Relationship of fen vegetation to long-term hydrologic processes in Rocky Mountain National Park, Colorado

By:

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INTRODUCTION

- Montane wetlands are characteristic features of the high elevation Rocky Mountain valleys. They support a larger number of plant and animal species and regulate the movement of water and sediment from the highlands to lowlands. Understanding long-term hydrologic processes that support critical wetlands is vital for protecting biodiversity, particularly in protected areas such as National Parks.
- Modeling water tables is commonly performed to develop a mathematical understanding of the hydrologic processes that influence ecosystems. Numerical models can be useful, but effective numerical models necessitate a thorough knowledge of aquifer properties, which demands copious information when investigating large watersheds. Statistical modeling, however, can also effectively be used to understand the processes that control water table variation. Statistical models can be used to link changes in water table depth to snow, rain, and temperature (Chen et al. 2002, Okkonen and Klove 2010).
- Fens are commonly thought to support high water tables throughout the entire growing season (Chimner and Cooper 2003a,b). In regions lacking substantial summer precipitation, as in the Sierra Nevada of California snowmelt recharge must be sufficient to sustaining long-term ground water discharge, soil saturation and peat formation. However, in areas where late summer monsoon rain occurs, this contribution may be a necessary complement to snowmelt in sustaining some peatlands.
- In high elevation ecosystems supporting high winter snowpack, early summer water tables are most likely a function of snow and temperature, but the influence of snow may be surpassed by rain as the summer progresses.
- Vegetation-based classification methods have been applied by others (Karlsen et al. 2005) to identify abiotic environmental growing conditions. Karlsen suggested that temperature was most critical to peat formation in Norway, while in the region of Rocky Mountain National Park, summer water table depth may be more important.

- The importance of hydrologic regime for supporting different plant communities and species is vital for management.

STUDY SETTING

Recent Climate

Rocky Mountain National Park (RMNP) is located in the southern Rocky Mountains in northern Colorado and straddles the Front Range (Fig. 1). Regional weather varies substantially, however a general climate-warming trend is projected for the future (Washington et al. 2000, Stewart et al. 2004). Nested within this projected temperature increase is substantial interannual weather variation, where the amount and seasonality of snow, rain, and temperature vary. RMNP's wetlands rely on precipitation recharged surface and ground water flow systems to maintain high water tables that support hydrophytes, peat formation, and pools used by amphibians and aquatic invertebrates as habitat. RMNP receives significant winter snowpack and also late summer monsoon rains. The importance of rain for recharging water tables that support wetlands is poorly understood. Most fens in RMNP are dominated by water inputs thought to be from the current water year's melting winter snowpack and summer rain (Cooper 1990), and increasing irregularity in hydrologic years could have deleterious effects on fens.

RMNP has experienced substantial interannual variability in hydrologic inputs since we began monitoring its wetlands in 1987 (Cooper 1990; Fig. 2, Fig. 3). The Phantom Valley SNOTEL site is located at the upper end of the Kawuneeche Valley on the western side of RMNP (UTM zone 13N 477870, 4472500; 2750 m.a.s.l.). It is within 12 km of all focal sites and has recorded snow, rain, and temperature data continuously since 1986 (Fig. 4). For water years 1987-2012, Phantom Valley averaged 64 cm of precipitation. The average day of peak SWE is March 30 with a standard deviation of +/- 14 days. The maximum snow water equivalent (SWE) per year is 10.6 +/- 3.0 cm. The snowpack typically has melted by May 12 +/- 15 days. The average total summer rainfall from July 10 through August 20 is

7.4 +/- 2.7 cm. The variance in these weather variables each year contributes to the ground water available during the summer to support wetlands and streams.

METHODS

Sites

Three RMNP fens with multi-year depth to water table (DTW) records were modeled to better understand the possible influence of climate variation to fen hydrologic processes. The three sites, Green Mountain fen, Big Meadows, and Sphagnum fen have growing season water table data for 6, 7, and 5 years, respectively. These sites also represent three distinct fens. Big Meadows (BM) is a large, gently sloping fen dominated by *Carex aquatilis*, *Salix planifolia*, and *Calamagrostis canadensis*. The peat is up to 2 m thick, and has a basal ^{14}C age exceeding 11,000 years BP (Cooper 1990). The area had been homesteaded and ditched to increase forage production and access to the meadow for livestock likely around 1900-1930, but the ditch was blocked and the fen hydrologic regime largely restored in 1990 (Cooper et al. 1998).

Green Mountain fen (GM) is a flat basin wetland supporting a thick peat body with a pond in the center. The pond is fringed by a floating mat created by *Carex limosa*. *Carex utriculata* dominates most of the fen on the thick peat body, as it is tolerant of seasonally standing water and deeper summer water tables. The basal peat has been ^{14}C aged at nearly 12,000 years BP.

Sphagnum Fen (SF) is a very gently sloping fen with an over story of *Picea englemanii*, *Salix wolfii*, and *Salix planifolia and* an understory of *Tomentypnum nitens* and *Plagiomnium ellipticum* mosses. It occurs on the Kawuneeche Valley floor and is supported by a large spring complex that discharges from the base of a glacial moraine. This site is unusual in RMNP for its forest over story and the presence of large *Sphagnum* dominated peat hummocks that create considerable microtopographic diversity.

A fourth wetland, Eleocharis Fen, was also included in this analysis of fen types. It has stable water table depths, with <10 cm of DTW variation across five summers of measurement. This DTW stability supports plant communities reliant on consistently high water levels. Dominant plant species are *Eleocharis quinqueflora* and *Carex aquatilis*, with an abundance of herbaceous dicots such as *Pedicularis groenlandica*, and mosses such as *Limprichtia cossonii* (or *Scorpidium cossonii*).

An example hydrograph from each fen during a near-average precipitation year indicates that fen water tables are ubiquitously near the soil surface in early summer, but its variance during summer is distinctively different among fens (Fig. 5). BM, GM, SF, and EF represent a spectrum of fen types in RMNP, and water table variations from these fens were used to provide model hydrographs that we would expect to measure in other RMNP fens. Poor Fen and Red Mtn Fen…

The Phantom Valley SNOTEL used in analysis is 10 m above Sphagnum Fen, 120 m below GM and BM fens, and 340 m below Eleocharis Fen.

Hydrology

Hydrologic regime, the full suite of hydrologic patterns and processes, is the main physical driver of wetland formation and persistence (Mitsch and Gosselink 2007). Of primary importance to a wetland's hydrologic regime is consideration of DTW and the timing and degree of water table changes during the growing season. These processes influence which plant species can occupy each site, determine wetland vegetation composition, and rates of organic matter production and decomposition. In montane ecosystems, spring snowmelt creates elevated water tables in early summer, and site's with a hydrologic regime that supports near-surface water tables for a long enough period during the summer, organic matter production will exceed decomposition, resulting in organic or peat accumulation, forming a fen (Chimner and Cooper 2003a, Lemly and Cooper 2012).

Depth to water table was measured by hand approximately once per week in all measures from the 1980's and 1990's. More recent data are hourly DTW measures made using pressure transducers submersed in monitoring wells within the study wetlands produced data sets suitable to isolate distinct water table variables at the beginning, middle, and end of the growing season that we hypothesized were of ecological significance. Water levels at these times were used for a quantitative inter-fen comparison. DTW on June 10 was chosen to represent early- season hydrologic conditions that occurred after snowmelt when fen plants are rapidly growing. July 10 represents mid-summer, when the warmest annual temperatures are occurring, transpiration is high, and typically little rain has occurred for many weeks. August 20 represents late-summer growing conditions after the influence of snowmelt has diminished, evapotranspiration demands have been high for months, and monsoon rains have contributed to the water balance.

Statistical Hydrologic Model

We created statistical models to identify the importance of snow, rain, temperature, and the interaction of these variables as they influence fen water tables. To do this we constructed models for three dates throughout the growing season: June 10, July 10, and August 20. Through investigation of DTW on these three dates we aimed to identify if the high water tables supporting RMNP fens are reliant on snowmelt, rain, or both throughout the growing season.

