Near-surface hydrological processes in sloping loessial landscapes of the northwestern USA
Les processus hydrologiques superficies dans les terrains de loess en pente du nord-ouest des États-Unis

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Introduction
Many loessial soils of the northwestern USA contain hydraulically restrictive subsurface horizons. These horizons, in combination with relatively high winter-time precipitation, create shallow, seasonal perched zones of saturation that are continuous over most of the upland areas receiving more than ~600 mm of annual precipitation. The majority of the seasonal precipitation is stored and redistributed within landscapes via these shallow perched water systems. In this paper, we report on some of the near-surface hydrological processes that occur in the soils and landscapes of this region.

Environmental Setting
The Palouse region of eastern Washington and northern Idaho is part of a 20,000-km² area of deep loessial soils in the northwestern USA (Fig. 1). The landscape is rolling with moderate relief and is mantled with Pleistocene and Holocene loess. Soils have formed under a dry-to-moist climatic gradient from west to east across the region (Busacca, 1989); in the eastern part of the Palouse region, mean annual precipitation (MAP) ranges from approximately 550 mm to over 900 mm along the eastern margin. Approximately 70% of the annual precipitation is received during the period between 1 November and 30 May. Despite the large differences in MAP, soils of the region exhibit similar horizonation: profiles generally consist of Ap, Bw, and E horizons overlying Btb or Bttxb horizons (Table 1). At about 550 mm of MAP, soils are classified as Argixerolls and begin to exhibit development of clay-enriched (argillic) subsoil horizons (Soil Survey Staff, 1996). As MAP increases, soils exhibit argillic horizons that also develop characteristics of fragipans and are classified as Fragixeralfs (Soil Survey Staff, 1996). In either case, the argillic/fragipan horizons are hydraulically restrictive; $K_{sat}$ values as low as 0.01 cm d⁻¹ have been measured for these soils (Rockefeller, 1997; Reuter et al., 1998).
Soils of the region are generally thought to have formed in two distinct loess units (Barker, 1981; Busacca, 1989; Kemp et al., 1998). The A and Bw horizons have developed in a younger loess unit which is probably Holocene in age. The Btb/Btxb horizon is generally part of a buried soil associated with an older loess unit estimated to be Late Wisconsinan. The relationship of the E horizons to these loess units is less clear, although recent research suggests that E-horizon morphology is related to contemporary hydrological regimes (McDaniel and Falen, 1994; Kemp et al., 1998). As a result, the pedogenic imprint of current hydrological process may obscure any macromorphological evidence of a discontinuity between the younger surface loess and the older loess in which the Btb or Btxb horizons have formed. The formation of these E horizons has been attributed to at least two processes. The relatively impermeable nature of underlying argillic/fragipan horizons and the sloping landscapes of the region suggest that considerable quantities of perched water move laterally within the E horizons, thereby removing colloidal materials that act as soil pigmenting agents. There is also evidence that the light, low-chroma appearance of these horizons is due to redoximorphic processes. As MAP increases along the climosequence, redoximorphic features such as Fe/Mn concentrations become more abundant in the E horizons. These features indicate the occurrence of seasonal reducing conditions and suggest that these conditions are more pronounced

Figure 1. Location map of the northwestern USA. Approximate extent of the Palouse region is indicated by dark shading.
in soils occupying the wetter end of the climatic gradient. However, little is currently known about the duration of seasonal perched water tables or the degree to which these soils become reduced.

**Materials and Methods**

Several study sites were chosen across the region to encompass the range in climatic regimes. At each site, monitoring wells were installed at several locations on hillslopes and equipped with pressure transducers connected to data loggers in order to capture the short-term changes in water table levels. An 8.9-cm-diam. core was extracted to a depth just below the top of the hydraulically restrictive argillic/fragipan horizon. A 6.3-cm-diam. PVC pipe was placed in the borehole with slotted well screen on the lower end of the well. The annular space was packed with sand around the slotted pipe and with bentonite at the top to provide a hydraulic seal. A pressure transducer was placed inside the well at a depth corresponding to the top of the hydraulically restrictive horizon. Transducers were calibrated to measure hydrostatic head in cm and then wired to a data logger programmed to obtain and store hourly readings. Platinum electrodes were used to monitor soil redox status in soil horizons adjacent to the monitoring well; the tips of five electrodes were placed in each the E and Btb/Btxb horizons. All redox potential measurements were reported relative to the standard H₂ electrode.

**Results and Discussion**

Representative monitoring data for the 1994-95 season indicate that perched water tables are present for ~6 months of the year (Fig. 2). Precipitation received during this period was 116% of the long-term average, as recorded at the nearest weather station located 13 km away. Water tables typically form in mid-to-late November and persist until late May. During this time, water tables periodically are present at or near the soil surface. Episaturation of surface Ap horizons occurs as numerous, short-duration events (Fig. 2). In contrast, episaturation of E horizons occurs for long, uninterrupted periods. The rise and fall of perched water tables is closely tied to rainfall/snow melt patterns. Periods of rain or snow melt result in rapid increases in thickness of perched zones of

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Table 1. Morphological and physical properties of a representative Fragixeralf from the eastern Palouse region of Idaho. Data are from McDaniel and Falen (1994).

