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DISCUSSION: "Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California" by Luke J.H. Hunt, Julie Fair, and Maxwell Odland

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ABSTRACT: We discuss a recent paper which evaluated the hydrologic changes resulting from a pond-and-plug meadow restoration project in the Sierra Nevada Mountains of California. In the study, measurements of streamflow into and out of the meadow suggested late-summer baseflow increased as much as five-fold when compared with prerestoration conditions. However, the volume of streamflow attributed to the restored meadow (49,000–96,000 m^3 over four months) would require that 2.5–4.8 m of saturated meadow soils drain during summer months. The groundwater data from this meadow record only 0.45 m of change over this timeframe, which is less than might be expected from plant use alone (0.75 m), suggesting this restored meadow may be acting as a water sink throughout summer rather than a source.

INTRODUCTION

This paper discusses Hunt *et al*.'s paper published in the October 2018 issue of JAWRA. The potential of wet meadow restoration to augment summer streamflow has motivated considerable interest from states in the Western United States seeking to mitigate against increasingly variable summer water availability. Several modelling studies have suggested that meadow restoration should decrease summer streamflow, due in part to more evapotranspirative use and reduced hydraulic gradients (e.g., Hammersmark et al. 2008; Essaid and Hill 2014; Nash et al. 2018). Field data has, however, been relatively scarce given how difficult it can be to accurately constrain the dynamic and often small hydrologic fluxes in these environments. There is thus considerable interest in the data presented by Hunt et al. (2018), who measured streamflow into and out of a restored meadow in the Sierra Nevada Mountains of California, concluding that summer streamflow increases nearly five-fold when compared with prerestoration conditions. The increased streamflow is attributed to larger volumes of water being stored in and drained from meadow soils. This reasoning is, however, contraindicated by their groundwater data, which show both that there was little change in the drainage dynamics of the meadow following restoration, and that the volume of water draining from the meadow soils was insufficient to account for the volumetric increase in outgoing streamflow. In this Discussion, we present a conceptual model of the physical processes necessary for meadows to act as sources of water that augment summer streamflows, and then examine data from Hunt et al. (2018) in light of that conceptual model, identifying the inconsistencies leading us to question the streamflow benefit attributed to meadow restoration.

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CONCEPTUAL MODEL OF MEADOWS

Wet meadows must act as "fill and spill" reservoirs to augment late summer streamflow. That is, they must act like irrigation reservoirs where the soils of the meadow fill with water during periods of high flow and later "spill" that water by allowing it to drain back into the stream under the force of gravity. In a wet meadow, the rise and fall of the water table shows the "filling and spilling"; there is no other source of water available to augment streamflow. The soils of the meadow comprise the reservoir, but water can only be held in the pore spaces between the soil particles. When the soil drains, some water is left behind — either in very small pore spaces or as films on the surface of the soil particles. The amount of water that can drain from a saturated soil under the influence of gravity is defined as drainable porosity. Wet meadow soils are commonly formed from flood deposits and often have silt-loam textures (Ratliff 1982) with drainable porosities ranging from 5% to 20%, even though total porosity may be as high as 50% (e.g., Hilberts et al. 2005). This has critical implications for the amount of water available to augment baseflow discharge — at 20% drainable porosity, a 1-m depth of saturated soil will only contain 0.2 m depth of liquid water that can drain to a stream. Given this conceptual model, we can evaluate the potential contribution from a meadow to streamflow using a simple calculation based on conservation of mass, and then comparing pre- and post-restoration changes in the water table height from the late spring ("filled" condition) to the late summer ("spilled" condition) to determine how much water has drained.

EVALUATING GROUNDWATER DATA AND POTENTIAL STREAMFLOW CONTRIBUTION WITH A CONSERVATION OF MASS APPROACH

The restoration project described in this paper encompassed a 0.1 km^2 (100,000 m^2) wet meadow in which soils were mapped as silt-loams (Soil Survey Staff 2019). Prior to restoration in 2012 the streamflow attributed to meadow drainage was 7,000 m^3 (table 1, Hunt et al. 2018), or approximately 0.07 m of free liquid water over the 100,000 m^2 area which, with a 20% drainable porosity, would be accounted for by a 0.35 m change in the water table. The prerestoration well data (figure 5, Hunt et al. 2018) indicate that the typical change in water table depth from June to October was approximately 0.2 m, with a maximum change in approximately 0.5 m (i.e., well 5, prerestoration, figure 5, Hunt et al. 2018) and thus the reported changes in streamflow are generally consistent with the reported change in the water table elevation over the summer assuming no plant use, which gives confidence in our estimate of drainable porosity.

Following restoration, the authors report that 49,000–96,000 m^3 of water drained from the meadow in 2013 and 2014, respectively (table 1, Hunt et al. 2018). This amounts to approximately 0.49–0.96 m of free liquid water over the 100,000 m^2 area which, when stored in soils with a 20% drainable porosity, would be accounted for by a 2.5–4.8 m change in the water table. The authors report a maximum water table rise of 0.64 m from pre to postrestoration (table 2, Hunt et al. 2018) and that the change in water table elevation from early summer to late summer (the total volume "spilled") for all wells is less than 0.5 m (figure 5, Hunt et al. 2018). These changes are too small to provide 49,000 m^3 of water, let alone 96,000 m^3.

