NAPA COUNTY BASELINE DATA REPORT

CHAPTER 15

SURFACE WATER HYDROLOGY

UPDATE CHRONOLOGY

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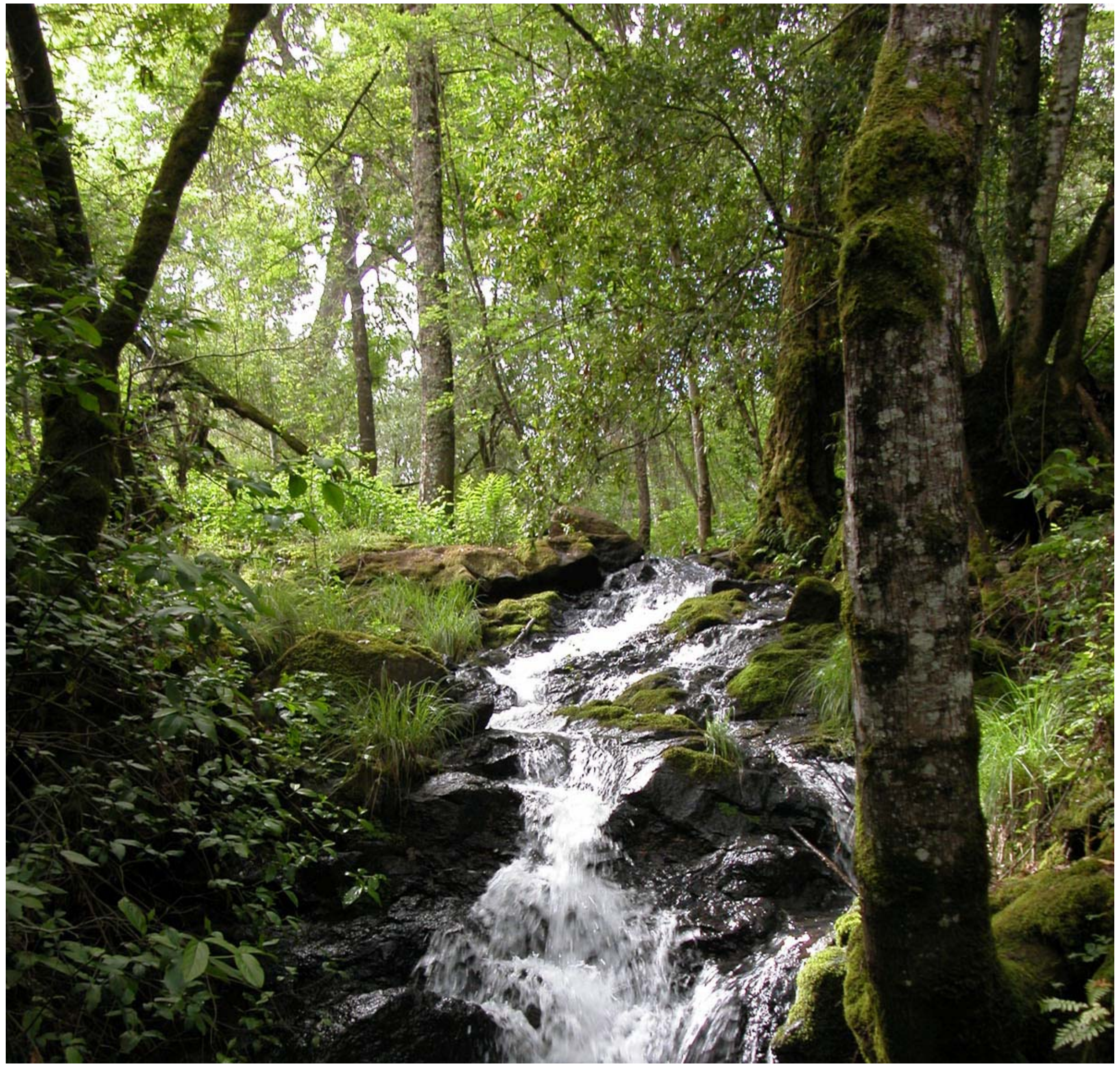

COUNTY STREAMS CONVEY RUNOFF, SUPPLY RECHARGE, AND PROVIDE HABITAT

PURPOSE

This chapter summarizes the basic hydrology of Napa County and documents the construction, calibration, and application of a regional integrated hydrology model. The surface hydrology analysis and model were designed to establish a baseline of existing conditions to support countywide programs.

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LIST OF ACRONYMS AND ABBREVIATIONS

afa	Acre-feet per acre
ac-ft	Acre-feet
asl	Above sea level
BDR	Napa County Baseline Data Report
CDEC	California Data Exchange Center
CDWR	California Department of Water Resources
cfs	Cubic feet per second
CGB	Carneros Groundwater Basin
CIMIS	California Irrigation Management Information System
cms	Cubic meters per second
DEM	Digital elevation model
DSOD	Department of Water Resources, Division of Safety of Dams
ET	Evapotranspriation
FCWCD	County Flood Control and Water Conservation District
FEMA	Federal Emergency Management Agency
FIRMs	Flood Insurance Rate Maps
lai	Leaf area index
MTSGB	Milliken-Sarco-Tulucay Groundwater Basin
NAVD	North American Vertical Datum
NFIP	National Flood Insurance Program
NNVB	North Napa Valley Groundwater Basin
NRCS	Natural Resource Conservation Service
OL	OSverland flow
RCD	Napa County Resource Conservation District
SID	Solano Irrigation District
SWRCB	State Water Resources Control Board
SZ	Saturated zone
USBOR	U.S. Bureau of Reclamation
USGS	United States Geological Society
UZ	Unsaturated zone saturation
θ_{FC}	Field capacity
θ_{S}	Saturation
θ_{WP}	Wilting point

INTRODUCTION

This chapter of the Napa County Baseline Data Report (BDR) describes the existing surface hydrology conditions of Napa County (County). This chapter has two principal objectives: to summarize the basic hydrology of Napa County; and to document the construction, calibration, and application of a regional integrated surface water, groundwater, and surface water quality model developed for the Napa County BDR.

