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REGIONAL MANAGEMENT CONSIDERATIONS OF THE GROUND WATER RESOURCES IN LAYERED VOLCANICS OF IDAHO, OREGON, AND WASHINGTON

JUNE 1983

State of
Washington

John Spellman
Governor

DOE 83-6

Department
of Ecology

Donald W. Moos
Director

REGIONAL MANAGEMENT CONSIDERATIONS OF THE GROUND WATER RESOURCES IN LAYERED VOLCANICS OF IDAHO, OREGON, AND WASHINGTON

by
Jeffrey C. Brown[1]

prepared for
Washington State Department of Ecology
Olympia, Washington

Under Agreement #81-068
June, 1981

[1] Consulting ground water geologist
S.E. 345 High St.   Pullman, WA 99163

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ABSTRACT

The thick sequences of layered volcanics present over large areas of the three states are divided into four major categories: 1) Snake River Basalt; 2) volcanic and volcaniclastic rocks of central Oregon; 3) Columbia River basalt group; and 4) volcanic and volcaniclastic rocks of the Cascade Mountains and southern Idaho. Comparison of geologic and hydrologic properties reveals that despite physical and chemical differences, considerable hydrologic similarity is present. Layered rocks of basaltic composition have primary flow structures which permit horizontal and vertical permeability. Sequences of basalt flows often exhibit vertical interconnection and the hydrologic system operates much like a water table system. Sediments and saprolitic zones often have low permeabilities and create perched or confined conditions. Silicic volcanics, while exhibiting some of the same properties as layered basic volcanics, depend more on secondary fractures for permeability.

Laws governing ground water resource development have evolved in each state from surface water appropriation codes. Ground water law is based on the appropriation doctrine, but precise interpretations of this doctrine differ among the states. Each state has a regulatory agency that controls resource development. The agencies regulate ground water withdrawal by a permit system. Ground water withdrawal is permitted if the proposed water use is considered beneficial and if supplies are adequate to sustain withdrawal. Each state agency has statutory means for designation of critical areas where adequacy of supply is questionable with special power to limit withdrawal permits and amounts. Beneficial use has traditionally been interpreted in economic terms, although recently such factors as storage, aesthetic impact and maintenance of stream flows have been included.

Continued resource development could produce supply problems on a regional scale. Similarity in ground water occurrence in layered volcanics and management philosophies in the three states indicate regional resource management is possible. For management, regional or local, to be most effective a program of research on the nature of ground water occurrence in layered volcanics using a variety of techniques currently available must be sustained.

(KEY TERMS: resource management; ground water; layered volcanics; Pacific Northwest; appropriation doctrine; water resources.)

ACKNOWLEDGMENTS

A study of this scope depends upon a variety of individuals and organizations. Grateful acknowledgment is extended to Dale Ralston and Doug Grant of the University of Idaho; Frank Sherman of the Idaho Department of Water Resources; Phil Oberlander, Fred Lissner, and Donn Miller of the Oregon Department of Water Resources; Bill Miller, Bill Smith, Linton Wildrick, Alan Wald, Gene Wallace, and Wick Dufford of the Washington Department of Ecology; and Ann Zurawski, Jerry Lindholm, and Dick Whitehead of the U.S. Geological Survey. Thanks is also extended to the staffs of the Washington and Oregon Water Research centers and the Idaho Water Resources Research Institute.

INTRODUCTION

As demand for water resources in the Northwest continues to grow, concern over the continued availability becomes manifest. Much of the current demand and related concern is directed toward ground water resources because, in many of the more arid locations, surface water supplies are either lacking or fully appropriated. In some areas, the effects of continued development cannot be contained within state boundaries and have regional significance.

Throughout much of the arid areas of the three states of Oregon, Idaho, and Washington, significant ground water development has occurred from layered volcanic sequences. In Idaho this development is from basalts of the Snake River plain and, to a lesser extent, the Columbia River group. In Washington, most development is from the Columbia River basalt group and in Oregon the Columbia River basalt and a variety of other volcanic units are significant ground water sources. Much study has been devoted to local areas of ground water development; however, very little study has been done on a regional scale.

This report is an analysis of the regional aspects of layered volcanic ground water hydrology and has three basic dimensions. First, a review of the wide variety of research that has been and is being done on ground water hydrology of these various volcanic sequences is presented. The purpose of this review is to look for similarities and/or differences in the nature of the various hydrologic systems with an eye toward the feasibility of regional management of the ground water resources of these volcanics should it become desirable. Second, an analysis of water right legislation and water resource management policy of Idaho, Oregon, and Washington is presented. Comparison of the various management systems reveals problems that might be anticipated if a regional management program were ever to be attempted. Finally, a brief discussion of ground water research methods and their applicability to layered volcanics is presented. This discussion of methods is to stimulate research development in the volcanics and to stress the need for basic research as an integral part of current and future management efforts.

This report presents information similar to that in the voluminous Columbia-North Pacific Region Comprehensive Framework Study (Pacific Northwest River Basins Commission, 1972). Unlike the framework study, however, this report is directed solely to ground water resources of the layered volcanic sequences of the three states. Furthermore, in the decade since assembly of the framework study, considerable progress has been made in understanding of ground water hydrology of these units and some important changes have also occurred in management policy and regulation within the three states. This report is designed to provide the basic data for further assessment of a regional approach to ground water management in the high use areas of the three states.

NATURE AND OCCURRENCE OF GROUND WATER IN LAYERED VOLCANICS

The Pacific Northwest enjoys a great diversity of geology, particularly in the nature and distribution of extrusive volcanics. Although there exists a wide variety of units of numerous textural, mineralogical, and chemical combinations, the broad scope of this study requires classification of these diverse units into four general categories. The categories are 1) Snake River basalt, 2) volcanics and volcaniclastic rocks of central Oregon, 3) the Columbia River basalt group, and 4) volcanic and volcaniclastic rocks of the Cascades and southern Idaho. Table 1 presents a brief description of each of these categories and their distribution is shown in Figure 1.

In the following sections, discussion is presented regarding the occurrence and hydrologic properties of these units in each of the three states of Idaho, Oregon, and Washington. In general, discussion is limited to the first three categories, as very little investigation has been done on the ground water hydrology of the older volcanics of the Cascades.

IDAHO

Nowhere within the three states is there greater diversity of ground water sources than in Idaho. Here ground water production comes from a wide variety of volcanics and related sedimentary units which differ markedly in occurrence, nature, and age. Because of this diversity, discussion of ground water occurrence in volcanic terrains of Idaho is broken into two general categories: 1) the occurrence of ground water in basalt of the Columbia River group, and 2) ground water in volcanics of the Snake River Plain.

Columbia River Basalt Group in Idaho

Distribution of Columbia River basalt flows was limited in Idaho by significant relief associated with the western edge of the Rocky Mountain chain. Individual eruptions generally do not extend far into Idaho and the area of Columbia River basalt occurrence is limited to a zone along the state's western edge, (Figure 1). The topography restricted flow deposition and thus the total basalt sequence is quite thin, often less than 1,000 feet. Also, interruption of the natural westward drainage of the Idaho interior by the incoming basalt flows resulted in deposition of both fluvial and lacustrine sediments which are interbedded with the basalts. In some areas several hundred feet of these interbedded sediments may be present.

In areas where the basalt is present, it is often a significant ground water source. These areas include the Weiser Basin and parts of extreme western Idaho, the Lewiston-Clearwater embayment areas, the Moscow area, and other areas along the Washington-Idaho border. Separation of these areas, in some cases, is quite large; however, they are quite similar geologically and hydrologically.

QUATERNARY	Pleistocene - Holocene	Snake River Basalt Recent olivine basalt flows and related sedimentary interbeds. Flow thickness and distribution highly variable. Good permeability in highly fractured and often scoriaceous flows. Significant ground water producer.
		Volcanic and Volcaniclastic Rocks of Central Oregon Olivine basalt and andesite flows of varying thickness and extent with locally abundant sedimentary interbeds. Includes extensive deposits of silicic ash flow tuffs and related rocks. Permeability dependent on stratigraphic relationships and fractures. Locally significant ground-water sources.
TERTIARY	Eocene -- Miocene - Pliocene	Columbia River Basalt Group Dense, massive fine-grained basalt flows locally with interbedded sediments. Flow thickness average 50-100 feet. Good permeability, a significant ground-water source.
		Volcanic and Volcaniclastic Rocks of the Cascade Mountains and Southern Idaho Includes layered tuffs, tuff breccias, welded ash flows with interbedded basaltic and andesitic lavas. Productivity dependent on fracture distribution.

Table 1. Description of Major Layered Volcanic Sequences in Idaho, Oregon, and Washington

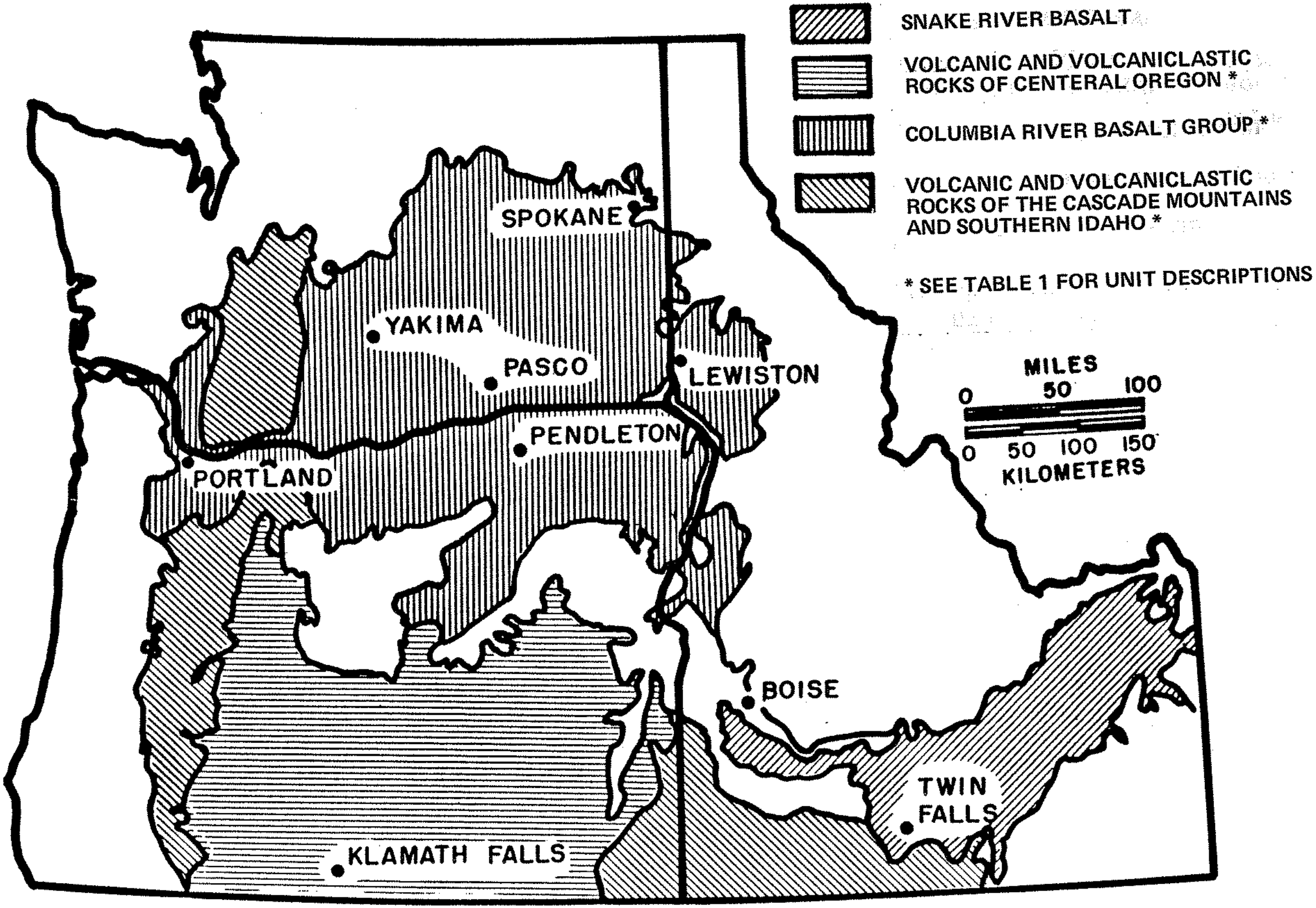

Figure 1. Distribution of Major Layered Volcanic Sequences in Idaho, Oregon, and Washington

In the Weiser Basin area, Columbia River basalt forms the surrounding hillsides and underlies recent alluvium in the valley bottoms. Where the valley is sufficiently wide, development has taken place and most ground water withdrawals occur in these lowlying locations. Drilling logs and hydrologic data indicate basalt flows interbedded with a substantial amount of generally fine grain sediment. Production is obtained from both the basalts and sediments; however, Walker and Sisco (1964) indicate that the basalts are consistently better aquifers. Many wells are drilled for domestic purposes and resulting yields are small (10-30 gpm). Young and others (1977) report that irrigation wells yield 500-1000 gpm indicating that the basalts are capable of significant production. Most wells are located in the valley bottom and normally exhibit increasing head with depth. Many of the wells flow at least part of the year.

The situation described for the Weiser Basin may be considered typical of other small basalt filled basins in western Idaho. Discussion presented by Ko (1974) of the Hangman Creek Basin in northern Idaho indicates the presence of interbedded Columbia River basalt and sediments. Production is normally not large and often comes from either basalt or coarse grained sediments. Many wells drilled at lower elevations of the basin exhibit positive head and/or flowing conditions. Pump test data obtained by Ko indicate transmissivities for basalt aquifers on the order of 7×10^4 gpd/ft.

Similar conditions exist in the Clearwater embayment, even though total thickness of the Columbia River basalt may be significantly greater than in previously described areas. Intercalation of basalt flows and sediments produces varied drilling and hydrologic conditions. Most production is obtained from basalt aquifers with sediments being zones of low permeability. In some locations, units of the Imnaha Basalt have been penetrated with generally poor productive results. Lack of production is likely a result of the highly weathered nature of the Imnaha which restricts permeability. Castelin (1976) reports incidents of perched conditions near Grangeville and, although he does not specify particular perching horizons, it is likely that they are either sedimentary zones and/or weathered basaltic horizons. He also refers to an "artesian" system which underlies these perched zones in the Grangeville area.

Basalt aquifers provide substantial amounts of ground water for locally dense populations in two locations (Moscow and Lewiston). In the Moscow area the total thickness of interbedded basalts and sediments is barely 1,000 feet, of which nearly half is low permeability sediments. In this area Barker (1979) describes two ground water systems in the Moscow area, an upper and a lower or primary system. Barker's primary system includes at least two distinct Grande Ronde basalt sequences separated by a significant interbed. Barker's research indicates that despite a significant thickening of the basalt sequence and marked decrease in the amount of interbedded sediments to the west, the primary system appears to extend to the Pullman, Washington area, eight miles west of Moscow. Furthermore, there is very little difference in hydrostatic head of wells which tap the primary system regardless of their location and depth of penetration. The lack of head change suggests a significant degree of vertical interconnection among the basalts of the area. Currently, the Moscow area derives most of its ground water from the lower or primary system.

In the Lewiston area a significant thickness of Columbia River basalt is present, although complicated by structural deformation. Work by Bond (1963) and later by Camp (1976) revealed the presence of a synclinal basin in the Lewiston area complicated by extensive faulting to the north and south. Within the basin, the upper basalt units are those of the Saddle Mountains and Wanapum basalts both of which are interbedded extensively with sediments. In contrast, lower basalts are units of the Grand Ronde Basalt and generally have little or no interbedded sediments. It is from aquifers associated with these lower basalt units that most of the major ground water production is derived. Production between 1500 and 2000 gpm is not uncommon and Cohen and Ralston (1980, p. 77) report one well pumping in excess of 4000 gpm. Cohen and Ralston (1980), studying the aquifers associated with the Grande Ronde Basalt, grouped the aquifers associated with several vertically separate zones as one system based on similarities in water levels and response to pumping tests. The similarity in heads and response to pumping of these zones indicates a degree of interconnection among vertically separate basalt aquifers noted in other locations.

Despite the geomorphic diversity among these areas along the state's western boundary, significant hydrologic similarities exist. In virtually all locations, sediments are interbedded with basalt flows and normally have low hydrologic conductivity. Ground water production in the sediment is normally available only from the infrequent coarse grain fraction. Research work has resulted in a similar distinction between an upper system and a lower one in most areas. The upper system is often a water table or perched system with the lower one invariabily referred to as confined or at least "artesian." Significant production is most often obtained from the lower system. In addition, water level and pumping data from many of these areas indicates vertical interconnection exists among stratigraphically separated aquifers and that this vertical continuity is more often restricted by sediments or weathered horizons than by individual basalt flows.

Volcanics of the Snake River Plain in Idaho

There is a tendency to refer to the volcanic sequence in southern Idaho as the Snake River basalt. While the Snake River basalt does cover a significant part of southern Idaho, numerous other units are present and, like parts of neighboring Oregon, these units range from silicic volcanics, including rhyolites and dacites, to tuffs and other volcaniclastic rocks, with interbedded sedimentary deposits. These volcanic units are layered much like the basalt sequences of the Snake River plain and can be significant sources of ground water. Therefore, both the layered volcanics and the Snake River basalt merit discussion.

Silicic Volcanics and Related Deposits

Mapping by several workers including Stearns and others (1938), Malde and Powers (1962), and Mundorff and others (1964), reveals the presence of silicic volcanic rocks at various localities around the margin of the Snake River plain (Figure 1). In general, these rocks appear to occupy a stratigraphic position between the Snake River basalt and the pre-Tertiary crystalline and sedimentary rocks which predominat in the highlands and on all sides of the Snake River plain.

Beneath the plain itself, it is not known if these silicic volcanics are present; however, drilling information from the Bruneau area along the Snake River valley about 15-20 miles south of Mountain Home (Ralston and Chapman, 1969), and at Idaho National Engineering Laboratory (INEL) (Nace and others, 1975), indicates silicic volcanics to be present at depth. Work on the Snake River plain led Stearns and others (1938, p. 25) to conclude that locally "there is some evidence that similar (silicic volcanic) rocks extend well under the plain."

It is not known if all silicic volcanic deposits present around the Snake River plain are necessarily stratigraphic equivalents; however, despite age differences which may exist, these volcanics can be significant hydrologically. For purposes of this discussion, it will suffice to delineate a group of silicic volcanics roughly equivalent in age and composition as a basal unit throughout much of the Snake River plain. Composition of this basal unit is highly variable but consists predominantly of thick welded ash flow and vitric tuff deposits with interbedded lava flows. The lavas range in composition from rhyolites and latites to basalts and andesites and vary widely in thickness and distribution. Sediment sequences are also present, mainly gravels, sands and clays formed as local fluvial or lacustrine deposits.