Overall, data from the five wells suggest that, while the water table height increased, the meadow's behavior as a "filling and spilling" reservoir did not change. The groundwater data (figure 5, Hunt et al. 2018) depict changes in water table heights from early to late summer under both pre and postrestoration conditions. The data clearly show an increase in water table height after restoration, likely due to the plugs' impounding and raising the elevation of surface water in the channel. This increases the baselevel for groundwater drainage and leads to increased water table elevations as the groundwater reaches a new equilibrium with the stream water elevation. This represents an increase in stored groundwater following restoration, an outcome consistent with results from other field and modelling studies (Loheide and Gorelick 2007; Hammersmark et al. 2008; Kasahara and Hill 2008; Moore et al. 2014).

The drainage rate of that stored water does not appear to change, however. The water table data (figure 5, Hunt et al. 2018) show that water table declines over the summer, for the pre and postrestoration conditions, are parallel in three wells (1–3), which can only happen if the amount of water draining from the meadow soils between June and October was the same in both time periods. Well 4 shows a slight increase in slope, indicating slightly more water drained from this area following restoration, and Well 5 shows a decrease in slope, indicating less water drained from this area of the meadow following restoration. Put another way, the "meadow reservoir" was filled with more water as a result of the plug structures impounding surface water. However, the meadow's capacity to "spill," or drain this additional storage was not changed. Consequently, there does not appear to be a mechanism by which the amount of water draining from the meadow could increase as a result of the restoration.

OTHER LIMITATIONS

A wet meadow does not simply "fill and spill." Plants also compete for water and can access water held in very small pores and as surface films — water that cannot drain under the force of gravity. However, water held in large pores is most easily accessed. Drainage and transpiration therefore compete for water held in those largest pores, particularly during summer months. Hunt et al. (2018) clearly show a rise in the water table after restoration, with a mean depth of 1.28 m prior to restoration and 0.98 m after restoration. These changes bring the water table closer to plant roots potentially making that water more accessible to plants. Evapotranspirational losses from a restored wet meadow in the Sierra Nevada might average, conservatively, 0.005 m/day (e.g., Loheide and Gorelick 2005). Over a 150-day growing season this would result in a loss of 0.75 m of free liquid water and would account for more than the entire observed change in water table elevation drawdown over the course of the summer. Such large losses could only be supported if the meadow gained water from subsurface flows from either the adjacent hillslopes, from the ephemeral tributaries shown in figure 1 (Hunt et al. 2018), or from groundwater upwelling. It is likely that much of the observed drop in the water table over the summer is caused by evapotranspiration.

Furthermore, drainage from a wet meadow is controlled by the hydraulic gradient across the meadow. Where gradients are very flat, as is common in wetland environments, water drains slowly. While this promotes storage, helping to "fill" meadows and in so doing create wetlands and wet meadows, very flat hydraulic gradients limit the potential for wet meadows to "spill" stored water into a stream. In the case of Hunt et al. (2018), prior to restoration in 2012, the depth of channel incision into the meadow was reported as 1.2 m. By 2014, restoration had raised the channel bed approximately 1 m, which would decrease potential cross-valley hydraulic gradients and thus slow drainage from the meadow, further supporting the possibility that restoration makes this meadow act more like a sink rather than a source of water.

CONCLUSION

How might we account for the reported increase in streamflow given that groundwater data show that the meadow cannot be the source of any additional water? We cannot say for sure, but given that the upper gaging station was buried by sediment in 2015, it is possible that sediment deposition also raised the channel bed at the lower gaging station, altering the rating curve from which discharges were calculated. It is also possible that the small summertime flows (i.e., $<0.003\ m^3/s$) fell below the accuracy rating of the gaging techniques used (e.g., Sauer and Meyer 1992) or that three to four small ephemeral tributaries contributed flow between the gages. Other study areas with longer postrestoration records in the Sierra Nevada have indicated that streamflow downstream of projects declines in late summer (e.g., table 6, Plumas Corporation 2013).

Field measurements are an essential component of restoration monitoring and evaluation, but conclusions drawn from those observations must satisfy mass balances and underlying physical processes. Mass balance discrepancies are common in the literature on meadow restoration and its contributions to baseflow (e.g., Tague et al. 2008, corrected in Aylward and Merrill 2012; Wegener et al. 2017), often due to the magnitude and complexity of incoming hydrologic fluxes. Generally, previous research suggests that meadows have neither the storage capacity nor the drainage dynamics to impact late summer baseflow in climates with arid summers (Hammersmark et al. 2008; Essaid and Hill 2014; Nash et al. 2018). The mass balance approach we present here should be useful for checking estimates of streamflow-related outcomes in future meadow restoration projects.

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