Hydrologic controls on the survival of Water Howellia (Howellia aquatilis) and implications of land management

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Abstract

Water Howellia (Howellia aquatilis) is a rare and endangered wetland plant listed as a threatened species under the Federal Endangered Species Act. 70% of the world population is found in the 1.7 × 10^5 ha Swan Valley, Montana, USA in wetlands of usually less than 1-ha. Survival of this aquatic species requires emergence during mid-summer, the drying out of occupied portions of the wetlands, a slight refilling of the wetlands in fall, and wetland re-establishment in the spring. This project was designed to establish the water source and seasonal controls on stage variation. Research approaches included water budgets derived from extensive micro-basin field measurements, including evaluation of ground water-surface water interaction, and standard geochemical analyses. Potential impacts to the wetland water balance from timber harvesting or stand replacement fires were evaluated using the WRNSHYD model. Results from two field seasons indicate that ground water inflow and plant transpiration control wetland stage. Snow survey recharge estimates, horizontal and vertical hydraulic gradient observations, seepage meter flux rates, wetland and ground water quality and the ground water inflow component of the water balance support the hypothesis that seasonal changes in the wetland are driven by a localized ground water flow system. Modeling predicts an increase in micro-basin water yield due to decreased plant transpirational water loss when watershed trees are removed by harvesting or a stand replacing fire. The duration of a potential increase in water yield is unknown.

Keywords: Wetlands; Water balance; Glaciated terrains; Ground water

1. Introduction

The forested wetlands of the Swan Valley of Missoula and Lake counties, Montana, USA contain a rare plant species, Howellia aquatilis (Water Howellia). It is listed as a threatened species under the Federal Endangered Species Act (US Fish and Wildlife Service, 1994). The highest known concentration of Water Howellia in the world is found in these glacially formed wetland systems of the Swan Valley (Shelly and Gamon, 1996). Other populations of H. aquatilis are found in ephemeral wetlands or the margins of shallow permanent wetlands located in northern California, western Oregon, Washington, and northern Idaho (Shelly and Gamon, 1996). The Swan Valley occurrence most likely appeared after mountain and valley glaciers retreated about 10,000 years ago. H. aquatilis is an aquatic annual requiring both emergent and dessication environments for
procreation (Lesica, 1992). In the spring, Water Howellia occupied wetlands fill with water. During the summer months, Water Howellia matures and flowers at or below the pool surface. It produces seeds which become incorporated into the wetland sediment. By the end of the summer or early fall, the wetlands desiccate, exposing the seeds to air. Seeds germinate in October under aerobic conditions and remain as a small seedling beneath the winter snowpack (Shapley and Lesica, 1997). They are then submerged as snow melt refills the wetlands in early spring (Shapley and Lesica, 1997). This wetland hydrological cycle of wetting and drying is necessary to maintain *H. aquatilis* populations. Though *H. aquatilis* seeds may remain viable in wetland sediment for several years (Mantas, 2001), this annual cycle of wetting and drying is necessary to maintain *H. aquatilis* populations, a process that has apparently been continuous since the end of the Pleistocene. Natural perturbations to these systems include climate shifts and stand replacing fires. Settlement and timber harvesting was initiated only within the last 100 years.

The majority of Water Howellia research in the Swan Valley has focused on *H. aquatilis* habitat from a biological standpoint (Lesica, 1992; Shelly and Gamon, 1996; Mantas, 1998) with only limited characterization of wetland hydrology (Shapley and Lesica, 1997; Shapley, 1998). Shapley (1998) classified *H. aquatilis* wetland morphology into four distinct basin types based on pond geometry, size, and slope. Anderson (1992) studied the hydrology of the Swan River Oxbow preserve, a wetland in the active flood plain of the river that contained a viable population of Water Howellia. He found that the exchange of ground water between the Swan River, the unconfined alluvial aquifer, and the oxbow wetland was controlled by the difference in seasonal vertical gradients. However, all other *H. aquatilis* occupied wetlands in the Swan Valley are found within depressions formed in the glacial till deposits located above the main valley floor.

This research was designed to determine source(s) of water and the mechanisms controlling the wetland hydrological cycle. Specific objectives included: (1) generation of wetland water balances; (2) identification of controls on the seasonal variation in water input; and (3) analysis of how natural and anthropogenic modification of the wetland watershed may alter wetland hydrology. Formulation of land management plans in the Swan Valley that allow multiple land use and protection of Water Howellia habitat is of local, state and federal interest (Shapley and Lesica, 1997; Shapley, 1998).

2. Site description

The Swan Valley is a north–south trending glaciated valley that is located approximately 130 km northeast of Missoula, Montana, USA (Fig. 1). The valley is approximately 80 km long, 20–45 km wide, and ranges in elevation from 930 m near Swan Lake to 2800 m in the Swan and Mission mountain ranges. The Swan Valley is bordered by two north–south trending normal fault block mountain ranges, the Swan Range to the east and Mission Range to the west (Johns, 1970; Kleinkopf and Mudge, 1972). The valley floor is covered by glacial sediments of late Wisconsin age (Witkind and Weber, 1982) and filled to a depth of 600–900 m with older Cenozoic deposits (Kleinkopf and Mudge, 1972).
Pleistocene lateral moraines, basal moraine and glaciofluvial sediments deposited by one of the two major diverging trunk glaciers occupying the Swan-Clearwater Valley during the late Pleistocene are exposed at the land surface (Shapley and Lesica, 1997). The thickness of the glacial till is unknown. The valley is filled with numerous glacially-formed shallow wetlands and lakes.