Initial impressions of a welded ash flow and tuff sequence suggest relatively low permeabilities and hence little hydrologic importance. Such an impression is not necessarily correct. In several localities the volcanics have a well-developed system of joints and fractures much like that of lava flows, which permit a relatively high degree of permeability. Ralston and Chapman (1969) report that deep wells in the Bruneau Valley and Little Valley areas near the Snake River Canyon obtain significant irrigation quantities from the silicic volcanic sequence. In some wells, production of 1,500 to 2,000 gpm is obtained. Permeability distribution is highly variable, however, as Nace and others (1975) report little significant production is obtained from silicic volcanic deposits at INEL indicating that permeability distribution is variable. In many locations the presence of highly productive units above these volcanics has precluded their exploration and, as a result, permeability distribution of the silicic volcanics is not well known.

Perhaps of even greater regional significance is the potential for recharge to the Snake River plain hydrologic system through the silicic volcanic rocks. Ralston and Champan (1969, p. 13) believe that the highly jointed and fractured nature of the silicic volcanic rocks exposed in northern Owyhee County allows both horizontal and vertical movement of ground water and is a major source area for recharge to the aquifers in the lowland to the north. Geologic mapping and isoheytal data presented by Mundorff and others (1964) indicate a significant outcrop area of silicic volcanics around the plain with most of it occurring in upland areas where precipitation is considerably higher than on the plain itself. Mundorff and others (1964) report that the overlying Idaho formation is partly recharged by upward leakage and that throughout the entire plain a significant amount of recharge is obtained through underflow from adjacent upland areas.

Between the overlying Snake River basalt and the silicic volcanics there is a sequence of predominantly clastic sedimentary deposits with occasional interbedded basalt flows. This sequence has a variety of units and has been called the Idaho Group by Malde and Powers (1962). Although discussion of individual units within this sequence is beyond the scope of this report, it is worthwhile to mention briefly one of the units, the Banbury Basalt, because of its significance as a ground water source in selected locations.

Malde and Powers (1962) describe three basic units of the Banbury Basalt including a lower unit consisting of several highly weathered basalt flows, a middle sedimentary unit, and an upper unit of several basalt flows which are considerably less weathered than the lower one. Ralston and Chapman (1969) describe a highly weathered Banbury Basalt in the western part of their study area and a much less weathered Banbury Basalt to the east. This relationship is of interest because Ralston and Chapman report ground water yield from the highly weathered sequence in the west is quite low. However, yields as much as 3,800 gpm have been obtained from the less weathered Banbury Basalt to the east. The production difference between the weathered and nonweathered basalt units reveals the importance of the degree of weathering on permeability of the volcanic sequence. A similar relationship between weathering and permeability is evident from other volcanic sequences as well.

With the exception of the Banbury Basalt, most units of this sequence are not significant ground water sources. Locally, however, coarse sand and gravel deposits within sedimentary units can produce substantial quantities of water. Ralston and Chapman (1969) report yields as high as 3,600 gpm from wells tapping these coarse fractions.

Snake River Basalt

Overlying this group of predominantly sedimentary units is the Snake River basalt. The Snake River basalt consists of numerous fresh olivine basalt flows of varying thickness and extent interbedded with lesser amounts of sediments. Individual basalt flows range from just a few to several hundred feet in thickness with an average thickness of perhaps 50 feet. Precise distribution and thickness of the Snake River basalt is not known. Near the margins of the Snake River plain the basalt sequence is thin (often less than 1,000 feet) with considerable interbedded sediment. Near the center of the plain the sequence is presumably much thicker, perhaps on the order of several thousand feet.

Commonly, flows of the Snake River basalt are highly jointed and fractured and exhibit rubbly vesiculated flow tops often with large open spaces present at the contact between flows. The open nature of the Snake River basalt flows makes them quite permeable and the principal source of ground water over much of the plain. The flows are highly permeable both horizontally and vertically and able to receive and transmit water readily. Stearns and others (1938) report specific capacities of 50 gpm/ft as not uncommon and that some have recorded specific capacities as high as 500 gpm/ft. Barraclough and others (1976, p. 48) report that regional horizontal hydraulic conductivity of Snake River basalt determined from pump tests and flow net analysis range from 100 to 10,000 ft/day, and that although vertical conductivities are generally less than horizontal, significant vertical conductivity does exist primarily through vertical fractures. They also report that field tests using gas injection and barometric pressure measurements of a single 100-foot thick basalt flow at the Idaho National Engineering Laboratory, produced average horizontal conductivities of 55 ft/day and vertical conductivities of 15 ft/day (Barraclough and others, 1976, p. 49). Thus, for the particular basalt flow investigated, a ratio of horizontal to vertical conductivities of 3.7 to 1 is obtained. They also mention that similar work on related interbed sediment produced conductivity values about 20 times less than those of the basalt.

Hydrology of the Snake River Plain

The preceding discussion leads to a conceptualization of the Snake River plain geologic framework involving three principle layers. The framework is, in very general terms, a sequence of olivine basalt flows overlying a predominantly sedimentary sequence which in turn overlies silicic volcanics. Although the three groups are thought to be part of the general system of the plain, hydrologic significance of the lower two sequences is apparent only at the western end of the plain and at some locations along the plain margin. Over a large area of the plain the thickness and productive capability of the Snake River basalt has prevented investigation of deeper units. The relationship and extent of all three units is also poorly known.

Water level data compiled by Mundorff and others (1964) illustrates a flow system of the Snake River plain with principal direction of flow to the west and southwest. In locations near the Snake River the contours suggest flow toward the river particularly from those areas lying south of the river. Water level contours from bordering highland areas along the margin of the plain indicate flow, often with a steep gradient, down to the plain generally orthogonal to principle flow direction within the Snake River plain aquifer itself. At the western end of the principal area of basalt deposition, numerous high volume springs discharge into the Snake River. These springs and others along the river to the east are discharging ground water from the Snake River plain system. The nature of this voluminous discharge indicates the high permeability of the basalt aquifers and the very direct relationship between ground and surface water in the Snake River plain.

In the largest area of the plain, that east of the Hagerman-Bliss area, water is obtained in the Snake River basalt with only a relatively few wells penetrating deeper units generally along the margins of the plain. Water level relationships have lead workers (Stearns and others, 1938; Mundorff and others, 1964) to conclude that ground water in the Snake River basalt is generally under water table conditions. Water level contour data presented by Mundorff and others (1964) indicate a relatively flat gradient over much of the plain. The flatness of this gradient is likely a combination of three things: 1) the relatively even topography of the plain, 2) the lack of significant precipitation over much of the plain, and 3) the relative high permeability of the Snake River basalt. Within the plain two areas in which the water table deviates markedly from its normal flat gradient have been studied in some detail and provide a clue to the importance of geological variation upon ground water flow.

Mundorff and others (1964) indicate a steepening of the ground water gradient in the center of the plain. Later work by Crosthwaite (1973) confirms the existence of the steeper gradient and, on the basis of additional data, resulted in some adjustments of water level contour lines in the area. The effect of this contour line adjustment was to produce an even steeper gradient than that previously shown. The cause of this gradient change is not immediately apparent although both Mundorff and others (1964) and Crosthwaite (1973) suggest that it is in response to the presence of the Craters of the Moon "great rift" which transects the area roughly parallel to and coincident with the steepening of the ground water gradient. Such a conclusion seems reasonable as it is expected that such a features as a major rift zone should have some effect upon the ground water flow system. In fact, it seems somewhat surprising that there is not a greater effect. That there is not says, perhaps, that significant water transmission capability still exists within these basalts despite major disruption of horizontal continuity.

The second area, the Mud Lake area, is located in the northeastern end of the Snake River plain. Significant change in gradient was noted as early as 1938 by Stearns and others who referred to it as the Mud Lake barrier. In the Mud Lake area a change in gradient from 5 to 10 ft/mile to 30 to 60 ft/mile occurs in the vicinity of the barrier. Detailed work by Crosthwaite (1973) revealed that no barrier, in the classic sense, exists to impede ground water movement, rather a significant change in geology occurs. The area north and east (upgradient) from the "barrier" is characterized by a significant amount of sediment interbedded within the basalt. Drilling logs from some wells indicate total sediment thickness to be twice that of basalt. South and west of the area, subsurface geology is predominantly basalt. From this, Crosthwaite concluded that the cause of the gradient change was not, in fact, a barrier but the change from a low permeability sediment basalt sequence to a much higher permeability predominantly basalt sequence.

The result of the Mud Lake study reveals the hydrologic significance of interbedded sediments. In general, the sediments have significantly less permeability than the basalt and can markedly affect the movement of ground water both vertically and horizontally.

In other parts of the plain, primarily the southern and western margin and, to a lesser extent, the eastern margin, the Snake River basalt is of less importance hydrologically because it may be quite thin, missing entirely, or above the regional water table. In these areas, ground water production is obtained from the sedimentary and interbedded basalt sequence and the older silicic volcanics which underlie the Snake River basalt.

In many locations, water obtained from these lower units may have a substantially different head than that in the overlying basalt and because of this head difference and differences in geology, there is a tendency to treat each unit as a separate hydrologic system. Despite the differences, however, it seems likely that the three units are part of one basic hydrologic system in which permeability differences associated with changes in flow macrostructure and unit lithology create locally differing hydrologic conditions.

OREGON

Most significant ground water production obtained from layered volcanics in Oregon comes from basalts of the Columbia River group. There is, however, a vast area throughout central and southeastern Oregon (Figure 1) which contains a wide variety of layered volcanics and from which ground water resource development occurs locally. Although the ground water resources of this group of volcanics is not as extensively developed as that of the Columbia River group, the size of the area, the potential for development, and the fact that it is a layered volcanic sequence, make discussion of it necessary.

Columbia River Basalt Group in Oregon

Examination of Figure 1 reveals that principal areas of deposition of the Columbia River basalt are along the state's northern border in the Columbia River Gorge, and in the north-central and northeastern part of the state. Columbia River basalt is also present in the Willamette Valley and the Deschutes Valley; however, in these locations the basalt is often interbedded with extensive sedimentary deposits and other layered volcanic sequences.

For reasons of geology, topography, climate, and landownership, significant use of the ground water resources from the Columbia River basalt is restricted primarily to locations along the Columbia River and some locations within the Willamette Valley. Ground water resource development has occurred extensively in the Boardman-Umatilla area in north-central Oregon, and in the Willamette Valley, particularly southwest of Portland in the Tualatin area. Some ground water development from the Columbia River group has also taken place in The Dalles area and it is the primary source for The Dalles municipal supply. Ground water development from Columbia River basalt has also taken place in the Milton-Freewater area in northeastern Oregon. The Milton-Freewater area is not of great areal extent, but it is part of the Walla Walla drainage basin from which considerable ground water withdrawal occurs in nearby Washington. Ground water is also obtained from Columbia River basalt in the Grande Ronde Valley in extreme northeastern Oregon. Most production in the area is for domestic and stock purposes and withdrawal is relatively limited.

In the Tualatin River valley near Portland, Columbia River basalt occurs on the surface in the basin sides and in the subsurface near the basin's center. Hart and Newcomb (1965) report the Columbia River basalt to be a significant source of ground water. Numerous wells exist in the area and while most are for domestic purposes and produce 50 gpm or less, a few irrigation and municipal wells produce as much as 500 gpm. The high production wells are drilled into Columbia River basalt and Hart and Newcomb (1965, p. 35) report that "at present, only wells in Columbia River basalt have yields greater than 200 gpm."

The basalt often appears to have a poorer production capacity than might reasonably be expected within the valley. The Tualatin area is, however, heavily dissected and contains some structural complications which tend to disrupt lateral continuity of aquifers. Production from the basalt in these dissected areas is more variable than it is in areas where the basalts are more uniformly distributed.

Another cause of variable production appears to be the extent of weathering on the basalt surface. Hart and Newcomb (p. 17) report that the basalt surface is often extensively weathered, finding as much as the upper 200 feet weathered to a lateritic soil. They suggest (p. 34) that one of the reasons for poor production from some basalt wells is that some of the wells may not have penetrated the basalt fully enough to test their true productive capability.

Hart and Newcomb did not speculate on the effect of this weathering zone on recharge but it is likely that weathering has a significant effect on permeability, both horizontal and vertical, of basalt flows. Investigation by Price (1967) in the French Prairie area appears to support this concept as he states (p. 18) that "such factors as fracturing, weathering, secondary mineralization, and structural deformation greatly affect the permeability of both the flow layers and interflow zones." In some locations it is likely that perched conditions are present because of weathering of the underlying basalt flow.

The Tualatin area also contains a sequence of younger basalt flows known as the Boring lava. Hart and Newcomb (p. 35) report that the Boring lava is similar to Columbia River basalt "but its flows are more irregularly layered than those of the older basalt." The irregular layering apparently results in significantly less permeability. The Boring lava is also often above the water table and contains only perched ground water in these circumstances.

The most significant development of ground water from the Columbia River basalt has occurred in the Boardman-Umatilla area in eastern Oregon. Here, extensive well irrigation begun in the late 1950s and early 1960s has created water level decline problems in some locations and resulted in a substantial amount of investigation into the nature and occurrence of ground water in the area.

Early work by Hogenson (1964) revealed the importance of the Columbia River basalt as a significant source of ground water, noting that some early irrigation wells in the area produced 1,500 to 2,000 gpm from basalt aquifers. Hogenson noticed an apparent complicated head relationship in many of the wells and suggested (1964, p. 37) that each water-bearing zone might have its own water table. He used this multi-head concept to explain changes in hydrostatic head with depth noted in the drilling of many wells. He also stressed the importance of topography on water level and on production capabilities, noting that wells in the upland areas generally had lower heads and poorer production than those in the lowland. An apparent abundance of flowing wells associated with a synclinal warp led him to suggest a relationship between structure and ground water hydrology (1964, p. 39). Hogenson's work reveals many similarities in basalt hydrologic characteristics with those of other areas including the occurrence of perched water zones associated with sediments or weathered zones in the basalts.

Robison (1971) also noted a variety of water levels in wells in the Umatilla-Boardman area and attributed it to lack of vertical interconnection among the basalt flows. The variety of heads made it difficult to produce the water level contour map; however, he felt that the flat gradient in the deeper zones and water level elevations in some wells adjacent to the Columbia River being below river level indicated little active flow in the system. Differences in carbon 14 dates from three wells, led him to suggest that three distinct hydrologic zones exist and are, in essence, stratified.

Recent work by the Department of Water Resources produces a somewhat different conclusion. Water level contours based on extensive well measurement indicate a general gradient towards the Columbia River and although the gradient flattens, it still slopes about 25 feet per mile to the river. The gradient changes appear to be coincident with a similar change in regional slope, a situation similar to that noted in other areas of the Columbia Plateau. Data collected by Department of Water Resources personnel indicate ages of all water sampled in the northern half of the area to be in excess of 22,000 years, suggesting that discharge is taking place at or near the river. Such a situation seems to be confirmed by water level data obtained from wells in the area (Oberlander, personal communication).

Initially, there seemed to be rather anomalous conditions in the Umatilla-Boardman area, but it now appears that the conditions are similar to those in the other areas in the state and elsewhere in the plateau. There appears to be significant similarity between the Boardman-Umatilla area and the Horse Heaven Hills area in Washington immediately across the Columbia River. The Saddle Mountain basalt is the youngest sequence present and although the section is somewhat thinner in Oregon, interbedded sediments are present. Significant production seems to come from deeper in the section from units of the Wanapum and, in Oregon, from the Grande Ronde basalt. Although the relationship between stratigraphy and hydrostatic head is less certain in the Oregon area, it does appear that the interbeds play a role in controlling vertical permeability similar to that described by the author (1978) for the Horse Heaven Hills area in Washington.

Virtually all areas in Oregon in which water is obtained from basalts have general similarities. Production is nearly always obtained from the basalts rather than from interbed sediments. The sediments and/or weathered basalt surface can act as perching layers on which small bodies of ground water can be located, or as a confining layer under which water in the basalt can be under significant pressure. Finally, it appears that ground water flow is controlled principally by topography with recharging conditions in the upland and discharge in the corresponding lowland areas.

Other Layered Volcanics in Oregon

The stratigraphy of the large area of layered volcanics in central Oregon is complex. It consists primarily of sequences of volcaniclatic rocks, often ash flow tuffs and tuff breccias with interbedded sediments and lava flows. Lava flows are commonly basaltic and andesitic but silicic volcanics includng rhyolites are also present. Russell (1905) reports that rhyolite and rhyolitic tuffs are the most common surface rocks in Malheur and Harney counties in southeastern Oregon. To the west, basalt predominates "although much eroded andesitic mountains or buttes and widely extended sheets of tuff of the same general nature are present" (Russell, p. 29). Russell continues to describe geologic relationships in central Oregon saying:

> Basalt occupies the surface throughout nearly all of the region bordering the Great Sandy Desert and throughout the extensive tract of country in the western portion of Crook County drained by the Deschutes River. To a conspicuous extent, as shown in the canyons of the streams, it occurs in comparatively thin sheets resting on lacustral deposits or beds of stratified volcanic tuff. The canyon walls are margined above by black cliffs or rim rocks of basalt forming eroded margins of sheets which in general are 80 to 125 feet thick. The basalt occurs as widely extended sheets, usually, it is presumed, of Tertiary age, which cannot be traced to the craters from which they came, and also as much later flows of a similar character, which in part occupy canyons cut in older basalt and underlying gravels, sands, and tuffs, and in many instances bear a definite and determinable relation to volcanic craters which still preserve their constructional forms.

From Russell's admirable description of central Oregon geology and geomorphology, it is apparent that conditions differ somewhat from either the Columbia Plateau or the Snake River plain. The principal differences are that unlike either the Columbia Plateau or the Snake River plain, the layered volcanic sequence in central Oregon has a much greater abundance of pyroclastic and related sedimentary deposits, and that structure, erosion, and depositional sequence have produced a dissruption of lateral continuity in many locations.

Most of the wells available for Russell's reconnaissanc consisted of dug or drilled wells into alluvial sediments in many of the valley areas. As the demand was for domestic and stock use, production from the sediments was generally sufficient. Russell does report occurrence of springs issuing at the base of a basalt flow which suggests the perching nature of underlying sediments.

Later work by Stearns (1930) in the Deschutes River Basin indicates that the basalts and/or andesites are the most consistent ground water producers in the area studied. He reports numerous high yield springs which issue at flow contacts within a basalt sequence. Analysis of his report suggests that even though basalts are the best producing lithology, they are highly variable, with production depending upon thickness of sequence, lateral extent, nature of over and underlying units, and on fracturing and vesiculation of the flow itself.

Discussion of the Fort Rock basin by Hampton (1964) indicates similar geologic and hydrologic conditions to those elsewhere in central Oregon. He reports the tuff units to be generally poor producers but that yields in excess of 4,000 gpm have been obtained from wells tapping the Fort Rock basalt.

