CHAPTER 1: INTRODUCTION

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1.1 BACKGROUND

The Arizona Department of Water Resources (Department or ADWR) prepared this technical report titled "Subflow Zone Delineation Methodology for the San Pedro River Watershed" ("Subflow Zone Methodology Report") at the request of the adjudication court in a judicial proceeding known as the Gila River Adjudication.[1] Pursuant to A.R.S. §§ 45-251 to 264, the adjudication court must determine the extent and priority of the rights of persons to use waters of the Gila River system and source, which includes all appropriable water and water subject to claims based on federal law. Appropriable water includes surface water and certain subsurface water known as subflow. This technical report is part of the litigation to identify those wells in the San Pedro River Watershed that will be part of the Gila River Adjudication.

1.2 HISTORY OF PROCEEDINGS

In a case known as *Southwest Cotton*, the Arizona Supreme Court defined subflow as "those waters which slowly find their way through the sand and gravel constituting the bed of the stream, or the lands under or immediately adjacent to the stream, and are themselves a part of the surface stream. It is subject to the same rules of appropriation as the surface stream itself."[2] Underground water withdrawn from a well is presumed to be percolating groundwater, and one who asserts that it is subflow must demonstrate that assertion by clear and convincing evidence. The following test was articulated by the Court:

> Does drawing off the subsurface water tend to diminish appreciably and directly the flow of the surface stream? If it does, it is subflow, and subject to the same rules of appropriation as the surface stream itself; if it does not, then, although it

[1] *In re the General Adjudication of All Rights to Use Water in the Gila River System and Source*, W-1, W-2, W-3, W-4 (Consolidated), Contested Case No. W1-103, Maricopa County Superior Court.

[2] *Maricopa County Municipal Water Conservation Dist. No. 1 v. Southwest Cotton Co.*, 39 Ariz. 65, 85, 96, 4 P.2d 369, 376, 380 (1931), *modified and reh'g denied*, 39 Ariz. 367, 7 P.2d 254 (1932).

> may originally come from the waters of such stream, it is not, strictly speaking, a part thereof, but is subject to the rules applying to percolating waters.[3]

This test is often referred to as the Direct and Appreciable Test.

In 1988, more than 50 years later, Judge Goodfarb, who was then presiding over the Gila River Adjudication, entered an order that described a test (known as the 50%/90-day test) to determine whether certain wells should be presumed to be pumping subflow based on the decision in *Southwest Cotton*. In 1993, the Arizona Supreme Court reaffirmed *Southwest Cotton*, but rejected the 50%/90-day test and remanded the matter for further proceedings. See *Gila II* decision.[4] After remand, at the request of Judge Goodfarb, the Department prepared a technical report titled "Technical Assessment of the Arizona Supreme Court Interlocutory Appeal Issue No. 2 Opinion" dated December 15, 1993 ("ADWR 1993 Technical Report"). Copies of the *Gila II* decision and the ADWR 1993 Technical Report are included in **Appendix A.**

By order dated June 30, 1994, after an extensive evidentiary hearing, Judge Goodfarb presented a new subflow test under which a well is presumed to be pumping subflow and will be included in the Gila River Adjudication if it is located within the subflow zone, or if its cone of depression intersects the subflow zone ("1994 Subflow Order"). Judge Goodfarb defined the subflow zone as the saturated floodplain Holocene alluvium, and summarized his conclusions as follows:

> 1. A "subflow" zone is adjacent and beneath a perennial or intermittent stream and not an ephemeral stream.
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> 2. There must be a hydraulic connection to the stream from the saturated "subflow" zone.
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> 3. Even though there may be a hydraulic connection between the stream and its floodplain alluvium to an adjacent tributary aquifer or basin-fill aquifer, neither of the latter two or any part of them may be part of the "subflow" zone.
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> 4. That part of the floodplain alluvium which qualifies as a "subflow" beneath and adjacent to the stream, must be that part of the geologic unit where the flow direction, the water level elevations, the gradations of the

[3] *Id.* at 96-97, 4 P.2d at 380-81.
[4] *In re the General Adjudication of all Rights to Use Water in the Gila River System and Source*, 175 Ariz. 382, 857 P.2d 1236 (1993).

water level elevations, and the chemical composition of the water in that particular reach of the stream are substantially the same as the water level, elevation and gradient of the stream.

5. That part of the floodplain alluvium which qualifies as a "subflow" zone must also be where the pressure of side recharge from adjacent tributary aquifers or basin fill is so reduced that it has no significant effect on the flow direction of the floodplain alluvium (i.e., a 200-foot setback from connecting tributary aquifers and a 100-foot setback from the basin-fill deposits).

6. Riparian vegetation may be useful in marking the lateral limits of the "subflow" zone particularly where there is observable seasonal and/or diurnal variations in stream flow caused by transpiration. However, riparian vegetation on alluvium of a tributary aquifer or basin fill cannot extend the limits of the "subflow" zone outside of the lateral limits of the saturated floodplain Holocene alluvium.

7. All wells located in the lateral limits of the "subflow" zone are subject to the jurisdiction of this adjudication no matter how deep or where these perforations are located. However, if the well owners prove that perforations are below an impervious formation which precludes "drawdown" from the floodplain alluvium, then that well will be treated as outside the "subflow" zone.

8. No well located outside the lateral limits of the "subflow" zone will be included in the jurisdiction of the adjudication unless the "cone of depression" caused by its pumping has now extended to the point where it reaches an adjacent "subflow" zone, and by continual pumping will cause a loss of such "subflow" as to affect the quantity of the stream.

1994 Subflow Order at pp. 64-66. In a decision known as *Gila IV,* the Arizona Supreme Court affirmed Judge Goodfarb's 1994 Subflow Order "in all respects."[5] Copies of the 1994 Subflow Order and the *Gila IV* decision are included in **Appendix A.**

Pursuant to minute entry filed January 22, 2002 by Judge Ballinger, who currently presides over the Gila River Adjudication, the Department filed a report in March 2002 that proposed steps for implementing the 1994 Subflow Order as confirmed by the Arizona Supreme Court ("2002 Subflow Report"). In July 2004, after briefing and argument on objections to the 2002 Subflow Report, Special Master Schade issued 39 recommendations adopting the 2002 Subflow Report in large part, with certain modifications ("2004 Subflow Recommendations").

[5] *In re the General Adjudication of all Rights to Use Water in the Gila River System and Source,* 198 Ariz. 330, 338, 344, 9 P.3d 1069, 1077, 1083 (2000).

Following another round of briefing and oral argument, Judge Ballinger issued an order dated September 28, 2005, which adopted the 2004 Subflow Recommendations, with certain exceptions, and directed the Department to present subflow zone mapping and related information in a technical report ("2005 Subflow Order"). Review of the 2005 Subflow Order by the Arizona Supreme Court was sought and denied. Copies of the 2004 Subflow Recommendations and the 2005 Subflow Order are included in **Appendix A**.

On June 30, 2009, the Department filed a report for the San Pedro River Watershed that included maps of the subflow zones for the San Pedro River, the Babocomari River, and Aravaipa Creek as determined by the Department, as well as a description of the Department's analyses, and supporting tables, figures and appendices ("2009 Subflow Report"). The subflow zone maps in this report were based on floodplain Holocene alluvium (FHA) boundaries delineated at surficial geologic contacts between Holocene river alluvium (HRA) and bounding geologic units as previously mapped and reported by the Arizona Geological Survey ("AZGS") in 2009 ("AZGS 2009 Report"). Objections and comments were filed to the 2009 Subflow Zone Delineation Report, to which the Department responded by report dated January 31, 2011 ("2011 Subflow Report"). Following three days of hearing from January 24, 2012 through January 26, 2012, Judge Ballinger directed the Department to develop a work plan for supplementing the 2009 Subflow Report to address certain issues. See January 26, 2012 Transcript Excerpt ("2012 Transcript") and Order filed February 22, 2012 (*nunc pro tunc* 01/26/12) ("2012 Order"). Copies of the 2012 Transcript and 2012 Order are included in **Appendix A**.

1.3 SCOPE OF REPORT

In this report, the Department recommends a methodology for delineating subflow zones in the San Pedro River Watershed based on surficial mapping of geologic units together with other geologically and hydrologically appropriate criteria. The subflow zone delineation methodology is described in detail in this report, and examples of how this methodology will be applied are demonstrated in a series of tables, figures and map sheets.

In the 2009 Subflow Report, the Department relied solely upon surficial exposures of geologic units to delineate the lateral extent of FHA, and in turn the subflow zone. It is understood that some additional FHA is present within the geologic floodplain overlain by recent alluvial fans and other tributary or piedmont alluvium that was not included in the subflow zones. In order to determine the presence of this additional FHA, the Department developed a methodology to evaluate several potential indicators, including distributions of surficial geologic units, topographic slope breaks, subsurface lithology and water level data, and riparian vegetation. The Department also reexamined the application of setbacks. The Department's analysis of potential indicators and reapplication of setbacks will result in revisions to the subflow zones mapped in the 2009 subflow report.