The area has a continental-maritime climate (US Environmental Protection Agency, 1980). The continental-maritime classification indicates that this area of Western Montana is located on the transition boundary between the two climate types and is subject to both maritime and continental influences. Mean annual precipitation in the valley ranges from 680 to 740 mm. Higher elevations in the Swan Valley receive over 2500 mm of precipitation annually. Annual mean temperature is 52\(^\circ\)C.

There are over a thousand isolated wetlands in the Swan Valley, 126 are Water Howellia occupied and an additional 86 are unoccupied but appear to be suitable \textit{H. aquatilis} habitats (Mantas, 2001). All \textit{H. aquatilis} occupied wetlands in the Swan Valley are less than 2 ha, except for a river oxbow wetland (Shapley and Lesica, 1997) and all sites are found below an elevation of 1500 m (Mantas, 1998). All Water Howellia wetlands in the Swan Valley occur in a coniferous forest dominated by \textit{Pinus ponderosa} (ponderosa pine), \textit{Pseudotsuga menziesii} (Douglas fir), and \textit{Pinus contorta} (lodgepole pine) (Mantas, 1998). \textit{Populus deltoides} (cottonwood) and \textit{Populus tremuloides} (aspen) trees commonly form a phreatophytic fringe surrounding the wetlands.

A subset of four individual or wetland groups were chosen to represent variable site conditions observed in the Swan Valley. Criteria for the selection of study sites were based upon (1) accessibility (United States Forest Service land), (2) general lack of land disturbance in watershed basin, (3) viable population of \textit{H. aquatilis}, and (4) previous research (Shapley, 1998). The elevation of these wetlands varies between 1070 and 1290 m AMSL. Three of the four wetlands are classified as pothole wetlands which are shallow, marsh-like ponds (Mitsch and Gosselink, 1993). The fourth wetland is classified as a ‘fen’, which is a peat accumulating wetland (Mitsch and Gosselink, 1993).

This paper focuses on one specific wetland group, Condon wetlands. The Condon group is composed of multiple pothole wetlands in a large basin, with each of the wetlands located in individual, closed micro-watershed basins that range in size from 0.10 to 1.5 ha. Four of the wetlands in this area (P20–P23) are included in this paper (Fig. 2). Wetland P20 was the focus of our efforts while P21, P22, and P23 were evaluated in less detail. There is a surface water connection between P20 and P21. As appropriate, data and observations from other sites are presented to support conclusions drawn from study of the Condon group.

3. Field methods

3.1. Source of water to the wetlands

A water balance approach was utilized to determine the primary source(s) of water to the wetlands and to identify the hydrological components. Water balances have been a common research tool for hydrologic studies of lakes and prairie-pothole wetlands (e.g. Winter, 1981; Hayashi et. al., 1998; Koerselman, 1989). The water balance equation for these wetland systems is:

\[
g_{\text{water inflow}} + \text{ppt} - \text{evap} - \text{trans} - \text{sw outflow} - \text{gw outflow} = \Delta \text{wetland volume} = 0
\]

where \text{gw inflow} is ground water inflow (discharge) from the micro-basin watershed into the wetland, ppt is direct precipitation over the wetland, evap is direct evaporation from the wetland free water surface, trans is plant transpiration from wetland plant species (phreatophytes), \text{sw outflow} is surface water outflow from the wetlands, and \text{gw outflow} is ground water outflow from the micro-basin watershed.

The measurement of specific water balance components were calculated once the wetland and watershed morphologies were established. Instrumentation used to quantify water balance parameters included: staff gauges, precipitation gauges, continuous level recorders, snow surveys and floating evaporation pans. Sampling frequency for the non-recording instruments was approximately bi-weekly.

Two precipitation gauges, one mounted in the wetland and one placed in the watershed, were used to
measure liquid precipitation inputs into the wetland and its watershed basin. In March 2000, a snow survey was conducted in the P20 micro-watershed basin and the snow water equivalent computed (Goodison et al., 1981). The snow survey consisted of numerous unbiased random measurements of snow pack depth in the wetland and micro-watershed basin. The snow survey was used to measure total precipitation during the winter months (October through March). Overland flow from the micro-watershed basin into the wetland was observed at all sites in early March during the snow surveys. However, overland flow was not present during water balance periods beginning in late April.

Two Stevens Type F continuous level recorders, one in the wetland and one in a shallow well located immediately adjacent to the wetland pool were used to measure changes in wetland stage and shallow water table. The change in wetland area over time was calculated from wetland stage measurements derived from staff gauge readings. The morphology of the wetland and surrounding watershed basin was determined through extensive topographic surveying using a total station. The surveys resulted in at least 200 point measurements within each wetland pond and over 400 point measurements for micro-watershed basin characterization.

