A HYDROGEOLOGIC RESOURCE ASSESSMENT OF THE
LOWER BABOCOMARI WATERSHED, ARIZONA

by

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SIGNED: ____________________________

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

______________________________  ____________________________
Stanley N. Davis  April 17, 1990
Professor Hydrology and Water Resources  Date
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Perennial streamflow and a rich riparian habitat along portions of the Babocomari River is supported by the regional ground-water system. A hydrologic resource assessment of the lower Babocomari Watershed (upper San Pedro Basin, Arizona) was performed to characterize the system which supports the current flow regime of the river, and estimate the effects of future pumping on hydrologic conditions along the river. Descriptions of the physiography, climate, vegetation, and geology of the study area were primarily derived from literature review. Descriptions of the ground-water system, surface-water system, surface-water/ground-water interaction, riparian vegetation, and water quality were chiefly derived from field work and laboratory analysis. Descriptions were substantiated with flow-net, water-budget, and aquifer-test analyses. Current and predicted future rates of pumping were quantified, and were used to make preliminary analytical estimations of drawdown effects on hydrologic conditions along the Babocomari River.
CHAPTER 1
INTRODUCTION

Overview

Hydrologic basins in the arid Southwest were once typically drained by perennial rivers in which baseflows were sustained by discharge from the ground-water system. Intensive ground-water exploitation in many such basins has lowered water-table elevations far below river-bed elevations and severed the link between ground-water systems and surface-water baseflows. Examples of perennial river stretches turned ephemeral by ground-water mining include portions of the Santa Cruz and Gila Rivers. Hundreds of thousands of acres of riparian habitat in Arizona have been lost due to groundwater development, by which water tables become inaccessible to the roots of riparian vegetation. Loss of over 95% of Arizona's original riparian habitat (Warner, 1979) has led to increased concern regarding the preservation of this valuable resource.

The upper San Pedro basin has not yet experienced the effects of heavy ground-water exploitation, and baseflow in several of its river stretches is supported by ground-water discharge. The basin contains over 40 river km of perennial stretches and approximately 130 river km of riparian habitat. Most of this habitat is found along the banks of the upper San
Pedro River; however approximately 19 km is along the Babocomari River. In addition, the Babocomari River has two perennial stretches; one 8 and one 14 km long. Riparian habitats and perennial baseflows make the Babocomari and upper San Pedro Rivers valuable natural resources in the desert of the Southwest. The riparian habitats fulfill recreational, aesthetic, flood control, and wildlife values. They support exceptional species diversity, especially high densities of rare and common birds (personal communication, Steven Friedman, 1986).

Recent studies have suggested that perennial baseflows and riparian habitat within the upper San Pedro basin may be in jeopardy (Jackson et al., 1987; Putman et al. 1987). Intensive groundwater development by Fort Huachuca and the City of Sierra Vista has resulted in formation of a cone of depression around their well fields. This pumping intercepts a portion of mountain-front recharge which would formerly have discharged into the San Pedro River. Statistical analysis of streamflows performed by the United States Geological Survey (USGS) show decreased minimum flows along the San Pedro River over the last forty years (personal communication, Tom Anderson, 1987). Analytical and numerical modelling by the U.S. Bureau of Land Management (BLM) and the Arizona Dept. of Water Resources (ADWR) predict that continued pumping will, at
minimum, decrease baseflows in the San Pedro River, and at maximum, draw the water table down below the riverbed (Jackson et al., 1987; Putman et al., 1987).

Although basin-wide hydrologic studies have addressed the possible effects of ground-water pumping on the upper San Pedro River, little work has been done to assess the potential effects of ground-water development on the perennial baseflows and riparian habitat of the Babocomari River. The ground-water development which threatens the San Pedro River also has the potential to affect hydrologic conditions along the Babocomari River. In addition, the ground-water demands of users close to the Babocomari River such as Huachuca City, and users far from the river such as Sierra Vista, are projected to increase significantly in the near future. In order to evaluate the potential effects of pumping on conditions along the Babocomari River, a hydrologic resource assessment must be performed to collect pertinent information about the Babocomari watershed.

**Purpose and Scope**

The purpose of this investigation is assess the hydrologic resources of the lower portion of the Babocomari watershed and to estimate the effects of ground-water development on hydrologic conditions along the Babocomari
River. The bulk of the thesis is descriptive and interpretive. Chapters cover: the geography and geology of the area studied; the ground-water system; the surface-water system; surface-water/ground-water interaction; water quality; and external stresses on the hydrologic system. A single predictive chapter estimates effects of pumping on hydrologic conditions along the Babocomari River.

Descriptions of the location, physiography, climate, vegetation, and geology of the study area are included in Chapter 2. The geology section is most intensive, as it defines the hydrogeologic framework for ground-water occurrence and flow. Chapter 3 presents a short overview of ground water in the upper San Pedro basin, followed by descriptions of aquifer properties, flow patterns, and historic water-level changes in the lower Babocomari watershed. In addition, the Babocomari River is divided into five stretches with distinctive surface-water and ground-water regimes. Hydrologic descriptions throughout the thesis are structured around this division. Chapter 4 describes the flow regimes of the five stretches of river and presents the results of seasonal stream gauging. Chapter 5 interprets the dynamics of surface-water/ground-water interaction along the Babocomari River in the context of the information presented in Chapters 3 and 4. This chapter also includes a flow-net
analysis of ground-water discharge to the river and an interpretation of seasonal water-table fluctuations in a riparian area. Chapter 6 describes the chemical composition, major ion concentrations, and occurrence of environmental isotopes in both ground water and surface water. Chapter 7 quantifies ground-water sinks and sources external to the hydrologic system, such as pumpage, recharge of sewage effluent, and consumption by riparian vegetation. Chapter 8 presents rough estimates of the effects of pumping on hydrologic conditions along the Babocomari River as well as the relative responsibilities for these effects attributable to individual users. Finally, Chapter 9 summarizes the conclusions presented in the preceding chapters.

Previous Studies

Hydrologic and geologic studies of the upper San Pedro basin generally fall into three categories: basin-wide resource assessments performed by state and federal agencies; localized water-supply investigations performed by consultants and federal agencies; and narrow scope master's theses performed by university graduate students. The basin-wide studies have attempted to construct a broad scale hydrogeologic framework of the entire basin, although they have often focussed considerable attention on local conditions of hydrological interest. Localized investigations relevant to
the Babocomari River have been conducted for the Fort Huachuca Military Reservation. Although neither type of study has focused primarily on ground-water conditions along the Babocomari River, Fort Huachuca water-supply investigations often mention the nearby river and town of Huachuca City, and basin-wide studies include the area in a general way. Master's theses generally focus on one single aspect pertinent to the overall hydrologic resource assessment.

Basin-wide hydrogeologic investigations have been completed by Heindl (1952), Roeske and Werrel (1968), and Putman et al. (1987). The investigations were extensive, and include descriptions of hydrogeologic conditions, recharge processes, present and historic water tables, aquifer properties and parameters, flow in the San Pedro River, surface-water/ground-water interaction, and basin-wide water budgets. Putman et al. (1987) presented results of a three dimensional finite difference model used to estimate the effects of projected future ground-water extraction by Sierra Vista and Fort Huachuca on ground-water levels and baseflows in the San Pedro River. Their modelling efforts followed the work of Freethey (1982) in which steady state and transient (pre-1979) hydrologic conditions were simulated with the same model. Freethey compiled and applied existing hydrologic information regarding aquifer thickness, aquifer parameters,
and pre-development ground-water contours to run the model. The model was used to modify estimates of aquifer parameters, ground-water recharge, discharge to streams, and evapotranspiration.

Localized hydrologic studies of the Fort Huachuca Military Reservation include work by Brown et al. (1966), the Army Corps of Engineers (1974), and Harshbarger & Associates (1974). Brown et al. provided detailed descriptions of the geology of the area, with considerable emphasis on the unconsolidated and semiconsolodated sediments. The hydrologic properties of existing aquifers were discussed, and several aquifer tests were interpreted. The Army Corps of Engineers (1974) presented the results of test well drilling on the Fort Huachuca "East Range", in which predictions made by Brown et al. concerning aquifer thickness, depth to bedrock, and porosity of semiconsolodated sediments below the East Range were corrected. Harshbarger and Associates (1974) reported the results of aquifer tests in the East Range wells and interpreted 1973 water levels west of the San Pedro River.

Although several hydrologically oriented master's theses have been written concerning the upper San Pedro basin, only one of these directly addressed the hydrology of the lower Babocomari watershed. Laura Strauss' treatment of the
occurrence of environmental isotopes in precipitation and
ground water near the Dragoon Mountains provided useful
correlations with isotopic analyses of samples taken from the
study area.

Geologic studies pertinent to the area include the water-
supply study by Brown et al. (1966) mentioned above, work by
Bryan (1934), Gilluly (1956), and master's theses by Vice
(1974) and Halverson (1980). Bryan (1934) pioneered the
classification of pediments in the upper San Pedro basin.
Gilluly (1956) described the igneous bodies which crop out as
hills across the flow path of the Babocomari River and
provided a good account of the geologic history of Cochise
County. Vice (1974) mapped and interpreted the geology of the
Babocomari Ranch, a Spanish land grant along the Babocomari
River from its headwaters to a point several km east of
Huachuca City. Although Vice emphasized the consolidated rocks
in the upper Babocomari watershed, he presented a map of river
terraces which extends into the study area. Halverson
performed a gravimetric survey of the entire San Pedro Basin
in order to estimate depths to bedrock. Her estimates provide
only a rough idea of depth to bedrock however, as wells within
the basin have both substantiated and refuted her results.

Various data-bases were useful in interpretation of the
hydrogeology of the area. Well data and chemical analyses of water were obtained from the USGS and the ADWR. Drillers logs were obtained from the local well drillers, the Arizona Oil and Gas Commission (AOGC) and the ADWR. The BLM performed a survey of riparian vegetation along the San Pedro River. Their identification of plant communities along the San Pedro River was useful in the initial identification of the riparian communities seen on aerial photographs of the Babocomari River.

Well Numbering System*

The well numbering system used in Arizona is based on the Gila and Salt River baseline and meridian (GSRB&M), which divide the State into four quadrants designated counterclockwise by the capital letters A, B, C, and D. Land northeast of the GSRB&M is in A quadrant, that northwest in B quadrant, that southwest in C quadrant, and that southeast in D quadrant. The first digit of a well number indicates the township, the second digit indicates the range, while the third indicates the section. The letters A, B, C, and D after the section number indicate the well location within the section. Well number (D-4-5)19CAA designates the well as being in the NE 1/4, NE 1/4, SW 1/4, section 19, T4S, R5E.

*Excerpted from Putman et al., 1987.
CHAPTER TWO

DESCRIPTION OF STUDY AREA

Location

The Babocomari watershed is in the upper San Pedro basin, approximately 100 km southeast of Tucson, Arizona (Figure 1). The Babocomari River has its headwaters west of Elgin, Arizona and runs eastward passing between the Huachuca and Mustang Mountains to the town of Huachuca City (Figure 2). The river then bends slightly northeast towards its confluence with the San Pedro River at the ruins of the town of Fairbank. The study area is in the lower portion of the watershed and encloses the river in a corridor approximately 8 km wide and 16 km long. Its western boundary is approximately 4.3 km west of Huachuca City and trends north-south; its northern boundary extends directly west from the town of Fairbank; its eastern boundary is coincident with the San Pedro River; and its southern boundary parallels the Babocomari River at a distance of approximately 4 km. All but the southern boundary are in areas of negligible ground-water exploitation. The southern boundary crosses the East Range of the Fort Huachuca Military Reservation, an area in which production wells have been withdrawing significant amounts of ground water since the early 1970's. The study area was chosen to include those components of the regional hydrologic system most closely
Figure 1 Location of Study Area
associated with the flow regime of the Babocomari River. Ground-water chemistry and elevation data from wells adjacent to the study area were incorporated into the data base in order to complete the "overall hydrogeologic picture".

Physiography

The upper San Pedro basin is part of the Basin and Range Province, in which mountain ranges rise abruptly from broad, plain-like valleys called basins. The Huachuca, Mustang, Whetstone and Rincon Mountains bound the west side of the basin. The east side is bounded by the Mule, Little Dragoon, and Dragoon Mountains. The valley floor slopes gently towards the San Pedro River and is cut by stream terraces and modern arroyos. Low lying igneous hills, such as the Tombstone and Bronco Hills, crop out upon the valley floor. The basin is approximately 100 km long and 26 km wide.

The Babocomari watershed drains the northern slopes of the Canello Hills, the north and northeast flanks of the Huachuca Mountains, the entirety of the Mustang Mountains, and the southern edge of the Whetstone Mountains. It is the largest tributary watershed on the western side of the basin, with a catchment area of 197 km² and a length of 45 km. The Babocomari Valley is steep and narrow between the Huachuca and Mustang Mountains. Farther downstream, where the Babocomari
River emerges from the mountain ranges onto the basin floor, its valley is broad and slightly concave. Many upland tributaries of the river originate within grassy plains and swales which gradually deepen to form wide canyons. Tributaries in the lower reaches generally take the form of arroyos. The physiographic surfaces of the upper San Pedro basin were mapped by Bryan (1934), and are shown in Figure 3. The Tombstone pediment is well developed in the Babocomari Valley, where it is dissected by the Babocomari River and its tributaries. Four paired terraces have been cut into the pediment during erosion of its surface. Reworked pediment deposits present along major streams and tributaries have been mapped as the Aravaipa surface, and are dissected by a fifth erosional terrace.

Relief is steep along the mountain ranges and moderate within the basin. Elevations exceed 1,900 m in the Mustang Mts. and approach 3,000 meters in the Huachuca Mts. The headwaters of the Babocomari River are at an elevation of approximately 1,525 meters. Some of its tributaries however reach elevations of over 2,100 m at their origins in the Huachuca Mountains. The upstream boundary of the study area is at a streambed elevation of about 1,300 m, and the downstream boundary (confluence with the San Pedro River) is at approximately 1160 m.
Figure 3  Map of the Physiographic Surfaces of the Benson Quadrangle, Arizona (After Bryan, 1934)
Climate

The climate of the upper San Pedro basin is characterized by moderate temperatures and low annual rainfall. Because the elevation of the basin is higher than most in southern Arizona, temperatures do not reach the typical desert extremes. Summer temperatures normally range between 25 and 38 degrees Celsius, and often exceed 38 degrees in the lower elevations. Winters are warm during the day and cool during the night. Nightly frost is common at all elevations; however regular freezing is restricted to the upper elevations.

Climatic data for four stations in the upper San Pedro basin (compiled by Sellers and Hill, 1974) were analyzed statistically by Putman et al. (1987), and is presented in Table 1. The period of measurement was from 1932 to 1971, except for the Fort Huachuca data which were collected from 1954 to 1971. Fort Huachuca statistics are representative of higher elevations in the study area, and Fairbank statistics represent lower lower elevations.

Precipitation in the vicinity of the study area ranges from 30.5 cm at Fairbank to 38 cm at Fort Huachuca. Areas close to mountain ranges receive greater amounts of precipitation. The variability of annual rainfall is high (see Table 1). Precipitation in the upper San Pedro basin is typically concentrated within two rainy seasons. The summer
TABLE 1
SUMMARY OF ANNUAL PRECIPITATION AND TEMPERATURE DATA AT WEATHER OBSERVATION STATIONS IN THE UPPER SAN PEDRO BASIN
(After Putman et al., 1987)

<table>
<thead>
<tr>
<th>STATION</th>
<th>Benson</th>
<th>Fairbank</th>
<th>Fort Huachuca</th>
<th>Tombstone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elevation:</strong></td>
<td>1,094</td>
<td>1,173</td>
<td>1,422</td>
<td>1,405</td>
</tr>
<tr>
<td>(m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Annual Precip:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>10.6</td>
<td>12.2</td>
<td>18.3</td>
<td>19.3</td>
</tr>
<tr>
<td>Average</td>
<td>29.3</td>
<td>29.6</td>
<td>38.7</td>
<td>35.4</td>
</tr>
<tr>
<td>Maximum</td>
<td>50.5</td>
<td>49.9</td>
<td>64.9</td>
<td>60.5</td>
</tr>
<tr>
<td><strong>Precip. Range:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Low % below annual ave.)</td>
<td>68</td>
<td>59</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>(High % below annual ave.)</td>
<td>54</td>
<td>68</td>
<td>68</td>
<td>71</td>
</tr>
<tr>
<td><strong>Temperature:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>-14.4</td>
<td>---</td>
<td>-12.8</td>
<td>-14.4</td>
</tr>
<tr>
<td>Average</td>
<td>17.1</td>
<td>---</td>
<td>16.8</td>
<td>17.6</td>
</tr>
<tr>
<td>Maximum</td>
<td>45.0</td>
<td>---</td>
<td>40.0</td>
<td>42.2</td>
</tr>
</tbody>
</table>
rainy season occurs between early July and mid-September.
According to Putman et al. (1987):

"The basin receives 50-60% of its annual rainfall in July, August and September when moist tropical unstable air from the Gulf of Mexico moves northwest into Arizona. Afternoon and evening showers and thunderstorms develop as the warm, moist air is forced up the southern slopes of the mountains and is sufficiently cooled. Although these storms are usually of short duration, they are intense enough to occasionally create localized flash flooding. During this "monsoon" season, precipitation is at its maximum on the windward or southeastern side of the mountains. Locations near major mountain ranges are more likely to receive greater amounts of precipitation during these months."

The winter rains generally occur during the months December, January, and February, and account for about 21% of annual precipitation (Putman et al., 1987). They originate off the California coast as middle latitude cyclonic storms, and move south and east across the West. On occasions when these storms reach southern Arizona, they typically cause several days of moderate winds, light rains, and occasionally snow. Although snow may linger for weeks in the higher elevations, its contribution to total annual precipitation is considered to be negligible (Putman et al., 1987).

Lake evaporation in the upper San Pedro basin has been estimated at 152-165 cm per year (Arizona State University, 1975).
Vegetation

The Babocomari watershed contains three major life zones, as described by Vice (1974). The upper reaches of the watershed (mountains and foothills) fall into the Upper Sonoran Life Zone, and include oak woodland and chaparral vegetation. The higher peaks and ridges of the Huachuca Mountains are classified as Transition Life Zone, and include ponderosa pine and douglas fir as dominant species. The study area, located predominantly on the basin floor, falls within the desert grassland category of the Lower Sonoran Life Zone. Desert grassland is characterized by sotol (*Dasylirion Wheeleri*), soaptree yucca (*Yucca elata*), century plants (*Agave Perryi* var. *huachucensis*), and various grasses. The basin floor has been encroached upon by several invasive trees and shrubs since the turn of the century. These include blackbrush (*Acacia vernicosa*), mesquite (*Prosopis juliflora*), ocotillo (*Fouquieria spinescens*) and graythorn (*Condalia lycioides*). Invasive species have become dominant in large portions of the basin, and have caused the recession of grasslands and oak woodlands towards higher elevations.

Riparian vegetation is encountered along the Babocomari River. Along with various shrubs and grasses, typical trees include fremont cottonwood (*Populus fremontii*), Arizona walnut (*Jugans major*), gooding willow (*Salix gooddingii*), netleafed
hackberry (*Celtis reticulata*), and mesquite (*Prosopis juliflora*). The distribution of riparian vegetation within the study area is described in detail in Chapter 7.

**Geology**

The upper San Pedro basin is a northwest-trending structural trough. Its graben-like structure is defined by large normal faults which offset the deeply buried bedrock floor from the mountain ranges bordering the basin. The mountain ranges act as impermeable boundaries which constitute ground-water divides along the eastern and western extents of the basin and partially obstruct outflow from its northern end. Within the basin, ground water flows through semi-consolidated and unconsolidated sediments and is obstructed in places by impermeable Cretaceous/Tertiary igneous bodies. Maximum depth to bedrock has been estimated gravimetrically to be between 2,750 and 4,250 m at the international border and between 1830 and 2,130 m north of Huachuca City (Halverston, 1980). Sediment thickness is considerably less on the basin margins and in areas underlain by Cretaceous/Tertiary igneous bodies.

The Pantano (?) Formation (mid Tertiary) is a semi-consolidated sedimentary deposit which unconformably overlies the downfaulted bedrock basin floor and the Cretaceous/
Tertiary igneous bodies (where present). The Pantano (?) has undergone tilting, deformation, and cementation. In places it comprises most of the thickness of basin sediments, however its low permeability makes it a poor aquifer. The basin fill unconformably overlies the Pantano (?) Formation, and serves as the major aquifer in the basin. These unconsolidated sediments have been divided into lower and upper units and range in age from Miocene to Pleistocene. Their combined thickness varies laterally and is known to approach 250 m beneath the Fort Huachuca main installation just west of Sierra Vista (Brown et al., 1966). The upper unit is capped with a veneer of gravel terrace deposits from the most recent period of erosion which began in the middle Pleistocene. Quaternary floodplain alluvial deposits are found along the San Pedro River and its tributaries. They exhibit high permeabilities and serve as a hydrologic connection between the basin fill and the modern rivers. An idealized geologic cross-section of this stratigraphy along the Babocomari River is presented in Figure 4. The stratigraphic units are described in greater detail below.

**Tertiary/Cretaceous Igneous Rocks**

Exposures of consolidated rock within the study area occur at the downstream end of the Babocomari watershed just west of the San Pedro River (Figure 5). These rocks were
Figure 4  Idealized Geologic Cross-Section of Stratigraphy in the Lower Babocomari Watershed
Figure 5  Exposures of Consolidated Rock within the Study Area  (After Gilluly, 1956)
emplaced during a period of igneous activity and volcanism in late Cretaceous and early Tertiary times, and are dissected by the Babocomari River. They crop out as low hills extending northward from a point three km southeast of Brookline to the San Pedro River near the old mill site of Contention. Exposures within the study area are overlain by the upper unit of the basin fill; however exposures of the same rocks located on the other side of the San Pedro River unconformably overlie the early/mid Cretaceous Bisbee group and underlie the mid Tertiary Pantano (?) Formation (Gilluly, 1956).