At the close of the 2012 subflow hearing, the Court provided guidance regarding the methodology to be developed by the Department for this report. As recognized by the Court, evaluating potential indicators of the presence of additional FHA, and preparing subflow zone mapping based on that evaluation must necessarily involve scientific reasoning and professional judgment. Uncertainty in the delineated lateral extents of FHA and the subflow zone cannot be avoided, but they must be defensible at every location. The court directed the Department to only apply indicators that are useful in delineating the lateral extent of FHA and the subflow zone with confidence, and recognized that not all indicators will be useful at every location. The subflow zone must be continuous and not have gaps within reaches of perennial or intermittent flow. Because strict applications of the language of rulings from previous court decisions may have resulted in unforeseen and scientifically incorrect results, the Department must apply prior court rulings in concert with scientific principles, particularly with respect to the application of setbacks. The Department will not be required to undertake new drilling or perform subsurface investigations. 2012 Transcript at pp. 10-17. The court's guidance is reflected in this report.

CHAPTER 2: CONCEPTS

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2.1 INTRODUCTION

As described in Chapter 1, the Court directed the Department to develop a methodology for delineating the maximum lateral extent of the subflow zone using surface geology maps supplemented by hydrologically and geologically appropriate criteria while applying relevant court rulings and instructions in manners consistent with scientific principles. This chapter reviews relevant court rulings and instructions and the scientific principles to which they relate. The methodology described in the next chapter was developed to be consistent with these principles and also with the conceptual models used by the courts for understanding the physical processes and behaviors of the subflow zone.

The 1993 *Gila II* Decision, 1994 Subflow Order, 2000 *Gila IV* Decision and the 2005 Subflow Order all describe certain aspects of (1) conceptual models for the hydrogeology of the San Pedro River Watershed, and (2) limitations on what constitutes subflow. Such descriptions relevant to this report are summarized in this chapter followed by discussions of scientific principles to which they relate.

2.2 CONCEPTUAL MODELS FOR THE SAN PEDRO RIVER WATERSHED AND SUBFLOW ZONE

Delineation of the subflow zone is the difficult task of locating a line which on one side any well drilled is presumed, as a matter of law, to have a direct and appreciable effect on streamflow, while at the same time, if constructed on the other side of the line, does not. This task is made more difficult by the inherent ambiguity in the distributions, properties and in situ condition states of geologic materials. These difficulties or limitations are common to any hydrogeologic study being contemplated and are normally addressed through development of a conceptual model. The conventional definition of a hydrogeologic conceptual model is that of a qualitative and often pictorial description of the hydrogeologic system, including a delineation of the geologic units and their properties, the system boundaries, and known or assumed inputs/outputs. In translating a real hydrogeologic system into a conceptual model, it is inevitable that some amount of simplification is required. Prior court rulings and directions are based on, among other considerations, conceptual models of geology and hydrogeology for the San Pedro River Watershed and the "Subflow Zone," developed by courts after extensive evidentiary hearings with testimony from experts in the field, including the Department. These conceptual models are used to understand the issues and make decisions.

2.2.1 Geologic Units

Generally, an understanding of hydrogeologic concepts begins first with an understanding of the relevant geologic concepts. Therefore, discussion of the hydrogeologic conceptual model for the subflow zone begins with a brief discussion of the geologic conceptual model and geologic units. Examples of concepts of geology that have been recognized by the courts include:

a. Both the Holocene or younger alluvium and the basin fill are descended from the same source, the rock of uplifting mountains. While the depositional processes were somewhat different, where these units meet it is sometimes difficult to discern the difference between one type of eroded, depositional debris from another, particularly where they may both be saturated and water bearing. (1994 Subflow Order at p. 56)

b. But, contrary to the groundwater users' argument that the trial court's definition of subflow is broader than *Gila II* and *Southwest Cotton* permit, the record reflects that saturated floodplain Holocene alluvium occupies only very narrow portions of the alluvial basins. Moreover, as Ford explained and as the trial court acknowledged, the Holocene or floodplain alluvium is only the most recent portion of "stream alluvium." The entire younger alluvium is of Quaternary age, which includes materials deposited during both the Pleistocene era (approximately 1.8 million to 10,000 years ago) as well as the Holocene era (approximately the past 10,000 years to date). (*Gila IV*)[1]

Figure 2-1 (inset Figures 2-1a, 2-1b, and 2-1c) demonstrates interrelationships between the geologic and hydrogeologic conceptual models used by the Court in the 1994 Subflow Order and the 2009 AZGS surface geology maps.

[1] 198 Ariz. at 342, 9 P.3d at 1081.

Figure 2-1a is a reproduction of Appendix Q from the 1994 Subflow Order showing a plan view delineation of the "interior formation[2]" for a reach of the San Pedro River near Benson, drawn using geology mapping available at that time, based on the ADWR 1993 Technical Report. In that report, ADWR defined the "interior formation" as the relatively narrow "inner valley" of "younger alluvium" set within the broad "outer valley" of "basin fill" alluvium.[3] It is shown as the reddish unit on the figure. "Younger alluvium" is a general term for alluvial deposits from rivers, streams and ephemeral washes. In *Gila IV,* the Arizona Supreme Court correctly described the age of geologic units within the younger alluvium as both Holocene and Late-Pleistocene in age. The use of the term "interior formation" maintains the distinction between younger alluvium deposited by perennial and intermittent rivers for which a subflow zone is to be delineated, and that deposited by ephemeral washes and streams, which are shown as green on the figure and referred to as the "younger alluvium formation." Basin fill, shown as yellow on the figure, is a generic term used for older alluvium of Tertiary age (deposits in excess of 2 million years old).

The conceptual models of the San Pedro River Watershed and subflow zone are built upon these three general types of geologic units: the interior formation deposited by the river, younger alluvium formation deposited by tributaries, and older basin fill weathered from the mountains over long geologic time. The concepts of the interior formation and younger alluvium formation are useful because floodplain Holocene alluvium is a subset of the interior formation and the younger alluvium. Although the mapping by the AZGS reflects greater effort, detail, and modern, more descriptive terminology, the concept of this "interior formation" of "younger alluvium" bounded by "basin fill" is easily discernible from the 2009 surface geologic maps.

Figure 2-1b is Figure 3 from the AZGS 2009 Report as revised in 2010 that shows a conceptual cross-section view with geologic units color coded by age and standard naming convention for surficial Quaternary mapping. This revised figure was presented in the 2011 Subflow Report. **Figure 2-1c** is described in the following section**.**

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[2] The interior formation is referred to as "proposed" in Appendix Q because at that time ADWR had proposed the younger alluvium as one of several possible options for defining the subflow zone. Although FHA, a subset of the interior formation, was selected by Judge Goodfarb, the geologic and hydrogeologic discussions related to the interior formation continue to be valid and instructive for understanding the FHA and subflow zone.

[3] The "interior formation" is sometimes referred to as the "river corridor," and sometimes instead of an "inner valley," the major river of a watershed, such as the San Pedro, is described as the "main axial drainage" because the river channel forms the physical axis of the broad alluvial valley.

2.2.2 Hydrogeologic Concepts

The 1994 Subflow Order relies on certain hydrogeologic principles that are outlined in the ADWR 1993 Report, including the following:

a. Descriptions of perennial, intermittent and ephemeral streams;

b. Descriptions of younger alluvium, tributary and non-tributary aquifers; and

c. Descriptions of alluvial valley, alluvial valley with confined zones, bedrock canyon and mountain-front types of groundwater/surface water interactions.[4]

These general principles, reinforced by other evidence and testimony, form the bases of the hydrogeological conceptual models for the San Pedro River Watershed and the subflow zone. These concepts are easy to understand and useful in communicating the basic model of two distinct aquifers, each comprised of unconsolidated alluvium.

Figure 2-1c is a figure created by the Department for the ADWR 1993 Technical Report and referenced in the 1994 Subflow Order. It shows a cross-section view of the simplified two-aquifer hydrogeologic conceptual model of the "younger alluvium aquifer" of the interior formation set within a larger regional aquifer of saturated basin fill. Groundwater flowing into the younger alluvium aquifer from the basin fill aquifer is called "tributary groundwater," and therefore, also referred to as a "tributary aquifer." These aquifers are called tributary because in some cases they "contribute" water to the younger alluvium.[5] In the subsurface, the older basin fill alluvium generally has lower permeability than younger alluvium aquifers.[6]

The width of the younger alluvium aquifer shown on **Figure 2-1c** is generally related to the width of the interior formation shown on **Figure 2-1a**, tying together both geologic and hydrogeologic concepts. **Figures 2-1b** and **2-1c** show how the detailed AZGS surface mapping correlates with the simplified two-aquifer hydrogeologic conceptual model.