A primary goal of this investigation was to use existing data to create expectations of water tables that support RMNP fens. This application will allow us to calculate expected DTW based on weather parameters measured in the coming years. We have created linear models that relate climate data to measured DTW at three reference fens, BM, GM, and SF. The models predict water levels from one year to another and may be used to predict DTW in a new year. Additionally, the models permit comparison of water table measurements across years and sites. To do this, each wetland’s models are based off of median values for all predictor weather variables, instead of the weather of a random year.

Identifying DTW when all predictors are in a hypothetical average year eliminates the influence of each predictor's deviation from average in a model.

Current year weather data collected at Phantom Valley were used as independent variables and were regressed against DTW to identify relationships across the growing season. Initially, five snow, six monsoon rain, and three temperature variables were tested to explain the measured DTW's (Appendix A). After preliminary correlation analyses, we retained the variables: maximum snow water equivalent (SWE), date of max SWE, date of complete snowpack melt, monsoon rain between July 10 and August 20, and mean temperatures for March-May, March-Jun, and March-August.

In multiple linear regression models, the number of predictor variables (i.e., weather metrics) is restricted by the number of observations (i.e., years with DTW data). If there are fewer years than predictors, the model is over parameterized (Kuchler et al. 2004). Similarly, if the number of observations is not considerably greater than the number of predictors, models will fit the training data but are unreliable when applied to test data, known as over-fitting. Preliminary analyses were conducted using stepwise multiple linear regressions of the raw predictors against DTW. These models produced high adjusted R^2 values ($0.66 \leq R^2 \leq 1$, mean = 0.86), but the models were over-fit and their predictions were often unreasonable when applied to test years. To avoid the pitfalls encountered with only 5-7 years of DTW data, we created composite weather variables and used simple linear regression techniques (Kuchler et al. 2004, Feldmeyer-Christe 2007). Raw predictors were first normalized using a z-score transformation. Then composite variables were identified by combining predictors into a weighted combination using the form:

$$\textit{composite} = C + a*x_1 + b*x_2+\ldots+n*x_n$$

where C is a constant representing a wetland's average water table depth across wells in a mean year, $x_{1\ldots n}$ are the normalized weather variables, and a…n are constants that were iteratively adjusted to maximize adjusted R^2 values in the final models. Through this process we identified a combination of coefficients that maximized correlation to water tables across training years for a given fen and date of the summer. This method had a much improved predictive capacity compared to the over-fit multiple linear regressions. This was a function of the transformed variables predicting changes starting with a mean weather year and DTW, and each component variable was forced to predict water table response in only the *a priori* reasonable direction (e.g., increasing SWE could not predict decreasing DTW). The combination of covariates considered for each composite variable is outlined in our conceptual diagram (Fig. 6). At each wetland the years used to calibrate models were clumped in time, but their distribution in the degree of variation sampled for each weather variable did a reasonable job of representing the spectrum of values over the past 30 years. The lm function in the R stats package was used for analysis.

Fen Vegetation

Cooper (1990) and Chimner et al. (2012) provide a summary of the ecology of the fens in the southern Rocky Mountains. Many peat bodies began to accumulate more than 10,000 years ago (Cooper 1990, Chimner et al. 2002). There is little information on vegetation changes in peatlands on the time scale of thousands of years, but we assume that sites with relatively stable hydrologic regimes generally have similar vegetation structure and composition over time. Fens in Rocky Mountain National Park vary widely in vegetation composition and can be dominated by herbaceous plants, shrubs with herbaceous plants, or even conifer trees with an understory of herbaceous species. Mosses may be abundant or a very minor component of the vegetation.

We described the vegetation over our period of record as well as the fidelity of vegetation to its wetland complex using a non-parametric multivariate ANOVA (Adonis in R). Mean cover with a decostand (log) transformation was used, with all rare taxa (species in less than 4 sites) removed (McCune et al. 2002). We treated wetland complex as a fixed factor and nested it within year so that the permutations used by adonis to estimate F and p values occurred only within each year and not across all years. We used data from reference wetlands and two additional sites (PF and RF) for which we had repeat sampling. We restricted data to a single event per season where we had within season revisits. To further illustrate patterns in vegetation we clustered all sites using agglomerative nested clustering (Agnes in R) and then performed both non-parametric and parametric multidimensional scaling ordination (metaMDS and cmdscale in R, respectively) with Bray-Curtis distances. Resulting models were qualitatively compared and if patterns were similar, the parametric model was used given more interpretable axes. Select environmental gradients were correlated with ordination scores and plotted. Significance of these gradients were determined through permutation and a goodness of fit statistic (R^2) generated.

Plant community composition was assumed to be stable at the time of survey, and equilibrated to the hydrologic regime of the calibration peatlands. Percent cover estimates were conducted at wells where water tables were measured. Multiple years of hydrologic data constituting a variety of annual weather conditions, paired with vegetation data, were used to develop relationships between water depth and vegetation composition. Linear regression was used to identify relationships between weather and hydrologic variation among years. We developed models to predict the water table supporting different vegetative communities across a variety of weather years. Identifying strong relationships between weather and water tables was a prerequisite for comparison among sites having measurements taken in different years. In doing this, we were able to transform each wetland’s measured water tables to expected values during an average year. Finally, we were then able to compare expected vs. observed vegetation-hydrology relationships across wetlands.

Numerous fens exist in RMNP that have never been studied; thus no long-term hydrologic data are available. Our framework for comparison of well studied to unstudied sites is based upon an indirect ordination of vegetation composition data using nonmetric multidimensional scaling (NMS) with Sorensen (Bray-Curtis) distance measure. NMS groups sites with similar vegetation composition. Plots from the four fens separated well, and a two-dimensional plot isolates each wetland (Fig. (appendix)). Data from additional fens were added in subsequent NMS runs, and we identified which reference fen vegetation was most similar to the new fen. Thus, NMS was used to classify fens that each is most similar to, and the subset of models created from this wetland were used for water table analysis at the new wetland. To minimize the effect of particular weather years, general linear models were used to predict the shift in water tables to a standardized weather year that had median environmental conditions of the environmental variables displayed in Fig. 6. In accounting for weather variation, we are able to compare water tables at different wetlands that were measured in different years, by translating data to a hypothetical "average" weather year.

RESULTS

Fen Water Table Depth Models

Water table depth models constructed for BM, GM, EF and SF indicate that these variables have the strongest influence on water levels in RMNP fens. The dates of maximum SWE and snowmelt were better indicators of June and July DTWs than temperature and maximum SWE. This suggests that watershed groundwater recharge by snow, and the discharge of groundwater into fens is a more important driver than water outputs determined by outflow and evapotranspiration. Temporal variables (i.e., max SWE and snow-off dates) incorporate the complex interactions between snow and temperature, including the rate of temperature rise in early summer and the timing and distribution of nights with temperatures exceeding 0° C. These variables are easily calculated from weather data collected at most USDA SNOTEL stations. However, by late summer the relative influence of snowmelt recharge vs. rainfall differs among fens. A Pearson's R correlation matrix shows how water table depth correlates with individual weather variables tested at the modeled fens (Table 1).

Using hydrograph analysis and statistical models we created predictions for DTW during the growing season at four fens in RMNP. Depth to water table patterns varied within and among years in GM, BM, and SF and the models that fit their patterns are distinct. We developed composite variables for different fens and dates. These were proportional combinations of weather variables, calibrated to maximize simplicity and predictive power for DTW. Within the three modeled fens, June and July DTW's were maximized by similar composite variables indicating the importance of snowpack and snow melt date for supporting water tables in all fens (Table 2).

Green Mountain Fen: The composite variable retained for predicting June and July DTW's at Green Mountain Fen was weighted: 2 * (max SWE date) + 1* (snow-off date), while max SWE and temperature were not retained. This weighting means that, for the 7 years of data available for GM used to calibrate the models, a linear regression incorporating the two timing variables best predicted measured DTW (Jun $R^2 = 0.55$, Jul $R^2 = 0.55$) compared to other combinations of variables. In contrast, 20 Aug DTW was much more heavily weighted toward monsoon rains than the previous winter's snow. Monsoon rain comprised 57% of the composite variable, while temperature contributed 29% and the timing of max SWE the remaining 14% (Fig. 7). Thus, early and mid-summer DTW's at GM are described by the timing of accumulation and melt of the previous winter's snowpack. However, by late summer, DTW connection to snow is minimal compared to monsoon rains. The measured low DTW on 20 Aug 1993 validates the weighting of the August model. Even though 1993 had the third most snow of the past 27 years, it was the third lowest monsoon year (Fig. 3) which led to a much lower than average August water table. Correspondingly, in GM's seven years of water table data, 1993 supported the highest Jun and Jul DTWs, but by late August DTW was the 2nd lowest. This illustrates the importance of both snow and rain in maintaining high water tables at this fen.