Evapotranspiration was calculated from the continuous surface water hydrographs at each wetland using an equation first developed by White (1932) and modified by Meyboom, 1967.

\[
ET = S_y (24r \pm \Delta s) A
\]

where \(S_y\) = specific yield, \(24r\) = change in wetland stage per day (graphically derived), \(\Delta s\) = difference between wetland stage at the completion of a 24 h period (graphically derived), and \(A\) = surface area of the wetland. This method was originally developed to quantify evapotranspirational demands on shallow unconfined aquifers subject to interaction with phreatophytic vegetation. In order to modify this equation for use in this study, specific yield was assumed to be 1 for the wetland water column.

Floating evaporation pans were used to establish direct evaporative loss from the water body. A pan coefficient was not used since evaporation pans floating in the wetland are subject to the same wind and thermal regimes as the wetland water body (Winter, 1981). A plant transpiration component of
the water balance was isolated from the evapotranspiration component by subtracting direct evaporation readings from the corresponding evapotranspiration value. Surface water outflow was derived by measuring the width and depth of the outflow channel and determining the flow velocity (Gordon et al., 1992). Net ground water inflow was calculated as a residual from the differences in inputs and outputs in the water balance equation.

3.2. Water balance error analysis

Although water balances are a common tool in studying lakes and wetlands, it is important to try to quantify error percentages for each component in the water balance equation. Major influences affecting rain gauges and their precipitation measurements include wind, evaporation, and height above ground. Each rain gauge was approximately 1 m above ground, and depending on wind patterns, an error of ±5 to 15% can be expected for long term data (Winter, 1981). It is expected that wind patterns did not heavily influence rain gauges due to the dense forest canopy surrounding the wetlands, minimizing introduced error in precipitation measurements. A ±5% error was used in the error analysis.

Floating evaporation pans are considered a direct measurement of evaporation and it is not possible to quantify an error since no other measurements of evaporation were performed. However, literature suggests a range of ±10 to 15% error (Winter, 1981). Water Howellia wetlands are located in pot-hole depressions within hummocky landscapes. Consequently, these areas are not subject to windy conditions. Due to lack of windy conditions, a ±10% error was used for floating evaporation pan values.

Evapotranspiration calculations using Meyboom’s analysis of surface water hydrographs can have significant error. Although the surface water charts are extremely accurate, determining the slope of the diurnal curves has some inherent error resulting from slope placement as the shape and size of the curves vary. Though the slope of the curves was taken near or at 6 am each morning, it was difficult to replicate each hydrograph measurement. Measurement differences on the hydrograph charts due to interpreted slope was typically 3 mm or less. Multiplying ±3 mm to the surface area of each wetland resulted in a mean error of ±20%. Since an error estimate is already assigned to the floating evaporation pan evaporation measurement, the error of ±20% was assigned to the plant transpiration component.

Determination of wetland stage involved using the staff gauge to measure to the nearest 1.5 mm. The wetland basin was intensively surveyed with state of the art surveying equipment. Error analyses of the survey indicate that instrument elevation error was 0.6 mm at the Condon Group wetland site. Due to the difficulty in capturing the exact morphology of the wetland, a ±10% error was assigned for the change in wetland volume (storage) component of the water balance.

Significant error could have occurred during measurement of surface water outflow by assuming a constant channel width, depth, and velocity. The surface water outflow was taken at the start of the water balance period and at the end of the water balance period. An average value for surface water outflow was calculated from these two measurements. The mean of several measurements during a water balance period would have been a better method in describing the variability in surface water discharge. Additionally, streams are subject to variations in discharge and often transmit the majority of discharge during brief, high-flow periods following heavy rains. Due to these factors, a ±50% error was assigned to surface water outflow values.

The determination of net ground water inflow from a difference in water balance components results in the accumulation of error from all of the other water balance components. Since the net ground water inflow component is calculated as the residual of all the other water balance components, a statistical error propagation method is used to quantify total error applied to this water balance component (Winter, 1981):

\[
\sqrt{E_{GWinflow}^2} = E_{ppt}^2 + E_{\Delta wetland volume}^2 + E_{evap}^2 + E_{trans}^2 + E_{swoutflow}^2
\]

where \( E_{GWinflow} \) is the total propagated error assigned to the ground water inflow component, \( E_{ppt} \) is error assigned to the precipitation component (±5%),
$E_{\Delta \text{wetland volume}}$ is the error assigned to the change in wetland volume component (±10%), $E_{\text{evap}}$ is the error assigned to the direct evaporation component (±10%), $E_{\text{trans}}$ is the error assigned to the plant transpiration component (±20%) and $E_{\text{swoutflow}}$ is the error assigned to the surface water outflow component (±50%).

The error propagation equation sums the individual variance of each water balance component and then solves for the standard deviation of error on the ground water inflow component by taking the square root of the sum of component variances. Assumptions used in the above equation include: (1) individual water balance component error is analogous to standard deviations of error (i.e. ±%), (2) individual water balance components are independent random variables, and (3) error for each water balance component is additive due to the linear nature of the water balance equation. Although, there may be some argument that each water balance component is not statistically independent from one another, it may be impossible to quantify covariances between components due to an unknown degree of interrelatedness.

