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REPORT OF THE TECHNICAL ADVISORY COMMITTEE ON THE CAPTURE OF SURFACE WATER BY WELLS

Recommended Technical
Methods for Evaluating the Effects
of Ground-Water Withdrawals on Surface Water Quantity

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

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TECHNICAL ADVISORY COMMITTEE ON THE "CAPTURE OF SURFACE WATER BY WELLS"

EXECUTIVE SUMMARY

Charge to the Committee

The Technical Advisory Committee on the Capture of Surface Water by Wells was convened by the Department of Ecology, with the support of the "Five Corners" legislative water policy group, to seek agreement among technical experts on appropriate technical methods for assessing and quantifying the effects of ground-water withdrawals on surface-water sources.[1] Agreement on technical methods for evaluating ground-water/surface-water interaction is important to ensure a sound scientific basis and regulatory consistency in the management of Washington's increasingly sought-after water resources.

The Technical Advisory Committee was charged only with examining the quantitative effects of capture, and did not address the technical evaluation of related water issues, such as surface-water hydrology, minimum instream flows, water quality and habitat. These areas are, of course, also important and relevant in watershed management. The Committee intentionally focused on technical issues, leaving the policy questions related to surface water capture to be taken up in different forums. (The Department intends to follow up the Technical Committee's work with a process to address policy issues related to surface water capture, including when capture constitutes impairment of existing water rights and what mitigation measures might compensate for potential impairments.) The Committee did consider what types of technical questions arise under the present regulatory framework so as to ensure that its technical recommendations would be useful and grounded in reality.

In this Report, the Committee has attempted to communicate its key scientific and technical conclusions in a way that is clear to the non-technical audience, as well as to hydrogeologists and technical experts in government and the private sector.

Committee Response to the Charge

The Technical Advisory Committee was asked to address several issues. These questions, and a summary description of the Committee's response to each, are listed below:

[1] The Five Corners group represents the majority and minority caucuses of the Washington State House and Senate, as well as the Executive Branch. It was convened to work together to develop legislation for key water-resource policies, including watershed planning. It authorized and supported the formation of the Technical Advisory Committee on Capture.

What methods should be used to assess not only where ground-water/surface-water interactions are important and where capture might occur in a given watershed, but also the quantity and timing of any capture?

No single technical approach will fit all circumstances; appropriate analytic tools for a given situation depend on hydrogeologic complexity, the nature of proposed withdrawals, regulatory constraints and management needs for information. In this Report the Committee reviews the scientific principles that should guide any technical analysis, and presents a general framework for selecting appropriate analytic tools to estimate quantity, timing and duration of capture.

How should the effects of individual wells or withdrawals be considered within the context of cumulative effects of all wells, both existing and proposed, within a watershed or ground-water basin?

The general framework developed by the Committee is appropriate for selecting analytic tools to evaluate surface water capture at both a site-specific and basin-wide level. The Committee also recommends that a concerted effort be undertaken to develop and/or improve the data and analytic tools that would support the assessment of cumulative, basin-wide effects in all basins in Washington State.

What is the tradeoff between amount of effort (and time) required, and the certainty or accuracy, for different technical methods?

The Committee reviews different categories of models and associated levels of data collection, and provides guidance as to which analytic tools are most suitable for which circumstances in its proposed framework. The level of effort appropriate in a given situation may still vary significantly, depending on site-specific factors such as the availability of existing data. The Committee believes that its recommendation for developing basin-scale analytic tools throughout the state will, in the long run, reduce the cost for analyzing the effects of individual withdrawals.

How well suited are the different technical methods for screening (i.e., watershed assessment), as well for more rigorous investigations?

Depending on the hydrogeologic circumstances and the technical questions posed, differing levels of analysis may be sufficient. Also, some analytic approaches are valid primarily at a local level, while others serve better for watershed-scale analysis. The Report presents a range of simple to complex analytic tools, and describes how to decide which approaches are technically valid and appropriate for different settings.

How do appropriate methods need to be tailored for different geographic areas or geologic settings in the state?

> While distinct hydrogeologic regions exist in the State, the Committee found that the definition of generalized hydrogeologic settings was sufficient to provide guidance on analytic tool selection. Although hydrogeologic complexity is a key factor, the selection of an appropriate analytic approach depends on other important factors as well, including the nature of regulatory constraints, management information needs, and available data.

Key Committee Findings and Recommendations

Capture Analysis Should Be Based on Accepted Scientific Principles

The Committee agrees that the technical analysis of surface-water capture by wells should be rooted in broadly accepted, state-of-the-art, scientific principles governing ground-water and capture effects on surface-water flow, including the law of conservation of mass and Darcy's Law. Based upon these principles, the Committee agrees that, in the long run, any ground water withdrawal will reduce ("capture") surface water flow in one or more hydraulically connected water bodies, and may also affect other parts of the water cycle, such as the amount of water returned to the atmosphere through evapotranspiration. Questions that may require further analysis are: *how much* of a surface-water body's flow will be captured, *where* will water be captured (i.e., which surface-water bodies will be affected; *when* will the effect occur, and *how long* will the effect last.

A Recommended Framework for Analyzing Surface-Water Capture

No single technical approach will fit all circumstances. Therefore, the Committee has developed a method for selecting appropriate analytic tools to analyze the capture of surface water, rather than attempting to prescribe specific analytic tools for the wide range of possible circumstances. The Committee recommends that the Department of Ecology and water-rights applicants use this framework to determine the best technical tools for evaluation of applications for ground-water rights. As circumstances in specific evaluation locations are often unique, appropriate discretion will also be required for each case.

The Framework, shown in Figure ES-1, applies a problem-solving approach to the evaluation of the capture of surface water by wells. First, existing data are synthesized, and a conceptual model of the basin's hydrogeology is developed. A conceptual model is a simplified representation of a complex hydrogeologic system – including, for example, defining ground-water flow system boundaries (such as rivers or other barriers to flow, like bedrock), ground-water-flow directions and gradients, recharge and discharge areas, and the characteristics of aquifer materials.

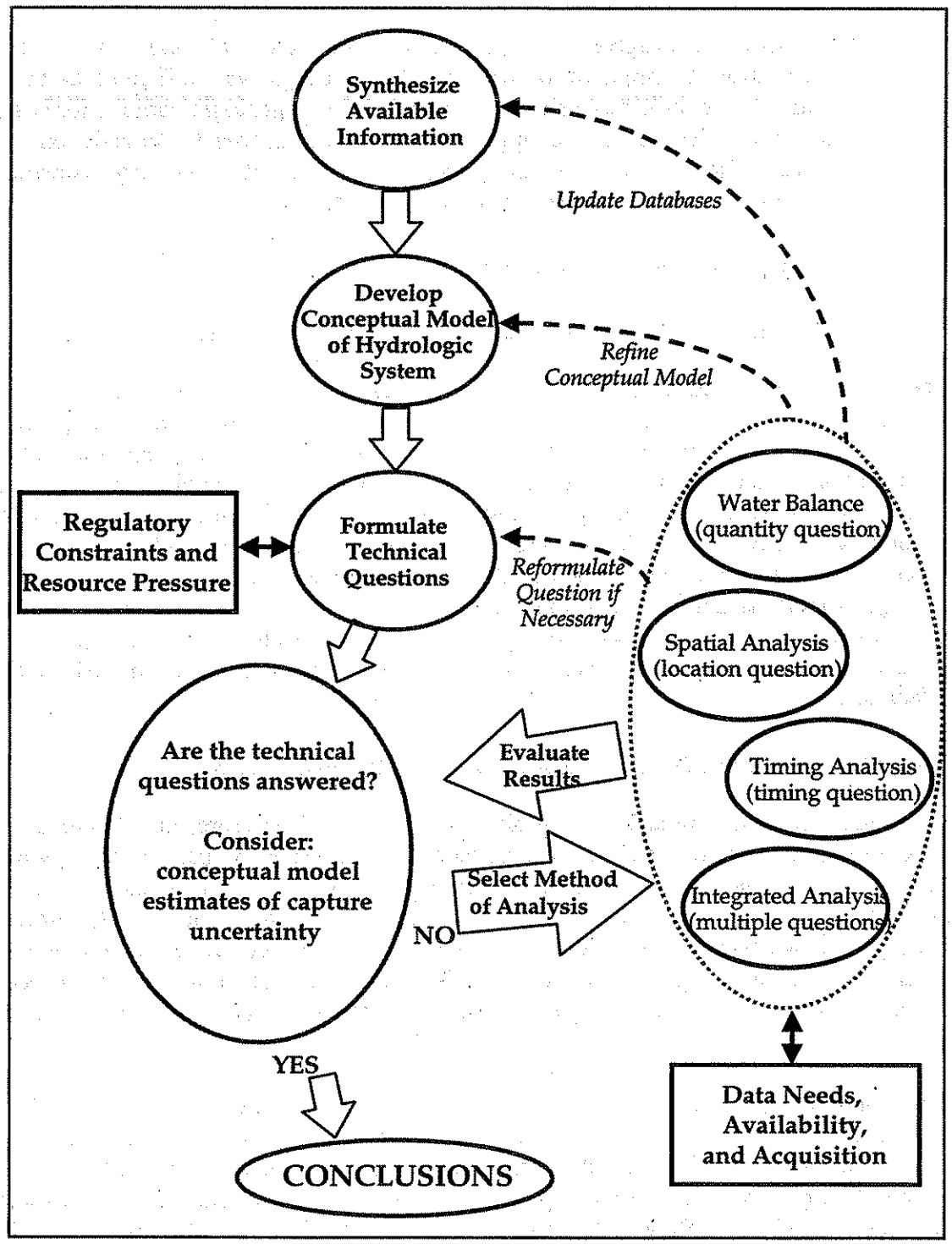

Figure ES-1 : Framework for Capture

Second, technical factors (i.e., hydrogeologic complexity are considered in selecting an appropriate method to answer technical questions. The Committee defined six generalized hydrogeologic settings that will describe most settings encountered in the State, and that may be analyzed using appropriate technical tools. Regulatory constraints (such as seasonal closures and minimum instream flows) and management-driven needs for information (such as the effects of potential mitigation actions) further focus and narrow the choice of appropriate method for a given situation. The Committee also recognizes that water-resource areas with higher development pressure and value may deserve a more detailed and thorough analysis.

Analytic approaches are grouped into four classes, depending upon the nature of the technical question to be answered and in increasing order of sophistication and effort required:

- *Water balance*, which simply identifies the inflows and outflows of water in a study area;

- *Spatial analysis*, which identifies the possible locations of capture due to ground-water withdrawals;

- *Timing analysis*, which estimates when effects will be felt at locations of interest; and

- *Integrated Analysis*, the most sophisticated and accurate approach, which estimates the magnitude, distribution and timing of effects, using a two or three-dimensional, time-dependent, numerical computer model.

Depending on the circumstances, different levels of analysis may be called for, ranging from a Conceptual Model coupled with a Water Balance to rigorous numerical modeling. In its Framework, the Committee recommends appropriate classes of modeling tools for specific hydrogeologic settings, regulatory constraints, and management information needs. (See Chapter 4 for details, and Appendix A for examples.) The more complex numerical models generally require more data, drawn from maps, well-logs, stream flow measurements, published reports or direct field tests and measurements. Indeed, monitoring and data-gathering may often be the most time- and resource-intensive aspects of the more complex methods for evaluating capture. Table ES-1 presents a general comparison of several types of groundwater models.

Table ES-1: Comparison of General Model Types

Tool or Technnique	Estimation of Timing, Location, Quantity	Most Useful Scale	Relative Effort to Obtain / Use	Relative Cost	Time Required to Apply	Relative Quality of Result
Conceptual Model	Qualitative only	**Local, Sub-basin, Basin**	Low to High	Low	Days to Years	Qualitative only, considered to be a necessary component of all types of analyses
Water Balance	Q	**Local, Sub-basin, Basin**	Low	Low	Days	Lowest level of detail and resolution. Simple accounting models assumes spatial impacts, no timing component.
Analytical Model	T, **Q**	**Local**	Low	Low	Days to Weeks	Lesser level of detail and resolution; assumes location is known, conservative analysis requiring simplifying assumptions
2D Areal Analytical Element or Numerical Model	T, **L, Q**	**Local, Sub-basin**, Basin	Med	Low - Med	Weeks to Months	Moderate level of detail and resolution; quantitative, analytical models requiring simplifying assumptions
3D Steady-state Numerical Model	**L, Q**	Local, **Sub-basin, Basin**	High	Low to **High**	Months to Years	High level of detail and resolution; quantitative, depends on boundary conditions and level of knowledge
3D Transient Numerical Model	**T, L, Q**	Local, **Sub-basin, Basin**	High	Low to **High**	Months to Years	Greatest level of detail and resolution; depends on boundary conditions and level of knowledge

NOTES:

1. Bold text indicates primary use.
2. Relative Effort reflects the sophistication of the mathematical model and the technical skill requirements of the analyst .
3. Relative Cost reflects the sophistication of the modeling approach, the time required to prepare and document the analysis and the importance of the result desired.
4. Time Required reflects the typical range of time expended, but will depend on the approach used, the dimensionality of the model, availability of data, required field investigations and data gathering and the skill of the analyst.

*Analytical element analyses are included where "numerical" is stated

After quantitative analysis is completed, results are evaluated to determine whether they are reasonable in light of the conceptual understanding of the basin, and whether they are sufficiently accurate to answer the technical question to the appropriate detail and reliability. If necessary, further refinement and analysis is performed until the question is adequately answered.

Basin-Scale Analyses and Data Sets Should Be Developed in All Basins

A key conclusion of the Committee is that water-withdrawal proposals are always best evaluated in the context of an entire watershed. Therefore, the Committee recommends that tools and capacity be developed for basin-scale analysis of water resources. The most effective and efficient way to manage water resources is at a watershed or basin scale. The whole-watershed perspective allows for better long-range planning, what-if analyses, evaluation of individual withdrawals in the context, of cumulative withdrawals, consideration of exempt wells and uncontrollable factors, and evaluation of systemic mitigation and management measures. Basin-scale analytic tools will also make the evaluation of water-rights applications less time-consuming, less costly and more consistent.

The Committee outlines three tiers of basin analysis that may be undertaken, depending on the urgency of problems and level of demand for water.

- Level I basins are those basins experiencing the least pressure on water resources, as evidenced by limited settlement and water demand, no habitat concerns, and available water for additional, future appropriations. Recommended basin analysis for a Level I basin would include development of a watershed-scale conceptual model and establishment of long-range data collection and monitoring strategies.
- Level II basins experience significantly higher demand on available water resources, as indicated by water rights not being met, population growth, and increasing habitat concerns. Recommended analysis for Level II basins is correspondingly more intensive, and includes resource mapping, data-gathering and development of basin models of moderate sophistication.
- Level III basins are those watersheds experiencing impairment of minimum instream flows or senior rights, significant water-quality degradation, or habitat degradation affecting threatened or endangered species. Analyses in these basins would include intensive field data collection and development of integrated, three-dimensional ground-water/surface-water models. The more sophisticated and resource-intensive analyses in Level III basins are necessary to support difficult and complex management decisions with high-stakes consequences.

The Committee recommends that Ecology, in partnership with the United States Geological Survey, other state, federal, and local agencies, tribes, citizens, and other entities, undertake a concerted program to develop the tools and data needed to support basin-scale analysis in all river basins in the State. Resources should be sought to undertake expensive data collection/monitoring efforts, and technical capacity should be

built at the watershed level. The Committee also recommends establishing priorities for limited financial and technical assistance resources, so as to address the need to support watershed management in basins experiencing strong pressures, as well as to protect less developed watersheds with high-quality water and habitat.

Monitoring and Data Collection

The Committee agrees that good data are critical to confident assessment of surface-water capture, but that current data in most basins in the State are inadequate. A long-term data collection and monitoring strategy should be defined in each basin, so as to build the needed information base for analysis and management. The analytic and data collection efforts of applicants and permittees should be pooled to support the basin-wide data collection plan. (Individual applicants with small applications should not be expected to contribute substantially to development of a basin model.) Ecology and partner agencies should also undertake coordinated data collection, establish data standards to ensure that data are consistent and can be shared, and use or build appropriate databases and Geographic Information Systems (GIS). The Committee recommends, in particular, the systematic measurement of actual water use (total and consumptive) and collection of basic hydrologic and geologic information – critical data that should be upgraded to support more detailed capture analysis in most basins. Data should be publicly accessible, preferably via the Internet.

Roles and Responsibilities

This report outlines a framework for conducting appropriate technical analysis of surface-water capture, but makes no recommendations as to who should be responsible for what steps or tasks in that process. The Committee recommends that the respective responsibilities for both a water-right applicant and Ecology in this process should be further defined. In general, water-right applicants should bear the responsibility of providing more sophisticated analyses and more extensive data where they wish to go beyond the conservative assumptions of simple analytic solutions.