The conceptual model for the subflow zone is similar to that for the younger alluvium aquifer, although they are clearly different. The *Gila IV* decision reaffirmed that the subflow

[4] 1994 Subflow Order at pp. 22 to 31.

[5] In the 1994 Subflow Order, Judge Goodfarb rejected the conclusion reached in *Gila II* that the younger alluvium stretches from ridge line to ridge line so that all the wells in the valley may be pumping from the younger alluvium. Judge Goodfarb noted that every witness found that this statement was not scientifically supportable, and that "it violates general principles of geology and hydrology." *Id*. at pp. 33-34.

[6] "Permeability" is a term that describes the ease with which water flows through a material.

zone is the saturated portion of the floodplain Holocene; in other words, it is an aquifer of floodplain Holocene alluvium.[7] As noted by Judge Goodfarb in the 1994 Subflow Order, the direction of subflow must be the "general overall direction of the stream," meaning within forty-five degrees of the main axial drainage of the watershed (e.g., the San Pedro River).[8] The direction of tributary groundwater flow is understood as being generally perpendicular to the stream or outside of forty-five degrees of the main axial drainage.

Flow directions and volumes in the subflow zone, younger alluvium aquifer and tributary aquifers are all governed by hydraulic head gradients. Gradients are vector quantities for which direction and magnitude can be resolved into two orthogonal components. This means that requiring a flow direction of less than forty-five degrees in the subflow zone is the same as requiring the component of gradient along the direction of the stream to be greater than its component transverse to the stream. In other words, the subflow zone must dip steeper in a direction along its axis than its edges dip towards its centerline. It is worth noting that the conceptual model for the subflow zone does not require there be no transverse slope, only that it be smaller than the longitudinal slope. In cases of gaining reaches, some non-zero transverse gradient from the tributary groundwater aquifer towards the younger alluvium aquifer will exist across the contact surface between the two aquifers indicated by the red arrow on **Figure 4-1c**. What is generally not known is the magnitude of this gradient.

It should be noted that the conceptual models used by the court have traditionally included only water-bearing geologic units, or aquifers. Such a narrow focus was appropriate when describing and discussing the concepts related to behavior and characteristics of the subflow zone. However, for the current task at hand of delineating the lateral extent of the subflow zone using surface geology maps and other criteria, a distinction is required between (1) hydrogeologic aquifer units partially exposed at the ground surface, and (2) non-water-bearing surficial geologic units of limited depth which overlay aquifer units, but are themselves not part of an aquifer. Floodplain Holocene alluvium and basin fill are examples of the first type. Mapped alluvial fans and other alluvium deposited by tributary drainages along the river's floodplain are examples of the second type. Such deposits have raised questions and concerns in this case. They were not part of the 1994 conceptual model for subflow because they are not

[7] 198 Ariz. at 342, 9 P.3d at 1081.
[8] 1994 Subflow Order at p. 57.

aquifers, but they are of Holocene age. They overlay aquifer units, and at shallow depths over geologic time, as described in the AZGS 2009 Report, they have interfingered with floodplain Holocene alluvium in complex three-dimensional patterns.

2.3 LIMITATIONS ON WHAT CONSTITUTES SUBFLOW

2.3.1 Inclusion of Certain Hydrogeologic Units

When the *Southwest Cotton* case was decided in 1931, the court articulated several concepts concerning the definition of subflow, which have been reaffirmed and restated since that time, including as follows:

> a. Whether a well is pumping subflow does not turn on whether it depletes a stream by some particular amount in a given period of time. As we stated above, it turns on whether the well is pumping water that is more closely associated with the stream than with the surrounding alluvium. For example, comparison of such characteristics as elevation, gradient, and perhaps chemical makeup can be made. Flow direction can be an indicator. If the water flows in the same general direction as the stream, it is more likely related to the stream. On the other hand, if it flows toward or away from the stream, it likely is related to the surrounding alluvium. (*Gila II*)[9]
>
> b. Throughout the hearings, field trip and later briefing, the parties have used the terms Holocene, younger alluvium and floodplain alluvium interchangeably. This Court believes the proper terminology for the geologic unit which defines subflow is the saturated floodplain Holocene alluvium….[O]nly the younger Holocene alluvium can pass the test of "subflow" as it is the only stable geologic unit which is beneath and adjacent to most rivers and streams, except those in the mountains where bedrock surrounds the flow. (1994 Subflow Order at 56.)
>
> c. The weight of the evidence points to the saturated floodplain alluvium is the most credible "subflow" zone. Its lateral and vertical limits have existed for some 10,000 or more years. It has far more stability of location than any other proposal including the principal channel which changes approximately every three years, or the post-1880 depositional layer which is really "post-1937" at best, or "post-1955" as indicated in the Hereford Report (exhibit 190 page 8). (1994 Subflow Order at 58).

[9] 175 Ariz. at 392, 857 P.2d at 1246.

d. Contrary to the groundwater users' argument, the saturated floodplain Holocene alluvium does not automatically or necessarily encompass the entire younger alluvium. Equating the two would fail to take into account the pertinent criteria that must be applied and satisfied for determining the "saturated" subflow zone in a particular area. See *Southwest* Cotton, 39 Ariz. at 96, 4 P.2d at 380 [parenthetical omitted]. It also would conflict with our rejection in *Gila River II* of any unqualified, blanket rule that invariably would include "all of an alluvial valley's wells" or all "waters pumped any place in the younger alluvium" in the definition of subflow. (*Gila IV*].)[10]

e. ADWR's saturation assumption is reasonable, practical, and consistent with the goal of permitting this adjudication to be completed "within the lifetime[s] of some of those presently working on the case" [cite omitted] (or at least their children's). And the Supreme Court's requirement that subflow be narrowly defined, coupled with the specific recognition that even wells pumping *de minimis* amounts of subflow may be excluded from the adjudication, ensures that groundwater users' rights will be protected. (2005 Subflow Order at 17-18.)

The conceptual model for subflow created in the *Southwest Cotton* case did not discuss a "subflow zone" within which any well drilled would be presumed to be withdrawing appropriable water. Instead, it conceived of subflow strictly in terms of the actual pumping of a well and whether some diminishment of the stream could be measured or not. Delineation of the lateral extent of a subflow zone for the purpose of identifying wells to be included in the general stream adjudications has necessitated new conceptual models, although courts continue to rely upon the *Southwest Cotton* standard for guidance.

The saturated floodplain Holocene alluvium has been identified as the geologic unit that best satisfies the *Southwest Cotton* standard and the conceptual model for a subflow zone. In the 2005 Subflow Order, the Court determined that the entire FHA should be assumed to be saturated. The assumption of saturation across the full lateral extent of the FHA seems to have been misunderstood by some to believe that it implies fully saturated conditions at the ground surface everywhere FHA is delineated. Instead, it can be thought of as implying the existence of a saturated zone within the vertical depth of FHA in hydraulic connection with the perennial or intermittent stream. This assumption is not unreasonable for reasons described in the 2005

[10] 198 Ariz. at 342, 9 P.3d at 1081.

Subflow Order and considering the possibility of steep subsurface geologic contacts for these incised deposits. Additionally, since delineation of the subflow zone must exclude Late-Pleistocene alluvium where identified, the saturation assumption does not result in inclusion of the entire younger alluvium.

2.3.2 Prohibitions on Certain Geologic Units

In addition to defining the subflow zone as the FHA, courts have indicated that certain geologic units may not be included in FHA, and have made the following statements:

a. The parameters of the "subflow" zone, if it is to be defined by reference to the saturated floodplain alluvium, Holocene alluvium, or younger alluvium, must be outside of and not include those tributary alluvial deposits known as "inliers" as indicated in figure 6 of the Stetson Report (exhibit 2). (1994 Subflow Order at 36.)

b. The Court should direct ADWR to limit its subflow analysis to the floodplain Holocene alluvium. If other deposits or materials (such as Pleistocene) are found within the floodplain alluvium of a stream, the presence and extent of those deposits shall be reported, but the criterion is the floodplain Holocene alluvium (2004 Recommendations at 38.)

These statements directly relate to the prohibition of including in FHA other geologic units which are not river alluvium and Holocene in age. As discussed above, there are non-water-bearing units of relatively shallow depth and of Holocene age that are not part of the delineated aquifer units but which overlie and interfinger with those units. If these non-water bearing units were excluded from the lateral extent of FHA, certain FHA could be excluded from the subflow zone as well.[11] Geologic units older than Holocene cannot be included within the lateral extent of FHA because they cannot overlie Holocene age units. The delineation of FHA must avoid these older geologic units where they are identified.