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Color</th>
<th>Particle-size distribution (%) of &lt;2-mm fraction</th>
<th>Bulk density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>0-10</td>
<td>10YR 3/3 10YR 5/3</td>
<td>10.2 70.0 19.8 -</td>
<td>-</td>
</tr>
<tr>
<td>AB</td>
<td>10-19</td>
<td>10YR 4/3 10YR 5/3</td>
<td>7.8 71.3 20.9 -</td>
<td>-</td>
</tr>
<tr>
<td>Bw</td>
<td>19-39</td>
<td>7.5YR 4/3 10YR 6/4</td>
<td>7.9 73.1 19.0 -</td>
<td>1.55</td>
</tr>
<tr>
<td>BE</td>
<td>39-51</td>
<td>10YR 4/3 10YR 6/3</td>
<td>7.3 72.3 20.4 -</td>
<td>1.63</td>
</tr>
<tr>
<td>E</td>
<td>51-68</td>
<td>10YR 6/3 10YR 7/2</td>
<td>10.9 66.7 22.4 -</td>
<td>1.64</td>
</tr>
<tr>
<td>Btxb1</td>
<td>68-95</td>
<td>7.5YR 4/4 10YR 5/4</td>
<td>7.1 67.0 25.8 -</td>
<td>1.75</td>
</tr>
<tr>
<td>Btxb2</td>
<td>95-120+</td>
<td>7.5YR 4/3 10YR 5/4</td>
<td>7.0 64.3 28.7 -</td>
<td>1.75</td>
</tr>
</tbody>
</table>
saturation, and periods of no rainfall or snow melt result in a steady decline of perched water table levels. Three main factors appear to be responsible for the rapid disappearance of perched water tables in late spring. Precipitation begins to decrease, increasing temperatures result in increased evapotranspirational demand, and most hillslopes tend to have relatively small contributing areas for recharge.

Because of the strong influence that argillic/fragipan horizons exert on near-surface hydrological processes in these landscapes, we examined some of the relationships between argillic/fragipan depth and the spatial patterns of perched water. A study site comprised of Fragixeralf soils receiving ~700 mm of MAP was instrumented with 63 wells arranged in a 10-m-by-15-m grid on a complex hillslope. Data obtained from the cores taken at each well location was used to construct a model of the depth to fragipan. The depth to fragipan averaged 72 cm for the 63 positions and ranged from 32 cm to 140 cm. In general, the deepest fragipans are present in the concave slope positions and the shallowest fragipans are present in the more convex slope positions (Fig. 3a). However, there is no apparent pattern between slope position and fragipan depth. For example, depth to fragipan does not appear to change systematically on linear hillslope segments. If fragipan depth is controlled by processes such as erosion and deposition, we would expect the deepest fragipans to occur in lower slope positions and this is clearly not the case (Fig. 3a). McDaniel and Falen (1994) concluded that fragipan depth (i.e. depth to Late Wisconsinan paleosol) reflects a relict landscape surface that has been modified by additions of younger loess and subsequent surficial processes. A strong relationship between depth to fragipan and thickness of the zone of episaturation is illustrated in Figure 3b. The largest quantities of perched water occur in areas of the landscape where the fragipan is deepest (compare Fig. 3a and 3b), as these tend to be areas of convergent flow. Conversely, the smallest quantities of perched water tend to occur in areas of the landscape where divergent flow dominates.

Considerable lateral transport of solutes via perched water tables can take place in the sloping landscapes of the eastern Palouse region. A study was initiated to measure the rates of solute movement through perched water at three sites across the region receiving 610, 700, and 830 mm of annual precipitation (Reuter et al., 1998). Grids of wells were installed downslope from a trench containing an added Br tracer. Bromide tracer movement and measured $K_{sat}$ of soil horizons were used to quantify flow of perched water. Depth profiles for $K_{sat}$ are similar among sites; values range from 63-129 cm d$^{-1}$ in the Ap horizons and decrease with depth to 0.10 to 0.21 cm d$^{-1}$ in the restrictive horizons. E horizons immediately above the argillic/fragipan horizons have relatively low $K_{sat}$ values ranging from 1.2 to 5.2 cm d$^{-1}$. Results indicate that maximum observed rates of Br movement via perched water tables decreased with annual precipitation and was ~86 cm d$^{-1}$ at the 830-mm site, ~50 cm d$^{-1}$ at the 700-mm site, and ~35 cm d$^{-1}$ at the 610-mm site. Because rates of Br movement as inferred from well data are considerably higher than measured $K_{sat}$ values for E horizons, it appears that much of the rapid solute transport via perched water tables in soils of the region occurs in the more permeable horizons overlying the E horizons.

Although E horizons do not appear to be zones of rapid, subsurface lateral flow, they are nevertheless saturated for extended periods during which redox potentials appear to be sufficiently
low for Fe reduction to occur. Eh values below 240 mV (the assumed Fe$^{3+}$/Fe$^{2+}$ transition for these soils) have been measured for periods of 1-3 months during the spring in E horizons of Argixerolls (Reuter, 1995; Kemp et al., 1998) and Fragixeralfs (Reuter, 1995). Kemp et al. (1998) observed numerous Fe/Mn nodules, segregations, hypocoatings, and depletions in thin section of an Argixeroll E horizon. McDaniel and Falen (1994) have also found a significant correlation between E horizon thickness and perched water table levels in Fragixeralfs of this region. These data strongly suggest that much of the E horizon character is a result of redoximorphic processes rather than of rapid lateral throughflow.

The shallow perched water systems in forested parts of this region are affected by land use. In particular, near-surface hydrology is altered by removal of forest canopy. Rockefeller (1997) found significant delay in the onset of episaturation in hillslopes that had been cleared of forest canopy. Formation of perched water tables in cleared hillslopes was delayed 4-6 weeks compared to adjacent uncut hillslopes. Late-summer and early-fall soil-water content is lower in cleared hillslopes, probably due to canopy interception of precipitation and increased water use by trees. Thus, the duration of episaturation in these areas has increased by approximately 10% as a result of conversion from forest to agriculture.

References

Keywords : episaturation, fragipans, perched water
Mots clés : saturation superficielle, fragipan, nappe perchée