Roles and responsibilities for collecting data and maintaining basin-wide databases, and for developing and updating basin-wide analytic/modeling tools, will also need to be clearly defined. The Committee recommends that these data collection and maintenance responsibilities be shared through a coordinated effort, involving federal, state, local, and tribal governments, citizens, industry, and other interested groups. An interagency/stakeholder effort could greatly enhance the consistency of data collection, the accuracy of analyses, and overall, the pace of completion.

TECHNICAL ADVISORY COMMITTEE ON THE "CAPTURE OF SURFACE WATER BY WELLS"

CHAPTER I: INTRODUCTION

Charge

The Technical Advisory Committee on the Capture of Surface Water by Wells was convened by the Department of Ecology, with the support of the "Five Corners" legislative water policy group, to seek agreement among technical experts on appropriate technical methods for assessing and quantifying the effects of ground-water withdrawals on surface-water sources.[1] These technical methods include suitable tools for evaluating the location, quantity, timing, and duration of surface water reduction, or "capture". "Tools" in this report encompasses numeric models and other analytical methods, as well as appropriate types of supporting field tests and other data.

The Technical Advisory Committee was asked to address several issues in its efforts. Among those questions the Committee was asked to consider are the following:

1. What methods should be used to assess not only where ground-water/surface-water interactions are important in a given watershed, but also the quantity and timing of any capture?

2. How should the effects of individual wells (i.e., withdrawals) be considered within the context of cumulative effects of all wells, both existing and proposed, within a watershed or ground-water basin?

3. What is the tradeoff between amount of effort (and time) required, and the certainty or accuracy, for different technical methods?

4. How well suited are the different technical methods for use at a screening (i.e., watershed assessment) level of analysis, as well as at a more rigorous level of investigation?

5. How do appropriate methods need to be tailored for different geographic areas or geologic settings in the state?

Agreement on technical methods for evaluating ground-water/surface-water interaction is important as Washington's surface waters are increasingly closed to new appropriations (water rights) or subject to intense competition, causing those seeking new water rights increasingly to apply for ground water as their source of supply. Scientific studies have

[1] The Five Corners group represents the majority and minority caucuses of the Washington State House and Senate, as well as the Executive Branch. It was convened to work together to develop legislation for key water-resource policies, including watershed planning. It authorized and supported the formation of the Technical Advisory Committee on Capture.

firmly established that ground-water withdrawals can reduce surface-water flows, so it is crucial that ground-water applications be evaluated for their potential effect on streamflow and senior water rights. Consistent and agreed upon evaluation methods will help to provide a sound scientific basis for, and support regulatory consistency in, the management of water resources including water-right permitting, regulation, and consideration of mitigation for effects of withdrawals.

Scope

The Technical Advisory Committee was charged with examining only the quantitative effects of capture and did not address additional issues such as surface-water hydrology, established instream flows, water quality, and habitat. Its mission was to consider appropriate technical means of evaluating how much, when, and where ground-water pumping will capture surface water. The Committee did recognize that ground-water pumping may affect the aquatic ecosytem in a basin in ways other than the direct reduction of stream flow. It agreed that these effects should also be considered in evaluating the effects of proposed ground-water pumping as such factors are relevant and important in watershed management. A more limited focus on relative hydrologic effects was the most practical approach for the Committee to take, however, given time constraints, the Committee's charge, and the Committee members' expertise. Though policy issues were not directly addressed, the Committee did consider what types of technical questions and settings arise under the present regulatory framework so as to ensure that its technical recommendations would be useful and grounded in reality. Its findings are presented in a manner consistent with the Committee's intent to clarify these sometimes complicated technical questions for all readers.

Committee Membership

The Technical Advisory Committee is a small group of technical experts whose qualifications include both scientific expertise in hydrogeology and ground-water/surface-water interaction, and practical experience in ground-water evaluations in Washington State. In addition, the Committee represents a range of institutional affiliations, including academia, Indian tribes, government, environmental/non-profit groups, and private consulting firms. A variety of technical backgrounds and geographic areas (both the east and west sides of the Cascades) is also represented.

Process of Developing the Report

The Committee accomplished its work through a series of five facilitated all-day meetings between the months of April and July, 1998. The first meetings provided Committee members with a working understanding of the legal and political history of the issue, the current regulatory framework used to evaluate water-right applications, and recent efforts to address the capture question. Subcommittees were also formed to help further develop specific aspects of the Committee's work. These products were then revised and refined based upon discussions of the full Committee.

What Will Follow the Technical Committee's Work?

After the Committee has completed its job of developing appropriate technical methods for assessing ground-water/surface-water interactions, Ecology intends to commence broad-based discussions on how to use the recommended technical tools. One focal point will be key policy questions, such as when do the effects of capture constitute an impairment of existing rights or established instream flows. A second focal point will be to investigate what might be appropriate in-kind and out-of-kind mitigation measures to compensate for potential impairments, and how the tools recommended by this process could be used to evaluate specific mitigation proposals. The Committee's scientific discussion will inform these important policy decisions and provide direction to the Department of Ecology with respect to ground-water/surface-water interaction issues.

Content

The remainder of this report represents the Technical Advisory Committee's discussions, deliberations, and final recommendations with respect to the appropriate technical methods for evaluating the effects of ground-water withdrawals on surface water. The contents of the remainder of the report are as follows:

- Chapter Two, ***History and Current Setting***, provides a brief explanation of the history of the issue and its importance. This chapter also includes a brief discussion of the present situation and the current legal setting.

- Chapter Three, ***How Ground-water Withdrawal Captures Surface Water***, describes the hydrologic cycle and the first principles of ground-water flow.

- Chapter Four, ***Tools for Evaluation of Surface-Water Capture by Wells,*** explains the evaluation process, part technical and part procedural, developed by the Advisory Committee. This evaluation process describes the recommended technical approach for analyzing the effects of ground-water withdrawals on surface water.

- Chapter Five, ***Watershed Management/Basin Planning,*** examines in greater detail the role of a basin-wide evaluation approach in the determination of surface-water capture by ground-water withdrawals.

- Chapter Six, ***Conclusion,*** revisits how the Committee responded to the questions posed in its charge, and recaps key recommendations.

CHAPTER II: HISTORY AND CURRENT SETTING

History of Issue

Washington State's water code, adopted in 1917, is based on the doctrine of prior appropriation ("first in time, first in right"). The code is designed to protect senior (prior) water rights from impairment by junior (later) rights. Rights were allocated based upon the actual diversion of surface water and the application of that surface water to a beneficial use. The ground water code, enacted in 1945, supplemented the 1917 water code and stated that senior surface-water rights were not to be impaired by subsequent uses authorized under the ground water code.[1]

Although the water code made protection of existing rights an integral part of state water law, those protections were not initially extended to instream flows. Laws later enacted, however, have acknowledged the need to keep water of sufficient quantity and quality within streams and lakes to protect instream and natural values and rights. Initially, the focus of these laws was fish, and Ecology was given the authority to refuse to issue a permit if to do so would lower the flow of water in a stream below the levels necessary to support the fish population.

In 1971, the water code was amended to authorize Ecology to establish and protect instream flows. The amendment declared that "[r]eservations of water for minimum flows or levels constitute appropriations with priority dates of the effective dates of their establishment," thereby emphasizing that minimum instream flows have priority dates and seniority like any other water right. It also specified that Ecology must give" full recognition" to "the natural interrelationships of surface and ground waters."

Over the years, Ecology has tried several methods to address the question of capture of surface water by ground-water withdrawals, including the use of setbacks of wells some distance from streams, requirements to case wells into confined aquifers, and the allowance of a percentage of streamflow capture within a given amount of time as calculated by the use of analytical solutions. These methods tended to allow for new ground-water withdrawals, as they were thought to be protective, based upon the assumption that most rates of streamflow capture by wells were *de minimus* (insufficient to warrant concern), and so were insufficient to warrant concern. These techniques were used to evaluate individual applications but did not consider the cumulative effects that additional withdrawals might have on the watershed. Many groups, including tribal governments, were not satisfied with these procedures as streamflows became depleted as a result of additional withdrawals.

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[1] There are other types of water rights, including Federal reserved rights and tribal treaty rights (including instream flows to support tribal fisheries), that are not directly administered by the state, but that the state is still legally required to protect. Frequently, if not generally, rights of these types have very senior priority dates. At the same time, these rights most often have not been quantified, making the task of protecting them more difficult.

The Present Situation

By contrast, Ecology's current approach is to examine water-right applications in the context of watershed assessments. This approach evaluates the overall availability of water for new uses. The agency recognizes that even small rates of surface-water capture might constitute impairment if senior surface-water rights, including established instream flows, are routinely not satisfied.

The subject remains controversial, in part because the cumulative effects of ground-water withdrawals on surface water are not always recognized, and in part because no agreement has been reached within the state about the appropriate methods for evaluating ground-water/surface-water interactions.

The Current Legal Setting

Water in Washington is allocated on the basis of a permit system. Anyone seeking to make use of water must, with some very limited exceptions, make application to the Department of Ecology for a permit to do so. Ecology is then required to investigate that application and issue written findings of fact (Report of Examination). To approve a permit, Ecology must find that:

- the proposed use is beneficial;
- the use will not be detrimental to the public welfare;
- water is available for appropriation; and
- the use will not impair existing rights.

Of these four tests, the last two are key questions with respect to the possible capture of surface water by a well. If any of these conditions cannot be satisfied, Ecology is obliged to deny the application absent satisfactory mitigation for predicted effects.

About half of the approximately 600 water-right decisions issued by the Department of Ecology between 1994 and 1996 were denials. In many cases, these denials were based upon 16 initial watershed assessments that found established instream flows were increasingly not being met. Ecology reasoned that if no further surface-water diversions could be permitted due to streamflow conditions, then ground-water withdrawals should be held to the same standard. These decisions have nearly all been upheld by the Pollution Control Hearings Board and the Superior Court of King County. Ecology currently evaluates new applications in the context of how the proposed water use will affect not only the most proximate streams but how they could affect the entire hydrologic system on a watershed scale.

CHAPTER 3: HOW GROUND-WATER WITHDRAWAL CAPTURES SURFACE WATER

3.1. Water Cycle and Water Balance

Following is a description of the fundamental physical systems and principles of hydrology.

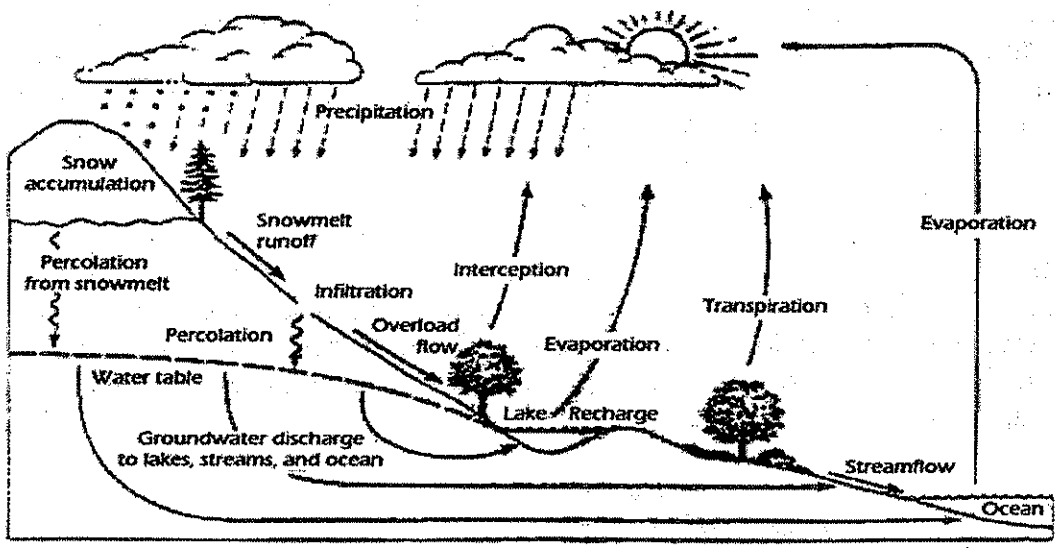


Figure 3.1 Visual Representation of the Water Cycle

Driven by physical forces, water, in its liquid, solid, and gaseous states is in constant motion. The term water cycle (pictured in Figure 3.1) refers to the constant movement and various interdependent processes that affect water above, on, and below the Earth's surface. It is a cycle because the same water molecules continuously circulate through the system and mass is conserved; that is water is neither created nor destroyed, just reused. Changes in one component of the water cycle usually affect another component, as is the case with the capture of surface water by wells.

Water molecules change form among liquid, solid, and gaseous states in the water cycle and change locations among surface water, atmospheric water, vapor, and ground water. Liquid water on the surface evaporates, flows through the atmosphere as water vapor, forms clouds, and falls as rain or snow. Precipitation, in turn, either runs off as surface water, returns to the atmosphere as water vapor by evaporation or transpiration through plants, or percolates down through the soil to become ground water.

Ground water and rivers have an interdependent relationship in the water cycle. At some locations, surface water seeps through the bed and banks of a river and becomes ground

water. At other locations, ground water flows back to the surface and contributes to streamflow.

Waters moving through various components of the water cycle are sometimes said to be in storage in various reservoirs. For example, within a watershed, at a given time, the total water in the watershed will be in snowpack storage, surface-water storage, soil-water storage, ground-water storage, and water held within vegetation. Use of the term storage does not mean that the water is stationary. Rather, while residing in one type of reservoir, water moves from areas of replenishment to areas of outflow. Averaged over a period of many years, water in each of these reservoirs is approximately constant, that is, inflow equals outflow if climatic conditions are stable. During a single year, the volumes in each reservoir usually change seasonally in accordance with the seasonality of precipitation and runoff.

In Washington, most precipitation falls during the winter months. Some of this water accumulates as snowpack. The ground-water reservoir tends to accumulate water during this time because precipitation is high and usage of soil moisture by vegetation is small, allowing the highest rates of percolation through soil to the water table. The ground-water and surface- water reservoirs in Washington tend to contain more water during the spring, when snowmelt is filling the rivers with water, than at other times. In late summer, when little seasonal snow remains and streamflow is approaching its annual low, much of the water in the rivers is being provided by ground water flowing to the surface. This is called the "base flow" of the stream. (This is a different usage of the term "base flow" than is contained in Washington water law).

Because mass is conserved in the water cycle, it is possible to speak of the "water budget" of a basin. Water-budget equations can be formulated to illustrate that for each water-budget component, inflow equals outflow plus change in storage. Therefore if water is removed from one storage compartment, outflow from that storage element will be reduced, which , in turn, affects the water budget of another component.

3.2. Principles of Ground-water Hydrology

Ground water flows according to well understood scientific principles. Although the details of the underground soil and rock materials are always imperfectly known, the basic processes by which water enters the ground, flows through soil and rock under the force of gravity, and flows back to the surface to contribute to streamflow are well described in scientific literature. Translation of these principles into mathematical equations, along with knowledge of the properties of subsurface materials, allows for estimation of the magnitude, location and timing of the capture of surface water by wells, the task of this advisory committee. The description of ground-water hydrology presented here is adapted from Heath (1992) and Toth (1970).

Hydrogeologic Environment

Within any watershed or drainage basin, the physical and chemical conditions in ground water result from the combined influence of climate, geology and topography, which together constitute the hydrogeologic environment (or setting).

The climate delivers a certain average amount of water to a given point in the landscape during a given period, as precipitation. This influences the success of vegetation, which in turn affects the amount of water returned to the atmosphere as evapotranspiration. *Geology* (including soil characteristics) determines how easily water can enter and flow through the ground-water system and how much water runs off across the surface. For example, when rain falls at a rapid rate on low-permeability materials, the capacity for water to infiltrate may be exceeded and runoff occurs. Conversely, rain falling at a lower rate on more permeable soils tends to infiltrate and recharge ground water. In watersheds with large volumes of porous and permeable underground material, streamflow is moderated as large volumes of water go into temporary ground-water storage during times of high precipitation and runoff, reducing peak flows and contributing to baseflow later in the season. *Topography* determines the amount of energy available to drive the water flow because the source of energy is gravity. The greater the difference in elevation between the point where water enters the ground and where it exits, the greater the energy.

Geology: Aquifers and Aquitards

Ground water flows through a continuum of geologic materials with varying hydraulic properties. The aquifer/aquitard system is a concept imposed on the continuum of geologic materials to aid understanding and calculation of flow processes. The ease with which water passes through a material is called *hydraulic conductivity* and is related to the size of the pores in the material. For example, gravel has a higher hydraulic conductivity than sand, which in turn is higher than that of clay. Layers or bodies of material which transmit water relatively easily (i.e. have high hydraulic conductivity) and yield useful quantities of water to wells are called *aquifers*. Layers with relatively low hydraulic conductivity are called *aquitards or confining beds*. When the water in an aquifer does not fully fill the aquifer material, that is there is unsaturated material above the water table, the aquifer is said to be an unconfined aquifer or water table aquifer. Where water completely fills an aquifer that is overlain by a confining layer, the aquifer is said to be confined. In some areas, particularly areas underlain by layered sedimentary or volcanic rocks, aquifer *systems* exist, consisting of several layers of aquifers connected to one another by leakage through a series of aquitards.