The igneous rocks exposed along the Babocomari River are predominantly Uncle Sam Porphyry with lesser amounts of Bronco Hill Volcanics. The igneous rocks are considered to be hydrologically impermeable and, therefore, act as a groundwater dam. The subsurface geometry of the body has not been established. Igneous rocks encountered on the east side of the San Pedro River are composed of the same units (Gilluly, 1956). Igneous rock was encountered at 107 m in a domestic well drilled along the San Pedro River directly between the two exposures (D-20-21 16DDC). Igneous rock was also encountered at a depth of 395 m in a Fort Huachuca test well (D-21-20 13CBB) 6 km southeast of Huachuca City (U.S. Army Corps of Engineers, 1974). These facts suggest that the igneous body is extensive and is probably connected with the
rocks east of the San Pedro River.

The Bronco Hill Volcanics are composed of two members differing in composition and separated by an irregular depositional contact. The lower member is dominantly andesite: two thirds to three quarters flow breccia and the remainder flows. The upper member, a quartz latite tuff, is mostly pyroclastic with few flows. Both members are present in the rocks along the Babocomari River. The entire unit is believed to have a thickness of 1,525 to 1,825 m based on interpretation at Bronco Hill (east of the San Pedro River), however structural complexities, alteration, and poor exposures combine to prevent a satisfactory estimate (Gilluly, 1956).

The Uncle Sam porphyry is an intrusive quartz latite porphyry named after its type area at nearby Uncle Sam Hill. The porphyry intrudes both the Bisbee Group and the Bronco Hill Volcanics (Gilluly, 1956). Stratigraphic relations show that deposition of the Bronco Hill Volcanics was followed by a period of tectonic activity and the subsequent intrusion of the Uncle Sam Porphyry. The porphyry may have intruded along thrust faults formed during this period of tectonic activity (Gilluly, 1956). Exposures of intrusive breccia within the porphyry along the Babocomari River contain fragments of both
the Bronco Hill Volcanics and the Bisbee group. The thickness of the porphyry has not been estimated, but for all practical purposes the combined thickness of the porphyry and the Bronco Hill Volcanics has the capacity to block groundwater flow in the basin sediments.

**Pantano (?) Formation**

The Pantano (?) Formation is a sequence of conglomerate, fanglomerate, sandstone, mudstone, and fresh-water limestone intercalated with ash-flow tuffs and basalt flows (Vice, 1974). The formation is probably correlative with the Miocene Pantano Formation of Brennan (1957, 1962), due to similarities of lithology, thickness, structural involvement, and geologic contacts (Brown et al., 1966). Potassium-argon dating of two volcanic beds exposed near the Babocomari Ranch indicate that the unit is Upper Oligocene (Shaiqullah, 1978). The Pantano (?) is considered to have low permeability, however relatively high permeabilities have been encountered along fault zones or in zones of high fracture density.

The Pantano (?) Formation crops out as brownish-red to brownish grey exposures along the eastern and northern fringes and canyons of the Huachuca Mountains. The sandstones are moderately lithified and arkosic; the mudstones are medium bedded to massive; and the limestone beds vary in thickness
from 15 cm to 10 m. The conglomerate has a matrix which varies in texture from grit to coarse sandstone and fragments which range in size from pebbles to boulders 1.2 m in diameter. The clasts (in approximate order of abundance) are composed of rhyolitic welded tuff, felsic welded tuff, andesite, shale and siltstone, granite, epidotized and chloritized andesite, limestone, and quartzite (Brown et al., 1966). The rock is moderately cemented, in places breaking indiscriminantly across matrix and fragments. The fanglomerate is similar to the conglomerate, except that it has larger, more angular clasts and a higher percentage of matrix (Vice, 1974).

Features such as local unconformities, inclusion of landslide materials and large boulders, and the highly angular appearance of clasts provide considerable evidence of high relief and contemporaneous uplift in the source area. The source of the clasts is volcanic rocks similar to the present Canello Hills (Gilluly, 1956). Imbrication suggests that the source area was to the south and southwest. The entire formation is tilted to the southwest fifteen to forty five degrees. Its thickness varies laterally and has not been fully measured. Brown et al. (1966) estimated a thickness of 4,600 m based on an exposure along the eastern margin of the Huachuca Mountains, however they assumed that no repetitive faulting exists. Vice (1974) estimated the thickness in the
upper reaches of the Babocomari watershed to be 600 to 900 m. Test wells on the Fort Huachuca Military Reservation indicate a thickness of at least 236 m near the "Libby Airfield" (D-21-20 30B) and 202 m on the "East Range" (D-21-20 13CBB) where it overlies the Cretaceous/Tertiary igneous body described previously. More than 2,100 m are present in an exploratory oil well seven km northeast of Huachuca City (D-20-20 16AA) which penetrated 2,440 m of sediments, thin volcanics and limestones without encountering bedrock (Arizona Oil and Gas Commission). Depth to bedrock is estimated by gravity data to be about 900 m beneath the Fort Huachuca Military Reservation, more than 2,100 m in the vicinity of Huachuca City, and more than 2,700 m at the international border (Figure 6) (Halverston, 1980). Failure to detect the presence of the Bronco Hill Volcanics which underlie the Fort Huachuca East Range casts some doubt on the accuracy of the gravimetric work and is probably related to the fact that gravimetric transects were not made in the vicinity of the East Range or Huachuca City. Estimates in the vicinity of the previously mentioned exploratory oil well (where transects were made) appear to be reasonable.

**Basin Fill**

The basin fill has been divided into upper and lower units on the basis of compositional, textural, and
Figure 6  Gravimetric Estimation of Depth to Bedrock in the Upper San Pedro Basin  (After Halverston, 1984)
depositional differences. Detailed descriptions of the units by Brown et al. (1966) are unfortunately limited to the area south of the Babocomari River. The basin fill probably attains its maximum thickness between the mountain ranges and the San Pedro River (Brown et al., 1966). Almost 245 m of basin fill has been encountered in a well on the Fort Huachuca Main Installation (Brown et al., 1966). Thicknesses of between 120 and 180 m have been encountered in test wells on the East Range (Army Corps of Engineers, 1974). Geophysical logs of the oil exploration well (D-20-20 16AA) mention a formation change at 283 m (Arizona Oil and Gas Commission) which may represent the contact between the basin fill and the Pantano (?) Formation. Well logs interpreted by Pool (in Halverston, 1980) specify the thickness of sediments overlying the Pantano (?) Formation as 120-180 m thick south of Huachuca City and in the vicinity of Sierra Vista. Farther west and south, the sediments become thinner. The basin fill pinches out upon the igneous hills which crop out several km west of the San Pedro River. Approximately 90 m of basin fill were encountered east of the exposed igneous body in a domestic well (D-20-2 16DDC) adjacent to the San Pedro River.

The Lower Unit of the basin fill is composed of interbedded gravels and sands. Its permeability ranges locally from medium to high due to variability in sediment size,
sorting, and cementation. Wells in the vicinity of Sierra Vista and Fort Huachuca penetrate between 70 and 128 m of the unit (Army Corps of Engineers, 1974). Exposures in the Huachuca Mountains in Lyle and Sunnyside Canyons place its thickness at 75-150 m but it may be much thicker in the valley center (Brown et al., 1966). Although the lower unit is lacking in fossils and marker beds, Brown et al. (1966) estimated it to be Pliocene based on an inferred correlation with fossiliferous beds cropping out in the vicinities of Redington, Arizona and a few miles southwest of Lone Mountain. Damon (personal communication, 1988) believes the unit to be late Miocene based on its attitude and structural relations.

Exposures of the Lower Unit are light gray and reveal interbedded lenses of sand and gravel tilted between several and twenty degrees. The bedding is lenticular to tabular, with scour and fill structures common and occasional crossbedding observed. Both sands and gravels are poorly sorted. The gravels contain fragments ranging in size from silt to boulders over 30 cm in diameter, and varying in roundness from subrounded to well rounded. The pebbles, cobbles and boulders consist mainly of quartz, granite, limestone, and quartzite, although all Huachuca Mountain rock types are represented. The matrix has a high content of quartz with lesser amounts of feldspar and rock fragments. The sands range in texture from
very fine to very coarse with variable amounts of pebbles, and are mainly composed of quartz, feldspar, mica, and interstitial clay.

The upper unit of the basin fill is comprised of weakly cemented and compacted soft reddish-brown clay, silt, sand and gravels. Its outcrops are recognized by a characteristic badland erosional topography where they are not capped by gravel terrace deposits. The middle and upper portions of the unit are Pleistocene, and the lower portion is either Pleistocene or Pliocene (Brown et al., 1966). Its thickness ranges between 130 and 190 m adjacent to the Huachuca Mountains (beneath the Fort Huachuca Main Installation) (Brown et al., 1966); 40 to 100 m between the mountains and the San Pedro River (beneath the Fort Huachuca East Range) (Army Corps of Engineers, 1974); and only about 3 m along the San Pedro River (Brown et al., 1966). Bedding is horizontal along the Babocomari River, although dips of five degrees are observed along the flanks of the Huachuca Mountains.

The permeability of the upper unit grades from very high near the mouths of major streams issuing from the Huachuca Mountains to very low in the silts and limy clays found along the San Pedro River. Brown et al. (1966) describe three principal facies within the unit based on grain size and mode
of deposition. Fan gravels are generally found along the fronts of the Huachuca Mountains, silt and clay in the basin center along the San Pedro River, and sand and silt in the intervening areas. Boundaries between these facies are gradational. The fan gravel facies crops out in a band several kilometers wide along the fronts on the Huachuca Mountains. It is principally composed of silty to sandy gravel and gravelly sand derived from local sources, and has high to very high permeability. Bedding layers are generally 7 to 46 cm thick. Gravel fragments are sub-rounded to well rounded, and up to 60 cm in diameter. The silt and clay facies crops out along the San Pedro River and has low to very low permeability. South of the study area near the Donnet-Fry Ranch the facies may extend eight km west of the San Pedro River (Brown et al., 1966). In the intervening areas the distribution of sands and silty clays exhibits high spatial variability and seems to be fluvially controlled. Along the Babocomari River near Huachuca City, the upper unit consists mainly of the sand and silt facies and thus has medium permeability (Brown et al., 1966). Interpretation of well logs from the Fort Huachuca East Range resulted in the conclusion that "Boulders and cobbles apparently decrease with distance from the mountains, and gravel sizes may also decrease, but sand and silty clay deposits do not follow a predictable pattern." (Army Corps of Engineers, 1974). Logs of wells drilled as little as 30 m
apart show poor stratigraphic correlations.

**Terrace and Floodplain Alluvial Deposits**

The upper unit of the basin fill is capped by terrace deposits which extend from the base of the mountain ranges to the river floodplains. The terrace deposits are correlated with a period of vigorous erosion which began in the mid to late Pleistocene and has continued into present times. According to Brown et al. (1966):

"...(The terrace deposits) are only 5-20 feet thick near the Huachuca Mountains, but, near the center of the basin, they may be as much as 50-100 feet thick in channels roughly parallel to the present course of the San Pedro River. The material in the terrace deposits is a poorly sorted mixture of light-reddish-brown to light-brown gravel, sand and clay derived from nearby sources. This material is very permeable; but because it is cut by numerous shallow washes and above the regional water table, it does not provide much groundwater storage."

Vice (1974) mapped five sets of terraces along the Babocomari River within the boundaries of the Babocomari Land Grant. They range in form from continuous and well defined with prominent scarps to discontinuous with poorly defined outer limits. The four older terraces cut into the basin fill (Tombstone surface of Bryan), and the youngest cuts into Quaternary floodplain alluvial deposits along rivers (Aravaipa surface of Bryan). The uppermost terrace is continuous and easily distinguished. Its upper surface is comprised of the original surface of the basin fill, and is cut in places by tributaries of the
Babocomari River. The three intermediate terraces are discontinuous and poorly defined. Vice (1974) explained:

"These terraces appear to represent periods of downcutting followed by relatively short periods of base level stability and lateral erosion. No alluvial deposits relating to the different periods of stability have been observed, but these may have been removed by a subsequent period of downcutting."

The youngest terrace was formed during a period of downcutting which occurred at the end of the nineteenth century and produced arroyos with streambeds 2 to 8 m below the floodplains. It is continuous and well defined by a prominent scarp on its outer limits, and appears to maintain a relatively constant height above the Babocomari River within the land grant (Vice, 1974).

The Quaternary floodplain alluvial deposits associated with the major watercourses are about 15 m feet thick and rest unconformably on the upper basin fill along the Babocomari River. The deposits are between 2 and 9 m thick along tributaries of the Babocomari and San Pedro Rivers. Brown et al. (1966) wrote:

"The alluvium is a very permeable mixture of sand and gravel and forms a productive aquifer along the Babocomari and parts of the San Pedro River. The stream alluvium of the Babocomari and San Pedro Rivers occupies the lowest topographic position in the San Pedro basin and receives ground water from the basin-fill units and releases it to the two rivers. The alluvium in the small tributaries issuing from the Huachuca Mountains near the fort is generally too thin to be a highly productive aquifer, although some discharge from the tributaries passes downward through this alluvium and recharges the underlying upper and lower units of basin fill."

Boreholes near the Babocomari River are reported to encounter about 15 m of permeable gravelly deposits underlain by silts and clays, with beds or lenses of gravel and sand becoming more common below 30 m (personal communication, Bliss, 1988). Drillers and residents along the river commonly refer to the "first water" as that in the shallow aquifer first encountered during drilling and the "second water" as that encountered in the second set of permeable deposits.

**Geologic History**

An account of the geologic history relevant to description of the study area begins in early to middle Cretaceous when a shallow sea covered all of southeastern Arizona. Deposition during this period is responsible for the mudstones, limestones, siltstones, and sandstones observed in the Bisbee Formation. During mid-Albian times, a marine delta covered all of southeastern Arizona. By the late Albian and Santorian the first pulses of the Pinan phase of the Laramide orogeny had caused mountain building, the retreat of marine waters, and terrestrial erosion. By the early Campanian broad valleys had eroded within the newly formed mountains, and fluvial sediments began to accumulate. Late Campanian time was marked by widespread volcanic activity which, along with continuing strong structural disturbances, persisted throughout the end of the Cretaceous and into the early
Tertiary. During this period the igneous bodies which crop out as hills within the upper San Pedro basin were emplaced. The body of Bronco Volcanics and Uncle Sam Porphyry along the Babocomari River is a product of this era, and its thrust faults testify to the tectonic activity which extended into the Tertiary (Gilluly, 1956).

Extensive uplift, faulting, erosion, and volcanic activity within the Tertiary were responsible for sporadic and discontinuous deposition of alluvial and volcanic units. The middle Tertiary marked the onset of block faulting and the formation of closed, isolated basins with impounded drainage. Internal drainage persisted for most of the remaining Tertiary, during which time the Pantano (?) Formation was deposited as the first basin sediments of significant thickness. Volcanic and tectonic activity persisted throughout the Oligocene and early Miocene and is manifested in the basalts, ash-flow tuffs, fanglomerates, coarse conglomerates, immature sandstones, minor unconformities, deformation and tilting of the Pantano (?) Formation (Gilluly, 1956). The lower unit of the basin fill was deposited during late Miocene/early Pliocene time, and demonstrates continuing tectonic activity in its tilting and faulting. Deposition of the upper unit of basin fill occurred mainly in the early Pleistocene, although its basal beds may be late Pliocene
(Brown et al., 1966). The overall lack of tilting and deformation within the upper unit indicates the cessation of tectonic activity.

Deposition of the upper unit of basin fill continued until the middle Pleistocene when the gradual integration of basins and the establishment of the Gila River drainage system began. The development of integrated drainage initiated a period of erosion which has extended into present times. More than 50 m of the upper unit of basin fill were lost from the basin center due to the vigorous erosion of the San Pedro River (Brown et al., 1966). Terrace deposits mark phases of relative stability within this period of overall degradation. The most recent erosive event took place in the 1890's, when arroyos cut 2-8 m below existing floodplains, probably due to the combined effects of overgrazing and rapid climatic fluctuations (drought and heavy flooding). Modern watercourses are just beginning to stabilize and even aggrade locally (Jackson et al., 1987), although small gullies are still cutting headward.
CHAPTER 3
THE GROUND-WATER SYSTEM

Overview: The Upper San Pedro Basin

Aquifer Systems

The principal aquifer systems in the upper San Pedro basin are the basin-fill aquifer, the floodplain alluvial aquifers, and the Pantano (?) Formation. The basin-fill aquifer supplies most of the ground water and, presumably, conducts the greatest portion of regional ground-water flow. The basin-fill aquifer is unconfined over most of the upper San Pedro basin, however artesian conditions exist along the basin axis near St. David and Hereford. A perched aquifer has been described near the Fort Huachuca main installation (Harshbarger and Associates, 1974), and locally anomalous water-table elevations encountered along washes suggest the possibility of other perched zones. Transmissivities in the basin-fill aquifer generally range from 0.00011 to 0.01613 m²/sec (100-15,000 ft²/d), although Brown et al. (1966) reported a value of 0.033 m²/sec (31,000 ft²/d) measured in a well on the Fort Huachuca main installation. Published values of specific capacity range from 0.00021 to 0.00828 m²/sec (1 to 40 gpm/ft) and average 0.00269 m²/sec (13 gpm/ft) (Roeske and Werrel, 1973). Specific yields have not been reported from the basin fill; however, sediments in similar southwestern
geologic settings typically have specific yields of about ten to twelve percent (Putman et al., 1987).

The floodplain alluvium occurs in bands along the modern drainages. The deposits are generally 1-2 km wide along the major watercourses, however they approach 10 km in width in places along the San Pedro River (see Figure 3). Saturated portions of the floodplain alluvial deposits form stringer aquifers along the major rivers which serve both as hydrologic connections between the rivers and the basin-fill aquifer, and as conduits for riparian underflow. The floodplain alluvial deposits are composed of reworked (sorted) basin fill and have higher permeabilities than their parent material. Aquifer tests have not been conducted in the floodplain alluvial deposits, however published specific capacity data range from 0.0021 to 0.0228 m^2/sec (10 to 110 gpm/ft) (Roeske and Werrel, 1973).

Specific capacity values can be used to estimate transmissivity values where transmissivity measurements have not been made. Linear regressions relating \( \log_{10}(\text{transmissivity}) \) to \( \log_{10}(\text{specific capacity}) \) have been completed, such as Clifton's (1981) analysis of the Avra Valley, about 100 km from the study area. Clifton reported the following relationship:
\[ T = (2.462 \times 10^{-4}) S_C^{1.07} \]
where:
\[ T = \text{transmissivity (m}^2/\text{sec)} \text{ and} \]
\[ S_C = \text{specific capacity (gpm/ft)} \]

If Clifton's results are extended to the floodplain alluvial deposits mentioned above, transmissivity values ranging from 0.0029 m\(^2\)/sec to 0.038 m\(^2\)/sec are obtained.

The role of the Pantano (?) Formation within the regional flow system is not well known, however it is believed to be less significant than the overlying sedimentary aquifers. The permeability of the Pantano (?) is generally low due to its high degree of compaction and cementation, yet relatively high yields have been encountered along fault zones or in zones of high fracture density (Brown et al. 1966), and low to moderate yields have been obtained from two wells on the Fort Huachuca Military Reservation (Army Corps of Engineers, 1974). Ground water was previously believed to exist primarily within fractures (Brown et al., 1966), however geophysical well logging has shown water to be held in pore spaces (Army Corps of Engineers, 1974). The Pantano (?) displays extremely high variability in the vicinity of Elgin, where it serves as sole aquifer. Although the role of the Pantano (?) Formation in the regional flow system is currently poorly characterized, it is assumed to be negligible in this study due to its low permeability relative to the basin fill.
Minor aquifers are encountered in some consolidated rock formations. The most productive of these aquifers are associated with limestone beds in the Huachuca Mountains. Springs are encountered in Garden Canyon, Huachuca Canyon, and Monkey Canyon. Some wells have been completed in the igneous rocks around the upper San Pedro basin. These wells are either dry or show extremely poor yields. The hydraulic conductivities of the igneous bodies are generally so low that they can be considered impermeable.

**The Regional Flow Pattern**

Ground water in the upper San Pedro basin flows from areas of mountain-front recharge towards the San Pedro River. Mountain-front recharge occurs primarily along the north-south trending ranges which bound the basin. Ground water flows roughly perpendicular to the San Pedro River within the valley flanks and parallel to the river along the valley axis. Some of the ground water reaching the valley axis is discharged into the San Pedro River. The floodplain alluvial aquifer supports a portion of the ground-water flow parallel to the river, some of which is lost to consumption by riparian vegetation. Flow parallel to the river also occurs as underflow from the Mexican portion of the San Pedro watershed, however the quantity of this underflow is small relative mountain-front recharge (Putman et al., 1987). Geologic
obstructions to ground-water flow (such as the buried igneous bodies) and ground-water pumpage locally perturb this generalized flow pattern. Pumpage occurring west of the San Pedro River has caused significant cones of depression in the areas of Sierra Vista and the Fort Huachuca East Range.