This chapter includes a general description of the components and characteristics of surface water hydrology of Napa County, as well as the methods used to determine existing hydrology and the policies that apply to hydrology in Napa County; documentation of model algorithms, methodology, and data used to construct and calibrate the model; and a presentation of representative results from the modeling analysis and discussion on how such results can be applied for planning purposes. In addition, there is a supporting technical report (Napa BDR Surface Hydrology Modeling Report), which contains a more complete discussion of the modeling process, including a comprehensive presentation of results, as well as a sensitivity analysis of the model results. Consulting hydrologists from DHI Water & Environment led the surface hydrology, groundwater, and water quality tasks of the BDR (Chapters 15, 16, and 17, respectively), working collaboratively with other specialists from the Jones & Stokes/EDAW project team.

PURPOSE

The surface hydrology analyses and model developed and conducted in support of the BDR were undertaken with the explicit purpose of applying this information and modeling analysis towards future planning considerations in Napa County. More specifically, the hydrology studies supporting the BDR were designed to establish *baseline* (existing) conditions by which countywide planning efforts and programs could be assessed and evaluated for their benefits, constraints, and environmental impacts. The model developed (as described below) is an analytical tool and data management system capable of evaluating the hydrologic outcomes of such landscape-scale planning processes. While the hydrology model was designed with regional countywide applications in mind, the model was also structured for future applications of more site-specific (or project-scale) analyses, although such project-scale analyses were not developed for this report.

SPECIALIZED TERMS USED

- *Boundary conditions*: The physical conditions at the boundaries of a system or model. Boundary condition values can be either at a single location, along a line, or distributed over a surface. For a transient model (occurring over time) a time series must be used to represent the model inputs through time.

- *Conceptual model*: A model that describes the general functional relationship among components of a system.

- *Evapotranspiration*: Vaporization of water through direct evaporation from wet surfaces plus the release of water vapor by vegetation.

- *Groundwater*: Subsurface water occupying the pores and voids of the saturated zone and moving under the force of gravity. In many instances, groundwater is an important source of well water for domestic and agricultural use.

- *Hydrologic Cycle*: A conceptual model of the Earth’s water system that explains the movement, storage, and distribution of water through the air (atmosphere), on the ground, and beneath the surface (lithosphere), and in oceans, rivers, lakes, glaciers, and other water bodies (hydrosphere). In the hydrologic cycle, water is found in gaseous, liquid, and solid states. Hydrology is the science of water in its motions through the hydrologic cycle.

- *Hydraulics*: The study or science of fluids in motion, including both water and air. For the purposes of most hydrology and engineering studies such as the BDR, hydraulics typically refers to the behavior of water in stream channels or other conveyance conduits (pipes, culverts, etc.) and the ability of water to perform mechanical work such as moving sediment.

- *Isohyetal*: A contour line on a map indicating a line of equal precipitation. Typically used to show lines of equal average annual precipitation, but can be used to map rainfall amounts of varying frequency, duration, or magnitude.

- *Mainstem*: The principal stream body in a watershed or basin. Mainstem is a relative term depending on the geographic scale involved and can represent varying features such as “the mainstem of the Napa River” or “the mainstem of the Sulpher Creek.”

- *Stream morphology*: The form or structure of a stream or river.

- *Surface water*: Water above the surface of the land, including surface runoff and water found in lakes, rivers, streams, and ponds.

- *Water Balance Approach (Thornthwaite-type)*: The partitioning, or accounting, of a region’s precipitation into either runoff or evapotranspiration. Thornthwaite (1948) pioneered the approach using climatic data and considering how potential and actual evapotranspiration differed according to available water and soil moisture conditions.

- *Unsaturated zone (Interflow zone)*: The unsaturated zone is the portion of the subsurface flow above the groundwater table. It often contains air as well as water in the pores. Its thickness can range from 0 feet, as when a lake or marsh is at the surface, to hundreds of feet, as is common in arid regions.

- *Watershed*: The specific land area that drains water into a river system or other body of water. Watersheds are defined at a point along a stream system and include all upstream areas that contribute flow to that point.

- *Thiessen Polygon approach*: Geometric approach to providing areal (or spatially) averaged precipitation amounts according to a distributed series of rain gauges across an area. Area precipitation is "weighted" according to the geometric representation of the surrounding gauges.

POLICY CONSIDERATIONS

The following federal, state, and local policies and agencies are pertinent to the management of surface hydrology, surface water supply, and flooding in Napa County.

FEDERAL POLICIES

REGULATIONS COVERING DEVELOPMENT ON FLOODPLAINS

FEDERAL FLOOD INSURANCE PROGRAM

Congress, alarmed by increasing costs of disaster relief, passed the National Flood Insurance Act of 1968 and the Flood Disaster Protection Act of 1973. The intent of these acts is to reduce the need for large publicly funded flood control structures and disaster relief by restricting development on floodplains.

The Federal Emergency Management Agency (FEMA) administers the National Flood Insurance Program (NFIP) to provide subsidized flood insurance to communities that comply with FEMA regulations limiting development on floodplains. FEMA issues Flood Insurance Rate Maps (FIRMs) for communities participating in the NFIP. FIRMs delineate flood hazard zones in the community.

EXECUTIVE ORDER 11988

Executive Order 11988 (*Floodplain Management*) addresses floodplain issues related to public safety, conservation, and economics. It generally requires federal agencies constructing, permitting, or funding a project in a floodplain to do the following.

- Avoid incompatible floodplain development.

- Be consistent with the standards and criteria of the NFIP.

- Restore and preserve natural and beneficial floodplain values.

U.S. BUREAU OF RECLAMATION

The U.S. Bureau of Reclamation (USBOR) built Monticello Dam on Putah Creek, which forms Lake Berryessa. The dam is now owned by USBOR and operated by the Solano Irrigation District, although USBOR is responsible for managing visitor services on the lake.

STATE REGULATIONS

SURFACE WATER RIGHTS

Surface water rights are administered through the State Water Resources Control Board (SWRCB). Two main types of water rights exist in California law: riparian and appropriative.