Topography (Gravity Drives Ground-Water Flow)

Gravity is the driving force that moves ground water through the flow system. Water enters the ground-water system at the highest point on its flow path and leaves by discharging to a surface-water body at lower point. As a consequence, topography is an important control on ground-water flow, and ground-water flow tends to mimic surface-water flow, flowing downhill from the drainage divides toward the valleys where it discharges to the surface. The amount of potential energy available to move water (called hydraulic head) is measured as the elevation to which water rises in a well.

Ground water moves from high head to low head, losing energy to friction as it goes. For example, ground water flows down the slope of the water table, which is the upper surface of the saturated zone. The loss in head divided by the length of flow is called the *hydraulic gradient.*

Recharge and Discharge Are Balanced if Climate is Steady

Water entering the ground-water system is called *recharge*. Recharge occurs by the downward flow of precipitation that falls on the land surface or by seepage from a river or lake through the bed or banks. Water leaving the ground-water system is called *discharge*. Ground water flows through openings in geologic materials until it eventually discharges into a stream or lake or by being returned to the atmosphere as water vapor through the leaves of plants with roots tapping shallow ground water (called *evapotranspiration*).

Darcy's Law

Darcy's Law is the fundamental equation governing ground-water flow. Darcy's Law states that the rate of ground-water flow is proportional to the hydraulic conductivity and the hydraulic gradient. This applies in three dimensions, to both horizontal and vertical flow within an aquifer. Ground water flows down the hydraulic gradient regardless of its orientation. Ground water movement from one aquifer into an aquitard and on into another aquifer is called *leakage*. Leakage may be either upward or downward, but it always proceeds from higher head to lower head. Ground water flows upward if the water head is higher at deeper levels than at shallower levels, a common occurrence near discharge areas. This results as water entering at the recharge area is being pulled downward by gravity, which in turn provides the pressure to push water back up to the surface beneath the discharge area. In multi-layered hydrogeologic settings, this pressure (called *artesian pressure*) forces the water in deeper units to leak vertically upward through successive overlying aquitards and aquifers until it discharges to the surface. In this situation, withdrawing ground water from the confined aquifers decreases the artesian pressure and decreases the quantity of upward leakage to the discharge area.

In some hydrogeologic settings, aquifer systems develop local, intermediate, and regional flow systems with respectively longer flow paths at deeper levels. Pumping from a deeper regional flow system does not exclusively intercept flow destined for the more distant regional discharge area, but also intercepts flow from local and intermediate systems by inducing additional vertical leakage. Therefore, to determine the location of capture effects, one must look not only at the discharge area for the aquifer being pumped, but at the potential relationship with all aquitard and aquifer units within the flow system. Measuring water levels in wells of different depths over a large area and applying Darcy's Law allows one to determine: (1) the locations of recharge areas; (2) flow directions (both horizontally and vertically); and (3) the surface-water bodies to which the ground water discharges.

Conservation of Mass and Capture of Surface Water by Wells

Conservation of mass, along with Darcy's Law, governs the response of aquifer systems to ground-water pumping. Within an aquifer or multiple aquifer system, inflow of water

equals outflow plus change in the amount of water in storage in the aquifer. Prior to beginning ground-water withdrawals, a balance (dynamic equilibrium) exists between discharge and recharge of ground-water. This equilibrium can be stated as the equality,

$$\text{natural discharge (D)} = \text{natural recharge (R)}$$

When a well begins pumping, water is initially removed from the vicinity of the well, forming a cone-like depression in the ground-water surface (called a "*cone of depression*"). At this stage, withdrawal (Q) is equal to reduction in storage (S),

$$Q = \Delta S$$

As pumping continues, the cone of depression causes the water to flow toward the well and the cone increases in size until as much water is flowing toward the well as is being removed. The cone of depression eventually reaches either a discharge area or a recharge area of the aquifer.

If the cone of depression reaches a discharge area, first, the hydraulic gradient toward the discharge area will be reduced, and less water will discharge from the aquifer. If the reduction in discharge (D) increases to equal pumpage, then the cone of depression will stop expanding and a new equilibrium will be reached. Then

$$(D - \Delta D) + Q = R$$

Conversely, if the cone of depression reaches an area of active or potential recharge first, the hydraulic gradient in the area will increase, and recharge from surface water may be induced (if water is available). If increased recharge (ΔR) becomes equal to pumpage, then

$$D + Q = R + \Delta R$$

Over time then, pumpage will become equal to change in discharge and/or recharge such that

$$Q = \Delta D + \Delta R$$

The above relationships apply to both confined and unconfined aquifers.

The timing of capture of surface water by wells depends on:

1. The rate of expansion of the cone of depression caused by the withdrawals. For a single aquifer, this rate depends on two properties of the aquifer: (1)*transmissivity* (the hydraulic conductivity of the aquifer times the thickness of the aquifer) ; and (2) *storativity* (a parameter relating the amount of water removed from the aquifer to the reduction in water level in the aquifer, for example if removing 1 cubic foot of water caused a three foot drop in water level, the aquifer has a storage coefficient of .33).

For pumping from a confined aquifer in a multi-layered ground-water flow system, where aquitards lie between the aquifer being pumped and the stream, the rate of expansion of the cone of depression in three dimensions depends on the three-dimensional distribution of hydraulic conductivity and storativity. In a confined aquifer the cone of depression is not a coned-shaped area where water is physically removed from the aquifer, but rather a cone-shaped decrease in artesian pressure in the aquifer. Simulations of the effects of ground-water pumping over time (called transient simulations) include these parameters in the calculations.

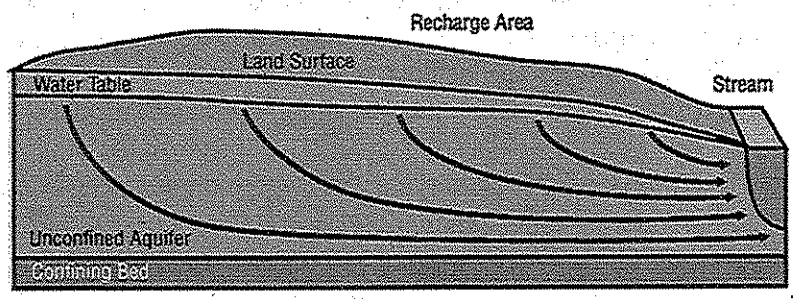
2. The distance from the well to discharge areas (where capture can occur).

3. The distance from the well to recharge areas where additional recharge may be induced, that is, to a surface-water body which can contribute additional recharge by leakage through the bed or banks.

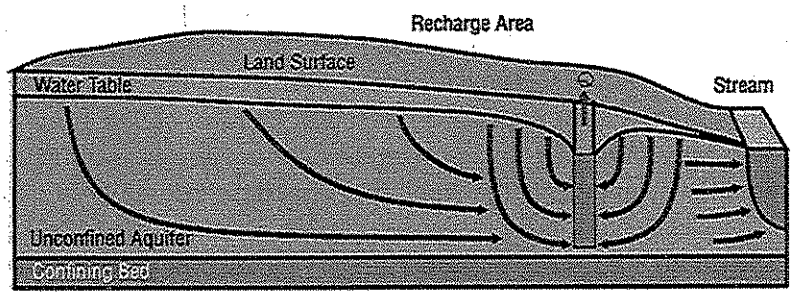
Streamflow capture continues after the cessation of pumping until the cone of depression disappears and water levels in the aquifer have returned to pre-pumping levels, (provided ground-water pumping has not exceeded the recharge rate, called ground-water mining). The affect of stopping pumping will propagate outward in three dimensions and capture effects will gradually disappear in the same way that they gradually began.

Just as in unconfined aquifers, pumping from a confined aquifer creates a cone of depression, which, in this case, alters the hydraulic gradient across the adjacent aquitards. This either intercepts upward leakage initially destined for overlying aquifers and induces area of ground-water discharge or induces additional downward leakage from overlying aquifers and surface -water bodies (Figure 3.3). As illustrated by the above, in the long run, ground-water pumping, always affects surface-water flow in one or more hydraulically connected surface-water bodies, and may affect other parts of the water cycle, such as evapotranspiration. The questions to address regarding the effect are: (1) when does it occur; (2) where; and (3)how much.

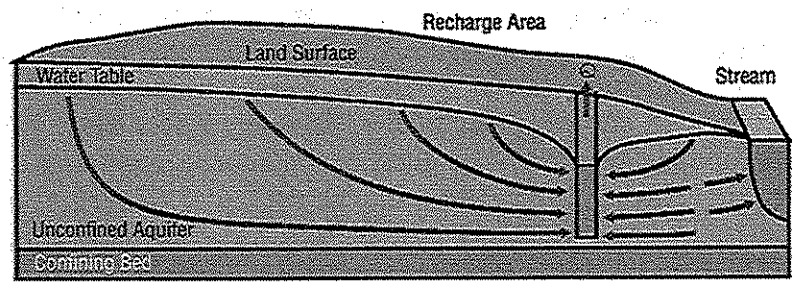
Figure 3.2 Source of Water Derived From Wells



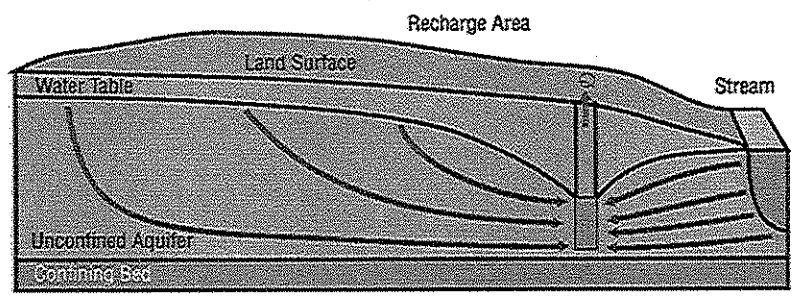
Discharge (D) = Recharge (R)



Withdrawal (Q) = Reduction in storage (ΔS)



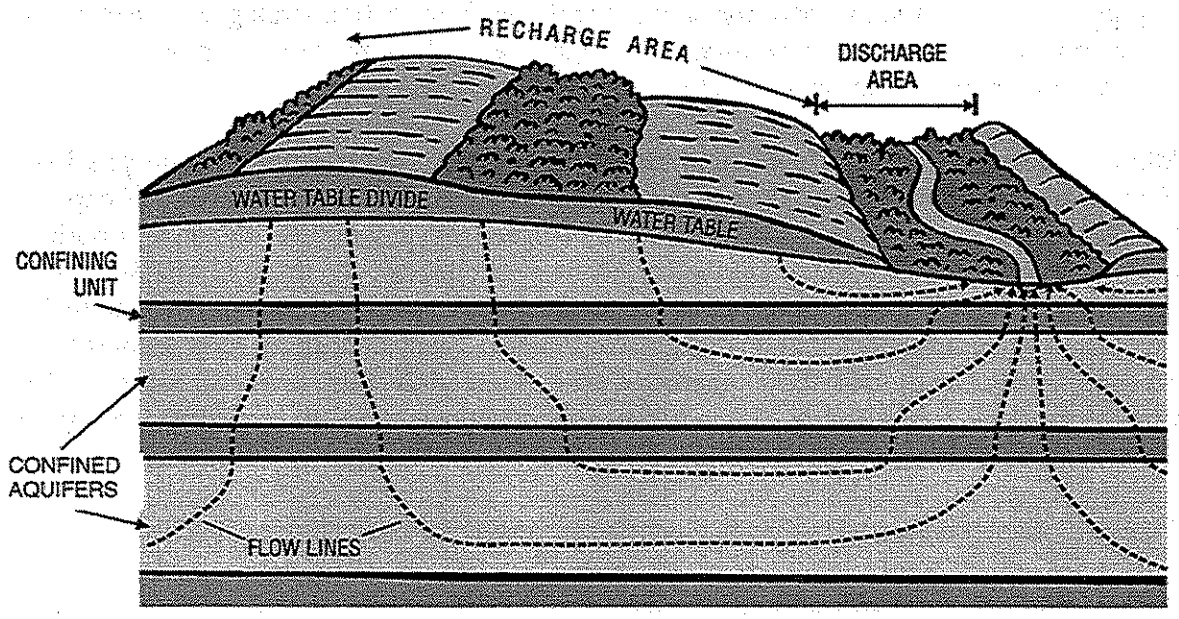
Withdrawal (Q) = Reduction in storage (ΔS) + Reduction in Discharge (ΔD)



Withdrawal (Q) = Reduction in Discharge (ΔD) + Increase in recharge (ΔR)

From Heath (1983)

Figure 3.3 Three-Dimensional Ground-Water Flow Through Multiple Hydrogeologic Units From Recharge Areas To Discharges Areas.



From Heath (1983)

CHAPTER 4: TOOLS FOR EVALUATION OF SURFACE –WATER CAPTURE BY WELLS

4.1 Introduction

This chapter presents the Committee's recommendations for technical methods that are appropriate for evaluating the capture of surface water by wells. The technical evaluation of pumping effects and, in some instances, of proposed mitigation strategies, is necessary for estimating the effects of proposed water rights, as well as for other purposes, such as watershed planning, water-resource management, and engineering.

Many combinations of hydrogeologic settings and water-supply situations are possible. No single mathematical formula can determine the rate, timing, and location of capture for every combination. On the other hand, by considering several factors, an appropriate methodology (several methods used together) may be chosen. To this end, the Technical Advisory Committee developed a methodology for selecting suitable analytical tools. This framework, uses technical and regulatory/management criteria to guide selection of the appropriate analytical tools, methods, data collection, and level of effort. The framework is also applicable to planning and management at the watershed or basin scale.

Typically, the technical questions that need to be answered in a capture analysis are:

- What surface-water body (or bodies) is affected?
- How much water is being captured?
- When does the ground-water withdrawal reduce surface-water flow or ground-water discharge?
- What is the duration of capture?

Technical analysis of these questions should, in all cases, be rooted in the fundamental scientific principles governing ground-water and capture effects on surface-water flow (hydraulics), described above in Chapter 3. One of the key implications of these principles is that, in the long run, any ground-water withdrawal will reduce ("capture") surface-water flow in one or more hyraulically connected surface-water bodies, and may also affect other parts of the water cycle, such as evapotranspiration. The level of sophistication and effort appropriate for studying these questions may vary significantly, depending upon two key factors: the hydrogeologic complexity and the regulatory or management situation.

The primary technical factor is the complexity of the hydrogeologic setting of interest. The Technical Committee identified six hydrogeolgic settings that can describe most or all actual settings found in Washington State (Table 4.2). For each setting, a list of general categories of appropriate modeling tools is presented.

The other key factors affecting the evaluation analysis chosen are regulatory and management considerations. These factors can further guide and narrow the choice of appropriate analytical tools. Regulatory factors include regulatory constraints, which define the objective or surface water target levels that must be achieved. Examples of regulatory constraints within a basin include: established instream flows, Surface Water Source Limitations (SWSLs), and full and seasonal stream closures. Different regulatory limitations may lead to different analytical approaches (for example, a more careful analysis of timing may be appropriate for a water body that is seasonally closed).

Another regulatory driver of the type of technical analysis need is the nature of the regulatory or management question being asked. For example a more complex and detailed analysis may be needed where hydrologic mitigation is to be assessed, as compared to a simple evaluation of capture within the same hydrogeologic setting. In general, less detailed and intensive analyses will frequently be appropriate in cases where more conservative assumptions are made of the effects of capture, (i.e., the assumption is made that the entire pumping rate will be extracted from flow in a given stream).

A further possible regulatory/management consideration is the pressure on potentially affected surface waters; and the resource value (e.g., salmon spawning area) of the water body in question. Pressures might include the potential for future population growth, how fully allocated the surface-water body is, and the presence of threatened or endangered species. Resources might be judged of higher value if, for example, they contain critical salmon spawning areas. Resources with higher pressure and value may deserve a more detailed and thorough analysis of capture effects, depending upon the question posed. For example, a simple analysis may be appropriate when addressing a question of impairment; a more complex analysis may be necessary when evaluating potential mitigation strategies.

Basin Scale Approach

A fundamental conclusion of the Committee is that water rights are best evaluated in the context of an entire watershed, and that tools should be developed to analyze capture, as well as other relevant water management questions, at a basin scale. While water rights examinations have typically been done at a site specific level historically, a basin-scale approach would generally be better. Using basin-scale analytical tools, water resource managers would gain a more complete understanding and better analysis of the potential effects of capture from a given withdrawal. Likewise, individual applications would be evaluated more consistently and, in all likelihood, with less time and effort than currently required. Equally important, water resource managers (including local stakeholders, governments and/or tribes and Ecology) could more effectively address basin-wide management issues (such as the cumulative effects of exempt ground-water withdrawals and changing land use and ground-water recharge due to growth and development) and develop basin-scale management strategies. Individual applicants' and permit holders' data collection, technical analyses and mitigation actions could then be coordinated as part of a larger watershed plan. Small individual water right applicants should not be

required to develop full-scale basin analysis tools; instead they should be able to add to, and access, existing basin modeling efforts.

