LATAH COUNTY HYDROLOGIC CHARACTERIZATION PROJECT

FINAL REPORT

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1.0 EXECUTIVE SUMMARY

The purpose of the Latah County Hydrologic Characterization Project was to evaluate the potential for shallow groundwater recharge to the upper aquifer in the Moscow area (the “Wanapum aquifer”) through sediments along the granite/basalt contact, in the vicinity of Moscow Mountain. 47 boreholes were advanced into near-surface sediments and 6 boreholes were cored into the top 20 feet of Priest Rapids basalt in the South Fork of the Palouse River and Paradise Creek drainages. The Wanapum aquifer is generally understood as being hosted within the Miocene Priest Rapids Member of the Wanapum Formation, includes the underlying sediments and sedimentary interbeds, and is believed to be distinct from the deeper Grande Ronde aquifer. Investigation showed a consistent pattern of sediment deposition, in which granite and/or metamorphic rocks were overlain by heterogeneous (intermixed coarse and fine) sediments of moderate to high permeability, ranging in thickness from 14 to 54 feet[1]. Basalt flows in the area of this investigation were ubiquitously overlain by a substantial thickness (20 – 25 feet) of low permeability fine sediments (poorly sorted silts, sands, and clays, and peat); these low-permeability sediments were overlain by heterogeneous sediments of relatively high permeability, similar in character to those overlying granitic bedrock. Many of the boreholes in basalt terrain encountered elevated moisture contents at the contact between the low permeability sediments and the overlying sediments of higher permeability. In addition, hydrologic testing and examination of core recovered from the boreholes that penetrated the Priest Rapids basalt suggests limited hydrologic connectivity with the overlying sediments, even though the basalt interior probably has substantial bulk (fracture) permeability.

On the basis of data gathered in this study, we conclude that recharge to the shallow aquifer along the eastern margin of the Palouse Basin is probably limited by thick, low permeability sediments and poor connectivity between the Priest Rapids basalt and the overlying sediments. It appears likely that the majority of infiltration entering the near-surface sediments flows laterally through discontinuous, high permeability sediments until it discharges into local streams (i.e., the South Fork of the Palouse River, Paradise Creek, or their tributaries) or intersects the land surface as spring discharge. There is some circumstantial evidence for this hypothesis from the presence of numerous springs in the area, and anecdotal observations of water discharging to Paradise Creek from sand lenses exposed by excavations near Joseph Street and Mountain View Road in Moscow, Idaho [personal comm., J. Bush]. Bush [2005] also notes that the rapid response of first and second order streams in Latah County, consistent with limited recharge and rapid return flow. Some lateral flow may eventually infiltrate the shallow basalt aquifer, either through spatially-discrete areas of high permeability (e.g., paleo-stream channels), or by flowing westward beyond the area of low permeability sediments[2]; however, evaluating the evidence for either of these possibilities was beyond the scope of the present study.

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[1] Not all shallow boreholes reached crystalline basement rocks; the quoted range of overburden thickness is based on those boreholes that did contact granitic basement.

[2] Data from this study, and from additional well logs and test pits west of the study area, indicate the fine sediments observed to overlie the granite/basalt contact in the study area probably extend as far west as Mountain View Road, but not as far as the Idaho-Washington state line.

2.0 PROJECT OBJECTIVE

The stated goals of the Hydrogeologic Characterization of the Latah Formation of the Moscow Sub-Basin project (referred to below as the Hydrogeologic Characterization Project, or HCP) were to "…map interbedded alluvial fan deposits, their relationship to the margin of the Wanapum Formation and the granitic basin boundary" and to "establish and map key paleotopographic and structural surfaces, correlate and refine stratigraphy, and characterize the groundwater flow regime" [Latah County, 2005]. Simply stated, the objective of the HCP was to investigate the potential for recharge to enter the shallow (Wanapum) aquifer near the granite/basalt contact along the base of Moscow Mountain.

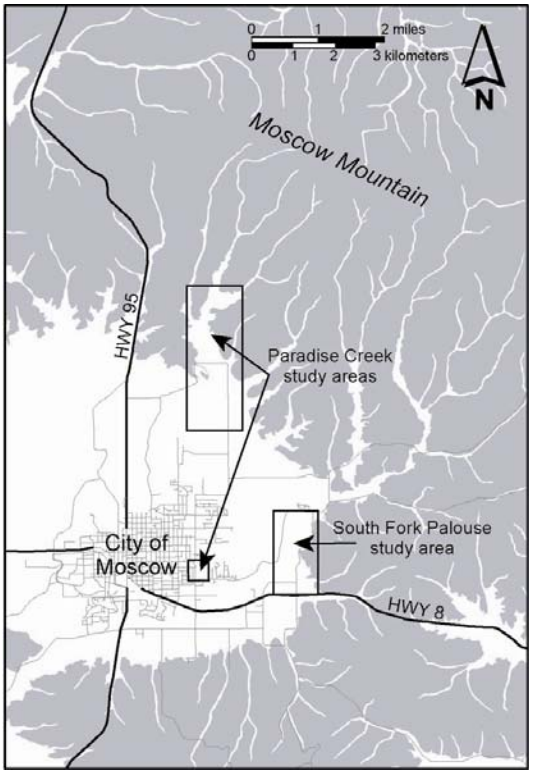

Figure 1: Location of the study area, near the City of Moscow, in Latah County, Idaho (gray shading indicates approximate extent of crystalline basement rocks exposed at the land surface; from Othberg and Breckenridge, 2001a, 2001b).

3.0 STUDY AREA LOCATION AND DESCRIPTION

This study examined the near-surface sediments and shallow basalts underlying a selected portion of the Moscow Mountain drainage located in Latah County, Idaho (Figure 1); the area of investigation is located about one mile west and north of the town of Moscow, within the areas contained in the USGS 7.5 minute Moscow East, Moscow West, Robinson Park, and Viola quadrangles. The eastern and northern portion of the study area is underlain by Cretaceous granites of the Idaho Batholith, and Precambrian Belt-Supergroup metamorphic and metasedimentary rocks; to the south and west basement rocks are overlain by a thick sequence of approximately 10 – 17 mya flood basalts belonging to the Columbia River Basalt (CRB) group. In the Moscow-Pullman area this group is divided into four formations; from the base upward: the Imnaha, Grande Ronde (consisting of four magnetostratigraphic units), Wanapum (including the Rosa and Priest Rapids Members), and Saddle Mountains basalts. These basalts dip towards Moscow, thinning from Pullman towards the study area, with discontinuous occurrence of formation members or individual basalt flows. The basalt units are internally heterogeneous, and sedimentary interbeds are known to occur between and within units. Only the Grande Ronde Formation and the Priest Rapids Member of the Wanapum Formation are present in the subsurface of the Moscow sub-basin; the Grande Ronde Formation hosts the deeper, “Grande Ronde” aquifer, while the basalts of the Priest Rapids Member, the interbedded sediments, and the underlying sediments of the Vantage Formation form the shallower or “Wanapum” aquifer. The granites, metamorphic- and metasedimentary basement rocks, and basalts are overlain by a variable thickness of sediments thought to be Miocene and younger in age that are thickest on the eastern margin of the basin and thin towards the west. These sediments, which form the uppermost part of the Latah Formation, are informally referred to as the Sediments of Bovill [Bush and Provant, 1998a, 1998b; Bush, 2005]. The Sediments of Bovill are the result of physical and chemical weathering of the granites and metasediments, and consist of clay, silts, sands and gravels thought to have been deposited in fluvial environments. In many areas the Sediments of Bovill are themselves overlain by a sequence of Pleistocene loess deposits and interbedded clays of the Palouse Formation, although the loess deposits generally thin to the east over the Sediments of Bovill. A stratigraphic column of the study area geology is shown in Figure 2. The bedrock geology of the area has been mapped at a scale of 1:24,000 by Bush et al. [1998, 2000] and Bush and Provant [1998a, 1998b]. For an excellent and detailed description of the Palouse Basin geology, the reader is referred to Bush [2005].