RIPARIAN RIGHTS

Riparian water rights are associated with property adjacent to a watercourse. Owners of such properties are allowed to use naturally flowing water from the watercourse (i.e., not including any artificial or augmented flows) for reasonable and beneficial uses. The riparian right only applies to use of water from the watercourse on the portion of the subject property that drains to the watercourse in question, and riparian water rights cannot be stored or transferred off of this portion of the property. Lands severed from a riparian parcel (e.g., land subdivision) do not continue to have riparian rights.

No permit is required from the SWRCB to establish or maintain a riparian water right; however, a Statement of Diversion is required to be reported to the SWRCB. This statement provides the water right holder with documented standing in disagreements regarding priorities and supply cutbacks during a shortage.

Riparian rights are generally senior to appropriative rights (discussed below), and unlike an appropriative right, are not lost (forfeited) by non-use. Riparian right holders do not have priorities with respect to one another, and each holder has a right to a reasonable share of the total riparian water available.

APPROPRIATIVE RIGHTS

Appropriative rights are water rights granted for diversions (and transfers) of water to non-riparian land (lands not adjacent to a watercourse) for reasonable and beneficial uses, including storage. Appropriative rights are subject to a seniority system, commonly referred to as "first in time, first in right," where the appropriative right holder with the longest standing right has first priority to water in a shortage. Appropriative water rights must be perfected (legitimized), and non-use results in loss of the appropriated right.

There are two types of appropriative rights: pre-1914 and post-1914 appropriative rights.

Executive Order 11988 (*Floodplain Management*) addresses floodplain issues related to public safety, conservation, and economics.

Riparian water rights are associated with property adjacent to a watercourse.

Pre-1914 Appropriative Rights. California's current permit system of appropriative water rights was established in 1914. Appropriative water rights established prior to 1914 are not subject to the permitting authority of the SWRCB, and hence do not need approvals from the SWRCB for transfers or changes in place or purpose of use. Changes in the point of diversion, however, remain subject to SWRCB approval.

Post-1914 Appropriative Rights. Since 1914, appropriative rights have been subject to the permitting authority of the state. Today, SWRCB issues and administers these permits, which specify the quantity, place, and purpose of use, as well as the point of diversion. SWRCB approval is required for any changes to the above, as well as for water transfers, and the agency may attach conditions to its permits and approvals to protect other water rights holders and public trust resources (e.g., fish and wildlife).

Dam safety in California is administered by the Department of Water Resources, Division of Safety of Dams (DSOD). DSOD reviews plans and specifications for the construction of new dams or for the enlargement, alteration, repair, or removal of existing dams, as well as performs inspections during dam construction and operation.

Dam Safety and Operation

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Local Policies

Napa County Conservation, Development and Planning Department

The Napa County Conservation, Development and Planning Department administers County Ordinance 1219 (as amended), which identifies development and land use standards for areas identified as domestic water supply watersheds. The ordinance is intended to protect the public health, safety, and community welfare, and otherwise preserve the natural resources of those watersheds. The regulations governed by the ordinance aim to ensure the continued long-term viability of County agricultural resources by protecting those lands from excessive soil loss, thereby preserving water quality and quantity and economic productivity of the County's domestic supply watersheds.

Napa County Department of Public Works

The Department of Public Works administers the County's Floodplain Management regulations, County Code Chapter 16.04. The purpose of those regulations is to reduce the potential for floods within the County and to minimize the potential for flood-related losses, both public and private, thereby promoting the public health and safety. In certain cases, the regulations require the issuance of permits for construction or land development undertaken within a floodplain of a stream or a river, which may specify specific standards. More information can be found on the County's website: http://www.co.napa.ca.us/GOV/Departments/DeptPage.asp?DID=17500&LID=638.

Napa County Flood Control and Water Conservation District

The County Flood Control and Water Conservation District (FCWCD) is a special district within the County. It is governed by a board of eleven elected officials: the five Napa County Supervisors; the Mayors of Napa, St. Helena, American Canyon, Yountville, and Calistoga; and one Napa City Council member. The FCWCD's mission is the conservation and management of flood and storm waters to protect life and property; the maintenance of the County watershed using the highest level of environmentally sound practices; and the provision of coordinated planning for water supply needs of the community.

The FCWCD is the lead agency on the Napa River Flood Protection Project along a section of the Napa River and Napa Creek. The flood project is designed to protect the community from 100-year flooding. To date, numerous improvements have been completed and many more are in process, including several new bridges and levees in the City of Napa, channel widening and floodplain creation, and tidal wetland reclamation. More information on the Napa River Flood Protection Project can be found on the project's website: http://www.napaflooddistric.org/.

Solano Irrigation District

The Solano Irrigation District (SID) owns and operates the Monticello Hydroelectric Power Plant at Lake Berryessa, and holds contracts with USBOR to most of the water in the reservoir. Dam/power plant operations and other diversions therefore guide reservoir levels and downstream flows, subject to permit requirements.

Other Local Reservoir Operators and Water Purveyors

There are several locally managed and operated reservoirs in Napa County. Those reservoirs and their managing entities are listed below.

- Lake Hennessey including Friesen Lakes and Milliken Reservoir, City of Napa.
- Friesen Lakes, Howell Mountain Water Company.
- Bell Canyon Reservoir, City of St. Helena.
- Rector Reservoir, Veterans Home of California, Plant Operations.
- Kimball Reservoir, City of Calistoga.
- Lake Curry and Lake Madigan, City of Vallejo.

METHODOLOGY

DEFINITION OF STUDY AREA

The study area for the analysis of surface hydrology is all of Napa County. The northwest-trending mountain ridges subdivide the County into three principal watersheds: Napa River watershed, Putah Creek/Lake Berryessa watershed, and Suisun Creek watershed. The study area and the three principal watersheds are shown in Map 15-1.

GENERAL APPROACH

The analysis conducted for this chapter of the surface water hydrology of Napa County followed a three-step approach.

- Step 1: Collect existing baseline information.
- Step 2: Analyze baseline information to develop conceptual model and hydrology overview.
- Step 3: Develop a numeric hydrology model.

As part of Step 1, an extensive literature review and data collection effort was conducted to provide a fundamental and scientifically valid background of hydrology in the County. Information sources included state and federal agency reports; publicly available data; academic research studies; professional engineering reports; and privately collected soils, climate, and water-use data from throughout the County. Individuals and agencies consulted for this analysis are listed in Chapter 19, *Report Preparation*, of the BDR.