[11] The non-water-bearing units could also overlie pre-Holocene geologic units in the subsurface. If within the interior formation then the non-water-bearing units could overlie late Pleistocene alluvium. As described in Section 2.2.3, when saturated, the FHA and late Pleistocene alluvium form a common younger alluvium aquifer within which water is free to move between them.

2.3.3 Delineating Floodplain Holocene Alluvium

The courts have made several statements regarding the methodology that should be used to actually delineate FHA and the subflow zone, including the following:

a. The Court should direct ADWR to use the criteria specified in *Gila IV* and any other criteria that are geologically and hydrologically appropriate for the particular location to delineate the subflow zone, if ADWR is unable to do so with the requisite accuracy and reliability utilizing the procedures approved by the Court. ADWR should report the reasons for selecting any other criteria it found appropriate for the location. (2004 Recommendations at 42-43.)

b. The evidence is undisputed that riparian plants directly draw off and diminish the surface flow of adjacent streams. Riparian forestation meets the test of "In re Gila" which asks, "Does the drawing off the surface water tend to diminish appreciably and directly the flow of surface stream" (cite omitted). (1994 Subflow Order at 54).

c. To the extent that phreatophication exists or can be documented in the areas adjacent to the principal channel, it does mark that portion of the area of the "subflow" zone. If it extends to the lateral edge of the saturated floodplain Holocene alluvium, then it is a vital marker. However, even phreatophytes cannot tell the difference between floodplain alluvium and tributary aquifer alluvium, and, therefore, can be a false marker. The boundaries of the riparian zones are helpful and certainly within the "subflow" zones if they do not extend over onto the top of tributary aquifer or basin fill. (1994 Subflow Order at 55-56).

d. Riparian vegetation may be useful in marking the lateral limits of the "subflow" zone particularly where there is observable seasonal and/or diurnal variations in stream flow caused by transpiration. However, riparian vegetation on alluvium of a tributary aquifer or basin fill cannot extend the limits of the "subflow" zone outside of the lateral limits of the saturated floodplain Holocene alluvium. (1994 Subflow Order at 65.)

e. The record reflects that the saturated floodplain Holocene alluvium is readily identifiable; that DWR can quickly, accurately, and relatively inexpensively determine the edge of that zone; and that some of the work already has been done. (*Gila IV*)[12]

f. [O]ur various descriptions of subflow in *Gila River II* and *Southwest Cotton* should not serve as a straitjacket that restricts us from reaching in the direction

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[12] 198 Ariz. at 342, 9 P.3d at 1081.

> of the facts and, so far as possible under those decisions, conforming to hydrological reality. (*Gila IV*)[13]

Although the courts have articulated certain principles, there is an unavoidable level of ambiguity inherent in understanding the distribution and extent of subsurface geologic units. Every subsurface investigation, no matter how extensive or how critically important the results, is limited to some degree by this constraint. A properly developed comprehensive methodology for analysis of available information will, at any given location, either: (1) indicate the likely presence of FHA or subsurface water conditions consistent with characteristics of the subflow zone; (2) indicate such presence or conditions are unlikely; or (3) yield inconclusive results. A reasonable application of these rulings consistent with scientific methods would gather useful available information, employ a process that minimizes user subjectivity, maximizes repeatability and defensibility of results, and carries a presumption of a narrower lateral extent of the subflow zone in the absence of a strong likelihood to the contrary.

<u>Setbacks for Side Recharge</u>

In the 1994 Subflow Order, Judge Goodfarb decided that setbacks should be applied to account for side recharge from tributary aquifers, and made the following statements:

> a. Further definition requires "subflow" to be part of the surrounding floodplain of the stream basin. Those parts of the alluvial plain which it may be a part of or which it is connected to must be the alluvial plain of a perennial or intermittent stream and <u>not</u> an ephemeral stream or a part of the alluvial plain of a tributary aquifer even if there is an alluvial connection. (1994 Subflow Order at 57, emphasis supplied.)
>
> b. Where the alluvial plain of tributary aquifers or ephemeral streams connects to the floodplain Holocene alluvium of the stream itself and provides tributary or basin fill recharge, that tributary aquifer must also be excluded because its flow direction is different and often perpendicular to the stream-flow direction. (*Id.*)
>
> c. As Steve Erb testified, as long as the subflow's direction is within 45 degrees of that general stream flow direction, the flow direction requirement is met. (*Id.* at 57.)

[13] 198 Ariz. at 340, 9 P.3d at 1079.

d. That part of the floodplain alluvium which qualifies as a "subflow" zone must also be where the pressure of side recharge from adjacent tributary aquifers or basin fill is so reduced that it has no significant effect on the flow direction of the floodplain alluvium. (i.e., a 200-foot setback from connecting tributary aquifers and a 100-foot setback from the basin-fill deposits). (*Id.* at 65.)

Tracking the development of these setbacks and understanding their intent is not difficult. Instead, the difficulty arises in determining (1) the circumstances for which "side pressures" have a measurable effect, and (2) in those circumstances, the distance over which those effects dissipate.

The 1994 Subflow Order followed an extensive evidentiary hearing during which several experts testified, including Steve Erb, who was in charge of the Department's Adjudication Section at that time. Erb testified regarding the application of setbacks to account for side recharge from tributary aquifer and basin fill. An excerpt from the transcript of Erb's testimony is included in **Appendix A**. In the 1994 Subflow Order, the use of different distances to overcome the side pressure of the tributary aquifer and basin fill were based on Erb's testimony and the different rates of permeability and transmissivity of the different geologic units.[14] Appendix Q to the 1994 Subflow Order, included in this report as **Figure 2-1a**, depicts where yellow basin fill contacts the interior formation. These are considered areas of "basin fill recharge," and areas where green younger alluvium contacts the interior formation are areas of "tributary recharge." As discussed above, **Figure 2-1c.** identifies the contact surface across which a gradient will exist either from the tributary aquifer towards the interior formation aquifer as in the case of a gaining reach, or vice versa for a losing reach.

Some practical issues not addressed in Erb's testimony or in the 1994 Order can arise during application of the prescribed setbacks. Primary among these is whether or not application of prescribed setbacks should in any case result in some portion of the active channel or hydrologic floodplain being eliminated from the lateral extent of the subflow zone. Also not explicitly addressed is whether or not setbacks should be applied along bedrock lined streams.

Consider first the active channel. When surface water flows are present in the active channel, it establishes constant hydraulic head boundary conditions across the full width of flow equal to the water surface elevation at every river location. This can also be thought of as an

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[14] 1994 Subflow Order at p. 58.

applied gradient condition equal to the slope of the water surface elevation across the full width of flow. It is unlikely that any transverse gradients, if present at these locations, would be of sufficient magnitude to cause the direction of flow to be generally towards the river. The active hydrologic floodplain adjacent to the channel experiences less frequent surface flows, but when they do occur would create analogous conditions to the channel. Overall, setbacks should not be applied in a manner that removes any portion of the active channel or active floodplain from the subflow zone. Also, significant transverse gradients would not be expected along the edges of bedrock lined channels and therefore setbacks should not be applied along those reaches.

Setbacks, as conceived of by the court, are most appropriately applied at the contact between the interior formation and tributary aquifer. Adding to this the practical considerations for active channel and bedrock lined reaches allows the prescribed setbacks to be applied in concert with general scientific principles and results in a continuous subflow zone delineation without anomalies such as those present in the 2009 Subflow Report.

However, just because setbacks can be applied in the same manner as they were originally conceived and create a continuous subflow zone without anomalous results does not assure such setbacks are meaningful, appropriate or accurate. Unfortunately, there is no data readily available by which a systematic evaluation of the prescribed distances can be made. General principles of science and the conceptual models used to understand the hydrogeology of the San Pedro River Watershed indicate that differential pressures can occur at the interface between the interior formation of younger alluvium and tributary aquifers. Positive pressures from tributary aquifers affecting gradients of the interior formation only occur at "gaining" reaches. However, over time, a reach can transition between gaining and losing and therefore, whether it is currently one or the other should not dictate whether or not setbacks should be applied. The locations where side pressures might be expected to be greatest are at the confluences of the San Pedro River with the Babocomari River and Aravaipa Creek. But, because there must be a continuous transition from subflow zones mapped for these streams and the San Pedro River, the concept of setbacks does not apply.

Although not intuitive or obvious, the occurrence of flowing surface water in the washes of tributary side drainages does not necessarily determine whether or not measureable side pressure effects might occur at that location. Groundwater exists at some depth almost everywhere within alluvial basins including the San Pedro River Watershed. The direction of flow within regional aquifers is generally towards the river forming the major watershed axis. It is this depth to water in the tributary aquifers and whether or not it is within the elevation range of the water table of the interior formation that determines whether a differential pressure interface occurs at the subsurface contact. If it is assumed that where the younger alluvium of the interior formation contacts the younger alluvium of side tributaries there exists an analogous type of mini interior formation of subsurface alluvium deposited in the recent geologic past extending below the present water table, then the seepage force acting on the contact with the interior formation would generally be greater (i.e., prescribed as 200 feet) than that force acting upon an adjacent contact with basin fill alluvium (i.e., 100 feet). This would be expected due to the higher permeability of the more recent alluvium and the likely steeper gradient associated with an incised drainage.

