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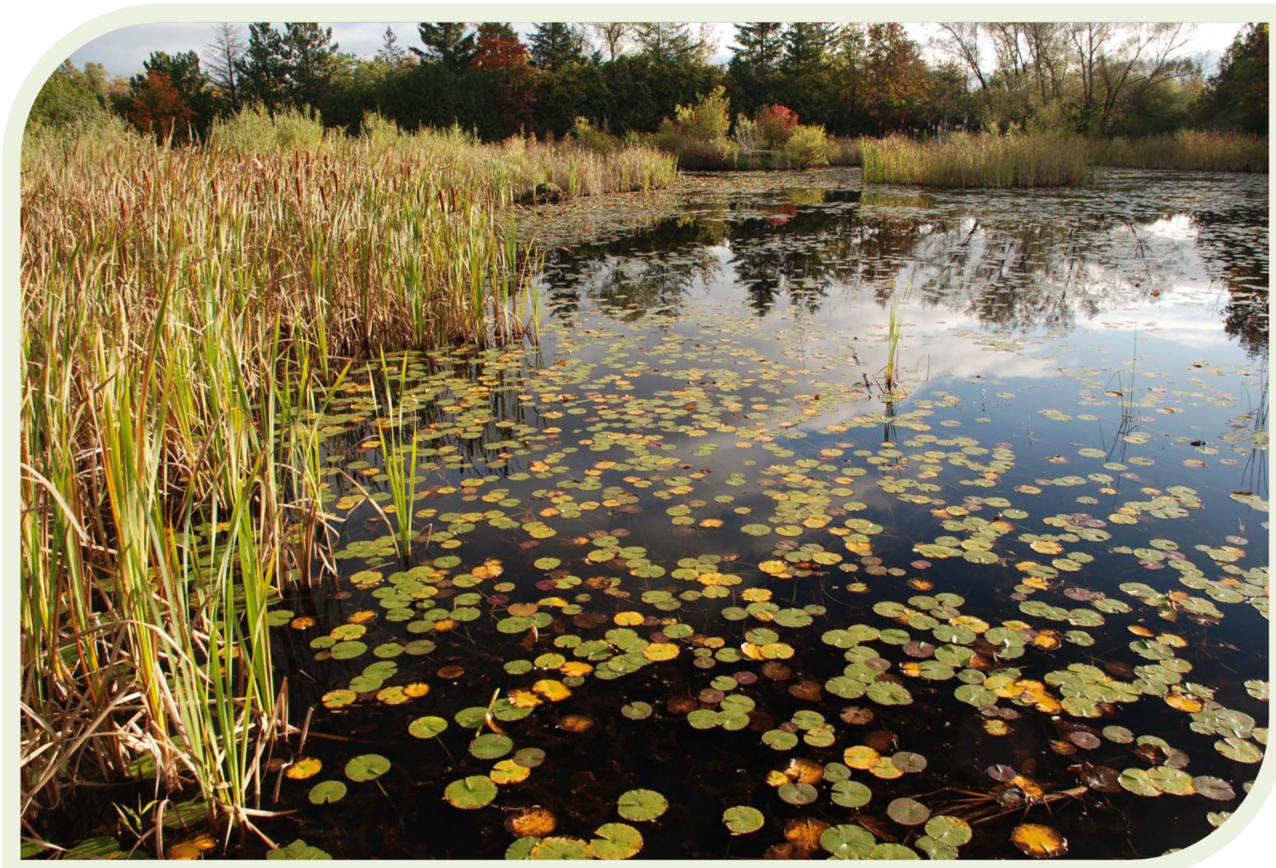

Wetland Hydrologic Assessment Method: A tool to characterize the hydrologic regime of wetlands for use in management and mitigation scenarios

Prepared by: Credit Valley Conservation

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OVERVIEW

The maintenance and protection of particular natural community types and their associated flora and fauna requires an understanding of the specific biotic and abiotic conditions that allowed them to emerge in the first place. The hydrology of a natural community is a particularly important determinant of such conditions, especially in features such as wetlands.

Credit Valley Conservation (CVC) has been developing an approach to characterize the hydrological regime in wetlands, for the purpose of monitoring hydrological and ecological change and guiding management and mitigation against impacts. This approach, referred to as the wetland hydrologic assessment method, aims to quantify the hydrologic characteristics that determine and maintain the ecological composition, structure, and function of a wetland under study. The method can be used to describe the natural hydrologic variation in a wetland, assess and compare different management and mitigation scenarios, and guide and support adaptive management programs for wetland management. It is intended to reduce the risk of negative impacts of activities that can influence or alter the hydrology of wetlands and other natural features.

The wetland hydrologic assessment method has been used in the review and the development of mitigation and management plans for the Acton Quarry Expansion Study (Conestoga-Rovers & Associates et al., 2014), Cedarvale Well Environmental Impact Study (Halton Region, 2014), and Inglewood Well 4 Environmental Impact Study (CVC and Region of Peel, 2016). While all applications of the method to date have focused on wetlands, in the future the approach may be extended to other habitat types, such as forests, meadows, lakes, watercourses, and ponds. Additional future work using this method may also include gathering hydrologic data on healthy, reference wetlands in order to provide guidance to the restoration and creation of other wetlands. It is also expected that new approaches or tools will be developed as our understanding of ecohydrology, or the ecological and hydrological relationships within ecosystems, improves.

This report provides some background information on the relationship between hydrology and ecology in wetlands as well as a brief description of the wetland hydrologic assessment method – including the theory behind it, a case study where it has been applied, potential additional applications, data requirements, and limitations.

BACKGROUND

Wetland ecohydrology

Hydrology is one of the most important factors in determining community composition, structure and function of wetlands (Mitsch and Gosselink, 2007). Every type of wetland has been formed and is sustained by its own unique combination of environmental characteristics (e.g. soils, climate, topography) and hydrological regime. For example, Freeman maple swamps on mineral soils are generally flooded from the spring until mid-June and are dry for the rest of the year, with the exception of short periods following summer storms. Alternatively, broad-leaved cattail shallow marshes prefer deep standing or flowing water for most or all of the growing season.

Important hydrologic parameters for the formation and maintenance of a wetland's ecological structure and function include the depth, duration, frequency, magnitude, source, and timing of water movements within the system. For example, the point at which a wetland is inundated with surface water in the spring and the length of time that this inundation lasts are crucial for determining which plants and animals can live and reproduce there.

Hydrology affects the biological diversity within natural features. Variations in hydrologic condition typically produce a diversity of ecological niches, resulting in high biological diversity. The productivity of wetlands and aquatic systems are enhanced by water flow through and pulsing high water levels (Mitsch and Gosselink, 2007). These pulses can influence sediment deposition and erosion, nutrient availability, and the movement of organisms and organic material between adjacent ecosystems; for example, the movement of fish from aquatic ecosystems to floodplain marshes and swamps.