Following (and sometimes concurrent with) Step 1, Step 2 began with the identification of the main features and driving forces of the natural hydrologic system. A conceptual model was then developed as part of Step 2 to describe hydrologic functioning and identify the significant hydrologic variables that would be required in the model.

These first two steps provided the foundation for Step 3, the development of a valid mathematical model. The numerical model selected to simulate the hydrologic cycle in Napa County was based on the MIKE SHE/MIKE11 code developed by DHI Water and Environment (2005 version). The MIKE SHE/MIKE11 code has the capability of simulating the major flow components of a hydrologic cycle, which makes the model well suited for simulating current and future water distribution in the County. A more complete description of the model's data requirements, computational algorithms, and outputs is provided below. (For more details, see http://www.dhisoftware.com/mikeshe/.)

EXISTING STUDIES AND DATA SOURCES

DHI reviewed hydrology, hydraulic, and water supply reports and studies prepared for Napa County. Only one of the reports reviewed (Napa County Flood Control and Water Conservation District 1991) appeared to provide a comprehensive overview of hydrology of the entire County. Based on this review, it appears that no existing hydrologic model comprehensively covers all of Napa County, although there are several local hydrology models that address conditions on smaller scales within the County.

The hydrology, hydraulic, groundwater, water quality, and water supply reports, documents, and memorandum reviewed in preparation of this document provided important information to develop a regional hydrology overview and modeling analysis. The following sections outline the significant hydrologic (rainfall and runoff prediction), hydraulic (in-channel and in-river flows), and water budget reports for characterizing the hydrology of Napa County.

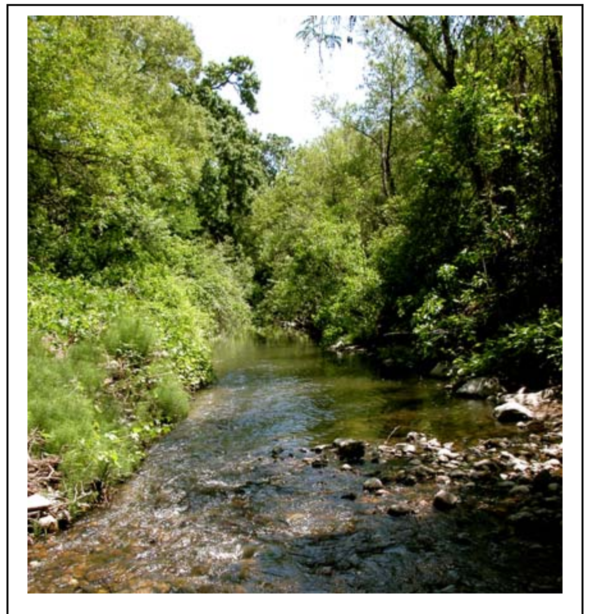
HYDROLOGIC STUDIES

Several water resource and water balance studies have been conducted for Napa County. The *Water Resource Study for the Napa County Region* (Napa County Flood Control and Water Conservation District 1991) examines the current and future water use needs for the County. The report used data collected from the General Plan, master water supply plans, water management plans, agricultural land use practices, historic water production and metered sales records, historic and projected population data, and land use maps and data, as well as consultation with various agency personnel. The report provides a comprehensive overview of the agricultural, domestic, commercial, municipal, and industrial uses of water, as well as the water sources that existed in the County during at the time the report was prepared.

Several local studies in the area have implemented aggregated conceptual rainfall/runoff models to predict timing and magnitude of flows into a river, stream, or other conveyance mechanism. These rainfall/runoff models have mostly been developed to support hydraulic models that examine flooding extent for flood studies and design purposes and geomorphic analysis. Because these studies are primarily concerned with large flow events, they contain little information on the total volume of precipitation, evaporation, and stream runoff. Examples of rainfall/runoff models that have been developed for the County include local studies for Garnett Creek, Hopper Creek, Huichica Creek, Napa Creek, Napa River, and Salvador Creek. DHI is unaware of any rainfall/runoff studies that exist for the Putah Creek/Lake Berryessa and Suisun Creek watersheds.

HYDRAULIC STUDIES

Whereas hydrology studies generally involve the surface components of the hydrologic cycle and typically focus on rainfall and runoff prediction, hydraulic studies involve the analysis of in-stream and



Hydraulic studies analyze the behavior of in-stream flows, including velocity and the ability to move sediment.

in-channel flows. Hydraulic information for Napa County was collected from various river channel and floodplain studies, flood control flow studies, flood management structural design studies, water quality studies involving channel flows, and channel restoration studies. For most of these hydraulic investigations, a series of one-dimension hydraulic models were developed to evaluate water surface elevations, basic hydraulic parameters such as water velocity and water surface slope, and water quality issues. Of the hydraulic studies reviewed for this report, the hydraulic model primarily used in Napa County is DHI's MIKE. This model incorporates topographic and channel geometry information along with stream and tidal gauge measurements and rainfall/runoff model results as boundary conditions.

In 1996, the mainstem Napa River was modeled from Kimball Reservoir to the outflow into San Francisco Bay to evaluate watershed-wide management decisions (Neary 1996). The model was updated by the Resource Conservation District (RCD) in 2001 to assist with the Lower River Plan (Zlomke et al. 2001). Since 1996, hydraulic models have been updated or developed for Garnett Creek (Zlomke et al. 1999), Hopper Creek (Zlomke et al. 1999), Huichica Creek (Zlomke et al. 1998, Jones and Zlomke 2001), Napa Creek (Zlomke et al. 1999), Napa River near Yountville (Jones and Zlomke 2001), and Salvador Creek (Jones and Zlomke 2004).

Channel restoration studies have been conducted for the Rutherford Reach of the Napa River (Phillip Williams and Associates [PWA] 2003). The PWA report summarizes channel geometry but does not include hydraulic modeling. DHI is not aware of any hydraulic or channel design studies that exist for the Putah Creek/Lake Berryessa and Suisun Creek watersheds.