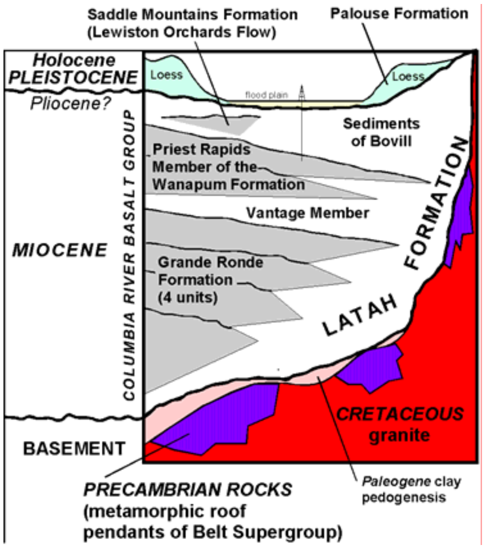

Figure 2: Schematic stratigraphic column, showing relationship between units in the Moscow sub-basin (not to scale). The Lewiston Orchards Member of the Saddle Mountains Formation was not encountered in the study area; it is not present in all areas of the basin, and is often thin and/or weathered where it is present. Terminology and unit relationships after Bush [2005].

4.0 PROJECT METHODOLOGY

Rates of recharge and/or downward percolation are notoriously difficult to constrain; although numerous methods for estimating groundwater recharge have been proposed [Simmers, 1988], few have been shown to be successful except in limited applications [Anderson and Woessner, 1992]. In the present study, we assessed the potential for recharge to enter the Wanapum Aquifer near the base of Moscow Mountain by examining the three factors that were hypothesized to constitute controlling factors on recharge: the availability of surface water that could provide a potential source of recharge, the presence (or absence) of laterally-extensive, low permeability units that could impede deep percolation of infiltrated water, and the connectivity between the basalts of the Priest Rapids Member of the Wanapum Formation (which hosts the shallow, or Wanapum, aquifer) and the overlying sediments. The rationale and methods used to investigate each of the hypothesized controlling factors are described in the sections below.

4.1 Availability of Surface Water

The prevailing hypothesis at the time this study was initiated was that that snow pack on Moscow Mountain provided the majority of recharge to the Wanapum Aquifer (and, potentially, the deeper Grande Ronde Aquifer); as the snow pack on Moscow Mountain melted it was assumed to infiltrate the near-surface soils and sediments either directly or as loss from stream bottoms, eventually percolating below the root zone and entering the basalt aquifers that underlie much of the Palouse Basin. With a limited number of drillholes, and using this hypothesis as a guideline, the decision was made to restrict subsurface investigation to those sub-basins of the Moscow Mountain drainage that carry the majority of yield from Moscow Mountain: the South Fork of the Palouse River, and Paradise Creek (Figure 3). These sub-basins were chosen on the basis of Idaho Geological Survey (IGS) maps, geospatial data, and precipitation maps obtained electronically from INSIDE Idaho (www.inside.uidaho.edu).

4.2 Permeability and Distribution of Near-Surface Sediments

At the inception of this study, the Sediments of Bovill were hypothesized to provide the primary pathway for infiltrating water to recharge the shallow aquifer. These sediments were believed to comprise primarily coarse sands, gravels, and talus derived from mechanical weathering of the Cretaceous granite of Moscow Mountain, and would therefore be predominantly of high permeability. If such were the case, laterally-extensive layers of clays, silts, and other fine-grained and/or cemented sediments posed the most likely impediment to recharge along the range front. The exploratory drilling program was therefore designed to provide data on the structure and distribution of the Sediments of Bovill (i.e., lateral continuity and vertical distribution of fine- and coarse-grained sediments) so that the probability of the existence of laterally-extensive, low-permeability layers that would impede recharge and encourage perching and lateral flow could be assessed. This characterization effort was the objective of the “Phase I” shallow drilling effort.

Phase I boreholes were distributed in discrete groups, or “nests” of five boreholes each[3]. Borehole spacing within each nest was varied to obtain a continuous spectrum of separation distances (Figure 4); that is, within each nest boreholes were placed such that there would be several pairs of boreholes separated by 0 – 100 m, several pairs separated by 100 – 200 m, etc. Borehole locations were arranged hierarchically, such that neighboring nests were, in general, located to allow the closest boreholes of neighboring nests to be used as pairs to develop longer-range correlations. Hierarchical data

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[3] Although all nests were originally planned with five boreholes, two nests were completed with less than the planned number, and one nest was completed with an additional borehole.

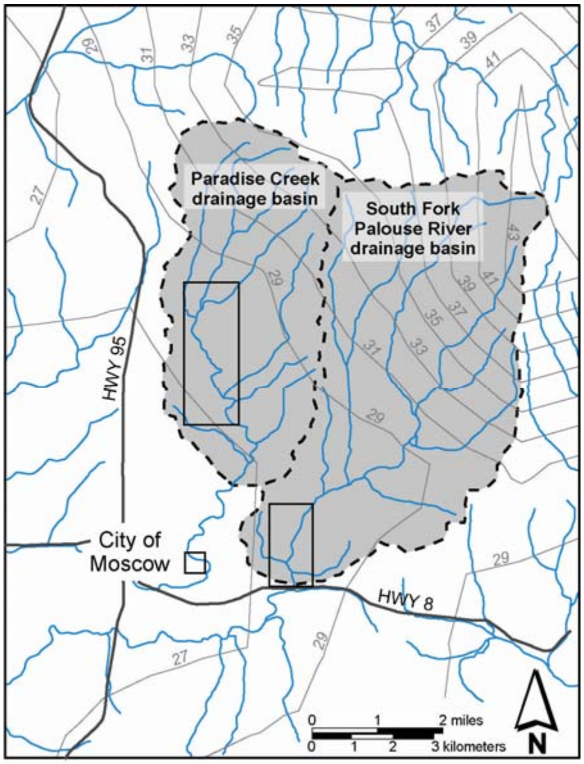

Figure 3: Map of the study area, showing approximate boundaries of the two drainages (South Fork of the Palouse River and Paradise Creek), with isohyetal (constant precipitation) intervals shown as a grey-scale ramp in average annual precipitation in inches, 1961 - 1990.

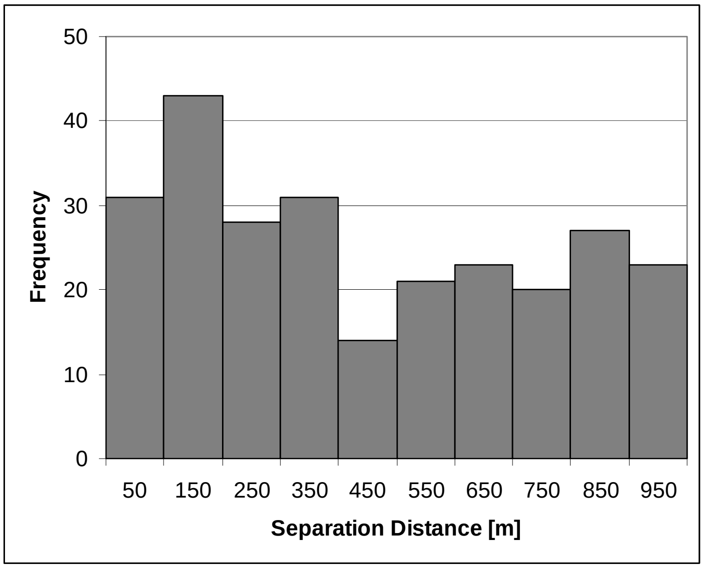

Figure 4: Histogram of borehole separation distance for Phase I boreholes. Separation distance identifies the center of the bin (bin widths = 100 m). The total number of pairs represented in the plot is 261.

collection schemes are a well-known and accepted response to characterizing spatial correlation structure in heterogeneous media [e.g., Haining, 2003:100–103], and are known to be a more efficient use of limited resources than the more common, but inefficient, evenly-spaced or gridded data collection schemes. The actual locations of the Phase I boreholes as drilled are plotted in Figure 5, and given in tabular format (UTM coordinates, NAD83), in Table 1.