Data is not available to assess the reasonableness of the prescribed distances, and if it were available, that data would only be snapshots of conditions expected to vary with time. Generally, any real effects of side pressures would be dependent on relative water levels in the interior formation and tributary aquifers as well as surface flow conditions. In this sense, the issue of setbacks is similar in nature to the issue of saturation for the full extent of FHA. In other words, it requires the development of a reasonable approach to deal with indeterminate conditions.

The methodology presented in Chapter 3 applies the prescribed setbacks at the lateral edge of the interior formation using the original concepts of "basin recharge" and "tributary recharge." The prescribed distances for setbacks are much narrower than the width of the interior formation at the vast majority of the locations throughout the watershed, even if applied on both sides. Therefore, except where delineated limits of FHA is in contact with basin fill or otherwise at the edge of the interior formation, it is expected that 100- and 200-foot setback lines will be outside of the delineated limits of FHA and therefore not alter the subflow zone delineation. At locations where the FHA does contact basin fill or tributary younger alluvium, the delineated FHA will be trimmed so as to not extend beyond the applicable setback line, as long as doing so does not exclude the active channel or floodplain or otherwise result in scientifically incompatible results. Chapter 4 provides an interesting example of the application of setbacks in a case such as this. Generally given the width of interior formation throughout much of the watershed, the application of setbacks will likely have little substantive affect on the width of the subflow zone in the vast majority of locations.

CHAPTER 3: METHODS

CHAPTER 3: METHODS

This chapter describes a comprehensive subflow zone delineation methodology that includes analyses of geology, topography, water levels, riparian vegetation, and lithology for implementation within the San Pedro River Watershed. **Figure 3-1** is a general location map that depicts the San Pedro River Watershed, areas of analysis, and the location of major streams, towns and roads. **Table 3-1** lists the twelve work tasks performed by Department staff[1] in preparation of this report and the methods described herein. As requested by the Court, the Department developed this new framework for evaluating the lateral extent of FHA to more effectively incorporate additional information. As explained in **Chapter 2**, exposed FHA was mapped by the AZGS using the standard naming convention of Holocene river alluvium (HRA). Throughout this chapter and the next, the terms FHA and HRA are used interchangeably when discussing exposed and buried floodplain Holocene alluvium.

Table 3-2 lists the eight river segments within the San Pedro River Watershed selected as areas that will be analyzed when implementing the subflow zone methodology for the entire watershed ("Analysis Areas"). The Analysis Areas range in length between 15 and 37 miles. Each Analysis Area will undergo an initial screening to identify whether it is best analyzed as a single continuous segment or as two or more smaller reaches ("Analysis Subareas"). Once the Analysis Areas and Subareas are selected, a series of data collections, analyses and assessments will be performed for each. After these are completed, the results will form the knowledge base for determinations concerning the likely lateral extent of FHA for each Analysis Area and Subarea.

The determination process initially presumes the narrowest reasonable lateral extent of FHA. Prior to applying setbacks, the delineations for any selected Analysis Subareas will be assembled into larger Analysis Area delineations of FHA. After an Analysis Area has a completed FHA delineation along its full river segment, setbacks will then be applied inward from the contact between the interior formation of younger alluvium[2] and the outer valley basin

[1] For this report ADWR contracted with the AZGS for their review of issues regarding geology.
[2] The "interior formation" and "younger alluvium" are discussed in Chapter 2 and depicted on Figure 2-1.

fill, subject to certain practical considerations**.** Overall, the methodology is intended to make effective use of available information and reasonable assumptions; minimize non-essential subjectivity; maximize repeatability and transparency of results; and maximize the amount of subflow included in the delineation with an appropriate degree of confidence. Examples of how this methodology is applied to a sample Analysis Subarea are presented in **Chapter 4**.

The recommended subflow zone methodology requires the performance of three primary tasks: (1) develop base maps, (2) collect data and perform analyses, and (3) delineate lateral extents of floodplain Holocene alluvium and the subflow zone. The steps required to complete each of the tasks include the following:

Task 1 – Develop Base Maps

- Develop Surface Geology Base Maps
- Develop Floodplain Holocene Alluvium Base Maps for Each Analysis Area

Task 2 – Collect Data and Perform Analyses and Assessments for Analysis Areas and Subareas

- Select Analysis Areas and Subareas
- Collect Data and Synthesize Information
- Analyze Topographic Cross-Sections
- Analyze Water Level Elevations
- Assess Riparian Vegetation
- Construct River Mile Summary-Analysis Tables

Task 3 – Delineate Lateral Extents of FHA and Subflow Zones

- Delineate FHA for Each Analysis Area or Subarea
- Assemble FHA Delineations in Analysis Subareas into Analysis Areas
- Apply Setbacks for Each Analysis Area
- Assemble Analysis Subarea Subflow Zone Delineations for the Entire Watershed

Each of these steps is further described in the following sections:

3.1 TASK 1 – DEVELOP BASE MAPS

Base maps are commonly used to show certain fundamental information and as a foundation upon which additional specialized data is compiled or overprinted. Two sets of base maps will be used for delineating the subflow zone: Surface Geology Base Maps and Floodplain Holocene Alluvium Base Maps.

3.1.1 Develop Surface Geology Base Maps

The Department created Surface Geology Base Maps for the San Pedro River Watershed during development of the methodology, and these maps will serve as the underlying basis for delineation of the subflow zone. The purpose for the maps is to simplify the details of AZGS surface geology maps and display other useful information. Because the floodplain Holocene alluvium is a subset of the interior formation of younger alluvium, the primary focus of these maps is on displaying Holocene and Pleistocene geologic units. The maps are plotted using the original 1:24,000 scale as well as the sheet sizes and layouts used by the AZGS in its 2009 Report. Also shown on the maps are one-mile river markings along the active channel as well as the historic composite active floodplain boundary from the 2011 Subflow Report ("Historic Floodplain").

Geologic units displayed on the maps are color-coded by the age and naming conventions used by the AZGS. This was done to present the units as they were categorized by the AZGS without further interpretation by the Department. **Table 3-3** lists the AZGS age and naming conventions shown on the Surface Geology Base Maps and the geologic units they represent. At contacts between geologic units of different age and naming conventions, the maps preserve the different line types used on the AZGS original mapping to show levels of accuracy. In its 2009 report, the AZGS explained the different line types that it used to delineate contacts between units as follows:

1. A solid line indicates that the contact is clear and the location of the line is accurate to within ±25 feet.
2. A dashed line indicates that the contact between is subtle or gradational and the location of the line is accurate to within ± 50 feet. Dashed line boundaries are also located within historically plowed fields.

3. A dotted line indicates that the contact has been thoroughly obscured by anthropogenic activity and the location of the line is accurate to within ± 250 feet, depending on the level of disturbance.

Surface Geology Base Maps for the entire San Pedro River Watershed are presented in **Map Sheets Nos. 1-6**, which are included in **Appendix B**.

3.1.2 Develop Floodplain Holocene Alluvium Base Maps for Each Analysis Area

Floodplain Holocene Alluvium Base Maps are the canvas upon which delineations of FHA and subflow would be drawn. FHA Base Maps will be developed from information on the Geology Base Maps and will identify the certain boundaries or "limits" on the investigation of the lateral extent of FHA.

The FHA Base Maps will delineate segments where the lateral extent of FHA is already known ("Known Limits"). These are at locations where either exposed HRA or the Historic Floodplain shares a contact with a pre-Holocene geologic unit. The Historic Floodplain is used in areas where it extends outside exposed HRA because those locations are where very recent tributary deposition has buried or altered the HRA.

Where not already known, the FHA Base Maps would delineate segments of the "inner" limit of possible lateral extents of FHA ("Inner Limit"). The Inner Limits would delineate: (1) areas of exposed HRA not included in the Known Limits, (2) fingerlike or otherwise readily apparent locations where Holocene piedmont alluvium or other Holocene deposits have buried or altered HRA, and (3) the edges of the Historic Floodplain where they share a contact with Holocene piedmont alluvium (HPA) or other Holocene deposits (OHD).