While the framework presented in this chapter applies to the development of basin-scale management tools as much as to site-specific analyses, the development of analytical tools to support basin management poses special technical and policy challenges. The Committee's recommendations on technical approaches, data collection, coordination of efforts, and relevant policy issues are presented in Chapter 5.

4.2 Framework for Capture Evaluation

No single formula exists with respect to evaluating the quantity, timing, duration, and location of capture effect, as there are numerous factors affecting an evaluation analysis. The framework developed by the Committee uses technical and regulatory criteria to guide an appropriate capture analysis. The framework does not recommend a specific tool for analyzing all capture effects, nor does it include a review of existing evaluation tools; instead it creates a methodology for selecting suitable analytical tools.

The conceptual framework for the evaluation of capture follows the classic problem solving approach: gather available information, develop an initial understanding of the system in question, identify the specific questions to be answered, determine and conduct the appropriate analyses, and evaluate the adequacy of the result. Applied to capture analyses, the traditional problem solving approach appears as presented in Figure 4.1. The text that follows contains a step-by-step discussion of the capture evaluation framework.

Synthesize Available Information

The initial step in the evaluation process is to synthesize relevant and available information. This information may be limited to raw data--such as water level data--that requires interpretation, or, at the other extreme, it may include interpretive studies—such as ground-water flow models—that require only inspection of the quality of the study and what it offers with regard to understanding the hydrogeologic system. Whether simplistic or complex, existing information is always the starting point for developing a conceptual model of the system adequate enough to formulate and solve the technical questions related to a proposed withdrawal. Typically, the available information will be rather disparate, and the effort at this stage will be focussed largely on synthesis—determining, or hypothesizing, the relationships among the various types of information. For example, in the case where only water-level data and topographic information are available, an analyst might synthesize the two types of information to determine the geographical congruity between the surface-water and ground-water basins. Where more complex information is available, an analyst might need to compare new interpretations of the structure of an aquifer/aquitard system with those imbedded in an existing ground-water flow model. In any case, the synthesis of available information is critical, leading naturally to a conceptual model of the hydrologic system and an understanding of how ground water and surface water might interact in it.

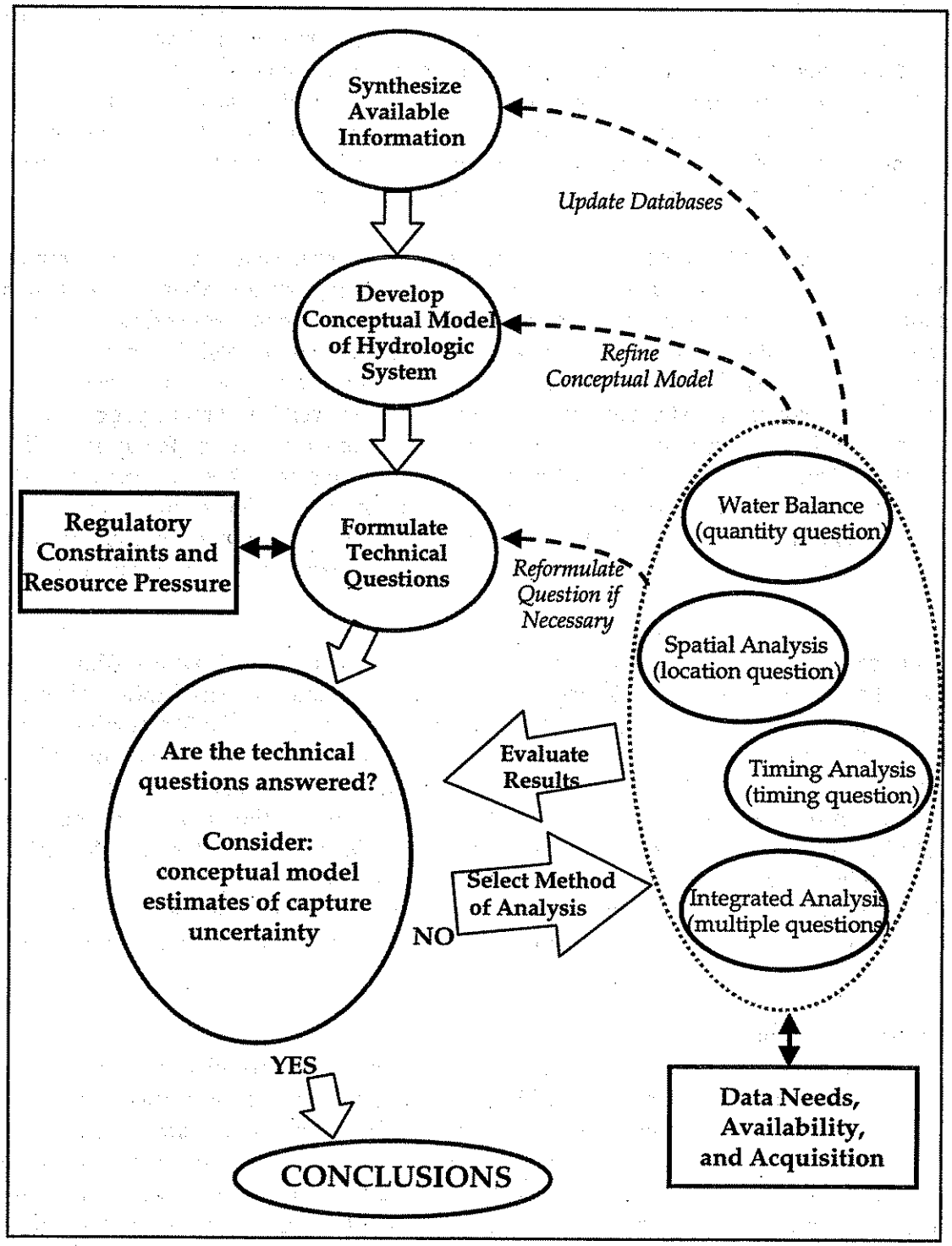


Figure 4.1 : Framework for Capture Evaluatio

Develop a Conceptual Model of the Hydrologic System

Following the synthesis of available information, a conceptual model of the hydrologic system is to be developed. A conceptual hydrogeologic model, or framework, is the single most important element of an analysis of ground-water/surface-water interactions. It is the link between the available data and the analysis or models used to predict effects. The development of an accurate conceptual model (based on available information) is essential as it provides the foundation for subsequent modeling efforts. If the conceptual model is flawed, results of modeling efforts will be inaccurate.

What is a conceptual model? It is the simplified representation of a complex hydrogeologic system – including, for example, defining ground-water flow system boundaries (such as rivers or other barriers to flow, like bedrock), generalized ground-water-flow directions and gradients, recharge and discharge areas, and the characteristics of aquifer materials. The conceptual model or framework can also include the distribution of pertinent data, such as those derived from wells or stream gages. It is a non-mathematical, essentially intellectual or pictorial, representation of the system. The conceptual model forms the basis upon which the mathematics that describe ground-water flow may be simplified enough to be solved practically. The simplifications may include assumptions such as making the release of water from storage instantaneous (in reality, it's gradual) when the piezometric head (i.e., water level) is reduced in the aquifer.

In some cases, a proper conceptual understanding of an area may allow a sufficient and conservative determination of the degree, location, and timing of withdrawal effects. If further analysis is needed, the conceptual framework determines the boundaries of the analysis and the conditions at those boundaries, as well as various simplifying assumptions that would be permissible in a quantitative analysis. For example, the conceptual model might indicate that a 'closed' stream in the area of a proposed withdrawal is likely to be affected by the withdrawal. The area of the investigation might then be limited to the area between the proposed well and the stream, and the target of the analysis might be limited to magnitude of effects. Simplifying assumptions could then be applied to yield an estimate of the magnitude of effects that erred initially on the 'safe side'.

Define the Technical Questions of Interest

The developed conceptual model then helps to identify and formulate the appropriate technical questions. As with any type of investigation, perhaps the most important step is clearly identifying exactly what one needs to know. For example, the appropriate target of an analysis could be estimating the quantity, location, or timing, of capture or some combination thereof. For each situation the applicable types of analyses, simplifying assumptions, and data requirements are different. Identifying the appropriate question relies heavily on the conceptual model—that is, the best available understanding of the system. The conceptual model frames the technical question by providing the answers to more general questions such as, "Does the proposed withdrawal clearly require a regional analysis?"

Another very important input to the formulation of the technical question, (and thus a determinant of the type of analysis needed), is the regulatory status of potentially affected surface-water bodies--hence the need to consider regulatory constraints. In some cases the question can be simplified by limiting it to the potential effects of a withdrawal on a specific water body. In other cases, such as if all surface waters were closed to further appropriation and the conceptual model clearly shows any withdrawal will affect the streams, the applicant can turn immediately to an alternative such as mitigation, which itself may drive technical questions or analyses. Additional pressures on the resource should also be taken into consideration in formulating analytical questions, especially at the basin scale. These pressures include Endangered Species Act listings and other habitat considerations, growth within a basin, competition for water, and degradation of water quality. In general, greater pressure on the resource leads to more urgency in answering technical questions, more complexity in the resource system, and (often) a need for greater certainty and precision in analytical results.

Can the Technical Questions be Answered?

After the technical questions are formulated, a determination may be made as to whether or not these questions can be answered with the information and conceptual understanding already in hand. As described above, in some instances no further analyses are necessary to arrive at a technically defensible answer. For example, if all streams in the area in question are subject to established flow regulations, and the conceptual model clearly indicates a withdrawal would effect them during critical periods, then no further analysis is required unless the question is revised to consider mitigative actions. Several things need to taken into consideration with regard to this decision making step:

- are the conclusions consistent with the conceptual model and available information?
- are the estimates of capture reasonable?
- what are the uncertainties associated with the conclusions?

In some cases, especially situations where limited data are available, this may be a subjective decision. A thorough assessment of uncertainty will help both the analyst/applicant and the state regulators determine not only whether the answer is adequate, but what further data collection and analysis is required if the answer is not sufficient.

Select Quantitative Tools for Further Analysis

If the technical questions have not been answered within the context of the conceptual model, then a further, quantitative method of analysis must be chosen. The grouped analytical elements on the right side of Figure 4.1 represent four general classes of analytical approaches—many different types of analytical tools may be utilized to address any of these elements. These classes of problems reflect the nature of the answer that is required: quantity, location, timing of capture, or some combination of these (an integrated analysis).

The analytical approaches are roughly ordered from top to bottom in increasing complexity. For example, the most complex analytical method would answer just about any question that could be answered, but would be 'overkill' for a simple water balance type of question. Any single type or combination of these types of analyses may be necessary for a given situation. It is not feasible, or advisable, to prescribe the specific analytical approach appropriate for every situation that might be encountered. The evaluation framework instead provides a logical sequence of steps necessary to determine which range of specific analytical tools is best suited for a given situation. These tools are the specific quantitative analyses and models used to predict the effects of ground-water withdrawal on surface water. Following is a description of the four general analytical approaches reflected in the framework:

- A water balance simply identifies the inflows and outflows of water within a study area, sub-basin, or basin.
- A spatial analysis identifies the location of possible effects from ground-water withdrawals, usually based on the spatial relationship between aquifers, ground-water flowpaths, and overlying surface waters. Both the vertical and horizontal geometry are important in conducting a spatial analysis, but specific hydraulic parameters may have less importance.
- A timing analysis adds a temporal dimension to the spatial analysis, indicating when effects are felt at various locations. This might be applicable for non-steady or seasonal pumping. For timing effects to be considered, hydraulic properties must be assigned to the various components of the aquifer system. Because of the need to make additional assumptions about these properties, the uncertainty of such an analysis may be greater than for the steady state.
- An integrated analysis combines the water balance, spatial analysis, and timing analysis, usually in a numerical model, and is the most rigorous approach to determining the magnitude, distribution and timing of effects. Both the spatial components and the hydraulic properties of the aquifer are necessary for this analysis, and the level of accuracy and confidence in the analysis is dependent on both the quality of the data used and the specific configuration and setting of the hydrogeology.

Have Technical Questions Been Answered?

Once an analysis is complete, the next logical step is to determine whether it has answered the question posed.. In Figure 4.1, this equates to returning to the decision step "Are the technical questions answered?" This feedback loop allows for refinement of understanding of two key technical elements of the evaluation process, the hydrologic system and step-wise analyses. The loop is comprised of two critical aspects of the analytical method: selecting the appropriate tool for a particular combination of problem definition and hydrogeologic system; and evaluating the results with respect to uncertainty, applicability to the defined problem, and sensitivity of the results to input variables that may be difficult to accurately determine. It is essential that the quality of the analytical results be evaluated, including as assessment of the uncertainty surrounding

numerical results. Analytic results should also be checked against the underlying conceptual model.

Contingency paths link analysis element(s) with the initial steps of the evaluation process. This reflects the fact that these initial steps sometimes need to be revisited after the results of analyses are considered. For example, if severely limited information is available at the point of developing a conceptual model, subsequent data collection and a basic analysis may require revision of the conceptual model of the system. These alternate paths also imply concerns about data and knowledge retention that are not addressed in this section. In studies where data can be expensive to obtain, and analyses expensive to conduct, it is especially important that they be retained in a useable form for future investigators.

The remaining sections of this chapter focus in detail on two of the key framework components described above. Section 4.3 addresses the specific analytical approaches. This discussion focuses on the different types of models/technical methods necessary for each approach. In addition, data needs and types needed to carry out these methods are discussed in Section 4.4. Section 4.5 focuses on the regulatory and management factors that help shape and guide a capture evaluation under the framework.

4.3 Technical Analytical Methods

Aquifer models can be used to study the effect of proposed management policies and decisions on water resources in a management area. In this case, the goal is determining the magnitude, timing, duration, and location of surface-water capture by wells. The technical and practical difficulties in physically testing the resource necessitate the use of models that can simulate or provide insight into how the aquifer would respond to actual pumping. A "model" is a method used to simulate the conditions found in the real world and as such is a simplification of complex physical reality and processes. A model should be sufficiently simple to apply, yet not too approximate to allow solutions which are realistically plausible and useful.

The water balance has been described as an element of a conceptual model. It also serves as the simplest tool to quantify capture of surface water by wells. A water balance, when used as an assessment tool, means that water that is pumped and not returned to the ground locally, is assumed to affect a surface-water body or bodies with 100% efficiency. That is, one gallon consumed is one gallon captured. This approach is often used, and is a logical starting point for assessing the feasibility of a water development plan. A water balance will often be all that is warranted in situations where capture is known to occur entirely within a basin with a year-round closure on surface waters. Although a water balance will often suffice to quantify capture, mitigation plans may require a more rigorous analysis. The location of the effects cannot be directly derived from a water balance analysis, although when coupled with a conceptual model, locations of effect can often be confidently identified. Likewise, timing of effects cannot be directly calculated

by this method and must be assumed or qualitatively evaluated based on a conceptual model.

The following models are mathematical models, which through use of equations, conservation of mass, and simplifying assumptions yield a simulation of the real world. Mathematical models can be classified into a few categories that reflect the scale and complexity of the problem being solved and the assumptions inherent in the construction of the model. The range of model computation extends from equations that can be solved on a calculator to highly sophisticated computer models that require careful preparation and detailed knowledge of the hydrogeologic environment. As the complexity of the hydrogeologic setting increases, the models used to simulate capture generally must be accordingly more complex. The most common reasons for greater complexity are the need to consider large areas, complex arrangements of aquifers and aquitards, and the need to predict the timing of effects. More complex models might also be required anytime there is a need for greater accuracy or precision.

All mathematical models rely on a basic understanding of all the pertinent hydrologic and geologic processes involved, as described in the "conceptual model" above. Once a conceptual model for a given problem has been developed, a mathematical model can be created.

"Analytical models", which offer a direct solution to the partial differential equations governing ground-water flow, are often the method of choice. Such solutions can be developed for steady or transient flow. (Transient solutions allow the estimation of intermediate states between the time pumping begins and equilibrium is reached, whereas steady state solutions only allow simulation of the final state, but not the length of time required to reach that state. Thus transient simulations allow estimation of capture effects over time, while steady state simulations are limited to spatial analysis). However, the simplifying assumptions for analytical solutions, (such as straight boundaries, uniform homogeneous layers) are often not appropriate for practical applications because they fail to capture the natural complexity and fully penetrating surface water features of the real world. This does not mean that analytical solutions cannot and should not be applied to provide useful results for some management decisions. In fact for small scale, simple settings, a simple, easily applied model is often desirable.

"Analytical element Models" are a relatively new and useful extension of analytical models. Analytical element models rely on superposition of analytical solutions in space (such as pumping wells, recharge and discharge boundaries, recharge, etc.). They have much greater capabilities to realistically simulate moderately complex hydrogeologic settings than do analytical models. Unlike analytical models, they can incorporate moderate levels of layering and inhomogeneity, and some allow simulation of streams that only partially penetrate aquifers and have sophisticated ground-water/surface-water interaction capability. They are more complex to use than analytical models, but are simpler than numerical models. Some examples of analytical element models include QUICKFLOW, WINFLOW, TWODAN, GFLOW, SLAM, and MLAM.