Phase I boreholes were advanced by the direct-push method, allowing continuous sampling of near-surface sediments. The Phase I holes were expected to extend to refusal at bedrock, or to a practical maximum depth of about 80 feet. For each borehole, a description of the sediments encountered was developed based on the Burmeister manual classification scheme, and included notes on color [GSA, 1975], perceived moisture (dry, slightly moist, moist, very moist, wet, very wet, saturated), and comments including notes on grain mineralogy, inclusion of organic materials (roots, peat, wood, etc.), or pertinent observations from drilling. A graphical summary of these logs, organized by nest, is provided in Appendix A of this report; the detailed logs for all Phase I boreholes are included in Appendix B. In addition, select samples were taken for mechanical grain-size[4] (Appendix C) and moisture analyses[5] (Appendix D). All Phase I soil cores were photo-documented, and are attached to this report as Appendix E. No field or laboratory permeability tests were conducted on the Phase I samples[6]; therefore, all references in this report to the "hydraulic conductivity" or "permeability" of materials should be considered broad categories based on expert judgment, mean grain size, sorting, etc., except as specifically noted in the text.

4.3 Connectivity of Basalt to Overlying Sediments

The second phase of drilling (Phase II) was designed to gain understanding about how well the Wanapum Aquifer was connected to the overlying sediments; in particular, it was recognized that, even if coarse, saturated sediments were deposited directly on top of the Priest Rapids Basalt, little recharge to the basalt could occur in the absence of fractures or other permeable pathways. To determine if such permeable pathways might exist, a series of deeper boreholes were targeted to core the upper 20 feet of basalt at several discrete locations. Ten to twelve boreholes were originally planned for the Phase II portion of the HCP; however, cost considerations dictated that six holes were actually completed. The Phase II boreholes were sited at varying distances from the basalt margin, with the location of the basalt margin estimated from data gathered in Phase I and a selection of relevant water-well logs obtained from the Idaho Department of Water Resources (IDWR) database (www.idwr.idaho.gov/water/well/search.htm). Well data taken from the IDWR database was assessed for reliability by a number of criteria, and well locations were field checked when possible; IDWR well locations and data used in this study are listed in Appendix F. Detailed logs were prepared of the core recovered

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[4] Grain-size analyses were generally performed on samples taken from predominantly sand or gravel horizons.

[5] Samples for gravimetric moisture content were taken from predominantly fine-grained (silt and/or clay) horizons; however, gravimetric moisture content was also determined as a by-product of grain-size analysis for coarser-grained samples, and is reported as part of Appendix D.

[6] Estimates of hydraulic conductivity based on grain-size distribution were made using the Hazen method [Fetter, 2001]; these estimates should be regarded as loose approximations, and are given in Appendix C.

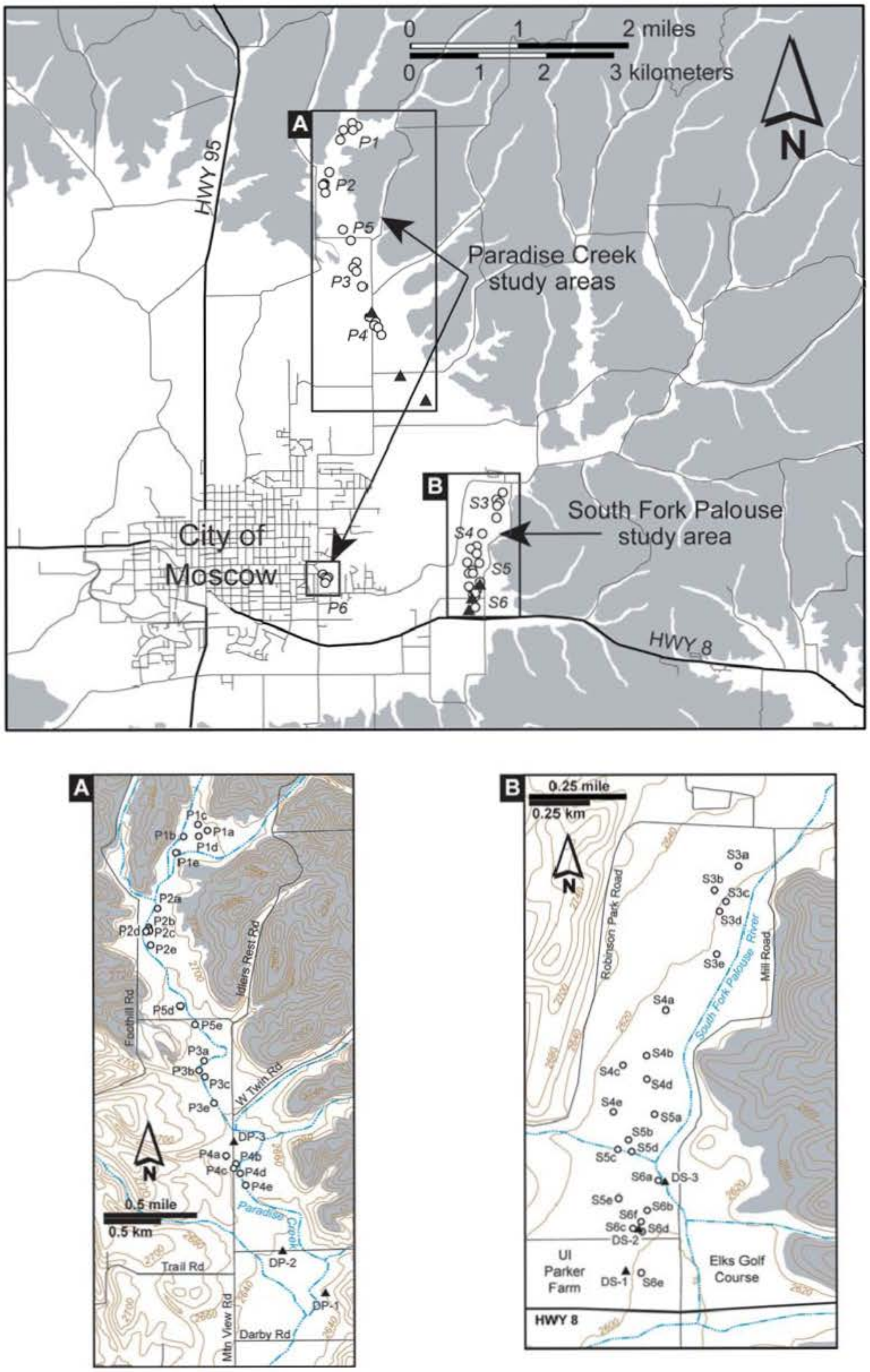

Figure 5: Locations of boreholes within the study areas. Circles indicate shallow borehole locations; triangles are deep boreholes.

Table 1: Locations of all Phase I boreholes.