Big Meadows Fen: Big Meadows models revealed similar trends as seen in GM. In June, average spring temperature was the single variable most closely related to DTW, but in July the timing of snowpack melt was the strongest predictor. For the June and July predictive models temperature was subsumed by other metrics, and the model was weighted 3:1:1 for variables date of snow-off, max SWE, and max SWE timing. Similar to GM, the combination of timing variables best predicts DTW in early and mid-summer rather than max SWE and Mar-May temperature alone. Also similar to GM, August DTW is best predicted by weighting monsoon rain as the strongest variable. The August model was weighted 4:2:1:1 for monsoon rain, max SWE, temperature, and snow-off timing, June and July DTW's are highest in 1993, a large snow year. Unlike at GM fen, August 1993 DTW was third highest of the 7 measured years in spite of the low monsoon rain totals for that year. Thus, the effects of the winter snowmelt recharge last far into the summer at this fen during very large snow years.

Sphagnum Fen: Sphagnum Fen water tables appear to be driven predominantly by snow throughout the summer. As at BM and GM, the timing of snowmelt is strongest predictor of DTW in June and July. Unlike models for the other study fens, the maximized composite variable did not include multiple variables; instead, snow-off date alone maximized the R^2 and was used for June and July predictive models. The August water table at SF, however, is more correlated to snow variables than temperature or monsoon rain. The August model was comprised of a 2:1:1 ratio of snow-off date, max SWE, and monsoon rain. When analyzed alone, monsoon rain had low correlation to August DTW (Table 1), but when factoring in maximum SWE and timing of snow-off, monsoon rain did contribute to the predictive model. Therefore, it appears that snow affects this fen more throughout the growing season at SF compared to GM and BM. However, we should use caution in accepting this relationship because the range in monsoon rain totals during the study years was relatively limited in comparison to the variation seen through the past 27 years (Appendix B).

Eleocharis Fen: EF had highly stable DTW during the growing season. Because measured DTW did not change more than 8 cm within or between growing seasons, linear regression models employed at the other fens were deemed inappropriate and not created. EF represents fens that are highly stable and are ordinarily unresponsive to annual weather variation. Four hand measurements in 2008-9 and continuous logger data in 2010-12 recorded less than 8 cm of water table variation. This reveals that this sloping fen has sufficient hydrologic inflow to maintain surface saturation throughout the growing season. This fen is a groundwater discharge site and is supported by either annual inputs that surpass water usage, or it is a part of a multi-year groundwater system that has a net surplus of water over the period of hydrologic influence. Regardless, this fen type is importantly distinct from the previous fens that tend to dry toward late summer. The inclusion of 2012 data in our final report will reveal if near-surface water tables persist throughout the growing season in even the driest of years. In the future, fens such as EF may reveal the effects of multiple years of environmental change, however. If DTW does start to dip at these stable fens, special attention should be given to the causes of this change. These fens drying would mark the crossing an important environmental threshold.

Model Testing

At two groundwater monitoring wells we have multiple years of data to test the predictions of our models. Well GM301 was one of seven wells averaged to develop predictive DTW models at GM.

Well BM511 was one of 12 wells averaged to develop predictive models at BM.

Model Assessment

- Models give Reasonable predictions
- The Median Year: we use this to standardize.
- It is necessary to incorporate this fundamental difference in comparison of wetlands hydrologic data collected indifferent years. In describing fen types, we can't simply consider the DTW in the measurement year. Since we expect different DTW's in different years, by applying the models we can translate measured water tables to what they would be in an average year.

Adonis:

```
Alladonis <- adonis(veg~Complex/VegYearText, data = env,   #June10DTW+Aug20DTW
method="bray",
#strata=env$VegYearText,
permutations=999)
print(Alladonis)
```

```
                      Df    SumsOfSqs   MeanSqs   F.Model   R2        Pr (>F)
Complex               4     3.3399      0.83496   5.9898    0.36927   0.001***
Complex:VegYearText   15    2.359       0.15727   1.1282    0.26082   0.268
Residuals             24    3.3456      0.1394    0.3699
Total                 43    9.0444      1
```

```
All adonis <- adonis(veg~AgnesGrpsText/VegYearText, data = env,
method="bray",
#strata=env$AgnesGrpsText,
permutations=999)
print(Alladonis)
```

```
                              Df   SumsOfSqs   MeanSqs  F.Model   R2        Pr(>F)
 AgnesGrpsText                 3      4.7383   1.57944  18.5171    0.5239   0.001***
 AgnesGrpsText:VegYearText    11      1.8325   0.16659   1.9531   0.20261   0.006**
 Residuals                    29      2.4736    0.0853  0.27349
 Total                        43      9.0444         1
```

Discussion and Conclusions

RMNP fens rely on winter snow and monsoon rain to recharge their watershed aquifers. Spring snow water equivalent, monsoon rain, and temperature are the primary drivers of fen water table depth during the summer and each fen's hydrologic regime. By creating linear models composed of variables that influence fen DTW, we have found that each study fens is influenced by somewhat different weighted combinations of weather variables. Fens in RMNP occur at high elevation where winter snow is a major component of the hydrologic cycle and sustains water tables, especially in early to mid summer. Maintenance of high water tables into the middle of the growing season is necessary for fen persistence, and our models for June and July at all three fens indicate that the timing of snowmelt is the most important factor in maintaining high water tables. The influence of the snow timing metrics, max SWE date and snow-off date, are weighted differently at BM, GM, and SF. A major projection of climate change in the Rocky Mountains is a shift to earlier snowmelt resulting in runoff in the high country earlier in the growing season (Stewart et al. 2004). This also results in longer drier and warmer summers. Our models indicate that early snowpack decline and disappearance directly relate to low water tables, and projected earlier melting will likely jeopardize near-surface fen water tables. Our models indicate that some fens, such as BM and GM, may already be dependent on monsoon rain for maintaining late-summer water tables that promote peat accumulation. In the future, earlier and greater monsoon rains may be necessary to keep RMNP fens from becoming carbon sources.

Our research substantiates the fact that not all RMNP fens are identical hydrologically. Fens, although all peat-accumulating, have different vegetation composition based on their environmental setting, history and hydrogeochemistry. Ongoing RMNP wetland monitoring efforts through the NPS Inventory and Monitoring Program include vegetation surveys and these data should be incorporated into the models in the future. Vegetation will be critical in assigning each RMNP fen to a reference fen. With known vegetation community composition, a new fen can be input into the NMS to select an appropriate reference fen, whose models can be used to predict the new fen's DTW. Verifying that this procedure works is a next step in operationalizing this effort. If this procedure consistently informs us of DTW, we will be able to identify fens that deviate from expectations of a healthy functioning site, and we can pay special attention to causes.

A primary factor in our selection of reference fens is the need to include sites with as many years of hydrologic data as possible. Multiple years of data are essential for creating robust models, since many environmental factors interact to create a fen's DTW patterns each year. A larger number of years of data used in parameterizing models and the more weather variability those years represent, the more power the model. Included in the ongoing plan to increase the strength of this project is to incorporate growing season 2012 and 2013 DTW data into the models. In addition to simply adding more years to the dataset, the extremely dry 2012 may inform us if threshold effects occur at some sites, and if the relationship among weather variables and DTW is not linear. This knowledge will help refine our understanding of RMNP fens, the hydrologic processes that supports them, and the potential for changes in the future.

References

Chimner, R.A., D.J. Cooper and W. J. Parton. 2002. Modeling carbon accumulation in Rocky Mountain fens. *Wetlands* 22:100-110.