**Description of Aquifer Systems Within the Study Area**

The basin fill and floodplain alluvial deposits comprise the main aquifer systems within the study area. The Pantano (?) Formation and the consolidated rock aquifers are assumed to have a negligible permeabilities. Results of aquifer tests are available for the basin fill only in areas of intensive ground-water development, and are unavailable for the floodplain alluvial deposits. Most test results are reported as specific capacities, although several transmissivity values have been published. Transmissivity measurements made by the author include a constant discharge pumping test on a Huachuca City production well and a flow-net analysis of the basin fill immediately upgradient of the Tertiary igneous body. The following paragraphs summarize the available aquifer parameter data for the study area.

**Basin Fill**

The basin fill is about 120 to 180 m thick beneath the Fort Huachuca East Range and perhaps 284 m thick about 7 km
northeast of Huachuca City (in the oil exploration well D-20-20 16AA). The thickness of the basin fill beneath Huachuca City is undetermined. The deposits thin towards the western boundary of the study area near the Huachuca, Mustang, and Whetstone Mountains. They completely pinch out above the Cretaceous/Tertiary igneous body near the eastern boundary (Figure 4).

The basin-fill aquifer is generally unconfined within the study area, however some well records show static water levels (measured days to years after drilling) to be higher than the water-bearing zones and water levels originally encountered during drilling. Depending on the circumstances, this can be interpreted as a sign of flow from overlying perched aquifers or slow release of water from fine grained sediments.

Hydrogeologic measurements from the study area are scarce. Nine aquifer tests were conducted in test wells on the Fort Huachuca East Range. Although specific capacity values were published for all nine tests, transmissivity values were published for only two tests. The specific capacity values range from 0.0018 to 0.0060 m²/sec (8.6 to 29 gpm/ft). According to Clifton's (1981) regression analysis cited above, this range corresponds to transmissivity values between 0.0024 m²/sec and 0.0090 m²/sec. Specific capacity values of 0.0018
and 0.0048 m²/sec (8.7 and 23.2 gpm/ft) correspond to measured transmissivities of 0.002 and 0.010 m²/sec (1,860 and 9,300 ft²/day) respectively.

Specific capacity data are available for production wells owned by Huachuca City. Well D-21-20 05CBA (a deep well less than 100 m from the Babocomari River) shows a value of 0.010 m²/sec (48.3 gpm/ft); well D-21-20 08CAA (in northern Huachuca City) shows a value of 0.001 m²/sec (4.5 gpm/ft); and well D-21-20 05ABC shows values of 0.0044 and 0.0033 m²/sec (21.3 and 15.9 gpm/ft) at pumping rates of 0.020 and 0.032 m³/sec (320 and 418 gpm) respectively. This range of specific capacity values can be related to transmissivities ranging from 0.0012 m²/sec to 0.0156 m²/sec by Clifton's (1981) regression analysis. A 24 hr aquifer test performed by the author on well D-21-20 05ABC showed transmissivity values of 0.029 m²/sec (27,000 ft²/day) during pumping and 0.020 m²/sec (18,600 ft²/day) during recovery. Jacob Cooper semi-logarithmic drawdown and recovery curves are presented in Figures 7 and 8 (respectively). The plots show linear drawdown and recovery curves with no apparent effects of delayed drainage or boundaries.

Aquifer data are especially scarce in areas of low ground-water exploitation. The results of a step drawdown test
Figure 7 Results of 24 hour Aquifer Test on Well D-21-20 05ABC: Drawdown Phase

Q = 0.0200 m³/s
Δs = 0.13 m
T = 0.029 m²/s
Figure 8  Results of 24 Hour Aquifer Test on Well D-21-20 05ABC: Recovery Phase

\[ Q = 0.0200 \, \text{M}^3/\text{S} \]
\[ \Delta s = 0.19 \, \text{M} \]
\[ T = 0.020 \, \text{M}^2/\text{S} \]
performed on well D-21-19 01DDD (114 m deep, 2 km west of Huachuca City, and 300 m south of the Babocomari River) are presented in Figure 9 (personal communication, Stockton, 1988). Drawdown from the first pumping step is inaccurate because the static water level in the well was artificially high due to leakage from an overlying perched aquifer. Values of specific capacity calculated for the second and third steps were 0.0082 and 0.0127 m²/sec (39.6 and 61.4 gpm/ft) respectively. Based on Clifton's (1981) regression analysis, these values correspond to transmissivities of 0.013 m²/sec and 0.020 m²/sec. Specific capacities for domestic wells north of Huachuca City are available from drillers reports, however these values are extremely variable and tend to reflect the poor efficiency of the wells rather than the transmissivity of the formation. A flow-net analysis of the area directly upgradient of the igneous body east of Huachuca City yielded a general transmissivity value of 0.0018 m²/sec (1,700 ft²/day). The details of this analysis are presented in Chapter 5.

The highest values of transmissivity and specific capacity within the study area are reported for the wells closest to the river near Huachuca City. Although the thickness of the aquifer is unknown in this vicinity, it is not surprising that materials of greater permeability would be
deposited along a relatively large and active watercourse such as the Babocomari River. The density of aquifer test points is not great enough to prove this assertion, however it is a possible relationship worth mentioning.

Floodplain Alluvial Deposits

The floodplain alluvial deposits along the Babocomari River maintain an exposure width of about 2 km between the western boundary of the study area and the igneous body exposed east of Huachuca City (Figure 3). The deposits are only about 15 m thick, however they provide an important hydrologic connection between the river and the basin fill. No aquifer tests are available for wells in these deposits, however they are believed to exhibit permeabilities higher than the basin fill, similar to the floodplain alluvial deposits described above.

The floodplain alluvial deposits along the Babocomari River contain perched aquifers in a stretch 5 km long and centered around Huachuca City. These are evidenced by local discontinuities in ground-water elevations and cascading water in wells. Additional perched areas may exist, however wells are not available to determine their locations. Interconnection between the perched zones has not been established. Recharge to the perched aquifers is associated
with transmission loss from intermittent streamflow in nearby rivers and washes. Interaction between the river and the perched aquifers is discussed in Chapter 5.

**Consolidated Rocks**

Ground water within the igneous body east of Huachuca City appears to occur in fracture zones. Four wells have been completed on the western edge of the igneous exposure. Two of these wells were dry and have been subsequently abandoned. The others show extremely poor yields and produce no more than several well volumes per day. For the purposes of this study the hydraulic conductivity of the igneous body is sufficiently low to be considered impermeable.

**Ground-Water Flow Patterns Within the Study Area**

Ground-water flow patterns within the study area are influenced by such factors as regional direction of ground-water flow, spatial variability of aquifer properties, geologic barriers to ground-water flow, ground-water recharge, and ground-water discharge to the river and wells. These factors are all represented in the flow patterns exhibited on Plate 1 - a contour map of 1987-1988 ground-water elevations in the lower Babocomari watershed. Most of the water-level data used to construct this map were measured by the author, and are presented in Appendix B. Procedures employed in
gathering the data are described in Appendix A. A brief summary of the observed ground-water flow patterns is presented below, followed by several sections which discuss the hydrologic significance of these observations.

Initial inspection of Plate 1 shows that ground-water flow in the study area is generally in an easterly direction except in areas of local sinks, sources, or geologic barriers. This follows the previously described basin-wide pattern of flow perpendicular to the San Pedro River within the valley flanks. Hydraulic gradients within the study area range from steep in the western portions of the study area, to gentle in the area east of (and including) Huachuca City, to moderate in the area immediately west of the igneous body. Mounding of the water table occurs along the Babocomari River in the vicinity of southern Huachuca City, and convergent ground-water flow occurs towards the Babocomari River immediately west of the igneous body. Ground-water elevations are locally depressed in the vicinities of the Fort Huachuca East Range and northern Huachuca City, and comprise a minor cone of depression characterized by V-shaped contour lines that point upgradient. The absence of ground-water elevation data east of the igneous body is due to the lack of wells in this area.
Significance of Hydraulic Gradients

Variations in the hydraulic gradient (in areas of negligible recharge and discharge) can be attributed to changes in aquifer transmissivity. For example, relatively steep gradients in the western portion of the study area are indicative of low transmissivities in this area. The basin fill thins towards the Mustang and Huachuca Mountains west of Huachuca City (Pool in Halverston, 1980) and thus decreases in transmissivity. The proximity of shallow bedrock is indicated by exposures of the rocks of the Mustang Mountains in the extreme western portion of Plate 1. Gentle gradients in the central portion of the study area suggest relatively high transmissivities. The magnitude of the transmissivities has been substantiated by aquifer tests, and is probably due to an increased thickness of basin fill. Gradients in areas immediately west of the igneous body are steeper than the central portion, but not as steep as the western portion. Reduction of transmissivity in this area presumably occurs due to thinning of the basin fill as the top of the igneous body approaches the land surface, as well as decreasing grain size of the basin fill associated with distance from the mountains. Gradients steepen along the edge of the igneous body where the basin fill pinches out entirely and ground water may have its maximum component of vertical flow.
Significance of Flow Patterns Near the Babocomari River

Ground-water flow patterns along the Babocomari River are best examined in the context of the associated flow regimes of the river. For the purposes of this study, the Babocomari River was divided into five stretches of distinctive flow regimes (as shown in Figure 10). Reference to this division occurs throughout the thesis in order to facilitate independent descriptions of the ground-water and surface-water systems, and of surface-water/ground-water interactions. The following paragraphs provide detailed descriptions of ground-water flow patterns near the Babocomari River.

Stretch 1 extends from points 4.3 km to 1 km west of Huachuca City. Ground-water flow patterns associated with stretch 1 are poorly defined due to a lack of wells in the area. Perched water tables are found in two wells several hundred meters on either side of the Babocomari River. The perched water tables are about 10 m below the riverbed and 30 m above the regional water table. Well S-3 is completed in a perched aquifer and is only 3 m from well D-13 which penetrates the regional aquifer. Water levels in the two wells differ by 32 m. Well S-2 shows a similar elevation difference with the regional aquifer.

The existence of perched aquifers along the Babocomari
Figure 10 Locations of "River Stretches" and Stream Gauging Stations Within the Study Area
river suggests that ground-water recharge is occurring in stretch 1. Poor definition of water-table elevations in the regional aquifer however make it difficult to distinguish where the recharge is occurring, and the magnitude of its effects. For this reason, ground-water contours for the regional aquifer were drawn without inferred mounding.

Perched or isolated aquifers also exist in stretch 1 along some of the tributary washes to the Babocomari River. Wells P-11 and D-12 along Slaughterhouse Wash show water-table elevations appreciably higher than the regional water table. Wells D-53 (alongside Huachuca Canyon) and well D-17 (along an un-named wash north of the Babocomari River) show water-table elevations approximately 15 m higher than the regional aquifer.

Stretch 2 extends from points 1 km west to 6.5 km northeast of Huachuca City. The regional ground-water system along the Babocomari River in stretch 2 shows evidence of mounding, the extent of which is inferred on Plate 1 based on the low resolution of water-table elevation data. The mound may extend farther along the river in both upstream and downstream directions. In addition to the mounding, a perched water table was found below the riverbed elevation in the vicinity of Huachuca City. Wells within 100 m south of the
river (D-2 and D-3) show cascading water at an approximate depth of 19 m (about 13 m below the riverbed). Farther from the river, well S-1 shows a perched water table also 13 m below the riverbed elevation.

Stretch 3 begins 6.5 km northeast of Huachuca City and extends into the igneous body exposure to the point where the floodplain alluvial deposits along the river pinch out. The Babocomari River has cut a channel through the igneous body which forms a canyon incised at least 25 m into the surrounding bedrock. Floodplain alluvial deposits occur along several hundred meters of the river where it enters and exits the igneous rocks. Ground-water contours in stretch 3 show that most of the water upgradient of the igneous body converges towards the Babocomari River, although some ground water flows around the igneous body. The igneous body therefore functions as a relatively impermeable ground-water dam. Ground water flowing towards the Babocomari River alternates from discharging into the river during the winter months to predominantly supplying riparian evapotranspiration during the pre-monsoon summer months. A flow-net analysis of the ground-water contribution to winter river baseflows is presented in chapter 6, and an evaluation of evapotranspiration losses due to riparian vegetation is presented in chapter 5.
Ground-water conditions in stretches 4 and 5 are undefined due to lack of wells. Stretch 4 is the portion of the river flowing through the bedrock canyon mentioned above. Wells within the igneous body are scarce, and have proved to be either dry or extremely low producers. Stretch 5 begins east of the igneous body at the point that unconsolidated sediments again appear along the river and ends at the San Pedro River confluence. Wells are non-existent in this stretch due to its inaccessibility. The land is used for grazing purposes during times of sufficient river flow.

Local Flow Patterns Associated with Pumping

Ground-water contours within the study area have been affected by pumping. Huachuca City and Fort Huachuca are the major ground-water users in the watershed. Ground-water elevation contours have clearly been lowered in the area of Northern Huachuca City and the Fort Huachuca East Range. The 4130 ft (1260 m) contour line is most affected. It has been drawn back almost to Huachuca City's production well D-1. The axis of the V-shape of the 4130 ft contour line has been portrayed north of Fort Huachuca's two East Range production wells, however water table measuring points are not available in sufficient detail to conclusively define this configuration. Minor domestic pumping occurs along the Babocomari River throughout stretch 3. The density of wells is
light in this area, and domestic pumping is not considered to have a significant effect on ground-water flow patterns. The extent of water-level declines due to pumpage within the study area is discussed below.

**Historic Water-Level Changes**

Ground-water elevations within the upper San Pedro basin show declines due to pumping by municipalities, water companies, and the military. The greatest declines are occurring several km south of the study area in the vicinity of Sierra Vista and the Fort Huachuca main installation. Rates of water level declines in wells in this area range from 12 to 119 cm/yr (0.4 to 3.9 ft/yr) and average 42.7 cm/yr (1.4 ft/yr) (Putman et al., 1987).

Moderate rates of decline are occurring within the study area on the Fort Huachuca East Range. Well hydrographs from the East Range are displayed in Figure 11A. Well D-21-20 16ADA1 is an observation well adjacent to a highly used production well. Water-levels in D-21-20 16ADA1 are monitored closely by the USGS and appear to be declining at a rate of 26.7 cm/yr (0.88 ft/yr). Well D-21-20 22BBB1 is about 1.5 km south of the above, and shows a decline rate of 18.8 cm/yr (0.62 ft/yr). Well D-20-20 35CCB is 5.2 km northwest of D-21-20 16ADA1 and only 2.1 km southeast of the Babocomari River.
Figure 11A
Hydrographs of Wells on the Fort Huachuca East Range

Figure 11B
Hydrographs of Huachuca City Production Wells
This Fort Huachuca test well is the farthest from the East Range production wells and the closest to the Babocomari River. It shows average declines of 11.1 cm/yr (0.36 ft/yr).

Ground-water levels in the vicinity of Huachuca City show mostly low rates of decline. Huachuca City's pumpage is currently equally distributed among wells D-21-20 05ABC, D-21-20 08CAA, and D-21-20 05CBA. Domestic wells are pumped in and around Huachuca City, however their numbers are small and their withdrawals are relatively insignificant. Most wells in the vicinity of Huachuca City show rates of water-level decline less than 9 cm/yr (0.30 ft/yr) (Figures 11B and 11C). Among Huachuca City's production wells, well D-21-20 05ABC, 700 m south of the Babocomari River, has shown a decline of 8.1 cm/yr (0.27 ft/yr); and well D-21-20 05DCD, a backup production well 1.7 km south of the river, has shown an average decline of 6.4 cm/yr (0.21 ft/yr). Well D-21-20 05CBA, less than 100 m south of the river, has no valid historical record because of previous errors in measuring due to cascading water. Water-level declines in well D-21-20 08CAA are unlike those in other Huachuca City production wells. Depth to water in this well has been measured in the past by air-line, a fairly inaccurate method. Original drillers logs note a static depth to water of 87.48 m in 1974. Depth to water measured with an electric sounder on 9/11/87 was 91.44
Figure 11C
Hydrographs of Domestic Wells in the Vicinity of Huachuca City

Figure 11D
Hydrographs of Wells in Areas Peripheral to Heavy Pumpage
m, yielding a decline rate of 30.5 cm/yr (1 ft/yr). This rate is the highest discovered within the vicinity of northern Huachuca City and the Fort Huachuca East Range, exceeding observed declines in Fort Huachuca well D-21-20 16ADA1.

Historic ground-water elevations in areas of negligible pumping are relatively stable. Figure 11D shows hydrographs of wells which are peripheral to intensive pumpage. Wells D-20-20 07BDB, about 7.5 km north of Huachuca City, and D-20-21 18CBB, along the Babocomari River near the bedrock obstruction, show virtually no variation. Wells D-20-20 16CBB and D-20-20 02DDD, both over 8 km northeast of Huachuca City, show respective average decline rates of 2.2 and 4.7 cm/yr (0.07 and 0.15 ft/yr).

The relatively rapid water-level declines documented in the Huachuca City production well D-21-20 08CAA appear to be anomalous in the Huachuca City area. Similar rates of decline are found in the Fort Huachuca East Range well D-21-20 16ADA1 only 2.6 km to the southeast, but are not observed in any nearby Huachuca City production or domestic wells including backup well D-21-20 05DCD, only 1 km to the north. The fact that pumping D-21-20 08CAA has not affected static water levels in neighboring Huachuca City wells suggests that drawdowns from the well are local and that the reason for
heavy declines around the well is probably due to the low aquifer permeability near the well. This hypothesis is supported by the low specific capacity of the well relative to other production wells nearby.

Historic water-table elevation data are not available for the perched aquifer in the vicinity of Huachuca City. The town's ground-water pumping probably has not affected water-table elevations in the perched aquifer(s) because all production wells are completed in the regional (basin fill) aquifer. The possibility exists however that water-table declines in the perched aquifer(s) may be occurring due to transfer of ground water to the regional aquifer in wells with cascading water. Transfer is definitely occurring, however rates and effects are unknown.

Seasonal Fluctuations

Depth to ground water was monitored continuously in a shallow irrigation well 50 m from a perennial portion of the Babocomari River (stretch 3) in order to determine the seasonal effects of riparian evapotranspiration and monsoon events. The well responded readily to both influences because of its location in permeable floodplain alluvial deposits inhabited by young cottonwood, willow trees, and riparian scrub vegetation. The shallow water table was drawn down by
almost 0.6 m (2 ft) in response to riparian evapotranspiration and showed rapid recoveries of over 0.4 m (1.3 ft) corresponding to individual monsoon events. Fluctuations were probably greater closer to the river. Further discussion of water-level fluctuations along the river is included in the Chapter 5. Continuous water-level monitoring was not performed on deeper wells or wells in the perched alluvial aquifers, however discrete water levels measured in several of these wells during both winter and summer (pre-monsoon) months showed no appreciable variation. Additional monitoring is needed to tell if water levels in the basin fill and perched aquifers exhibit seasonal fluctuations.
CHAPTER 4
THE SURFACE-WATER SYSTEM

Overview

The Babocomari River is classified as a predominantly ephemeral stream, however it bears little resemblance to the entirely ephemeral tributaries of the upper San Pedro River. Associations between the Babocomari River and shallow water tables serve to maintain streamflow over most of the year throughout much of the study area. Perennial and seasonally flowing portions of the river are supported by shallow water tables, and generally exhibit stable baseflows between late October and early April. Winter rainfall may cause short-term runoff events between December and February. Streamflows are depleted during the hot summer months which precede the monsoon season (late April through early July). The monsoon rains (mid-July through late September) generally restore streamflows to (or above) their winter baseflow values and cause high discharges associated with individual monsoon events. Streamflows may fall below winter levels towards the end of the growing season (early October) after the monsoon rains have ceased. Streamflows return to their winter condition after the growing season ends.

The Babocomari River has not been gauged previous to this
study. Accounts of historical streamflows furnished by local residents are contradictory and shed little light on possible historic changes in the flow regime of the river. Annual runoff generated by precipitation events within the Babocomari watershed has been estimated by Putman et al. (1987) with the Mooseburner regional regression equation for watershed yield. The equation was successfully calibrated by Mooseburner at the U. S. Department of Agriculture Walnut Gulch Experimental Watershed, on the east side of the basin directly across the San Pedro River from the Babocomari River. Putman et al. extended Mooseburner's conclusion that variations in watershed characteristics as elevation, relief, soil type, vegetation cover, and stream channel material are statistically insignificant at Walnut Gulch to the rest of the upper San Pedro basin in order to arrive at rough estimates of watershed yields. Annual runoff generated in the Babocomari watershed was estimated at 2.38 mcm/yr (1,477 Af/yr) (personal communication, Putman, 1989).

In the preceding chapter, the Babocomari River was divided into five river stretches, each with a distinctive flow regime (Figure 10). Beginning at the western boundary of the study area and proceeding east, the Babocomari River changes from a perennial river with very low baseflow, to an ephemeral river with scattered standing pools and puddles, to
a dry riverbed which loses flow during runoff events, to a gaining river supplied by ground-water discharge, to a perennial river flowing through a bedrock canyon, and back to an ephemeral river which loses its discharge to the surrounding unconsolidated sediments. Below, these portions of the flow system are described within the framework of the pre-defined five stretches.

Description of Flow Regimes

The riverbed throughout stretch 1 is incised about 5 m into the surrounding floodplain alluvial deposits and is absent of significant riparian vegetation. Perennial baseflow is present from its western boundary to a location slightly upstream of Rock Ranch (personal communication, Miegs, 1987). The perennial baseflow is too small to be gauged. In the downstream portion of the stretch 1, pools of standing water were observed in the riverbed approximately 0.4 km upstream of well D-15 (10/30/87) and in the vicinity of the Rock Ranch (6/22/88). The pools were not remnants of recent runoff events as they were observed during periods of little (6/88) and no (10/87) rainfall.

