, Mattiske EM. 2000. Impact of groundwater abstraction on *Banksia* woodland, Swan Coastal Plain, Western Australia. Ecological Management and Restoration 1:117-124.

Hardy TB. 2009. Technical Assessments in Support of the Edwards Aquifer Science Committee "J Charge" Flow Regime Evaluation for the Comal and San Marcos River Systems. Prepared for the Edwards Aquifer Recovery and Implementation Program. San Marcos, TX: Texas State University. Available at: https://www.edwardsaquifer.org/wp-content/uploads/2019/02/Appendix-H.pdf (accessed 09/25/20).

Horton JL, Kolb TE, Hart SC. 2001. Responses of riparian trees to inter-annual variation in groundwater depth in a semi-arid river basin. Plant, Cell & Environment 24:293-304.

Kochendorfer J, Castillo EG, Haas E, Oechel WC, Paw UKT. 2011. Net ecosystem exchange, evapotranspiration and canopy conductance in a riparian forest. Agriculture and Forest Meteorology 151:544-553.

Lv J, Wang XS, Zhou Y, Qian K, Wan L, Eamus D, Tao Z. 2013. Groundwater-dependent distribution of vegetation in Hailiutu River catchment, a semi-arid region in China. Ecohydrology 6:142-149.

Merritt DM, Bateman HL. 2012. Linking stream flow and groundwater to avian habitat in a desert riparian system. Ecological Applications 22:1973-1988.

National Academies of Sciences, Engineering, and Medicine. 2018. Review of the Edwards Aquifer Habitat Conservation Plan: Report 3. Washington, DC: The National Academies Press.

O'Grady AP, Carter JL, Bruce J. 2011. Can we predict groundwater discharge from terrestrial ecosystems using existing ecohydrological concepts? Hydrology and Earth System Sciences 15:3732-3739. doi: 10.5194/hess-15-3731-2011.

Randklev, Charles. Texas A&M Agrilife, unpublished preliminary data.

Scott ML, Shafroth PB, Auble GT. 1999. Responses of riparian cottonwoods to alluvial water table declines. Environmental Management 23:347-358.

Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality. Available at: https://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/eflows/urgbbest_finalreport.pdf (accessed 09/25/20).

Wang P, Zhang YC, Yu JJ, Fu GB, Ao F. 2011. Vegetation dynamics induced by groundwater fluctuations in the lower Heihe River Basin, northwestern China. Journal of Plant Ecology 4:77-90.

Zinko U, Seibert J, Merritt DM, Dynesius M, Nilsson C. 2005. Plant species numbers predicted by a topography-based groundwater flow index. Ecosystems 8: 430-441.

Zunzunegui M, Barradas MCD, Novo FG. 2000. Different phenotypic responses of *Halimium halimifolium* in relation to groundwater availability. Plant Ecology 148:165-174.