Hydrology can also affect the physiochemical properties of natural features including oxygen availability, salinity, toxins, sediment movement, detritus, and soil composition. The formation and maintenance of soils in wetlands is strongly influenced by hydrology. For example, organic wetland soils form in areas where water accumulates to saturate the soils for most of the year. These extended periods of saturation produce soil conditions that are very low in oxygen, affecting the microorganisms that are responsible for breaking down organic matter and slowing the rate of decomposition.

Natural variation in hydrological regimes

The hydrologic conditions under which wetlands exist are not static. The climate naturally fluctuates on a daily, seasonal, annual, and even decadal frequency. As climate fluctuates, so do temperature, precipitation, wind, humidity, natural disturbance, and water levels within natural areas. These fluctuations are part of the environmental conditions under which ecosystems have formed. However, even within this naturally occurring variation, some conditions are common while others are rare or extreme.

Ecological impacts of hydrological disturbance

Hydrological changes caused by disturbances associated with human activity are not within what is considered natural variation. Human disturbances to hydrology are frequently associated with activities that result in water diversions, impoundments, discharges, or withdrawals. These activities can make common hydrological conditions less common and consequently historically rare or extreme conditions may become more common. All vegetation communities, habitats and species are sensitive to hydrologic changes to some degree, but some are more sensitive than others.

The potential effects of hydrologic alteration in wetlands include biotic and abiotic changes. Biotic changes include shifts in species composition, richness, and distribution as well as loss of productivity, while abiotic changes include shifts in soils, nutrients, and physical structure. Together, these changes may results in loss of wetland area as well as lost or altered function of the wetland.

The significance of the change or impact depends on the magnitude, frequency and duration of the change in environmental conditions as well as the sensitivity of the biological elements that depend on that natural area or habitat. Even small changes to the hydrology of a wetland may produce a significant response. Furthermore, altering the hydrology of one wetland can have a cascading impact on adjacent or downstream wetlands and watercourses. Lastly, hydrologic alteration may make species and their habitats more sensitive and vulnerable to other natural and human caused stressors.

WETLAND HYDROLOGIC ASSESSMENT METHOD

Background

The aim of the method is to identify key hydrologic characteristics that determine and sustain a vegetation community's ecological composition, structure and function. These characteristics are identified by analyzing existing hydrologic data for a particular wetland and characterizing its current hydrologic regime. This approach identifies the range of natural hydrologic variation in the wetland, which includes identifying common, uncommon, rare and extreme hydrologic conditions or events. As previously discussed, maintaining the timing, frequency, duration and magnitude of these hydrologic events is critical to the maintenance of wetlands and their functions. Details of the method, including steps in statistical analysis and interpretation, are described in the case study below; here we present some of the theory used to inform the method.

The analysis is influenced by statistical process control; a commonly used method of quality control in manufacturing that has recently been adopted in environmental monitoring (e.g. Anderson & Thompson 2004; Morrison 2008; Parker et al. 2015). Statistical process control uses the variation seen within a set of baseline data for a particular metric (e.g. water level) to define what range of values should be expected under natural conditions. These values can then be plotted as thresholds in a tool called a control chart, allowing the identification of extreme values that fall outside of the range of natural variation. The frequency and duration of extreme values can allow managers to identify when a system has changed significantly or is stressed or "out of control".

The methods of statistical process control generally assume that sample data come from a normal distribution; in other words, data that display a typical bell curve (Figure 1a). Normally distributed data have an equal distribution of occurrences or events on either side of the mean (i.e. average). The standard deviation (σ) is used to quantify the amount of variation or distribution in the data. Approximately 68% of the data will occur within one standard deviation on either side of the mean, 95% will occur within two standard deviations, and almost all of the data (99.7%) will be contained within three standard deviations.

Standard deviations can also be used to identify ranges of common, uncommon, rare, and extreme values (Table 1). As noted above, 68% of the data will occur within one standard deviation (-1σ to +1σ) – these values are defined as common, and can be seen in the green zone in Figure 1a. Uncommon values correspond to 27% of the data (13.5% on either side of the mean), and are defined as those that occur from +1σ to +2σ and -1σ to -2σ (i.e. the yellow zone). Rare values, only 4.7% of the data, occur from +2σ to +3σ and -2σ to -3σ

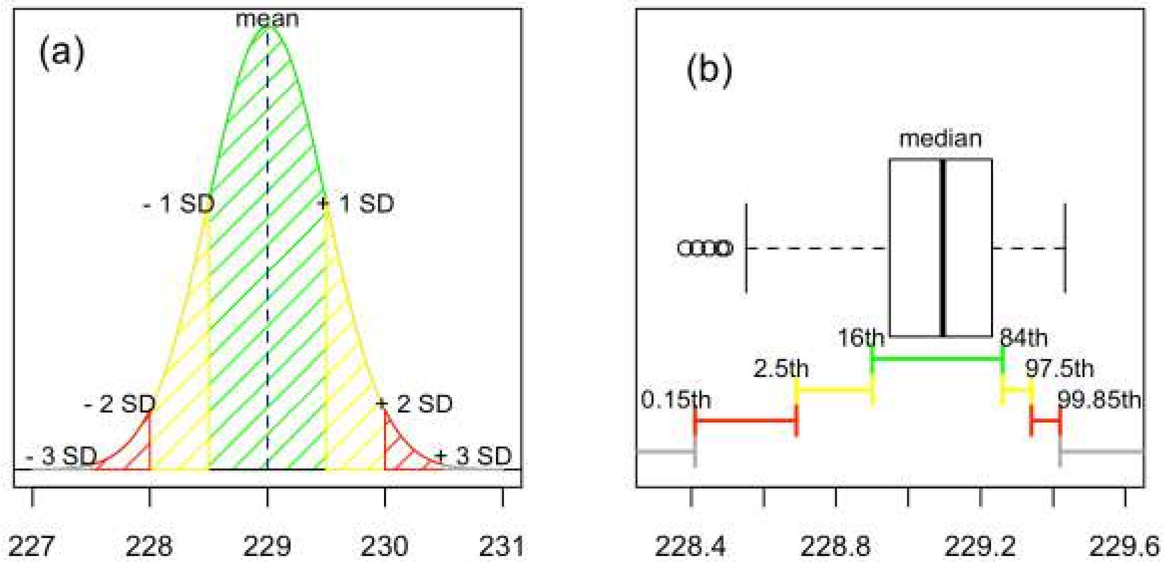

Figure 1. Illustration of the (a) normal distribution, mean and standard deviations, and the (b) non-normal distribution, median and percentiles, for fictional groundwater level data in the range of many of CVC's study wetlands (227 to 231 metres above sea level)

(i.e. the red zone). Anything beyond three standard deviations (i.e. $<-3\sigma$ or $>+3\sigma$) is an outlier or extreme value (i.e. the grey zone). Within the context of natural variation this includes only 0.3% of the data. However, in the context of hydrologic alteration related to human activity, the range of extreme events extends infinitely beyond what occurs naturally.