In the Cow Valley, younger olivine basalts are an important ground water source in apparent connection with overlying sedimentary zones. Here a sequence of medium to coarse grained sediments overly a sequence of basalt flows. Foxworthy (1961) notes that both the sediments and the basalt can be good ground water sources and that similarity in water levels from wells penetrating only sediments with those cased into basalt indicate good hydraulic interconnection between the two sequences. This interconnection suggests that individual basalt flows have relatively good vertical permeability in the area.

Basalt and other layered volcanic sequences in central Oregon are similar to units in the Snake River plain and in the Columbia Plateau. The principal differences stem from the isolated nature of the basalts both in the vertical stratigraphic section and in areal distribution. Where a substantial thickness of extrusive volcanics exist with adequate distribution, they seem to have generally good productive capabilities. When, however, they occur as isolated flows of limited areal extent sandwiched between less permeable pyroclastic and sedimentary units, they are noticeably less productive. Often the interbeds will act as aquitards or perching horizons to water moving through the more permeable overlying extrusive volcanic flow.

WASHINGTON

Development of ground water resources from layered volcanics in Washington State is almost exclusively from the Columbia River basalt group. For this reason the discussion is devoted almost exclusively to hydrologic investigations of this group. A brief discussion is included on general hydrologic properties of some of the other layered volcanics where attempts have been made to use them as ground water sources.

Columbia River Basalt Group in Washington

Examination of Figure 1 reveals that the greatest areal distribution of the Columbia Plateau flood basalts occurs in Washington. Much of the plateau in Washington is level, readily farmed, and receives only minor amounts of natural precipitation. These circumstances have led to development of extensive irrigated agriculture with much of the water being obtained from the layered basalts of the Columbia River basalt group.

The extensive development has necessitated considerable study of the basalts and related ground water hydrology.

Much of the early work involved basic collection of geologic and hydrologic data on an area or county-wide basis. Areas studied include Whitman County (Walters and Glancy, 1969; Foxworthy and Washburn, 1963), Walla Walla County (Newcomb, 1964), the Odessa area (Garrett, 1968), parts of Yakima County (Foxworthy, 1962), and more recently, Klickitat County (Brown, 1979a). Another study phase involved development of digital ground water model simulation for selected areas including the Odessa-Lind area (Luzier and Skrivan, 1975), the Walla Walla basin (MacNish and Barker, 1976), the Columbia Basin Irrigation Project (Tanaka and others, 1974), the Moxee-Ahtanum area near Yakima (Cearlock and others, 1975), and the Pullman area (Barker, 1979).

Throughout its wide areal distribution in Washington, the Columbia River basalt exhibits a significant amount of geologic diversity and, at the same time, considerable hydrologic consistency. In the western part of the plateau within Washington, reconnaissance mapping by Swanson and others (1979a) and detailed work by Bond and others (1978) indicate that flows of the younger formations of the Columbia River group, the Wanapum and Saddle Mountains basalt, are present at or near the surface. Further east and north, these younger units gradually thin and/or disappear and units of the older Grande Ronde basalt are often exposed. Around the margin of the plateau, sedimentary deposits are often interbedded with basalt flows, particularly in the west where extensive interbeds are present between individual flows of the Saddle Mountains basalt. In some areas (e.g. Yakima River Valley) these interbeds can reach a thickness of 500 feet or more.

The proximity of the western part of the plateau to the Cascade Mountains has resulted in significant tectonic deformation of the layered basalt sequence in that area. Numerous large-scale anticlines, often associated with thrust faulting (Bentley, 1977), produce topographically prominent ridges with related synclines producing lowlying valley areas. Thus, much of the western part of the plateau in Washington is broken into a series of basins separated by major ground water divides associated with these structurally caused topographic prominences. Much of the new ground water development for the basalts in Washington is occurring in these basin and ridge areas specifically in the lower Yakima River Valley and the Horse Heaven Hills to the south.

Borehole geophysics obtained from deep wells in the lower Yakima Valley reveal the distribution of subsurface basalt units and related sedimentary interbeds (Lobdell and Brown, 1977). Drilling and production data indicate that despite a significant thickness of sedimentary units, basalt units are consistently better producers. Earlier work by Foxworthy (1962) indicates a similar situation exists in the Ahtanum Valley west of Yakima. Although various sediments are capable of producing irrigation quantities, Foxworthy (p. 36) states that the "basalt sequence contains the most productive aquifers in the Ahtanum Valley."

The importance of the basalt aquifers in these areas of interbedded basalts and sediments appears substantiated by information from the area around Pasco and in the Horse Heaven Hills. Ground water production information is generally lacking in the Pasco basin because much of the irrigation is from surface water sources and a large part of the basin is federal reservation which has not been developed. Available information indicates that basalts interbedded with sediments, predominantly those of the Saddle Mountains basalt, are less productive than the underlying Wanapum basalt. A few irrigation wells have been drilled into the upper part of the Wanapum in the northwestern part of the Pasco basin and are quite productive (Gephart and others, 1979) and Brown (1979) concludes that the aquifer associated with the upper part of the Wanapum basalt may be one of the more important aquifers in the Pasco basin.

A similar hydrologic situation appears to be present in the Horse Heaven Hills. Virtually all significant production comes from units in the Wanapum with units of the Saddle Mountains basalt and related interbedded sediment producing only domestic quantities, often from water perched on the sedimentary layers. The importance of one of the interbeds and the basalt flow immediately underlying it in controlling vertical head distribution and acting as a confining member in certain locations within the Horse Heaven Hills has been documented by Brown (1978).

The importance of sedimentary interbeds as perching horizons and aquitards is not restricted to the western part of the plateau. Work by Bush and others (1972), Brown (1978, 1979a), and by Barker (1979) reveals that sedimentary interbeds and/or related saprolitic zones have a similar effect upon the basalt hydrologic system throughout the plateau.

In the central and eastern parts of the plateau, the basalt sequence is virtually uninterrupted by interbedded sediments. With the exception of near-margin areas where sediments associated with erosion of adjacent highlands are interbedded with basalt flows, only one significant interbed is present throughout much of the central plateau region. This interbed varies in thickness and is located between the Wanapum and Grande Ronde basalt sequences. In some locations only a weathered saprolitic horizon on top of the uppermost Grande Ronde flow is present (Swanson and Wright, 1976).

Throughout much of the central and eastern parts of the plateau, significant ground water production is obtained from aquifers associated with flows of the Grande Ronde basalt. In some cases deep wells (2,500 ft) have been drilled and the upper 1,500 feet cased off. Production data from these wells generally indicate that good production is available from basalt units deep in the Grande Ronde as well as those closer to the surface. Production from the Grande Ronde in the eastern part of the plateau is similar to that obtained from the younger Wanapum basalt in the western part.

Traditionally, there has been a tendency to view basalt aquifers as operating independently of each other because of assumed low permeability of the basalt flow centers. Work by Brown (1979b) indicates, however, that such a view may not be correct. Analysis of subsurface stratigraphies and hydrostatic head data from various locations throughout the plateau reveals strong head similarities among various aquifers separated by substantial vertical distances. This relationship leads to a conclusion that a higher degree of vertical interconnection exists in the Columbia River basalt than previously thought and that, despite aquifer separation, a vertical sequence of several basalt flows acts as a single hydrologic system. The work also indicates that when major head changes occur, they are most often associated with interbeds and/or weathered horizons, suggesting that it is those zones and not the basalts which have low vertical conductivities. The apparent vertical interconnection of several separated aquifers is also noted in modeling efforts in the Walla Walla (MacNish and Barker, 1976) and Pullman areas (Barker, 1979).

Basalt ground water systems have long been thought to be made up of a series of confined aquifers. The concept developed from the idea of the low vertical permeability of the massive basalt flow center and from storage coefficients developed from short-term pump tests. This conceptualization presented problems as it required exposure of permeable aquifer zones at the surface for recharge and suggested that significant head differences should exist among vertically separated zones.

Water level data presented for the Goldendale area in the extreme western part of the plateau (Brown, 1979a) indicate a surface that closely mirrors overlying topography, suggestive of a water table configuration. Water level data used to construct the contour surface came from wells varying in depth which penetrated a variety of basalt flows and related interflow zones. Storage coefficients determined from volumetric analysis in the Odessa area (Luzier and Burt, 1974) are on the order of 10^{-3} which are at least intermediate between water table and confined storage coefficients. This information indicates that while the basalt of the Columbia River group exhibits some properties of classic confined systems, the hydrologic system appears to act much more like a water table system than previously thought. Data indicate that recharge to the system is not restricted to locations where permeable interflow zones are exposed at the surface, but can occur vertically through the flow.

Other Layered Volcanics in Washington

In addition to basalts of the Columbia River group, other volcanics are present within the state, although less significant hydrologically. The other volcanics consist primarily of older volcanic and volcaniclastic rock of the central Cascade Mountains (Figure 1) and the more recent olivine basalt and andesites associated with late eruptive stages of the Cascades. These units are restricted to the rugged areas of the central Cascade Mountains and there has been little investigation of their ground water potential.

The older volcanic and volcaniclastic rocks consist primarily of thick sequences of tuffs and tuff breccias with some interbedded basalt and andesite flows. Little is known about their productive capability although, based on what little information was available in south-central Washington, Brown (1979a) concluded that they were relatively impermeable and had limited productive capability. Like other layered volcanic sequences, however, fracture permeability is important and in areas where sufficient permeability is present the units could have significant productive potential.

The recent basalts and andesites are likewise restricted primarily to the central Cascades area, and are generally of limited extent, often consisting of channel filling flows or flows covering small areas around local eruption centers. In south-central Washington, however, the Simcoe Mountain Volcanics (Sheppard, 1967) cover an area near Goldendale, Washington, and several wells, primarily domestic, have been drilled into these volcanics. The Simcoe Mountain Volcanics consist primarily of olivine basalt flows which are thin and highly variable in distribution. Production from these basalts is generally poor with most significant production coming from coarse sediments which underlie the basalts in some locations.

Reports of water in wells drilled into the Simcoe Mountain basalt becoming turbid following heavy rains suggests the units might have a high degree of vertical permeability. Furthermore, local large volume springs issue from these younger volcanics and lava tubes and similar features are present. The nature, occurrence, and waterbearing properties of these younger volcanics indicate significant hydrologic similarity between these volcanics and the basalt of the Snake River plain in Idaho.

COMPARISON OF HYDROLOGIC PROPERTIES OF LAYERED VOLCANIC SEQUENCES

Figure 1 illustrates the general distribution of layered volcanic groups in the three-state area. These volcanics include tuff breccias and interbedded lavas of the Cascades; Columbia River basalt; silic, latitic, basaltic lavas and associated pyroclastic deposits of central Oregon and southern Idaho; and the Snake River basalt and other recent olivine basalt and andesite flows. Because these layered volcanics often occur in areas of low precipitation, they are an important source of ground water and knowledge about the nature and occurrence of ground water in the layered volcanics is essential to ensure its proper utilization.

The layered flows of basaltic and andesitic composition appear to be most significant in terms of ground water production for several reasons. First, in terms of sheer area and volume, basalt and andesites far exceed that of other volcanics. The Columbia River group alone covers 250,000 mi^2 with an average depth of perhaps 4,000 feet. Secondly, much of the area covered by basalts is relatively stable tectonically and is mild climatically. Thus, they provide a large expanse of relatively flat land suitable for agricultural development and ground water development in these agricultural areas is extensive.

Thirdly, differences are apparent in waterbearing properties in basalts and andesites versus those of the silicic volcanics. Although conditions vary markedly among flows, rhyolitic and latitic flows have less well developed primary jointing and lack the thick scoriaceous and open contact zones more typical of basic flows. Permeability in the silicic volcanics is more dependent upon secondary jointing and fracturing which is more highly variable in distribution than primary features.

Finally, the relationship of layered volcanics to pyroclastic and sedimentary deposits is of hydrologic significance. Extrusion of many of the basic sequences was apparently much more continuous than corresponding silicic volcanics and, in many areas, successive layers of basalt and/or andesite have been deposited with little or no interbedded sedimentary or pyroclastic material. In contrast, silicic volcanism appears to have been more sporadic with occasional eruptions separated by extensive deposits of tuffs, tuff breccias, welded ash flows and fluvial and lacustrine sediments. These pyroclastic and sedimentary deposits generally have significantly less permeability than the layered volcanics and thus production from these sequences is much less consistent than that from the layered basalt and andesitic ones.

Thus, discussion of comparative hydrologic properties of the layered volcanics in the three states is in reality a comparison of the Columbia River basalt with the younger basalts of the Snake River plain. Many of the features of the Snake River basalt are, however, also apparent in the younger olivine basalts and andesites of the Cascades and other locations in Oregon, Washington, and Idaho.

For many years the most striking feature of the Columbia River group was the "sameness" of the thick basalt flow sequence, and geologists were quick to notice the differences between these basalts and the olivine basalt characteristics of the Snake River plain and Cascade Mountains. Not only do the olivine basalts differ from the Columbia River group petrologically and chemically, but there are generally noticeable physical differences as well. Olivine basalt flows of the Snake River plain and of the Cascades generally exhibit a fresher appearance and normally occur as relatively thin flows of limited extent. Jones (1970) indicates that the basalts of the Snake River plain were erupted from point sources (shield volcanoes) rather than from linear fissures typical of Columbia River basalt sources. He reports (p. 219) that many flows of Snake River basalt are local and confined to slopes and the immediate vicinity of the parent volcano. Leeman and Vitaliano (1976, p. 1777) report the McKinney basalt of the Snake River plain covers approximately 300 km^2 (116 mi^2) in flows from 5 to 10 m (16 to 33 ft.) thick. Thickness of these flows can be greater when ponded or filling old channels. Flows are often distributed in a liner fashion, filling erosion channels on the axes of saddles between adjacent volcanoes. In addition, the general thinness of individual flows prevents formation of a noticeable jointed colonnade and entablature typical of Columbia River basalt.

Work by Sheppard (1960) indicates many of these characteristics of Snake River plain and other younger basalts to be evident in the olivine basalts of the Simcoe Mountains in southern Washington. He reports numerous flows of limited areal extent averaging between 15-20 feet in thickness. Newcomb (1961) reports average flow thickness of the Columbia River basalt of about 50 feet; however, at least in the area of significant ground water development, this average may be closer to 100 feet. Swanson and others (1975) illustrate the voluminous nature of Columbia River basalt extrusion and report that at least some individual flows cover thousands of square miles.

Walker (1969) presents a brief comparison of basalt units in Oregon with those of the Columbia River basalt, (p. 227-229):

> Although prebasalt relief was as much as several thousand feet and quite rugged in parts of southeast Oregon, the basaltic eruptions ponded infrequently so that thick, individual flows are rare or absent. In contrast to the 50- to 100-foot-thick flows of both the Picture Gorge and Yakima basalts, most flows are less than 20 feet thick and many are only 5 to 10 feet thick. Some flow sequences exposed on high fault scarps, such as at Abert Rim, Poker Jim Ridge on the northeast side of Warner Valley, and Steens Mountain, consist of more than 100 flows stacked one above another with little intervening clastic material. Few of the flows display well-developed columnar jointing, which characterizes so many of the flows of the Columbia River group, although flow-jointing parallel to flow surfaces is prominent locally, particularly in somewhat more silicic units that are transitional in composition between basalt and basaltic andesite. Zones of red, iron-stained clinkery and scoriaceous material occur between some flows, and some lenses of baked tuffaceous sediments are present locally, but in many thick sections the flows rest directly upon another, suggesting rapid accumulation. In some areas characterized by numerous and closely spaced normal faults and tilted

> fault blocks, petrographically identical flows are conformable in one block and discordant in adjoining blocks, indicating significant deformation contemporaneous with eruption. Peperites and pillow-palagonite complexes are rare in southeast Oregon in middle and late Tertiary basaltic piles, except along the southern margin of the Picture Gorge basalt in the vicinity of the Maury Mountains; such rocks are abundant, however, in some of the latest Tertiary and Quaternary rocks of southeast Oregon.

The younger olivine basalt lavas were apparently more viscous than those of the Columbia River group, and exhibit markedly different flow characteristics. Both basalts are normally jointed and fractured, but the olivine basalt commonly are quite rubbly and vesiculated throughout. In addition, open lava tubes are often present in the younger basalts while evidence of lava tubes in the Columbia River basalt has yet to be reported.

Although little actual comparative work has been done, the significant physical differences between the younger basalts and those of the Columbia River group has created a general feeling that there must be significant hydrologic differences between them as well. In part, the feeling was a logical outgrowth of what has been perceived as the nature of basalt ground water flow systems. Early investigation of Columbia River basalt ground water hydrology suggested that individual basalt flows were nearly impermeable and this significantly impeded ground water movement between flows. As a result, a conceptualization of a series of isolated confined aquifers associated with porous and permeable interflow zones developed.

No similar conceptualization evolved for the most significant occurrence of olivine basalts, that in the Snake River plain. Here, the highly fractured and vesiculated nature and the generally limited extent and thickness of individual flows indicated high permeability. Thus, early workers like Stearns and others (1938), recognized the hydrologic system of the Snake River plain basalts to be basically a water table one with good interconnection among vertical sequences of flows.

Recent work on Columbia River basalt hydrology (Brown, 1978, 1979b; Barker, 1979; MacNish and Barker, 1976) has indicated that previous conceptualizations of dense impermeable basalt flows and isolated aquifers may not be correct. Hydrostatic head relationships studied by Brown (1979b) indicate that a fair degree of vertical interconnection does exist through a sequence of several basalt flows. Rather than occurring across basalt flows, major head changes appear to occur across stratigraphic intervals associated with sedimentary interbeds and/or weathered saprolitic horizons on related basalt flows. Brown also suggests that in many locations a water table system exists in the basalt with confined conditions often occuring at depth as a result of the presence of sedimentary and/or saprolitic horizons. Such a situation appears to exist in the Pullman area as described by Barker (1979) and Brown (1980).

Although there is a dearth of information on hydrologic parameters of many of the younger basalts, particularly those within the State of Oregon, considerable study has been done of the Snake River basalts. Thus, comparison of hydrologic parameters of the Snake River plain with those of Columbia River basalts might prove useful in studying the consistency and/or variability of layered volcanic hydraulic systems.

Previous discussion has illuminated basic physical and chemical differences between Columbia River basalt and that of the Snake River plain, yet in spite of these differences there is noticeable hydrologic similarity. Mundorff and others (1964) report the results of porosity tests made on basalt of the Snake River plain. Porosities of basalt samples collected from high volume spring discharge areas in the Snake River valley ranged from 3.8 to 24.8 percent while samples from borehole cores yielded porosities of 3.8 to 37.4 percent (Mundorff and others, 1964, p. 158). Samples from the spring discharge site were tested only for interconnected pore space while those from the boreholes were tested for total porosity. Mundorff and others (1964, p. 158) state that the core samples were taken "at regular five-foot intervals from holes 50-100 feet deep to get representative samples of the basalt between interflow zones." This statement suggests that the interflow zones were not sampled and it is likely that significantly higher porosity values would have been obtained from these horizons.