Well ID	East[1] (m)	North[1] (m)	Elevation[2] (m)	Elevation[2] (ft)	Total Depth (ft)	Terminated in:
P1a	502081	5181568	821	2694	50	clay to clayey sand
P1b	501873	5181517	819	2687	50	decomposed granite (clay above)
P1c	502000	5181620	821	2694	45	clay
P1d	502005	5181520	820	2690	45	clay
P1e	501817	5181377	817	2680	55	decomposed granite
P2a	501660	5180900	817	2680	55	sandy clay
P2b	501585	5180735	817	2680	50	silty/clayey sand
P2c	501590	5180715	817	2680	55	clay
P2d	501560	5180710	817	2680	45	sand
P2e	501599	5180596	817	2680	55	clay
P3a	502050	5179600	811	2661	45	clay
P3b	502005	5179514	811	2661	50	clay
P3c	502055	5179460	811	2661	65	clay
P3d	--	--	--	--	not drilled	--
P3e	502133	5179234	810	2657	60	clay
P4a	502236	5178780	805	2641	55	clayey sand
P4b	502319	5178716	805	2641	75	clay
P4c	502301	5178674	805	2641	40	sandy clay
P4d	502357	5178633	804	2638	40	clayey sand
P4e	502404	5178528	804	2638	50	clayey sand
P5a	--	--	--	--	not drilled	--
P5b	--	--	--	--	not drilled	--
P5c	--	--	--	--	not drilled	--
P5d	501850	5180070	811	2661	38.5	decomposed granite
P5e	501970	5179910	811	2661	45	decomposed granite
P6a	501554	5175032	791	2595	50	sandy clay
P6b	501585	5174990	791	2595	55	clay
P6c	501640	5174985	791	2595	60	clay
P6d	501610	5174960	791	2595	40	clay
P6e	501587	5174908	790	2592	50	clay
S3a	504182	5176224	798	2618	25	decomposed granite/metamorphics
S3b	504082	5176123	798	2618	30	decomposed granite/metamorphics
S3c	504130	5176077	797	2615	20	decomposed granite/metamorphics
S3d	504103	5176036	797	2615	35	decomposed granite/metamorphics
S3e	504091	5175861	797	2615	20	decomposed granite/metamorphics
S4a	503879	5175630	796	2612	18	decomposed granite/metamorphics
S4b	503798	5175441	795	2608	9	granitic sand
S4c	503700	5175400	796	2612	25	decomposed granite/metamorphics
S4d	503800	5175340	795	2608	25	decomposed granite/metamorphics
S4e	503660	5175205	795	2608	19	decomposed granite/metamorphics
S5a	503830	5175195	794	2605	20	decomposed granite/metamorphics
S5b	503722	5175089	793	2602	25	decomposed granite/metamorphics
S5c	503677	5175049	792	2598	34	decomposed granite/metamorphics
S5d	503735	5175040	792	2598	20	decomposed granite/metamorphics
S5e	503680	5174850	793	2602	38.5	basalt
S6a	503845	5174920	792	2598	30	clay
S6b	503800	5174800	793	2602	27	clay
S6c	503778	5174712	792	2598	35	basalt
S6d	503740	5174725	792	2598	35	basalt
S6e	503774	5174540	791	2595	42.5	basalt
S6f	503774	5174753	792	2598	44	basalt

[1] Easting and Northing locations are in geographic coordinate system: UTM, nad83, zone 11 (units: meters).

[2] Elevation is approximate.

from the Phase II boreholes, including notes on mineralogy, fracture and fracture filling descriptions, Rock Quality Determination (RQD, a measure of fracturing), and complete photo-documentation of all core recovered. Phase II borehole logs are included with this report in Appendix G; Phase II photo-documentation is included in Appendix H.

In addition to the data acquired from the Phase II core, a number of hydrologic tests and observations were made in the field during drilling to assist with the determination of hydraulic connectivity between the basalt and the overlying sediments. In particular, pressure injection (packer) tests and in-situ falling-head permeability tests were attempted in all six Phase II boreholes, and paired head measurements (one above the packer, representative of head in the overlying sediments, and one below the packer, in the basalt) were attempted whenever practical. When useful data was obtained from these tests it was analyzed, and the results are compiled in Appendix I.

5.0 PROJECT RESULTS

5.1 Phase I Drilling Results

A total of 47 boreholes were placed during the Phase I drilling, of which 21 encountered granitic or metasedimentary bedrock; 21 terminated at basalt or in sediments believed to overlie basalt, but at locations where basalt was likely below the maximum penetration depth for the direct-push method of drilling[7], and 4 were completed with uncertain relationships to bedrock. As a result of Phase I field operations, 1,900.5 linear feet of core were obtained, on which 137 mechanical grain-size analyses and 587 gravimetric moisture content tests were completed. These laboratory tests, the borehole logs, and drilling notes formed the basis for the interpretations presented in this report with respect to the distribution of near-surface sediments and the potential for recharge to enter the shallow aquifer in the study area.

Possibly the single most important finding of the HCP was the determination of the distribution of near-surface sediments in the study area that resulted from the detailed logging of the Phase I core samples. All Phase I boreholes showed a sequence of heterogeneous sediments directly underlying a relatively thin horizon of loess or silty loam[8]. This deposit of sediments comprised well- to poorly-sorted sands, gravels, and silts, often thinly-interbedded, and sometimes displaying fining-upward sequences characteristic of fluvial environments. Sands and larger clasts were often observed to be subangular to subrounded, indicating minimal to moderate distance of transport and slight to moderate chemical weathering. It was not possible to directly trace layers from one borehole to the next, even in the most closely-spaced holes; however, rough relationships between sediment distributions in nearby holes may be discernable in some instances. In

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[7] The determination that a borehole was completed in sediments overlying basalts (as opposed to sediments overlying granite or metasedimentary rocks) was made on the basis of the composition of the sediments – thick sequences of clays, silts, and peat being observed primarily over basalt bedrock – and by comparison of HCP borehole logs with logs from nearby water wells obtained from the IDWR well log database.

[8] In many, if not most, areas of the study site these sediments are overlain by a thick layer of loess; however, given the ~80 foot maximum penetration of the direct-push method of drilling, the Phase I boreholes were specifically located in areas of thin surficial cover to minimize the amount of loess to be penetrated, and maximize the data obtained on the underlying sediments.

general, these characteristics imply deposition in fluvial and alluvial environments; coarse sediment horizons in particular may have greater continuity in the direction of flow/transport at the time of deposition (e.g., channel deposits or alluvial fans) while demonstrating irregular boundaries and poor lateral correlation normal to the direction of transport. Finer-grained sediments are likely to be horizontally discontinuous, lenticular or irregular in shape, and may have little correlation at scales greater than 10 – 50 m. Taken together, however, these sediments probably have relatively high hydraulic conductivity, at least in a horizontal orientation, and areas of high moisture content were frequently observed in the Phase I core, indicating a high potential for infiltration and (lateral) transmission[9].

In areas underlain by granitic or metasedimentary bedrock the above-described heterogeneous sediments overlie and are in direct contact with the crystalline bedrock; however, in areas underlain by basalt, the heterogeneous sediments were deposited above a sequence of fines (clays, silts, peat, or poorly sorted combination of clays, silts, and fine sands). These fine sediments, in direct contact with basalt, were observed in every HCP borehole that terminated on basalt. Furthermore, clays or fine sediments overlying basalt are mentioned in most of the water well logs obtained from the IDWR database for wells in or near the study area[10]. From these observations, we infer that an extensive, low-permeability clay horizon lies directly in contact with the Priest Rapids Basalt from the area of the granite/basalt contact near the margin of Moscow Mountain westward as far as Mountain View Road in Moscow, Idaho. These fine sediments locally include occasional lenses or thin layers of coarser sediments, but are generally lacking varves or laminations that would indicate extensive still-water deposition, although many boreholes encountered peat and/or wood deposits near to the basalt/sediment contact. On the basis of these observations we hypothesize that encroachment of the flood basalts caused a local decrease in hydrologic gradient in a relatively narrow northwest-southeast band roughly parallel to the Moscow Mountain front. This locally small gradient resulted in pooling of water and the development of peat bogs and wetlands[11], accompanied by drainage reversal (drainage exiting the basin to the northwest, rather than the west or southwest as previously and presently). Although some of the fine sediment deposits encountered may be depositional, the majority probably developed in-place from weathering of basalt (and granite clasts) in the resulting high-moisture, low-energy environment. These inferred events are consistent with those proposed by Bush [2005] to describe the geologic development of the Palouse Basin and its sub-basins.

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[9] In an idealized "layered-heterogeneous" system, effective horizontal hydraulic conductivity can be calculated as the arithmetic average of the hydraulic conductivity of the individual layers, weighted by their thicknesses. In contrast, the effective vertical conductivity is the harmonic average of the individual layers weighted by their thicknesses [e.g., Freeze and Cherry, 1979]. Harmonic averaging gives more weight to extreme low values; thus a thin, low-permeability layer will dominate the vertical hydrologic response of an otherwise high-permeability system. This weighting strongly encourages lateral flow in a layered heterogeneous system such as the one described in this report.