Another important category of models is that known as 'numerical models'. Like analytical models, and analytical element models, numerical models solve the fundamental equations of ground-water flow, but use approximation methods and iterative techniques to solve them. The formulation of numerical models allows greater flexibility in application of boundary conditions, and simulation of complicated hydrogeologic conditions and steady or transient flow conditions. These models utilize finite-difference, finite-element, boundary elements, particle tracking, integrated finite-difference or other techniques to provide solutions, and typically require considerably more computational effort than analytical solutions.

Several commonly applied capture models utilize analytical solutions (e.g., Methods of Jenkins, Glover, Theis, Wallace et al, Spalding and Khaleel, etc.) which address the needs of the timing and magnitude of capture, but generally cannot simulate the effects of variable pumping or seasonality (such simulation may be possible by inserting opposite effects). Only simple aquifer conditions are assumed, but confined, leaky aquifers or streambed layer conductance may be included. Unfortunately, the availability of data to enable adequate selection of leakance (the resistance to flow across aquitards) values is often lacking. Ground-water flow is assumed to be horizontal and streams are treated as fully penetrating an aquifer. Typically such analytical solutions tend to be conservative and overpredict the capture of surface water by wells.

Application of two dimensional models (e.g., analytical element and numerical computer modeling codes such as QUICKFLOW, GFLOW, PLASM, MODFE and MOD-FLOW (MODFLOW can be run in either 2D or 3D mode)) simulate ground-water flow either in the two horizontal dimensions (as in a map view) or in some models, one horizontal dimension plus the vertical (as in a cross-section). Applied in the map view approach, these models can show the areal shape of the effects of ground-water withdrawals and thus indicate where capture effects are most likely to be felt. They treat aquifers rather simply in this mode, and cannot simulate complex layering of aquifers and aquitards. In cross-section mode, some of these models can simulate complex layering, however the simulation is then limited to the effects along a line between a well and an area of particular concern.

The most sophisticated and complicated models involve simulation of flow in three-dimensions (e.g., MLAM, MODFLOW, or MODFLOW variants such as MODRST). These models can simulate ground-water flow systems that include numerous aquifers, and aquitards and they can calculate discharge to streams and springs, include known ground-water withdrawals and simulate areally distributed recharge. To utilize the strengths of three-dimensional models, a great deal of detailed information should be gathered concerning the extent, thickness, and hydraulic characteristics of aquifers and aquitards as well as information about recharge, existing ground-water withdrawals, and water levels in all of the aquifers. Careful preparation and calibration is required but these models offer the most robust simulation of an aquifer's response to pumping.

In certain situations, models are required to simulate changing or transient conditions such as seasonal changes in recharge or seasonal ground-water withdrawals. Transient

models have the additional benefit of allowing timing effects to be evaluated, but they require additional data and computational effort. Simple analytical techniques are capable of modeling timing to a limited degree, and are most useful in narrow circumstances where simple conservative assumptions are made. More sophisticated transient 3-D models however, although more costly and time-consuming, are often necessary in more complicated circumstances (e.g., the hydrogeology is more complex). Table 4.1 presents summary information comparing six model types or classes, listed generally in order of increasing complexity and level of effort required.

As a general rule, the type of model chosen to perform a capture analysis will depend primarily on the hydrogeologic setting or complexity, the answer desired, and the degree of accuracy required from the assessment. For example, in situations where a significant amount of water is available without affecting senior water rights or causing other adverse impacts, a simplified, conservative analysis (e.g., analytical solution) may be acceptable to manage the resource. Conversely, in complicated, multi-layer settings where large geographic areas and seasonal pumping may be involved, a higher level of accuracy would likely be required necessitating the use of a more complicated modeling effort (e.g., 3-D numerical solution).

The quality and availability of data is also a very important consideration during any modeling exercise and should not be overlooked. It directly relates to selection of parameter values, boundary conditions and the uncertainty associated with the resulting interpretation and management decision. (See Section 4.4).

Table 4.2 provides an indication of model type selection for various types of analysis that might be utilized for different hydrogeologic settings. Generally, an analysis of capture due to ground-water pumping may be concerned only with location of the capture or spatial analysis (i.e. continuous pumping and steady-state conditions), a transient analysis when pumping or seasonal elements are non-steady, and an integrated analysis when both location and timing of capture are important. Application of the analytical tools described here and in Table 4.2 is not necessarily limited to the hydrogeologic settings depicted. For example, a three dimensional model could conceivably be prepared to test a hypothesis without having all of the information required to answer initial questions about streamflow capture of a specific ground-water withdrawal. In any case, the analyst bears the responsibility to assess properly the hydrogeologic setting, the scale of the required assessment, and the applicability of the model used. All models have inherent assumptions and limitations that must be considered in order for the simulation to be useful and reasonable.

Table 4.1: Comparison of General Model Types

Tool or Technnique	Estimation of Timing, Location, Quantity	Most Useful Scale	Relative Effort to Obtain / Use	Relative Cost	Time Required to Apply	Relative Quality of Result
Conceptual Model	Qualitative only	**Local, Sub-basin, Basin**	Low to High	Low	Days to Years	Qualitative only, considered to be a necessary component of all types of analyses
Water Balance	Q	**Local, Sub-basin, Basin**	Low	Low	Days	Lowest level of detail and resolution. Simple accounting models assumes spatial impacts, no timing component.
Analytical Model	T, **Q**	**Local**	Low	Low	Days to Weeks	Lesser level of detail and resolution; assumes location is known, conservative analysis requiring simplifying assumptions
2D Areal Analytical Element or Numerical Model	T, **L, Q**	**Local, Sub-basin**, Basin	Med	Low - Med	Weeks to Months	Moderate level of detail and resolution; quantitative, analytical models requiring simplifying assumptions
3D Steady-state Numerical Model	**L, Q**	Local, **Sub-basin, Basin**	High	Low to **High**	Months to Years	High level of detail and resolution; quantitative, depends on boundary conditions and level of knowledge
3D Transient Numerical Model	**T, L, Q**	Local, **Sub-basin, Basin**	High	Low to **High**	Months to Years	Greatest level of detail and resolution; depends on boundary conditions and level of knowledge

NOTES:

5. Bold text indicates primary use.
6. Relative Effort reflects the sophistication of the mathematical model and the technical skill requirements of the analyst.
7. Relative Cost reflects the sophistication of the modeling approach, the time required to prepare and document the analysis and the importance of the result desired.
8. Time Required reflects the typical range of time expended, but will depend on the approach used, the dimensionality of the model, availability of data, required field investigations and data gathering and the skill of the analyst.

*Analytical element analyses are included where "numerical" is stated

Table 4.2: General Techniques for Assessing Capture According to Hydrogeologic Setting[1 2]

Hydrogeologic Setting	Type of Analysis		
	Spatial *(i.e. where?, steady-state)*	***Timing*** *(i.e. when?, transient)*	***Integrated*** *(space and time)*
1. Unconfined aquifer, single layer, saturated, gaining or losing	Analytical 2-D Numerical (SS) 3-D Numerical (SS)	**Analytical** 2-D Analytical 2-D Numerical (T) 3-D Numerical (T)	Analytical 2-D Numerical (T) 3-D Numerical (T)
2, Unconfined aquifer, single layer, disconnected locally from surface water	**2-D Numerical (SS)** **3-D Numerical (SS)**	**2-D Numerical (T)** **3-D Numerical (T)**	**2-D Numerical (T)** **3-D Numerical (T)**
3. Unconfined aquifer, single layer, ephemeral stream	2-D Numerical (SS)[3] 3-D Numerical (SS)	Analytical 2-D Numerical (T) 3-D Numerical (T)	Analytical 2-D Numerical (T) 3-D Numerical (T)
4. Semi-confined aquifer,multi-layers, connected to surface water	Analytical **2-D Numerical (SS)** **3-D Numerical (SS)**	Analytical 2-D Numerical (T) **3-D Numerical (T)**	Analytical 2-D Numerical (T) **3-D Numerical (T)**
5. Semi-confined aquifer, multiple-layers, disconnected locally, but not regionally, from streams	2-D Numerical (SS) **3-D Numerical (SS)**	2-D Numerical (T) **3-D Numerical (T)**	2-D Numerical (T) **3-D Numerical (T)**
6. Semi-confined aquifer, multiple-layers, ephemeral surface water	2-D Numerical (SS) **3-D Numerical (SS)**	2-D Numerical (T) **3-D Numerical (T)**	2-D Numerical (T) **3-D Numerical (T)**

Notes: SS - steady state
T - transient
Bold - identifies typical minimum approach that might be applied. The choice of model will depend on several site-specific factors and the level of knowledge concerning the setting.

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[1] A Water Balance is a simple, conservative analytic tool that may apply to all hydrogeologic settings. This tool is often a preliminary assessment step to a more detailed analysis of spatial or timing effects, using the tools presented in this table.

[2] For the sake of brevity, Analytical Element analyses are included where "numerical" is stated. They are not formaully "numerical " models, but are often used in the same circumstances.

[3] Spatial tools may be used to analyze seasonal steady state periods

The scale of observation is important in model selection. The scales of drainage basins can be classified into three simplified, general types: local, intermediate (or sub-basin), and regional (or basin). A local flow system is that draining to the smallest stream, one with no tributaries, and possibly containing only an unconfined aquifer. A regional system, on the other hand, is the largest identifiable flow system and extends to distant and deep boundaries of ground-water flow. An example of a regional system is the drainage basin of a large river, such as those draining an entire WRIA in Washington. Intermediate systems, of course, fit somewhere between local and regional. There may be many adjacent local and intermediate systems within a regional system.

Some types of analysis will be appropriate at all scales, but others may be applicable only at certain scales. For example at the local scale, an analytical model may yield acceptable results and if desired, so could a three-dimensional (3-D) numerical model. However, outside of the local scale, simple analytical solutions become less applicable. At the intermediate and regional scales, deeper ground-water-flow paths may be important, in which case simplifying assumptions for analytical solutions are not accurate.

4.4 Technical Data Needs and Types

Table 4.3 presents a general list of data types used for capture analyses, typical sources of the data, and which data are needed for the six fundamental analytical or modeling methods. In general, all available information should be incorporated into the conceptual model, although a conceptual model is by nature qualitative and not quantitative. On the other end of the analysis spectrum, the most rigorous analytical method—3-D transient numerical modeling—also requires most or all available data to determine the relevant inputs to and outputs from the ground-water system, hydraulic characteristics, and current conditions. The numerical model is different from the conceptual model in that all of the data must be carefully quantified, while they may be considered more generally for development of a conceptual model. Accordingly, the data sources for the two types of assessment are different. For example, for a conceptual model, it may be sufficient to estimate the gaining and losing reaches of a stream by evaluating the stream gradient from a topographic map (Table 4.3, see 'inferred'), while for a detailed numerical analysis it may be required to physically measure these quantities in the field (Table 4.3, see 'measured'). Examples of field testing may include long duration pumping tests to determine hydraulic properties of the aquifer, or well drilling and sampling to obtain geologic and water quality information. In some cases, the conceptual model for an area may be well characterized, with abundant data in reports or databases.

In the spectrum of analytical methods, the simpler models require less data, and data needs increase with model complexity and capability. This can be attributed to the increasing ability of more sophisticated models to simulate real conditions; for more realistic simulations, more data is required to assure that the system is being modeled accurately. Because the simplicity of models generally results from simplifying assumptions about the flow system, data needs increase as fewer simplifying assumptions

Table 4.3 Technical Data Needs and Types for capture analysis

Information Categories	Information Needed	Typical Source of data	Conceptual Model	Water Balance (as a capture analysis tool)	Analytical Model	2D Areal Analytic Element or Numerical Model	3D Steady-state Numerical Model	3D Transient Numerical Model
Hydrologic	Location of surface water	Map	X		X	X	X	X
	Precipitation, Evaporation, Temperature	Reports, Measured	X					
	Infiltration	Inferred, Measured	X			X	X	X
	Streamflow Gaging (monthly)	Reports, Measured	X				X	X
	Continuous Streamflow Gaging (daily)	Reports, Measured	X					X
	Surface Water stage	Reports, Measured	X					X
	Location of gaining or losing reaches	Inferred, Measured	X			X	X	X
	Streambed properties	Inferred, Measured						
Geologic	Topography / land elevations	Map	X			X	X	X
	Subsurface lithology and stratigraphy	Reports, Field	X				X	X
	Surficial soil type	Map, Reports, Field	X			X	X	X
	Surficial geology	Map, Reports, Field	X			X	X	X
Hydrogeologic	Groundwater potentiometric level(s)	Reports, Measured	X		X	X	X	X
	Groundwater flow direction and velocity	Inferred	X					
	Well locations (existing)	Map, Field	X			X	X	X
	Well locations (proposed)	Map	X		X	X	X	X
	Aquifer location (depth and distribution)	Reports, Field	X			X	X	X
	Hydrostratigraphic layers	Inferred, Field	X		X	X	X	X
	Aquifer / aquitard thicknesses	Reports, Field, Inferred	X			X	X	X
	Aquifer / aquitard hydraulic properties	Reports, Field, Inferred	X		X	X	X	X
	Detailed 3-D mapping	Reports, Field, Inferred	X				X	X
	Recharge / Discharge areas	Reports, Field, Inferred	X				X	X
Developmental	Consumptive use			X				
	Existing landuse	Map	X					
	Groundwater extraction rates (exisitng)	Reports	X	X				
	Man-made hydrologic features (retention ponds, inj. wells)	Map	X	X		X	X	X

Notes: Reports - refers to data which has been obtained from available literature, unpublished or published sources
Measured - refers to data which has been obained by direct measurement
Field - refers to data which usually requires field observation or investigation to obtain
Inferred - refers to results, values or conclusions which are primarily derived by interpretation of other data

are made about the flow system. One example is to assume that a stream channel penetrates the full thickness of an aquifer. If a stream is not fully penetrating, the assumption results in overestimation of the rate of capture, and underestimation of the drawdown on the opposite side of the stream.

The most fundamental data needed are the hydraulic characteristics and boundary conditions of the aquifers and aquitards. Numerical models do not yield unique solutions—for any given distribution of water levels have endless combinations of hydraulic characteristics and boundary conditions that will satisfy the governing equations of ground-water flow and predict the same ground-water levels and surface-water capture. Therefore, in order to constrain the solution, reasonably accurate estimates of these parameters are essential. Estimates of recharge and discharge (flow into and out of the ground-water system) are comparatively more difficult to obtain, and while very important, are typically given less weight than estimates of transmissivity and storativity.

Two inputs for 3-D models that stand out as the most difficult, time-consuming, and expensive to develop are detailed 3-D maps of aquifers and aquitards, and time-series data needed for transient modeling. These types of models are therefore the most expensive and time consuming to develop. In Table 4.3, model types are listed in order of increasing complexity and data requirements from left to right.

4.5 Regulatory and Management Factors

By the statutory authority related to water rights, Ecology is required to determine the degree, timing, and location of the effect that withdrawing ground water has on surface water. Three initial questions guide the choice of which technical method should be used to estimate the rate and/or timing of capture.

Question 1: Which Surface Water Will be Affected by the Proposed Ground-water Withdrawal?

Depending on the complexities of the hydrogeologic environment (regime) from which the ground water will be withdrawn, this first question requires a conceptual model of the drainage basin and, perhaps, a spatial analysis tool to determine the interrelationships between the ground water being pumped and the surface waters from which the capture might occur. If planning/managing at the basin level, the appropriate scale for this analysis is the watershed where the withdrawal and effect will occur.

Question 2: Do Any Regulatory Constraints Apply to the Surface Waters Identified in Question 1?

Five broad categories of constraints affect the availability of surface water for new appropriation: (1) year-round closures to further appropriations as per 173-500 WAC, (2) seasonal closures to further appropriations as per 173-500 WAC; and (3) Minimum

Instream Flows as per 173-500 WAAC, a form of surface water right that requires a certain amount of flow to be left in the stream and having the same standing under the law as any other surface water right; (4) Surface Water Source Limitations (SWSLs), which are informal closures based on biological considerations and requested by the Washington State Department of Fish and Wildlife (WDFW); and (5) established instream flows as limiting conditions for individual senior water rights.

At the watershed scale, there may also be additional constraints on surface-water bodies. These include pressures on the resource such as water quality degradation, population growth, and declining fish and wildlife habitat. Where any of these or the above restrictions exist, it may be necessary to engage in an analysis to determine the effect of a withdrawal. Similarly, where senior surface-water rights exist, an evaluation analysis may also be necessary to determine the effect of ground-water withdrawals on these rights.

Seasonal closures and established instream flows require an analysis of the timing and duration of capture by wells (Timing Analysis tool.) Depending on the physical properties of the aquifer in question and the type of withdrawal requested (seasonal or year-round), the timing of the capture (relative to the closure period or the established instream flow period) may allow Ecology to issue a ground-water right even though the associated surface-water body is seasonally closed or is subject to an established instream flow. If the effect will not occur during the restricted periods and if the effects of pumping do not extend into the restricted periods in succeeding years (either seasonal closure or low flow period), then the ground-water right may be issued. It is important to remember that capture usually does not begin immediately after pumping starts, nor does it end with the cessation of pumping. Normally, there is a lag time between the onset of pumping and its associated effect on the related surface-water body. Similarly, capture can last for a long period of time after the well has ceased pumping. These timing-related questions (i.e., when will pumping effect the stream) are best resolved with a Timing Analysis tool.