Most hydrologic data associated with wetlands does not fit a normal distribution. Non-normally distributed data are generally not evenly distributed on either side of the middle value, or median (Figure 1b); in this case, percentiles are used instead of standard deviations to describe the variation in the data. Percentiles can be chosen that correspond to the range of standard deviations described below (Table 1).

Table 1. Definition of common, uncommon, rare, and extreme zones and thresholds

Zone colour	Zone name	Natural data Frequency	Thresholds: Standard deviations	Thresholds: Percentiles
Green	Common	68 %	-1σ to $+1\sigma$	16^{th} to 84^{th}
Yellow	Uncommon	27 %	-1σ to -2σ $+1\sigma$ to $+2\sigma$	2.5^{th} to 16th 84^{th} to 97.5^{th}
Red	Rare	4.7 %	-2σ to -3σ $+2\sigma$ to $+3\sigma$	0.15^{th} to 2.5^{th} 97.5^{th} to 99.85^{th}
Grey	Extreme	0.3 %	$<-3\sigma$ $>+3\sigma$	$< 0.15^{th}$ > 99.85th

Case study

Over the last 15 years CVC and Toronto and Region Conservation Authority (TRCA) have been monitoring wetlands and other vegetation types in natural areas as part of their watershed monitoring programs. More recently, CVC and TRCA have begun installing hydrologic monitoring equipment at their wetland monitoring stations to improve the understanding of the ecologic and hydrologic relationships and variation in wetlands. Recently, it was proposed that a new municipal well be developed adjacent to one of the monitored wetlands. This scenario provides an opportunity to use a real-world situation to demonstrate the application of the wetland hydrologic assessment method.

The monitored wetland is located within an area of wetland complexes, mixed forest, and old fields on the lower slope of the Niagara Escarpment. The wetland itself contains two Ecosystem Land Classification (ELC) vegetation community types – willow mineral thicket swamp (SWT2-2) and swamp maple mineral deciduous swamp (SWD3-3). Amphibian breeding is known to occur in the wetland, and it is considered candidate significant wildlife habitat. The aquifer underlying the wetland is part of a buried bedrock valley aquifer complex.

The Regional Municipality has proposed the development of a new municipal well (well 4) adjacent to the monitored wetland. In addition to this proposed well, there is an existing regional municipal well (well 3) adjacent to this wetland that has been in operation since 1998. A series of pump tests were carried out in 2015 to assess the performance of the aquifer and the impact of pumping of the proposed well on adjacent natural heritage features in the area. Due to the proximity of the proposed well to the existing well, these pump tests also included a scenario where both of the wells were pumped simultaneously. Information gathered from these pump tests will assist the Region in operating these wells in a manner that avoids negative impacts on the aquifer or the adjacent natural heritage features. Table 2 provides details of those tests.

CVC has been monitoring vegetation in the wetland since 2007 as part of the long-term Integrated Watershed Monitoring Program. Hydrologic equipment was installed in 2011 to supplement the vegetation monitoring as part of a pilot wetland ecohydrology study. The

Table 2. Record of pumping tests performed at wells 3 and 4 in 2015

Date(s)	Well(s)	Description
Oct 23, 2015	well 4	One day step drawdown test pumping up to 1420 L/min.
Oct 26 - Nov 13, 2015	well 4	18 day aquifer performance pump test at approximately 900 L/min.
Nov 16 - 20, 2015	wells 3 & 4	Four day combined pump test, where both wells were pumped simultaneously at approximately 900 L/min. each

vegetation monitoring protocol consists of a 50 m transect running along the wetland's hydrological gradient from dry to wet. Pairs of vegetation monitoring plots occur at 10 meter intervals along the transect, and hydrologic monitoring stations are placed adjacent to the 10 m and 40 m plots.

Each hydrologic monitoring station consists of a 1 m deep drive-point piezometer and a 2 m deep drive-point piezometer. Schlumberger Diver pressure transducer loggers were deployed into each piezometer to record groundwater levels. Another logger was attached to a t-bar to measure surface water levels at the hydrologic station sites. The loggers were set to collect readings at one-hour intervals. A barometric logger was also installed on site to allow for barometric corrections. The top of each piezometer and the t-bar associated with the surface water logger were surveyed using a Nikon Total Station to relate recorded water levels to mean sea level and between equipment.

Statistical Analysis

Hydrologic equipment installed at the wetland collects hourly groundwater elevation data, which has been used to characterize the hydrologic regime of the wetland. Analyses were carried out using data from the 10 m and 40 m station 2 m deep piezometers – the two stations with the most complete data records – which from here on are referred to by their transect location (e.g. 10 m) for brevity.

Hydrographs of median daily groundwater elevation data at the 10 m and 40 m piezometers were plotted to visually assess the annual patterns at the wetland. Daily precipitation amounts were also included on the hydrographs; precipitation data were obtained from the closest Environment Canada weather station (approximately 18 km away).

Groundwater levels from the four years of monitoring (2011-2015) were used to define the thresholds of the common, uncommon, rare, and extreme zones for each day of the year at both the 10 m and 40 m piezometers. Hourly groundwater levels were summarized as daily medians; data from days when performance and pumping tests were conducted were excluded. Daily medians were then modeled as a function of day of year (1-366, to account for leap years), using a generalized additive model (Hastie, 2015).

Generalized additive models are useful when the relationship between the predictor (e.g. day of year) and response (e.g. daily median groundwater level) variable is nonlinear and complex, such as in wetland hydrology time series data. Residuals and fitted values from the model were then used to plot the 0.15th, 2.5th, 16th, 84th, 97.5th, and 99.85th percentile prediction intervals for each day of the year, identifying continuous thresholds of the common, uncommon, rare, and extreme zones. Daily medians from the performance and pumping test dates were then plotted on the same graphs.

Results and interpretation

Data from both the 10 m and 40 m stations yielded similar results; as such, only the results from the 10 m station are shown. Water levels patterns at the 10 m piezometer exhibited an annual hydrograph typical of other temperate wetland systems (e.g. Mitsch and Gosselink 2007). Water levels are at their lowest during the late summer and early fall and at their highest during the late winter and early spring, with a short period of falling water levels and a longer period of rising water levels in between the two extremes (Figure 2).