[10] Coarse sediments overlying basalt were reported in one or more wells in the IDWR database, located south and west of the study site. There is presently no way of verifying these logs in the field; however, the logs do offer the possibility that coarse sediments may directly overlie basalt in limited areas near the Moscow Mountain margin.

[11] Examination of peat samples taken from core S6 contained hickory and other pollens [W. Rember, personal comm.].

5.2 Phase II Drilling Results

During the Phase II drilling, six boreholes were advanced into basalt at three locations in the South Fork of the Palouse drainage and three locations in the Paradise Creek watershed (Figure 5, Table 2). All six boreholes were advanced by wet-rotary drilling through the overlying sediments to the basalt/sediment contact, with split-spoon samples taken at intervals as determined by the field geologist. Continuous coring was initiated upon contact with basalt, and the top 20 feet of bedrock was cored and retrieved for analysis. Upon completion of each hole various hydrologic tests were attempted to gain further information on the hydrologic properties of the basalt, and its connectivity to the overlying sediments; the nature and results of these tests are described later in this section.

Table 2: Locations of all Phase II boreholes.

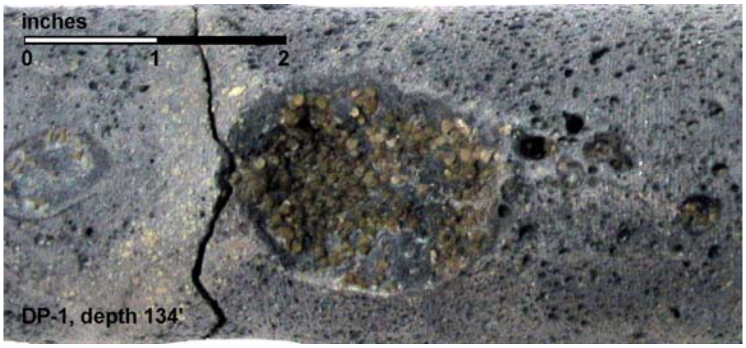
Well ID	East[1] (m)	North[1] (m)	Elevation[2] (m)	Elevation[2] (ft)	Total Depth (ft)	Notes
DS-1	503709	5174548	792	2598	77.5	top of basalt at 57.5 ft
DS-2	503763	5174722	792	2598	61.5	top of basalt at 41 ft
DS-3	503873	5174913	792	2598	105.8	top of basalt at 85 ft
DP-1	503084	5177611	805	2641	145	top of basalt at 125 ft
DP-2	502716	5177974	802	2631	170	top of fine-grained, muddy, grey sandstone at 150 ft (contains basalt and wood fragments)
DP-3	502300	5178902	805	2641	159.5	top of basalt at 139 ft

[1] Easting and Northing locations are in geographic coordinate system: UTM, nad83, zone 11 (units: meters).
[2] Elevation is approximate.

5.2.1 *Phase II boreholes (South Fork of the Palouse drainage).* Examination of core from the three boreholes sited in the South Fork of the Palouse drainage showed the basalt to be fractured and vesicular at the contact with overlying sediments. Below the contact the basalt rapidly becomes less vesicular; the rock becomes more competent, and fractures are more discrete, often displaying larger apertures than those at the basalt/sediment contact. Secondary silica deposits associated with flowing water are found in many fractures, and hydrothermal silica, deposited during original cooling of the basalt flows, is visible in some vugs (lithophysal cavities, see Figure 6).

Apart from the secondary silica deposits, many fractures were found to be partially or wholly filled with clay, which is likely to have been formed in-place, as a result of weathering reactions between basalt and groundwater. Many of the clay fillings were compressed as a result of the lithostatic load, and expanded after the core was removed from the sampling sleeve. Analyses by X-Ray Diffraction (XRD) confirmed the fracture filling is clay, probably a variety of smectite [T. Williams, personal comm.], which is a family of swelling clays that are generally of low permeability (Figure 7). In one borehole in particular (DS-2), clay fracture filling near the basalt/sediment contact was light-colored and the basalt showed orange staining, indicating iron precipitation in an oxygenated environment; however, within a few feet of the basalt/sediment contact the iron staining disappeared, and the clay becomes flat black in color, indicating a change to a reducing environment. This color change reinforces the overall impression of low recharge flux and poor connectivity with the more oxygen-rich sediments overlying the basalt.

Figure 6: Lithophysal cavities exposed during drilling of Phase II corehole DP-1. The grainy, yellowish crystals lining the large cavity in the center of the photograph are hydrothermal silica deposits.



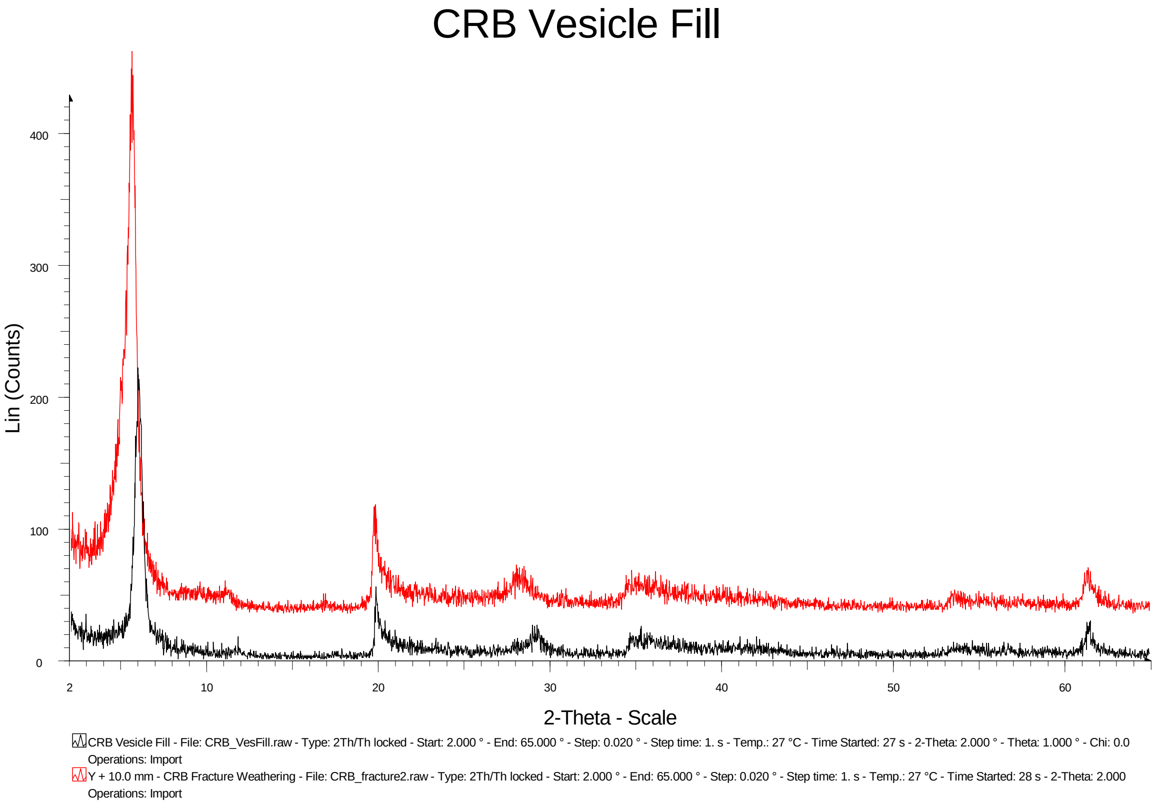


Figure 7: XRD scan results from two samples of void-filling materials (Phase II). Red (upper) scan presents results from fill material sampled from fractures in borehole DS-1; the black (lower) line was sampled from a lithophysal cavity (vug) in the same borehole. The shapes and locations of the peaks in the scans clearly demonstrate that the materials is the same in both samples, probably representing clay of the smectite family (XRD results courtesy T. Williams, University of Idaho College of Science).