Also, where not already known, the FHA Base Maps would be used to delineate segments of the "outer" limit of reasonably expected lateral extents of FHA ("Outer Limit"). The Outer Limits would delineate the lateral extent of exposed HPA and OHD within the interior formation as estimated by marking pre-Holocene deposits and extrapolating between locations where Holocene deposits obviously extend beyond the interior formation. The Outer Limit would be drawn as continuous lines except in areas of sparse and irregular pre-Holocene geologic units where discontinuous line segments would be drawn. It is possible that in some locations FHA could extend beyond the Outer Limit. A preliminary FHA Base Map for a sample Analysis Subarea is included in **Chapter 4**.

3.2 TASK 2 – COLLECT DATA AND PERFORM ANALYSES AND ASSESSMENTS FOR ANALYSIS AREAS AND SUBAREAS

This task would collect and efficiently utilize available information for each of the eight Analysis Areas listed in **Table 3-2**. Subtasks would include: (1) selection of Analysis Areas and Subareas, (2) collection of data and synthesis of information for each Analysis Area or Subarea, (3) analysis of topographic cross-sections, (4) analysis of water level elevations, (5) assessment of riparian vegetation, and (6) construction of River Mile Summary-Analysis (RMSA) tables. Each of these subtasks is further described below:

3.2.1 Select Analysis Areas and Subareas

Each Analysis Area would be examined to determine whether it would be best analyzed as a single continuous river segment or as two or more smaller reaches within Analysis Subareas. For each Analysis Area, ranging in length from 15 to 37 miles, the following information would be reviewed: (1) the general geologic setting shown on the Surface Geology Base Maps, (2) characteristics of Known, Inner and Outer Limits shown on the FHA Base Maps, (3) consistency in riparian vegetation growth, (4) availability of water level elevation measurements and well hydrographs, and (5) availability of geologist and other detailed soil boring logs. The screening process is for determining whether the availability and distribution of data throughout the Analysis Areas would most effectively be analyzed through a single analysis (e.g., more uniform physical and data conditions) or through more than one analysis, each tailored to different conditions or data sets.

3.2.2 Collect Data and Synthesize Information

Once the Analysis Areas and Subareas would be selected, a series of data collections, analyses and assessments will be performed for each. These will begin with collection of all available information related to: (1) water level elevations and well hydrographs, (2) geologist logs and other relevant professional quality field investigation results, (3) available information regarding riparian re-vegetation or mitigation projects in the area, (4) available information regarding changes in historic vegetation patterns, and (5) other potentially useful information such as stream channel slopes, local thickness of younger alluvium aquifer, and extent of groundwater confining conditions, if any.

The Department recommends that analysis of lithology be limited to soil boring logs prepared by geologists or other trained geotechnical professionals. An effort will be made to collect as many geologic logs or other professional field investigation results as possible. Locations of logs will be mapped and the detailed logs will be analyzed by qualified personnel to determine the elevations and depth ranges of granular alluvium consistent with the concept of subflow. Information and data obtained will be used to characterize the areas where they were drilled and also be used to supplement and inform other analysis methods that will be planned for that Analysis Area or Subarea. Differences and similarities will be made of logs drilled within the Inner Limits versus those drilled in between the Inner and Outer Limits for individual logs in proximity to each other as well as the aggregate data sets. The use of driller's logs is not recommended due to issues with lack of consistent reliability and usefulness of the data. The Department suggests that including an analysis of the very large number of driller's logs in the recommended methodology would not improve the overall delineation of the subflow zone.

3.2.3 Analyze Topographic Cross-Sections

The analysis of the topographic cross-sections uses a knowledge-based approach applying sets of simple and consistent criteria based on similarities and trends learned from observations of other cross-sections. In order to form definitive conclusions some basic assumptions of geology need to be made.

The analyses will include construction of a series of two-dimensional cross-sections for each Analysis Subarea. Locations for section lines will be selected to provide representative views of different geologic and geomorphic relationships. Section lines will be oriented normal (perpendicular) to the axis of the interior formation and will avoid side tributary drainages. Because the valley is not perfectly symmetric about its axis, some minor deviations from perpendicular will be necessary. At some locations due to meander, there is a significant difference in orientation between the edge of the active river floodplain and the edge of the interior formation. In these cases, in order to best capture the true topography, section lines will be drawn first normal to the floodplain edge, and pivot to be normal to the contacts with basin fill.

Cross-sections will be plotted using USGS 10-meter digital elevation model data overlain by the surface geology mapping. Slope breakpoints, elevated terraces and other topographic features will be visually identified. Vertical to horizontal exaggeration ratios will be used to allow rapid visualization of potential features. For each potentially significant slope breakpoint, the cross-section (X, Y) data points will be exported and linear regression analysis[3] performed on the slope angles for both sides of the breakpoint. This analysis is to confirm the significance of each breakpoint and eliminate any visual bias created by the vertical distortion. In cases where the perceived break is subtle, a second regression analysis will be performed. If the results of the first analysis do not show a better fit than the second, then the breakpoint will not be considered significant and will not be considered further in the analysis.

Two examples of knowledge-based approaches are provided below. The analyses focus attention on the first significant topographic features located outside the exposed FHA where the area in question is as shallow as possible. The first example is a straightforward application of a similarity analysis between a series of sections with recurring topographic features.

1. For example, review of data from across a river basin might find that every mapped Qy2r terrace is between 11 and 32 feet above the active channel. At a given cross-section, there is a significant topographic feature underlying Holocene piedmont alluvium at 18 feet above the active channel. A downstream section shows an exposed FHA terrace at 21 feet and an upstream section shows an exposed FHA terrace at 14 feet. Using similarity, the information would be interpreted as being consistent with a likely extent of FHA to this feature or beyond.

   Consider this example again and the buried feature is not 18 feet above, but 44 feet above. Using similarity, it would be interpreted as not being consistent with a likely extent of FHA to this feature or beyond.

[3] For this problem, x = distance along cross-section, y = ground elevation, and m = ground slope.

The second example of a knowledge-based approach utilizes assumptions on the underlying geology. These assumptions would provide a framework for rational and repeatable interpretation of topographic indicators that can either be supported by other information, or not. The analysis assumptions would be the following:

2. Based on results of the AZGS surficial geologic mapping along the river, the composite late Holocene floodplain (essentially, the Qy2r terrace) is close to the maximum level of river aggradation in the Holocene. The AZGS mapped very few remnants of older Holocene terraces (Qy1r), and these are only slightly higher than Qy2r. Therefore, it could reasonably be assumed that there are no remnant Holocene terraces above the obvious Qy2r terraces along the San Pedro River. The primary implication of this assumption is that deposits of Holocene piedmont alluvium or other Holocene deposits greatly elevated above the late Holocene floodplain do not overlie FHA at a shallow depth. If they do not overlay FHA at a shallow depth, then any higher slope breaks would not be direct indicators of the extent of FHA, because if FHA extended laterally well beyond surface exposures it would be in the subsurface below or at most slightly above the Qy2r terrace elevation.

   It could also be assumed that the FHA and adjacent deposits are deeply incised with steep or nearly vertical side walls. Then, the first significant topographic feature beyond the edge of exposed FHA and within the Holocene piedmont alluvium or other Holocene deposits, if not elevated greatly above the late Holocene floodplain, could be inferred as the lateral extent of FHA. Note that the assumption of the steep walls implies the FHA deposits stop at that location and allow the inference of its lateral extent. If generally the deposits are not nearly vertically incised, then the FHA could either not extend that far to begin with or could extend beyond. It is unknown.

Results of the cross-section analyses will be used to assist in the determination of the likely lateral extent of FHA for each Analysis Area or Subarea. Generally, results of the cross-section analyses will indicate either: (1) it is likely that FHA may extend to or beyond a certain area based on consistently applied assumptions, (2) it is unlikely that FHA may extend to or beyond a certain area based on consistently applied assumptions, or (3) the data is inconclusive. A preliminary analysis of cross-sections for a sample Analysis Subarea is included in **Chapter 4**.

3.2.4 Analyze Water Level Elevations

Within each Analysis Area or Subarea, the locations of wells, water level measurement data, and well hydrographs held by the Department or the U.S. Geological Survey (USGS) will be reviewed. Water level data will be restricted to relatively shallow wells to prevent regional aquifer data from confusing the results. Initially, wells with depths or perforations no deeper than about two hundred feet will be considered shallow, but this depth may be varied in some Analysis Areas or Subareas. It is well established that there are not enough water level measurements in close enough proximity to each other and consistently located throughout the watershed to allow direct analysis of equipotential lines and their inferred flow directions on a small enough scale to identify the edge of the subflow zone. Instead, an analysis method was developed to test whether the water level data is either consistent or inconsistent with the conceptual model of the subflow zone.