If both the location and rate of capture cannot be reliably estimated with simple methods, then the estimates must be derived from an appropriate mathematical model, the "Integrated Analysis Tool." The determining factor in guiding the development and use of an Integrated Analysis Tool is largely a function of the complexity of the hydrogeologic environment. In most situations, the appropriate tool will be a basin-wide (but not necessarily a whole WRIA), 3-dimensional, numerical model. When completed, this model will be capable of estimating capture for any proposed well within the modeled region.

Question 3: Determine Which Regulatory or Management Question(s) will be Addressed

The elements of a withdrawal proposal are some of the key factors in determining the choice of method for evaluating the capture of surface water by wells. Of these elements, a key determinant of the level of technical analysis needed is whether or not mitigation of impairment will be considered. Determining the types of mitigation that may be

appropriate and how to implement the mitigation often requires a much more detailed analysis of the situation than if no mitigation plan were proposed. For a mitigation strategy to be accepted by Ecology, the applicant would have to demonstrate that the proposed course of action would fully compensate for the captured surface water.
In the context of basin-scale analysis to support basin planning and management, additional management questions may be asked. For example, managers may be interested in the effects of anticipated future growth and development or assessing several possible management strategies to mitigate or protect ground-water supplies (e.g., protection of recharge areas, regional off-season storage and summer release, regional recharge facilities). Such questions may require more sophisticated ground-water analytical tools (including, in some cases, linked surface-water/ground-water models) and additional data (see Chapter 5).

Table 4.4 summarizes the way in which regulatory constraints and management questions combine with hydrogeologic complexity to indicate an appropriate tool or tools for analyzing capture.

Table 4.4 Regulatory/Management Criteria for Selecting Analytical Tools

Regulatory Constraint/Question	Hydrogeologic Setting: Simple	Hydrogeologic Setting: Complex
Which surface-water body is affected by ground-water withdrawal?	Conceptual Model Water Balance Tool	Conceptual Model Water Balance Tool Spatial Tool
Year-round regulatory constraint *Is there impairment?*	Conceptual Model Water Balance Tool	Conceptual Model Water Balance Tool Spatial Tool
Year-round regulatory constraint *Will mitigation be considered?*	Water Balance Tool	Spatial Tool Timing Tool
Seasonal regulatory constraint *Is there impairment?*	Water Balance Tool Timing Tool	Water Balance Tool Spatial Tool Timing Tool
Seasonal regulatory constraint *Will mitigation be considered?*	Water Balance Tool Timing Tool	Spatial Tool Timing Tool Integrated Tool
Minimum instream flow *(Interruptible Right)*	Conceptual Model Water Balance Tool Timing Tool	Spatial Tool Timing Tool Integrated Tool

The hydrogeologic settings are defined as illustrated in Table 4.2:

Simple Hydrogeologic Settings:

- Unconfined, single layer, saturated, gaining or losing
- Unconfined, single layer, unsaturated, disconnected
- Unconfined, single layer, ephemeral

Complex Hydrogeologic Setting:

- Semi-confined, multi-layers, connected to surface water
- Semi-confined, multi-layers, disconnected to surface water
- Semi-confined, multi-layers, ephemeral surface water

CHAPTER 5: WATERSHED MANAGEMENT/BASIN PLANNING

5.1 The Case for Basin-wide Hydrologic Analysis

Historically, examinations of water-rights applications have been conducted on a site-by-site or application-by-application basis. Investigations of surface-water capture by wells and collection of data to characterize a basin's hydrogeology have, therefore, tended to be geographically uneven, driven by the specific need to analyze a particular withdrawal. Frequently, analyses have been largely qualitative and encompassed only small parts of basins. Furthermore, limited resources at Ecology have hampered the receipt, review, and analysis of data required of applicants under the terms of water–rights permits, such as monthly water-level measurements and records of water withdrawals. Thus, only limited data exist in most basins on hydrology and water use, and these data are generally not easily accessible.

This report has presented specific, recommended methods for assessing surface-water capture by wells; these methods include data-gathering, hydrogeologic interpretation, and mathematical modeling. As described earlier, the area of investigation for capture analysis must be large enough that 100% of the capture for a well or group of wells can be accounted for; this may only extend to the nearest surface water, but more often extends out to the flow system's boundaries, that is, to the boundaries of the ground-water basin and, sometimes, beyond into adjoining basins. Appropriate analysis and data collection of this kind requires extensive effort, particularly if, as is frequently the case, the capture analysis is done without the benefit of previously developed base information on a basin's hydrogeology. Such efforts may not be affordable to many, if not most, applicants.

Ideally, capture analysis related to water rights, as well as other related aspects of water resource planning and management, would always be evaluated at the basin scale. The systematic collection and management of data, and the development of basin-scale conceptual models and analytical/numerical modeling capability, in basins experiencing high water demand and facing strong regulatory constraints would ultimately be fairer and less costly to an applicant, and would support better resource management. For water-rights processing, the analyses and models that are developed at the regional/basin scale would be available to evaluate both individual applications for new water rights and applications for changes to existing water rights. Thus, an individual applicant, Ecology, or any basin-planning entity, would be able simply to use or add to a pre-existing base of knowledge and set of analytical tools in a watershed, rather than start from scratch.

Better resource management would be possible because individual water-right applications could be evaluated consistently, based upon a common understanding of a basin's hydrogeology and well developed quantitative tools. This approach would give regulators more confidence that they have a complete understanding of the full effects of capture (at the basin scale, not just localized effects), and possess the right information for making regulatory decisions. Basin-scale data and analytical tools could take into

account cumulative effects (including the effects of exempt ground-water withdrawals) and the effects of land use changes on recharge and base flow. Basin-scale models could also be used to evaluate which management and mitigation strategies (e.g., regional recharge facilities) are most effective basin-wide, thus identifying appropriate and effective mitigation strategies for individual water-rights applicants. They could also be used to anticipate and analyze the effects of future development and population growth. Finally, basin-scale hydrogeologic analyses would provide important information for the analysis and management of important environmental and resource management problems related to water quantity, such as declining water quality and loss of fish and wildlife habitat.

5.2 A Vision of Watershed Analysis in Support of Watershed Management

This Committee envisions a shift over time from case-specific analysis of hydrogeology and capture to basin-scale analysis throughout the state. In ten years or so, a basic understanding and core set of data would have been developed for all basins in the state, with more detailed data and sophisticated tools developed for those basins experiencing environmental problems and/or intense water-use competition. Federal, state, local, and tribal governments, basin residents, and other stakeholders would be involved in determining the scope of analysis and making basin management decisions.

Data would be collected according to a master plan that supported increased basin-scale hydrogeologic understanding over time, would be shareable among agencies and accessible to the interested public and prospective applicants, and arrangements would be made for the effective management, maintenance, and archiving of data. Among the elements of basin databases and Geographic Information System layers would be the locations and amounts of surface-water diversions and ground-water withdrawals, locations of stream gaging stations, long-term streamflow records, minimum instream flow determinations by stream segment, water-quality data, fish-habitat data, and any regulatory determinations. Long-term monitoring programs would provide accurate information on hydrology, geology, and water use over time. Data collection and analytical tool development would be accomplished by combining the data from individual applicants or permit holders and through systematic efforts funded by local, state and Federal agencies.

Individual water-rights applicants would be able to use and build upon existing data and models, which would be readily available over the Internet, augmenting them as necessary and adding to the knowledge base. Applicants with small applications would not be expected to generate or contribute substantially to the development of basin models, however, and the incremental cost of data collection and analysis/modeling incurred by an applicant would typically not be great. In some cases, simply exercising the existing basin model would be sufficient to assess the effects of a proposed withdrawal. Water-rights applications would typically be evaluated in batches by basin, according to a publicly announced schedule, to allow an efficient evaluation of their collective effect.

Basin planning and management authorities, guided by stakeholders, would evaluate cumulative effects, anticipate future growth problems, and assess management and mitigation strategies. The most effective management strategies would be implemented either as regional solutions and/or piecemeal, by individual applicants, as part of a watershed-scale model. In addition to coordinating effectively across levels of government (local, state, tribal, and Federal), a focus on analysis at the watershed scale would support the effective integration of a broad range of management objectives, including water-quantity management (both for human consumptive use and protection of instream aquatic life), water-quality protection, and habitat conservation. Using basin-scale analytical tools, stakeholders and agencies would make careful, well-informed decisions balancing competing human uses and natural resource/environmental values in managing each watershed.

5.3 Uses of Basin-level Analysis

A variety of water-management questions requires the analysis of surface-water capture by wells, and would be better served by basin-scale, ground-water/surface-water analytical tools and data sets. These uses include:

1. Processing water-right applications for new appropriations, changes, and transfers to determine whether the additional use or changes in use impair senior rights.
2. Regulating permitted uses when senior surface-water rights (diversions or established minimum instream flow) are not satisfied. The causes may be drought, increased water use with unanticipated results, or climate change.
3. Mitigation design, which could include:

    - purchasing and moving a senior surface-water or a ground-water right such that the effects don't occur farther upstream;
    - changing timing of withdrawals to avoid impairment during seasonal low flow periods or closures;
    - off-stream storage and later release;
    - aquifer storage and recovery (ASR), also known as artificial recharge;
    - pumping of ground water directly into a stream;
    - habitat restoration requiring the weighing of environment tradeoffs.

    (note that the Capture Committee did not evaluate the issues surrounding the determination of the adequacy of particular types of proposed mitigation. The above are offered as examples.)

4. Assessing cumulative effects, such as estimating surface-water capture by all permitted, exempt, and (perhaps) claimed ground-water uses.
5. All questions about water quantities (volumes and rates) in a basin. Several important analyses that include ground-water/surface-water interaction estimates as an important input include:

- Determining minimum instream flows for fish and wildlife habitats;
- Determining the effect of capture by wells on the contaminant-dilution capacity of a stream, such as during the review of NPDES permits which is based, in part, on a TMDL analysis;
- Dam relicensing by the Federal Energy Regulatory Commission;
- Determining optimal reservoir operations;
- Identifying and interpreting the causes of water-quality problems.

5.4 Technical Guidance on Basin-scale Analysis

How should interested parties develop basin-scale tools for analyzing surface-water capture due to ground-water withdrawal, and how might watershed-scale tools differ from tools used to analyze individual withdrawals? This Committee offers its initial suggestions on these topics in this section.

The Framework described in Chapter 4 applies to the selection and development of watershed-analysis tools as well as to the analysis of individual capture events. The logical steps and the array of available analytical options are the same. Indeed, an individual ground-water withdrawal with regional effect on surface water may require essentially the same analysis as is needed to support basin management of water. More frequently, a basin analysis will cover a larger geographic scope than is required to analyze an individual withdrawal. Hence, basin analysis may require data collection and analysis/modeling over a broader area (although perhaps in less detail) than for an individual analysis.

Key differences that may emerge in applying the Framework to analyze basin-wide issues are:

- *The scale of analysis and data collection may be greater*, as noted above.
- *The regulatory/management questions that require technical analysis may be broader or different.* For example, at a basin level, managers may be interested in assessing cumulative effects (including those from exempt ground-water withdrawals), projecting future effects of withdrawals from expected growth, and evaluating the effects of proposed basin-wide mitigation or management strategies (e.g., regional recharge of ground water). These more complex basin-wide questions, in turn, may require more sophisticated analytical tools.
- *Pressure on the resource (as evidenced by intense competition for water use, increasing impairment of senior rights, and/or degradation of habitat or water quality) and resource value may become prominent drivers* of the level of effort and analytical sophistication needed. Typically, more threatened basins will have more acute and urgent management and analytical needs. In a world of limited resources, it may be appropriate to set priorities for developing analytical tools based on the level of pressure a basin is experiencing.

Analysis to support basin-wide planning and management may be done at very different levels of time, effort, and sophistication, depending on the complexity of questions facing basin managers and the degree of pressure/threat the basin is experiencing. A basin-wide effort might start with the more easily accomplished scientific analyses and with the initiation of long-term monitoring to lay the groundwork for more intensive analyses. Later, the data and analyses would be used to accomplish more advanced analyses and, ultimately, to design predictive models. Both the improved conceptual models and the mathematical models would become the analytical tools for basin planning and for permit processing.

Three possible levels of basin analysis are described below.

BASIN-WIDE ACTIVITIES -- LEVEL I

Level I activities are needed in all basins in Washington. Even the most remote drainage basins experience human activities that affect the water balance and cause environmental changes. The principal goal is to assemble readily available information and provide interpretations of the hydrologic system to enable better informed water-management decisions, including permitting, enforcement, and regulation in both water quantity and quality. Examples of drainage basins needing Level I activities, at a minimum, include:

- Water Resource Inventory Areas (WRIAs) without much settlement (e.g., most Pacific coastal areas and mountainous areas),
- Areas where water use is low and additional appropriations probably are available, e.g., if there are no fish listings under the Endangered Species Act (ESA),
- WRIAs where there don't appear to be serious flow constraints related to habitat or use

Level I activities and results might suffice for the foreseeable future in some basins.

<u>Suggested Level I Activities</u>

Data Collection and Management:

1. Annual water-use reporting. Use Ecology's Environmental Information Management System (EIM) as shareable database.
2. Statistically sample (spot check) rates of stream diversions and ground-water withdrawals. Use statistics to estimate water use by basin.
3. Create and update databases.
4. Develop and initiate monitoring networks.
   a) ground-water levels and chemistry,
   b) streamflow rates and chemistry.

Analysis and Uses:

5. Describe 3-dimensional conceptual model of the ground-water/surface-water flow system interactions, publish periodic updates (as in Washington Geology).

6. Develop water balance describing ground-water and surface-water inflows and outflows basin-wide.

BASIN-WIDE ACTIVITIES -- LEVEL II

Level II activities build on Level I, but require greater effort and funding. Examples of criteria indicating the need for Level II activities might include:

- Senior water rights, including established instream flows, are not being met with increasing frequency (whether due to drought or water use)
- Where mitigation for new appropriations will be 100%, but where it is difficult to predict which surface waters would be captured.
- Minimum instream flows must be established or revised. This requires improved accuracy in calculating steady-state (long-term) or transient (seasonal or short-term) capture by wells.
- Watershed planning efforts to accommodate growth in water use in areas of moderate population but increasing growth.
- Fish listings under the Endangered Species Act (ESA) require concerted efforts toward habitat restoration.

<u>Suggested Level II Activities:</u>

Data Collection and Management:

1. Fully implement and operate monitoring networks.

Analysis and Uses:

2. Resource mapping: geology, water-level maps, recharge/discharge areas, wetlands, etc.
3. Map gaining and losing reaches of streams based on wading discharge measurements and geologic mapping;
4. Analyze base flow conditions from streamflow (baseflow-recession analysis);
5. Develop two-dimensional (2-D) cross-sectional, steady-state ground-water flow models across basin, testing aspects of the three-dimensional conceptual model.
6. Conduct one-dimensional (1-D) and two-dimensional transient analyses of subbasins where such are justified by three-dimensional (3-D) conceptual model or by specific regulations (subarea or basin plans.)
7. Re-evaluate or set new minimum instream flows:
8. Combine with IFIM study results to set flows and select stream and lake gaging locations.

BASIN-WIDE ACTIVITIES -- LEVEL III

Level III activities include the most advanced techniques in hydrologic science and water-resources management. These would occur in basins where the environmental

problems are severe and the need for accurate information and predictions are critical. Examples of criteria indicating a need for Level III activities might include:

1. New water rights or new water-quality permits are limited by one or more ESA listings, or where established instream flows not met frequently.
2. Pending ESA listings, severely declining fish runs.
3. Populous areas with serious growth, several big water suppliers such as Public Utility Districts (PUDs) or irrigation districts.
4. Desire to prove that there is some water available, at least part of the year, to avoid 100% mitigation.
5. Many water-right applications in the basin.
6. Serious, overlapping environmental problems where more water use would affect water quality, habitat, recreation, etc.
7. Implementing "subarea" management schemes, such as Odessa subarea (irrigated region).
8. Ongoing surface water adjudication, or completed adjudication and full appropriation.
9. 303(d) listed stream segments for flow, temperature, or related water quality parameters.

Suggested Level III Activities:

Analysis and Uses:

1. Develop fully 3-D, transient ground-water flow model and use for the following:
   - Calculate capture of surface water for new wells for permit processing.
   - Calculate capture of surface water for existing wells.
2. Couple water-rights information with streamflow routing (accounting) model to test whether senior surface-water rights would be satisfied under particular scenarios of ground-water withdrawals.
3. Plan for orderly growth by using 3-D model and further field studies to research areas where further withdrawals may be possible.
4. Develop plans for area-wide water-right mitigation, using 3-D model.
5. Support apportionment of mitigation for various surface waters.
6. Support apportionment of mitigation to various parts of a basin.
7. Test how moving withdrawals to other areas might restore streamflows

Table 5.1 lists selected techniques relevant to surface capture by wells that are most economically and reliably accomplished at the basin scale, several of which are described above. This Table does not repeat analyses and data types already described in Chapter 4, unless those techniques would be applied differently at a basin scale.