WATER BUDGET STUDIES

A Thornthwaite-type water balance model providing an annual water budget was developed for Carneros Creek (Zlomke 2003). The model states that the annual precipitation and stream runoff in Carneros Creek is 710 mm (27.9 inches) and 371 mm (14.6 inches), respectively. Peak precipitation occurred in January, with low accumulations in July and August. Stream flows followed this trend, though low flow conditions occurred in September through November. Actual evapotranspiration (ET) followed potential ET from October through April, though ET tended to decrease through the summer months as the soil moisture decreased.

DATA COLLECTION

An extensive effort was made to collect spatial and temporal datasets to characterize components of the hydrologic cycle throughout Napa County. Examples of spatial data included topography, reservoir depth, and land use; examples of time series information included precipitation, evaporation, rooting depth, irrigation demand, and groundwater pumping.

An extensive effort was made to collect spatial and temporal datasets to characterize components of the hydrologic cycle throughout Napa County. Spatial data included topography, reservoir bathymetry (depth), land use, soil distribution, stream and precipitation gauge locations, and the stream network. Time series information included precipitation, evaporation, stream gauge, leaf area index, relative crop, rooting depth, irrigation demand, and groundwater pumping. These data and their use for the hydrology overview and modeling analysis are discussed below. The supporting technical report (*Napa BDR Surface Hydrology Modeling Report*) for this chapter includes a more complete description of these data, their sources, and their use in the modeling exercise.

OVERVIEW OF HYDROLOGY OF NAPA COUNTY

The hydrologic cycle represents the occurrence, movement, and distribution of water through the air (atmosphere), on the ground and beneath the surface (lithosphere), and in river, lakes, and other water bodies (hydrosphere). Water movement in the landscape can be understood by examining the movement within particular zones (or phases) of the hydrologic cycle. Precipitation, evapotranspiration, surface runoff, unsaturated zone flow, saturated zone flow (groundwater), streamflow, and anthropogenic water use are all components of the hydrologic cycle that can be evaluated, measured, and simulated. The schematic in Figure 15-1 depicts how water can move between these zones. The hydrology and modeling analysis discussed in this chapter considered each of these components to characterize the hydrology and water movement within Napa County.

A descriptive overview of the primary components of the hydrologic cycle for Napa County is presented below. Based on an understanding of these hydrologic components, a conceptual model can be established. A conceptual model is a simplified yet functioning model of the natural hydrologic system. The conceptual model includes the main features and driving forces of the natural hydrologic system and is suitable for implementation in a mathematical model. The following section provides a general background for the factors controlling the hydrologic cycle in the County. More specific information on geology and soils, climate, vegetation, and land uses can be found Chapters 1, 3, 4, and 9, respectively, of the BDR.

PHYSIOGRAPHIC AND REGIONAL SETTING

Napa County is located within the Coast Range physiographic province northeast of San Francisco. The County is bordered to the east by California's Central Valley and to the west by the Coast Ranges. The topography of Napa County consists of a series of parallel northwest-trending mountain ridges and intervening valleys of varying sizes (Map 15-2). These parallel northwest-trending mountain ridges subdivide the County into three principal watersheds: Napa River watershed, Putah Creek/Lake Berryessa watershed, and Suisun Creek watershed. The general geologic conditions of Napa County are shown in Map 15-3. For a more complete discussion of geologic conditions in Napa County, see Chapter 1, *Geologic Resources*, of the BDR.

NAPA RIVER WATERSHED

The Napa River watershed extends in a northwesterly direction roughly 45 miles from San Pablo Bay to the hills north of Calistoga, and includes primarily a central valley floor and eastern and western mountains to either side of the valley floor (Map 15-2). Valley floor elevations in the Napa Valley range from approximately 400 feet above sea level (asl) in the northern mountains to sea level at San Pablo Bay. The highest peak surrounding the valley is Mt. St. Helena at an elevation of 4,343 feet. The valley is bound to the west by the Mayacama Mountains ranging from 1,000 to 2,700 feet asl, to the north by Mt. St. Helena, and to the east by a northwest-trending range of mountains that are generally above 2,000 feet asl. The southern portion of the Napa Valley is very flat, and elevations range from near sea level to approximately 200 feet asl along the flanks.

Moving north, the width of the valley floor becomes progressively narrower, from around 5 miles wide in the south to about 1 mile wide in the northern Napa Valley. To the southwest of the valley lies the Carneros region, and to the southeast lies the American Canyon area. Located within the valley floor area are the City of Napa and the towns of Yountville, Oakville, Rutherford, St. Helena, and Calistoga.

The Napa River, the largest river in the Napa County, drains the watershed and empties into San Pablo Bay to the south. The lowest reaches of the Napa River and tributaries in the lower Napa Valley are tidally influenced due to the proximity to San Pablo Bay. Along the Napa River, the tidal influence is observed northward into the City of Napa.

In terms of water supply resources and infrastructure, approximately 1,000 natural and human-made surficial storage facilities are thought to exist in Napa Valley (Napolitano and Whyte 2005). (See also the fish section of Chapter 4, *Biological Resources*, of the BDR for information regarding surficial storage facilities.) Of these storage facilities, five were considered significant enough to be included in the regional study and modeling analysis: Kimball Reservoir, Bell Canyon Reservoir, Lake Hennessey, Rector Reservoir, and Milliken Reservoir. Their source, size, and operational purpose are presented in Table 15-1.

Table 15-1. Major Storage Facilities in Napa River Watershed

Storage Facility Name	Storage Capacity (acre-feet)	Primary Sources	Operation/Ownership	Safe Yield (acre-feet/yr)
Kimball Reservoir	335	Napa River	City of Calistoga	110
Bell Canyon Reservoir	2,050	Bell Creek	City of St. Helena	480
Lake Hennessey	31,000	Conn Creek, Sage Creek, Chiles Creek	City of Napa	5,000
Rector Reservoir	4,000	Rector Creek	State Dept of Vet Affairs	1,200
Milliken Reservoir	2,000	Milliken Creek	City of Napa	400

Source: Napa County Flood Control and Water Conservation District 1991.