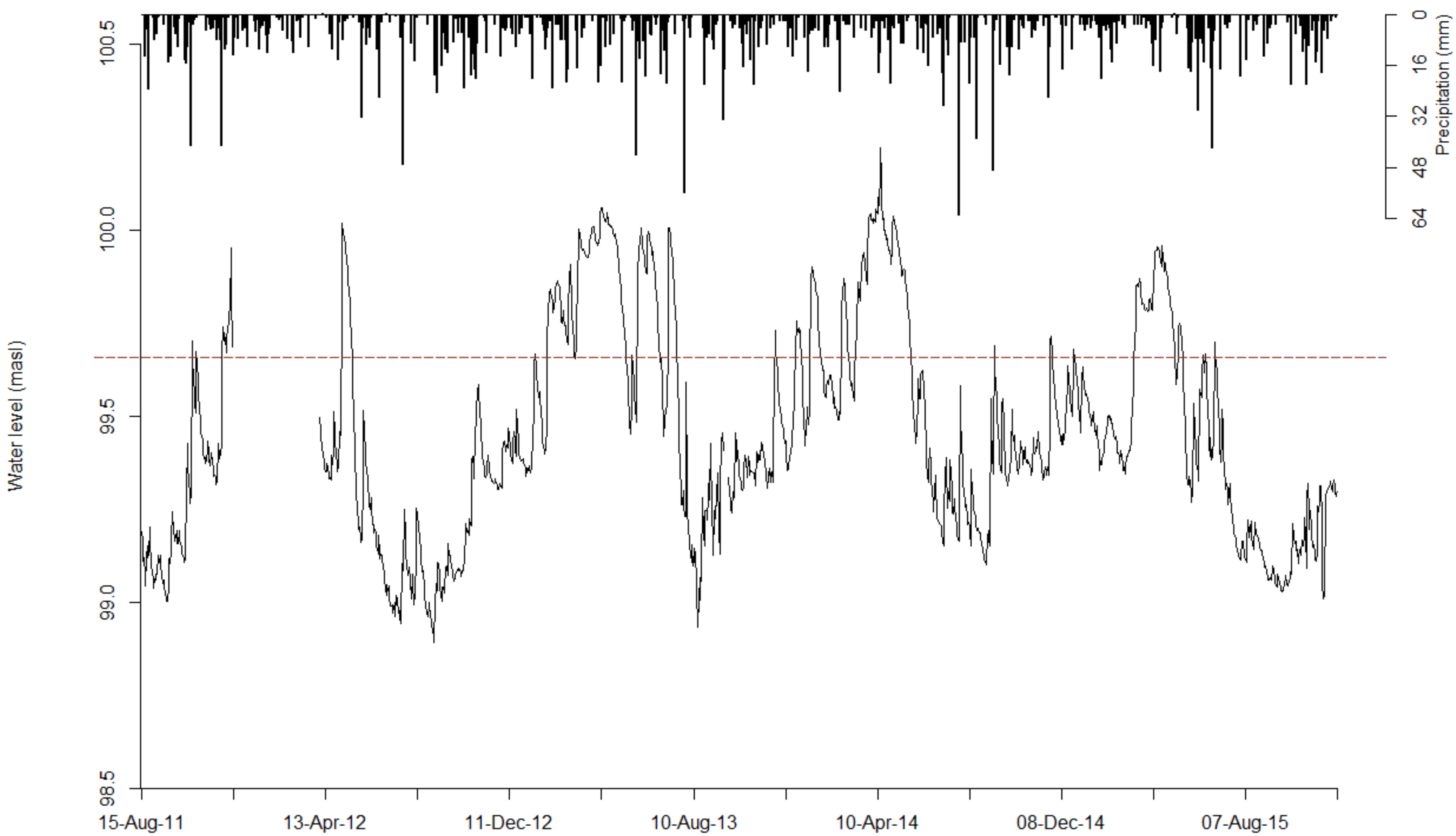

Figure 2. Hydrograph showing daily groundwater levels from the 10 m piezometer at the case study wetland from August 15 2011 to December 7, 2015 (note missing data from December 14, 2011 till April 4, 2012 and September 21-25, 2013). Daily precipitation amount is shown at the top of the hydrograph; precipitation data come from the nearby Environment Canada weather station in Orangeville. The dotted brown line indicates the level of the ground surface.

Daily water levels during the pump tests were graphically compared to the natural range of variation in daily water levels (Figure 3). The 18 day pump test of well 4 produced water levels that were mostly in the range of common to uncommon (blue points, Figure 3), while the four day combined pumping of wells 3 and 4 produced water levels that were mostly in the rare to extreme range (purple points, Figure 3). A comparison of the results of the 18-day pump test of well 4 versus the four day combined pump test for wells 3 and 4 may indicate that these wetlands are more under the influence of the operation of well 3. The aquifer in the vicinity of well 3 is unconfined which may explain the higher level of drawdown during the four day combined pump test.

We note that the pump tests were conducted during a time of the year when groundwater levels should be rising. During the rising period, the overall trend in water levels should be increasing as the wetland recharges after the low period in the summer and early fall (black points, Figure 3). However, the trend in groundwater levels during these tests was downward – moving from the common to uncommon to rare zones (blue points, Figure 3). In addition, the groundwater levels moved into the extreme zone during the four day combined pump test (purple points, Figure 3). This downward trend occurred despite significant rainfall events that occurred during these dates (Figure 2).

The fact that the pump tests caused groundwater elevations to decline during a period when they should be rising may also suggest that the range of drawdown could be greater during times of the year when groundwater levels are naturally falling or low. This could have significant impacts because the drawdown during these periods could shorten the wetland’s hydroperiod (i.e. timing and duration of surface water inundation) and produce drier conditions during the hottest and driest time of the year. This may produce conditions that stress wetland species, making them more vulnerable to disease and competition from invasive and non-wetland species.

Drawing down groundwater may reduce the period that the rooting zone in the wetland is saturated. In this wetland, groundwater levels have been shown to respond to significant precipitation events (e.g. Figure 2) indicating that there is a connection between the groundwater and surface water system. Consequently, a drawdown of the groundwater system could produce a reduction of the wetland’s hydroperiod. Currently, groundwater may be contributing to the amount of standing water in the wetland; however, under a drawdown scenario those contributions could be reduced or lost and surface water in the wetland could infiltrate quicker because of the lower water table.

The combined impact to both the groundwater and surface water systems could produce a shift in the wetland’s floral community. If the hydrologic alteration produces conditions locally or throughout the wetland that are not known to support wetlands, then species that have established and developed based on the existing hydrology may become vulnerable to extreme environmental conditions and disease. The existing floral community of the wetland would also be subject to increased competition from other wetland, terrestrial and invasive species whose hydrological requirements are more similar to the new hydrological conditions.