Stretch 2 is characterized by a dry gravelly streambed also incised about 5 m into the surrounding alluvium and lacking significant riparian vegetation. Water is generally
present in the streambed only during runoff events, although a large expanse of standing water was observed 4.5 km downstream from Huachuca City during the height of the monsoon season (August, 1988). The standing water resembled a pond which covered the entire riverbed and extended at least 100 m downstream. The "pond" was not observed during reconnaissance conducted in the dryer month of November.

Stretch 3 shows less incision than stretches 1 and 2. Much of the stretch is characterized by gently sloped banks inhabited by lush riparian vegetation. Baseflow is present over the entire stretch during most of the year. The upper 2.4 river km of the stretch are seasonally ephemeral and the lower 4.1 river km are perennial. Discharge in stretch 3 is large enough to enable gauging of the river, which was performed on a seasonal basis. Stream gauging was performed in the unmodified river channel with a Pygmy current meter (see appendix A for a complete description of procedures). Figure 10 indicates the locations of the gauging stations established. The seasonal gauging was conducted under conditions of steady baseflow (constant river stage) and the absence of rain. Baseflow was determined to be stable based on repeated observation of the river stage elevation. The gauging was performed once in late winter (March 15/16, 1988) and once in early summer (June 30, 1988). March baseflow extended all
the way from the upstream boundary of the stretch to the confluence of the Babocomari with the San Pedro River. June baseflow was greatly depleted evapotranspiration and was only measurable between gauges 4 and 6. Results of the seasonal stream gauging are presented in Figure 12 and in Table 2.

TABLE 2
RESULTS OF SEASONAL STREAM GAUGING ALONG THE BABOCOMARI RIVER

<table>
<thead>
<tr>
<th>Station</th>
<th>March Baseflow $M^3/sec$ (cfs)</th>
<th>June Baseflow $M^3/sec$ (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0003 (0.01)</td>
<td>not measurable</td>
</tr>
<tr>
<td>2</td>
<td>0.0062 (0.22)</td>
<td>not measurable</td>
</tr>
<tr>
<td>3</td>
<td>0.0125 (0.44)</td>
<td>not measurable</td>
</tr>
<tr>
<td>4</td>
<td>0.0632 (2.23)</td>
<td>0.0082 (0.29)</td>
</tr>
<tr>
<td>5</td>
<td>0.0739 (2.61)</td>
<td>0.0091 (0.32)</td>
</tr>
<tr>
<td>6</td>
<td>0.0770 (2.72)</td>
<td>0.0099 (0.35)</td>
</tr>
<tr>
<td>7</td>
<td>0.0685 (2.42)</td>
<td>not measurable</td>
</tr>
<tr>
<td>8</td>
<td>0.0717 (2.53)</td>
<td>not measurable</td>
</tr>
<tr>
<td>9</td>
<td>0.0572 (2.02)</td>
<td>not measurable</td>
</tr>
<tr>
<td>10</td>
<td>0.0476 (1.68)</td>
<td>not measurable</td>
</tr>
</tbody>
</table>

The results of March stream gauging show that the Babocomari River was gaining water consistently throughout stretch 3 under winter baseflow conditions. During pre-monsoon summer baseflow conditions the river was not gaugable over the
upstream portion of stretch 3, although water was observed in pools and puddles. The June baseflow was gaugeable only at stations 4, 5, and 6 and was depleted by approximately 87 percent relative to that observed in March. Maximum baseflow was measured at gauging station 6 (the point where unconsolidated sediments pinch out upon the exposed igneous body) during both seasons.

Stretch 4 consists of the portion of river running through the bedrock canyon incised into the igneous body. The canyon is steeply cut with walls about 25 m above the riverbed. Stretch 4 has no floodplain alluvial deposits associated with the river and supports relatively little riparian vegetation. Perennial flow occurs throughout the stretch. Baseflow at the upstream entrance to the canyon was gauged at station 6. Baseflow at the canyon exit was not gauged due to lack of suitable channel characteristics. Changes in baseflow within the canyon stretch are believed to be negligible due to the impermeable nature of the bedrock and lack of significant riparian vegetation.

Stretch 5 is incised about 5 m into the surrounding basin fill sediments. The incision along this portion of the Babocomari River is equivalent to that along the San Pedro River. Both appear to be the result of the same period of
downcutting. Moderate densities of riparian vegetation are present in a narrow strip surrounding the Babocomari River. Baseflow was present over all of stretch 5 during March stream gauging, but was absent over most of the stretch during June stream gauging. March stream gauging indicated that the river was losing water throughout most of the stretch (gauging stations 7-10). Assuming that no baseflow losses or gains had occurred through the canyon, approximately 0.0294 m³/sec (38 percent of baseflow) was lost to the sediments between the canyon exit and the San Pedro River. The majority of this loss occurred in the downstream portion of the stretch where igneous exposures are not present along the river (east of station 8). During the June stream gauging, baseflow emerging from the canyon was entirely lost within several hundred meters of entering stretch 5. During the monsoon season stream stages in stretch 5 were the highest observed annually (as in all stretches with perennial or seasonal baseflow). Stream gauging was not performed during the monsoon season because of day to day variability of the river stage.
CHAPTER 5
SURFACE-WATER/GROUND-WATER INTERACTIONS

The previous two chapters have shown that ground-water flow patterns near the river and flow regimes of the river are largely influenced by surface-water/ground-water interactions. The gaining stretch of the river is associated with an adjacent water table trough, and the losing stretches are associated with such features as mounding of the regional water table and the existence of perched aquifers. In addition, pools and puddles of standing water in the riverbed imply the existence of shallow water table(s) along the river. Description of the hydrologic system along the river therefore, should include an analysis of surface-water/ground-water interactions.

The boundaries of the pre-defined five stretches were chosen based on differences in the dynamics of their surface-water/ground-water interactions rather than based on differences among their ground-water or surface-water systems independently. Stretch 1 exhibits a direct connection between the river and a shallow water table which intersects the riverbed. Stretch 2 exhibits a dry riverbed without a saturated connection to the underlying water table (with the exception of the seasonally ponded water observed in its lower
reach). Ground-water recharge in stretch 2 must therefore occur as vadose zone migration of stream transmission losses to the underlying water table(s). Stretch 3 exhibits a direct connection between the river and shallow regional water tables in which the ground-water system discharges to the river. Surface-water/ground-water interaction in stretch 4 is believed to be negligible due to the presumed impermeable nature of the igneous body. Finally, streamflow in stretch 5 recharges the ground-water system.

The degree to which surface-water/ground-water interaction can be described within a given stretch is limited by the availability of data. Unfortunately, interactions in stretches 1, 2, 4, and 5 can only be described qualitatively due to insufficient data. Qualitative descriptions are presented for all five stretches in the first section of this chapter. A quantitative analysis of the ground-water contribution to river baseflow in stretch 3 is included in a separate section. The final section describes water table responses to runoff events in stretch 3 based on continuous monitoring of a single observation well.

**Qualitative Descriptions**

Stretch 1 is characterized by losing perennial flow in its upstream reach and ephemeral flow in its downstream reach.
Definition of both surface and ground-water systems is poor within this stretch because the baseflow is too low to gauge and wells are sparse. The year-round loss of streamflow in the upper portion of the stretch implies recharge to the ground-water system. The existence of multiple pools of standing water in the riverbed during times of little and no rainfall in the lower portion suggests a possible connection between the river and a shallow ground-water system. Perched water is found about 10 m below the elevation of the riverbed in wells several hundred meters on either side of the river. Assuming a perched water-table elevation along the river equivalent to the riverbed elevation, perched water tables which decrease in elevation with distance from the river suggest that the river is a source of recharge to the overall ground-water system.

Poor detail of ground-water contours in stretch 1 prevents confirmation of ground-water recharge to the regional aquifer, however contours in neighboring stretch 2 reveal that the river is recharging the ground-water system. Evidence of recharge in stretch 2 includes mounding of the regional water table and the presence of perched aquifers along the river. Conditions for recharge are favorable along the stretch. High permeability of the riverbed is demonstrated by the presence of a gravel mine adjacent to the river about 1.7 km downstream from the Huachuca City sewage ponds. Definition of ground-
water conditions along the river is insufficient to discern the proportion of recharge directly reaching the regional aquifer versus that first reaching the perched aquifer(s). The upstream reach of stretch 2 (near Huachuca City) contains sufficient measuring points to allow reasonable definition of the ground-water system. The downstream reach contains no wells.

Perched aquifer(s) in the upstream reach are evidenced by cascading water and anomalously high water-table elevations in wells. Measured elevations of cascading water and the perched water table are both about 10 m below the riverbed elevation. The fact that the elevations of the perched water-table(s) are below the riverbed concurs with the observed lack of standing pools and puddles in the riverbed. Mounding of the regional water table is seen clearly in the contours in Plate 1. The 4150 ft (1266 m) contour enclosing the Babocomari River in the vicinity of Huachuca City and the 4170 ft (1272 m) contour enclosing the unlined sewage ponds suggests that leakage from the sewage ponds is a second source of ground-water recharge. Calculations presented in Chapter 7 imply that 49,000 m$^3$ of sewage leachate are lost to the ground-water system from the ponds annually.

Evidence of ground-water mounding in the lower reach of
stretch 2 is not seen in Plate 1. The extent of the recharge mound has been inferred only on the basis of limited data concerning ground-water levels in wells. The mound may extend farther in both the downstream and upstream directions, however definition of the ground-water system is poor in both of these directions. A large expanse of ponded water observed in the riverbed 1.5 km downstream from the sewage ponds suggests the possibility of a seasonally shallow water table in this vicinity. The "pond" was observed only during the monsoon season. The type of aquifer (perched or regional) supporting this standing water is unknown.

In addition to perched aquifers along the Babocomari River, anomalous water-table elevations measured along small tributary washes in stretches 1 and 2 suggest that recharge from ephemeral streams to local or perched aquifers may be a common occurrence. For example, the high water-table elevation measured in well D-12 seems to be connected with recharge from runoff events in nearby Slaughterhouse Wash. Well D-12 is a domestic well approximately 37 m deep which functioned for many years without any problems. Depth to water was measured in October, 1987 at 25.02 m. By June of 1988 the water level in D-12 had declined to an unprecedented depth of 33.09 m and showed diurnal water-table variation in phase with evapotranspiration. This dramatic drop in water-table
elevation was non-existent in the perched aquifer along the Babocomari River (well S-3). The drop might have been partly due to a particularly dry year, however a second explanation is related to diversion of runoff from the upper portions of Slaughterhouse Wash to a parallel drainage in order to construct a new runway for Fort Huachuca. Although conclusive evidence is lacking, loss of runoff in the wash could account for reduction of recharge to the local aquifer thus causing the unprecedented water table decline. Other wells which appear to demonstrate perched or local water-table conditions are mentioned in Chapter 3.

Stretch 3 differs from stretches 1 and 2 because the river predominantly gains flow from the ground-water system. Unlike stretches 1 and 2, stretch 3 contains abundant data available for definition of both the ground-water and surface-water systems. Gauging of baseflow has shown that increase in baseflow occurs over the entire stretch during the winter months. During early summer (pre-monsoon) months, baseflows are greatly reduced and exist only in the downstream half of the stretch. Standing puddles and pools in areas seasonally devoid of baseflow reveal that the water table remains close to the riverbed. Throughout the year, baseflow attains its highest discharge immediately upstream of the impermeable igneous body. At this location virtually all ground water
flowing upgradient of the body has been forced to flow either into the river or around the body. The role of the river as a ground-water drain is demonstrated by the water table trough centered along the river (Plate 1). The disappearance of baseflow in early summer in the upper portion of stretch 3, and its reduction in the lower portion is associated with deepening of the water table trough along the river due to riparian evapotranspiration. A simple water-budget analysis presented in Chapter 7 shows that the early summer baseflow reduction is of the same order of magnitude as the estimated riparian evapotranspiration. A flow-net analysis of stretch 3 is presented in the following section.

Stretch 4 comprises the passage of the river through the bedrock canyon incised into the formentioned igneous body. Surface-water/ground-water interaction along this stretch is presumed to be non-existent due to the impermeability of the igneous body.

Stretch 5 begins where the river emerges from the bedrock canyon and extends to the San Pedro River. Ground-water information is altogether absent in this area due to the lack of wells, however reasonably good seasonal baseflow measurements have been obtained. Winter measurements showed that baseflow was lost to the surrounding ground-water system
as it proceeded down the river stretch. Significant loss of baseflow in stretch 5 began downstream of station 8, where the river moves away from surface exposures of the igneous body. This suggests that shallow bedrock is preventing significant loss of baseflow upstream of station 8. During pre-monsoon summer stream gauging the discharge passing through the canyon was completely lost to the ground-water system over a distance of several hundred meters. The presence of abundant weedy riparian vegetation in the riverbed however, suggests that shallow underflow was occurring within the alluvial sediments surrounding the river. Noticeably humid air observed along the river during the hot pre-monsoon months indicated evaporation from the riverbed and is explainable by shallow underflow.

**Flow-Net Analysis of Stretch 3**

Detailed measurements of winter baseflow and water-table elevations in stretch 3 allowed sufficient definition of the water table and the groundwater contribution to baseflow to perform a flow-net analysis of the hydrologic system. The purpose of this analysis was to utilize quantitative data to calculate a general value for transmissivity in the region immediately upgradient of the igneous body. The flow net is presented in Plate 2 and was constructed based upon the following assumptions:
1) The aquifer is heterogeneous and pinches out along the igneous body, increasing in thickness and transmissivity with distance away from the body.
2) The aquifer is horizontally isotropic.
3) Ground-water elevation contours and river baseflows measured in the "non-rainy seasons" represent quasi-steady state hydrologic conditions.
4) Ground-water discharge due to year-round pumping and winter riparian transpiration is negligible.
5) Recharge to the ground-water system is insignificant within the flow net region.
6) Vertical flow is only significant close to the igneous body (within 1 km).
7) The river represents a "no-flow" ground-water boundary.

Each of these assumptions can be reasonably justified or explained. Heterogeneity of alluvial aquifers is very common, and the fact that the aquifer pinches out as it approaches the igneous body (as well as the fact that sediments generally get finer with distance from the mountains) accounts for the reduction in transmissivity. Vertical anisotropy is also common in alluvial aquifers. Riverbank exposures displaying thin horizontal layers of sand and silt attest to such anisotropy. A study by Johnson and Morris (1962) showed that
horizontal hydraulic conductivities can be two to ten times greater than vertical conductivities in fluvial sediments. The assumption that hydrologic conditions during the "non-rainy seasons" are in a quasi-steady state can be justified by the fact that short-term stresses on the hydrologic system (such as runoff events) are few and far between. The assumption that recharge to and discharge from the ground-water system are negligible is justifiable by the facts that desert-floor recharge is believed to be negligible basins of the Southwest, ground-water pumping only meets the domestic needs of a low density of area residents, and winter measurements were made outside of the phreatophyte growing season. The assumption that vertical flow is only significant within 1 km of the igneous body is not substantiated, however it is necessary in order to derive a meaningful transmissivity value for the sediments behind the igneous body because flow-net analysis assumes horizontal flow. Finally, treatment of the river as a ground-water "no-flow boundary" is probably acceptable because ground water discharges to the river from both sides.

Construction of the flow net was accomplished by choosing an arbitrary point (gauging station 3) and drawing flow lines on either side of the river to that point. Additional flow lines were drawn in order to create a set of flow tubes on either side of the river. Spacing of the flow tubes was
selected so that the flow net cells between contours 4080 and 4090 were square. The transmissivity of these cells is taken as a "reference transmissivity" representing the general transmissivity of the flow net area. Changes in transmissivity relative to the "reference cells" are indicated by variation of the ratio of \( dw \) (the cell width measured perpendicular to flow lines) to \( ds \) (the cell length measured parallel to flow). Higher ratios correspond to lower transmissivities and vice versa.

Ratios in the upgradient portion of the flow net are approximately one third that of the reference cells, and ratios in the downgradient portion of the flow net (adjacent to the bedrock body) are as much as four times greater than the reference cells. Apparent increased transmissivities upgradient of the reference cells are presumably due to increased thickness of the basin fill with distance from the bedrock obstruction. Apparent reduced transmissivities near the bedrock obstruction are due to decreased aquifer thickness and an increased component of vertical flow. Several cells north of the river between the 4060 and the 4050 contour lines show relatively increased transmissivities although they are closer to the bedrock obstruction. Although potentially due to locally shallow depths to bedrock, this phenomenon is probably due to an ill-placed contour line based on lack of sufficient
Determination of a general "reference cell" transmissivity value was accomplished by considering the ground-water discharge through all of the flow tubes which discharge into a known stretch of the river and assuming that all flow tubes transmit equal amounts of water. Because the ground-water flow converges towards the river, the net gain in river baseflow over a defined stretch can be attributed to the ground water flow in the flow tubes discharging into that stretch. The formula used for this analysis is:

\[ Q = mT(dh)(dw/dl) \]

where:

- **Q** = ground-water contribution to baseflow over defined stretch of the river (m³/sec)
- **m** = number of flow tubes discharging into river
- **dh** = head drop between contour lines (m)
- **T** = transmissivity (m²/sec)
- **dw,dl** = width and length of cell as previously defined (m)

The winter baseflow gain of 0.0507 m³/sec between stations 3 and 4 can be attributed to the contribution of nine flow tubes (see Plate 2). Given that \( dh = 3.05 \text{ m} \) (10 ft), a \( T \) value of 0.00185 m²/sec is determined for the "reference
"cells". Similarly, the gain between gauges 4 and 5 of 0.0107 m³/sec can be attributed to the contribution of two flow tubes (both north of the river). A transmissivity value of 0.00175 m²/sec is arrived upon by similar calculation.

These T values are believed to represent the general aquifer transmissivity upgradient of the bedrock obstruction, and appear to be consistent with nearby transmissivity measurements and published reports of sedimentary texture. The flow-net derived transmissivity values are similar to the lower transmissivity values measured from aquifer tests and estimated from specific capacity values in the vicinity of Huachuca City and the Fort Huachuca East Range (Chapter 3). A reasonable estimate of aquifer thickness in the "reference cell" vicinity is 60-120 m, based on greater thicknesses of the basin fill west of the reference cells and the fact that the aquifer pinches out as it approaches the igneous body. Given a general aquifer transmissivity of 0.0018 m²/sec, the hydraulic conductivity of the aquifer material ranges from 3 X 10⁻³ to 1.5 X 10⁻³ cm/s. This range corresponds to laboratory measured hydraulic conductivity values of silty sand (Freeze and Cherry, 1979), a reasonable description of the basin fill in this vicinity (Brown et al., 1966).
Seasonal Ground-Water Level Fluctuations Along the River

In order to further describe surface-water/ground-water interactions along the river, the water-table elevation at a single location in the floodplain alluvial aquifer within stretch 3 was monitored continuously. The monitoring allowed quantitative measurement of ground-water responses to runoff events and to the consumptive use of riparian vegetation. Continuous data were obtained from well S-19 (D-20-20 23DC) for the period beginning November, 1987 and ending September, 1988 by installing a Stevens water-level recorder on the well. The well is approximately 50 m south of the Babocomari River in floodplain alluvial deposits inhabited by riparian scrub vegetation and a low density of young Cottonwood and Gooding Willow trees. The water table in the vicinity of well S-19 is only about 1 m below the land surface (roughly equivalent to the river stage). Unfortunately, continuous monitoring of the river stage elevation was not performed. Continuous data from both the river and the adjacent water table would have provided excellent definition of the dynamics of surface-water/ground-water interaction. Instead the dynamics must be implied by interpretation of the limited data.

Figures 13A-C present monthly well hydrographs of water level relative to an arbitrary datum (0.91 m below the land surface). Several breaks in the record occurred due to human
Figure 13A  Monthly Hydrographs of Monitoring Well S-19
Figure 13B  Monthly Hydrographs of Monitoring Well S-19
Figure 13C  Monthly Hydrographs of Monitoring Well S-19
error and equipment malfunction. The hydrographs show that the water table was relatively stable between mid-November and early April. During this period several precipitation events caused short term water table rises of less than 3 cm and only one event (dated December 17 and 18, 1987) caused a significantly greater water table rise of 12 cm. The water table response to this event showed a relatively slow ascent (about 15 hrs) and a recession drawn out over 5 days. Between late April and early July slow, constant decline of the water table and diurnal water table oscillations were recorded. Only one water-table rise (June 18-22, 1988) occurred during this period and was associated with an early summer storm. From early July to mid September abrupt water-table responses to monsoon storms are superimposed over steady diurnal variations and declines of the water table. The first monsoon storms occurred between July 6 and July 11, however the water table response was not recorded due to human error. The second notable event began on July 25, however only the ascending limb of the response curve was recorded because of equipment malfunction. The ascension was extremely steep with a water table rise of 25 cm. Throughout the latter portion of August, similar water table responses were recorded. Ascending limbs of the response curves were extremely steep (lasting only several hours) and recessions were moderate in slope. Two water table rises were recorded in early September. The first
(9/3/88) shows an ascension curve of moderately high slope (but less steep than the August responses) and a moderate recession similar to those described above. The second (9/12/88) shows a very moderate ascension and recession, similar to the winter responses.