Error estimates of net ground water inflow into the four wetland sites ranged from 24 to 55%. The lowest value (±24%) corresponds to water balance periods with no surface water outflow or precipitation. Propagated error on the residual term (net ground water inflow) is dominated by the high error (±50%) assigned to the surface water outflow water balance component. The lack of a surface water outflow component drops the propagated error to ±25%.

### 3.3. Identification of factors influencing seasonal variation in water influx

The use of a water balance approach allows for the gross quantification of the principal sources of water entering and leaving the wetland. However, additional analyses are required to assess how individual watershed and wetland characteristics directly influence wetland response to natural or human induced changes to the watershed basin. As ground water was believed to be an important component in the water balance, additional wetland-ground water interaction analyses were performed.

Methods for studying ground water-surface water interaction involve comparing ground water elevations in nested shallow wells surrounding the wetland with the stage of the wetland, the determination of wetland hydraulic vertical gradients using mini-piezometers, and the magnitude, timing, and location of seepage flux. Wells in this study were used to establish basin and near pond vertical gradients, perform slug tests, to interpret ground water flow direction, and for collection of water samples for chemical analyses. At each fully instrumented wetland (P20 for the Condon group), three well nests consisting of 20 mm diameter steel pipe, were driven into the shoreline during the maximum areal extent of the wetlands. Two of the three nests consisted of two wells completed at depths of approximately 1.2 and 2.5 m below land surface. The other well nest consisted of three wells finished at depths of approximately 1.0, 1.2, and 2.5 m (labelled by the well nest number and SS for super shallow, S for shallow, and D for deep). Deeper wells (MW) constructed from 20 mm diameter PVC, ranging in depth from 2.5 to 5.5 m and perforated over the bottom 0.3 m, were installed using a GEOPROBE. Vertical hydraulic gradients within the wetland sediment were measured using mini-piezometers constructed from 13 mm diameter electrical conduit (Lee and Cherry, 1978). Seepage meters adjacent to the mini-piezometers constructed from 0.50 m diameter plastic drums were used to measure water exchange through the wetland and to compute vertical hydraulic conductivity values (Lee and Cherry, 1978).

### 3.4. Geochemistry

The geochemistry of the wetland water, micro-basin ground water and deeper ground water were analyzed for common anions using an automated chromatograph (Pfaff, 1993) and for common cations using an ICP-ES (Martin et al., 1994). Alkalinity, calculated via volumetric titration, was also determined for each water sample (Langmuir, 1995). Three rounds of water samples were collected. Field measurements of pH and specific conductance were measured as part of a bi-weekly data collection process.
3.5. Land use modifications and influences on wetland hydrology

The watershed of the Swan River is densely forested and has undergone periods of timber harvest and natural modification by fire. The potential affect of timber harvesting on changes in water yield to the local wetland system was assessed using the WRNSHYD® (WRNSs HYDrology) modeling program (Minister of Supply and Services, 1989). The WRNSHYD model carries out all of the graphical lookup and bookkeeping required to use the hydrology section (Chapter 3) of the WRENSS (An Approach to Water Resources Evaluation of Non-point Silvicultural Sources) procedural handbook (US EPA, 1980). Specifically, the WRNSHYD model is designed to determine the effects of silvicultural activities on basin water yield. The approach outlined in the WRENSS procedural handbook is a water balance approach that implements empirically derived relationships between basin-scale stream flow (basin yield) and climate zone, precipitation, interception of precipitation by vegetation, snow ablation and redistribution by wind, forest cover density, plant transpiration, and evaporation due to solar radiation. Hydrogeologic and soil properties are not input into the model. However, the relationship between ground water discharge, overland flow, and soil-moisture is empirically related to stream flow. For the application of WRNSHYD model in this study, basin yield as stream flow is assumed to be analogous to both ground water discharge into the wetland from the micro-watershed basin and overland flow during snow melt periods.

Model input parameters include climate, longitude and latitude, area of the watershed basin, aspect, monthly precipitation averages, tree type, absence/presence of snow scouring, basal area of trees, total area of clear cut, roughness of possible cut, width of cut block, and area of cut block. Climate type combined with latitude and longitude is automatically used by the model to determine solar radiation, dominant type of precipitation (rain or snow), evaporation rates, and snow ablation. This modelling allowed for examination of the effects of fire and logging on the annual water yield from a typical Swan Valley Water Howellia wetland. Modelling results were then used to suggest how changes in micro-basin water yield may affect Water Howellia’s ability to survive and reproduce.