5.2.2 *Phase II boreholes (Paradise Creek drainage).* Two of the three Phase II boreholes in the Paradise Creek drainage (DP-1 and DP-2) cored through a mixture of basalt and sandstone, while the third (DP-3) advanced through basalt exclusively. The presence of mixed basalt and sandstone suggests that these two boreholes were located directly on the margin of the Priest Rapids Basalt, at the maximum extent of the sampled flow at that point. Two of the three Phase II boreholes in the Paradise Creek watershed demonstrated very low permeability in hydrologic testing (see following section); the remaining borehole appeared low permeability until it encountered an interval of high permeability near the total depth of the hole. In addition to the sequence of clays and silts that overlie basalt in the area of drilling on Paradise Creek, the sandstone contacting the basalt in the cores retrieved from boreholes DP-1 and DP-2 appears to be unfractured, and to possess very low permeability and porosity. The presence of basalt clasts within the sandstone (and stringers of sandstone within the basalt) suggests the sandstone may have pre-dated the basalt, and the basalt flow was intruded into, under, or around the sandstone during emplacement; if this is the case, the sandstone may be locally baked and/or subject to contact metamorphism, which would further reduce its permeability and porosity. In any case, the presence of the sandstone at the leading margin of the basalt probably acts in concert with the overlying low-permeability sediments to isolate the basalt from hydrologic interaction with the near-surface sediments.

5.2.3 *Phase II hydrologic testing.* Both active hydrologic testing and passive hydrologic observations were performed in the Phase II boreholes when circumstances permitted. Active tests that were attempted were constant-pressure and step-pressure injection tests and falling head tests; these tests were analyzed using the procedures outlined in the Bureau of Reclamation's *Ground Water Manual* [1985], applying calculations for pipe losses presented in Driscoll [1986] when appropriate. Passive observations consisted of examining the head differential between the basalts and the overlying sediments, when sufficient time was available to allow some reasonable equilibration between the borehole and the surrounding porous medium (e.g., overnight). Testing and hydrologic observations in the boreholes generated much useful information, the majority of which tended to reinforce the findings inferred from the drilling logs.

In both falling head and pressure injection tests the basalt is isolated from the overlying sediments by an inflatable packer (Figure 8); the packer can be raised or lowered in the open interval of the borehole (in this case, the borehole was open for the 20 foot length of the core runs) to isolate particular intervals of interest, and to position the packer in a section of the borehole against which the packer can form a good seal[12]. In the case of a pressure-injection test[13] the top of the drill string (which is in communication with the basalt aquifer) is sealed from the atmosphere, and water is injected into the formation at a specified pressure. During injection the rate at which the

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[12] In all the hydrologic tests described in this report, the packer was seated within five feet of the basalt/sediment contact; thus, the data reported is representative of the highest permeability section of the basalt below the packed-off flow tops (since the hydrologic response of the highest permeability interval will dominate the test results).

[13] If injection proceeds at a single pressure, this test is sometimes referred to as a "constant-pressure injection test." Often a pressure test is conducted at multiple, progressively higher, injection pressures, in which case it may be referred to as a "step-injection test." The term "pressure-injection test" is generic in this respect.

formation accepts water is tracked, and can be analyzed to determine the formation permeability. Falling head tests, on the other hand, are conducted by filling the drill string with water to some (arbitrary) datum; the rate at which the water level in the drill string drops is a function of the conductivity of the open interval. In general, falling head tests are superior in low-permeability formations, where the high pressures needed to provoke sufficient response in a pressure injection tests may result in hydrofracturing and artificially-increased permeability; the drawback of falling head tests is that they often require long periods of observation to return useful results. In contrast, pressure tests are often very successful in high permeability units where large quantities of water (i.e., many borehole volumes) can be injected in a short period of time to achieve good results. Both types of tests have pluses and minuses in media of intermediate conductivity, where either or both may return good data.

Figure 8: Photograph of packer assembly, taken during field operations at borehole DP-1.

Of the six Phase II holes tested, nine falling head tests (including six in borehole DP-3) and three pressure tests (in DS-1, DS-3, and DP-3) yielded useful data regarding hydraulic properties of the basalts. Hydraulic conductivity was ranged between 10^{-5} and 10^{-9} m/s (equivalent to permeabilities of 10^{-12} to 10^{-16} m^2); however, these conductivities should be viewed in the context of the heterogeneous nature of the basalt being tested. Because equipment for testing restricted intervals of borehole was not available (i.e., double packer strings), the value of hydraulic conductivity calculated for any particular test is an integral along the entire open section of borehole below the packer, usually 16 to 18 feet in length. For most tests, however, the majority of the conductivity may be attributable to one or a few high-permeability fractures. The test results in borehole DS-1 are particularly illustrative in this respect: the basalt in this borehole was originally felt to be low permeability[14], but the borehole intersected a large, high-permeability fracture zone near the total depth of the hole, resulting in a loss of circulation, i.e., all water pumped into the borehole was taken by the formation, with no returns to the surface. Subsequent testing returned a value for hydraulic conductivity averaged over the entire open interval of about 3×10^{-5} m/s; more realistically, however, the fracture zone encountered during drilling may have a hydraulic conductivity of 10^{-3} m/s or more, with

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[14] This determination was made by the driller on the basis of the very small amount of water loss associated with coring operations.

the remainder of the basalt having a hydraulic conductivity of 10^{-7} or 10^{-8} m/s. Of the two boreholes in this study that encountered high permeability (DS-1 and DP-3), it is important to note that the high-permeability zones were located near the bottom of the cored interval, well away from the overlying low-permeability sediments and areas of clay-filled fractures that appear common in proximity to the basalt/sediment contact.

In addition to the active tests of hydraulic properties, observation of differential heads (i.e., comparison of hydraulic head observed in the basalt with that in the overlying sediments) provided information on the vertical gradient of head between the basalts and the overlying sediments. In the case of DS-3 and DP-1, equilibration time between completion and hole abandonment was sufficient to show a strong downward gradient from the sediments to the basalt; this is a particularly interesting finding at DS-3, which is in close proximity to the South Fork of the Palouse River, and might be expected to constitute a source of recharge to the basalts in the event that permeable pathways did exist. In fact, borehole DS-3 was the only one of the six Phase II boreholes in which water levels appeared to asymptotically approach equilibrium above the total depth of the hole (Figure 9); the apparently shallow potentiometric surface, coupled with the proximity of this borehole to the South Fork of the Palouse River, may have implications for recharge in the study area. Even in boreholes that did not have sufficient time to approach hydraulic equilibrium, it can be inferred that the vertical hydraulic gradients were oriented downward, since high saturation or perched water was commonly observed in the sediments overlying the basalt, while only the lowest-permeability holes retained water for any significant length of time, indicating the equilibrium surface was below the total depth of the boreholes. In general, the indications of downward vertical gradient in the basalt observed in the present study are consistent with similar observations by water well drillers over much of the basin.

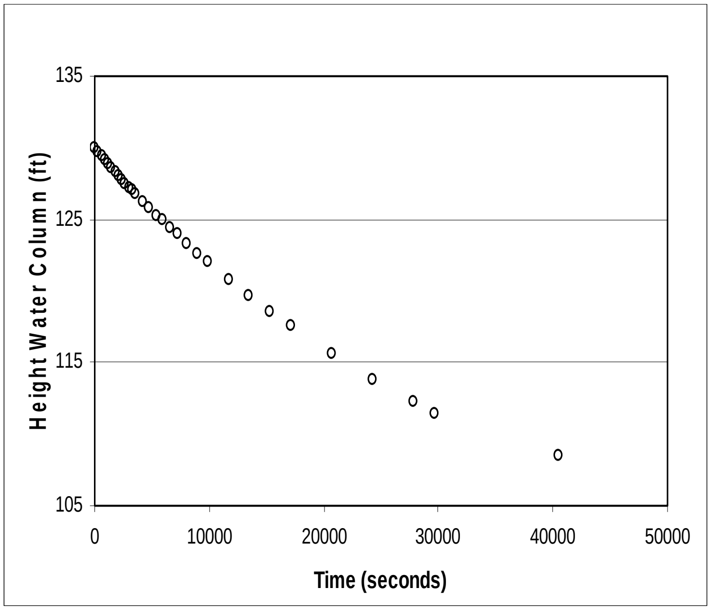

Figure 9: Falling head data from borehole DP-1. The data shown were obtained over ~11 hours, beginning at 7:15 PM June 23, and ending at 6:30 AM, June 24, 2006.