The monthly well hydrographs show that water levels in the floodplain alluvial aquifer adjoining the river are very responsive to rainfall/runoff events. Unfortunately, a quantitative relation between river stage and ground-water elevations could not be established due to lack of continuous river stage data. River stages of about 0.3 m above normal were observed during heavy monsoon runoff events (0.6 m at peak flow). The magnitude of these raised river stages is similar to the water-level changes recorded in well S-19, however the recorded ground-water responses may not be entirely attributable to a change in river stage. During monsoon events considerable overland flow may occur as runoff towards the river, and some of this flow may directly recharge the floodplain alluvial sediments before reaching the river. In this case rising ground-water levels would be attributable partly to an increased river stage and partly to infiltration from overland flow. More investigation is needed to distinguish the roles of these two modes of aquifer recharge.
The shape of the recorded ground-water responses to rainfall/runoff events can be related to the general intensity of seasonal precipitation events. Summer monsoon precipitation is usually intense, short-lived, and localized whereas winter storms are often gentle, drawn out, and aerially intensive. During the summer, recorded ground-water response ascensions were quite steep (raising several tens on cm in a period of several hours) as would be expected with an intense influx of runoff into the system. Winter ascensions normally lasted several tens of hours and were lesser in magnitude, thus reflecting more gradual introduction of water to the system. The rapid ground-water responses observed during the summer monsoons illustrate the believed high permeability of the floodplain alluvial sediments.
CHAPTER 6
WATER QUALITY

Chemical analyses of water samples taken in the vicinity of the Babocomari watershed have been compiled and compared in order to characterize the regional water chemistry and distinguish specific chemical features associated with components of the hydrologic system. In the first section of this chapter the chemical evolution of ground-water composition is evaluated by comparison of trilinear plots of analyses taken from different positions along the regional direction of flow. In the second section, the spatial distribution of major ion concentrations is examined quantitatively by comparison of basic statistical parameters for water quality data from various portions of the flow system, and qualitatively by graphical comparison of contour plots of the major ion concentrations. The third section examines D/H and \(^{18}O/^{16}O\) ratios in order to further define recharge processes within the watershed. Finally, the fourth section presents an interpretation of the chemical data described above.

Samples were taken from a variety of sources - including: deep wells in the basin-fill aquifer; wells both fully and partially completed in the Pantano (?) Formation; shallow
wells in the floodplain alluvial deposits; a perched aquifer in the vicinity of Huachuca City; the Babocomari River; and springs issuing from the Huachuca Mountains. A total of seventy seven analyses were compiled: thirty six from within the study area; thirty two from Sierra Vista/Fort Huachuca vicinity; and nine from the upper reaches of the watershed. By necessity, the sampling distribution followed patterns of ground-water development and was therefore not uniformly distributed over the study area. Twenty-nine of the samples were collected by the author; the others were taken by various government agencies. Chemical analyses of the latter group are published in the data bases of the Arizona Department of Water Resources (ADWR), U.S. Geological Survey (USGS), and the Arizona Water Commission (now the ADWR). Sampling dates of published analyses range from 1941 to 1987, and many older analyses are incomplete. The major ion analyses, trace ion analyses, and well-construction data are presented in Appendix B. Sampling and analytical procedures are presented in Appendix A.

Composition of Water Samples

Analysis of Trilinear Diagrams

The evolution of ground-water composition in the vicinity of the Babocomari watershed was evaluated by plotting trilinear diagrams of sample groups taken from contiguous
"sampling locations" along the regional direction of flow (west to east). The "sampling locations" comprise north-south trending bands defined by the "range" of the legal location of the well (Gila and Salt River baseline and meridian system). Range is a convenient indicator of general east-west position. Range 18 represents the far upgradient portion of the regional flow path; range 19 represents the upper portion; range 20 represents the middle portion; and range 21 represents the lower (downgradient) portion. In addition, a separate trilinear diagram was plotted for samples taken from the river and the adjoining floodplain alluvial aquifer east of Huachuca City. The purpose of isolating this portion of the flow system was to identify chemically distinguishable processes associated with this stretch of the river.

Figure 14 is a trilinear diagram of all the sample analyses compiled by the author. The plot shows the water to be entirely of the calcium-bicarbonate chemical facies with the exception of four "outliers" (discussed below). The majority of points are tightly grouped and show only minor compositional variability. The absence of strong linear trends suggests no evidence of mixing or ion exchange. Figures 15 through 18 show trilinear plots of ground-water analyses taken along the regional direction of flow (from ranges 18 through 21 respectively). Range 20 clearly contains the
Figure 14  Trilinear Plot of All Analyses Compiled
Figure 15  Trilinear Plot of All Analyses from Range 18
Figure 16  Trilinear Plot of All Analyses from Range 19
Figure 17  Trilinear Plot of All Analyses from Range 20
Figure 18  Trilinear Plot of All Analyses from Range 21
Figure 19  Trilinear Plot of River Samples and Ground-Water Samples Taken from the Floodplain Alluvial Aquifer East of Huachuca City
majority of data points, and data from range 18 are scarce. There are no visually apparent differences between the groupings exhibited on the trilinear diagrams of the four ranges. Figure 19 shows the compositions of river water and ground water from the floodplain alluvial aquifer adjacent to the river. Again, no marked differences are observed between the compositions of waters associated with the river and the compositions of waters from the overall region.

Two of the four outliers mentioned above show relatively high concentrations of sulfate and two show high concentrations of chloride. Well D-20-20 18DCB (4.5 km due north of Huachuca City) shows a sulfate concentration of 110 mg/l; well D-20-20 07BBD (6.5 km due north of Huachuca City) shows a sulfate concentration of 750 mg/l; well D-20-18 05DAB (between the Mustang and Whetstone Mountains) shows a chloride concentration of 160 mg/l; and well D-21-20 30BDB (in the vicinity of Sierra Vista) shows a chloride concentration of 61 mg/l. Well D-21-20 30BDB is 278 m deep and screened in both the basin fill and Pantano (?) Formations. Well D-20-18 05DAB is located on an exposure of basin fill. Nearby bedrock exposures suggest that the deposits are relatively thin. Well D-20-20 07BBD is 112 m deep and completed in the upper portion of the basin-fill aquifer. Well D-20-20 18DCB, a domestic well, is probably also completed in this upper portion. High
chloride and sulfate concentrations are not common in the basin-fill aquifer. Possible explanations for their occurrence are included in the "interpretation" section.

**Spatial Distribution of Major Ion Concentrations**

**Description of Statistical Analyses**

Basic statistical analysis was performed on nine groups of samples in order to detect major ion concentration differences between various portions of the flow system and to establish the range of variability encountered between individual sample analyses. The groups include: 1) all surface and ground-water samples; 2) all ground-water samples; 3) samples taken from the river or the floodplain alluvial deposits adjoining the river; 4) river samples taken during October 1987; 5) river samples taken during June 1988; 6-9) ground-water samples taken from ranges 18 through 21 (respectively). Ranges 18 through 21 were again chosen to represent increasingly downgradient portions of the regional flow system. The four outlier analyses were withdrawn from the sample pool. Means and standard deviations of the major ion concentrations (including TDS) were calculated for all nine groups. The percent differences between mean major ion concentrations in groups 3, 7, 8, 9 with respect to those in group 1 (populations in groups 4-6 are too small to be considered statistically significant) were calculated with the
formula:

\[ Pd = 100 \times \frac{(Mx - M1)}{M1} \]

where:  
- \( Pd \) = percent difference  
- \( Mx \) = mean ion concentration for group \( x \)  
- \( M1 \) = mean ion concentration for group 1

A summary of these statistics is presented in Table 3.

Variability of major ion concentrations among all sample analyses (group 1) is low. Standard deviations of concentrations are less than 10 mg/l for all major ions except calcium (SD = 17 mg/l). Mean major ion concentrations in the four ground-water groups (6-9) are all within one standard deviation of the mean major ion concentrations calculated for the entire sample set (group 1) except for the mean magnesium concentration in group 6 and the mean silica concentration in group 7. Within groups 6, 7, and 9, the magnitudes and signs of percent difference from group 1 are variable and inconsistent among major ions. Percent differences from group 1 are consistently low in group 8 (predominantly Sierra Vista and Fort Huachuca wells) and consistently high in all of the groups associated with the Babocomari River (3-5). The magnitudes of the percent differences are relatively small (less than 13 percent) in group 8 and relatively large (less
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<th>NA (MG/L)</th>
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NOTE: % DIFF = PERCENT DIFFERENCE BETWEEN SAMPLE GROUP VALUE AND THE AVERAGE VALUE FOR ALL GROUND-WATER ANALYSES (% DIFF = (SAMPLE GROUP VALUE - GROUND-WATER VALUE)/GROUND-WATER VALUE)

ALSO, SAMPLE SIZES MAY VARY BETWEEN SPECIES - SOME ANALYSES ARE INCOMPLETE.
than 70 percent) in groups 3-5. The largest percentages in groups 3-5 (16.7 to 69.3 percent) are shown by sodium, potassium, chloride, and sulfate. Slightly smaller increases (2.7 to 27.4 percent) are shown by bicarbonate, calcium and magnesium. Nitrogen is severely depleted in the river samples. Consistent major ion concentration increases for groups 3-5 are reflected in the fact that their mean TDS values are all above one standard deviation higher than the mean value for group 1. Individual major ion concentrations which exceed group 1 values by more than one standard deviation occur for sodium (group 4), potassium (groups 4 and 5), and sulfate (groups 4 and 5).

Description of Contour Maps

Contour maps of major ion concentrations were made by digitizing the locations of sampling points and entering their coordinates and corresponding ion concentrations to a computer plotting package. Both ground-water and surface-water analyses were included among the sampling points. The contouring package constructed a grid based on interpolation between known points, and a sensitivity analysis was performed to ensure that the mesh of the grid was fine enough to accurately represent variations arising from individual data points. The four "outlier" analyses were withdrawn from the plots presented in this chapter, however several plots which include
the outliers are presented in Appendix C. These plots (Figures C-1 through C-5) demonstrate that the inclusion of isolated, strongly discordant data values can yield misleading representations of spatial distribution.

The contour maps reflect the fact that concentrations of most major ions in the southeast quadrant of the map are slightly lower than concentrations elsewhere, especially relative to concentrations along the Babocomari River. The maps also demonstrate that contouring large areas based on scarce data can lead to broadly generalized and potentially misleading results. Figure 20 shows the locations of the sampling points (some sampling points may be absent from specific maps due to incomplete analyses). High densities of data are present in the southeast quadrant of the plots and along the Babocomari River east of Huachuca City, however low densities are present in the northwest and southwest quadrants and north of the Babocomari River. Contours obtained by interpolation in areas of high data density are based on weighted averages of many surrounding data values and can therefore be assumed to accurately represent the local chemistry. Contours obtained by interpolation in areas of low data density however, may be based on too few points to accurately represent the local chemistry.
Contours of all major ions show high concentrations along the river relative to the southeast quadrant of the map. Elevated concentrations along the river are most apparent on plots of TDS, bicarbonate, chloride, sulfate, and potassium (Figures 21-25). Contour lines depicting higher concentrations along the river may inaccurately extend into areas farther from the river due to lack of data points in these areas. Contours depicting high concentrations in areas north of the river tend to overshadow the high concentrations associated with the river in plots of TDS, potassium, and sulfate; however these areas are supported by few data points and may be inaccurately represented. Concentrations of TDS, bicarbonate, chloride, and sodium (Figure 26) along the river reach their highest values east of Huachuca City in the area of dense riparian vegetation and scattered domestic residences.

The contour map of calcium (Figure 27) shows a slight "ridge" of high concentrations which trends to the northeast, however few data points support its existence. Calcium concentrations in the vicinity of the Babocomari River are higher than in the vicinities of Fort Huachuca, Sierra Vista, and northern Huachuca City. Magnesium concentrations (Figure 28) show a similar but less pronounced increase. Silica concentrations (Figure 29) show no appreciable trends.
Figure 24: Contour Map of Sulfate Concentrations in the vicinity of the Lower Babocomari Watershed
Figure 25 Contour Map of Potassium Concentrations in the Vicinity of the Lower Babocomari Watershed
Figure 26  Contour Map of Sodium Concentrations in the Vicinity of the Lower Babocomari Watershed
Figure 27  Contour Map of Calcium Concentrations in the Vicinity of the Lower Babocomari Watershed
Figure 28: Contour Map of Magnesium Concentrations in the Vicinity of the Lower Babocomari Watershed
Figure 29 Contour Map of Silica Concentrations in the Vicinity of the Lower Babocomari Watershed
Figure 30 Contour Map of Ground-Water Temperatures in the Vicinity of the Lower Babocomari Watershed
Finally, the plot of temperature (Figure 30) shows cooler values along the river relative to adjoining areas (with considerably fewer data points).

**Environmental Isotopes**

Ratios of $^{18}O/^{16}O$ and D/H were measured in eleven samples taken from the vicinity of the Babocomari watershed. Two samples were from springs in the Huachuca Mountains; three samples were from wells completed in the basin-fill aquifer, one sample was from the Pantano (?) Formation in the vicinity of Elgin; four samples were from shallow wells completed in the floodplain alluvial deposits along the river (including one sample from well D-21-19 01AAC - completed in a perched aquifer); and one sample was from the river in the vicinity of Rock Ranch. The results are presented in Figure 31 as a graph of delta deuterium versus delta $^{18}O$ (exact locations and values are listed in Appendix B). The graph shows that the eleven samples fall closely along a straight line. The line has a gentler slope than the meteoric water line, indicating that evaporation has occurred prior to recharge (Freeze and Cherry, 1979). Samples from the mountain springs are on the more depleted end of the line, whereas the river sample and most well samples are grouped on the more enriched end of the line. The available data points show no distinction between delta D and $^{18}O$ values in samples from the basin-fill aquifer, the
Figure 31  Delta D vs. Delta $^{18}O$ Values of Samples Taken in the Vicinity of the Lower Babocomari Watershed
floodplain alluvial aquifer, and the river.

Delta D versus delta $^{18}$O values have been compiled for precipitation in the vicinity of the Dragoon Mountains (Strauss, 1986) and are presented in Figure 32. The Dragoon Mountains are on the eastern side of the upper San Pedro basin and experience the same precipitation events as the Babocomari watershed. The graph shows a distinct difference between the isotopic compositions of summer monsoon and winter storm precipitation. Distinct differences in isotopic composition were also found for ground-water samples taken from the area between the Dragoon Mountains and the San Pedro River (Strauss, 1986). Water samples taken from the mountain front aquifers and springs were more depleted than samples from the basin fill and (local) artesian aquifers (see Figure 33). Delta D and $^{18}$O values from the mountain front samples were found to occupy a range coincident with the values for the winter precipitation. Similar trends are shown in the vicinity of the Babocomari watershed. Delta D and $^{18}$O values from the mountain springs tend to fall within Strauss' range for winter precipitation. Samples taken from the floodplain alluvial and basin-fill aquifers are more enriched and show values at the interface between Strauss' ranges for winter and monsoon precipitation.
Figure 32  Delta D vs. Delta $^{18}$O Values of Precipitation Samples Taken in the Vicinity of the Dragoon Mountains (From Strauss, 1986)

Figure 33  Delta D vs. Delta $^{18}$O Values of Ground-Water Samples Taken in the Vicinity of the Dragoon Mountains (From Strauss, 1986)
Interpretation

The quality of water in the lower Babocomari watershed is good, although moderately hard. The composition of groundwater and surface-water samples appears to be uniform in the vicinity of the Babocomari watershed. Sampling points are unfortunately concentrated in the areas east of the Huachuca Mountains (Fort Huachuca, Sierra Vista, and Huachuca City) and along the Babocomari River. Portions of the hydrologic system (specifically the far upstream reaches of the watershed and the area north of the Babocomari River) are under-represented in the sample set and require further sampling to state strong conclusions. Assuming that the available data are representative in areas of low sampling density, the lack of variability on the trilinear plots suggests that there are no components of the flow system that are compositionally detectable with major ions. This conclusion is certainly applicable to the areas of high data density.

One sample was obtained from a perched aquifer along the river in stretch 1. The fact that this sample is compositionally analogous to samples from the basin fill and floodplain alluvial aquifers suggests that the perched aquifer(s) in stretch 1 are recharged by ground water from the regional flow system. A probable source is the ground water which supplies the losing perennial baseflow in the upper
portion of stretch 1. The presence of "outlier" analyses from four wells completed in both the basin fill and Pantano (?) Formation are not easily explained. Although limestone beds are present in the Pantano (?) Formation, evaporite minerals have not been described in either aquifer. Furthermore, major ion ratios do not approach the ratios in gypsum or halite (as would be expected with simple dissolution of the evaporites). Contaminated wells or inaccurate data may explain the anomalous compositions.

Statistical analyses suggests that the variability of major ion concentrations is low. The magnitude of this variability is believed to reasonably represent the expected variation for a single ground-water facies in relatively uniform aquifer materials. Means of major ion concentrations measured along the river, however, are consistently higher than the regional means, and suggest a process of concentration or addition of major ions. The statistical analysis compares "sampling groups" which do not distinguish between areas north and south of the Babocomari River. Higher ion concentrations shown north of the river on the contour maps of TDS, sulfate, potassium, calcium, and magnesium (Figures 21, 24, 25, 27, and 28) are, therefore, missed by the statistical analysis. These higher concentrations however, are only supported by several data points and are not consistent
among all points north of the river. They occupy large areas of the plot due to lack of data north of the river. High major ion concentrations associated with the river are more pronounced under the statistical approach because the overall sample set is dominated by analyses taken in the vicinities of Sierra Vista and the two Fort Huachuca well fields, and these analyses show lower concentrations than the few analyses taken north of the river. Additional sampling is needed north of the river to determine if higher concentrations exist in that locale.

Sample densities are high enough along the river to state that increased concentrations are present relative to samples in the southeast quadrant of the map. The slightly higher concentrations are present on both sides of the river. Because the river is probably a ground-water "no-flow" boundary (refer to flow-net analysis) high concentrations cannot be attributed to the influx of potentially more concentrated ground-water from the north. Other processes must be considered to explain this trend. Concentration of dissolved constituents due to evapotranspiration is one possibility, however one would expect fairly uniform percent increases in the concentrations of major ions. Although increases are observed in all common ions, TDS, chloride, and sulfate appear to show the greatest percent increases. Because the concentration increases are of
the same order of magnitude as the range of variation, it is difficult to state the true degree of uniformity. Non-uniform increases suggest that other processes may be occurring simultaneously with concentration due to evapotranspiration. The relatively large increase in chloride may indicate some contamination from local septic systems. If so, this contamination is very low and not currently a serious threat to water quality. Nitrate concentrations in wells along the river were not high enough to conclusively suggest contamination, and the absence of nitrate in river water is probably related to plant uptake.

Analysis of delta D and $^{18}O$ values shows that mountain front samples are depleted in the heavier isotopes relative to samples taken towards the basin center. The coincident ranges of values for winter precipitation and mountain front groundwater illustrated both in the Babocomari watershed and the Dragoon Mountains may indicate that mountain-front recharge occurs predominantly during winter storms. Winter precipitation events are generally gentle and prolonged, and are therefore more amenable to infiltration in areas characterized by steep rocky slopes than the short intense rains associated with summer monsoons. The more enriched ground water encountered in downgradient portions of the Babocomari watershed may be due to a higher percentage of
recharge from summer precipitation as well as the effects of lower elevation. Water table mounding observed along the Babocomari River in the vicinity of Huachuca City indicates that recharge from streamflow does occur; and the gravelly, low gradient riverbed is more amenable to absorbing the rapid, short-lived summer runoff events than the mountain front tributaries. $^2$H and $^{18}$O values from the perched aquifer sample taken from stretch 1 are similar to those taken from the nearby regional flow system and suggest similar modes of recharge to both systems.
The hydrologic system in the lower Babocomari watershed is affected by three types of external sinks and sources: pumpage from wells, recharge from the Huachuca City sewage ponds, and evapotranspiration by riparian vegetation. This chapter will quantify their current magnitudes, and predicted future increases in pumpage. Production wells are associated with three major ground-water users in the vicinity of the Babocomari watershed: Sierra Vista, Fort Huachuca, and Huachuca City. Domestic wells are present along the river and throughout the watershed, however their effect on the ground-water system is believed to be minimal relative to the effects of production wells. Current rates of ground-water pumpage and sewage effluent disposal were obtained directly from the water users or from Putman et al. (1987). Estimation of the rate of riparian evapotranspiration along the Babocomari River was accomplished by application of the Blaney-Criddle equation to the results of a riparian vegetation survey performed by the author, and by a method suggested by White (1932) based on analysis of the diurnal water table recovery curve. The validity of these estimations is verified by a water-budget analysis. Estimation of the potential effects of continued pumping (at current and increased rates) is presented in
Chapter 8.

**Pumpage**

**Huachuca City**

Huachuca City currently pumps 333,000 m$^3$/yr (270 AF/yr) from the basin-fill aquifer (personal communication, McGriff, 1989). Pumping is managed so that the withdrawal is divided evenly among the three production wells (D-21-20 05CBA; D-21-20 05ABC; and D-21-20 08AA). Two of these wells are in southern Huachuca City within one kilometer of the Babocomari River, and the third is in northern Huachuca City approximately 2.7 km from the river. Pumpage is expected to double in the next ten years. Huachuca City's 1988 population was 2,450, and a population of about 5,000 is expected by the year 2000 (personal communication, McGriff, 1989). Per capita water consumption is assumed to remain constant over this period at 0.37 m$^3$/capita-day (98 gallons/capita-day).

**Fort Huachuca**

Fort Huachuca currently pumps approximately 4.046 mcm/yr (3,289 AF/yr) from its well fields on the main installation and the East Range (Putman et al., 1987). The main installation well field is in the vicinity of Sierra Vista approximately 6 km south of northern Huachuca City and 8.3 km south of the Babocomari River. The East Range well field
consists of two production wells located 2.3 km east and 3 km southeast of northern Huachuca City, and respectively, 4.8 and 6.2 km south of the Babocomari River (D-21-20 16ADA2 and D-21-20 22BBB). The east range wells currently provide about 23.2 percent of the Fort's annual pumpage (940,000 m$^3$/yr) and are active only during the months of April through the end of August (personal communication, Cochran, 1989).