Chimner, R. A., Joanna M. Lemly, and David J. Cooper. 2010. Mountain fen distribution, types and restoration priorities, San Juan Mountains, Colorado, USA. *Wetlands* 30: 763-771.

Cooper, D. J. 1990. The ecology of wetlands in Big Meadows, Rocky Mountain National Park, Colorado: the correlation of vegetation, soils and hydrology. *US Department of the Interior, Fish and Wildlife Service*, Biological Report 90(15). October 1990. 45p.

Kuchler, M, K. Ecker, E. Feldmeyer-Christe, U. Graf, H. Kuchler, L.T. Waser. 2004. Combining remotely sensed spectral data and digital surface models for fine-scale modeling of mire ecosystems. Community Ecology 5: 55-68.

Feldmeyer-Christe, E., K. Ecker, M Kuchler, U. Graf, L. Waser. 2007. Improving predictive mapping in Swiss mire ecosystems through re-calibration of indicator values. Applied Vegetation Science 10: 183-192.

McCune, Bruce, James B. Grace, and Dean L. Urban. *Analysis of ecological communities*. Vol. 28. Gleneden Beach, Oregon: MjM software design, 2002.

NOAA NWS. http://www.crh.noaa.gov/gjt/Weather_Info/monsoon.php. Modified 11 Feb 2010. Accessed 13 March 2013.

Stewart, I., Cayan, D., Dettinger, M., 2004. Changes in snowmelt runoff timing in western North America under a “business as usual” climate change scenario. Climatic Change 62: 217-232.

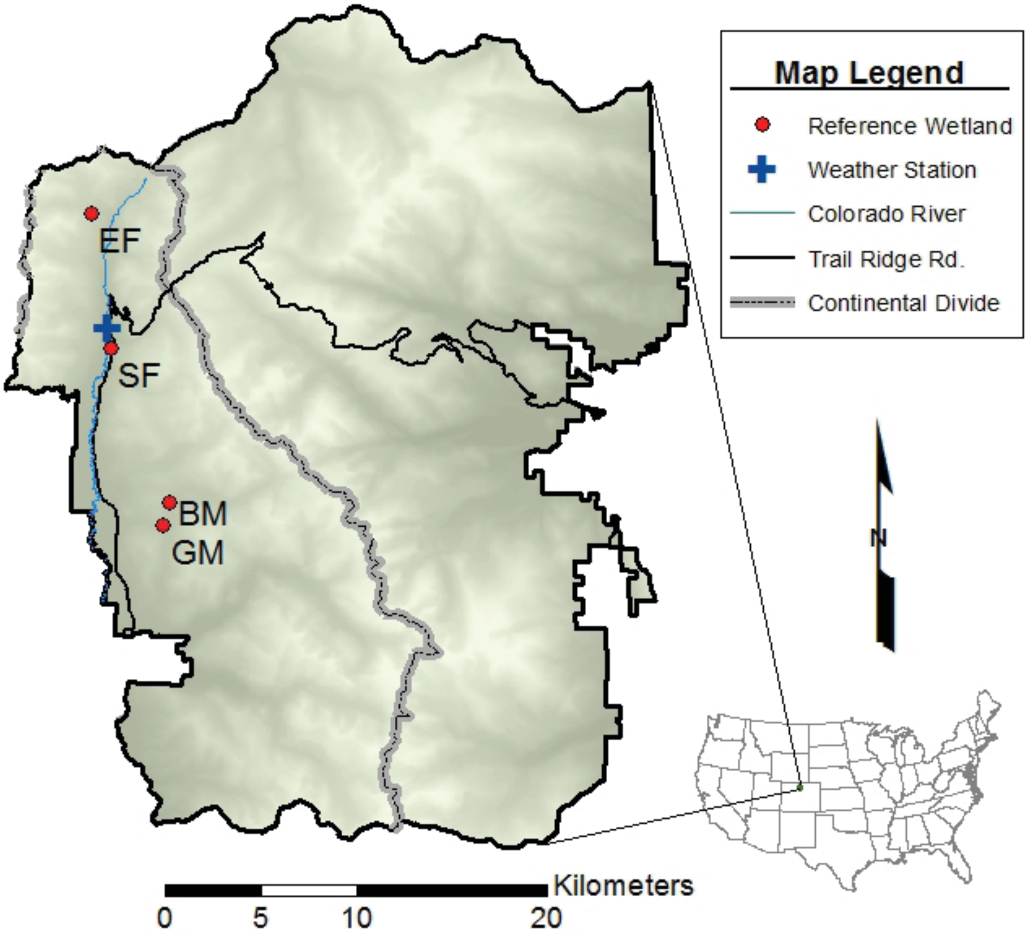


Figure 1. Rocky Mountain National Park, Colorado, USA, illustrating the location of four reference fens (EF = Eleocharis fen, SF = Sphagnum fen, BM = Big Meadows, GM = Green Mountain fen) and the Phantom Valley SNOTEL.

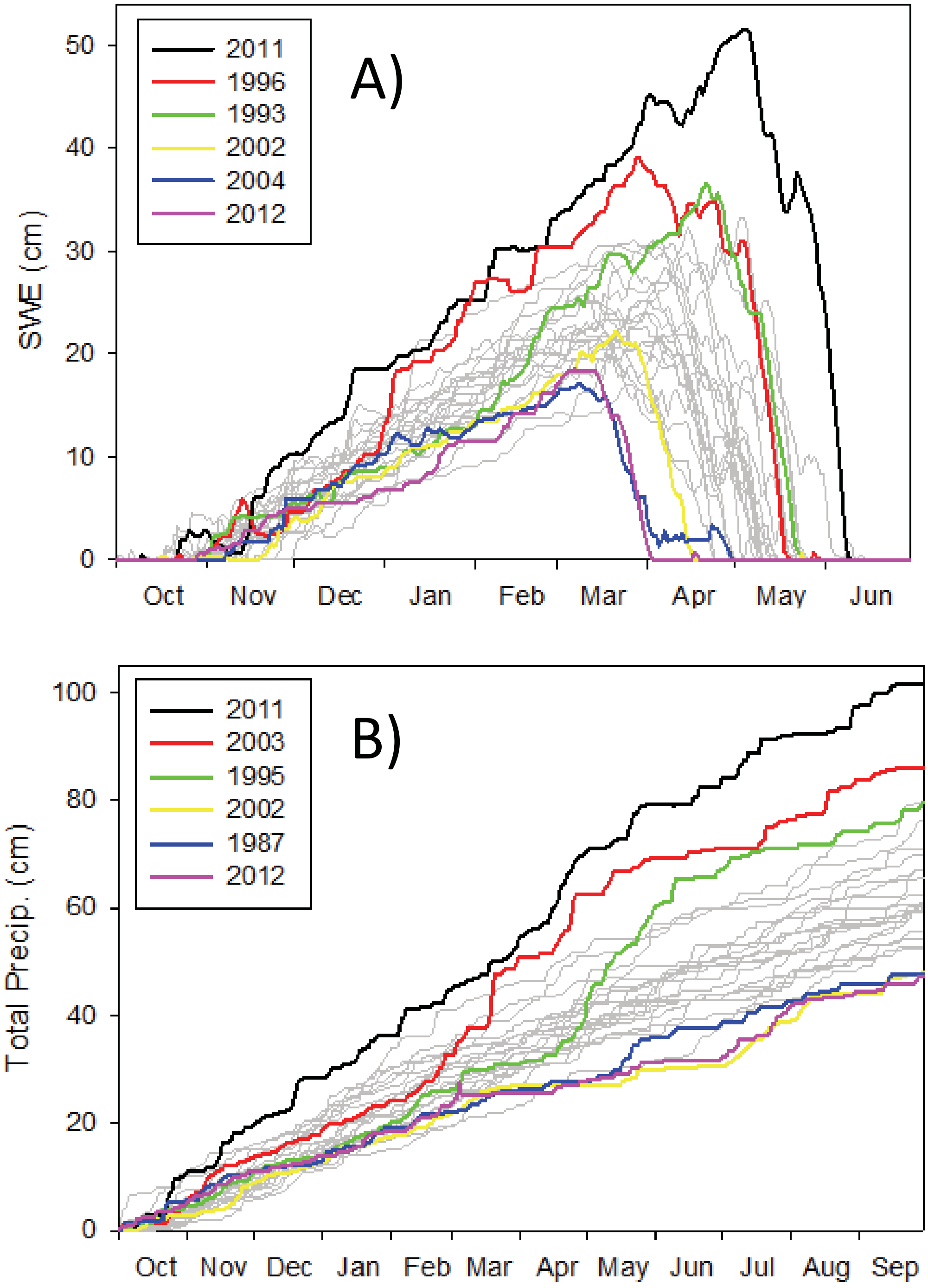


Figure 2. Phantom Valley SNOTEL precipitation, 1987-2012. Total (A) SWE, and (B) accumulated precipitation per year. Three high and three low years are colored in each panel to highlight the continuous patterns recorded in example years.