The overall pattern of flow of the subflow zone may be idealized as one-dimensional curvilinear flow. In other words, while the subflow zone gradually turns and follows the primary axis of the alluvial valley, the water level elevations are approximately equal within the subflow zone along a line perpendicular to the flow path. As discussed in **Chapter 2**, there may be transverse water slopes within the subflow zone either away from the zone for a losing reach or towards the zone in a gaining reach. These gradients must be smaller in magnitude than the slope in the direction of subflow. The available water level measurements can be tested to see whether they are distributed in a manner consistent with these idealized flow patterns. Once the shallow wells are selected, the analysis will be performed as follows:

1. Approximate the centerline for subflow as a series of generally straight-line segments using engineering judgments and following the overall direction and slope of the inner alluvial valley while staying near the middle of the interior formation (river corridor) and weighted towards the active river channel. Note

that subflow, while following the same corridor of the river, does not follow the meandering of the river within the interior formation. Instead, subflow (like all flow through porous media) obeys Darcy's Law and moves as a distributed front across the width of permeable sediments (i.e., the younger alluvium). In some cases there would be some minor preferential leading flows along buried river channels where permeability is locally quite high.

2. Draw a straight line between each well and its perpendicular intersection with the centerline of subflow.
3. Select the downstream extent for analysis and label it as station "zero."
4. Measure distance "X" upstream from station zero to each intersecting line for a well. Label as station "X."
5. Create an "X,Y" graph by plotting the stationing (in feet) and water level elevation (in feet MSL) for each well.[4]
6. Perform a series of linear regression analyses[5] for the following data sets:
    - All shallow wells
    - Shallow wells within the Inner Limits
    - Shallow wells between the Inner and Outer Limits
7. For each of the analysis sets evaluate results for:
    - Whether the data suggest a constant slope of water level elevation along the general orientation of the interior formation
    - Whether the data suggest that water level elevations measured from the shallow wells within the Inner Limit follow the same slope as those drilled between Inner and Outer Limits
    - Whether the data suggest the existence of a significant transverse gradient between water level measurements from the shallow wells within the Inner Limit from those wells drilled in between the Inner and Outer Limits

[4] MSL is mean sea level.

[5] Linear regression is a common statistical technique used to examine correlation between two variables, commonly denoted x and y. The solution is the best-fit of the data to an equation in the form of straight line, y = mx + constant, where "m" is the slope of the line. For this problem, in the formula y = mx + constant, x = distance upstream from some reference point, y = measured water level elevation, and m = slope of water table in direction of subflow.

Results of the water level analyses will be used to assist in the determination of the likely lateral extent of FHA for each Analysis Area or Subarea. Generally, the results will indicate flow conditions across some width of a shallow aquifer which may either be: (1) consistent with subflow, (2) inconsistent with subflow, or (3) inconclusive. A preliminary analysis of water levels for a sample Analysis Subarea is included in **Chapter 4**.

3.2.5 Assess Riparian Vegetation

For each Analysis Area and Subarea, riparian vegetation growth would be assessed by modifying the FHA Base Maps to display two riparian vegetation data sets:[6] (1) cottonwood and willow and (2) mesquite and salt cedar. The riparian data would be displayed this way in recognition of how the two pairs of vegetation are generally classified. It is understood that such classifications are inexact and vegetation patterns are complicated by flood flows and many other factors. However, cottonwoods and willows are commonly classified as obligate phreatophytes, meaning that shallow subsurface water (e.g., less than ten feet) is essential for their survival. They commonly grow on the active floodplains of perennial and intermittent rivers. Mesquite and salt cedar are commonly classified as facultative phreatophytes, meaning that while they can use relatively shallow or deep subsurface water, they can also survive solely on rainfall. These trees can be found growing in upland areas, but dense stands of mesquite and salt cedar are most common on river floodplains and low river terraces. The assessment will also:

1. Use available information to identify areas where riparian vegetation has been planted and cultivated by man including mitigation and re-establishment projects.
2. Use available information, including a 1994 ADWR analysis,[7] to identify areas for which significant changes in vegetation are known to have occurred.

There are certain limitations inherent in the riparian vegetation assessment. As referenced in **Chapter 2**, the 1994 Subflow Order acknowledged that where riparian vegetation

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[6] The GIS data will be the same as used in the 2011 Subflow Report, but displayed in a different way for easier understanding and noticing of trends. Data comes from the USFWS National Wetlands Mapper website. Mapping is based on 1:24,000 scale aerial photographs primarily taken in 2001. The last four miles of the lower San Pedro River and about five miles in the middle Babocomari River were mapped using 2005 and 1996 aerial photographs.

[7] June 1994 ADWR Memo to Interested Parties titled, "Channel and Riparian Vegetation Changes along the San Pedro River," from Charles Cullom. A copy of the memo is included in Appendix A.

draws water from the stream it meets the subflow test and that riparian vegetation may be useful in marking the lateral limits of the subflow zone. However, it can be a false marker. Riparian vegetation on the alluvium of a tributary aquifer or basin fill cannot extend the limits of the subflow zone outside the lateral limits of the saturated FHA.

The findings of the riparian analysis within each Analysis Area and Subarea will be used to support other available information in the determination of the likely lateral extent of FHA. The lack of vegetation at any location will not be considered a negative indication that FHA does not extend. In many cases, riparian vegetation may be limited to within the Inner Limit for FHA and therefore not directly factor into the determination. A preliminary assessment of riparian vegetation for a sample Analysis Subarea is included in **Chapter 4**.

3.2.6 Construct River Mile Summary - Analysis Tables

For each Analysis Area or Subarea, findings and results from the complete sets of data collections, analyses, and assessments will be compiled using standardized data collection tables known as River Mile Summary-Analysis (RMSA) tables. The tables will help to summarize information and document the analysis and determination processes. **Table 3-4** shows the standard template for the RMSA tables.

3.3 TASK 3 – DELINEATE LATERAL EXTENTS OF FHA AND SUBFLOW ZONES

After the base maps are developed, the available useful information will be collected and analyses performed. What remains is delineating the lateral extent of the FHA, applying setbacks and finally delineating the extent of the subflow zone. This task will be accomplished through a series of four steps: (1) the likely lateral extent of FHA will be delineated within each Analysis Area or Subarea, (2) the delineations for each Analysis Area or Subarea will be assembled into a single delineation, (3) setbacks will be applied in the manner described in **Chapter 2** to develop subflow zone delineations, and (4) the subflow zone delineation for the San Pedro River Watershed will be assembled from the eight individual Analysis Area subflow zones.

3.3.1 Delineate FHA for Each Analysis Area or Subarea

For each Analysis Area or Subarea, there are Known Limits where the extent of FHA is well defined and the delineation of FHA must pass through them. In other locations, there will be lines or markers that delineate the lateral extent of the FHA. The lines will represent the Inner Limit, Outer Limit, and markers from the finding of the analyses and assessments. All of the compiled information, data, and results will be reviewed and then used to make a series of determinations concerning these lines and the likely presence of FHA. The evaluation process presumes a narrower lateral extent in the absence of a relatively high likelihood to the contrary. The following determinations will be made:

No. 1. Whether it is likely that FHA or subflow extends beyond the Inner Limit.

- If it is not likely, then delineate the lateral extent of FHA at the Inner Limit.
- If it is likely, then go to No. 2.

No. 2. For locations determined to likely extend beyond the Inner Limits, whether it is likely that FHA or subflow extends to or beyond marker locations between the Inner and Outer Limits from the findings of the analyses and assessments.

- If not, then delineate the lateral extent of the FHA at the Inner Limit.
- If otherwise (but not beyond), then delineate the lateral extent of the FHA at the marker.
- If it is likely to extend beyond, then go to No. 3

No. 3. For locations determined to likely extend beyond the Inner Limits and beyond marker locations , whether it is likely that FHA or subflow extends to the Outer Limit.

- If it is not likely, then delineate the lateral extent of FHA at the marker locations between the Inner and Outer Limits from the findings of the analyses and assessments.
- If it is likely, then delineate the lateral extent of FHA at the Outer Limits.

3.3.2 Assemble FHA Delineations in Analysis Subareas into Analysis Areas

Within each Analysis Area, the lateral extents of FHA delineated in each of the Analysis Subareas will be mapped and their edges connected using smooth transitions across Analysis Subarea boundaries.

3.3.3 Apply Setbacks for each Analysis Area

Within each Analysis Area, setbacks will be established as described in **Chapter 2**, by applying either the 100- or 200-foot prescribed distances inward from the lateral edge of the interior formation and using the definitions of basin and tributary aquifers described in the 1994 Subflow Order. In many locations, it is expected that 100- and 200-foot setback lines will be outside of the delineated limits of FHA and therefore would not alter the subflow zone delineation. In other cases, the delineated FHA will be trimmed so as to not extend beyond the applicable setback line, as long as doing so does not exclude the active channel or floodplain or otherwise result in scientifically incompatible results. After application of setbacks is performed, the remaining delineation will be the lateral extent of the subflow zone.