Pumping from the main installation well field currently amounts to about 3.11 mcm/yr. Some of the main installation wells are beginning to lose efficiency, and a higher portion of future pumping could be assigned to the East Range well field (personal communication, Cochran 1989). Although only two wells are presently in use on the Fort Huachuca East Range, nine wells (of various specific capacities) were installed on the Range in 1971 and seven of these wells are sitting dormant. Predictions of population growth for the Fort have not been published, however recent U.S. Army reorganization has resulted in an approximate 10% increase in personal at the Fort (personal communication, Cochran, 1989). Additionally, the Fort has recently been designated as an Air National Guard training center, and will increase in population with the constant presence of trainees.
Sierra Vista

Sierra Vista is supplied by five water companies which own wells in its vicinity. Estimated 1985 pumpage is 4.405 mcm/yr (3,581 Af/yr) (Putman et al., 1987). The Sierra Vista wells are east of Fort Huachuca's main installation well field, however they are about the same distance (8.3 km) from the Babocomari River. Population is growing relatively fast in Sierra Vista. Putman et al. (1987) report a 1980 population of 24,937 and predict a population of 53,345 by the year 2000.

Recharge from Sewage Effluent

Recharge of municipal sewage effluent to the regional aquifer within the study area occurs only from the Huachuca City sewage ponds. Outside of the study area, Sierra Vista applies its sewage effluent to irrigation of alfalfa at rates less than the consumptive use of the crop (Schwartzman, 1987). Fort Huachuca uses its sewage effluent to irrigate recreational areas on the main installation. It is not known whether any of the Fort's effluent presently recharges the basin-fill aquifer, but significant effects of recharge are doubtful in this area due to a depth to ground water of about 50-100 m.

Huachuca City currently generates about 200,300 m$^3$/yr of raw sewage which is discharged into three holding ponds
located approximately 2 km northeast of the southern municipality (personal communication, McGriff, 1989). The ponds, two of which are unlined, have an open surface area of 86,500 m² (23 acres). Based on the published lake evaporation rate of 1.65 m/yr (Arizona State University, 1975), the ponds lose about 142,700 m³/yr to evaporation. The remainder of this effluent (57,600 m³/yr) is assumed to enter the ground-water system and recharge the underlying regional (and possibly perched) aquifer(s).

**Riparian Evapotranspiration**

A survey of the riparian vegetation along the Babocomari River was conducted in order to determine the areas, species compositions, and percent vegetative cover of land parcels defined by distinct and relatively uniform plant communities. The Blaney-Criddle equation was applied in order to estimate the amount of ground water consumed by riparian vegetation within each parcel and, ultimately, within the entire area considered. The survey was confined to the third stretch of the river (as shown in Figure 10) for two reasons. First, because the surface-water and ground-water systems in stretch 3 have been sufficiently defined so that an estimate of riparian evapotranspiration can be substantiated by a water-budget analysis of the area. Second, because stretches 1, 2, and 4 have no significant riparian vegetation and stretch 5
only has relatively small parcels of riparian vegetation located near the San Pedro River where ground-water data are unavailable. Ground-water consumption in stretch 5 has little effect on the rest of the study area because the stretch is hydrologically isolated by the Tertiary igneous body, a bedrock barrier to ground-water flow.

**Survey Results**

The survey commenced by delineating areas of significant riparian vegetation on areal photographs of the Babocomari River. Blueprints of transparencies of the area extending from Huachuca City to about 2 km west of the igneous body, photographed in 1987 and presented at a 1:2,000 scale, were supplied by the Cochise County Planning Department. Black and white prints of the area 4 km west of the igneous body extending to the San Pedro River, photographed in April of 1985 and presented at a 1:24,000 scale, were supplied by the Safford office of the U. S. Bureau of Land Management. Boundaries were drawn to enclose areas showing uniform vegetative appearance and plant density on mylar overlays. Species composition and area boundaries were confirmed and corrected during a field survey of riparian vegetation conducted in July of 1988. Species composition was designated as either 1) Cottonwood; 2) Cottonwood - Gooding Willow; 3) mesquite; or 4) riparian scrub. These general designations are
common to most riparian vegetative surveys (Gatewood et al., 1950; Anderson, 1976). Percent cover was estimated visually from the areal photographs, again a commonly accepted method (Gay, personal communication 1989). Areas of the delineated parcels were determined by weighing pieces of paper of equal map area, and converting from milligrams of paper to square meters of land area. A map of the delineated parcels and a table of their areas, species compositions, percent covers are presented in Plate 3.

Blaney-Criddle Analysis

The data obtained by the survey were employed to estimate riparian consumptive use by the Blaney-Criddle equation. Consumptive use is defined as the amount of water used on a given area in transpiration, building of plant tissues, and evaporation from adjacent soil (Putman et al., 1987). The Blaney-Criddle equation states that:

\[ U = KFAC \]

where:

- **U** = seasonal consumptive use in acre-feet
- **K** = empirical consumptive use coefficient for the growing season
- **F** = sum of monthly consumptive use factors for the period
- **A** = area of land parcel in acres
- **C** = percent cover of riparian vegetation
The K coefficient is empirically determined for a given species assemblage over the entire growing season. It is based solely on the physiology of the plant and can be broken down into a series of "k" factors which correspond to different life cycle stages. In this report, the seasonal K coefficients (weighted averages of "k" coefficients) were used because they have already been calculated by Putman et al. (1987) based on measurements made by Gatewood et al. (1950) along the Gila River at Safford. Because the K coefficient is independent of climatic influences, coefficients determined for the Safford area can be transferred to the upper San Pedro basin. The K coefficients determined by Putman et al. were: 1.131 for Cottonwood-Willow and 0.622 for Mesquite. The K coefficient for riparian scrub was estimated by the author as 0.271 based on information suggesting that the annual water use of riparian scrub is approximately 1/4 that of a Cottonwood-Willow community (Anderson, 1976).

Climatic influences are taken into account in the F factor. This factor is defined as the sum of the products of mean monthly temperatures and monthly percentages of daytime hours of the year (obtained from tables for any given latitude). Putman et al. (1987) have computed F factors based on temperature data from Tombstone and the Apache Powder Company near St. David. Respective values of 64.8 and 63.8
were obtained, and a mean value of 64.3 was used in this report to calculate consumptive use along the Babocomari River. Other climatic factors which affect consumptive use include wind velocity, relative humidity, and frequency of cloud cover, however these are not included in the Blaney-Criddle approach.

Depth to ground water is another major variable which has significant influence on potential evapotranspiration and is not considered in the Blaney-Criddle method of estimation. Locations in the study area which support riparian vegetation have depths to ground water ranging from approximately 1 m near the river to 5 m on the edge of the riparian corridor. Data compiled by Anderson (1976) indicate that consumptive use by mesquite varies greatly between 0.7 and 3 m and relatively little at depths to ground water greater than 3 m. Cottonwood and willow commonly occupy the most recent stream terrace in which ground water is extremely shallow. Mesquite communities are commonly located on the edge of the Cottonwood-Willow community where ground water is deeper (3 m or more). Plate 3 shows several mesquite communities close to the river, and failure to consider the effects of depth to ground water introduces some error into this analysis.

Table 4 lists the results of applying the Blaney-Criddle
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<td>19</td>
<td>64396</td>
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<td>70</td>
<td>45804</td>
<td>10993</td>
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</tr>
<tr>
<td>20</td>
<td>28689</td>
<td>MESQUITE</td>
<td>60</td>
<td>17491</td>
<td>4198</td>
<td>0.00162</td>
</tr>
<tr>
<td>21</td>
<td>63094</td>
<td>MESQUITE</td>
<td>35</td>
<td>22439</td>
<td>5385</td>
<td>0.00208</td>
</tr>
<tr>
<td>22</td>
<td>67538</td>
<td>MESQUITE</td>
<td>30</td>
<td>20598</td>
<td>4944</td>
<td>0.00191</td>
</tr>
<tr>
<td>23</td>
<td>52223</td>
<td>MESQUITE</td>
<td>65</td>
<td>34493</td>
<td>8278</td>
<td>0.00319</td>
</tr>
<tr>
<td>24</td>
<td>60243</td>
<td>C/W</td>
<td>30</td>
<td>33393</td>
<td>8014</td>
<td>0.00309</td>
</tr>
<tr>
<td>MEADOW</td>
<td>177148</td>
<td>RIPAR. SCRUB</td>
<td>100</td>
<td>98106</td>
<td>23545</td>
<td>0.00908</td>
</tr>
</tbody>
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**TOTAL:** 1981499

<table>
<thead>
<tr>
<th></th>
<th>SEASONAL (CUBIC M)</th>
<th>JUNE (CUBIC M)</th>
<th>JUNE (CUBIC M/SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1537676</td>
<td>369042</td>
<td>0.14238</td>
</tr>
</tbody>
</table>

**NOTE - C/W = COTTONWOOD/WILLOW**
equation to the data presented in Plate 3. Seasonal evapotranspiration was computed for each parcel based on its area, species composition, percent cover and the K and F coefficients mentioned above. A total area of 1.981 sq km of riparian vegetation is estimated to consume about 1.54 mcm (1,250 AF) of water per year. Anderson (1976) showed that most of this consumption occurs during the months of April through October, and this growing period is confirmed by the continuous well hydrographs presented in Chapter 5. Consumptive use during the month of June was estimated based on data compiled by Anderson (1976) which indicate that mesquite and cottonwood-willow communities consume about 25 percent of their annual water intake during this month. Consumptive use for the month of June was converted into m$^3$/sec to facilitate the water-budget analysis presented below. The water-budget analysis was performed in order to confirm the general accuracy of the above estimate based on measured hydrologic phenomena.

**Diurnal Recovery Analysis**

Rates of riparian evapotranspiration were estimated by a method suggested by White (1932) in order to verify the Blaney-Criddle results. White's analysis relates the slope of the recovery portion of the diurnal water-table fluctuation to the mean daily rate of ground-water discharge per unit area,
and thus to the mean daily rate of evapotranspiration per unit area. The diurnal recovery rate is normalized to the net daily change in water-table elevation in order to compensate for change in aquifer storage. The relationship is represented by the equation:

\[ R_{ET} = S_y (24h + s) \]

where:

- \( R_{ET} \) = daily evapotranspiration per unit area (m/d)
- \( S_y \) = specific yield (dimensionless)
- \( h \) = hourly diurnal water-table recovery (m/hr)
- \( s \) = daily change in water table elevation (m/d)

This equation was applied to the continuous hydrographs of observation well D-20-20 23DC (Figures 13A-C) to calculate representative rates of evapotranspiration for weekly periods throughout the growing season. A specific yield value of 0.15 was believed to represent a reasonable value for the floodplain alluvial deposits, however well logs and aquifer tests were not available to substantiate this estimate. Water-table elevation data were missing for several weeks both during and at the end of the growing season (past mid-September). For each week with available data, daily slopes of the diurnal water-table recovery and the net water-table decline were measured and representative values were selected. Representative rates of riparian evapotranspiration per unit
area were calculated in the manner described above, and were multiplied by the estimated area of riparian vegetation (1,981,500 m³) to calculate volumetric rates of evapotranspiration. Volumetric rates of evapotranspiration were estimated for weeks without water-table data based on calculated rates from neighboring weeks. Rates for weekly periods in the middle of the growing season were estimated from surrounding trends. Rates for weekly periods at the end of the growing season were estimated based on the assumption that evaporation declines almost linearly to zero between September 15 and October 15.

Table 5 presents the rates of riparian evapotranspiration estimated with the diurnal recovery method. The seasonal volume of riparian evapotranspiration was estimated to be about 2.14 mcm (1,730 AF) based on addition of the weekly volumes. The evapotranspiration rate for the month of June was obtained by averaging the four weekly values. Comparison of the results of the diurnal recovery method and the Blaney-Criddle method are included in the "interpretation" section.

Water-Budget Analysis

Water budgets can be used to obtain estimates of unknown components of a hydrologic system provided that enough background information is known. For example, the baseflow
### TABLE 5

**ESTIMATION OF EVAPOTRANSPIRATION BY DIURNAL RECOVERY METHOD**

<table>
<thead>
<tr>
<th>Week</th>
<th>Diurnal Recovery (m/d)</th>
<th>Net Change (m/d)</th>
<th>Evapot. Volume of Evapot. (m³/s)</th>
<th>Volume of Evapot. (m³/week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/1-7</td>
<td>0.027</td>
<td>0.002</td>
<td>0.030</td>
<td>0.0996</td>
</tr>
<tr>
<td>5/8-14</td>
<td>0.040</td>
<td>0.003</td>
<td>0.045</td>
<td>0.1479</td>
</tr>
<tr>
<td>5/15-21</td>
<td>0.055</td>
<td>0.004</td>
<td>0.062</td>
<td>0.2035</td>
</tr>
<tr>
<td>5/22-28</td>
<td>0.067</td>
<td>0.008</td>
<td>0.078</td>
<td>0.2570</td>
</tr>
<tr>
<td>5/29-6/4</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>6/5-11</td>
<td>0.061</td>
<td>0.010</td>
<td>0.075</td>
<td>0.2444</td>
</tr>
<tr>
<td>6/12-18</td>
<td>0.061</td>
<td>0.012</td>
<td>0.076</td>
<td>0.2496</td>
</tr>
<tr>
<td>6/19-25</td>
<td>0.049</td>
<td>0.006</td>
<td>0.058</td>
<td>0.1888</td>
</tr>
<tr>
<td>6/26-7/2</td>
<td>0.037</td>
<td>0.009</td>
<td>0.048</td>
<td>0.1573</td>
</tr>
<tr>
<td>7/3-9</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>7/10-16</td>
<td>0.030</td>
<td>0.013</td>
<td>0.046</td>
<td>0.1500</td>
</tr>
<tr>
<td>7/17-23</td>
<td>0.021</td>
<td>0.006</td>
<td>0.029</td>
<td>0.0944</td>
</tr>
<tr>
<td>7/24-30</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>7/31-8/6</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>8/7-13</td>
<td>0.030</td>
<td>0.010</td>
<td>0.042</td>
<td>0.1385</td>
</tr>
<tr>
<td>8/14-20</td>
<td>0.037</td>
<td>0.009</td>
<td>0.047</td>
<td>0.1552</td>
</tr>
<tr>
<td>8/21-27</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>8/28-9/3</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>9/4-10</td>
<td>0.030</td>
<td>0.009</td>
<td>0.042</td>
<td>0.1364</td>
</tr>
<tr>
<td>9/11-17</td>
<td>0.030</td>
<td>0.010</td>
<td>0.043</td>
<td>0.1395</td>
</tr>
<tr>
<td>9/18-24</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>9/25-10/1</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>10/2-8</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>10/9-15</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SUM</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** ND = no data; * = interpolated or extrapolated value
method (Anderson, 1976; Gatewood et al., 1950) assumes that seasonal changes in river baseflow occurring during the growing season are entirely attributable to the effects of riparian evapotranspiration (i.e., all other ground-water sinks and sources remain constant). The analysis presented below follows similar assumptions, however it accounts for changes in ground-water storage by comparison of water budgets for March and June baseflow conditions. The comparison eliminates the need to estimate unknown components of the water budget which are believed to remain relatively constant throughout the year.

The seasonal water budgets were conducted for the floodplain alluvial aquifer along the river between gauging stations 1 and 6. This portion of stretch 3 was chosen due to the availability of river baseflow data. The hydrologic components considered include: 1) ground-water discharge from the floodplain alluvium to the river; 2) riparian evapotranspiration from the floodplain alluvium; 3) underflow in the floodplain alluvial deposits upgradient of gauging station 1; 4) underflow in the floodplain alluvial deposits downgradient of gauging station 6; 5) ground-water inflow to the floodplain alluvial deposits from the basin-fill aquifer; 6) ground-water pumping in the floodplain alluvial aquifer; and 7) change in ground-water storage in the floodplain alluvium.
alluvial aquifer. All components besides the June riparian evapotranspiration are either known, estimated, or cancel out due to constancy. Riparian evapotranspiration is believed to occur solely within the floodplain alluvial aquifer. Comparison of the March and June water budgets allows estimation of the June riparian evapotranspiration. The results are presented in Table 6 and discussed below.

The ground-water discharge from the floodplain alluvial deposits to the river is calculated by adding the observed gain in river baseflow between gauges 1 and 6 to the open channel evaporation determined for the flowing portion of this river stretch. Rough estimates of open channel evaporation were obtained by multiplying the monthly percentages of annual evaporation for March and June by the annual lake evaporation rate and the length and width of the open channel. Monthly percents of annual pan evaporation were calculated from 1975 evaporation data from the University of Arizona Climatic Station (Number 1) at Tucson (National Climatic Data Center, 1976) and were assumed to correlate with monthly percentages in the upper San Pedro basin. Lake evaporation in the upper San Pedro basin is estimated to be 152-165 cm per year (Arizona State University, 1975). Approximate lengths of river stretches containing baseflow were 5 km in March and 3.5 km in June. The average channel width was approximated by field
### TABLE 6

**COMPARISON OF WATER BUDGETS FOR THE FLOODPLAIN ALLUVIAL AQUIFER DURING MARCH AND JUNE BASEFLOW CONDITIONS**

<table>
<thead>
<tr>
<th></th>
<th>March</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-water discharge to the River</td>
<td>-0.0768</td>
<td>-0.0101</td>
</tr>
<tr>
<td>Riparian Evapotranspiration</td>
<td>0</td>
<td>???</td>
</tr>
<tr>
<td>Entering Underflow at Gauging Station 1</td>
<td>N/C</td>
<td>N/C</td>
</tr>
<tr>
<td>Exiting Underflow at Gauging Station 6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ground Water Inflow from the Basin-fill aquifer</td>
<td>N/C</td>
<td>N/C</td>
</tr>
<tr>
<td>Ground Water Pumping in the Floodplain Aquifer</td>
<td>N/C</td>
<td>N/C</td>
</tr>
<tr>
<td>Total Change in Storage</td>
<td>0</td>
<td>-0.0206</td>
</tr>
</tbody>
</table>

**NOTE:** All values are in m³/sec; N/C means no change.
observation as 0.6 m in March and 0.5 m in June. The respective estimates of open channel evaporation were 0.0001 and 0.0002 m$^3$/sec - negligible values relative to the baseflow gains observed in the river.

Underflow in the floodplain alluvial aquifer at station 1 is believed not to change seasonally because ground-water elevation declines due to riparian evapotranspiration are assumed to be uniform along the river west of station 1, thus maintaining a constant water table gradient parallel to the river. Underflow at station 6 is zero because the alluvium pinches out on top of the igneous body at this location.

Ground-water inflow from the basin-fill aquifer to the floodplain alluvial aquifer is assumed to remain constant, although slightly greater inflow may occur in the early summer months due to increased gradients towards the river. Convergent ground-water flow occurs at an angle to the river, therefore declines in the water table along the river would lead to steeper gradients.

The effects of ground-water pumping close to the river are assumed to be negligible due to the low rates of consumption common to rural housing densities. The seasonal change in pumped ground-water consumption is also assumed to
be negligible because gardens and evaporative coolers do not seem to play a large role in summer ground-water consumption.

Change in ground-water storage occurred along the river during the summer months, and this ground-water disappearance must be accounted for. The rate of change in storage was estimated by assuming that the June water table decline of 0.213 m observed in monitoring well D-20-20 23DC (see Figure 13B) was uniform over the entire area considered. The total volume of storage change was calculated by multiplying the sum of the areas of delineated parcels along the river between stations 1 and 6 (1,667,850 m² - the total vegetated area minus the areas of parcels 1, 2, 3, and one third of parcel four) by the total ground water decline observed in well D-20-20 23DC during June (0.213 m) and a specific yield of 0.15. The total June change in storage was estimated as 53,300 m³ (0.0206 m³/sec). Several sources of potential error are present in this estimation of change in storage. Well D-20-20 23DC is 50 m from the river in floodplain alluvial deposits inhabited by riparian scrub vegetation and young cottonwood and willow trees. Because this assemblage of vegetation consumes significantly less water than mature mesquite or cottonwood-willow communities, the observed water table decline may be somewhat smaller than in areas of different species composition. Another source of potential inaccuracy
lies in the fact that the area assumed to be affected by ground-water declines only includes those areas delineated as supporting significant riparian vegetation. Water-table declines in areas adjacent to the delineated portions are not accounted for. Finally, error may arise due to the selection of 0.15 as a representative specific yield. Applicable values of specific yield range from about 0.08 for silt to about 0.28 for medium sand (Todd, 1980). A conservative value was selected due to the shallow water table condition and the presence of a soil layer at the ground surface.

Riparian evapotranspiration between gauging stations 1 and 6 was estimated by balancing the two water budgets based on the fact that the sums of the components which do not change remain equal throughout the year. The water budgets are set up so that the sum of sinks and sources equals the change in storage. For the purpose of this analysis, the sum of the "non-changing" components was solved for in terms of all other sinks and sources and change in storage. By setting the totals of the "non-changing" components equal for the March and June water budgets, a value for (unknown) June evapotranspiration of about 0.088 m³/sec was obtained. This compares to the Blaney-Criddle June evapotranspiration estimate (for the same area) of about 0.121 m³/sec.
Interpretation

Estimated rates of riparian evapotranspiration are greatest by the diurnal recovery method and smallest by the water-budget method. Seasonal evapotranspiration was estimated as about 2,139,000 m$^3$ by the diurnal recovery method compared to only 1,538,000 m$^3$ by the Blaney-Criddle method. Seasonal evapotranspiration was not estimated by the water-budget method. June rates of evapotranspiration were estimated as 0.2100 m$^3$/sec by the diurnal recovery method and 0.1424 m$^3$/sec by the Blaney-Criddle method. The June value obtained by the water-budget method, after normalization to the total area of vegetation, was estimated as 0.1040 m$^3$/sec. Normalization was accomplished by multiplying the June value by the ratio of the total area of riparian vegetation to the area considered in the water-budget analysis.