PUTAH CREEK/LAKE BERRYESSA WATERSHED

East of the Napa River watershed is the Putah Creek watershed, which contains Lake Berryessa (Map 15-2). This region consists of several small valleys, including the Pope and Capell Valleys, surrounded by topography that is generally mountainous and steep. Elevations in the Lake Berryessa watershed are generally higher than in the Napa Valley. To the west of the Napa Valley, hills rise to an elevation of approximately 1,500 to 2,000 feet asl, forming a divide between the Napa Valley and the adjacent Putah Creek. Approximate elevation ranges for the smaller valleys are 575 to 700 feet asl for Pope Valley in the northwestern portion of the watershed, and 550 to 650 feet asl for Capell Valley just west of Lake Berryessa.

Putah Creek is the largest river in the Lake Berryessa basin. It originates in Lake County to the north, flows into Napa County and into Lake Berryessa, and flows out of the County at Lake Berryessa's outlet (Monticello Dam) along the eastern border where it eventually flows into the Sacramento River. Other notable tributaries in the drainage include Pope Creek, Chiles Creek, Capell Creek, and Eticuera Creek.

Lake Berryessa is the largest body of surface water in the County, with a storage capacity of 1.6 million acre-feet. It is controlled by Monticello Dam. Lake Berryessa spills at an elevation of 439.96 feet asl. Approximately 40 streams flow into Lake Berryessa, which has a total drainage area of 576 square miles (mi^{2}). The United States Bureau of Reclamation (USBOR) owns the dam, and the Solano Irrigation District operates it. The primary uses of the lake are as a water supply for the irrigation of agricultural lands and municipal and industrial users, power generation, and recreation.

SUISUN CREEK WATERSHED

The Suisun Creek watershed lies to the south of Lake Berryessa and the Putah Creek watershed, and contains Lake Curry and Wooden Valley (Map 15-2). Suisun Creek flows to the south and into Solano County, and only the upper portions of the watershed are located within Napa County. The valley elevations range from approximately 200 to 600 feet asl. To the north of the watershed, mountains rise to an elevation of approximately 2,000 to 2,500 feet asl, and to the east, mountains rise to an elevation of approximately 2,500 feet asl.

Lake Curry is a human-made reservoir created by the damming of Suisun Creek. Historically it has been a supply of water for municipal and industrial use in the City of Vallejo.

PRECIPITATION

Napa County has a Mediterranean climate, with distinct wet and dry seasons. Approximately 90% of the precipitation occurs between November and April, and precipitation varies significantly throughout the County, both in a north-south direction and with elevation (National Oceanic and Atmospheric Administration 2003, California Department of Water Resources 2005). Map 15–4 shows an isohyetal map of the County and values of average annual precipitation. Storms approach the County both from the west, rising over the Mayacama Mountains and moving into the Napa Valley and beyond, and from San Pablo and San Francisco Bay to the south, and moving northward up the valleys (Faye 1973).

Annual precipitation varies significantly from year to year, and deviations can be as high as 200% from the 85-yr average (Farrar and Metzger 2003). Figure 15-2 illustrates this by showing how annual precipitation at Carneros has varied between 1993 and 2002. In general, precipitation increases from

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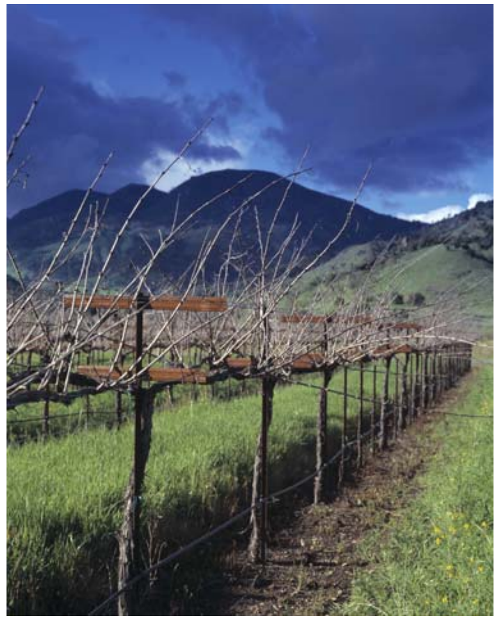


Napa County has a Mediterranean climate, with distinct wet and dry seasons. Approximately 90% of the precipitation occurs between November and April, and precipitation varies significantly throughout the County. Annual precipitation also varies significantly from year to year.

south to north and with increasing elevation, and average annual precipitation varies by more than a factor of three throughout the County, from 22.5 to 75 in/yr (California Spatial Information Library 1997). Precipitation is lowest in the southern portions of the County and in the vicinity of Lake Berryessa, at about 22.6 in/yr. Average annual precipitation in the City of Napa is on the order of 26.5 in/yr (California Department of Water Resources 2005). Average annual precipitation is highest in the higher portions of the Mayacama Mountains, the mountains north of Calistoga, and the mountains in the northern portion of the Lake Berryessa subarea (i.e., Knoxville area).

Snowfall is not uncommon at higher elevations. However, the vast majority of the precipitation occurs in the form of rain, and snow generally does not persist for more than a few days following a storm event except in the very highest areas (National Oceanic and Atmospheric Administration 2003, California Department of Water Resources 2005).

For the modeling effort, records were collected from 24 precipitation gauges at meteorological stations in and around the County (Table 15-2, Map 15-4). The data show agreement with the annual isohyetal contours. Map 15-4 shows the location of the gauges in relation to the isohyetal contours.