Porosity information from Columbia River basalts indicates similar variation to that of the Snake River basalts. Agapito and others (1977) report porosities of 0.6 to 13 percent from 14 samples collected and porosity on five core samples in the Pasco basin ranged from 2.1 to 25.4 percent. Poeter (1980) reports porosity measurements made at varying intervals for a 600-foot section of a core in the Columbia River basalt. Porosity values ranged from less than one percent in the massive part of the basalt flow to more than 60 percent near the interflow zones.

Comparison of porosity information from these two groups of basalts indicate a general similarity of range of values, although the data does not allow comparision of statistically weighted values. It is quite possible that because of the difference of thickness and character of the two flow groups, mean porosities of the flow centers of Snake River basalt might be slightly higher than those of Columbia River basalt; however, these porosity measurement indicate porosities of the two groups to be of similar ranges.

Analysis of permeability information also provides for interesting comparison. Both the Snake River and Columbia River basalts are known to be highly productive sources of ground water. Mundorff and others (1964, p. 159) report an average transmissivity determined in 33 pumping tests of 5×10^6 gpd ft (6.7×10^5 ft^2/day). They also report (p. 158) that laboratory measurements produced permeabilities from 4×10^{-4} to .9 gpd/ft^2 (5×10^{-5} - 1.2×10^{-4} ft/day) with an average of .14 gpd/ft^2 (1.9×10^{-10} ft/day). They note that this contrasts markedly with an average aquifer permeability of 2×10^4 gpd/ft^2 (2.6×10^3 ft/day) obtained from aquifer tests. Barraclough and others (1976) indicate that on a regional scale, horizontal conductivities range from 10^2 to 10^4 ft/day. Analysis of a particular basalt flow produced average horizontal conductivity of 55 ft/day and an average vertical conductivity of 15 ft/day.

Data from the basalts of the Columbia River group indicate that generally conductivities are somewhat less than those of the Snake River plain. Drill-stem testing in small diameter boreholes (La Sala and Doty, 1971; Apps and others, 1979) yield conductivities similar to those obtained from the laboratory tests on Snake River plain basalt mentioned above. Although there has been no real attempt to determine permeabilities of the Columbia River basalt on a regional scale, estimates based on specific capacity data and well depth suggest values ranging from 1 to 100 ft/day might be reasonable.

It is apparent that the basalts of the Snake River plain have generally higher permeabilities than those of the Columbia plateau. Such a conclusion seems reasonable, particularly in light of the occurrence of lava tubes and other open spaces in the Snake River basalts which are not in the Columbia River basalt. Although there is little information available on hydrologic characteristics of olivine basalts and other younger basalts in the Northwest, it seems likely, based upon the physical similarity of the flows with those of the Snake River basalts, that they may share comparable permeabilities.

One indication of the higher permeability of the younger basalt is present in the relationship between ground water and surface water. Basalts of the Snake River plain are well known for massive spring discharge along the Snake River canyon and for the effects of surface diversion on ground water levels. Stearns and others (1938) documented the effect on spring flow of surface irrigation development and Mundorff (1967) has studied the surface water/ground water relationship in the American Falls area.

Examination of younger basalts in other areas indicate a similar immediacy of interaction between ground and surface water. Stearns (1930) describes numerous high volume springs virtually all issuing from olivine basalts and/or andesites in the Deschutes and Crook River Canyon, Oregon. Large volume springs issuing from young olivine basalts are also present in the upper Klickitat River Canyon in Washington (Brown, 1979a; Cline 1976).

Large volume springs in the Columbia River basalt are rare. Furthermore, changes in surface water levels often do not always affect immediate change in nearby wells as evidenced in wells near the Columbia River in The Dalles, Oregon (Newcomb, 1969, p. 196). The difference in response to surface water changes between the Columbia River and younger layered basalts is probably a result of permeability differences of the two basalt groups. The lack of large capacity springs in Columbia River basalt may indicate lower but more uniform permeability distribution and thus a more uniform discharge.

Although there appears to be some difference in permeability distribution between younger basalts and those of the Columbia River group, there does appear to be a greater similarity particularly in the vertical component than previously thought. Recent work indicates that basalts of the Columbia River group have a relatively high degree of vertical interconnection, and that vertical movement through basalt flows is significant.

Work on other basalt sequences in the tri-state area indicate a similar importance of vertical permeability. Stearns (1930, p. 199-200) reports that tunnels constructed to maximize spring yield from a set of springs in the Crooked River Canyon revealed the water was not moving horizontally along the flow contact from which it issues, rather the tunnels

> "Follow the water southwestward and usually rise along joints to the contact above, indicating that much of the water issuing from the contact of the first and second flows has dropped a short distance back of the canyon wall from the contact between the second and third flows."

The situation as described by Stearns indicates vertical permeability through the basalt flows sufficient to sustain a spring flow of 20 cfs. This situation indicates not only the relatively good vertical permeability of the basalt flows but also indicates the unconfined nature of the flow system.

The vertical permeability in the Snake River plain basalts is apparent from studies conducted by Barraclough and others (1965). In a well, two zones separated by a single basalt flow were isolated from each other and the rest of the well by a series of packers. Trace ejector tests and water level measurements indicated that heads in the lower zone were .03 to .07 feet lower than that in the upper zone. Monitoring of water levels in these two zones for a year revealed that in spite of the head differences, the two zones responded identically to barometric and other effects indicating that the zones were not isolated from each other. Thus, despite permeability differences which may exist, it is evident that many of the layered volcanic sequences behave similarly, particularly in the movement of water vertically through individual units.

Comparisons of pump test data from the two areas provide information on storage coefficients. Storage coefficients obtained from pump tests in the Columbia River group are generally on the order of 10^{-4} and 10^{-5} (La Sala and Doty, 171; Gephart and others, 1979), and those values are often used as evidence of the confined nature of the system. Similarly, pump tests on the Snake River plain yield storage coefficients normally associated with confined conditions, although not as low as those obtained from Columbia River basalt. Mundorff and others (1964, p. 156) report storage coefficient calculated from time drawdown data to be on the order of 10^{-2} to 10^{-3}. They note, however, that storage coefficients calculated from distance drawdown data are higher and that with increasing length of testing time the storage coefficient increases with resulting coefficients of 10^{-1} to 10^{-2} more typical of water table conditions. They (p. 158) calculate an averge coefficient of .04 based on 18 separate pump tests and attribute the increase in storage coefficient with time to increased leakage from the overlying basalt. They state that the aquifer "then acts as a water table aquifer, and the coefficient of storage is the average coefficient of the material dewatered" (p. 159-160).

Work by Luzier and Burt (1974) in the Columbia plateau indicates similar conditions exist in the Columbia River basalt. They determined storage coefficients based on total drawdown over an entire pumping season and obtained values several orders of magnitude higher than those obtained through short-term pump tests. Barker (1979) used coefficients of the same scale (.005-.006) in his model of the Pullman area. He found, however, that in order to match water level decline curves in the most recent years, it was necessary to increase storage coefficients to .075 to account for dewatering of the primary aquifer. Barker (p. 67) states

> "The storage coefficient of a typical sedimentary aquifer under water table conditions is a functon almost entirely of gravity drainage, as only a small part of the yield from such an aquifer comes from compression of the aquifer and expansion of the water. However, when water is released from or taken into storage in a basalt aquifer system under water table conditions, the process becomes more complicated because of the heterogeneous nature of the joint and cavity structures within a basalt sequence. As a result, the storage coefficients of unconfined basalt aquifers are generally somewhat lower than the values commonly quoted for other nonartesian aquifers, such as the 0.1-0.3 values of Lohman (1972)."

Two things become apparent from comparison of storage coefficient data of the Columbia River and Snake River plain basalts. First, long-term storage coefficients are more indicative of water table rather than confined conditions which seems to agree more closely with the conceptualization of the systems as operating similar to water table systems. Secondly, although some variation in storage coefficients between the two areas is evident, values from each are not significantly different, suggesting that storage characteristics of the basalts may be similar.

In addition to comparison of the various hydrologic parameters, the nature of similarities and differences of the layered volcanics in the three-state area is apparent from the rock units themselves. Despite differences in chemistry, thickness, and extent, most of these volcanics are layered and as such share that similarity. In many locations they are interbedded with pyroclastic or sedimentary units of varying thickness and most all possess a varying degree of fractures and joints, both primary and secondary.

Early in the study of the Snake River plain the importance of sedimentary interbeds was recognized. Stearns and others (1938) felt the interbeds were important low permeability layers in the otherwise quite permeable basalt. Later work by Crosthwaite (1973) revealed the importance of these interbeds in the flow system near Mud Lake. In addition, the importance of the interbed as perching horizons in the Snake River plain has long been recognized. Work by Hogenson (1964), Stearns (1930), and Hart and Newcomb (1965) indicate that sediments interbedded among Columbia River and younger basalt flows produce similar effects as those described on the Snake River plain.

Until recently, the hydraulic importance of the sedimentary interbeds of the Columbia River basalt in Washington was perhaps not as well recognized. The basalt flows themselves were thought to be low permeability horizons in eastern Washington. Work by Brown (1979b) indicates that it is the interbeds rather than the basalts which significantly restrict ground water movement. The importance of the interbeds as perching horizons is also becoming apparent.

Weathering of basalt flows also appears to be important. Stearns and others (1938) report part of Thousand Springs is issuing along a contact of a fresh basalt flow with the weathered Banbury basalt. Brown (1979b) indicates that weathered saprolitic horizons, often associated with sedimentary interbeds, have significant control over vertical permeability. Work in Oregon and in northern Idaho also reveals the importance of weathering on permeability of the basalts.

It seems evident that despite considerable diversity in composition, physical character, thickness, and distribution, layered volcanic sequences in Idaho, Oreon, and Washington have noticeable hydrologic similarities. Although confined conditions can be present in many areas, the general hydrologic system appears to operate like a water table one with relatively good vertical movement of water through the individual volcanic units. Vesicular and/or scoriaceous zones, fractures and cooling joints, lava tubes and open zones at flow contacts often produce zones of high horizontal permeability which can be highly productive sources of ground water. Availability of ground water from these sources is controlled by the distribution of these permeable zones and by erosional dissection, weathering, and interbedded sediments which can reduce permeability and limit recharge. Generally, interbeds have lower permeabilities than the related volcanic sequences and thus tend to retard ground water movement. Often significant changes in head will occur across sedimentary units and, if structural or stratigraphic complications are present, the sediments can be significant confining layers.

WATER LAW AND MANAGEMENT POLICIES

Water law in Idaho, Oregon, and Washington is based on the doctrine of prior appropriation. The appropriation doctrine is basically that everyone, whether a riparian landowner or not, has a right to obtain and use water for a beneficial use so long as it does not interfere with that of prior appropriations. The statement "first in time, first in right" is often used to characterize the appropriation doctrine. Although it is currently the basis for water laws of the three states, the doctrine evolved differently in each. As part of a study on regional aspects of the ground water resource and its management, it is necessary to look, at least generally, at the present methods and related legal basis for water resource management within the three states. The following section presents a brief history of the water right law and a discussion of the general management regulations and methods for each state. Differences and similarities are examined and consideration is given to potential problems that might be present in attempting a regional resource management program.

IDAHO

Like its neighboring states to the west, diversion of and irrigation with surface water began in Idaho coincident with early settlement in the late 1800s. Perhaps because, unlike either Washington or Oregon, earliest habitation in Idaho occurred in arid areas, use of the water resources was foremost in the minds of even the framers of the state's constitution. Article 15, section 3, of the Idaho Constitution adopted in 1889 states, "The right to divert and appropriate the unappropriated waters of any natural stream to beneficial uses shall never be denied, except that the state may limit the use thereof for power purposes."[1] While other state constitutions make reference to appropriation or specific uses which are acceptable, none has a guarantee like that of Idaho. With such a constitutional guarantee, an individual could simply divert unappropriated water without posting notice or obtaining a permit and, so long as it was put to a beneficial use, secure a water right. In 1903 the state Legislature enacted a permitting system. Early court tests of the legislation determined that the statutory method did not preclude obtaining a right through direct appropriation and thus two methods existed for obtaining a water right (Grant, 1979).

Ground water was, in the earlier days, of lesser importance than surface water and early law regarding ground water appropriation consisted entirely of case law. The Idaho Supreme Court in 1922 distinguished between percolating ground water and that flowing in underground streams, ruling that constitutional and statutory provisions regarding water appropriation applied to underground streams but not to percolating ground water.

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[1] This section added by amendment, 1928 (Grant, 1979).

In 1931 the court reversed itself and applied the doctrine of appropriation to all ground water (Hutchins, 1974). In spite of these earlier cases, no statutes pertaining to ground water appropriation were enacted until 1951. The Ground Water Act of 1951 and its subsequent amendments provide the basic procedural framework for appropriation of ground water in Idaho. The law provides that a person wanting to withdraw ground water should apply for a permit for the State Reclamation Engineer (later to become the Department of Water Resources). If, after investigation by department personnel, it is determined that the proposed withdrawal does not violate any of four conditions, a permit is granted. These conditions are: 1) that it will reduce the quantity of water currently under existing rights, 2) that the water supply itself is insufficient for such appropriation, 3) that the application is made for purposes of speculation, and 4) that the applicant does not have adequate financial resources to complete the project. Once the applicant diverts the water and applies it to beneficial use as prescribed in the permit, the license is issued which becomes the water right. Three uses are specifically exempted from permitting regulation, they are: 1) withdrawal of less than 13,000 gallons per day for domestic use, 2) drainage wells, and 3) drainage and/or recycling of irrigation water.

Despite statutes governing ground water appropriation, the permitting procedure was not mandatory because an individual could still obtain a right through the so-called constitutional method. In 1963 the Legislature amended the ground water act making the permitting procedure mandatory for ground water appropriation.[2] As might be expected, statutory modification of a perceived constitutional guarantee was, at the very least, subject to challenge.

In 1968 the Idaho Supreme Court decided Tappan v. Smith which tested the constitutionality of the Department of Water Resources' power to deny a permit in a critical ground water area. In its decision the court said that "The mandatory permit statute does not deny the right to appropriate ground water but regulates the method and means by which one may perfect the right to the use of such water" (Grant, 1979, p. 491). Thus, the statutory ground water permitting procedure appears to be firmly established.

In addition to the criteria for considering a permit application, the law also provides for the establishment of critical ground water areas. Such areas can be designated by the Department of Water Resources in cases where supply does not appear to equal existing appropriations and water level declines are evident. In the case of critical ground water areas the department has adopted a policy of approving permits for domestic and nonconsumptive use and no permits for consumptive agricultural, industrial, or municipal uses are approved.

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[2] Surface water permitting was not made mandatory until 1971.

To date, eight critical ground water areas have been established in Idaho. These critical areas are, in chronological order of original closing date, the 1) Oakley-Kenyon, 2) Artesian City, 3) Cottonwood, 4) Raft River, 5) Blue Gulch, 6) Curlew Valley, 7) Cinder Cone Butte, and 8) West Oakley Fan areas. Unlike Oregon and Washington, most of Idaho's critical ground water areas do not involve aquifers associated with layered volcanic sequences. Only in the Cinder Cone Butte area is primary productivity obtained from layered volcanics. The seven remaining areas lie in tributary valleys south of the main stem of the Snake River and most ground water is obtained from alluvial fill and related sediments. In each case, limited precipitation has resulted in extensive irrigation development which, because of a combination of low recharge and variable aquifer properties, has produced significant declines in ground water levels.

The mechanism of critical area designation does not lend itself well to controlling areas where ground water level decline problems are evident though not as yet severe. To provide a means of regulating ground water resource development in areas that could become critical, legislation was passed in 1982 that provided for the designation of ground water management areas. If in the opinion of the director of the Department of Water Resources, an area is approaching the conditions of a critical ground water area, he may designate it as a ground water management area. Within a management area the director may approve permits on an individual basis, require all water right holders within the designated area to report data useful in managing the area, and shut down junior appropriators as necessary. Two such areas have been designated, one in the Grandview area of southwestern Idaho and the other around the Cinder Cone Butte critical ground water area.

As is the case in most western states, it became apparent that some method of adjudicating water right claims was necessary in Idaho. The Legislature passed a statutory procedure for water right adjudication in 1969. The process is initiated by court action begun by the director of the Department of Water Resources (Hutchins, 1974, p. 282). The procedure involves obtaining a court order authorizing the director, or his designee, to make an examination of the water system, and, if claimed, the water rights within that system. A report detailing the findings of this examination is filed along with water right claims with the court and the court issues a decree adjudicating the water rights. Adjudication of ground water rights within Idaho has only just begun, despite the existence of the statute for over a decade. Conversation with the Department of Water Resources personnel indicates that adjudication of ground water rights has been done in only one location. This location is the Cottonwood critical ground water area in the southwestern part or the Snake River plain (Figure 2).

Development and administration of Idaho's water management policy is a rather interesting and unique combination of organizations and merits some discussion. Originally, all regulation of water resource appropriation was handled by the Department of Reclamation, headed by the State Reclamation Engineer. The State Engineer was directed by statute to implement the permitting procedure, although, until recently, this procedure was not mandatory.