4. Results

4.1. Controls of glacial till on wetland hydrology

Physical and hydrological properties of the wetland sediment and watershed till matrix control the amount and rate of ground water recharge, and the rate and quantity of ground water–surface water exchange in the wetlands. The majority of Water Howellia inhabited wetland depressions are shallow, undrained, and are probably kettles formed in ablation till. Massive soils with bimodal grain-size distributions consisting primarily of gravel and coarse sand in a silt matrix are present in the micro-basin watersheds. Estimates of hydraulic conductivity both from permeameter and slug tests for each of the wetland sites indicate that the vertical hydraulic conductivity for these wetland systems is low, ranging from $4 \times 10^{-10}$ to $5 \times 10^{-12}$ m/s. However, the likely presence of sand lenses, fractures, plant roots, and macropore channels within the near surface watershed soil most likely results in preferential flow paths, increasing recharge and ground water flux rates (Baker and Spaans, 1997; Van der Kamp and Hayashi, 1998; Hayashi et al., 2003). When the micro-basin scale vertical hydraulic conductivity is computed using estimated ground water discharge to the wetlands, values of $2 \times 10^{-6}$–$3 \times 10^{-7}$ m/s are obtained. Within the wetlands, a clay layer ranging from 80 to 100 mm at the pond margin thickens towards the center of the wetland. This clay layer probably restricts ground water exchange in the center of the basin, having a less limiting impact at the littoral margins of the wetland.

4.2. Source and timing of water to the wetlands

Water balance measurements were collected during both 1999 and 2000 field seasons. Plant transpiration, ground water inflow and surface water outflow (when present) are the dominant hydrological controls in these wetland systems from spring through early fall (Table 1). Water balance results for the other researched wetlands are similar. The ground water
inflow component declined after mid-May at all wetlands. The magnitude of the diurnal fluctuations on the surface water hydrographs ranged from 6 to 27 mm for all wetlands and generally increased from spring to late summer/early fall. Although the magnitude of the diurnal fluctuation on the surface water hydrographs (not presented) increased from spring to late summer/early fall, the highest rate of plant transpiration occurred during a period from mid-May to mid-June. After this period, plant transpirational loss decreased due to a declining wetland stage and water table. Instantaneous discharge estimates of surface water outflow were small (2.0 \times 10^{-5} – 5.0 \times 10^{-4} \text{ m}^3/\text{s}), but total seasonal surface water discharge was significant.

Snow surveys of the wetland watershed basins were conducted in early March and initially used to compute annual water balances for the 2000 field season. Snow water equivalent was computed from the snow surveys to determine if significant water was available within the local wetland watershed basin to sustain wetland hydrology. If the wetland hydrology is driven by its local water balance, the snow pack melt water would (1) fill up the wetland pond basin to full stage and (2) recharge soil and ground water that would supply spring and summer inflow to the wetlands.

However, computations based on these surveys suggested that water accumulated in the watershed basins as snow was inadequate to drive these hydrological systems. In an attempt to explain if snow survey results could be supported by precipitation, snow survey results from the research sites were compared to records collected at nearby Lindbergh Lake and Swan Lake weather stations. This comparison suggested that the snow surveys conducted at the research sites accounted for only 27–35% of the total winter precipitation that fell during the study period. The most likely explanation for the under representation of total winter precipitation is that the snow surveys missed later season wet snow events that added water to the snow pack prior to final melting. If the study snow survey data better represent available water to the wetlands, possibly a more intermediate or regional ground water flow system contributed water to the ponds, though this is not clearly supported by physical or geochemical data.

A mean value for snow water equivalent derived from winter precipitation data collected at the Lindbergh Lake and Swan Lake weather stations was used in the water budget calculations. Based on the mean winter precipitation data set, two of the four wetlands, including the P20 Condon wetland, required a 20% infiltration rate to provide the necessary ground water recharge to satisfy annual hydrological demands. The other two wetlands required higher infiltration rates. One of these wetlands is situated in a topographic high, suggesting either the micro-watershed basin contributing to this wetland was underestimated or the surface water outflow component measured in early spring overestimated the ground water inflow component. The fourth wetland is a ground water fen and may have been receiving ground water discharge from a more regional source.

### 4.3. Water chemistry

Ionic concentrations in the shallow ground water and surface water of the Condon P20 wetland are less than 10 mg/l for all ionic species (Table 2). The wetland surface chemistry and shallow ground water is calcium bicarbonate dominated with lesser
concentrations of potassium, magnesium, manganese, sodium, and fluoride. Water chemistry of the wells on the shoreline of the wetland (i.e. W20-2D) and surface water (i.e. SW20) are similar for all Condon wetland systems (Table 2). Calcite was the only mineral that was over-saturated in some of the shallow and deeper ground water samples. Over-saturated calcite may be precipitated in the wetland, decreasing its concentration in the wetland surface water. Wells driven into the deeper portion of the watershed ground water flow system (i.e. MW20-3, 5.5 m below land surface) have higher ionic concentrations than shallow ground water and surface water samples. Chemical signatures from the deeper wells located near the wetland basins are similar to chemistry results from domestic wells (15–50 m below land surface) indicating a more regional ground water source.

Geochemical results for the Condon group wetlands demonstrate that both pH and specific conductance are seasonally variable (Figs. 3 and 4). The lowest specific conductance values for all wetlands were measured in the early spring, during snow melt inputs. Though wetland pH values for all wetlands were seasonally variable, ranging from 5.62 to 7.97, no distinct trends were observed.