6.0 DISCUSSION AND CONCLUSIONS

It has been suggested by several investigators that recharge may enter the Wanapum aquifer (and, potentially, the Grande Ronde aquifer) through shallow, coarse-grained sediments along the eastern margin of Moscow Mountain, near the granite/basalt contact [e.g., Bush, 2005]. This hypothesis is intuitively appealing for a number of reasons: The majority of snow pack that constitutes potential recharge to the Palouse Basin aquifers is found on Moscow Mountain; the near-surface sediments near the granite margin are known to be coarse-grained and permeable, and it is tempting to postulate that groundwater moves from east to west in the basin, following the general pattern of surface drainage[15]. Unfortunately, the present study found little evidence to support this widely-accepted hypothesis.

In keeping with previous investigators [e.g., Pierce, 1998], the present study found the near-surface sediments overlying and in the vicinity of the granite/basalt margin to comprise interbedded clays, silts, sands and gravel lenses, consistent with deposition in fluvial and alluvial settings. Overall, these sediments probably have high infiltration capacity and a high horizontal permeability. In general, subsurface exploration found these sediments to lie in direct contact with granite bedrock; however, in the areas investigated by the HCP a thick (~20 – 25 foot) layer of low-permeability silts, clays, and peat was found below these coarse and heterogeneous sediments in any area overlying basalt flows. Furthermore, hydrologic tests indicate that the basalt is of low permeability near to the basalt/sediment contact, although the interiors of two of the basalt flows were found to have discrete, highly permeable zones. In both boreholes that demonstrated high permeability, the interval of high permeability was near the bottom of the cored interval, placing it between 15 – 20 feet from the basalt/sediment contact. Closer to the basalt/sediment contact the majority of fractures were found to be filled with smectite (clay), possibly developed in-place through weathering of the basalt in a “self-sealing” process that isolated the basalt interior from direct hydraulic communication with the overlying sediments.

On the basis of our testing and observations, we propose the following conceptual model for near-surface hydrology in the study area: surface water (e.g., runoff, snow melt, stream flow, etc.) infiltrates to the near-surface sediments throughout a broad area along the margin of Moscow Mountain. These near-surface sediments generally have high infiltration capacity; however, the strongly anisotropic structure of the sediments encourages lateral flow in a generally westward direction (with local variation). The majority of infiltrated water is probably prevented from becoming deep percolation (recharge) by the relatively impermeable granite or low-permeability clays that underlie the coarser near-surface sediments; ultimately, much of this shallow groundwater probably returns to the land surface as spring discharge, or by intersecting an incised channel and becoming stream (or hyporheic) flow. In short, the majority of the water

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[15] Although Bush [2005] did hypothesize that recharge may enter local aquifers along the basalt/granite contact, the same manuscript discusses an alternative mechanism for recharge – infiltration entering the aquifer near the Washington-Idaho state line – and states that it is likely groundwater moves from the state line eastward, towards the City of Moscow. These latter hypotheses are in agreement with the findings of this study.

infiltrating sediments on the east side of the basin probably discharges locally at the land surface (i.e., becomes return flow).

Although the majority of infiltration on the east side of the basin does not become recharge to the basalt aquifers in our conceptual model, we cannot state that the basalt receives no recharge from the granite/basalt margin. Some of the lateral flow may travel far enough westward to move beyond the clays and infiltrate the basalts through permeable fractures. Furthermore, hydraulic gradients were found to be uniformly downwards throughout the study area, and even low-permeability clays and silts may transmit appreciable amounts of groundwater when considered cumulatively over a large enough area. The low-permeability basalt and smectite-filled fractures observed in this study may not exist in all parts of the study area; if local zones of highly-permeable fractures do exist, they may provide conduits for funneling distributed recharge coming through the silt and clay layers, or through localized, high-permeability sediments embedded in the low-permeability clays. The fact that water levels in the basalt aquifer apparently were higher near the South Fork of the Palouse River (in borehole DS-3) than in other, nearby Phase II boreholes may offer some circumstantial support for localized recharge through discrete, high-permeability pathways. Unfortunately, the DS wells are located near several pumping wells[16]. Because DS-3 was farther removed from local pumping than DS-1 and DS-2, the higher potentiometric surface may be an artifact of pumping, rather than indicating local recharge from the South Fork of the Palouse River. Further investigation would be required to clarify this point (see "Recommendations" section below).

In spite of the possible exceptions discussed in the preceding paragraph, the investigations described in this report showed little evidence for large amounts of recharge to the basalt aquifers near the granite/basalt margin. If localized, high-permeability recharge areas do in fact exist, there is a low probability of being able to locate and exploit them to increase recharge to the shallow aquifer. Attempting to increase distributed recharge to the basalt aquifer through the clay overburden is both impractical and inefficient, since most water would undoubtedly be lost to lateral flow. It may be possible to increase recharge to the shallow aquifer in the vicinity of the study area using a series of holding ponds, directly connected to the basalt by passive recharge wells. Whether this strategy is technically, economically, or politically feasible is presently unknown; however, we think the development of recharge ponds farther west, beyond the areas where clay and silt directly overlie the basalt, is more likely to be practical. In any case, additional work will be necessary before any pilot recharge project should be attempted.

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[16] Two wells, owned by the Elk's Club, are completed in the Priest Rapids basalt near the DS holes, and may have been located close enough to the DS wells to cause perturbation of the observed potentiometric surface. Although pumping data for these wells were not available to the investigators, one of the wells is used for irrigating the Elk's golf course, and so is likely to exert considerable influence on the local potentiometric surface (the other pumping well is used for potable water supply at the Elk's clubhouse). Another pumping well, owned and operated by the University of Idaho Plant Science Farm (Parker Farm), is farther away, but may also influence potentiometric surface elevations in the DS wells.

7.0 RECOMMENDATIONS

Apart from the stated objective of this research, which was to evaluate the potential for recharge to the Wanapum Aquifer from the granitic margin at the base of Moscow Mountain, it was agreed that the investigators would comment on the potential to use engineering means to increase recharge to the Wanapum Aquifer along the Moscow Mountain range front. As stated in the preceding section, we think it is unlikely that such measures could be practically implemented, particularly in the current political, social, and economic climate. Although there are several challenges to increasing recharge to the Wanapum Aquifer in the eastern side of the basin, the present study points out the possibility of opportunities for increasing recharge to the shallow aquifer to the west of Moscow (i.e., near and to the west of the state line). On the basis of borehole logs from the IDWR database and observations in trenches near the intersection of Perimeter Drive and State Highway 8 [J. Bush, personal comm.], the sediments in contact with the Priest Rapids basalt in the vicinity of the state line are believed to be coarser-grained and of higher permeability than on the east side of the basin (where, as detailed in this report, drilling consistently found low-permeability silts and clays at the basalt/sediment contact). The basalts come very close to the land surface in the vicinity of the state line, and dip gently to the east [Bush, 2005]. We agree with Bush [2005] that the area near to, and west of, the state line may be a potential recharge area for the shallow aquifer, in which losses from Paradise Creek and the South Fork of the Palouse River spread laterally in near-surface, high-permeability sediments, and infiltrate the basalt through fractures and higher-permeability flow contacts. If this is the case, groundwater flow in the Wanapum (and perhaps the Grande Ronde) Aquifer is likely to be eastward, following structural control down the dip of the Priest Rapids basalt towards Moscow. It may therefore be possible to increase recharge to the Wanapum Aquifer by a series of infiltration ponds and check dams near the state line, along Paradise Creek and the South Fork of the Palouse River. Evaluating the potential for recharge near the state line, and the feasibility of increasing recharge to the shallow aquifer west of the City of Moscow through engineering means, are beyond the scope of the current project; however, we briefly outline below a study to test for the existence of recharge to the shallow aquifer in the area of the Idaho/Washington state line, along with several other tasks that we believe would contribute to the overall understanding of groundwater movement in the Palouse Basin.