3.3.4 Assemble Analysis Subarea Subflow Zone Delineations for the Entire Watershed

The lateral extents of subflow zones delineated in each Analysis Area will be mapped and their edges connected using smooth transitions across Analysis Area boundaries. This process will complete delineation of the subflow zone for the entire San Pedro River Watershed. The Department estimates, given available resources, this methodology could be implemented for the watershed in a time of between twelve and fifteen months.

CHAPTER 4: RESULTS

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This chapter demonstrates the analyses of the comprehensive subflow zone delineation methodology by presenting the results of a preliminary analysis for a Sample Subarea. The Sample Subarea chosen is a ten-mile long reach ending at the “Narrows” near Pomerene within the Benson Analysis Area shown in **Table 3-2**. Although an actual river reach is used for demonstration purposes, these results are preliminary and subject to change. Upon full implementation of the methodology, this reach may not be selected as a subarea for analysis; instead, it may be part of a larger subarea or may be split into portions located in more than one subarea. Due to time limitations in preparing this report, initial results that would normally require some follow-up analysis for confirmation of information are noted.

4.1 BASE MAP DEVELOPMENT

As described in **Chapter 3**, Surface Geology Base Maps have been developed for the entire San Pedro River Watershed. **Figure 4-1** shows the Surface Geology Base Map for the Sample Subarea. Two preliminary FHA Base Maps for the Sample Subarea were developed using methods described in **Chapter 3,** which are presented on two figures. **Figure 4-2a** shows the FHA Base Map, and **Figure 4-2b** shows the FHA limit lines plotted over recent aerial photography.

4.2 DATA COLLECTION AND ANALYSIS

Preliminary analyses of topographic cross-sections and water level elevations, as well as a preliminary assessment of riparian vegetation growth were each preformed for the Sample Subarea and the results presented herein.

4.2.1 Analysis of Topographic Cross-Sections

The preliminary analysis of topographic cross-sections for the Sample Subarea used the methods described in Chapter 3. Locations and orientations of fourteen cross-section lines selected for the analysis are shown in **Figure 4-3**. Highlighted on the figure are seven cross-section lines presented later as results. The second analysis approach presented in Chapter 3 was selected for demonstration using these cross-sections. This approach primarily involves identification of the first significant topographic feature or slope breakpoint beyond the edge of exposed FHA on both sides of the river, so long as it does so at an elevation generally consistent with that of the late Holocene floodplain (i.e., the Qy2r terrace). Given the assumptions discussed in Chapter 3, the lateral extent of the feature is an indication of the lateral extent of FHA. Each cross-section was examined to identify significant topographic features and the elevation at which the feature occurred relative to the Qy2r floodplain. Subtle features were confirmed using regression analysis to calculate true slope angle. **Figure 4-4** is an example of such a check performed for a slope breakpoint identified on the west side of the river at Section Line 89-A.

Significant topographic features were identified for thirteen of the fourteen cross-sections. At the fourteenth cross-section, no significant topographic features could be identified. For each cross-section line, the locations of the identified features on both sides of the river were recorded as follows:

- At the location of the Inner Limit
- Between the locations of the Inner and Outer Limits
- At the location of the Outer Limit
- Beyond the Outer Limit

It should be noted again that the Outer Limit was chosen as a readily identified marker towards the outer edge of FHA and is not an actual “limit” beyond which FHA cannot extend. Also, the Outer Limit is commonly extrapolated for substantial distances between pre-Holocene outcrops. Some identified features extend, beyond these areas of extrapolation. **Table 4-1** lists the findings of the preliminary analysis. As noted in the table, some of the findings indicate that follow-up or further investigation would be warranted, but that has not been completed for this preliminary analysis. **Figures 4-5** through **4-11** show a series of cross-sections displaying the identified topographic features and their relations to the Inner, Outer, and Known Limits of FHA plotted in prior steps. **Figure 4-12a** shows the lateral extents of the first significant topographic features plotted onto the FHA Base Map. **Figure 4-12b** shows the same information over recent aerial photography.

4.2.2 Analysis of Water Level Elevations

The preliminary analysis of water level elevation data for the Sample Subarea followed the methods described in **Chapter 3**. Twenty-two shallow wells were identified, of which 13 were within the Inner Limits and 9 were between the Inner and Outer Limits. For the Sample Subarea, wells with drilled depths 201 feet or shallower were used. Results of the regression analyses, as well as locations of wells and conceptualized subflow patterns for the Sample Subarea are shown on **Figure 4-13a,** and also shown on **Figure 4-13b** plotted over recent aerial photography. The results are generally consistent with the idealized flow pattern of subflow and the assumed centerline of flow. The shallow aquifer from which the wells within the Inner Limits draw water exhibits a slope that is essentially identical to the slope of the interior formation or river corridor with little apparent deviation. When the wells drilled between the Inner and Outer Limits are included in the analysis, the overall slope of the water table is statistically unchanged, a result consistent with their drawing water from the same shallow aquifer. It is also apparent from the results that some transverse gradient does exist within the Outer Limits. This is indicated by the wells between the Inner and Outer Limits consistently showing somewhat higher water level elevations than wells within the Inner Limits along the same assumed line of constant head. Magnitudes of the transverse gradients suggested by the results are of the same order or smaller than the gradients along the direction of flow. This result is generally consistent with the conceptual model of subflow discussed in **Chapter 2**, wherein the transverse gradient must be smaller than longitudinal gradient.

4.2.3 Assessment of Riparian Vegetation growth

Figure 4-14a shows riparian vegetation plotted onto the FHA Base Maps and **Figure 4-14b** shows the same riparian information plotted onto recent aerial photography. This preliminary assessment is limited to use of the United States Fish and Wildlife Service (USFWS) GIS data which shows cottonwood or willow growth within the Sample Subarea limited to only a few locations adjacent to the active channel in the Southern portion of the subarea. Mesquite and Salt Cedar growth is shown to be present across the full width of exposed FHA between river miles 82 to near mike 84, and expands beyond the exposed FHA to the east in the area of river mile 85 at a large fan deposit. Other than these areas, the riparian growth covers only a limited area of the exposed FHA, plus a few locations around river miles 88, 89 and 91 where the growth expands outside the exposed FHA for a limited distance in an irregular pattern.

4.3 FHA DELINEATION AND APPLICATION OF SETBACKS

A preliminary delineation of the likely lateral extent of FHA and the procedure for applying setbacks were performed for the Sample Subarea in a manner described in **Chapters 2** and **3**.

4.3.1 Delineation of the Lateral Extent of Floodplain Holocene Alluvium

A series of preliminary determinations as described in **Chapter 3** regarding the likely lateral extent of floodplain Holocene alluvium were performed for the Sample Subarea.

No. 1. Determine whether FHA or Subflow could extend beyond the "inner limit."

- At river miles 83, 88, 90, and 91, preliminary topographic and water level analyses indicate the likely presence of FHA beyond the “inner” limits.

- At river miles 82, 84, 85 and 86, preliminary topographic and water level analyses indicate the likely presence of FHA at the "inner" limits.
- At river miles 87 and 89, sufficient information is not available upon which to make a determination that FHA or Subflow extends beyond the "inner" limits.

No. 2. For locations that could extend beyond the "inner" limits, determine whether FHA or Subflow could extend to or beyond locations of first significant topographic features.

- In areas near river miles 83, 90 and 91, the locations of first significant topographic features correlate with the "outer" limits.
- In the area of river mile 88, there is no bounding pre-Holocene geology to define an "outer" limit, however the location of first significant topographic feature aligns closely with upstream and downstream locations where the feature does correlate with the "outer" limit.

Results of the determination indicate the following preliminary delineation of the FHA for the Sample Subarea:

- In areas near river miles 82, 84, 85, 86, 87, and 89 the lateral extent of FHA should be delineated as a smooth line defined by the "known" limit, "inner" limit, and locations of first significant topographic features.
- In areas near river miles 83, 88, 90, and 91, the lateral extent of FHA should be delineated as a smooth line defined by the "known" limit, "outer" limit, and locations of first significant topographic features.

Figures 4-15a and **4-15b** show the delineated lateral extent of FHA for the Sample Subarea plotted onto the FHA Base Map and on recent aerial photography, respectively.

4.3.2 Application of Setbacks

Preliminary application of setbacks is demonstrated at a location within the Sample Subarea where the delineated FHA is in direct contact with basin fill. For the majority of its length, the width of the interior formation along the Subarea is a mile or wider. The width of delineated FHA for much of the area is also on the order of one mile. Only in a relatively small number of locations does the application of setbacks alter the delineation of FHA. **Figures 4-16a** and **4-16b** show the application of setbacks on the east side of the river at approximately mile marker 87 displayed on the FHA Base Map and recent aerial photography, respectively. As shown on the figures, the active river channel is in direct contact with the basin fill or meanders close to the basin fill at several locations. In this example, the 100- and 200-foot setbacks are truncated in several locations.