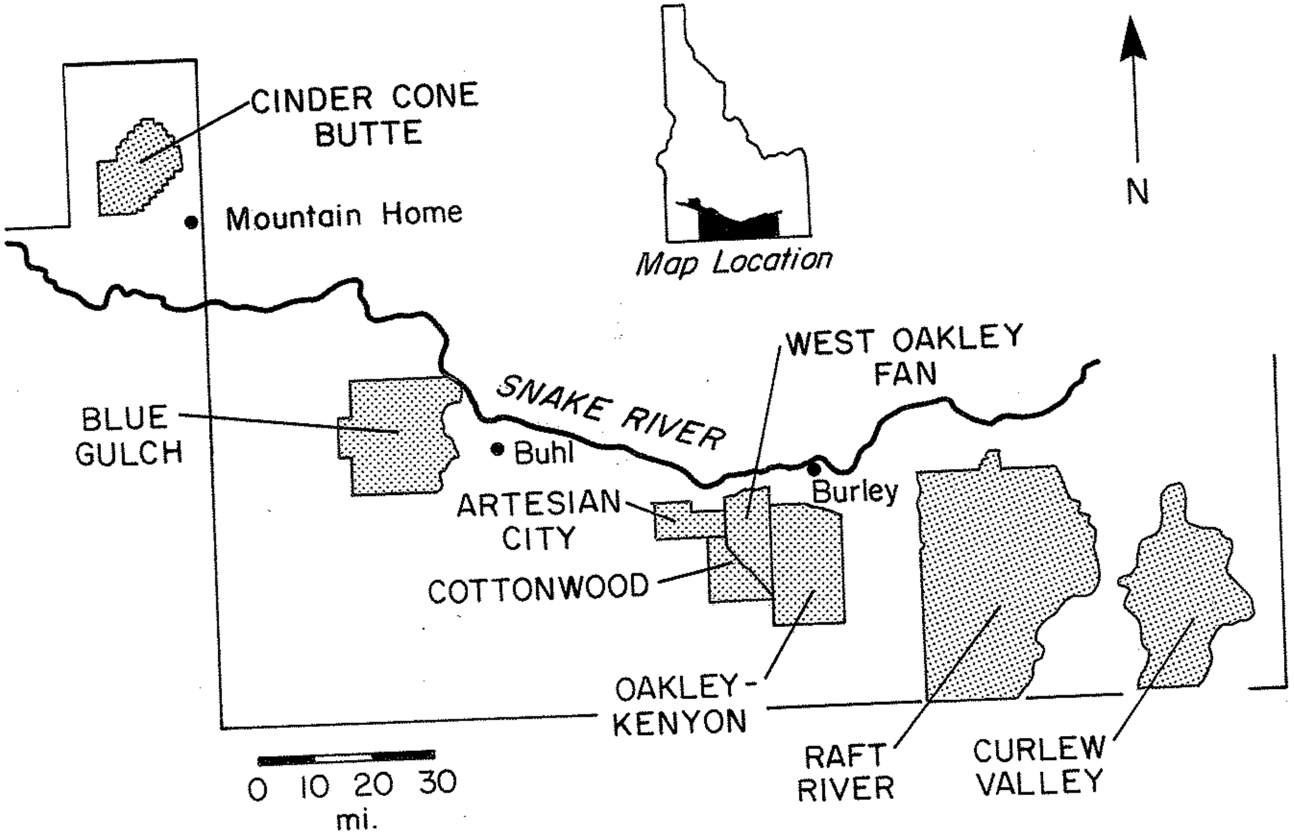

Figure 2. Critical Ground—Water Areas, Idaho

Suggestions by southwestern states concerning the diversion of Snake River water to the southwest created a sudden interest in maximum utilization of water resources within the state and the governor proposed that a constitutional amendment be adopted to allow the state to finance water resource development projects (Grant, 1979). It was also suggested that an organization be established to plan this development on a statewide basis. In 1964 a constitutional amendment was passed directing the establishment of a water resource agency, and that the agency "formulate and implement a state water plan." In the following year the Legislature created the Water Resources Board. The board is made up of individuals appointed by the Governor and consists of four at-large members, and one member from each of the state's four Water Resource Management districts (Figure 3). The Water Resources Board, with its own staff, operated independently of the Department of Water Administration (changed from Department of Reclamation in 1970), and formulated a three-part plan. The first part involved obtaining basic data and stating basic objectives on which to base the subsequent two parts. The second part consists of several (37) policies which the board felt were necessary to successful achievement of the objectives of part one. Part three is intended to be detailed technical and feasibility studies for small geographic areas or tributary basins (Grant, 1979, p. 450).

In 1974 the staff of the Water Resource Board was combined with that of the Department of Water Administration, and the Department of Water Resources was formed. Although the staffs were combined, the Water Resources Board remained independent of the Department of Water Resources. In 1976 the Water Resources Board adopted the policies of plan two. At the same time, however, the Legislature passed a statute affirming its power to approve, amend, modify, or reject the board's policies before they became effective. Questions arose as to the relationship of the constitutionally-based Board to the Legislature and to the statutory-based Department of Water Resources. A subsequent attorney general's opinion found no problem with legislative statute exercising control over the board's policy. Litigation followed in which the board and the Department of Water Resources were on opposite sides and the court ruled that the board derived its power from the constitution voiding the legislative statute (Grant, 1979).

As a result, a situation exists where a quasi-independent organization, the State Water Resources Board, is charged with formulating and implementing state water policy, and its relationship to the Legislature and other administrative agencies is not clear. Interestingly enough, one of the principal mechanisms for implementing water resource policy is the appropriation permit system which is clearly a statutory responsibility of the Department of Water Resources and not the Water Resources Board. Yet, as Grant (1979, p. 487) points out, "Although the board no longer has its own staff but relies upon staff of the Department (of Water Resources) it is still a separate entity. Board members are not employees of the department or subject to control of the director of the department. Conversely, the director is not an employee of the board." So a situation exists in Idaho of a division of responsibility for the management of the state's water resources. To date there has been little problem with such an arrangement but questions regarding ultimate responsibility and control are still unresolved and could conceivably be a source of future problems.

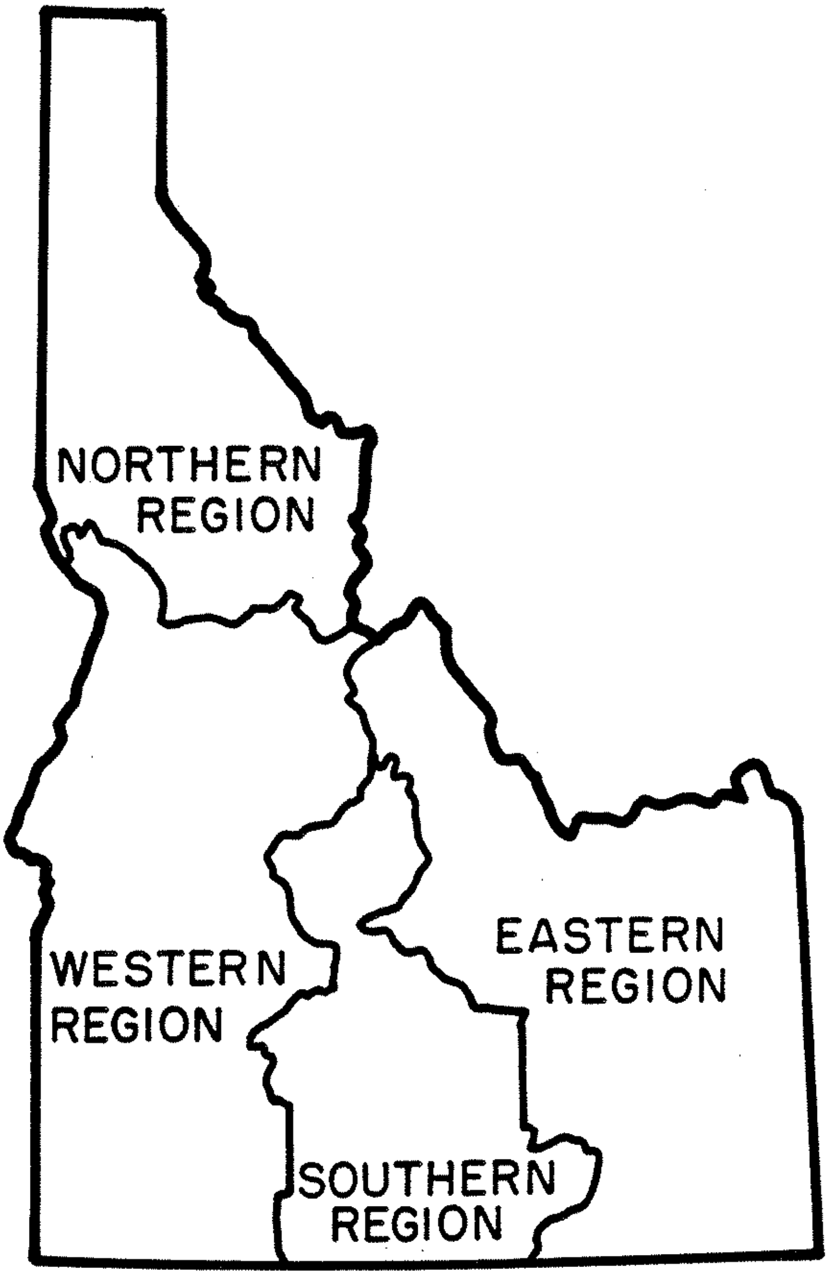

Figure 3. Water-Resource Administration Regions, Idaho

Two concepts are present within the Idaho water appropriations statute that are the critical factors on which most permit decisions are based. These concepts will be discussed in more detail in the following regional discussion, but they have been significant in Idaho and warrant some discussion here. The two concepts are that of beneficial use and safe yield.

Article 15, section 3, of the Idaho Constitution assures the right to appropriate water as long as it is for a beneficial use. The constitution also establishes some relative priority of beneficial use saying that water for domestic purposes should have preference over all others. The constitution also gives water appropriation for agricultural and mining uses high priority. Traditionally, beneficial use has been interpreted in an economic sense although the term has never been defined either in the constitution or by statute. Recently, there has been a greater interest in water, primarily surface water, for noneconomic uses such as recreation and aesthetics. Recently a change in the concept of beneficial use has occurred as described by Young (1975).

> "In 1971 the Idaho Legislature enacted a statute directing the Department of Parks to appropriate in trust for the people of Idaho certain unappropriated natural waters of Malad Canyon in Gooding County, Idaho. Additionally, it declares (1) that preservation of the waters for scenic beauty and recreation uses is a beneficial use of water; (2) that the public use of those waters is of greater priority than any other save domestic. . . ."

Subsequent testing in the Idaho Supreme Court resuted in an affirmation of the statute. Thus, a change in the concept of beneficial use is apparent.

In its proposed policies in part two of the State Water Plan, the Idaho Water Resources Board recommended analyzing new permit applications on the basis of "public interest." The Legislature substantially modified the policy statement but accepted in principle the concept of public interest. Presently, the director of the Department of Water Resources determines what is in the public interest for all but mininum stream flow appropriations. Conflicts of interpretation of beneficial use and public interest are likely to develop in areas where there is high demand for a diminishing resource. It is likely that questions of public interest will ultimately be determined by the courts.

The second concept is that of safe yield and is a concept upon which most ground water management programs are based. The reason for a permit procedure is to control the amount of water withdrawn from a particular area, providing maximum utilization, while not depleting the supply. This amount of water is often called the safe yield. Although the term "safe yield" is not employed in Idaho statute, the concept is clearly accepted. Idaho code provides that the Department of Water Resources may prohibit or limit withdrawal of water from any well if the water is being withdrawn "beyond the reasonably anticipated average rate of future natural recharge (Idaho Code, 42-237). The code also states that "early appropriators of underground water shall be protected in the maintenance of reasonable ground water pumping levels" (Idaho Code, 42-226). The intent is to allow development of the ground water resource while, at the same time, protecting against excessive depletion of the resource and abbrogation of senior water rights. To do this, withdrawal is normally limited to an amount approximately equal to the amount of annual recharge available to the area. As Ralston and others (1974) indicate, there are many problems with this, not the least of which being that it is difficult to determine what the natural recharge to any given area is.

The above described regulations were put to a test in Baker v. Ore-Ida. In this case the Idaho Supreme Court affirmed a lower court ruling which determined that withdrawal had greatly exceeded the average anticipated natural recharge such that mining of ground water was taking place. The court directed the junior appropriators to cease ground water withdrawal so that the mining be stopped and that reasonable pumping levels be maintained for senior appropriators. The case is significant because it is one of the few instances to date in which courts have affirmed the power of a regulating agency to curtail existing ground water withdrawal to safeguard ground water supplies. The case is also significant because it raises the question of ground water mining which, although not prohibited expressly by statute, appears to have been prohibited in the court's interpretation.

OREGON

Early water law in Oregon was a curious mixture of riparian and appropriation doctrines. Hutchins (1977) reports that early Oregon Supreme Court decisions showed a gradual preference for the doctrine of appropriation. In 1909 the Oregon Legislature passed the Surface Water Act which clearly recognizes the appropriation doctrine, but protects vested and inchoate rights. The act declared all water to belong to the public and recognized the importance of beneficial use declaring that it shall be "the basis, the measure, and the limit of all right to use water in the State" (Oregon Revised Statute, 540.610). The law established a permit system as the only means of perfecting a right for surface water appropriation. An individual wishing to divert water applied for a permit and, once approved, could begin construction of the diversion system. Once construction is completed and water diverted and put to a beneficial use, a certificate is issued recognizing the appropriation right.

No statutory treatment of ground water was done in Oregon until 1927. In this year the Legislature applied the appropriation doctrine to all ground water east of the Cascade Mountains. The Legislature established a permitting system similar to that for surface water as the only method of obtaining a right to ground water in eastern Oregon.

Despite continued development of the state's ground water resource, little modification of the 1927 Ground Water Code was done for nearly 30 years. In 1953 a legislative authorized committee reported that an estimated 100,000 domestic and stock wells were in use, and new wells were being drilled at the rate of about 5,000 annually (Clark, 1974, p. 194). From this study, it became apparent that the Ground Water Act of 1927 was insufficient to adequately control ground water use and the Legislature enacted a comprehensive Ground Water Act in 1955.

The Ground Water Act of 1955 applied regulations similar to those of the 1927 act to the entire state. The act incorporates much of the earlier Surface Water Code and like it, creates a method of permitting appropriation of the state's ground water resources; however, the Ground Water Act allows a greater degree of latitude to the Water Resources Director to regulate the use of ground water and to assure proper conservation. Clark (1974, p. 45) states that the differences between the two acts "Lie not so much in the allocation of the resources which still depends largely upon decentralized initiative, both public and private, but in the higher level of public interest expressed in the Ground Water Act as contrasted to the Surface Water Code), in the state's control of the use of ground water to meet the objective of conservation."

The 1955 statute, along with later amendments, defines public interest and sets out guidelines for determining what shall be deemed to be in the public interest. Oregon Revised Statute 537.170 directs that in the determination due regard shall be given for 1) conserving the highest use of water for all purposes including irrigation, domestic use, municipal water supply, power development, public recreation, protection of commercial and game fishing and wildlife, fire protection, mining, industrial purposes, navigation, scenic attraction or any other beneficial use to which the water may be applied for which it may have a special value to the public; 2) the maximum economic development of the water; 3) control of water for all beneficial purposes including drainage, sanitation, and flood control; 4) amount of water available for appropriation; 5) prevention of wasteful and other undesirable uses; 6) all vested and inchoate rights in the water of the state and means necessary to protect them; and 7) the state water resource policy.

The act recognized the right of individuals to appropriate ground water as long as it is put to a beneficial use and such withdrawal does not interfere with exiting surface water rights, deplete ground water below economic levels, or impair natural ground water quality. Although there is no prohibition against mining of ground water, the act states that "reasonably stable ground water levels be determined and maintained."

An important part of the 1955 Ground Water Act and its subsequent modifications was to establish a permit system for perfecting a right to withdraw ground water. A person interested in securing a new right to withdraw ground water must first apply for a withdrawal permit. As part of the permit application, the individual must supply necessary information, including the proposed use of the water, the size, the capacity, and the nature of the well and related pump work, depth to water table, well location, and a description of the land to be irrigated if the withdrawal is for irrigation purposes. Once the application is received, the Water Resources Director or his designate evaluates the application in light of existing rights and known hydrologic conditions. Based upon the determination by the director, the permit may be granted, limited, changed, or rejected entirely. Once the permit is obtained, the individual may withdraw the approved amount of water. Once the withdrawal facility has been established and it is determined that the appropriation has been properly realized, a ground water rights certification can then be issued.

The Ground Water Act specifically exempts particular uses from the registration and permitting procedure essential to establishing an appropriative right. These exempted uses are: 1) water for stock watering purposes, 2) water for any lawn or noncommercial garden not exceeding one-half acre in area, 3) water for single or domestic uses not exceeding 15,000 gallons per day, and 4) water for any single industrial or commercial purpose up to 5,000 gallons per day. Although these uses are exempt from the registration and permitting procedures, they are still recognized as appropriative rights and the uses considered beneficial. It is important to note that exempting the above uses from the registration and permitting system does not exempt them from other provisions of the Ground Water Act (Clark, 1974). Uses exempted from the registration procedure are subject to adjudication, regulation in critical ground water areas, and the reporting requirements of well contractors.

In addition to establishing an appropriation permitting system for ground water of the entire state, the 1955 Ground Water Act recognized vested rights subject to adjudication of any rights claimed before the passage of the Ground Water Act. Recognition of these vested rights is subject to registration of the rights and their subsequent adjudication. Despite the existence of the adjudication procedure for over 25 years, adjudication of ground water rights has only just begun, with the Harbor Bench area on the southern Oregon coast being the only area in which adjudication of ground water rights has been accomplished (F. Lissner, personal communication).

To ensure protection and/or conservation of the state's ground water resources, the Ground Water Act of 1955 gave the State Engineer power to declare critical ground water areas and broad power to control ground water use within those areas. The State Engineer (now Director of the Water Resources Department) may initiate proceedings to establish a critical ground water area where there is evidence that 1) ground water levels are declining, 2) there are substantial well interference problems, 3) ground water supply is overdrawn, or 4) ground water quality has been or is likely to be impaired (Hutchins, 1977). Since 1955 several revisions of the state's ground water code have been enacted, the most recent occurring in 1981. In the 1981 version the actual or potential effects of ground water withdrawal on geothermal resources was added as a criteria under which a critical ground water area could be established.

Once the proceedings for determination of a critical ground water area is initiated, a public hearing is held and, if the results of the hearing indicate that one or more of the above circumstances exist, an order declaring a critical ground water area is issued. Hutchins (1977, p. 470) indicates that the order

> ...may include any one or more of the following provisions: (1) closing the area to further appropriation; (2) determinng total withdrawals each day, month or year and, insofar as possible, apportioning such withdrawals among appropriators within the area in accordance with priority dates; (3) establishing water use preferences, irrespective of time priorities, with domestic and livestock given first preference; (4) reducing the permissible withdrawal by one or more appropriators or wells; (5) adjusting total withdrawal by one appropriator

> owning two or more wells, or forbidding completely his use of one or more of the wells; (6) requiring the abatement or sealing of any well polluting the ground water; (7) require a system of rotation of use; or (8) any other provisions necessary to protect public health, welfare, and safety.

To date, five critical ground water areas have been declared within the state. The five are: 1) the Cow Valley area in extreme eastern Oregon; 2) the area in the immediate vicinity of The Dalles, Oregon; 3) the Ordinance area which includes two separate critical areas; 3) Ordinance basalt; 4) Ordinance gravel; and, 5) the Cooper Mountain-Bull Mountain area southwest of Portland. The location and approximate size of the areas is shown in Figure 4.

In all but the Cow Valley area, ground water resources of the Columbia River basalt are of principal concern. In Cow Valley, pumping interference and related water level decline have occurred in wells tapping a sedimentary sequence and underlying basalt flows which apparently act as one system (Foxworthy, 1961).

Administration of Oregon's water laws has undergone considerable evolution since the early 1900s. The Surface Water Code of 1909 established a Board of Control which four years later was changed to the State Water Board. The function of the board was to supervise and control the use of the state's water. In 1923 the board was abolished and its duties transferred to the State Engineer (League of Women Voters, 1976). As is noted elsewhere, subsequent ground water legislation gave the State Engineer considerable latitude in dealing with ground water appropriation.