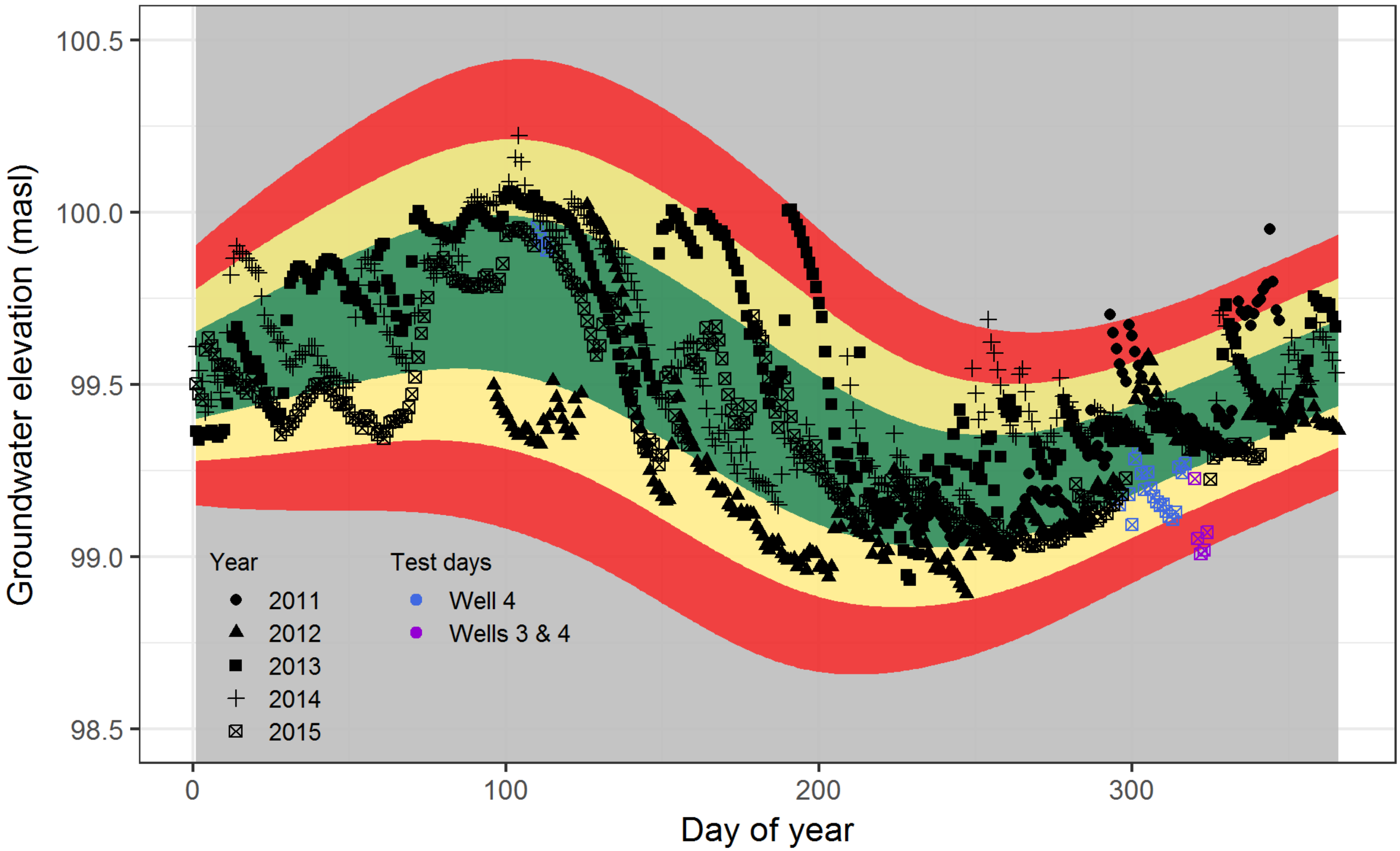

Figure 3. Continuous thresholds of natural variation in daily water levels at the 10 m station in the case study wetland over the years 2011-2015, as described by common (green), uncommon (yellow), rare (red), and extreme (grey) zones (see text for more detail)

Amphibian breeding within the wetland may also be affected by changes to its hydrology. The hydroperiod of amphibian habitat is critical to determining which species of amphibian are able to successfully breed in the wetland, and alteration of the hydroperiod could therefore impact breeding success (Hamer and McDonnell 2008). If the wetland dries up earlier than it currently does, then amphibians may not be able to successfully complete their metamorphosis into amphibious adults.

ADDITIONAL APPLICATIONS

Risk assessment

The results of the wetland hydrologic assessment method can be used to assess the risk of a hydrologic alteration causing negative impacts on the ecological and hydrological function of a wetland. In addition to the qualitative interpretation of results as discussed above, the shift in the median water elevations could be modelled based on the results of an extended pump test or a hydrologic model. This was not carried out in our case study because the short duration of both pump tests did not provide enough information on how median water levels might change with extended pumping.

It is important to remember that uncommon, rare, or extreme hydrologic conditions naturally occur in wetlands; however, problems may occur when the median water levels shift into those ranges. The full range of common, uncommon, rare and extreme hydrologic events are responsible for compositional, structural and functional characteristics of a wetland. Wetland managers should strive to implement management options that maintain the frequency, duration and timing of existing groundwater elevations within the expected ranges in order to reduce the risk of negatively impacting the ecological and hydrological function of the wetland.

For example, the four simple scenarios shown in Figure 4 demonstrate how the seasonal pattern of water levels in the wetland might change with a decrease in median groundwater levels, an increase in median groundwater levels, an increase in seasonal variation, and a decrease in seasonal variation. These shifts can make the current uncommon or rare groundwater elevations more common, or reduce the frequency, timing and duration of rare (i.e. disturbance) events. When this occurs, the wetland’s ecological structure and function may be affected.

Table 3 illustrates the general level of risk expected with the shift of the median water elevations in relation to the existing range of hydrologic conditions. For the pump test scenario above, the pumping of well 4 has the potential to shift the median groundwater elevations to mostly within the common to uncommon range for the 10 m station. As a result, the risk of negatively impacting the ecological function of these wetlands would be considered low to moderate. Under this scenario, the wetland should persist although some localized wetland loss could occur and there may be some notable alteration of species abundance and distribution over time.