### 4.4. Controls on seasonal variation in water input

*H. aquatilis* occupied wetlands display complex ground water-surface water interactions. Several researchers have described the complexities of the flow systems associated with lakes and wetlands (e.g. Meyboom, 1967; Winter, 1978; Hayashi et al., 1998; Van der Kamp and Hayashi, 1998) and have observed seasonal gradient reversals in the flow system (Anderson and Munter, 1981; Rosenberry and Winter, 1997). Reversals in vertical hydraulic gradients in *H. aquatilis* occupied wetlands occur seasonally as wetland re-establishment occurs in the spring and the wetlands dessiccate in late summer or early fall.

From spring to mid-summer, positive vertical ground water gradients in all of the Howellia occupied wetlands indicate local watershed ground water discharge into the wetlands (Fig. 5a). Then vertical gradients between a shallow flow system and the wetland stage decline until there is a short period of minimal water exchange between the wetland and

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**Table 2**

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<th>Mn (mg/l)</th>
<th>Na (mg/l)</th>
<th>S (mg/l)</th>
<th>F (mg/l)</th>
<th>Cl (mg/l)</th>
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<td>&lt;0.50</td>
<td>47</td>
<td>120</td>
<td>6.36</td>
<td></td>
</tr>
<tr>
<td>W20-3D Shallow gw</td>
<td>8.57</td>
<td>1.09</td>
<td>3.38</td>
<td>0.32</td>
<td>1.75</td>
<td>0.26</td>
<td>&lt;0.10</td>
<td>&lt;1.00</td>
<td>&lt;0.50</td>
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<td>120</td>
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<tr>
<td>MW20-1 Deeper gw</td>
<td>62.94</td>
<td>11.16</td>
<td>20.01</td>
<td>1.70</td>
<td>8.25</td>
<td>2.26</td>
<td>0.89</td>
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<tr>
<td>MW20-2 Deeper gw</td>
<td>77.34</td>
<td>7.28</td>
<td>29.25</td>
<td>5.50</td>
<td>13.21</td>
<td>2.67</td>
<td>0.29</td>
<td>4.26</td>
<td>5.07</td>
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<td>520</td>
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</tr>
<tr>
<td>MW20-3 Deeper gw</td>
<td>61.69</td>
<td>10.11</td>
<td>18.25</td>
<td>0.67</td>
<td>10.61</td>
<td>4.65</td>
<td>0.69</td>
<td>6.18</td>
<td>5.38</td>
<td>317</td>
<td>600</td>
<td>7.35</td>
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**Fig. 3.** pH values for Condon Group wetlands.
In late summer, the vertical ground water gradients generally become negative and the wetlands lose water through seepage to the subsurface (Fig. 5c). Observed positive vertical gradients for these wetland systems ranged from 0.15 to 0.003 m while negative vertical gradients ranged from 0.24 to 0.003 m.

Water balance results also show a net inflow of ground water that decreases with time, corresponding with seasonal wetland gradient reversals (Table 1). Additionally, seepage flux rates from another study wetland indicated seasonal gradient reversals.

In summary, vertical gradients in the wetland and watershed basin, seepage meter flux rates, and the ground water inflow component of the water balance support the hypothesis that seasonal changes in the wetland are driven by a localized micro-basin ground water flow system.

4.5. Land management implications

Watershed modeling was used to assess the watershed basin water budget under current conditions (unimpacted) and after vegetation removal (impacted) by either forest management practices or natural stand replacing fires.

The WRENSS handbook classifies the Swan Valley as having a continental-maritime climate that is dominated by both snow and rain precipitation. Monthly precipitation averages from the Lindbergh Lake weather station were used for both sites. Snow in the Swan Valley is relatively ‘wet’ so snow scouring (snow redistribution by wind) was not allowed in the model. The area of the micro-watershed basin for the P20 wetland was 1.5 ha. An east–west aspect was used to represent an ‘average’ exposure to the sun. A tree type of spruce and fir was the closest match for the species found at these sites. The size of the clear cut was equal to the entire area of the micro-watershed basins. A value of 35 m\(^2/ha\) was used to estimate basal area of the trees in the watershed. Additional parameters such as roughness of cut, width of cut block, and area of cut block were automatically calculated by the model.

Modelling results from the WRNSHYD model predict that removal of watershed vegetation result in a gain of 50 mm in annual water yield. The increase in water yield was attributed to decreases in evapotranspirational demands.

5. Discussion

5.1. Sources of water to the wetlands

Water balance analyses show that *H. aquatilis* wetlands are dominated by surface water outflow (when present), ground water exchange, and plant transpirational outputs (Table 1). Furthermore, annual water balances and water chemistry analyses (Table 2) indicate that the dominant source of water to these wetland systems is ground water inflow from a localized flow system with minimal contribution by regional ground water flow systems. Annual water balance calculations for the P20 wetland for the 2000 field season indicate that 20% of snow pack water in the micro-watershed basin provides sufficient recharge for the localized ground water flow system.