Table 15-2. Maximum Rate and Average Annual Precipitation Rate from Precipitation Gauges

Station	Source – Frequency	Period of Record	Max Rate (inches/hour)	Annual Precipitation (inches)
Angwin	CDEC – daily	1987–present	0.25	43.9
Oakville	CIMIS – daily	1989–present	0.18	37.5
Carneros	CIMIS – daily	1993–present	0.13	25.7
Atlas Peak	CDEC – daily	1987–present	0.25	43.9
Berryessa	CDEC – daily	1997–present	0.15	25.5
2216	Terra Spase – hourly	2000–present	0.53	25.7
2262	Terra Spase – hourly	2000–present	0.83	53.7
2390	Terra Spase – hourly	2000–present	0.91	62.3
2582	Terra Spase – hourly	2000–present	1.36	41.7
2851	Terra Spase – hourly	2000–present	1.09	41.3
4037	Terra Spase – hourly	2000–present	0.93	36.4
4236	Terra Spase – hourly	2000–present	0.86	34.8
5415	Terra Spase – hourly	2000–present	0.67	45.5
5438	Terra Spase – hourly	2000–present	0.8	33.0
5456	Terra Spase – hourly	2000–present	0.75	27.8
7897	Terra Spase – hourly	2000–present	0.85	39.0
8116	Terra Spase – hourly	2000–present	0.8	31.2
8180	Terra Spase – hourly	2000–present	1.19	23.6
8219	Terra Spase – hourly	2000–present	0.78	54.3
8223	Terra Spase – hourly	2000–present	0.8	31.9
9370	Terra Spase – hourly	2000–present	0.87	35.3
9373	Terra Spase – hourly	2000–present	0.68	42.0
9837	Terra Spase – hourly	2000–present	1.14	40.9
10162	Terra Spase – hourly	2000–present	0.8	43.2

Notes:

CDEC = California Data Exchange Center

CIMIS = California Irrigation Management Information System

Rainfall intensity generally follows the topography and isohyetal distribution (Figure 15-3) (Miller et al. 1973). The greatest rainfall intensity is in the mountains along the northern and western edges of Napa County. Greatest rainfall intensities are predicted at Mt. St. Helena. Ranges in rainfall intensity indicate that the maximum rates can be more that double the minimum rate for the 6-hour event, and almost three times the minimum rate for the 24-hour event (Table 15-3). For the 100-year 6-hour and 24-hour storm events, the maximum precipitation is predicted to be 5.0 and 14.0 inches, respectively (Miller et al. 1973).

Table 15-3. Rainfall Intensity Ranges for the 100-Year Storm

	Duration	
Return Period [year]	6 hour [inches]	24 hour [inches]
2	1.4–2.9	2.5–6.5
5	1.6–3.4	3.0–8.5
10	1.8–4.0	3.7–10.0
25	2.0–4.1	4.0–12.0
50	2.3–4.7	4.6–13.0
100	2.5–5.0	4.8–14.0

Note:

Values are in inches and were taken from rainfall intensity maps of California.

Source: Miller, 1973

STREAM NETWORK

STREAM MORPHOLOGY

In general, tributaries to major drainages form canyons in their steeper upstream reaches, where they flow over the more resistant bedrock of the mountainous areas. In terms of geomorphic form, County streams typically descend from steep headwater reaches (possibly through side valley canyons) onto alluvial fan surfaces, and then on to a valley floor setting (Map 15-5).

STREAM FLOW

Some of the upstream reaches of tributaries are intermittent, and others are perennial; downstream reaches, especially of the larger streams, are generally perennial (United States Geological Society 2005, California Department of Water Resources 2005). In some areas, mountain streams drain into alluvial fan deposits and are perennial in upstream reaches and intermittent in downstream reaches, because water tables fall below the level of the streambed during the dry season due to the contrasting permeabilities of mountain bedrock and adjacent unconsolidated alluvial fan deposits (Planert and Williams 1995).

Streamflows peak generally peak in January or February and are lowest from August through November (Figure 15-4). Average and maximum stream flows are scaled with drainage area. From the period of record (1999 to 2004), the peak flow events for the Napa River near St. Helena and near Napa are 10,200 and 12.200 cfs (Table 15-4) (U.S. Geological Survey 2005). Using the methods outlined in Bulletin 17b (Interagency Advisory Committee on Water Data 1981), these have a return frequency of 3 and 1.1 years, respectively.

Table 15-4. Stream Sources and Flow Records for Stream Gauges in Napa County

Stream Name	Source	Period of Record	Average (cfs)	Maximum (cfs)
Napa River at St. Helena	USGS	1929–2004	92	3,858
Napa River at Napa	USGS	1929– 2004	199	11,733
Tulucay Creek	USGS	11/2001–5/2002	15	250
Huichica Creek	Napa RCD	3/2000–8/2003	7	741
Carneros Creek	Napa RCD	12/2001–2/2004	9	1,426
Salvador Creek	Napa RCD	11/2003–2/2004	13	751
Lake Hennessey Inflow	City of Napa	1999–2004	11	1,050
Lake Hennessey Outflow	City of Napa	1999–2004	8	1,188
Lake Berryessa Inflow	CDWR	1994–2004	502	29,453

Notes:

cfs = cubic feet per second

USGS = United States Geological Society

Napa RCD = Napa Resource Conservation District

CDWR = California Department of Water Resources

EVAPOTRANSPIRATION

Evapotranspiration rates change throughout the year and are influenced by soil type, vegetation, and meteorological conditions. Sources of evapotranspiration include interception of rainfall by the canopy, evaporation from the canopy surface, evaporation from the soil surface, and uptake of water by plant roots and its transpiration.

Potential (or reference) evapotranspiration (ET) is the rate of ET from a reference surface with an unlimited amount of water. It depends only on climate, not on vegetation. The potential ET rates in the Napa River watershed vary throughout the year, with the highest rates occurring in the summer months and the lowest in the winter months. Figure 15-5 and Table 15-5 show the average monthly distribution of potential ET in the Napa River watershed.

Streamflows peak generally peak in January or February and are lowest from August through November.

Reach of the Napa River through Napa Valley.

Table 15-5. Potential Evapotranspiration Rates in Napa County

Month	ET rate (inches/month)
January	1.2
February	1.7
March	3.4
April	4.0
May	5.8
June	6.3
July	6.3
August	5.6
September	4.4
October	3.1
November	1.6
December	1.0

In the hydrologic cycle, vegetation influences the evapotranspiration, surface ponding, infiltration rate, and direct runoff of precipitation. Vegetation in Napa County varies significantly as a function of elevation, aspect, and land use.

VEGETATION

In the hydrologic cycle, vegetation influences the evapotranspiration, surface ponding, infiltration rate, and direct runoff of precipitation. Vegetation in Napa County varies significantly as a function of elevation, aspect, and land use. This section discusses non-agricultural vegetation in Napa County. Agricultural land is discussed below in the section *Land Use Influence on Regional-Scale Hydrology*, and a more detailed description of the vegetation in Napa County is found in Chapter 4, *Biological Resources*, of the BDR.