Recommendations

The Committee's recommendations on developing technical tools to analyze basin-scale capture of surface water by wells are presented below. Some of these recommendations go beyond the purely technical, and address issues related to building the infrastructure, coordination, and capacity to accomplish watershed analyses.

- A concerted program to develop the tools and data needed for basin-wide analysis of surface-water capture effects should be undertaken by state, federal, tribal, and local governments in partnership with citizens and other entities. Such tools would be used to aid in the technical analysis of both water-rights applications and broader basin-scale water-management questions, such as cumulative effects, future growth, and effective management/mitigation strategies. Initial thoughts (which could be further developed into technical guidance) on appropriate data and analytical tools for basins in different circumstances are offered above.

- Currently, the resources and capacity to develop and maintain basin-scale analytical tools do not exist at Ecology or in most other agencies. Methods and sources of funding will need to be sought to undertake expensive data collection/monitoring efforts, and technical capacity will need to be built at the watershed scale. Interagency partnerships may be a practical way to share the burden, but will require a high degree of coordination. The Committee recommends that Ecology and other funding agencies allocate limited financial and technical assistance resources according to priority needs, along the lines outlined earlier in this chapter. Management and funding priorities should address the need to protect existing watersheds with high-quality water and habitat, as well as to develop strategies in those watersheds already experiencing problems due to increased pressure on the resource.

- A key early activity will be to define, for each basin, a data collection and long-term monitoring strategy that will, over time, build the needed information base for analysis and management. Once data needs are defined, data collection costs can be distributed among different agencies, as well as individual water-rights applicants and permittees, as a way to leverage and coordinate data collection. To ensure data consistency and the ability to share data among different entities, it will be important to define data standards (e.g., how location is recorded) and standard software and tools (e.g., ARCINFO, MODFLOW). Two types of information that the Committee recommends be collected comprehensively and systematically in all watersheds are actual water-use, and the basic hydrologic and geologic information needed to characterize a basin. Currently, these critical data are inadequate to support analysis in most basins.

- Roles and responsibilities for collecting data and maintaining databases, and for developing and updating analytical/modeling tools, will need to be considered carefully and defined clearly. Responsibilities should be related to entities' technical expertise, resources, and, perhaps most importantly, who needs the data for management purposes. Responsibility for different technical activities may rest with any or all those involved: Ecology, local authorities, other state or Federal agencies, tribes, other entities created for the above purposes and/or private parties.

TABLE 5.1
SELECTED BASIN-WIDE DATA COLLECTION AND HYDROGEOLOGIC ANALYSES

Technical Effort	*Hydrogeologic analysis methods*	Objective	*Duration*	*Cost & effort*	*Where (scale)*	**Accuracy or Comment**
Annual water use accounting (reporting) for water rights and claims	Add-up amount per ground-water basin or watershed.	Relate streamflow (or lake level) changes to actual use; improve accuracy of water-rights records.	Annually	moderate	Every WRIA by actual basin.	Moderate, no substitute. Estimates every 5 yr. by USGS not sufficient, not tied to individual water rights.
Streamflow gaging, database, and statistical analysis	standard statistics	Status of resource; set or watch minimum instream flows; detect long-term capture by wells; climate change.	long-term, either periodic or continuous	low to moderate	Needed on main rivers and tributaries everywhere for baseline and trends.	No substitute, can't estimate!
Ground-water-level monitoring (periodic synoptic; some continuous), database, and numeric analysis	Standard, simple methods	Status of resource; head change trends; map water level elevations; model input; climate change.	long-term, periodic or continuous	low to moderate	Needed in all basins, some close to well fields and one far away from pumping per sub-basin.	No substitute, can't estimate!
Stream loss/gain measurements	Map findings	Understand in detail where wells could capture water; verify conceptual model.	Once or twice during low flow period. Repeat if extensively urbanized	moderate, repeat only for local details	Each major river and stream, usually second-order and above, except in semi-arid climate.	High; need to verify estimates based on other data (such as geology, slope, soils).
Base flow recession analysis	Separate ground-water inflow rate from storm runoff rate.	Assess dependency of stream on base flow; trends in ground-water outflow; distinguish climatic effects from capture by wells.	Office analyses; repeat every 5 yr. or sooner as necessary.	moderate	Analyze data for principal rivers and tributaries every few years to look for trends.	Essential to determine cause of lowflow changes;
Resource mapping (springs, seeps, water quality)	Field mapping; visual analyses; produce GIS maps and database.	Better understand ground-water outflow's relation to geology/topography; compliments gain/loss survey.	Periodic as improved information needed.	moderate	Local (verify local conditions) to basin.	High, compared to methods of estimation; needed to verify estimates based on other data (such as geology, slope, soils)

CHAPTER 6: CONCLUSION

6.1 Response to Charge

This chapter briefly reviews how the Committee responded to the elements of its charge in this report. Elements of the charge are restated, followed by a summary of the Committee's response and references to appropriate sections of the report.

What methods should be used to assess not only where ground-water/surface-water interactions are important in a given watershed, but also the quantity and timing of any capture?

> No single technical approach will fit all circumstances; appropriate analytical tools for a given situation depend on hydrogeologic complexity, the nature of proposed withdrawals, regulatory constraints and management questions or needs for technical information. The Committee reviews the scientific principles that should guide any technical analysis (Chapter 3) and has developed a general methodology, or framework, for selecting the appropriate analytical tools to measure quantity, timing, and duration of capture (Chapter 4).

How should the effects of individual wells or withdrawals be considered within the context of cumulative effects of all wells, both existing and proposed, within a watershed or ground-water basin?

> The general framework developed by the Committee is an appropriate method for selecting suitable analytical tools to determine the surface-water capture effects of pumping both at the site-specific level and basin-wide level (Chapter 4). The Committee recommends that data and analytical tools be developed to allow the assessment of cumulative, basin-wide effects in all basins in Washington State; individual withdrawals would then be analyzed within the context of broader basin understanding. Basin-wide analytical tools would enable better and more cost-effective evaluation of individual withdrawals, as well as evaluation of basin-wide pressures, potential future effects, and management and mitigation strategies. Initial criteria and recommendations for basin-wide data collection and analytical tools are presented in Chapter 5.

What is the tradeoff between amount of effort (and time) required, and the certainty of accuracy, for different technical methods?

> A general comparison of the level of effort, the relative cost, and relative quality of result among different technical methods appropriate for evaluating capture is presented in Table 4.1, A Comparison of General Model Types. The Framework provides guidance as to which analytical methods are likely suitable for which circumstances. However, differing site-specific factors, the availability of existing data, and the levels of pressure on the water resource may result in widely varying

levels of effort within the categories and approaches described. The Committee believes that its recommendation for developing basin-scale analytical tools throughout the state will, in the long run, reduce the cost for analyzing the effects of individual withdrawals.

How well suited are the different technical methods for use at a screening (i.e., watershed assessment) level of analysis, as well as at a more rigorous level of investigation?

Some analytical approaches are valid primarily at a local level, while others may serve better for watershed analysis. Section 4.3 and Table 4.1 describe the most appropriate scale (i.e., basin, sub-basin, local) for specific technical methods.

Depending on the hydrogeologic circumstances and the technical question(s) posed, differing levels of analysis may be sufficient. As discussed in Chapter 4 (and illustrated through examples in the Appendix), a Conceptual Model understanding of a watershed and a simple Water Balance may sometimes be enough to answer the question. In other circumstances, more rigorous numerical modeling and additional data will be required. The level of rigor necessary for basin-wide analysis (to support basin management) under different circumstances is discussed in Chapter 5.

How might appropriate methods need to be tailored for different geographic areas or geologic settings in the state?

Table 4.2, General Techniques for Assessing Capture by Hydrogeologic Setting, defines six basic hydrogeologic settings within the State of Washington. Analytical tools appropriate for analyses within these settings are described in Chapter 4. (While distinct hydrogeologic regions exist in the state – within which many model parameters and assumptions would be similar - the definition of generalized hydrogeologic settings was sufficient to provide the guidance on analytical tool selection in this report.) While hydrogeologic complexity is key, the selection of an appropriate analytical approach also depends on the nature of regulatory constraints and management questions requiring technical support.

6.2 Summary of Key Recommendations and Findings

Basis in Science

The Committee agrees that the technical analysis of capture of surface water by wells should be rooted in the fundamental scientific principles governing ground-water and capture effects of surface-water flow, including conservation of mass and Darcy's Law governing flow. Based upon these principles, the Committee unanimously agrees that, in the long run, any ground-water withdrawal will reduce ("capture") surface-water flow in one or more hydraulically connected surface-water bodies), and may affect other parts of the water cycle, such as evapotranspiration. Questions requiring further investigation and

analysis are where (which surface-water bodies will be affected), when will the effect occur, how long will the effect last, and how much of a specific surface-water body's flow will be captured.

Recommended Framework for Analyzing Surface Water Capture

The Committee recommends that the Department of Ecology and water-right applicants use the framework described in this report, along with appropriate attention to specific local circumstances, to determine the best technical tools for evaluation of individual wells/ ground-water withdrawal applications.

The Committee recognizes that both technical (hydrogeologic complexity) and regulatory/management factors (e.g., regulatory constraints on a water body and potential mitigation actions that might be undertaken) affect the appropriate approach and level of rigor of a technical analysis. These factors influencing tool selection are captured in the framework. The Committee also recognizes that water resources with higher pressure and value may deserve a more detailed and thorough analysis, depending upon the question posed. The Committee recommends a method of selecting analytical tools, rather than attempting to prescribe specific types of analysis for given situations, agreeing that it is not possible to prescribe specific analytical tools for the range of circumstances likely to be encountered.

The Committee recommends that the accuracy and precision required to answer a technical question be incorporated into the process of selecting an analytical approach, and that some level of uncertainty analysis always be performed (to assess the level of uncertainty in quantitative results). The Committee also recommends incorporating a results evaluation step within the framework process, to evaluate whether results are reasonable in light of conceptual understanding of a basin, and to evaluate whether results are sufficiently accurate to answer the technical question at an appropriate level of detail.

Recommended Basin-Scale Analysis and Data Collection

A key conclusion of the Committee is that water withdrawal proposals are always best evaluated in the context of an entire watershed, and recommends that tools and capacity be developed to perform basin-scale analysis of water resources. The whole-watershed perspective allows for better long-range planning, what-if analyses, evaluation of individual withdrawals in context, consideration of exempt withdrawals and uncontrollable factors, and evaluation of systemic mitigation/management measures. The Committee agrees that it is the most effective and efficient way to manage water resources. In particular, the Committee recommends:

- A concerted program to develop the tools and data needed for basin-wide analysis of surface-water capture effects should be undertaken by Ecology, in partnership with federal, state, and local agencies, tribes, and other entities. Initial thoughts on appropriate data and analytical tools are described in Chapter 5.

- Resources will be needed to undertake expensive data collection/monitoring efforts, and technical capacity will need to be built at the watershed scale. The Committee recommends establishing priorities for limited financial and technical assistance resources, so as to address the need to support watershed management in basins experiencing strong pressures, as well as to protect existing watersheds with high-quality water and habitat.

Monitoring and Data Collection

A long-term data collection and monitoring strategy should be defined in each basin, so as to build the needed information base for analysis and management. Individual applicants' and permittees' analytical and data collection efforts should be leveraged to support the basin-wide plan. Ecology, USGS, and other partner agencies should also undertake coordinated data collection, establish data standards to ensure that data are consistent and can be shared, and use or build appropriate databases and GIS systems. The Committee recommends, in particular, the systematic collection of actual water use and basic hydrologic and geologic information – critical data that are currently inadequate to support capture analysis in most basins. Data should be publicly accessible, preferably via the Internet.

Roles and Responsibilities

This report outlines a framework for conducting appropriate technical analysis of surface-water capture, but makes no recommendations on who should be responsible for what steps or tasks in that process. The Committee recommends that the respective responsibilities a water right applicant and Ecology would have in this process be further defined. In general, water-right applicants should bear the responsibility of providing more sophisticated analyses and more extensive data where they wish to go beyond the conservative assumptions of simple analytical solutions.

Roles and responsibilities for collecting data and maintaining basin-wide databases, and for developing and updating basin-wide analytical/modeling tools, will need to be clearly defined. The Committee recommends that these data collection and maintenance responsibilities be shared through a coordinated effort, involving federal, state, tribal and local governments, residents, and other interested parties. An interagency/stakeholder effort could greatly enhance the consistency of data collection, the accuracy of analyses, and overall, the pace of completion.

Appendix A

Examples

APPENDIX A: EXAMPLES

The following examples of water-right applications illustrate the application of the Framework for Capture Evaluation to some of Washington's typical hydrogeologic settings, together with some of the regulatory constraints that are encountered in water-rights processing. For each example, we explain how the proposed Framework might be used to perform appropriate technical analysis supporting a water-right decision in the particular situation. The examples are partly or entirely hypothetical to protect actual applicants. These examples are organized by the type of approach (water balance, spatial, timing, or integrated) that was used to resolve the questions surrounding the location, timing, and duration of capture.

Example 1: Water Balance

The Proposal

A developer applied for a ground-water permit to withdraw public ground water in the amount of 32 gallons per minute, not to exceed 4 acre-feet per year, for multiple domestic supply to 9 homes.

The Hydrogeologic Setting and Conceptual Model

The property is situated northeast of Oakville, Washington and north of the Chehalis River. An unnamed tributary to Harris Creek flows through the property. Harris Creek discharges to the Chehalis River. The well is located a few miles north of the confluence of the Black and Chehalis Rivers, at an elevation of approximately 400 feet above mean sea level.

This example represents Hydrogeologic Setting # 3 -- unconfined, single Layer, ephemeral (Table 4.2).

The conceptual model for the watershed indicates that the well will withdraw ground water that would ultimately discharge to Harris Creek and the Chehalis River. Capture of these waters will contribute to reduced base flows.

Regulatory Constraints

The applicant's well is located within Water Resource Inventory Area (WRIA) 23 which is subject to the Water Resources Program in the Chehalis River Basin, WRIA 22 and 23, Chapter 173-522 WAC. Minimum base flows have been established for the Chehalis River. Under the WAC, numerous tributary streams are closed seasonally to further appropriations.

Streamflow data for the upper Chehalis River watershed indicate a trend of declining annual mean flows in many of the watershed's streams. A review of discharge records for the Chehalis River at Porter indicates that established instream flows were not met an average of 73 days per year between 1953 and 1991. During this period, established instream flows for the Chehalis River near Grand Mound were not met an average of 68 days per year.

Data shows that stream flows in the area are most often not met during the months of May, June and July. Ecology has judged that any withdrawal of water must be mitigated such that flows during this period will not be further reduced or impaired.

Analytical Approach/Tool Chosen

The applicant agreed that 100% of the withdrawn water would be captured from Harris Creek and, therefore, was not required to conduct further analysis. He then chose to mitigate his entire appropriation by augmenting summer low flows. To accomplish this, he created off-stream storage ponds that store excess runoff from the spring high flow period and release the stored water during the low flow months. This is a Water Balance Approach (replacing the entire quantity of ground water appropriated with additional storage of surface water) as described in the Analysis Framework, Chapter 4. The applicant created three ponds on the property, which together are capable of capturing and holding approximately four acre-feet of excess runoff water.

Because of the ponds, the flow now occurs most of the year in the small swale below the ponds where, previously, flow occurred only during the wet season. This stream is tributary to Harris Creek, which is, in turn, tributary to the Chehalis River. Therefore, the ponds are augmenting the low flow of all three streams. Evaporation from these ponds is expected to be less than 20 inches per year due to shading and topographic position of the ponds.

Example 2: Water Balance - Seawater Intrusion

The Proposal

A municipality applied for the right to withdraw public ground water in the amount of 2,250 gpm, not to exceed 1850 acre-feet per year, from five wells for year-round municipal supply. A preliminary permit was issued to drill and test a well to provide Ecology with information concerning the expected effects of pumping. The proposed appropriation will supplement existing water rights, so no new annual quantity of water would be allocated. This well field will replace the city's current primary water supply, which is an infiltration trench adjacent to the Northing River.

The Hydrogeologic Setting and Conceptual Model

The well site is located on the northern Olympic Peninsula and several miles east of the Northing River, a large river that flows north out of the Olympic Mountains. Nor'easting Creek drains a small foothills watershed and lies just east of Northing River. This creek flows northeasterly to the Strait of Juan de Fuca, and passes approximately 500 feet east of the proposed well.

Three aquifers and two aquitards have been defined in the regolith that underlies the area. The aquifers are designated as Unit 1 (the unconfined aquifer), Unit 3 (the upper confined aquifer), and Unit 5 (the lower confined aquifer).

The test well is completed in Unit 5, which occurs at a depth of 264 to 439 feet below ground surface at this site. The production zone consists of fine sand with variable amounts of interbedded silt and gravel.