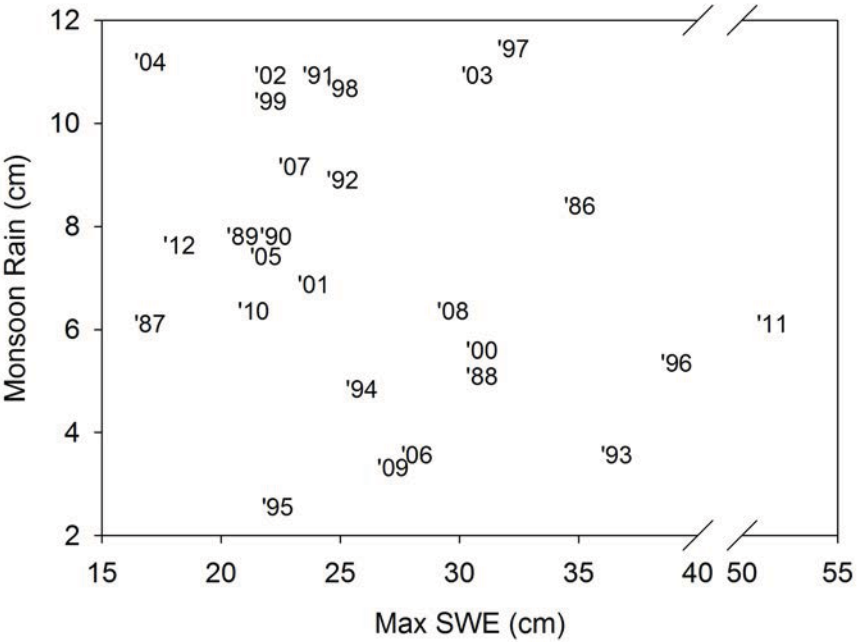


Figure 3. Distribution of the snow and rain hydrologic inputs that affect RMNP wetland water tables, 1986-2012. Maximum SWE represents snow input while and monsoon rain indicates depth of late summer precipitation available to supplement groundwater levels.

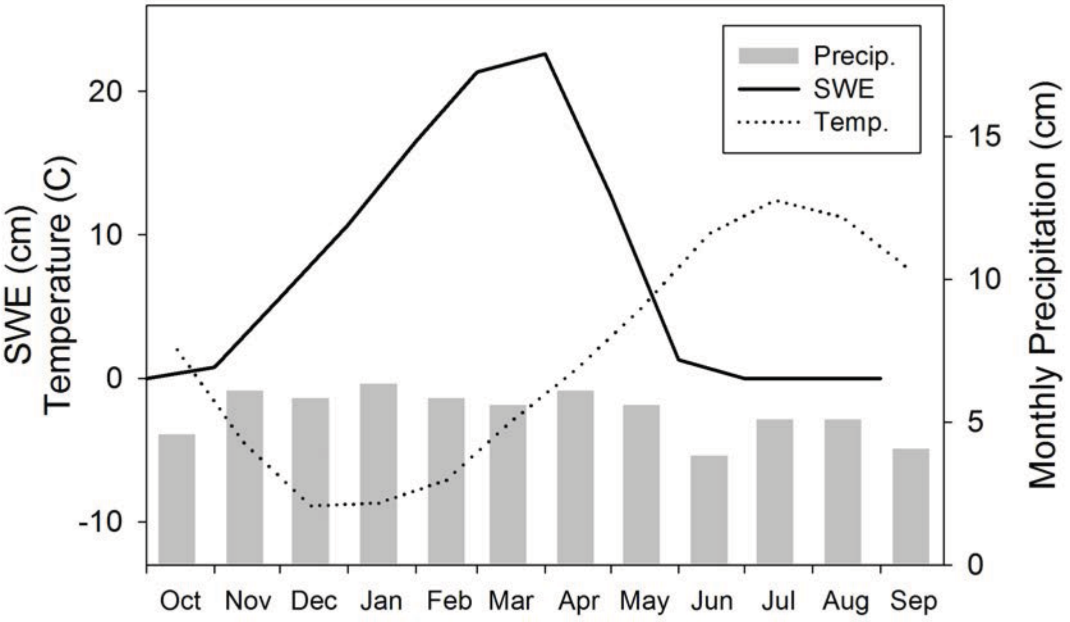


Figure 4. Mean SWE, monthly precipitation, and temperature at Phantom Valley SNOTEL, 1987-2012. SWE values are displayed for the first of the month, while precipitation and temperature are monthly averages.

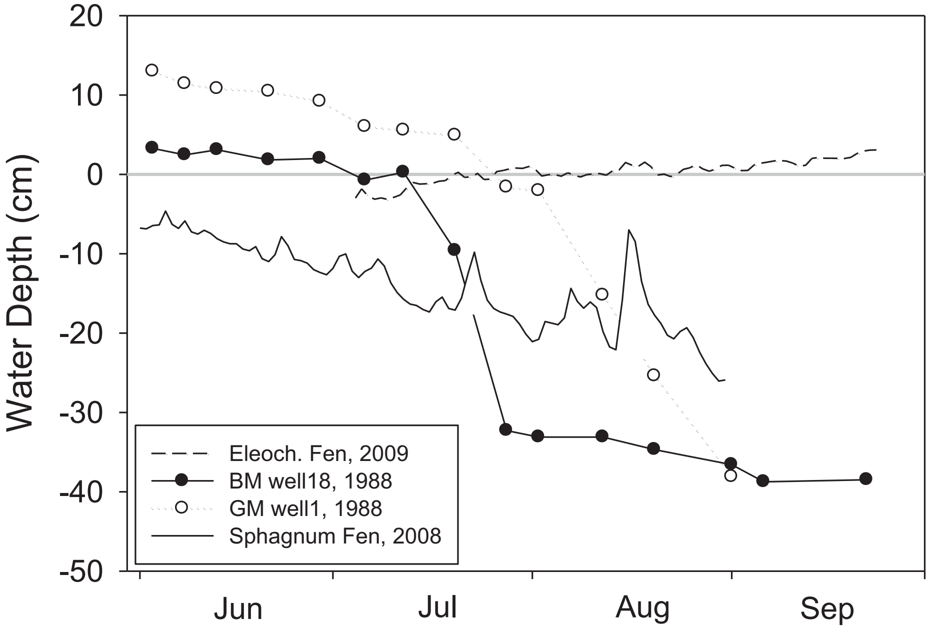


Figure 5. Example summer hydrographs from each of the four reference fens. Hydrographs illustrate water table variation during an example growing season at one well at Big Meadows, Green Mountain Fen, Sphagnum Fen, and Eleocharis Fen. Circles depict hand measurements, while EF and SF's had data hourly logger data. Even though the four hydrographs exhibit unique characteristics, importantly, each maintains saturated conditions through much of the growing season which promotes peat formation.