The three methods of analysis appear to define a reasonable range for riparian evapotranspiration in the area considered. Although the diurnal recovery method yields a June value twice as large as the water-budget method, the variability is not excessively large considering the accuracy of the data and the assumptions employed. There are several sources of possible error inherent in the analyses. The Blaney-Criddle method provides only a rough estimate of evapotranspiration because the effects of climatic influences
are greatly simplified and the effects of depth to ground water are ignored. The diurnal recovery method may contain error due to an inaccurate estimate of specific yield, and the assumption that the water-table fluctuation observed in well D-20-20 23DC is representative of the entire vegetated area. Although well D-20-20 23DC is located in permeable floodplain alluvial deposits, the silty soil exposed at the surface may extend to the shallow water table below. High silt content would decrease the specific yield and therefore decrease the estimated evapotranspiration. Finally, the water-budget approach has several potential inaccuracies which may result in a low value for evapotranspiration. These include neglecting the change in gradient towards the river which may ensue from declining ground-water levels, and the problems associated with estimating change in storage (detailed above).
CHAPTER 8

EFFECTS OF PUMPING ON GROUND-WATER ELEVATIONS NEAR THE RIVER

Ground-water elevations in the vicinity of the lower Babocomari watershed are declining due to the effects of pumpage. Relatively high rates of decline have been observed around Sierra Vista and the Fort Huachuca main installation; moderate rates of decline are documented on the Fort Huachuca East Range; and low to moderate rates of decline are found in the vicinity of Huachuca City. Inevitable increases in pumping associated with growth and development will cause continued drawdowns in previously affected areas as well as water-table declines in more distant areas as cones of depression expand. This chapter examines the potential effects of continued pumping on the hydrologic system and riparian community associated with the Babocomari River. Potential water-table declines and effects on baseflow in the river will be examined. The calculations presented in this section provide a rough idea as to the order of magnitude of possible effects. Large data gaps prevent precise determination of drawdowns along the river, and estimations tend more towards "maximum" values. Calculations of the "degrees of responsibility" attributable to individual pumpers for future effects on the riparian system are also included. Although the calculations are based on several simplifying assumptions, they are
believed to give a realistic indication of the proportions of future effects caused by the major ground-water consumers of the basin.

The data necessary for a precise prediction of future effects of pumping do not exist at this time. Additional information about the spatial distribution of hydraulic conductivity, thickness, and storage coefficient of the regional aquifer are necessary for sufficient characterization of the ground-water flow system. Consideration of factors such as recharge from the river in the vicinity of Huachuca City, drain effects of the river in stretch 3, boundary effects of the igneous body blocking ground-water flow in stretch 4, and regional ground-water flow patterns is also necessary. These factors would best be represented in a numerical model of the flow system, however lack of data prevent the construction of such a model. The Theis (analytical) equation was therefore used to predict the effects of pumping.

Application of the Theis equation involves simplification of the hydrologic system by assuming that the regional aquifer is an isotropic homogeneous aquifer with an initially flat water table, infinite aerial extent, and no sinks or sources besides the pumping wells. Because the Theis equation considers transmissivity instead of hydraulic conductivity and
aquifer thickness, only horizontal flow is permitted to occur in the system and wells are assumed to penetrate the entire aquifer. The analysis makes use of the principle of superposition by assuming that future water-level declines due to pumping will be superimposed on the current water-table configuration.

Several sources of error are introduced into the analysis based on these simplifications. Ignoring the igneous body directly upgradient of riparian community in stretch 3 will result in underestimation of drawdowns because of missing impermeable boundary effects. Ignoring the present role of the river as a ground-water drain in stretch 3 fails to account for the fact that water-level declines adjacent to the river will cause ground-water discharge to the river to decrease and make more water available for pumping. Similarly, as water-levels decline near the river less water will be consumed by riparian vegetation and the drawdown effects of pumping will be mitigated. Furthermore, if water levels decline below the streambed, increased recharge will be induced into the ground-water system. The assumption that calculated future drawdowns can be superimposed upon the current water table configuration (ie that rates of ground-water discharge to the river, phreatophyte consumption, and recharge during runoff events will remain constant) leads to overestimation of projected
drawdowns near the river. Finally, ignoring regional ground-water flow will lead to an overestimation of drawdowns because it fails to account for a potential steady state achieved through interception of mountain-front recharge.

All these uncertainties cast doubt on the prospect of predicting precise water-table declines due to pumping along the river. However, if calculated water-level declines along the river are sufficiently large in the simplified system described above, their potential threat to the riparian system should be seriously considered. After all, the analysis overestimates drawdown along the river largely because it does not account for the decreased ground-water discharge to the river and phreatophyte consumption associated with the declining water table. Although the calculated drawdowns may be overestimated, resulting diminished baseflows are a reasonable prediction.

Regardless of the magnitude of the future effects ultimately observed, the proportions of these effects caused by individual water users are accurately predictable (based on several simplifying assumptions), and are equivalent to the water user's proportion of the total calculated drawdown along the river. Total drawdowns are attributable to the superposition of the water-table declines caused by individual
users. Calculation of the drawdowns caused by individual users is subject to the assumptions previously described. Furthermore, the analysis assumes that the relative proportions of pumping between individual water users will stay constant throughout the time period addressed. The accuracy of the calculations is, therefore, limited by neglecting the predictions of differential rates of future growth in population and ground-water consumption.

Drawdowns were calculated for four time periods (10, 25, 50, and 100 yrs) at two "points of interest" along the river. Point 1 is the farthest upstream parcel of riparian vegetation in stretch 3 and is located at D-20-20 27DAB. The riverbed is dry at this location. Point 2 is the farthest upstream river location in stretch 3 currently demonstrating perennial flow and is located at D-20-20 24BA. Drawdowns predicted at point 1 will be more accurate than those calculated at point 2 because the water table is already below the streambed at point 1 (i.e. ground-water discharge to the river does not occur). Predicted values of water table decline at point 1 are probably only slightly overestimated due to neglecting induced recharge and decreased riparian evapotranspiration, whereas predicted water-table declines at point 2 are likely to be more overestimated due to neglecting induced recharge, decreased riparian evapotranspiration, and decreased ground-
water discharge to the river.

Drawdowns at points 1 and 2 were predicted with the Theis equation, which states that:

\[ s = \frac{Q*W(u)}{(4*pi*T)} \]

where:

- \( s \) = drawdown (m)
- \( Q \) = pumping rate of well (m³/sec)
- \( W(u) \) = the well function of \( U \) (dimensionless)
- \( u = \frac{S*r^2}{4Tt} \) (dimensionless)
- \( S \) = storage coefficient of aquifer (dimensionless)
- \( T \) = transmissivity of aquifer (m²/sec)
- \( r \) = distance from well to point of interest (m)
- \( t \) = time since pumping began (sec)
- \( \pi = 3.1416 \) (constant)

Drawdowns from wells in the vicinities of Sierra Vista, the Fort Huachuca main installation, the Fort Huachuca East Range, and southern Huachuca City were calculated as if they each result from only one pumping well located in the middle of their respective well fields. The error incurred with this approach is negligible because the distance between the wells in any of these vicinities is much smaller than the distance to the point of interest (i.e., the distance to the point of interest is roughly equivalent for all real wells represented by the single imaginary well). The resulting "single well"
drawdowns at the points of interested were summed to obtain the predicted total drawdown. Three values of transmissivity were considered to represent the documented range of measured transmissivities: 0.004 m$^2$/sec was weighted towards the lower values determined for stretch 3 and the poorer producing wells on the East Range; 0.016 m$^2$/sec was weighted towards the higher values measured on the Fort Huachuca main installation and the Huachuca City production well near the Babocomari River; and 0.010 m$^2$/sec was taken as an intermediate value. Because values of storage coefficient have not been published for the upper San Pedro basin, a value of ten percent was employed and is believed to be a reasonable estimate of the specific yield of a southwestern basin fill aquifer. The pumping rates and distances to the points of interest were taken from Chapter 7 and measured directly from maps. Table 7 lists the pumping rates and distances considered, and Tables 8 and 9 show the predicted drawdowns at points 1 and 2.

A comparison of all the generated predicted drawdowns would be lengthy and exhaustive, therefore only the estimated 50 and 100 yr drawdowns are discussed in this analysis. Predicted 50 yr water-table declines at point 1 range from 2.4 to 3.5 m at present pumping rates and respective transmissivity values of 0.016 to 0.004 m$^2$/sec. Considering the fact that Huachuca City currently has a predicted doubling
<table>
<thead>
<tr>
<th>Location</th>
<th>Annual Pumping Rate (m$^3$/yr)</th>
<th>Distance to D-20-20 27DAB (Point 1)</th>
<th>Distance to D-20-20 24BA (Point 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Huachuca City (2 wells)</td>
<td>222,000</td>
<td>4,700 m</td>
<td>8,200 m</td>
</tr>
<tr>
<td>Northern Huachuca City (1 well)</td>
<td>111,000</td>
<td>6,300 m</td>
<td>9,900 m</td>
</tr>
<tr>
<td>Fort Huachuca East Range (2 wells)</td>
<td>940,000</td>
<td>7,200 m</td>
<td>10,200 m</td>
</tr>
<tr>
<td>Fort Huachuca Main Installation (&gt;5 wells)</td>
<td>3,110,000</td>
<td>11,700 m</td>
<td>14,700 m</td>
</tr>
<tr>
<td>Sierra Vista (&gt;5 wells)</td>
<td>4,405,000</td>
<td>11,700 m</td>
<td>14,400 m</td>
</tr>
</tbody>
</table>
TABLE 8
PROJECTED GROUND-WATER DECLINES DUE TO PUMPING
AT POINT 1 (D-20-20 27DAB)

<table>
<thead>
<tr>
<th>Southern Huachuca City</th>
<th>Northern Huachuca City</th>
<th>Fort H. East Range</th>
<th>Fort H. Main Install.</th>
<th>Sierra Vista</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T = 0.004</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 yr:</td>
<td>0.09</td>
<td>0.02</td>
<td>0.12</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>25 yr:</td>
<td>0.19</td>
<td>0.06</td>
<td>0.41</td>
<td>0.37</td>
<td>0.53</td>
</tr>
<tr>
<td>50 yr:</td>
<td>0.27</td>
<td>0.10</td>
<td>0.71</td>
<td>1.01</td>
<td>1.42</td>
</tr>
<tr>
<td>100 yr:</td>
<td>0.36</td>
<td>0.14</td>
<td>1.10</td>
<td>1.93</td>
<td>2.73</td>
</tr>
<tr>
<td><strong>T = 0.010</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 yr:</td>
<td>0.07</td>
<td>0.02</td>
<td>0.16</td>
<td>0.15</td>
<td>0.21</td>
</tr>
<tr>
<td>25 yr:</td>
<td>0.12</td>
<td>0.04</td>
<td>0.32</td>
<td>0.51</td>
<td>0.72</td>
</tr>
<tr>
<td>50 yr:</td>
<td>0.16</td>
<td>0.06</td>
<td>0.47</td>
<td>0.91</td>
<td>1.29</td>
</tr>
<tr>
<td>100 yr:</td>
<td>0.20</td>
<td>0.08</td>
<td>0.63</td>
<td>1.37</td>
<td>1.94</td>
</tr>
<tr>
<td><strong>T = 0.016</strong></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>10 yr:</td>
<td>0.06</td>
<td>0.02</td>
<td>0.15</td>
<td>0.19</td>
<td>0.27</td>
</tr>
<tr>
<td>25 yr:</td>
<td>0.09</td>
<td>0.04</td>
<td>0.27</td>
<td>0.48</td>
<td>0.68</td>
</tr>
<tr>
<td>50 yr:</td>
<td>0.11</td>
<td>0.05</td>
<td>0.36</td>
<td>0.76</td>
<td>1.08</td>
</tr>
<tr>
<td>100 yr:</td>
<td>0.14</td>
<td>0.06</td>
<td>0.46</td>
<td>1.06</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Note: All T (transmissivity) values are in m$^2$/sec.
All projected ground-water declines are in m.
Storage Coefficient was assumed to be 0.10.
### TABLE 9

**PROJECTED GROUND-WATER DECLINES DUE TO PUMPING**

**AT POINT 2 (D-20-20 24BA)**

<table>
<thead>
<tr>
<th></th>
<th>Southern Huachuca City</th>
<th>Northern Huachuca City</th>
<th>Fort H. East Range</th>
<th>Fort H. Main Install.</th>
<th>Sierra Vista</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T = 0.004</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 yr:</td>
<td>0.02</td>
<td>0.00</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
</tr>
<tr>
<td>25 yr:</td>
<td>0.07</td>
<td>0.02</td>
<td>0.18</td>
<td>0.14</td>
<td>0.23</td>
<td>0.64</td>
</tr>
<tr>
<td>50 yr:</td>
<td>0.14</td>
<td>0.05</td>
<td>0.40</td>
<td>0.55</td>
<td>0.83</td>
<td>1.97</td>
</tr>
<tr>
<td>100 yr:</td>
<td>0.22</td>
<td>0.09</td>
<td>0.71</td>
<td>1.29</td>
<td>1.90</td>
<td>4.21</td>
</tr>
<tr>
<td><strong>T = 0.010</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 yr:</td>
<td>0.03</td>
<td>0.01</td>
<td>0.07</td>
<td>0.06</td>
<td>0.09</td>
<td>0.26</td>
</tr>
<tr>
<td>25 yr:</td>
<td>0.07</td>
<td>0.02</td>
<td>0.20</td>
<td>0.30</td>
<td>0.45</td>
<td>1.04</td>
</tr>
<tr>
<td>50 yr:</td>
<td>0.10</td>
<td>0.04</td>
<td>0.33</td>
<td>0.64</td>
<td>0.93</td>
<td>2.04</td>
</tr>
<tr>
<td>100 yr:</td>
<td>0.13</td>
<td>0.06</td>
<td>0.47</td>
<td>1.06</td>
<td>1.54</td>
<td>3.26</td>
</tr>
<tr>
<td><strong>T = 0.016</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 yr:</td>
<td>0.03</td>
<td>0.01</td>
<td>0.03</td>
<td>0.10</td>
<td>0.15</td>
<td>0.32</td>
</tr>
<tr>
<td>25 yr:</td>
<td>0.05</td>
<td>0.02</td>
<td>0.18</td>
<td>0.32</td>
<td>0.48</td>
<td>1.37</td>
</tr>
<tr>
<td>50 yr:</td>
<td>0.08</td>
<td>0.03</td>
<td>0.27</td>
<td>0.57</td>
<td>0.83</td>
<td>1.78</td>
</tr>
<tr>
<td>100 yr:</td>
<td>0.10</td>
<td>0.04</td>
<td>0.36</td>
<td>0.86</td>
<td>1.25</td>
<td>2.61</td>
</tr>
</tbody>
</table>

Note: All T (transmissivity) values are in m²/sec. All projected ground-water declines are in m. Storage coefficient was assumed to be 0.10.
rate of 10 yrs and Sierra Vista has a predicted doubling rate of 20 yrs, it is probably safe to double these declines for the 50 yr period. Hundred-year water-level declines at point 1 are predicted to range from 3.2 to 6.3 m and can again be safely doubled.

All of these values of water-table declines are large enough to warrant serious concern for the health and stability of the riparian community. Cottonwood and willow trees thrive in areas with water tables 1 to 2 m below the land surface. Water-table declines to 3.3 m or more can seriously impact a cottonwood-willow community. Reduced leaf canopies are the initial effects as the trees begin to experience water stress, however destruction of the population is possible if the water table falls below the maximum rooting depth of about 3.3 m (personal communication, Groeneveld, 1989). This outcome is partly due to the rooting depth limitations of the trees and partly due to the very low water retention capacity of a gravelly streambed. Gravelly materials quickly lose their ability to conduct water with distance above the water table because of their narrow capillary fringe and the steep reduction in unsaturated hydraulic conductivity associated with reduction in soil moisture. Soil nutrients also become less available when the water table drops (most available nitrogen is found in the upper few feet of the soil). Decline
of cottonwood-willow populations, or even loss of their vitality, can make the riparian corridor accessible to invasion of foreign species such as salt cedar, as is already occurring in the lower reaches of the upper San Pedro River. Therefore, although the extent of predicted drawdowns may be exaggerated due to the inaccuracies described above, their general magnitudes are high enough to warrant serious consideration.

Predicted 50 yr ground-water declines at point 2 are smaller than those predicted at point 1 due to greater distance from the pumping wells. Values range from 1.8 to 2 m and likewise can be doubled due to increased ground-water withdrawals associated with population growth. Predicted 100 yr water-table declines range from 2.6 to 4.2 m at current pumping rates. Decreased ground-water discharge to the river and riparian evapotranspiration would reduce the magnitudes of the predicted drawdowns, as would induced recharge if the water table declines below the riverbed elevation. However, baseflow declines will occur as the ground-water gradient towards the river diminishes. It is beyond the scope of this analysis to predict the actual future magnitudes of effects on river baseflow.

Although the range of estimates of water table declines
presented in Tables 8 and 9 may be rough, imprecise, and somewhat high, the proportions of the actual total drawdown attributable to individual water users are still reasonable based on the assumptions previously discussed. Table 10 presents the ranges of the proportions of predicted drawdowns attributable to individual water users at the two points of interest for 10, 25, 50 and 100 yr pumping periods. These ranges were calculated from the predicted drawdowns presented in Tables 8 and 9 at the three transmissivity values already cited. Because drawdown is directly related to pumping rate (see Theis equation) changes in the relative proportions of pumping between water users will affect the relative proportions of the resulting drawdowns. The relative proportions of drawdowns also varies with the length of the pumping period considered. The percent of water-table declines observed along the river attributable to users closer to the points of interest declines with increasing time. At later times, the users farther from the points of interest gain in influence. Table 10 shows that after ten years of pumping all parties are about equally responsible for the effects upon the hydrologic system. However, after fifty years of pumping Sierra Vista and the Fort Huachuca main installation have the greatest responsibilities. This is due to the fact that Sierra Vista and the Fort Huachuca main installation well field pump much more ground-water than Huachuca City and the Fort
TABLE 10
RANGES OF PERCENT RESPONSIBILITY FOR BASEFLOW AND WATER-TABLE DECLINES ALONG THE BABOCOMARI RIVER

<table>
<thead>
<tr>
<th></th>
<th>Huachuca City</th>
<th>Fort H. East Range</th>
<th>Fort H. Main Install.</th>
<th>Sierra Vista</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-20-20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27DAB</td>
<td>10 yr:</td>
<td>12-34</td>
<td>22-38</td>
<td>13-28</td>
</tr>
<tr>
<td></td>
<td>25 yr:</td>
<td>9-16</td>
<td>17-26</td>
<td>24-31</td>
</tr>
<tr>
<td></td>
<td>50 yr:</td>
<td>8-11</td>
<td>15-20</td>
<td>29-32</td>
</tr>
<tr>
<td></td>
<td>100 yr:</td>
<td>6-8</td>
<td>14-18</td>
<td>31-33</td>
</tr>
<tr>
<td>D-20-20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24BA</td>
<td>10 yr:</td>
<td>12-29</td>
<td>9-43</td>
<td>14-31</td>
</tr>
<tr>
<td></td>
<td>25 yr:</td>
<td>5-14</td>
<td>13-28</td>
<td>22-30</td>
</tr>
<tr>
<td></td>
<td>50 yr:</td>
<td>6-10</td>
<td>15-20</td>
<td>28-32</td>
</tr>
<tr>
<td></td>
<td>100 yr:</td>
<td>5-7</td>
<td>14-17</td>
<td>31-33</td>
</tr>
</tbody>
</table>

Note: ranges of percent responsibility were calculated from the drawdowns and transmissivity values presented in Tables 8 & 9.

D-20-20 27DAB is at the farthest west plot of riparian vegetation in stretch 3 (see Plate 3).

D-20-20 24BA is at the farthest west occurrence of perennial flow in stretch 3 (see Plate 1).
Huachuca East Range well field, however it takes time for their cones of depression to expand enough to intercept the river. By the time their cones of depression intercept the river, the Huachuca City and the East Range cones of depression have begun to stabilize and their rates of drawdown along the river decrease.

After about 50 years Sierra Vista and Fort Huachuca share equal responsibilities for the effects of water-table declines along the Babocomari River, and the remaining (Huachuca City's) responsibility is relatively small (< 10%). If proportions of total pumpage change due to differential patterns of development and ground-water consumption, these percentages will be altered accordingly. For example, if Fort Huachuca assigns more of its pumping to the East Range well field, it will have a greater responsibility for the observed effects than Sierra Vista because more of its pumping will occur closer to the river. Although the Fort's total drawdown along the river would stabilize sooner, it would also be greater. Huachuca City's projected growth rate is currently twice Sierra Vista's. Because Huachuca City's rate of pumpage will probably increase at a faster rate than Sierra Vista's, its proportion of responsibility for effects along the river will probably be greater than those values listed in Table 10, especially at the later times.
Although the values generated by the above analyses may not be precise, their overall order of magnitude is high enough to warrant concern for the riparian resources in stretch 3 of the study area. Further analysis is clearly required, however more data must first be gathered concerning aquifer parameters, floodflows, and ground-water recharge from the river. Such information would allow numerical analysis by a computer model, reduce the degree of simplification relative to that permitted above, and allow consideration of additional factors known to affect the hydrologic system.
CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Perennial streamflows and riparian habitats along the Babocomari River are supported by discharge from the groundwater system, and make the river a valuable natural resource in the arid southwest. Within the study area the river can be divided into 5 stretches, each with a distinct flow regime. Stretch 1, in the far west portion of the study area, is a losing stretch which displays very low perennial discharge in its upper portion. Stretch 2, in the vicinity of Huachuca City, is characterized by a dry gravelly riverbed which sustains only intermittent flows. Stretch 3, located east if Huachuca City, maintains significant seasonal and perennial flow as well as an associated lush riparian habitat. In stretch 4 the river has cut through a body of Tertiary/Cretaceous igneous rock and formed a dramatic bedrock canyon. Discharge is perennial through the canyon. Finally, stretch 5, immediately upstream of the confluence with the San Pedro River, is a losing stretch which transmits outflow from the bedrock canyon towards the San Pedro River and supports moderate densities of riparian vegetation.