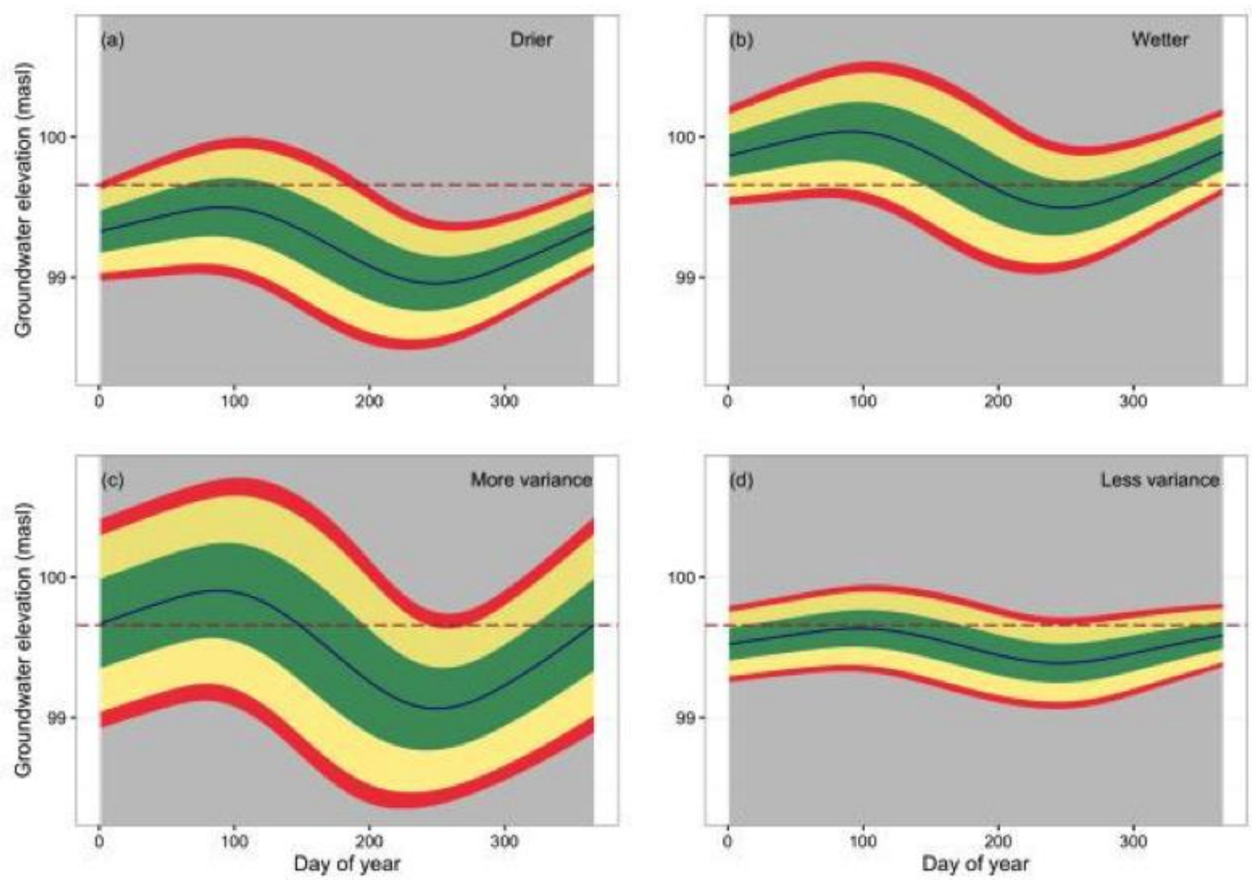

Figure 4. Examples of alteration scenarios modifying the size and shape of green, yellow, red, and grey zones in annual hydrographs including: a) a decrease in median groundwater elevations (i.e. drier); b) an increase in median groundwater elevations (i.e. wetter); c) an increase in seasonal variation; and, d) a decrease in seasonal variation; the dotted brown line indicates the level of the ground surface in each case.

The combined pumping of wells 3 and 4 however, has the potential to shift the median groundwater elevations to mostly within the rare to extreme range for the 10 m station. In this case, it is anticipated that the hydrologic shift would at the very least produce a significant alteration of species abundance and distribution in the wetland. Due to the close proximity to the threshold between wetland and non-wetland hydrology that exists in swamps, there is a significant risk of the hydrologic alteration producing conditions that are not known to support wetlands or their associated species, which may subsequently result in the loss of the wetland.

Setting thresholds and targets for management or mitigation

As shown in Figure 3, the wetland hydrologic assessment method produces a hydrograph with thresholds between common, uncommon, rare, and extreme water levels that change daily. These thresholds can be used to trigger management or mitigation actions. Each threshold can be assigned specific management or mitigation actions as appropriate for

Table 3. Risk assessment based on the shift of median water elevations

Shift from common zone	Colour transition	Risk of negative impacts
Within common	Green -> Green	Low
To uncommon	Green -> Yellow	Moderate
To rare	Green -> Red	High
To extreme	Green -> Grey	Very High

addressing the relevant level of risk of negatively impacting the function of the wetland (e.g. Table 3). Water levels are monitored, and when a threshold is crossed it triggers managers to take appropriate action (e.g. rebalancing pumping between wells, implementing water restrictions). However, without real-time monitoring and automation, it is difficult to implement management targets that change daily. As a result, managers are frequently interested in setting seasonal targets or triggers.

In the past, wetland managers have often chosen to establish two seasonal targets or triggers to direct their management of wetland water levels, where the two seasons correspond to the high winter water levels and low summer water levels. This approach overlooks the dynamic nature of hydrological patterns, and can artificially flatten a wetland's hydrograph. In addition, it does not account for the importance of shoulder seasons – the transitional periods between high and low water levels that occur in the spring and late fall. The spring transitional period is an especially critical time for wetland flora and fauna, as it is during this period that many plants begin their growth and many faunal species breed. In cases where a proposed activity is likely to produce lower water levels a common approach is to set targets at the historic low for the summer season, based on the argument that the wetland has experienced those conditions under natural variation and can therefore tolerate them. However, this historic low will actually be in the range of an extreme water level and is not something that the wetland should experience more than a small percentage of the time.

As an alternative, cluster analysis can be used to define a number of distinct periods within the annual hydrograph and then set targets for each period. This approach analyzes the hydrologic data from the wetland to identify periods with similar characteristics in order to set targets that better reflect the seasonal variation associated with the wetland. This may particularly help to reduce the risk of negative impacts during the spring, when many species and communities are vulnerable to hydrologic changes.