7.1 Evaluating Recharge Near the Idaho/Washington Stateline

We recommend a complementary surface water/groundwater study to evaluate the potential for recharge to enter the shallow aquifer from stream losses in the vicinity of the Idaho/Washington state line. The surface water portion of the study would estimate the quantity of water lost from Paradise Creek[17] using “seepage meters” [Sanders, 1998] and by estimating differential discharge at a large number of sites, starting at Line Street in Moscow, and continuing west beyond the state line. This surface water monitoring program should be carried out four to six times over at least one year; the estimated loss

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[17] We recommend concentrating on Paradise Creek for this study, because of the potential for discharge from the City of Moscow Waste Water Treatment Facility to form a substantial portion of water recharging the shallow aquifer. This has practical implications both for groundwater quality and study implementation, as is discussed later in this section.

from Paradise Creek over one year could then be compared with existing estimates of recharge to the Wanapum Aquifer.

If losses from Paradise Creek are recharging the shallow aquifer, discharge from the City of Moscow Waste Water Treatment Facility (WWTF) should form a component of that recharge. We therefore recommend that all shallow wells (those located in the Priest Rapids basalt, the underlying Vantage Formation, or the overlying sediments) within two miles north or south of Paradise Creek, one mile west of the WWTF, and three miles east of the WWTF, be sampled and tested for components that would indicate the presence of WWTF discharge (e.g., ammonia, THM, temperature, etc.). It may be necessary to place a number of additional shallow wells to obtain adequate coverage of the area; fortunately, these wells would be relatively shallow, and the cost of placement may therefore be reasonable. Furthermore, any wells placed for the proposed study could be maintained as permanent sampling stations for groundwater quality monitoring and protection. If compounds in the shallow groundwater could be unambiguously identified as having originated at the WWTF, the data obtained may be used to develop a map of the direction (and possibly rate) of groundwater flow and recharge in the area, and, when combined with the results of the surface water monitoring, could yield important information for the evaluation and management of groundwater resources. In any case, it is likely the study could be fielded quite economically, particularly if no new wells, or a relatively small number of new monitoring wells, were needed to map groundwater quality.

7.2 Monitoring Facility at the UI Plant Science Farm

As was discussed in Section 6.0 (Discussion and Conclusions) of this report, there is some possibility that recharge may be entering the shallow aquifer in the area of DS-3, on land owned by the University of Idaho (the UI Plant Science Farm, or “Parker Farm”). On the basis of the data gathered in this study it is impossible to know if the elevated potentiometric surface observed in DS-3 is the result of recharge from the South Fork of the Palouse River, or is an artifact of pumping at the nearby Elk’s Club golf course. To discriminate between these two possibilities, we recommend placing one to three pairs of piezometers, with one at the (now abandoned) location of DS-3, and additional nests placed to the south and southwest of DS-3 as funding allows. In each pair, one piezometer should be finished below the potentiometric surface in the basalt, and the other in the overlying sediments. These piezometer nests would allow researchers to track water levels in the basalt and overlying sediments, calculating hydraulic gradients and monitoring for response to nearby pumping and changes in the discharge of the South Fork of the Palouse River. The value of data collected from the monitoring points could be increased by installing a permanent stream discharge gauge (weir or stage gauge) on the South Fork of the Palouse River, so that discharge data from the river could be correlated with changes in the potentiometric surface in the basalt and in the overlying sediments. In addition to allowing monitoring of the effects of nearby pumping, the proposed monitoring points may provide data on the hydraulic diffisivity (hydraulic conductivity divided by storage coefficient) of the basalts and sediments, connectivity between the shallow aquifer and overlying sediments, and may allow calculations to be made of the diffuse recharge through the fine-grained sediments, if any. The reaction of UI Plant Science personnel to informal inquiries regarding the possibility of a permanent monitoring facility for groundwater/surface water interaction has been positive;

furthermore, such a facility may be a good strategic investment: the Palouse Basin Aquifer Committee's (PBAC) shallow aquifer monitoring project recent lost access to the Elk's Club (non-pumping) well, and there is currently no shallow monitoring well in this part of the basin.

7.3 Additional Margin Studies

The findings of the present study are unlikely to apply directly to other margin areas in the Palouse Basin, i.e., areas of contact between granite or metasedimentary belt rocks and basalt, such as exist at Kamiak Butte, Smoot Hill, Bald Butte, etc. During the emplacement of the Priest Rapids Basalt (and continuing to the present), Moscow Mountain probably received relatively large amounts of orographic precipitation in comparison with other topographic highs in the area. The wet, low-energy environment that developed between Moscow Mountain and the basalt margin was important for the weathering of basalt to clay, and for development of peat bogs and marshlands; however, these conditions were unlikely to exist (or might have existed to a lesser extent) in areas that received less orographic precipitation.

Although thick clay horizons may not have developed along the margins of other topographic highs in the Moscow Sub-basin, two additional factors observed in the present study may limit communication between the shallow basalt aquifer and the near-surface sediments: the development of a low-permeability contact due to intrusion of basalt flows into existing sediments (as seen in boreholes DP-1 and DP-2), and the potential for a low-permeability zone (with either poorly-connected fractures or clay-filled fractures) to directly underlying the flow tops of the basalt, limiting the opportunity for shallow groundwater to infiltrate the basalt.

It is not known whether either of these, or other, as yet unknown, conditions may exist at contacts between the shallow basalts and crystalline bedrock (i.e., granite or metasedimentary belt rocks) and limit recharge to the basalt aquifers. Given the recent interest in increasing recharge to the shallow aquifer in the vicinity of Kamiak Butte, however, an assessment of the connectivity between basalt and the overlying sediments, similar to the HCP, would be a good investment prior to any artificial recharge field trials.

7.4 Reliable Electronic Database of Well Information

It has come to our attention during this investigation that there is a need for a universally-available, field-checked database of information on wells drilled in the Palouse Basin. IDWR does currently maintain an electronic water-well database, which contains a great deal of data submitted by water well drillers; this is an important resource for groundwater scientists working in the basin, and we commend IDWR for making this information available to scientists and the public. Unfortunately, all data in the IDWR database require stringent review and field checking before they can be used for scientific purposes. In many cases we have found that data entered in the database are in error with respect to section, well location within a section, or even in reported Township and/or Range. Even in situations where well location is reported correctly, the "quarter-quarter section" location scheme used is accurate at best to within about 660 feet, a distance that can easily result in a difference of a hundred feet in the estimated elevation of a geologic contact. We encourage IDWR to require water well drillers to report well coordinates using UTM/NAD83 coordinates (or any other common system). Drillers with whom we have discussed this situation have been unanimously in favor of such a measure. The drillers feel that the quarter-quarter section scheme is cumbersome and difficult for them to apply accurately; furthermore, most drillers are equipped with handheld GPS units by their companies (which can be purchased for under $100 at any sporting goods store), and one driller pointed out that many cell phones are now GPS-enabled. In short, there seems to be little reason to continue to use an antiquated and error-prone location system when quicker, more accurate methods are readily available.

Apart from encouraging IDWR to update their well location system, we recommend that IDWR, PBAC, or the individual PBAC entities undertake a comprehensive program of field checking well locations and geologic/hydrologic data (where possible) for relevant wells in the IDWR database. We applaud efforts by F. Leek and J. Wu (Washington Statue University), funded by PBAC, to create such a comprehensive database; however, we must stress that the data in the new PBAC database is no more accurate than the sources it was taken from. We suggest that PBAC retain a full- or part-time staff member to compile and field check all well information in the basin, and place the compiled information in an electronic database that is freely available on the web, with accompanying metadata, so a researcher can be certain of the source and quality of the data being used. As our initial contribution to this effort, we include in Appendix F of the present report a complete list of well data, obtained from the IDWR database and field checked to the best of our ability. The source, perceived quality, and level of field checking associated with each well is indicated for each entry; although more elaborate methods of presenting the data can be envisioned, we here follow a “simple is best” approach, and offer the information in the appendix as a possible model for compiling and reviewing well data throughout the basin.

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