The 1955 Ground Water Act created the Oregon State Water Resources Board with the goal of placing responsibility for the state's water resource policy and planning in a single agency. The law creating the board also directed that the State Engineer would serve as engineer for the board. The additional control granted the State Engineer by the Ground Water Act effectively prevented realization of the single agency concept. An Oregon State Attorney General's opinion, resulting from attempts by the board to place some restrictive limitations on ground water use in selected locations, concluded that despite the legislative expressed policy of coordinating all water resources programs under the Water Resource Board, it had, in fact, specifically permitted control over ground water to remain with the State Engineer under the powers granted him by the Ground Water Act (Clark, 1974). This split control arrangement existed until legislative action in 1975.

In 1975 the Legislature created a Water Resources Department under the control of a Water Policy Review Board which replaced the older Water Resources Board. As part of this legislation, the duties formerly vested in the State Engineer were transferred to the Water Resources Director who is both the head of the Water Resources Department and the Chief Executive of the Water Policy Review Board. The director is responsible for administering the statutes and carrying out policies set by the board.

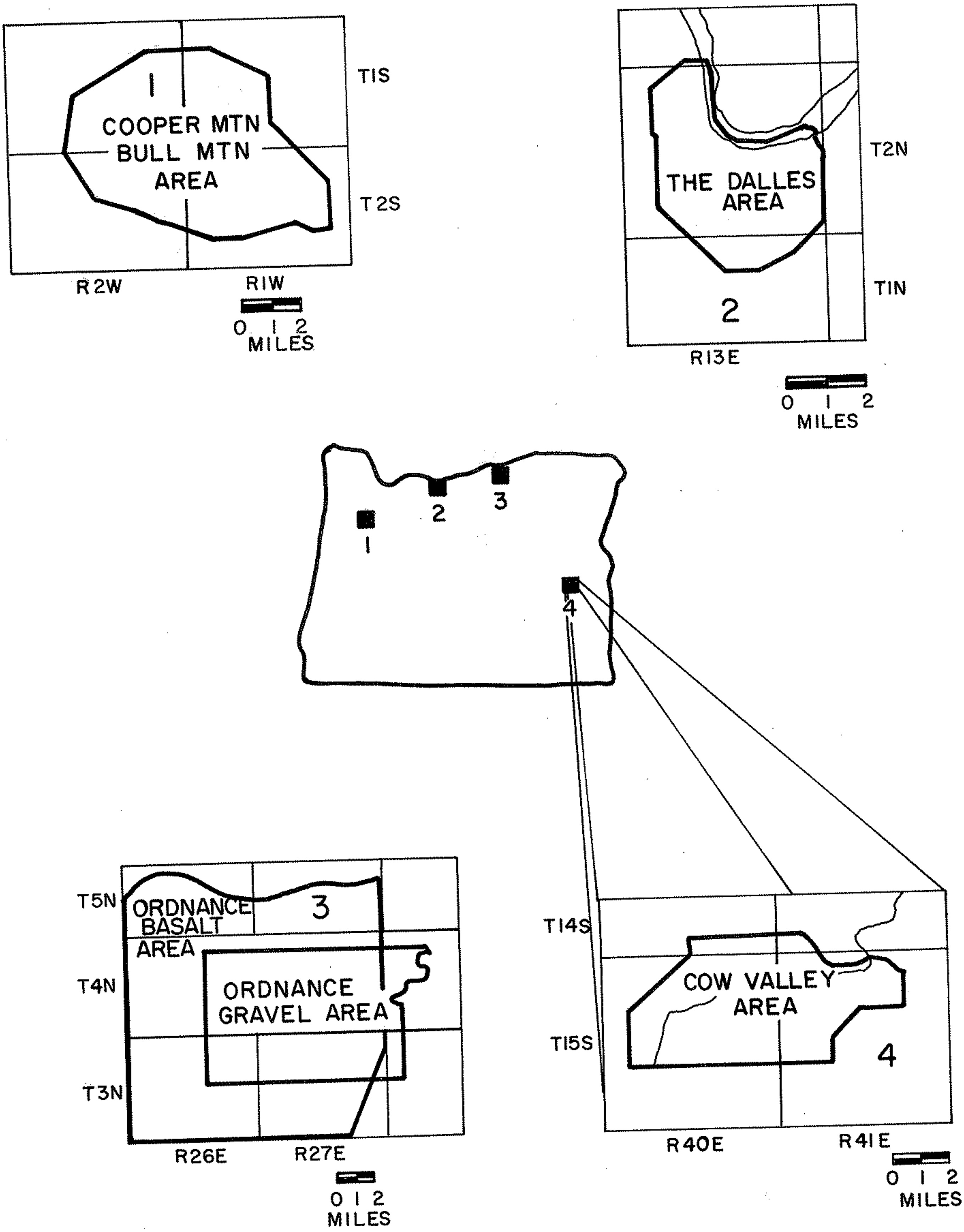

Figure 4. Critical Ground—Water areas, Oregon

Unlike either Idaho or Washington, the Oregon Water Resources Department does not have regional offices at various locations throughout the state. Within the state, some 18 water master districts have been created primarily for control of surface water appropriation. Location of these water master districs is shown in Figure 5. Because of the geographic isolation of the Water Resource Department offices, a small technical staff, and limited field funds, much of the field investigation related to the withdrawal permit system falls to water masters and/or their assistants. There are numerous problems with this arrangement as outlined by the League of Women Voters (1976, p. 7).

> While the state funds only one water master for each district, counties or water user groups in many areas provide funds for assistant water masters, as well as for the overhead costs of the district offices. This has not always resulted in uniform administration of water rights and judicial use of water resources. Counties have not cooperated equally in paying for actual distribution costs; some of the county-paid assistants have been confined to working on distribution matters only; others have been limited to working within a single county whereas the districts extend beyond county lines; finally, some counties have not paid assistant water masters enough to attract and hold qualified people.

Historically, the Water Policy Review Board and its predecessor, the Water Resources Board, have attempted to implement policy through the preparation of basin programs. The basin programs attempt to inventory both ground and surface waters of individual drainage basins within the state with an eye toward classifying unappropriated water for specific uses. The concept of the basin program is to determine a water budget in light of existing ground and surface water rights, minimum stream flow, and critical ground water areas. The intent of the basin program is to provide a rational approach to water resource use throughout the state and ultimately protecting these resources.

While the basin program seems a most reasonable approach, numerous problems hamper accurate use of any basin's water resources. These problems include: lack of accurate stream flow data, poor estimate of basin ground water storage, lack of ground water recharge data, lack of accurate knowledge of the state of both existing ground and surface water rights, and lack of any record of those water rights exempted from registration and reporting. The uncertainty associated with the above problems, both individually and collectively, hampers both the establishment and implementation of these basin programs.

WASHINGTON

Development of Washington's water management program was an evolutionary process. Early water regulation was under the supervision of the State Hydraulic Engineer. In 1921 a Division of Hydraulics in the Department of Conservation and Development was established and was changed in 1951 to the Division of Water Resources. In 1957 the Department of Conservation and Development was changed to the Department of Conservation and later a separate Department of Water Resources was established. In 1970 the Department of Water Resources was incorporated in the Department of Ecology.

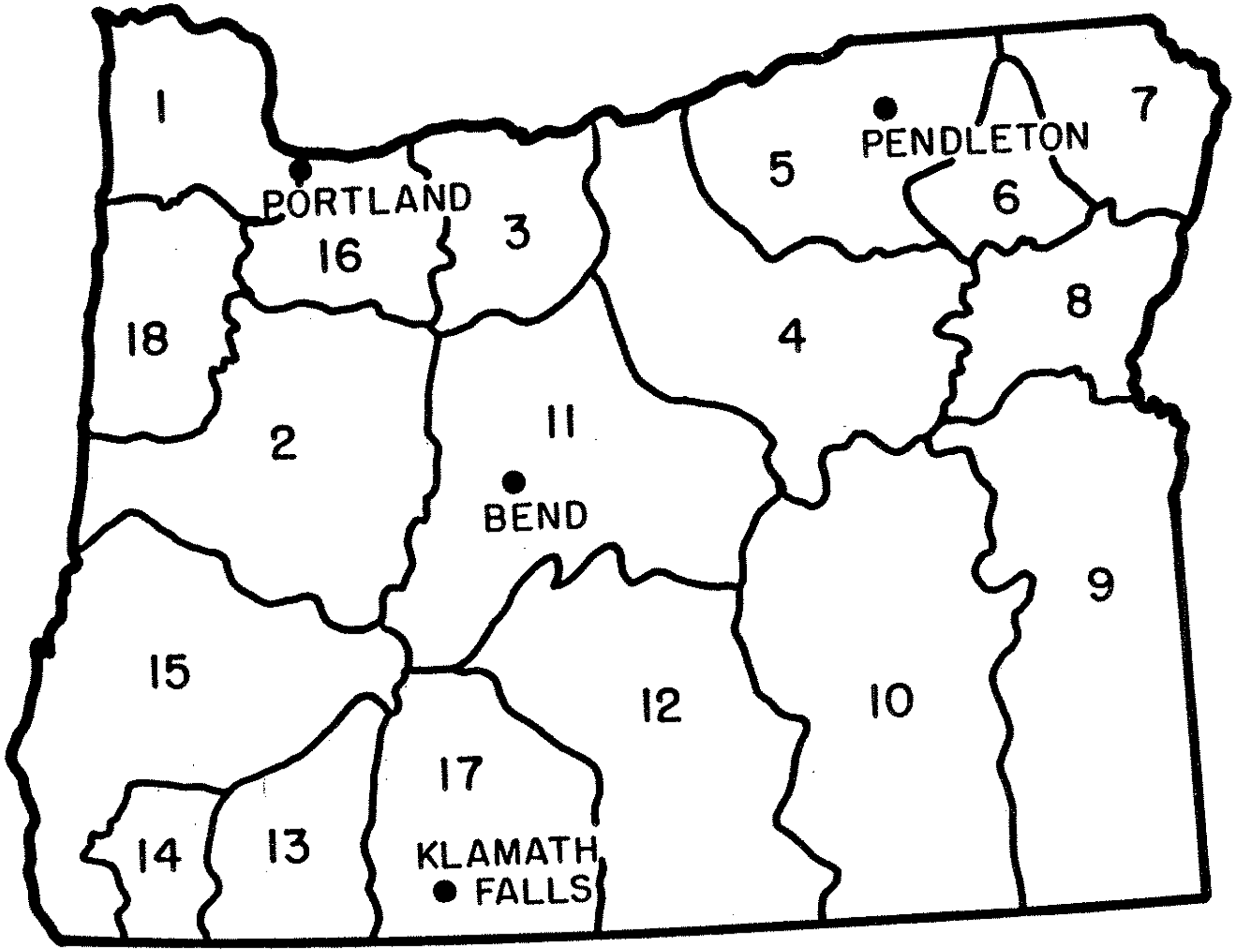

Figure 5. Watermaster Districts, Oregon

In the act that created the Department of Ecology, the Legislature also set up an Ecological Commission. The commission consists of seven members appointed by the Governor and its duty is to provide advice and guidance to the director of the Department of Ecology. Although the commission does have veto power over some of the functions of the department, it has not been granted any power over functions authorized to the department with regard to water resources.

In order to better handle the management of the state's water resources, four regional offices of the Department of Ecology were established (Figure 6). Each office handles the withdrawal applications for proposed diversions within the respective region and maintains a staff to monitor resource availability within each region. Each region enjoys a certain amount of freedom in determining management criteria for individual areas of development within the region.

Like other western states, concern over management of the state's water resources was coincident with early settlement. Prior to attaining statehood, there was little statutory control over water rights in the Washington Territory. Early territorial laws and court decisions recognized the doctrine of appropriations but recognition of rights to use water was pursuant to local custom (Hutchins, 1977).

Shortly after attaining statehood, the Legislature established a procedure for appropriating surface water and, although it recognized other uses, the procedure applied only to appropriation for irrigation. The procedure, similar to that of other states, involved the posting of notice and the point of diversion and recording of such notice with the county auditor. In spite of the act, the statutory method for effecting a right was not the exclusive method. One could still simply begin diverting water and establish the right (Hutchins, 1977). In 1917 the Legislature passed a comprehensive act which declared that, subject to existing rights, all waters within the state belong to the public and declared beneficial uses to be public uses. The act also made the statutory method of obtaining a right to appropriate the exclusive method and gave the State Engineer power to administer the appropriation system.

The first significant legislation dealing with the appropriation of ground water came in 1945. This act declared all ground water, subject to existing rights, to be public and established the procedure for acquiring a right to appropriate. As with surface water, the statutory procedure is the only method for obtaining a right to appropriate ground water.

The 1945 legislation also introduced the concept of a reasonable pump lift stating:

> "No permit shall be granted for the development or withdrawal of public ground waters beyond the capacity of the underground bed or formation in the given basin, district, or locality to yield such water within a reasonable or feasible pumping lift in the case of pumping developments, within a reasonable or feasible reduction of pressure in the case of artesian developments..." (Revised Code of Washington, 90.44.070)

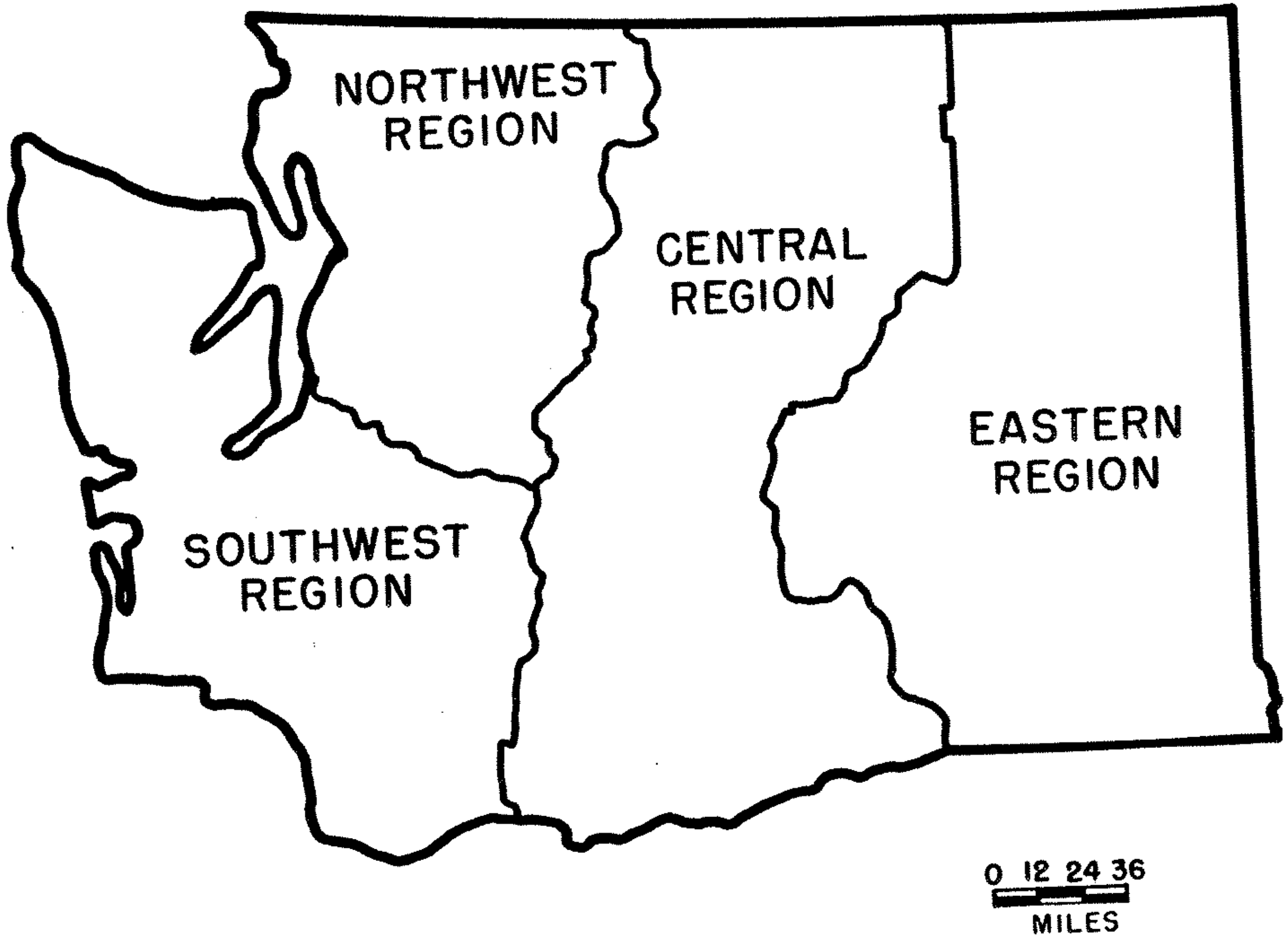

Figure 6. Department of Ecology Administrative Regions, Washington.

The act directs the supervisor of water resources (now director of Department of Ecology) to limit withdrawal to maintain safe sustaining yields.

The basic surface and ground water codes of 1917 and 1945 have been modified by later amendment. Perhaps the most extensive modification is the Water Resources Act of 1971. This act further defines water management policy and provides direction for the agencies involved in directing the water resource management program. The act declares that allocation of water among potential users shall be based upon securing maximum net benefit (defined as total benefit less costs including opportunities lost) for the people of the state. The act also defines those uses considered beneficial:

> "Uses of water for domestic, stock watering, industrial, commercial, agricultural, irrigation, hydroelectric power production, mining, fish and wildlife maintenance and enhancement, recreational, and thermal power production purposes, and preservation of environmental and aesthetic values, and all other uses compatible with enjoyment of the public waters of the state are declared to be beneficial..." (RCW 90.54.020)

Although, historically, beneficial use has been a largely economic criteria and in spite of the above definition of maximum net benefit, the act specifically states that utilization of water resources means not only uses for generally accepted economic uses such as irrigation or mining, but "includes the retention of water in lakes and streams for the protection of environmental, scenic, aesthetic, and related purposes, upon which economic values have not been placed historically and are difficult to quantify" (RCW 90.54.120). The act also recognizes the interrelationship of ground and surface water.

Pruzan (1974) suggests that the act firmly establishes the concept of public interest. References to public interest in the administrative code, however, generally refer back to the 1917 Water Code, rather than to the 1971 act. The act does, however, state that "lakes and ponds shall be retained substantially in their natural condition" and that withdrawal of water which "would conflict therewith shall be authorized only in situations where it is clear that overriding considerations of public interest will be served" (RCW 90.54.020). The 1971 legislation does recognize the interrelationship of ground and surface water so it could conceivably be argued that the same public interest criteria applies to ground water. As yet, no formal determination of the public interest aspect of ground water appropriation has arisen.