To illustrate this target setting approach, we can use the case study discussed above – again focusing only on data from the 10 m station. First, weekly groundwater elevation means for each year were assembled into a matrix with weeks as rows (1-53) and years as columns (2011-2015).   Weekly standard deviations were also included in the matrix as an additional descriptive measure, as different time periods demonstrate characteristically more or less variation in groundwater levels (e.g. water levels are more stable in the spring). Data from days when performance and pumping tests were conducted were excluded. The data were standardized (subtracting the mean and dividing by the standard deviation for each column) and converted to a Euclidean distance matrix. A hierarchical cluster analysis was then performed using Ward's clustering criterion (Murtagh & Legendre, 2014). The resulting clusters were assessed visually to identify distinct seasonal periods; for example, the first cluster in the dendrogram includes weeks 30 to 42 – a period from the end of July till mid-October (Figure 5).

Results of cluster analysis of average mean weekly water levels show four distinct seasonal periods, corresponding to periods where water levels were low, rising, high, and falling (Figure 5). The first branch and clearest distinction was between the low period and the other three, followed by the separation between high period and the two periods of changing water levels. The rising and falling periods were the least distinct from each other but did show some separation. This pattern of clustering reflects known patterns of wetland hydrology, and provides the additional benefit of defining approximate start and end dates for each season in this wetland.

The thresholds of the extreme (grey), rare (red), and uncommon (yellow) zones in each seasonal period were calculated as the 0.15th, 2.5th and 16th (lower thresholds) plus 84th, 97.5th and the 99.85th (upper thresholds) percentiles of the observed hourly groundwater data for that season (Figure 6). Data from hours when performance and pumping tests were conducted were excluded from these calculations. The groundwater elevation associated with these thresholds can then be used as triggers for each defined hydrologic season, providing a practical number of steady thresholds throughout the year that can lead to wetland management and mitigation actions. Different actions may be assigned to each threshold; the higher the risk, the more significant the action should be. Table 4 provides some examples of general management or mitigation actions that might be taken. A different set of actions may be appropriate under other scenarios; we recommend that a unique water management plan or strategy be developed for each situation where the wetland hydrological assessment method is used to set thresholds and targets for management.

ADDITIONAL CONSIDERATIONS

Data requirements

Carrying out the analyses described in this wetland hydrological assessment method requires appropriate data. There are two important factors – the source of the data, and the length of the data set. First, we recommend that water levels should be monitored using data loggers with an hourly recording frequency. Weekly or monthly manual water level readings using staff gauges do not provide enough information to calculate the daily or weekly averages and variation required to define the thresholds of common, uncommon, rare, and extreme zones. Second, the analyses should be based on at least three years of data from the same wetland, so that some amount of between-year variation can be captured. Ideally, the years of data available will include average, wet, and dry years. Note

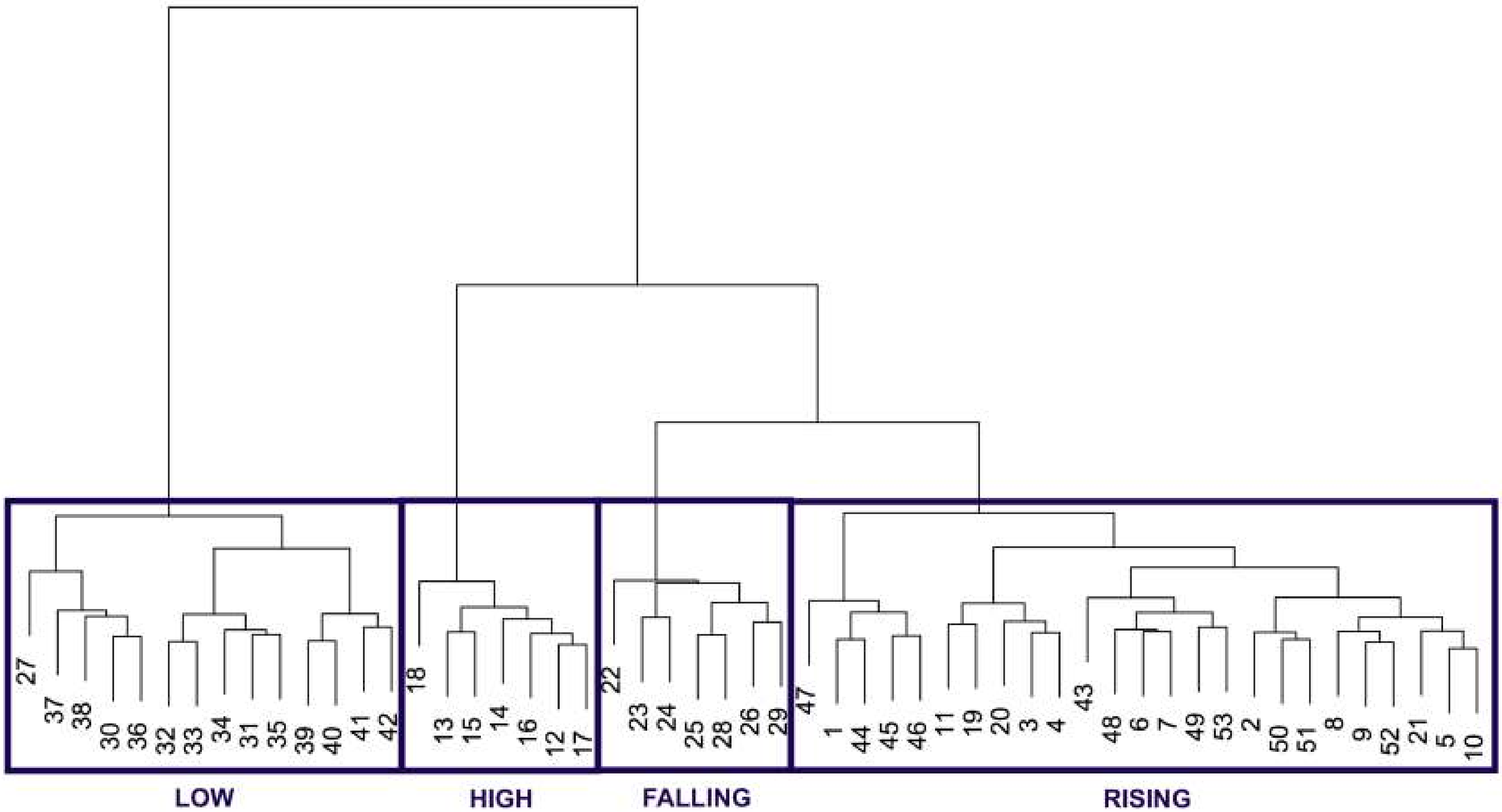

Figure 5. Dendrogram of the hierarchical cluster analysis of weekly means and standard deviations of groundwater levels at the 10 m station in the case study wetland. Numbers at the ends of the branches represent weeks of the year (1-53, to account for leap years). Interpretation of the clusters as seasonal hydrological periods was done visually (see text for more details)