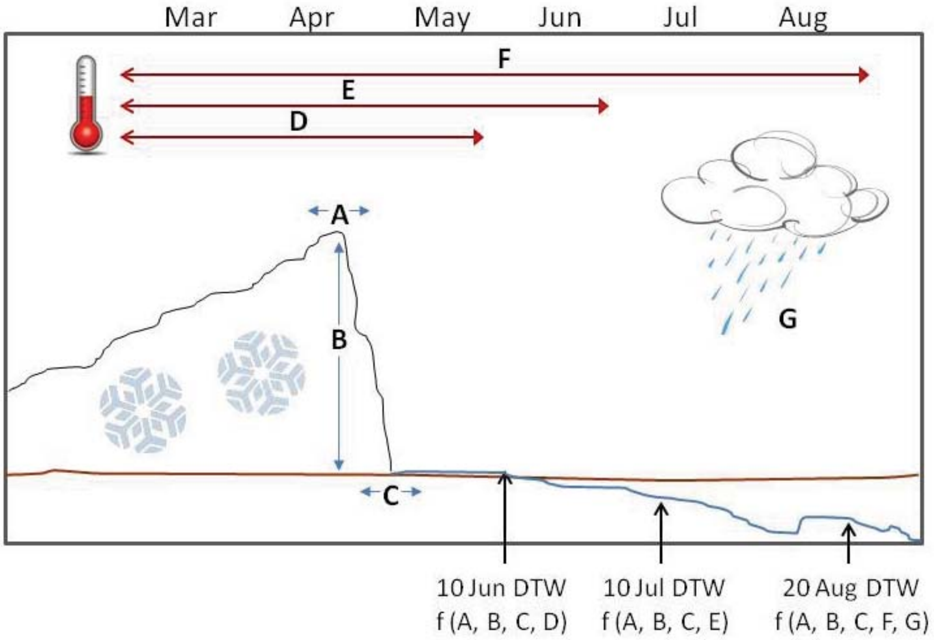


Figure 6. Conceptual Diagram of weather variables tested for each date's DTW models. A = date of max SWE, B = max SWE depth, C = date of snow-off, D = Mar-May average temp, E = Mar-Jun average temp, F = Mar-Aug average temp, G = monsoon rain depth. Variables considered for each date's model are listed as f(x) in the diagram.

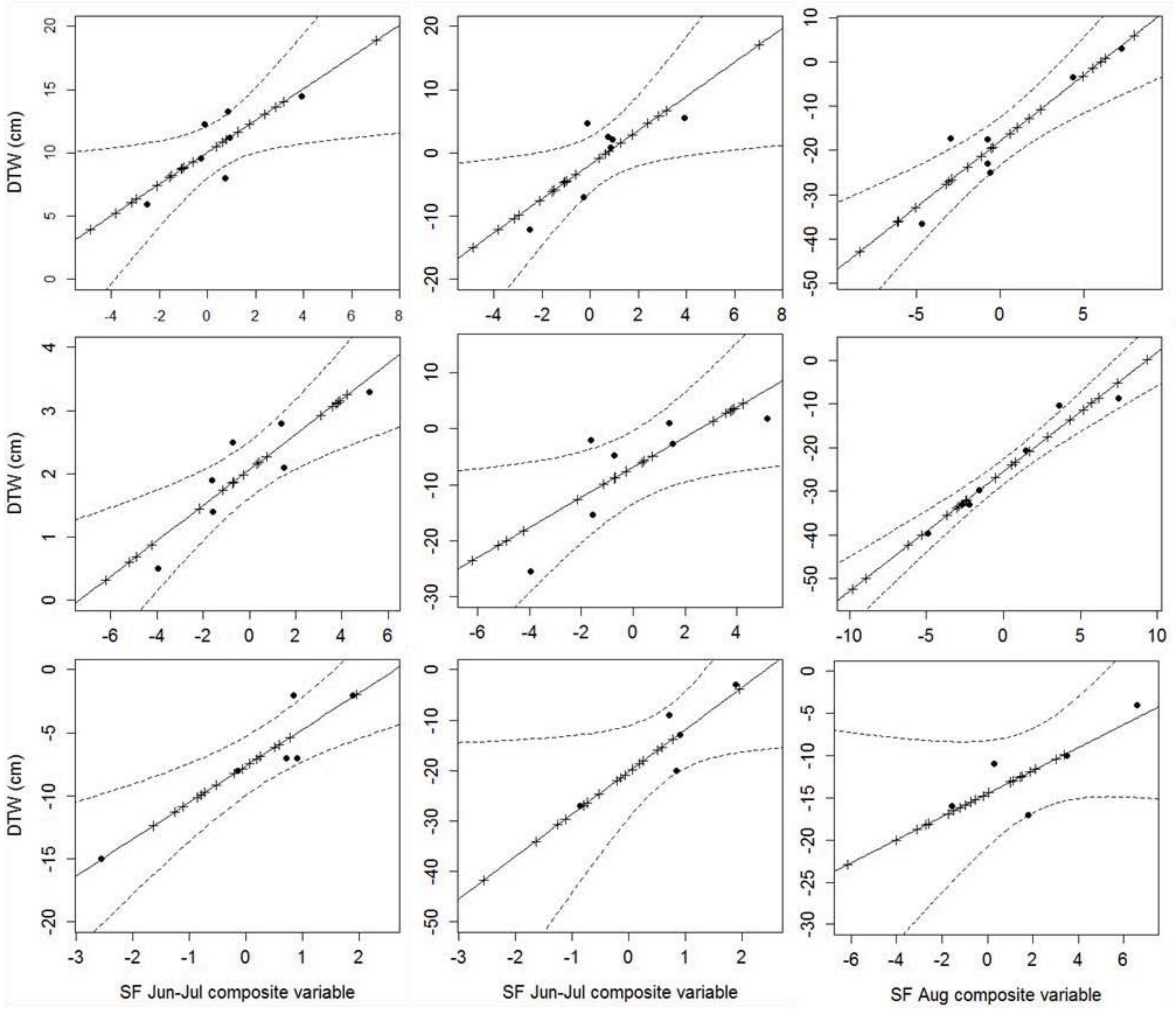


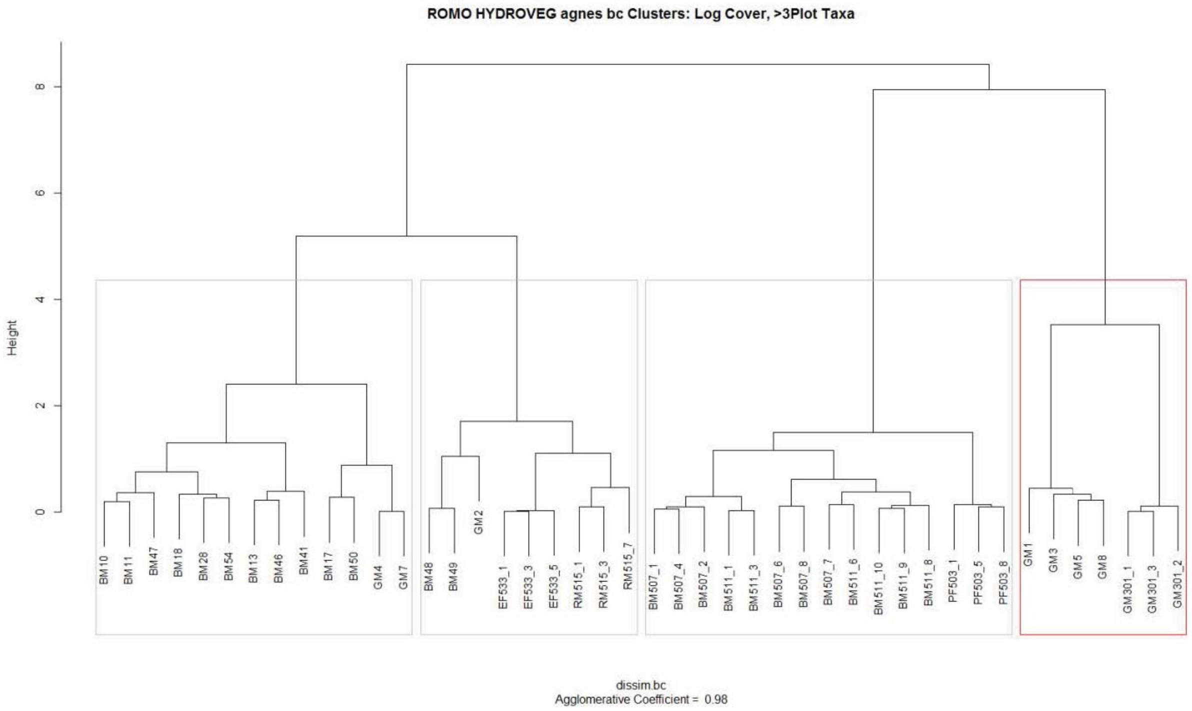
Figure 7. The nine models created for DTW at GM, BM, and SF (rows) for Jun, Jul, and Aug (columns). Circles are measured DTW's for years used in model calibration, while crosses are predictions for each year without data, 1987-2012. Dashed lines are 95% confidence interval of the mean. Note that axes change among panels.