Because perennial and seasonal flow in Babocomari River
is supported by the ground-water system, an understanding of the major aquifers and ground-water flow patterns in the watershed is essential to evaluating the hydrologic stability of the riparian habitat. The basin fill comprises the regional aquifer and supports the majority of ground-water development. The floodplain alluvial deposits occur along the rivers and serve as high permeability local aquifers which connections the basin fill aquifer and the rivers. The Pantano (?) Formation underlies the basin fill aquifer, and is considered to have negligible hydrologic importance due to its relatively low permeability. Tertiary/Cretaceous igneous rocks are exposed across the regional ground-water flowpath, and due to their extremely low permeabilities serve as a local "ground-water dam".

Ground-water flow in the study area follows the regional flow pattern (west to east: from the mountains toward the San Pedro River) except where influenced by local sinks and sources such as the river, riparian vegetation, and wells. Flow patterns along the river are highly affected by surface-water/ground-water interaction. Rapid water table responses to runoff events recorded in an observation well adjacent to the river attest to the interconnection between surface-water and ground-water systems.
Ground-water flow patterns along stretch 1 are poorly documented due to lack of wells, but the coexistence of losing streamflow and underlying perched aquifer(s) suggests that ground-water recharge is occurring in that stretch. Likewise, perched aquifer(s) and mounding of the regional water table along stretch 2 shows that recharge is occurring from the overlying gravelly riverbed. Ground-water elevations in stretch 3 are just below the land surface and locally depressed along the river. Flow-net analysis and seasonal stream gauging shows that ground water is discharging to the river and supporting both seasonal and perennial baseflows. Stretch 4 supports negligible surface-water/ground-water interactions due to the impermeable nature of the igneous body. Stream gauging of stretch 5 shows that the river loses baseflow to the underlying unconsolidated sediments.

Riparian evapotranspiration seasonally affects flow patterns along the Babocomari River in stretch 3. Stream gauging of the river showed that baseflows are severely depleted in the pre-monsoon hot summer months in stretches 3 and 4, and the river completely dried up in stretch 5. Water table drops measured along stretch 3 in the pre-monsoon growing season show that reduced baseflows are due to interception of ground-water discharge towards the river by riparian vegetation. Blaney-Criddle and water-budget analyses
demonstrate that the rate of riparian evapotranspiration is consistent with the observed quantities of lost baseflow.

Pumpage has affected flow patterns in the vicinity of northern Huachuca City and the Fort Huachuca East Range. A minor cone of depression has formed in this area. Historic water-level declines have been moderate in the northern Huachuca City - East Range vicinity, ranging from 11 to 31 cm/yr (0.36 to 1.0 ft/yr). The moderate rate of decline observed in a northern Huachuca City production well is anomalous in relation to other nearby Huachuca City wells which show only low rates of decline, and may be due to local low permeability of the formation. Declines have been low (generally less than 9 cm/yr) in the vicinity of southern Huachuca City and in areas of negligible groundwater exploitation. The most rapid water-table declines are occurring outside the study area in the vicinities of Sierra Vista and the Fort Huachuca main installation (12 to 119 cm/yr).

Continued ground-water level declines have the potential of altering hydrologic conditions along the Babocomari River and adversely affecting the riparian community. Analytic calculations were performed over the documented range of aquifer transmissivities in order to estimate the effects of
pumping at present rates for 10, 25, 50 and 100 year periods on hydrologic conditions along the river. Five pumping centers were included: southern Huachuca City; northern Huachuca City; the Fort Huachuca East Range; Sierra Vista; and the Fort Huachuca main installation. The effects of each pumping center were compounded for two locations along the river: one which supports a riparian community but zero baseflow; and one which supports a riparian community and perennial baseflow. Predicted 50 yr drawdowns at the first location range from 2.4 to 3.5 m, and can probably be effectively doubled due to anticipated high rates of population (and therefore water consumption) growth. Such declines are large enough to make the water table inaccessible to the roots of cottonwoods and willows (the major species of the present riparian habitat). Predicted 50 yr drawdowns at the second location are estimated at 1.8 to 2.0 m at present pumping rates. Predicted watertable declines may be reduced and offset by the effects of decreased evapotranspiration, induced recharge, and (at location 2) decreased ground-water discharge to the river. Predicted 100 yr declines are even more significant, and the magnitudes of estimated declines for both pumping periods are sufficient to warrant serious concern.

In addition to prediction of the magnitudes of future drawdowns along the river, relative responsibilities of the
major ground-water consumers were estimated based on the present ratios of groundwater pumping rates. The results showed that although responsibilities are roughly evenly distributed after only 10 yrs of pumping, Fort Huachuca and Sierra Vista sustain most of the responsibility for effects incurred along the river after 50 yrs of pumping.

Predicted drawdowns and estimated responsibilities were derived based on simplifying assumptions about the hydrologic system which may limit their accuracy. Great care should be taken in employing these predicted effects without qualifying the associated assumptions.

Water quality in the vicinity of the lower Babocomari is good, although somewhat hard (rich in calcium and magnesium). Ground-water and river water composition is relatively uniform and representative of the calcium-bicarbonate facies. The lack of variation among the major constituents precludes precise chemical detection of isolated components of the hydrologic flow system. Major ion concentrations show slight increases along the river, especially in relation to concentrations measured south of the river near Sierra Vista and Fort Huachuca. It is difficult to conclude whether slightly higher concentrations along the river are due to evapotranspirative concentration or leaching of sewage disposal systems.
Regardless of the source, the very low increases in concentration are not cause for concern.

Recommendations

Accurate documentation and analysis of hydrologic conditions and pumpage in the vicinity of the Babocomari watershed are necessary for sound management of the hydrologic resource and protection of the riparian community. A monitoring program should be initiated in which ground-water elevations in wells are measured, pumpage records are maintained by major water users, and baseflows are gauged in the Babocomari and San Pedro Rivers.

Water levels in wells should be measured in pumping centers, along the river, and in intermediate areas. Inactive (not pumped) wells would be optimal for such monitoring, however actively pumped wells are much more common (and therefore likely) candidates. Measurements should be performed in active wells only after a sufficient period of recovery following pumping. If possible, wells along the river should be measured semi-annually: in the pre-monsoon summer season and in the post-monsoon late autumn. This seasonal range of water levels can be related to the health of the riparian community. Wells farther than several hundred yards from the riverbed should be measured annually, as there is presently
little evidence of seasonal water-level variations at such a distance. Optimally, private well owners, municipalities, and the military would participate and volunteer access to wells for monitoring.

Major water users in the vicinity of the lower Babocomari watershed should maintain a monthly record of volume of ground water pumped. Finally, the Babocomari River should be gauged during baseflow conditions in order to monitor changes in ground-water contribution to streamflow. Gauging should be performed during both winter and pre-monsoon summer baseflow conditions. Care should be taken in selecting gauging days which are not affected by recent rainfall, such as those several weeks after any rainfall event.

The data obtained by the above mentioned activities can be used to assess the current state of the hydrologic system, and to predict future changes based on past trends. The information included in this thesis, when supplemented with additional aquifer parameter and streamflow transmission-loss data, is sufficient to support a computer model of the hydrologic system capable of predicting the effects of continued pumping. Accurate and complete monitoring data, as described above, are necessary input for calibration of such a model.
Although the hydrologic system has been characterized in this thesis, significant data gaps remain. Eliminating these gaps would contribute to the accuracy of predictive hydrologic models. Ground-water elevations and flow patterns have been accurately delineated in areas of high well density, but are poorly defined in areas of low density. Hydrologically significant low-density areas exist on the Fort Huachuca East Range and directly east of the Huachuca City sewage ponds. Additional data would be helpful in these areas in order to evaluate water-table declines near to pumping centers and recharge-discharge relationships along the river, respectively. Several additional wells may be available for monitoring on the East Range, but none currently exist directly east of the Huachuca City sewage ponds.

Aquifer parameters are poorly defined in the study area. Additional aquifer tests are necessary to define the spatial distribution and the range of aquifer transmissivity and storage coefficient values. If possible, complete results of aquifer tests conducted on the Fort Huachuca East Range in the early 1970's should be obtained. In addition, water purveyors owning production wells, such as water companies in the vicinities of Whetstone and Sierra Vista, should be encouraged to participate in additional aquifer testing.
Finally, estimation of aquifer recharge from streambeds during runoff events is an essential component of the water budget, and must be estimated in order to predict the effects of continued pumping on hydrologic conditions along the river. Unfortunately, it is probably unfeasible to directly measure transmission losses during runoff events in the Babocomari River (and its tributaries) due to non-uniform channel geometries. Existing watershed runoff computer models should therefore be used to make such an estimation.
APPENDIX A
METHODS

I. Water-Table Elevations
A. Equipment
   1. Powers 300 ft. electric well sounder
   2. steel measuring tape (300 ft.)
   3. engineers pocket measuring tape (10 ft.)
   4. Nikon auto-zeroing level
   5. tripod and stadia rod
   6. American Paulin System altimeter model M-1
      (Ser. # NF1063)
   7. Wallace & Tiernan altimeter model FA-181
      (Ser. # L00785)
   8. U.S.G.S. topo-maps (7.5 minute quads)
   9. aerial photographs (orthophotoquads and personal collection).

B. Procedure
   1. Measure depth to water in well (from land surface).
      a. Obtain information concerning well construction,
         perched layers, and cascading water.
      b. Determine prior pumping history. Ensure ample
         time for recovery (at least twice as long as
         pumping period).
      c. Measure depth to water (from top of casing) with
         steel tape or electric well sounder.
      d. Measure the distance between top of well casing
         and land surface. Subtract from c.
   2. Determine location of well on map.
      a. In field: Mark approximate area on topo-map.
         Note any useful landmarks.
      b. In office: Either
         (i) Determine location on orthophotoquad and
             transfer directly to topo-map with light
             table. Or:
         (ii) Locate well on projections of color
              slides and use relative distances from
              apparent landmarks to determine location on
              topo-map.
   3. Determine elevation of well head.
      a. Where high accuracy is desired, survey wellhead
         elevations with level and stadia rod.
         (i) Begin survey at established U.S.G.S. or
             A.D.O.T. benchmark.
         (ii) Cover area of interest; visit wells;
             measure station foresites and backsights;
             calculate elevations of all stations.
         (iii) Close survey loop on initial or other
established benchmark to confirm accuracy of measurements and calculations.

b. Where good accuracy is desired, survey wellhead elevations with altimeters.
   (i) Begin survey at known U.S.G.S. or A.D.O.T. benchmark.
   (ii) Adjust Paulin altimeter so that its elevation matches the elevation displayed on W & T. Record "initial" elevation and time.
   (iii) Drive to wellhead(s). Place altimeters on ground. Record displayed station elevation(s) and time(s).
   (iv) Return to benchmark (total travel time less than twenty minutes). Record final elevations and time.
   (v) For each instrument:
       Compare initial and final benchmark altimeter elevations. Determine disparities, and calculate combined instrument and barometric drift rates (ft/min).
       Determine elevation differences between station(s) and benchmark.
       Adjust measured elevation differences to account for drift with the formula:
       \[ AD = MD - (ST)DR \]
       where:
       \( AD \) = adjusted elevation difference between benchmark and station (ft)
       \( MD \) = measured elevation difference between benchmark and station (ft)
       \( ST \) = travel time from benchmark to station (min)
       \( DR \) = drift rate (ft/min)
   (vi) For each station:
       Average the \( AD \) values for the two altimeters. Add averaged \( AD \) value(s) to the true benchmark elevation to determine station elevation(s).

c. Where moderate accuracy is desired, read approximate wellhead elevations directly off topo-map.

C. Perceived Accuracy
1. Wellhead elevations surveyed with level and rod:
   a. All loops closed within 0.5 ft. of the true benchmark elevations. Therefore, accuracy is +/- 0.5 ft.
2. Wellhead elevations surveyed with altimeters:
   a. Five wellheads surveyed with altimeters were checked with level and rod. Altimeter elevations
were within three feet of elevations surveyed with level and rod.
b. For the majority of station elevations, drift disparities between altimeters were less than five feet.
c. Occasionally the two altimeters would drift radically and at different rates. This was believed to be due to instrument malfunction, and measurements were repeated. Altimeter elevations with instrument disparities approaching ten (in one instance twenty) feet were used when distinct topo-map elevations were impossible to obtain.
d. Accuracy for altimeter elevations is believed to be ± 5 ft.

3. Wellhead elevations estimated from topo-maps:
   a. Believed accuracy is +/- 10 ft.

II. Streamflow Gauging

A. Equipment
   1. Pygmy current meter
   2. digital stopwatch
   3. yardstick
   4. graph paper
   5. planimeter

B. Procedure
   1. Choose gauging station.
      a. Locate stretch of stream where banks are roughly parallel, flow is uniform, channel geometry is simple, and stage is greater than six inches.
      b. Mark station location on topo-map.
   2. Determine cross-section of stream channel.
      a. Between banks, record stage of stream at regular intervals (every three to six inches).
      b. Draw cross-section of stream channel on graph paper.
   3. Measure current velocity at regular intervals across the stream (every three to six inches). For each interval location:
      a. Submerge current meter to a depth of six-tenths the stream stage.
      b. Count the number of cup revolutions during a reasonable time period (30-60 seconds). Repeat several times to ensure reproducibility.
      a. Divide cross-section of stream channel into vertical sections based on location of current
velocity measurements. Section boundaries are chosen to provide equal section widths, accept where streambed geometry and current velocities suggest otherwise.
b. Measure area of each vertical section with planimeter. Determine section discharge by multiplying current velocity by area.
c. Add all vertical section discharges together to determine total stream discharge at gauging station.

C. Perceived Accuracy
1. Reproducibility of current meter measurements was excellent.
2. Most stations had fairly simple channel geometry.
3. Perceived accuracy is +/- 30% (standard accuracy of Pygmy Current Meters).

III. Sample Collection

NOTE: Two separate sampling rounds were performed by the author, each employing different equipment and methods. The first round was performed in fall, 1987 with U.S.G.S. equipment. Analyses from this round are identified in Appendix B under the source code PNS-GS. The second round of sampling was performed in early summer, 1988 with University of Arizona equipment. Analyses from this round are identified under the source code PNS.

A. Equipment (PNS-USGS round)
1. USGS pH meter and buffers
2. thermometer
3. 250 ml plastic and 50 ml glass sample bottles
4. buret, ring stand, beaker, volumetric pipette, agitator, sulfuric acid (titrant)
5. nitric acid (preservative)
6. wash basin

B. Equipment (PNS round)
1. VWR model 2000 pH meter and buffers
2. mercury thermometer
3. YSI conductivity meter
4. dissolved oxygen meter
5. Nalgene filtering apparatus, hand vacuum pump, 0.47 micron filters
6. Hach digital titration assembly for alkalinity (with titrant and indicator pillows)
7. 250 ml plastic sample bottles
8. nitric acid (preservative)
9. wash basin, beaker

C. Procedure (PNS-USGS round)
1. Determine pumping history and construction specifications of well (not necessary for river sample).
2. Pump well in order to flush the system and obtain a representative sample (not necessary for river sample).
   a. Most wells were domestic, and as such were used throughout the day.
   b. Pumping period, in addition to domestic use, was usually around thirty minutes.
3. Equilibrate temperatures of buffers and sample by immersing buffer containers in wash basin in which sample water flows continuously (well discharge is taken from outlet closest to the pump).
4. Measure temperature of sample water.
5. Calibrate pH meter with buffers, collect beaker full of sample water and measure pH.
6. Perform alkalinity titration.
   a. Collect 50 ml well water in volumetric pipette and place in beaker.
   b. Fill buret with sulfuric acid.
   c. Titrate sample water to pH 4.5
7. Collect samples in clean sample bottles.
   a. Rinse bottles several times with sample water. Fill completely with sample water and cap.
   b. Add several drops of nitric acid to cation samples in order to prevent adsorption of ions.
   c. Store samples in cold, dark environment to prevent microbial consumption of nitrogen.

D. Procedures (PNS round)
1. same as steps 1-5 above
2. Measure conductivity of water (in beaker) directly with conductivity meter.
   a. Meter was calibrated in the lab. Conductivity was used only to provide a rough index of TDS.
3. Measure dissolved oxygen content of water with D.O. meter.
4. Filter sample water (as needed) to:
5. Perform alkalinity titration with Hach digital titrator.
   a. Measure 100 ml of sample. Place in ehrlmeyer flask. Add one pillow of indicator.
   b. Titrate with sulfuric acid in digital titrator until indicator turns pinkish gray.
6. Fill sample bottles.
   a. same as above (step 7) except use filtered water
E. Perceived Accuracy

1. Accuracy of temperature and pH measurements are equivalent to the accuracies of the instruments. The instruments used are considered to have high accuracy by 1980 standards.

2. Accuracy of alkalinity titrations performed in the field was good for the PNS-USGS round and fair for the PNS round. Field-determined alkalinites were reproducible and concurred with those measured in the lab by ± 5%. During the PNS round, field-measured alkalinites were reproducible but were consistently about 15% less than the lab-measured alkalinites. I believe that the HACH digital titrator (or the titrant) was inaccurate, and therefore used the lab values in my major ion analyses.

IV. Sample Analysis

NOTE: The compilation of water analyses presented in Appendix B come from a variety of sources. Analyses bearing the source code "PNS" were analyzed by the author. All others were analyzed by federal and state agencies at their respective labs. The U.S.G.S. and the A.D.W.R. use the federal lab in Denver, Colorado. Analyses from this lab are reported with a 2% cation-anion balance.

A. Equipment

1. Instrumentation Laboratory Inc IL951 Atomic Absorption Unit
2. Spectra Physics SP8750 High Pressure Liquid Chromatograph; SP4100 integrator; Dianex AG4A Anion Column
3. Beckmen model 71 pH meter
4. buret, beaker, graduated cylinder
5. sulfuric acid

B. Procedure

1. Titrate samples to determine laboratory alkalinity
   a. measure 100 ml of sample and place in beaker
   b. titrate sample down to pH 5.5; continue dropwise while recording titrant volume until inflection point is established
2. Run samples on ion chromatograph to determine anion concentrations
   a. calibrate IC with solutions of known concentrations
   b. run samples through machine, calibrating after each round of 7 samples.
3. Run samples on atomic absorption unit
   a. add buffers to samples to prevent ion
interference
b. inject samples to AA
c. read output directly

C. Perceived Accuracy - concentrations of major ions are accurate to within ± 5%.
APPENDIX B

RAW DATA
**Water Level Elevation Data in the Vicinity of the Lower Babocomari Watershed**

### Table B-1

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**Notes:**
- All land surface elevations were surveyed by level, except those marked by "^" (alimeter), "©" (read knowing level).
- Sources of well construction information: O - Owner; ADWR - Arizona Dept. of Water Resources.
- Identification numbers coded: R - River; B - Shallow Well; D - Deep Well; P - Published Data.

**Source of Well Construction Information:**
- O - Owner
- ADWR - Arizona Dept. of Water Resources
- USGS - United States Geological Survey
- AOGC - Arizona Oil and Gas Commission

**Legal Surface Depth to Water Table, Date of Well Construction, Land Source:**

### Table B-2

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**MEASUREMENT OF ISOTOPIC RATIOS (DEL NOTATION):**

\[ \text{DEL} = \left( \frac{R - R_{\text{STANDARD}}}{R_{\text{STANDARD}}} \right) \times 1000 \]

WHERE R = SAMPLE ISOTOPE RATIO (018/016; H2/H1)

RF = STANDARD ISOTOPE RATIO (018/016; H2/H1)

\( \text{SAMPLE SOURCE CODES: USGS - U.S. GEOLOGICAL SURVEY; ADWR - ARIZONA DEPARTMENT OF WATER RESOURCES; AWC - ARIZONA WATER COMMISSION; PRS - COLLECTED BY AUTHOR, ANALYZED BY USGS; HU - COLLECTED BY AUTHO; ANALYZED AT UNIVERSITY OF ARIZONA) \)

**NOTES:**

- FOR MEASUREMENTS A REPORT OF 0.003 WITH A 0.0035 STANDARD DEVIATION
- FOR MEASUREMENTS A REPORT OF 0.01 WITH A 0.01 STANDARD DEVIATION
- ALL ALKALINITY VALUES FOR FRY SAMPLES ARE BASED ON LABORATORY ANALYSES
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NOTE: "<" INDICATES THAT CONCENTRATION IS BELOW DETECTION LIMIT

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**WELL INFORMATION CODES:**
- USGS: U.S. GEOLOGICAL SURVEY
- ADWR: ARIZONA DEPT. OF WATER RESOURCES
- AMC: ARIZONA WATER COMMISSION
- O: OWNER
APPENDIX C

ADDITIONAL FIGURES
Figure C-2 Contour Map of Chloride Concentrations in the Vicinity of the Lower Babocomari Watershed with Outliers Included
Figure C-4  Contour Map of Calcium Concentrations in the Vicinity of the Lower Babocomari Watershed with Outliers Included
LIST OF REFERENCES


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PLATE 2. FLOW NET NEAR BEDROCK OBSTRUCTION