The procedure for obtaining a right to appropriate ground water in Washington State is similar to that in other western states. An application for withdrawal permit must first be tendered to the Department of Ecology. If, after study, the department determines that additional withdrawal will not affect reasonable pumping lifts, then a permit is normally granted. Once the facility is completed and it is determined that the water is being put to a beneficial use, then a certificate of water right is issued. Waters for domestic, stock watering, and other withdrawal less than 5,000 gallons per day are exempted from this procedure.

In anticipation of adjudication of water rights within the state, the Legislature enacted a water right registration law. The law provided a five-year period from 1969-1974 in which anyone claiming a right to appropriate water could file a claim for that right. Filing of the claim did not guarantee a right but did allow the claim to be considered during subsequent adjudication proceedings.

Adjudication of surface water rights has proceeded in fits and starts since the early 1900s. Estimates by Department of Ecology personnel suggest that perhaps surface water rights of 20 percent of the area of the state have been adjudicated. Ground water adjudication has only just begun within the state, largely in response to the Water Right Claims Registration Act. Currently, there is an active adjudication program going on within the state with basins being adjudicated in an order of need. In some basins both ground and surface water rights are being adjudicated while in others, only surface water right adjudication is proceeding. The decision whether or not to include both ground and surface water rights in the adjuciation process is based primarily upon criticality of the situation in each basin.

Regulation of ground water in the state is primarly tied to the concept of reasonable pump lift. Although some regulation refers to safe yield, the pump lift requirement is the technique used. To date no significant court tests involving management based on this concept have occurred but it is likely that if pumpage is reduced or restricted in an effort to maintain a particular pumping level, litigation involving the department regulation will occur.

In an effort to assure a safe sustaining yield and maintenance of reasonable pumping lifts, the Washington ground water statute provides for the establishment of ground water management areas. Section 90.44.130 of the Revised Code of Washington directs that the supervisor of Water Resources has the responsibility of maintaining a safe sustaining yield and for this purpose:

> "the supervisor shall have authority and it shall be his duty from time to time, as adequate factual data becomes available, to designate ground water areas or subareas, to designate separate depth zones within any such area or subarea, or to modify the boundaries of such existing area, or subarea, or zone to the end that the withdrawal therefrom may be administratively controlled as prescribed in RCW 90.44.180 in order that overdraft of public ground waters may be prevented so far as is feasible..."

Unlike the Oregon statutes regarding critical ground water areas, the Washington Code says little about the manner in which ground water management areas are to be regulated, and the specific powers granted to the Department of Ecology with respect to these management areas. Most of the policy regarding the individual ground water management areas is detailed in the administrative code dealing with each area.

Currently three areas within the state have been designated ground water management areas (Figure 7). The areas are the Quincy and Odessa management areas in central Washington and the Duck Lake area in the Okanogan

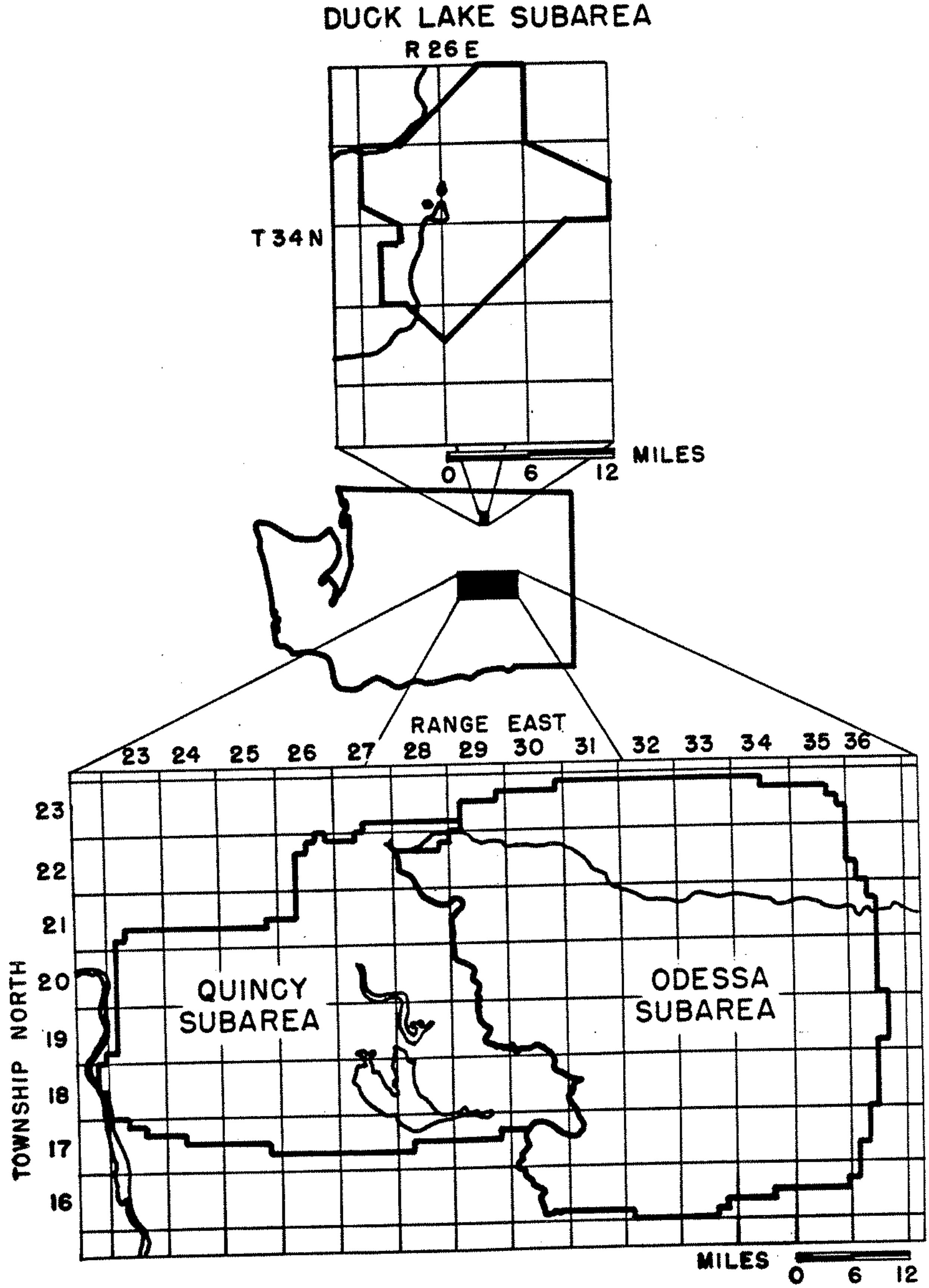

Figure 7. Ground Water Management Subareas, Washington.

River valley in the north-central part of the state. Of the three, the Quincy and Odessa areas deal with water obtained from the Columbia River basalt. The Duck Lake area involves water obtained from glacial sediments.

The Quincy and Odessa areas adjoin but differ slightly in both geology and in management approach. In the Quincy area a significant amount of consolidated sediment overlies the basalt, and ground water resources of both the sediments and the underlying basalt is developed. In addition, the Quincy management area is located within the Columbia Basin Irrigation Project which uses Columbia River water for irrigation purposes. As a result, considerable recharge occurs from this surface water irrigation and a situation of artificially stored ground water is present.

In the Odessa area all ground water production is obtained from the basalts. Regulations for management of the Odessa area are the most extensive of the three areas. Attempts have been made by the Department of Ecology to define zones within the subsurface and regulate withdrawal by zone. So far, to control the ground water level declines, the policy has been to not issue any additional withdrawal permits within specific zones in the Odessa area. If declines were to continue to predetermined limits, the department would then have to decide whether to revise those limits or reduce total withdrawal in some fashion.

As ground water resource development proceeded in the state, it became apparent that it might be desirable to have a degree of control over future permits other than just a "one-time" approval or denial. Discussion by Sorlie and Wallace (1976) relates the concern over granting withdrawal permits in perpetuity and its potential effect on future management of the resource. In response to this concern the Department of Ecology adopted regulations directing that water right permits of "regional or state-wide significance" will be issued for a 50-year period, subject to renewal. The rationale of the term permit was that it would allow reevaluation of hydrologic conditions at the end of the term and if the situation were critical, renewal of the permit could be withheld or the amount permitted could be reduced.

Shortly after implementation of the term permit, an initiative was placed on the general election ballot and was subsequently approved by referendum. This initiative produced the Family Farm Water Act which states that the "maximum benefit to the greatest number of citizens through the use of water for the irrigation of agricultural lands will result from providing for the use of such waters on family farms" (RCW 90.66.030). According to the act, a family farm can be of any size so long as it contains no more than 2,000 acres of irrigated agricultural land.

The act restricts all subsequent permits issued by the department for purposes of irrigated agricultural land to four possible classes. The classes are: 1) family farm permits, 2) family farm development permits, 3) publicly owned land permits, and 4) public water entity permits. Of the four possible permits, only the family farm development permit is time limited, the rest are to be granted in perpetuity. The legislation had two basic effects: 1) to limit the size of irrigated agricultural holdings within the state, and 2) to effectively end the granting of term permits for agricultural irrigation.

Within Washington there has been a curious difference of law between that enacted by the Legislature and that interpreted by the courts. Early case law recognized a distinction between percolating ground water and that moving through underground streams or channels. In an 1894 case the court recognized that water in underground streams would be protected under established doctrine the same as surface water, but this doctrine would not apply to percolating ground water. In Evans v. Seattle (1935) the court assumed that unless there was clear evidence to the contrary, all ground water was of the percolating variety and the reasonable use or correlative rights doctrine would apply (Hutchins, 1977).[3] Thus, while the appropriation doctrine was firmly established for surface water, it was not so established for ground water.

Although early case law was developed before passage of the Ground Water Code, recent court cases seem to extend this idea of correlative rights in spite of statutory recognition of the appropriation doctrine. Agnew and Busch (1971) point out the reliance on the concept of correlative right in Wilkening v. State (1959), State v. Ponten (1969), and Bjorvatn v. Seattle (1970) and suggest that the cases "breathe new life into Evans v. Seattle, a 1935 (before the ground water code) case which held that a landowner may do whatever he wishes to aquifers underlying his land, even though he causes damage to others using the aquifer" (Agnew and Busch, 1971, p. 134). Hutchins (1977) indicates that a minority opinion in State v. Ponten suggested that percolating ground waters were not included in the 1945 Ground Water Code. Neither the majority opinion nor subsequent court decision address this question; however, a 1973 amendment to the Ground Water Code specifically includes percolating ground water within the code. The issue has not since come before the court and thus it is not known how it might rule in subsequent decisions regarding percolating ground water in light of the statutory amendment.

COMPARISON OF STATE MANAGEMENT POLICY

Discussion of water management, law, and regulations has thus far dealt with the three states individually. As this work is intended to pursue the regional aspects of ground water hydrology and related resource management, comparison of the three state's water management policy seems necessary. Certainly, if attempts are made in the future to manage interstate ground water on a regional basis, whatever policies are developed will have to incorporate at least the intent if not the substance of policies already existing in the states involved.

From preceding discussions it is apparent that there is considerable similarity in ground water resource management policy among the three states. Each state has an advisory board of individuals appointed by

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[3] The concept of correlative right or reasonable use is a modification of the absolute ownership doctrine which held that a landowner could do anything with the water on his land even to the detriment of adjacent landowners. The reasonable use doctrine modified this absolute ownership doctrine to the extent that the water could not be wasted but must be put to reasonable use. (See Corker, 1971.)

the Governor that oversees to varying degrees the nature and implementation of resource management policy. In Idaho this board apparently plays a fairly active role in determination of policy while, in contrast, Washington's advisory board has very little to do with water resources policy. Significant question still exists in Idaho as to the nature of the water management agency.

In each state a water right is secured through an exclusive permitting procedure. In each case the regulating agency reviews the application to see if 1) the proposed use is a beneficial one, and 2) if supplies are adequate to sustain the additional withdrawal. If these principal conditions, along with other lesser ones which vary slightly depending upon the state, are met then a withdrawal permit is issued. Once the withdrawal has begun and evidence that the amount requested is indeed being withdrawn and serving a beneficial use, the water right is issued. Each state requires that notice of the permit application be published and provides an avenue through which other parties may object to the issuing of a withdrawal permit.

Besides a similarity in permit procedure, all states have a similar means for dealing with potential problem areas. Statutes of each state permit the recognition of critical ground water areas and give the administrating agency broad powers to manage these critical areas. The powers include, but are not limited to, curtailing pumpage by junior appropriators, restricting the amount of withdrawal allowed with each permit, and/or closing the area completely to any further development.

While there is a general similarity among the ground water management programs of the three states, differences do exist. Many of these differences are only procedural ones; however, some are more significant and could pose problems if programs from neighboring states were to be integrated. Agnew and Busch (1971) list eight differences among the states of Oregon, Idaho, and Washington and the province of British Columbia. These differences are:

1. Definition of ground water for statutory coverage.
2. Methods of ensuring a permanent or maximum benefit supply.
3. Protection of means of diversion.
4. Critical area designation and control.
5. Deviation from strict priority.
6. Recognition and definition of artificial storage.
7. Preservation of existing rights.
8. Surface water preferences.

Of these, number 2, 5, and 6 deserve comment here.

The issue of ensuring a permanent or maximum benefit supply is the reason for every ground water resource management program. The reason for management policy is, of course, that the resource is not in infinite supply and some means must be employed to ensure that the resource remains available for future use. Because there are a great number of uses for ground water, demand can often outstrip supply (particularly in arid areas) and create the need for resource management. The question facing the hydrologists, the regulating agency, and ultimately the people of each state, is how much water can be used without seriously endangering the total supply. To deal with this question each state has established criteria which are intended to both allow development of the resource while protecting it from irreversible damage. Traditionally, these methods have been to prohibit mining of ground water or to allow mining to proceed at a predetermined rate and/or to a particular depth.

Previous discussion indicates that Idaho code prevents issuing a withdrawal permit if of it will cause water to be withdrawn at a rate beyond that of "future natural recharge." Additionally, the code encourages full development of the resources but directs that early appropriations are to be protected by the maintenance of reasonable ground water pumping levels. Although nothing in the Idaho code specifically prohibits ground water mining, the Idaho Supreme Court in a recent case held that the law directing withdrawal to not exceed average future natural recharge prohibited ground water mining. As a result, a certain amount of confusion exists as to just exactly how ground water in a particular basin should be managed. The questions raised by the decision (Baker v. Ore-Ida) are thoroughly discussed by Ralston and others (1974).

Besides creating questions within the state, interpretation of the Idaho statute as prohibiting mining of ground water marks a significant difference between Idaho and the neighboring states of Oregon and Washington. Washington has no provision against mining but statutes direct the maintenance of safe yield. The concept of safe yield has been tied to that of a reasonable and feasible pump lift and, although there have not been any court challenges, the department policy has been to set minimum ground water levels in critical areas and, through control of permits, attempt to stabilize ground water levels at some point above the minimum. Presumably, if ground water levels declined to a point below the stated minimum and the minimum was still determined to be the limit of reasonable and feasible pump lift, then withdrawals by junior appropriators would be limited or terminated.

Grant (1980) has produced a thorough discussion of the concept of reasonable pump lift which provides an idea of the nature of the problem. The question of reasonable pump lifts is not simply one of determining physical parameters of the hydrologic system involved, although these parameters are an important component. In addition, economic and social goals must also be weighed.

Oregon statute is the least explicit regarding ensuring supply. The code does direct that reasonably stable ground water levels be determined and maintained but allows that depletion of supplies is to be prevented or controlled within practicable limits. Agnew and Busch (1971, p. 126) note that the code "recognizes the need for controlling overdraft but by no means rules out overdraft completely."

It is apparent from the above discussion that considerable variation exists among the states concerning methods of ensuring an adequate supply. Thus, in a management situation involving two or more of the states, problems could arise in balancing philosophical differences of the states involved. In reality, water resource management personnel are likely to be in closer agreement as to method of ensuring adequate supply than the various codes may suggest because the manifestation of ground water availability problems is virtually identical in all states. It seems likely, therefore, that agreement could be reached among states as to the method for ensuring adequate supply. Whether this agreement could withstand court challenges in the various states is unknown.

Agnew and Busch (1971, p. 130) note that Oregon statute allows assigning of preferred status to particular uses without regard to priority of right within critical areas. The status gives initial preference to domestic and stock uses. Neither Washington nor Idaho go so far as ordering of priorities, although each state has generally given preference to domestic uses.

While this particular difference does not appear large, it does raise the question of beneficial use which is a cornerstone of water law in each state. In each a right to withdraw water can be obtained only if the use of the water is a beneficial one. As Corker (1971, p. 132) points out, a major purpose of the requirement is to prevent the waste of water. "Historically, the concept of beneficial use has been viewed predominantly in economic terms although preference of domestic uses over all others is probably more social than economic." Recent litigation in Idaho described earlier indicates that this concept may be broadened to include traditionally noneconomic uses such as aesthetics and/or recreational uses and even storage. As it currently stands, beneficial use is a rather broad and somewhat vague concept which is important because of the latitude it allows and because of the basic reliance upon the concept in water law. As competition for a dwindling supply of water increases, the concept of beneficial use will play a role of increasing importance. Corker (1971, p. 117-118) discusses this concept and the ramification of establishing priorities of use.

> A criticism of the rule (beneficial use) is that a better way to curtail waste is to charge the water user enough so that he has adequate incentive to curtail his own waste, but he remains free to follow his own choices so long as he is willing to pay the price. The criticism is theoretically sound, but it is unlikely to be widely implemented until general patterns of taxpayer subsidies to water users is eliminated, and water becomes sufficiently valuable to meter and to police. Meanwhile, categories of use as beneficial or nonbeneficial regardless of circumstances are likely to produce misallocation of resources even more serious than preferences, which do not go as far as to forbid nonpreferred uses.

Thus, in a given interstate management situation, the question of competing beneficial use and their relative priorities may have to be resolved. This could be difficult as the hydrologic relationship between ground and surface water becomes better defined and the current trend of interest in noneconomic beneficial uses increases.

Another difference noted by Agnew and Busch is that of the procedures involving artificially stored ground water. Oregon law recognizes recharge using surface water as a beneficial use, however, no mechanism is present for protecting that water once it is in the ground. Washington statute recognizes the difference between natural and artificially stored ground water and when claims to artificially stored ground water "have been 'abandoned or forfeited' they are public ground water available for appropriation" (Agnew and Busch, 1971, p. 131). Practically, the question of artificial storage relates to recharge occurring from surface water irrigation. Not surprisingly, with the presence of the large Columbia Basin Irrigation Project within the state, Washington has a more extensive coverage of the issue.

The Washington State Department of Ecology recognizes artificially stored ground water resulting from distribution of surface water by the Columbia Basin Project. In the Quincy ground water management area the Department of Ecology recognizes an upper zone, which contains artificially stored ground water, and a lower zone. Although the department is responsible for the permitting procedures for both the upper and lower system, it must take into account Bureau of Reclamation desires relative to its surface water distribution system.