Table 1. Correlation coefficients at GM, BM, and SF between DTW and the individual weather variables tested in regression models. Values of "na" are listed for relationships not tested for models of the given dates.

	DTW Model:		
Fen and Metric	**10-Jun**	**10-Jul**	**20-Aug**
Green Mountain Fen			
max SWE	0.24	0.42	-0.24
max SWE date	0.77	0.74	0.21
snow-off date	0.38	0.43	0.13
Mar-May ave temp	-0.38	na	na
Mar-Jun ave temp	na	-0.62	na
Mar-Aug ave temp	na	na	-0.47
monsoon rain	na	na	0.83
Big Meadows			
max SWE	0.73	0.60	0.05
max SWE date	0.52	0.39	0.36
snow-off date	0.82	0.77	0.31
Mar-May ave temp	-0.86	na	na
Mar-Jun ave temp	na	-0.65	na
Mar-Aug ave temp	na	na	-0.82
monsoon rain	na	na	0.63
Sphagnum Fen			
max SWE	0.74	0.62	0.76
max SWE date	0.77	0.67	0.62
snow-off date	0.93	0.88	0.73
Mar-May ave temp	-0.83	na	na
Mar-Jun ave temp	na	-0.33	na
Mar-Aug ave temp	na	na	-0.19
monsoon rain	na	na	-0.15

Table 2. Model parameters for DTW prediction using weather variables. The last 4 columns are the fens, and the three major rows describe models for 10Jun, 10Jul, and 20Aug at the fens.

Model	**Variables Tested**		**GM**	**BM**	**SF**	**EF**
Jun	max SWE, max SWE date, snow-off date, Mar-May av. temp.	**comp. var.:**	2*max SWE date + 1*snow-off date	1*max SWE + 1* max SWE date + 3*snow-off date	1*snow-off date	na
		equation:	10.06 + 1.257*comp	2.06 + 0.2807*comp	-7.63 + 2.9*comp	0
		R^2:	0.55	0.75	0.82	na
Jul	max SWE, max SWE date, snow-off date, Mar-Jun av. temp.	**comp. var.:**	2*max SWE date + 1*snow-off date	1*max SWE + 1* max SWE date + 3*snow-off date	1*snow-off date	na
		equation:	-1.83 + 2.697*comp	-6.88 + 2.675*comp	-20.24 + 8.37*comp	-1.3
		R^2:	0.55	0.55	0.71	na
Aug	max SWE, max SWE date, snow-off date, monsoon rain, Mar-Aug av. temp.	**comp. var.:**	1*max SWE date - 2*Mar-Aug ave temp + 4*monsoon rain	2*max SWE + 1*snow-off date - 1*Mar-Aug ave temp + 4*monsoon rain	1*max SWE + 2*snow-off date + 1* monsoon rain	na
		equation:	-17.96 + 2.97*comp	-25.49 + 2.742*comp	-14.51 + 1.39*comp	-2
		R^2:	0.83	0.94	0.55	na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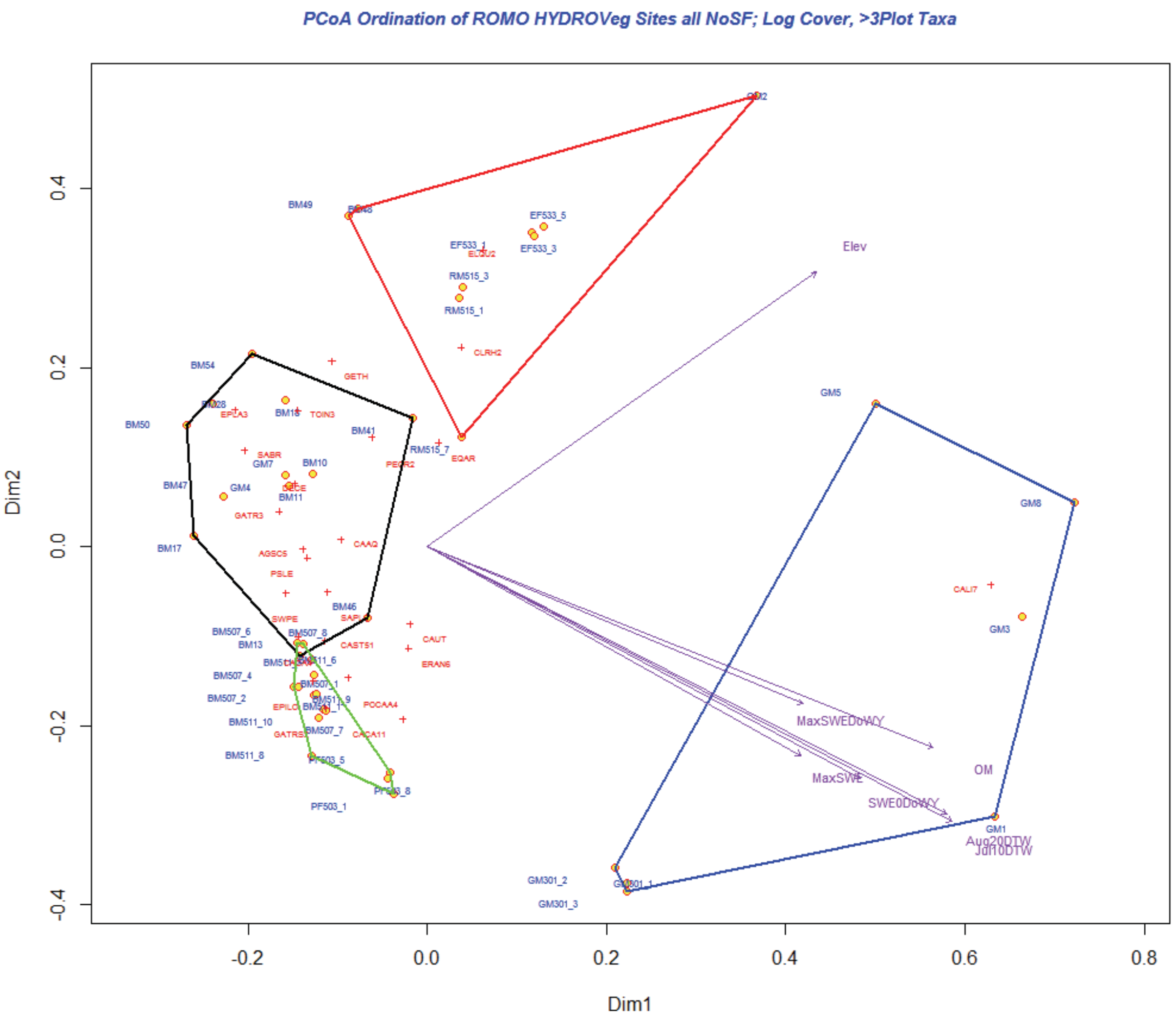
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TOIN3
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EPLA3
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PECR2
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GM4
DECE
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GM8
GATR3
BM17
CAAQ
AGSC5
PSLE
CALI7
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CAST51
CAUT
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ERAN6
BM507_4
BM507_1
BM507_2
BM511_9
POCAA4
EPILO
BM511_10
GATRS
BM507_7
CACA11
MaxSWEDoWY
BM511_8
PF503_5
OM
MaxSWE
PF503_8
SWE0DoWY
PF503_1
GM1
Aug20DTW
Jul10DTW
GM301_2
GM301_1
GM301_3

Appendices

Appendix A.

Table A1. Preliminary variables tested in water table model development. Independent variables in grey were not retained in any model.