Ground water generally flows north-northeast in this area, eventually discharging to Easterly Bay and the Strait of Juan de Fuca. Water-level measurements indicate that ground water flows vertically downward from Unit 1 down through Units 3 and 5 at the well site. The predominant flow direction in the confined aquifers is horizontal toward the Strait. Aquifer Unit 5 probably also is recharged by infiltration during winter storms and naturally by stream leakage in the foothills.

The well site is located approximately two miles from the Strait of Juan de Fuca. Although the distance from marine waters makes it unlikely that seawater intrusion would affect wells at this site, seaward wells might be impaired by water-level drawdown due to withdrawals from inland wells. Certain evidence indicates that the saltwater-freshwater interface lies well offshore. Near-coastal wells sampled along Dungeness Bay in 1993, all produced ground water with chloride concentrations less than 50 mg/L. To mitigate the uncertainty about seawater intrusion, Ecology required that a water-level monitoring program be established in wells that withdraw from Unit 5 and are located seaward of the applicant's wells. If monitoring indicates a progressive increase in chloride levels, withdrawals from the well field may need to be reduced.

The proposed well probably will not impair other wells completed in aquifer Unit 5 due to the small number of wells withdrawing from that aquifer. However, pumping from Unit 5 is likely to induce some vertical leakage from Unit 3. This, in turn, could induce leakage from Unit 1 and thereby capture surface waters from Nor'easting Creek and Northing River.

In summary, the conceptual model for the drainage basin suggests that due to the abundant flow of ground water discharging through Unit 5 to the Straits of Juan de Fuca and the presence of two intervening aquitard units, the drawdown in aquifer Unit 1 and capture from the stream and river is likely to be only a small percentage of the pumping rate and will be dispersed over a very large area. Nonetheless, pumping this aquifer will reduce base flows in these surface-water bodies.

This example represents Hydrogeologic Setting #4 -- leaky, confined, multi-layered (Table 4.2).

Regulatory Constraints

The Northing River supports critical and depressed salmonid stocks. Any further reduction in base flows would be detrimental to fish habitat. Withdrawals from aquifer Unit 5 may capture a small percentage of the pumping rate from the river, but because the proposed appropriation is for supplemental supply only (no new annual quantity of water is being allocated), any adverse effect should be offset by the benefit of increased flows made possible through decreased reliance on an infiltration trench on the Northing River. Based on production from the first new well, the withdrawals from the infiltration trench will initially be reduced by 50%. Successful development of the well field will make it possible to further reduce withdrawals from the river.

Analytical Approach/Tool Chosen

The fact that this application is for supplemental water dramatically simplifies the analysis required to determine where capture might occur. The municipality already held water rights to capture surface water from Northing River through infiltration trenches and plans to reduce these withdrawals as it switches to reliance on the proposed wells. The important question becomes whether pumping these wells will create seawater intrusion problems for existing wells, that is, will the surface water captured by pumping this well cause the freshwater/seawater interface to move inland. To address this question, the applicant chose a Water Balance Approach (chapter 4) to quantify the potential seawater intrusion. The applicant will monitor the quantities of water pumped, the ground-water levels, and the water chemistry in order to detect the onset of seawater intrusion before it becomes a serious problem.

Short-term effects in aquifer Units 1 and 3 are not expected. Long-term effects can be predicted by recording the city's withdrawals and by monitoring static water levels in all three aquifers as the well field is developed to full capacity. Periodic analysis of monitoring data by Ecology will enable regulation of the city's withdrawals, if necessary, to prevent impairment of existing rights and stream flows.

If senior wells are impaired through drawdown interference or water-quality degradation as a result of operating the well field, the city must reduce its withdrawals at the well field to allow impaired users to exercise the full extent of their water rights.

Example 3: Spatial Analysis Example

The Proposal

A developer applied for the right to withdraw public ground water at the rate of 1650 gallons per minute (gpm), not to exceed 724 acre-feet per year, for community domestic supply and irrigation. The rate of pumping would be steady throughout the year.

The Hydrogeologic Setting and Conceptual Model

The target aquifer consists of glacial and non-glacial sediments deposited during the Pleistocene epoch within a deeply incised bedrock valley of a major river in the western Cascades. Non-glacial, fluvial sediments directly overlie the bedrock and, in turn, are overlain by advance outwash, subglacial sediment, and recessional deltaic sediment.

Two primary aquifers have been identified and will be referred to as the deep and shallow aquifers. The deep aquifer occurs within non-glacial, fluvial sediments and ranges from about 50 to 70 feet thick in the vicinity of the proposed well field. This aquifer is overlain by an aquitard comprised of fine-grained advance outwash and subglacial deposits. A secondary aquifer was identified within the advance outwash and ranges from 60 feet to over 120 feet thick. The aquifers are separated by leaky aquitards of varying thickness and permeabilities. The aquitard directly overlying the deep aquifer consists of 50 to 70 feet of clayey silt, which pinches-out to the south and east. Fine-grained subglacial deposits directly overlie the secondary aquifer and act as an aquitard.

The shallow aquifer discharges to Tributary Creek and contributes about 5.0 cfs, based on stream measurements in 1992, a much-drier-than-average year when the streamflow was about 25 cfs.

The conceptual model for the flow system suggests that pumping from the deep aquifer will induce leakage from both the secondary aquifer and the shallow aquifer. Leakage from the shallow aquifer will reduce surface-water discharge to Tributary Creek and to the Big River, both above and below a large waterfall.

This example represents Hydrogeologic Setting #4 – leaky, confined, multi-layered, connected to surface water (Table 4.2).

Regulatory Constraints

The applicant's well is located within a Water Resource Inventory Area, which is subject to the Instream Resource Protection Program by a formal agency rule. In this rule, minimum base flows are established for both Big River and Tributary Creek.

Long-term flow records for control-point gages indicate that flows in Big River are satisfied in 8 of 10 years. However, the established instream flows for Tributary Creek are not met during more than 110 days in an average year.

Analytical Approach/Tool Chosen

Because the large river appeared to have water available for further appropriation, the applicant chose to use a Spatial Analysis Approach (chapter 4) to resolve the question of which surface waters will be captured by the proposed ground-water withdrawal. Capture of streamflow by the proposed wells was evaluated with a ground-water-flow model (MODFLOW). For a 425-gpm average annual withdrawal from the deep aquifer, the simulations indicated a long-term capture of 55 gpm from Tributary Creek. Another

210 gpm would come from increased recharge and 160 gpm would come from decreased discharge in various reaches of the Big River. Therefore, the applicant probably would be required to mitigate for the 55 gpm capture from Tributary Creek, either year-around or during certain months.

Example 4: Timing Analysis Example

The Proposal

An Applicant applied for a water right to withdraw public ground water at the rate of 55 gpm for domestic supply and the seasonal irrigation of 10 acres. The project site is located in the Walla Walla River basin, near the town of College Place, Washington. The well site is located about 300 feet south of a small, perennial tributary of the Walla Walla River.

The Hydrogeologic Setting and Conceptual Model

Wells associated with this type of project in the Walla Walla River basin typically penetrate varying percentages of gravel, sand and clay to a final depth of less than 250 feet below ground surface. Upon completion, wells in this setting will have shallow static water levels, often within 50 feet of ground surface.

The Walla Walla River basin is a structural trough, within the Columbia River Basalt Group, that has been filled by sediments. The lower-most sediment is the blue clay, which rests directly upon basalt bedrock. Directly over the blue clay and interfingered with it is the gravel unit, comprising the uppermost, aquifer.

This example represents Hydrogeologic Setting #1, Unconfined, Single Layer, Saturated, Gaining or Losing (Table 4.2).

Regulatory Constraints

The Walla Walla River Basin Management Program was developed during 1977 to determine water availability and to insure that the issuance of permits for water withdrawal would be in the public interest. The management program is administered through Chapter 173-532 WAC, which was adopted on December 14, 1977. The proposed appropriation is subject to this management program.

Through this management program, the Walla Walla River and its tributaries have been closed to further appropriation of surface-water rights during the primary irrigation season. The management program also says that if it can be shown that a ground-water withdrawal will capture water from closed surface-water bodies during the irrigation season, then the application for a new water right must be denied.

Analytical Approach/Tool Chosen

To evaluate the timing of capture of surface water by pumping ground water from the gravel aquifer, the Department of Ecology would use a Timing Analysis Approach (chapter 4).

A specific analytical stream depletion model is referred to in the Walla Walla Basin Management Program. Ecology is instructed to use Glover's "Colorado Model," a particular computer program using the mathematical method of Glover.

This implementation of the "Colorado Model" used the hydraulic characteristics of the uppermost aquifer, a constant pumping rate of 55 gallons per minute, and a distance from the well to the stream of 300 feet. Results of the model simulation indicate that pumping from the subject well would capture flow from a nearby tributary during the irrigation season, the period for which that surface-water body is closed to further consumptive uses.

Example 5: Integrated (Spatial and Timing) Analysis

The Proposal

A water district in western Washington applied for the right to withdraw public ground water at a rate of 2,000 gpm, not to exceed 400 acre-feet per year, for public supply. The withdrawal rate would vary throughout the year and would be much higher during the summer and early fall.

The Hydrogeologic Setting

The proposed well field is located on a broad glaciated terrace extending westward for 15 miles from the Cascade foothills to a major river valley that wraps around the south and east sides of the upland. The average elevation of the terrace is 300 feet above sea level. Several small creeks discharge to one large creek that discharges to a large river at an elevation of about 50 feet above sea level. Numerous springs discharge along the bluff above the large river. The springs in one such area have combined flow of 800 gpm and were appropriated by a small city many years ago.

The conceptual model of the flow system indicates the presence of an unconfined aquifer and three successively deeper confined aquifers beneath the uplands. These units are bounded by bedrock beneath the foothills to the east. To the north lies a topographic and ground-water divide shared with another glaciated drainage basin. Aquitards between the aquifers are leaky, with scattered, discontinuous lenses of sand and gravel, and are up to 100 feet thick in places. The unconfined aquifer discharges to the smaller streams crossing the terrace. Abundant leakage from this aquifer recharges the underlying units. The uppermost confined aquifer discharges to the lower reaches of the large creek and to the springs along the river bluff. The deeper confined aquifers are recharged beneath the terrace and discharge via upward flow to the river valley alluvium. This layered

sequence continues northward into the adjoining drainage basin. The large river discharges to an estuary of Puget Sound.

The proposed wells will pump from both the unconfined aquifer and the second or third confined aquifer, depending on test drilling results, though each well would be completed in only one aquifer. During low flow periods, the supplier proposes to cease withdrawing from the unconfined aquifer and then to withdraw only from the confined aquifer.

Regulatory Constraints

Minimum instream flows have been established for the large river and large creek but not the small creeks. Streamflow data indicate that baseflow flow in the large creek has decreased about 20% in 15 years, partly due to drier weather and partly due to ground-water withdrawals. Both senior surface-water rights and established instream flows are impaired during August and September in dry years.

Analytical Approach/Tool Chosen

The applicant chose to demonstrate that withdrawals could occur during the summer months, even during dry years, by temporarily ceasing pumping from the unconfined aquifer during times when established instream flows or senior surface-water diversions were impaired. This required the determination of the proportions of capture from each stream and the river for the proposed configurations of pumping. Because the total withdrawal rate would be highest during the lowflow period, the analysis also involves predicting the short-term rate of capture from each stream and the river. The complexities involved in this analytical approach dictated the use of an Integrated Analysis Tool (Chapter 4).

A three-dimensional computer model of the flow system indicated that the wells withdrawing from the unconfined aquifer would capture some water from the nearest small creek within a few hours and from the large creek within a few days. Leakage to the underlying aquifer would be reduced slightly. Withdrawals from the second or third confined aquifer would increase leakage from the overlying confined and unconfined aquifers, such that discharge to the springs along the river bluff would be reduced by a significant amount, though not enough to impair the water right for the small city. Withdrawals from the deeper confined aquifer would capture a higher proportion of its pumping rate from the large river and a lower proportion from the large and small creeks and springs. Capture from the creeks due to increased leakage from the unconfined aquifer would be about 5% of the pumping rate after 30 days. Thus, even if the wells in the unconfined aquifer were turned off, some capture from the creeks would continue, due to delayed recovery from pumping the unconfined aquifer and to pumping from the confined aquifer.

Ecology might approve the application for ground water but would require extensive gaging of streamflows in several small creeks, monitoring of water levels in wells in all aquifers, and recording of pumping rates in the district's wells. To mitigate the capture from the creeks and equivalent amount of ground water from the confined aquifer would be pumped into the nearest creek during the critical periods. If established instream

flows were not being met on the large river, a much larger percentage of the withdrawals from the confined aquifer also would be reduced. The complex 3-D computer model provided the necessary information on the changing rates of capture from creeks, springs, and the river, as well as rates for streamflow augmentation needed for mitigation.

Example 6: Water Balance Approach (Case 1) or Integrated Analysis Approach (Case 2)

The Proposal

A growing municipality located on a tributary of the Palouse River wants to pump additional water from its ground-water source to meet future demands. The town applies for a maximum summer-time peak withdrawal rate of 100 gpm with an average annual demand of 25 acre-feet per year (equivalent to 16 gpm continuously) to serve 50 new homes. Based on an average consumptive use of 60 percent, an estimated return flow of six gpm is anticipated.

The Hydrogeologic Setting and Conceptual Model

Surficial soils in the area vary in thickness from zero to 300 feet depending on the location. These sediments provide temporary storage of spring runoff and contribute to small but significant base flows throughout the relatively dry summer months. The uppermost hydrogeologic unit is an aquitard. Underlying the surficial soils is an aquifer within the Wanapum Basalt Member of the Columbia River Basalt Group, which is typically less than 400 feet thick in this area. The potentiometric surface of this confined aquifer tends to parallel the land-surface topography and discharges to tributaries of the Snake River that are actively eroding and bisecting the Wanapum Basalt. The next deeper unit is an aquitard comprised of the sparely fractured uppermost part of the Grande Ronde Basalt Member of the Columbia River Basalt Group. Beneath the aquitard, the Grande Ronde Basalt Member has numerous fractures, forming a confined aquifer

This example represents Hydrogeologic Setting #4 -- leaky, confined, multi-layered (Table 4.2).

Regulatory Constraints

Owing to extremely low summer base flows, the Palouse River is closed to further appropriations for the period after June 15 of each year. Furthermore, the Palouse River is tributary to the Snake River. Withdrawals of surface water from the Snake River, or withdrawals of ground water that is tributary to the Snake River, have been under a moratorium (no new water rights can be approved) established in 1992 under Chapter 173-564 WAC. This was done in response to the listing by the National Marine Fisheries Service of Snake River sockeye salmon as endangered under the federal Endangered Species Act in December 1991. Additionally, the National Marine Fisheries has established "Target Flow" requirement at McNary Pool in support of salmon and steelhead which is generally not met in July and August.

Analytical Approach/Tool Chosen

Case 1 - The Town wishes to use an existing shallow well located approximately 2 miles away from river. A decade of recorded ground-water levels from wells in the area suggests that the upper surficial aquifer is connected locally to the stream. Because the stream is part of a seasonally closed basin, the only viable solution is to purchase and retire an existing water right. The analytical tool required to assess this mitigation is the simple Water Balance Approach. Furthermore, because the capture effect will be fairly immediate, the mitigation must provide water to match the depletion induced by the maximum pumping rate less the return flow (100 – 6 = 94 gpm), not simply the average.

Case 2 - The Town proposes to drill a deep cased well into the Grande Ronde Basalt aquifer some 1200 feet below the surface. A three-dimensional "modular finite-difference" (Integrated Analysis Tool) code is used to evaluate the effects. The model uses no-flow boundary conditions around the known area of the aquifer not in contact with the Columbia and Snake Rivers and constant head boundaries at locations along the Rivers. Because of the spatial scale required to model such a large area, the effects are diminutive. The depth of the withdrawal, the aquifer properties of the Grand Ronde Basalt aquifer, and the relatively low vertical recharge rate through the Wanapum/Grande Ronde confining layer result in no discernable withdrawal from the local tributary. However, as indicated in Chapter 3 of this report, continuity to surface water must be present somewhere to complete the flow system and conservation of mass must be preserved. Therefore, it is assumed that ground water would eventually seep out of the Grand Ronde Basalt aquifer along the southwestern and western boundaries of the model. It follows that capture of surface water would occur at this location. Although this effect occurs below the mouth of the Palouse River, the water would have eventually surfaced in the Snake and Columbia Rivers, making it subject to the NMFS's discharge requirement at McNary.

Assuming that the average withdrawal of 16 gpm (25 acre-feet/year) is the amount depleted from the McNary flow at some time in the future and that 6 gpm is returned to the stream by the return flow of treated wastewater, a deficit of 10 gpm is required for July and August (approximately 2.6 acre-feet). Mitigation of this could be the off-stream storage of the treated wastewater in winter months for flow augmentation during July and August. This may be acceptable because the capture effects are expected to be felt below the mouth of the Palouse River and, consequently, are outside of the regulatory constraints applied to the local watershed.

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