In Idaho, legislative action concerning artificially stored ground water has occurred only recently. Ralston and others (1974) observed that the use of the term natural in the average natural recharge clause could foreclose the option of artificial recharge in determining the policy toward water level declines. In 1978, however, the Idaho Legislature authorized a ground water recharge project in southeastern Idaho and provided for the formation of an artificial recharge district in several southern Idaho counties. In 1982, the storage of unappropriated water in underground aquifers was declared to be a beneficial use of water anywhere in the state (Idaho Department of Water Resources, personal communication).

The problem of artificially stored ground water is not great at this time; however, it has the potential for becoming much more serious. In areas where surface water irrigation is taking place, there is undoubtedly recharge to the ground water system. If ground water development in such areas were to progress to the point where restriction in ground water withdrawal was necessary, considerable conflict is likely over whether the ground water being used is naturally or artificially stored and who has control of the artificially stored water.

There has as yet been little conflict between surface and ground water rights, but the potential for such conflict is clearly evident. Preceding discussion of basalt hydrology indicates a definite interaction between ground water and surface water. In some areas, such as the Snake River plain, this interaction is quite pronounced and the effect on nearby streams of altering ground water recharge or withdrawal has been long recognized. As demand for water resources mounts and more areas are managed to some controlled decline rate or level, the effects of this use upon existing surface water resources will become more apparent. The potential for interstate problems is significant as ground water development in upstream areas could conceivably reduce flow in lower reaches of the stream which may lie in a neighboring state. Because many streams are fully appropriated, such a flow reduction could have serious consequences.

Agnew and Busch (1971) and Corker (1971) list six possible methods for ground water management on an interstate level. These are 1) suit in the original jurisdiction of the supreme court, 2) litigation in state or federal courts, 3) reciprocal legislation among the states involved, 4) federal legislation, 5) interstate compact, and 6) administrative agreement. Both sources provide complete accounts of the advantages and disadvantages of each method and draw a similar conclusion; of the six, the last two, interstate compacts and administrative agreement, seem the most feasible. The interstate compact has the advantage of being an interstate rule of law and thus conflicting state-created rights would not present problems. The principal problem is that the process is quite cumbersome involving substantial negotiation, approval by state legislatures and finally, consent of Congress. Because of this extensive process, subsequent modification of the compact is difficult. Such a compact is also often difficult to administer and enforce (Corker, 1971, p. 241).

The administrative agreement involves giving the necessary individual (probably director of the state water resource management agency) in each state the power to negotiate an agreement. This has the distinct advantage of eliminating the cumbersome process of the compact and conceivably would facilitate modification at some later date. The principal question is the relationship of the agreement to the statutes of each state and whether the agreement could be changed by legislative fiat of one state or challeneged successfully by an individual litigant.

Regardless of the mechanism chosen, regional management of an interstate resource has the potential advantage of administering the development of the resource in a more consistent, equitable manner than if managed piecemeal by the individual states involved. Ground water resource management on a regional scale suffers the same limitations present in the management of any basin, that of lack of detailed knowledge of the amount of the resource available for use. The concepts on which most management programs are based, those of safe yield and reasonable pump lift, are still not clearly defined because our understanding of the hydrologic properties on which these concepts are based is severly limited.

DIRECTION OF ONGOING RESEARCH

Study of the nature and occurrence of ground water in layered volcanics is still a relatively new phenomenon. As demand for the resource is likely to continue to increase and management of it will become more critical, supporting research must continue to provide more accurate assessment of resource availability. Although it is not the main purpose of this study, it seems relevant to briefly discuss the direction of future research and some of the techniques which might prove useful in this research effort.

Previous discussions have illustrated the importance of geologic control of ground water in the layered volcanic sequences of Oregon, Idaho, and Washington. It is evident that thickness and distribution of stratigraphic units, as well as variation in their physical properties such as weathering and joint distribution, have a profound affect upon permeability and head relationships within the hydrologic systems. For these reasons it is important that mapping and related research of surficial geology and stratigraphy continue. The basis for understanding any hydrologic system lies in knowing its basic geologic framework.

Extensive geologic investigation is currently directed toward the Columbia River basalt group as part of a program to ascertain the feasibility of radioactive waste storage within the basalt. Preliminary results of this mapping presented by Swanson and others (1979a) and Myers and Price (1979) indicate a variety of features which could have significant effect upon ground water distribution and availability. Similar work should continue in areas of Oregon and Idaho as well to better define geology and stratigraphy.

Along with continued surficial mapping, geophysical methods should be applied toward definition of geologic and hydrologic parameters and for extrapolation of surficial geologic data. Studies by Swanson and others (1979b) and Mabey and Oriel (1970) indicate the usefulness of areomagnetic survey in defining basin geometry and the occurrence of structures and related features. Comparisons of borehole geophysical data with the areomagnetic map reveals the presence of flow system disruption coincident with magnetic anomalies. This relationship suggests that areomagnetic methods would be very useful in relating subsurface geologic features to ground water flow.

Work reported by Barker (1979) and Zhody and others (1974) indicates that electrical methods are also quite useful in volcanic terrains. Heigold and others (1980) successfully used resistivity to trace lateral changes in permeability. This study was in an area of sediments with substantial drilling and pump test data. Applicability of this method to layered volcanics is likely to be more difficult. Yet the technique does illustrate the potential of electric methods in determining ground water parameters. In addition, electrical methods are useful in defining basin boundaries and subsurface geology.

Use of remote sensing techniques could also provide valuable data both on definition of possible structural lineaments and on evapotranspiration and ground water use. Photo lineament maps have been produced for the three states (Day, 1979; Lawrence and Carter, 1974; Brewer, 1977) and comparison of data on ground water flow and occurrence with photolineament information could be useful. As part of the U.S. Geological Survey, regional aquifer study of the Snake River plain discharge estimates for irrigation are being developed based upon water use for various crop types. Much of this information on crop distribution is being developed from remote sensing data (J. Lindholm, personal communication). Similar uses for remote sensing data are being tested by the Washington State Department of Ecology for estimating ground water use in eastern Washington. If such estimation techniques can be properly calibrated, the potential for reliable low cost estimates of ground water use is great.

Besides continued surface investigation, continued collection and analysis of borehole data is imperative. The borehole data can provide a wealth of hydrologic information and include everything from geologic and stratigraphic information, to pump tests and water level measurements.

Evaluation of subsurface stratigraphy is possible through collection of core and chip samples. While core sampling is the most desirable, core drilling is seldom done except in specific site studies. In many of the layered volcanic areas, however, water supply wells are being drilled with regularity and drilling samples obtained from these wells can be a valuable resource obtained at virtually no cost. Furthermore, related drilling information such as lost circulation or caving zones, location of waterbearing zones, and changes in drilling conditions or pressures, is also quite useful.

The use of borehole geophysics in water resource investigation has produced significant results in determining both subsurface stratigraphy information and hydrologic parameters. Keys and MacCary (1971) present a good discussion of various borehole geophysical methods and discuss electrical, radiation, and fluid logs. Work by Crosby and Anderson (1971) and Siems and others (1974) indicates radiation logging to be generally more useful than electrical logging methods in basalts of the Columbia River group. Using primarily neutron porosity and natural gamma logs by a variety of workers (Siems, 1974; Robinette, 1975; Brown, 1978, 1979b) has helped define distribution of subsurface units on the Columbia plateau and contributed significantly to the development of structure contour and isopach maps of the Columbia River basalt group in Washington (Swanson and others, 1979c).

In addition to stratigraphic information, porosity and density logs provide information on physical parameters of units significant to ground water distribution and occurrence. Porosity and density logs can provide qualitative evaluation of these formation parameters. Recently, however, Poeter (1979) successfully modeled neutron and gamma log responses from a basalt borehole using Monte Carlo simulation techniques. Although the model deals only with a single borehole, the close correspondence between model prediction and log response suggest that quantification of porosity and density data might be possible.

Fluid logs (fluid temperature, fluid resistivity, and vertical flowmeter) also provide valuable information on occurrence and movement of borehole fluid. Vertical flow within a borehole is in response to head differences and detectable through use of the fluid temperature and flowmeter logs. Furthermore, these logs can locate zones of high permeability where influx or efflux is occurring. Data from fluid temperature logs may be useful in determining vertical ground water velocity in the surrounding wall rock.

Temperature logs can also be used for tracing ground water movement as indicated by Keys and Brown (1978), and can often locate areas of artificial ground water recharge. Results of analysis by Robinette and others (1977) of temperature logs from the central part of the Columbia plateau indicate a plume of cooler than normal water associated with recent recharge from the Columbia Basin Irrigation Project.

There are also several techniques yet to be used extensively in layered volcanics which could prove useful in continuing research efforts. These techniques involve the use of tracers and age dating of ground water. One of the reasons they have not been used extensively in the past is that results from a few initial attempts appeared inconsistent and confusing. The reason for this confusion rests in the lack of understanding of the geologic and hydrologic framework of the system being studied. Since the time of these earlier tests, a much better conceptualization of the hydrologic system has been developed for some locations. With a better understanding of the hydrologic system it would now be possible to sample much more accurately and thus reduce the risk of error. Careful sampling and analysis of tracers and/or age dates would likely produce valuable data on permeability and ground water velocities.

A wide variety of ground water tracing and dating techniques have been employed in the past. Davis and others (1980) presents a good overview on ground water tracers and the advantages and disadvantages of each. One of the principal problems is what tracer to use. Many of the tracers such as solids, dyes, temperature, or ionized substances would probably not be useable in fractured volcanic rock except over very short distances. Radioactive tracers might be much better but concern over and regulation of the use of radioactive substances in ground water make significant use of radioactive tracers unlikely. Davis and others (1980) report substantial interest in use of fluorocarbons as potential tracers. Fluorocarbons have advantages of being mobile, readily detectable, and nontoxic. Marine (1979) suggests the use of naturally occurring helium as a possible tracer to determine ground water velocities.

Another problem is the lack of knowledge about the nature of ground water movement in fractured volcanic rocks. Questions exist as to the validity of assumptions made in calculating velocities and about the scale of such tests. In spite of the problems, however, it seems that usefulness of tracer tests should be considered in future research efforts. Most tracer studies done to date in layered volcanics have been restricted to tracing radioactive plumes associated with waste disposal on federal reservations (Gephart and others, 1979; Robertson and others, 1974).

Age dating of ground water also could be more useful than previously thought. Early work in basalt by Crosby and Chatters (1965), Silar (1969), and Robison (1971) produced a wide variety of ages with little consistency and did little to explain the nature of volcanic ground water flow systems. Recent progress in understanding the flow system in some areas suggests that ground water age dating might be more useful at this time. In addition to standard methods such as carbon-14 and tritium, use of fluorocarbons as suggested by Thompson and Hayes (1979) might provide good indication of relative age of ground water.

Other important data to be gained from borehole studies is that developed through hydrologic testing within the borehole itself. Most common of these testing techniques is that of pump testing to determine aquifer properties and productive capability. Pump testing theory was originally developed for clastic sedimentary aquifers and, as a result, much of the original theoretical treatment does not take into account flow to a well in a fractured material such as an extrusive volcanic flow. A considerable amount of research into the theory of well hydraulics has continued and much of it involves analysis of aquifer response under a particular set of constraints. The workers and related papers are too numerous to list here, however, Streltsova (1976) presents a good overview of the theoretical work. As this theoretical work evolves, pump test data is likely to become more valuable and efforts should be made to collect pump test information whenever possible.

One of the problems associated with obtaining pump test data in layered volcanics is that test results are often most accurate if water levels can be recorded in nearby observation wells. Because of the depth to water in most locations and the nature of the volcanics themselves, drilling of test wells and related observation holes, is quite expensive and, as a result, seldom done. In many locations, however, there has been extensive development of ground water resources for irrigation purposes and numerous large capacity wells are present in these areas. While perhaps not being ideal conditions, a considerable amount of useful information could be obtained from testing these irrigation wells. Often situations exist where capacity tests are to be performed and cooperation with well owners, drillers, and pump companies could result in obtaining useable aquifer test data.

Besides standard pumping tests, numerous other tests can be run and data collected. Hydrostatic head data can be obtained through installation of piezometers and/or measurement of water levels in wells. A wide variety of drill stem testing procedures also exists which provides information on both hydrostatic head and aquifer properties. These tests include injection, swab, slug, and other packer isolation tests. Like radioactive tracing, the use of these tests in layered volcanics of the Northwest has been largely within federal reservations in south-central Washington and southern Idaho. Early drill stem testing on basalts at the Hanford reservation was done by La Sala and Doty (1971). More recently, extensive drill stem testing has been done as reported by Gephart and others (1979b) and Apps and others (1979). Drill stem testing eliminates the need for large diameter test holes and observation holes. Initial results of drill stem testing in volcanics appear encouraging, however, it should be checked with head information from piezometer installations and pumping test data. A principal advantage of drill stem testing is the ability to isolate particular zones and test them independently.

One of the most extensively used and useful techniques in water resource investigation is that of computer modeling. Modeling provides an opportunity to describe a particular hydrologic system and then test the effect of varying certain parameters. The ability to vary inputs makes models useful in ground water management applications. Initially, most ground water models were of the analogue variety which consisted of building a physical model of the system using electrical components and basing ground water flow on the analogue of flow of electricity. With the advent of higher speed digital computers capable of handling large amounts of data in short time periods, numerical modeling of ground water has become more popular. Numerical models have the advantage of being more quickly constructed than analogue models and also the output is generally in a more useable form (Moore, 1979). In contrast, the analogue model can handle large complex hydrologic problems "such as those that make two or more aquifers with varying degrees of hydraulic interconnection" (Moore, p. 122). In addition, Prickett (1979) notes that a principal advantage of analogue models is that time does not have to be discretized.

Despite limitations, the overall advantage of numerical modeling results in its extensive use today. Numerical models have been constructed for numerous locations in the three-state area. Currently, a regional model is being constructed for the Snake River plain and a similar regional model is contemplated for the Columbia plateau.

Gradual evolution of modeling capability has resulted in increasingly more accurate ground water models. In addition, attempts are now being made to incorporate both ground water and surface water in models. Cunningham and Sinclair (1979) report on a coupled ground and surface water model which was successful in predicting both river stage and ground water levels in wells near the river. In addition, numerical models are being used more to predict aquifer properties through parameter estimation techniques (Land, 1977).

The speed, versatility, and cost-effectiveness of computer modeling has made it very popular, particularly for ground water resource management. Despite the popularity of numerical models, problems exist which are often overlooked or realized too late. Numerical models are based upon ground water flow theory which is still in its formative stages. Often, in order to describe the system numerically, various assumptions and/or simplifications are made. Generally, these assumptions are valid for the particular case being modeled; however, the case modeled may not be representative of an entire aquifer system. There is also a tendency to forget the limitations of these assumptions particularly as the model results are used by someone other than the person constructing the model. Furthermore, all models require input of various parameters which are often difficult if not impossible to determine. Thus, the use of a particular model as a predictive management tool is sometimes jeopardized by questionable input parameters. Prickett (1979) lists three other problems with models particularly for management applications. One of these problems is that with the advent of numerous published programs, often the wrong model is chosen for a particular application. Another problem is that the contracting agency for whom a particular model is prepared is often disappointed with the results because they had originally been oversold on the potential of a ground water model. Finally, there is the problem of lack of understanding of the code by anyone other than the person or persons who drafted the model. Thus, often the division and specialization of people who use the models and the people who construct them can produce serious problems in correct use of the model.

The problem of division between construction and use of the model is particularly acute in water management agencies. Often the modeling is done by staff members who have little involvement in the application of the model or model development is contracted from another organization. Not only is communication between the two groups difficult, but often once the model has been developed and tested successfully there is little follow-up to see if its predictions are correct. Mido (1980) suggests that some of these problems inherent in large models could be avoided through the use of small desk-top microcomputers and modeling of smaller areas. He suggests that a person involved in management could learn the code and develop a model for a particular small area of interest. The model could be tailored to fit that particular area and could easily be modified if results were inconsistent with field observations. The advantage of this approach is that not only is a person directly involved with management involved in the modeling but also, after initial investment which is not large, the model could be continually refined with little additional cost.

The key to ground water modeling and to hydrologic research in general, lies in continuity. The overwhelming tendency in resource management is to react to crisis situations. The reaction to a particular crisis often produces expensive, large-scale, short-term studies and results in a highly complicated predictive model. Once the crisis is past or money is gone, data collection ceases and the model is often shelved. Until the next crisis, collection of drilling samples, water level measurements, pump test data, and other inexpensive ongoing studies halt and much information is essentially lost forever.

Although there is certainly a place for intensive study of a particular location and solution of emergent crises, there is even a greater need for continuing data collection. Such a data collection and research effort could be tremendously cost-effective. Relatively small amounts of money to provide travel for data collection and to encourage and support student work in solving specific problems would ultimately yield a far greater return than expensive one-time projects.

CONCLUSIONS

Layered volcanics occupy a significant area in Idaho, Oregon, and Washington. In many locations these volcanic sequences are capable of sustaining a high level of ground water production and, despite a wide degree of compositional variety, these volcanics have many similar physical and related hydrologic properties. This hydrologic similarity indicates that similar resource management criteria and proceses might be applicable for widely separated areas. It also seems likely that research methods used in investigating ground water resources in one area might well be applicable to other layered volcanic areas. Thus, technically, it seems quite possible that ground water resource management could be done on virtually any scale.

Despite its technical feasibility, it is likely that any plan to manage ground water resources on an interstate or regional basis might have to overcome serious administrative problems. Current laws and water resource management policies of the three states are generally similar and there is a general consensus about the need for and method of management, yet there are still problems which are not easily overcome. One of the problems is the lack of adequate administrative methods to deal with a constantly varying situation in management of a ground water basin. Another is the general lack of testing of the legal validity of much of the ground water law. Although the laws have been in existence for some time, there have been relatively few court tests, particularly of the procedures for limiting and controlling resource development and use. Thus, it is not certain that if after considerable effort were taken to establish an interstate or regional resource management program that the program would necessarily withstand legal challenge.

Finally, there is perhaps the biggest problem of all, that of public acceptance. Given the rather possessive and independent nature of state populations and their governments, particularly related to natural resources, it is likely that there would be no small amount of resistance to sharing control of the resource with a neighboring state. In general, states are reluctant to enter into such a relationship unless a crisis necessitates it.

It is likely, therefore, that it will be in a crisis situation that the first attempts to manage ground water resources on an interstate or regional basis will be made. Although responding to a crisis situation may produce some hastily designed policy, it is probably the only situation that will provide the incentive to overcome the obstacles to such a program. If the incentive to manage ground water resources on an interstate or regional basis ever becomes present, it is apparent that such a management program is feasible.

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