Independent Weather Variables		DTW Response Variables	
Variable Description	**Variable Abbrev.**	**Variable Description**	**Variable Abbrev.**
April 1 SWE	Apr1SWE	DTW on 10 Jun	10Jun
Annual maximum SWE	MaxSWE	DTW on 10 Jul	10Jul
Maximum SWE after April 1	PostApr1	DTW on 20 Aug	20Aug
Date of Maximum SWE	MaxSWEDoWY	DTW Difference: 10 Jun – 10 Jul	JunJulDif
Date of snow off	SWE0DoWY	DTW Difference: 10 Jul – 20 Aug	Jul20AugDif
Mar-May average temp.	MarMayAvT		
Jun-Aug average temp.	JunAugAvT		
Jul-Aug ppt.	JulAugPpt		
10 Jul-Aug ppt.	Post10JulTot		
Aug ppt.	AugTot		
Maximum 1 day rainfall, 10 Jul-Aug	1DayMax		
Maximum 2 day rainfall, 10 Jul-Aug	2DayMax		
Maximum 3 day rainfall, 10 Jul-Aug	3DayMax		
Maximum 7 day rainfall, 10 Jul-Aug	7DayMax		

Appendix B: Range of years included in the August model at SF, showing the distribution of each variable ranked among all years 1986-2012. Highlighted years had DTW data and were used to create the model. SF's August composite variable consisted of 1*max SWE + 2*snow-off day of water year + 1*monsoon rain, in contrast to monsoon rain comprising at least 50% of the August models for GM and BM. Note that the distribution of monsoon rain years sampled at SF ranked among all years since 1986 were clumped, not representing the variety of years that occur (last two columns). This may have resulted in the model not integrating this variable as much as the more dispersed snow variables.

Year	Snow-off DoWY	Year	Max SWE	Year	Max SWE DoWY	Year	Mar-Aug av temp (C)	Year	Monsoon Rain (cm)
2012	185	2004	16.9	1995	160	1993	4.2	1995	2.5
2002	199	1987	17.018	2004	160	1995	4.7	2009	3.3
1989	205	2012	18.1	1994	164	1991	4.9	1993	3.6
1987	207	2010	21.2	2007	165	1992	4.9	2006	3.6
2007	211	1989	21.4	2012	165	1999	5.2	1994	4.8
2004	212	1990	21.7	1998	166	1998	5.2	1988	5.1
2006	213	2005	21.7	1999	169	1997	5.4	1996	5.3
1992	216	1999	21.9	2002	172	2005	5.4	2000	5.6
1990	221	2002	21.9	2010	172	1996	5.5	1987	6.1
2000	221	1995	22.2	2005	173	2004	5.7	2011	6.1
2009	222	2007	22.9	1987	178	2008	5.7	2008	6.4
1994	223	2001	23.7	2006	179	1987	5.8	2010	6.4
2001	223	1991	23.9	1996	180	2003	5.9	2001	6.9
1998	225	1992	24.9	1991	183	1988	6.0	1989	7.6
1988	227	1998	24.9	1992	184	2009	6.0	1990	7.6
2005	227	1994	25.7	1988	185	1986	6.0	2005	7.6
1999	228	2009	27	2001	186	1989	6.2	2012	7.6
1996	232	2006	28	1986	188	1990	6.2	1986	8.4
1991	233	2008	29.5	1989	188	1994	6.4	1992	8.9
1997	233	2003	30.5	2000	188	2001	6.4	2007	9.1
2010	235	1988	30.7	1990	189	2010	6.4	1999	10.4
1986	236	2000	30.7	2009	191	2011	6.4	1998	10.7
1993	236	1997	32	2003	192	2000	6.5	1991	10.9
2003	237	1986	35.052	1997	197	2002	7.3	2002	10.9
2008	238	1993	36.3	2008	197	2006	7.4	2003	10.9
2011	253	1996	38.8	1993	203	2007	7.5	2004	11.2
1995	254	2011	51.2	2011	217	2012	8.5	1997	11.4

Table M1. Variables tested for final water table models. The window of temperatures began in March and ended in the month nearest the tested date. Monsoon rain was considered in August models but not early summer models.

Model	**Variables Tested**
Jun	max SWE, max SWE date, snow-off date, Mar-May av. temp.
Jul	max SWE, max SWE date, snow-off date, Mar-Jun av. temp.
Aug	max SWE, max SWE date, snow-off date, monsoon rain, Mar-Aug av. temp.

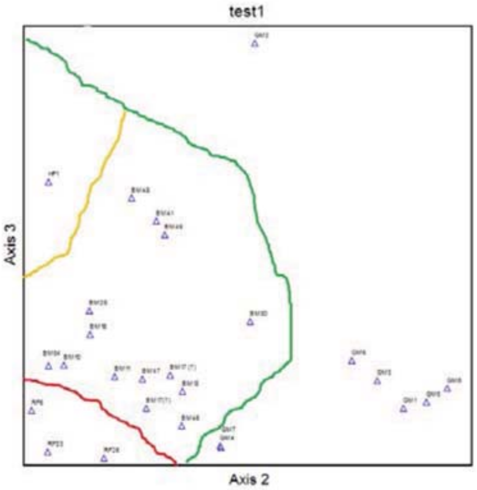

Figure M1. ORIGINAL NMS for vegetation from all wells from the three wetlands with models made, plus for Hell’s Fen. Water levels at Hells Fen varied by <2cm during two full growing seasons (1997-8), so its hydrograph is assumed to not change among years.

Table R1. Environmental drivers of fen water tables. Listed is the most highly correlated environmental variable to water depth at each of the three calibration wetlands. Snow variables have a strong effect on early-to-mid summer water levels, while temperature and monsoon rain better predict late summer conditions.

	10Jun	10Jul	10Jun-10Jul	20Aug	10Jul-20Aug
Green Mt	MaxSWEDoWY	MaxSWEDoWY	Apr1SWE	Post10JulTot	Post10JulTot
	r2=.54, p=.04	r2= .40, p=.08	r2=.47, p=.05	r2=.8, p=.01	r2=.81, p=.01
Red Fen	SWE0DoWY	SWE0DoWY	SWE0DoWY	JunAugAvT	Post10JulTot
	R2=.96, p= .002	R2=.96, P= .002	R2=.83, P=.02	r2=.65, p = .06	r2=93, p=.005
Big Meadows	Apr1SWE	Apr1SWE	Apr1SWE	JunAugAvT	Post10JulTot
	r2=.58, p=.03	r2=.55, p=.03	r2=.82, p=.003	r2=.73, p=.01	r2=.49, p=.05

Table R2. Results from descriptive model development. A) Formulae for the descriptive models that explain the weather-water table relationship. B) Goodness of fit metrics for the models in A). Grey cells are repeat metrics from Table R1, as only one predictor variable was retained in the model.

A)	10Jun	10Jul	10Jun-10Jul	20Aug	10Jul-20Aug
Green Mt	-29.5+.21*MaxSWEDoWY	-97.71+.4*MaxSWEDoWY+.81*Apr1SWE	30.08-.79*Apr1SWE	-46.85+3.47*Post10JulTot	45.95-3.56*Post10JulTot
Red Fen	-272.51+1.16*SWE0DoWY	-456.1+1.92*SWE0DoWY	183.63-0.76*SWE0DoWY	129.7-17.59*JunAugAvT+6.91*AugTot	77.73-5.97*Post10JulTot
Big Meadows	-2.11-.17*Apr1SWE	-51+1.8*Apr1SWE	e^(7.16-.22*Apr1SWE)	-17.11-4.68* JunAugAvT+2.29*Post10JulTotal+0.97*Apr1SWE	-38.4-8.85*X3DayMax+5.21*JunAugAvT+.74* Apr1SWE

B)	10Jun	10Jul	10Jun-10Jul	20Aug	10Jul-20Aug
Green Mt	r2=.54, p=.04	r2=.49, p = .12, aic = 27.15	r2=.47, p=.05	r2=.8, p=.01	r2=.81, p=.01
Red Fen	R2=.96, p = .002	R2=.96, P= .002	R2=.83, P = .02	r2=.94, p=.03	r2=93, p= .005
Big Meadows	r2=.58, p=.03	r2=.55, p=.03	r2=.82, p=.003	r2=.88, p=.02	r2=.82, p=.04