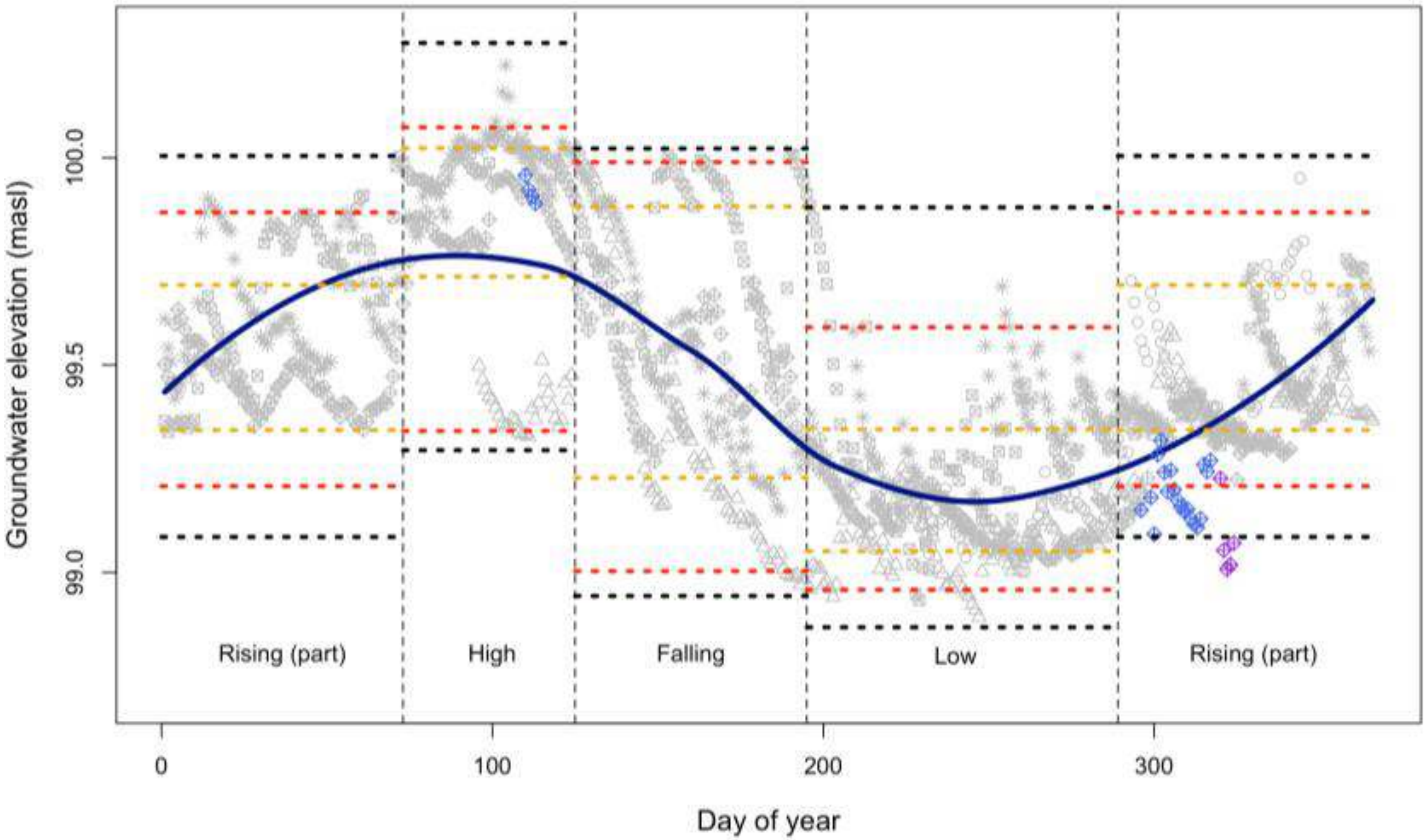

Figure 6. Seasonal thresholds of natural variation in daily water levels at the 10 m station in the case study wetland over the years 2011-2015, based on four defined seasonal hydrological periods (see text for more details); yellow dashed lines indicate the transition from the green to yellow zones, red lines the transition from yellow to red zones, and black lines the transition from red to grey zones

Table 4. Examples of potential mitigation actions to follow once water levels in a monitored feature cross the threshold from the common (green) zone to any of the other zones; note that actions from lower levels of risk should be carried forward to the next level(s)

Threshold crossed	Risk	Possible actions
None	None	• Monitor water levels in the feature • Conduct routine maintenance to ensure that monitoring and management equipment is functioning properly
Green -> Yellow	Moderate	• Contact and consult the appropriate agencies • Check monitoring and management equipment to ensure it is functioning as required • If applicable, increase manual monitoring frequency (note: use of data loggers is strongly recommended) • Analyze the data and share with appropriate agencies • Assess potential threat in the context of pumping and precipitation • Assess significance of water level and flow changes to the feature • Prepare to implement next level of water management strategy or plan (see below) • Consider water restrictions if hydrologic condition persists for extended periods
Green -> Red	High	• Implement next level of the water management strategy or plan to minimize the potential for impacts during sensitive periods, as appropriate (e.g. adjustment of dam or weir, implement water use restrictions or bans, rebalancing of pumping to other wells) • Discharge water to feature according to the water management strategy or plan (e.g. surface water distribution systems, groundwater injection system)
Green -> Grey	Extreme	• Reduce or cease pumping or water detention during sensitive periods, as appropriate

that three years should be considered a minimum – the more data there is available, the more accurate the description of the natural range of variation will be.

Limitations of the method

At present, the wetland hydrologic assessment method is still limited by our relatively poor understanding of ecohydrological relationships. For example, it is unclear precisely how changes in hydrology will lead to different ecological outcomes, or if the outcomes will be the same in every context. As such, we recommend that the wetland hydrologic assessment method should not be used on features that are considered highly sensitive to hydrologic alterations or irreplaceable, such as species at risk habitat, fens, or bogs.

SUMMARY

This wetland hydrologic assessment method analyzes existing hydrologic data for a particular wetland to quantify the hydrologic characteristics that determine and maintain the ecological composition, structure, and function of that wetland under study. The method can be used to describe the natural hydrologic variation in a wetland, assess and compare different management and mitigation scenarios, and guide and support adaptive management programs for wetland management. It is intended to reduce the risk of negative impacts by activities that can influence or alter the hydrology of wetlands and other natural features.

As part of a management program, the method measures hydrologic changes within the wetland, helps to assess the significance of the change and how those changes relate to the observed natural hydrologic variation of that wetland. The method can also be used to establish thresholds to trigger actions to mitigate impacts as part of an Adaptive Management Program.

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