Wetland surface water chemistry is also similar to the chemistry of the shallow ground water. This trend was observed at each wetland. The low TDS water suggests that the localized micro-basin ground water flow system is principally recharged by snow melt, and the ground water has a short residence time. Ground water sampled from the deeper wells in the watershed (i.e. MW20-1) has a different ionic concentration than water samples from the shallow wells around the wetland margin (i.e. W20-1D) and the wetland surface water (P20-SW). This suggests water from the deeper wells (2.5–5.5 m below land surface) in the watershed are more representative of an intermediate to regional ground water flow system.
Fig. 5. Cross-sections of P20 wetland with seasonal variation in wetland stage and water table configuration. (a) positive vertical gradients indicate GW discharge, (b) flow-through conditions, and (c) downward vertical gradients indicate surface water seepage. The staff reading represents wetland surface elevation while the dashed line represents shallow ground water equipotential lines.
a system similar to the sampled domestic wells (data not presented). This observation further supports the conceptual model that the ground water from the shallow wells (1.2–2.5 m below land surface) near the wetlands is dominated by a localized ground water flow system.

Water quality data also show wetland chemistry does not significantly change as the surface water volume is dramatically reduced. Low TDS ground water appears to be continually discharging to the pond during the summer, partially replacing the volume lost from evapotranspiration. Again, this data supports the dominance of the shallow ground water system in the wetland water balance.

5.2. Conceptual models of wetland hydrology

Potentiometric maps of the Condon group (P20-23), constructed from water level data measured on 6/20/00 and 8/16/00, demonstrate the seasonal change in the localized ground water flow systems from ground water discharge into the wetlands (Fig. 6) to flow through systems in late summer (Fig. 7). Cross-sections (Fig. 8) of watershed flow paths of the Condon group wetlands were constructed based on site potentiometric maps (Figs. 6 and 7). The cross-sections were orientated along a flow line to show the interpreted and conceptualized flow paths of both localized and more intermediate to regional flow systems, and their associated divides. Localized flow systems dominate wetland hydrology (discharge systems) in mid-June. However, in late summer as the wetlands dry out and water tables decline, flow-through ground water systems dominate wetland hydrology.

In summary, the wetland hydrological cycle and its relation to the life cycle of *Howellia aquatilis* can be constructed from seasonal data and observations. In April and early May, snow melt fills the wetland from overland flow, recharges the surrounding watershed flow system, and submerges *H. aquatilis* seedlings. During mid-June through mid-August, little direct precipitation is added and ground water inflow from the sediment immediately adjacent to the wetland mitigates wetland stage decline and water quality. Plant transpiration from phreatophytes in and
surrounding the wetland and direct evaporation over-power ground water inflow rates and result in a gradual decline in wetland stage. Water Howellia matures, flowers, and produces seeds that are dropped into the saturated wetland sediment in early August. By late August through early September, the water table drops below wetland stage creating a gradient reversal that induces leakage of wetland surface water and eliminates inflow to the system. With transpiration continuing, the reduction in wetland volume accelerates under these conditions. Once the ponds have dried, *H. aquatilis* annuals quickly die and decompose. Water Howellia seeds recently dropped into wetland sediment are exposed to air. During late September through October after several ‘hard frosts’, plant transpiration ceases, reducing outputs from the watershed flow system. The loss of transpiration and late fall precipitation events result in a rise in the water table, and a slight refilling of the wetland. Water Howellia germinates in October and remains as a small seedling beneath the winter snowpack (Shapley and Lesica, 1997). Winter snows accumulate within the forested watershed priming the system for another annual cycle.

### 5.3. Land management implications

*Howellia aquatilis*, designated as a threatened and endangered species, is entitled to conservancy strategies to ensure its survival and viability. Previous research has indicated that the most important factor in conserving this wetland plant species is for the wetland habitat to remain intact (Lesica, 1992; Shapley and Lesica, 1997). The checker board ownership of land in the Swan Valley raises concern as to how land management decisions may impact the future of Water Howellia wetlands.

Analyses of water balance studies, ground water-surface water interactions, and water chemistry results indicate that a localized flow system, principally recharged by snow melt, maintains water quality, wetland stage, and is the dominant hydrological input into these forested wetland systems. The growth cycle of Water Howellia is

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Fig. 7. Potentiometric map for Condon Group wetlands 08/16/00. All values are in meters.
dependant upon a transient hydrologic system. Since *H. aquatilis* inhabited wetlands and the surrounding localized ground water flow systems are annually recharged from snow melt, it is important to understand and attempt to predict how natural and human induced management practices may affect wetland hydrology. Timber harvesting, large-scale stand replacing forest fires and associated road building to a lesser degree are of concern when attempting to assure survival of Water Howellia.

Fig. 8. Cross-section of Condon Group wetlands. (a) watershed flow path 06/20/00, (b) watershed flow paths 08/16/00, and (c) watershed flow paths 09/30/00.
Modelling that simulated the removal of trees in the micro-watershed basin (clear cutting or stand replacing fire) found that micro-basin water yield increased. The increase in water yield is caused by different factors, primarily the loss of trees decreases soil-water depletion from plant transpirational demands (US EPA, 1980; Troendle, 1983; Cheng, 1989; Adams et al., 1991; Hicks et al., 1991). Although an initial gain in water yield is observed immediately after tree loss, returning successional vegetation cover may reduce the water yield after only a few years if successional plant species use more water than the tree dominated system (Troendle, 1983; Adams et al., 1991) or a water surplus could exist for 25–40 years, the time necessary for the forest to reach a similar successional state. Adams et al. (1991) report that a clear cut in a Douglas-fir forest resulted in an initial 100 mm surplus in water yield. In 5 years, this surplus turned into a 25 mm deficit.

Although *H. aquatilis* occupied wetlands are surface water bodies, it is the localized ground water flow systems that sustains them until late July and August. A number of adverse impacts may occur if the watershed basin is managed in such a way that all trees are removed. First, opening the canopy allows for more energy to reach the ground resulting in snow melt events that occur earlier in the spring (up to 3 weeks earlier) and are of higher intensity, resulting in an increased amount of overland flow (Troendle, 1983; Cheng, 1989). Even though the wetland would receive more water from overland flow, the localized ground water system will not have the same amount of recharge due to a suspected reduction in melt water infiltration. Due to the low permeability of the watershed till matrix (\(4 \times 10^{-8} - 5 \times 10^{-12} \text{ m/s}\)), optimal ground water recharge would occur during a slower snow melt period, which would allow for frozen soil to thaw and enhance melt water infiltration. In wetland systems having surface water outlets, excess water would be lost from the micro-watershed basin as surface discharge increases due to higher pond stages. The lack of canopy would also result in an increase in direct evaporation of wetland surface water. These additional water losses would most likely decrease available recharge to the localized ground water flow system as potential recharge is evaporated or is lost from the system by overland flow. A temporary reduction in wetland volume in late summer and early fall would probably occur. The wetland would most likely dessicate at an earlier time than observed.

Fire in these forested wetland systems can also affect these wetlands in a similar manner as timber
harvest. Fire has been suppressed in the forests of the Swan Valley over the last 60 years (Mantas, 1998). Research on the age of fire scars on trees in old-growth plots in the Swan Valley have determined a fire frequency ranging from 25–30 years (Arno et al., 1995, 1997). The 25–30 year fire cycle represents surface fires that clear the forest of ground fuels and most likely do not affect the hydrology of the watersheds of *H. aquatilis* wetlands. Stand replacement fires best represent logging. Research indicates that old growth plots in the Swan Valley revealed a stand clearing fire occurred during the 1600’s, resulting in a stand replacement fire cycle of 350–400 years for these plots (Arno et al., 1995). Arno et al. (1997) suggest an overall stand replacement fire cycle of 150–350 years for the Swan Valley. The stand replacement fire cycle implies that the watershed surrounding *H. aquatilis* occupied wetlands has been naturally ‘logged’ a minimum of every 150–400 years during this species’ existence in the Swan Valley, possibly over the last 12,000 years.

It is apparent that the existing Water Howellia occupied wetlands have not been detrimentally impacted by forest fires. However, it is unknown if other wetlands in the Swan Valley have previously contained a viable population of Water Howellia which have been detrimentally impacted by a stand replacing forest fire. There are approximately 86 non-Water Howellia occupied wetlands, which have been designated, as suitable Water Howellia habitat by US Forest Service botanists (Maria Mantas, personal communication). The reason Water Howellia is not found in these ‘suitable’ wetlands is unknown.

In summary, tree removal in the local watershed, would most likely affect the wetland hydrological support system. If an initial increase in water yield would occur, it may be either short lived or could extend to 25–40 years. However, the degree to which the Water Howellia life cycle would be altered is unknown. It would appear that the natural fire cycle has not resulted in a loss of minimal hydrologic conditions needed for Water Howellia survival.

6. Conclusions

Water Howellia occupied wetlands are unique, glacially formed pothole basins that are sustained by a localized ground water flow system which exhibits complex ground water-surface water interaction. Snow melt runoff into the wetland and infiltration in the watershed basin recharges the localized ground water flow system for each wetland. The localized ground water flow system mitigates wetland stage and water quality in the wetlands until mid-August/early September when the wetlands partially or fully dessicate. The dominant hydrological controls in these wetland systems are ground water inflow, surface water outflow (when present), and plant transpiration. Ground water levels, mini-piezometer, and seepage meter flux data show seasonal ground water gradient reversals change the wetland from ground water discharge (spring), to flow through (summer), to recharge (fall).

Processes that would remove all trees from the wetland watershed may alter wetland hydrology by increasing initial water yield and most likely enhancing direct evaporation. The surplus of water may only be a short-term gain until successional plant species are established in the micro-watershed basin or a water surplus could exist until a more mature forest similar to the present watershed is established. A reduction in ground water recharge due to less than optimal recharge conditions from a lack of canopy may most likely cause *H. aquatilis* wetlands to dessicate earlier than observed.

This study primarily focused on wetland hydrology of these pot-hole wetlands and then recommended possible land management implications for the surrounding micro-watershed basins based on predictive modelling and previous watershed studies. In order to formulate responsible land management plans, additional studies are needed in the following areas: (1) ground water recharge to the localized ground water flow systems, (2) the relationship between micro-watershed basin disturbances and Water Howellia population dynamics and (3) hydrological and geochemical characterization of non-Water Howellia occupied wetlands.

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