Evergreen and coniferous forest (e.g., pine, fir, redwood) can be found throughout Napa County, although predominantly in the mountains west and east of Napa Valley (Map 15-6). Coniferous forests are common along the slopes of the Mayacama Mountains, in the northwest-trending mountains in the northern Napa Valley watershed, and at the higher elevations in the mountains to the north of the Putah Creek watershed. Evergreen broadleaf woodlands are common at mid-range elevations along the western and eastern margins of the Napa River watershed, the mid-range elevations along the western slopes east of Lake Berryessa, and along the margins of the Pope, Capell, Wooden, and Suisun Valleys. Evergreen shrublands are dominant throughout the high and mid-range elevation areas of the Putah Creek and Suisun Creek watersheds. Although less common than in the Putah Creek watershed, evergreen shrublands also occur along the northern and eastern edges of the Napa River watershed over a wide range of elevations, and along the western edge of Napa Valley primarily at low- to mid-range elevations (Jones & Stokes 2004).

Deciduous forests (e.g., oak, eucalyptus), and to a lesser extent deciduous shrublands, occur along the riparian corridor major rivers and tributaries, including the Napa River and Putah Creek (Map 15-6). Deciduous forests are also common at mid-range elevations throughout the Putah Creek and Suisun Creek watersheds, in particular along the western slopes of the mountains rising to the east of Lake Berryessa and along the margins of the Pope, Capell, Wooden, and Suisun Valleys. Eucalyptus is not native and is relatively uncommon in the region; it occurs sporadically on the floor of the southern portion of the Napa Valley (Jones & Stokes 2004).

Grasslands (e.g., bunchgrass, upland annual grasslands, saltgrass) are scattered at low- to mid-range elevations throughout the County and are most common in the southern portion of Napa Valley, in Pope Valley, along the eastern shores of Lake Berryessa, in Wooden and Suisun Valleys, and in of the southern portion of the Napa Valley (Map 15-6) (Jones & Stokes 2004).

The type of land use or vegetation in a basin has a significant effect on the overland flow velocities, infiltration capacities, and evapotranspiration rates. Listed below are various ways in which land use and vegetation types influence these components of the hydrologic cycle.

- The ability of the canopy to intercept rainfall.
- The ability of the roots to transport water from the soil.
- The friction of the ground surface.
- Surface water detention.

These factors vary through time as the vegetation leaf cover and root depth change seasonally or as climate maintains the ground surface as wet or dry.

UNSATURATED ZONE (INTERFLOW ZONE)

Flow through the unsaturated zone is a function of precipitation rate, vegetation, soil properties, soil moisture content, and potential head (depth of ponding). Soils properties govern the infiltration rate, soil moisture content, and evapotranspiration rate components of the hydrologic cycle. Below is a description of the soils that occur in Napa County. See Chapter 1, *Geology and Soils*, of the BDR for a more in-depth discussion of Napa County soils.

SOILS

The Natural Resource Conservation Service (NRCS) classified the soils of Napa County into 11 major soil associations, based on landscape units with a distinct pattern of soil composition, relief, and drainage features (Lambert and Kashiwagi 1978) (Map 15-7). These 11 classified soil units are described below.

- Bressa-Dibble-Sobrante unit, which makes up about 29% of the County, consists of moderately sloping to very steep, well-drained loams, silt loams, and silty clay loams. It occurs on uplands to the east, north, and northwest of Lake Berryessa as well as near Wooden Valley and south of Browns Valley.

- Henneke-Montara unit, which makes up about 18% of the County, consists of moderately sloping to very steep, excessively drained and well-drained gravelly loams and clay loams. It occurs on uplands primarily in the northwestern portion of the Putah Creek/Lake Berryessa watershed near Pope Valley and the area west of Lake Berryessa.

- Maymen-Lodo-Felton unit, which makes up about 10% of the County, consists of steep to very steep, somewhat excessively drained and well-drained, gravelly loams and loams. It occurs on uplands near Zim Zim Creek and west of Spanish Flat around Lake Berryessa.

- Rock outcrop-Kidd-Hambright unit, which makes up about 9% of the County, consists of rock outcrop and gently sloping to very steep, well-drained very stony loams and loams. It occurs on uplands around Blue Ridge bordering Yolo County, in the Oat Hill-Palisade Ridge area in the northwestern portion of the County, and in the Soda Canyon-Atlas Peak area.

- Forward-Boomer-Felta unit, which makes up about 8% of the County, consists of gently sloping to very steep, well-drained loams, gravelly loams, and very gravelly loams. It occurs on the uplands along the northern portion of the western margin of the County.

- Forward-Aiken unit, which makes up about 5% of the County, consists of gently sloping to steep, well-drained gravelly loams and loams. It occurs on uplands in the Angwin area.

- Fagan-Millsholm unit, which makes up about 5% of the County, consists of moderately sloping to very steep, well-drained loams and clay loams. It occurs on uplands in the southeastern portion of the County.

- Bale-Cole-Yolo unit, which makes up about 6% of the County, consists of nearly level to gently sloping, well drained to somewhat poorly drained loams, silt loams, and clay loams. It occurs on floodplains, alluvial fans and terraces along the Napa River, Dry Creek, Conn Creek, and Napa Creek, and to a lesser extent on the flatlands around Carneros.

- Tehama unit, which makes up about 3% of the County, consists of nearly level to gently sloping, well-drained silt loams. It occurs on floodplains and alluvial fans primarily within Pope Valley and along the east side of Lake Berryessa.

- Reyes-Clear Lake unit, which makes up about 4% of the County, consists of nearly level, poorly drained silty clay loams and clays. It occurs on tidal flats, basins, and basin rims in the extreme southwestern portion of the County.

- Haire-Coombs unit, which makes up about 3% of the County, consists of nearly level to moderately steep, moderately well-drained and well drained gravelly loams, loams, and clay loams. It occurs on terraces to the north and south of the City of Napa.

SATURATED ZONE (GROUNDWATER)

The primary water-bearing units within Napa County are the unconsolidated and semiconsolidated surficial deposits and unwelded tuffaceous beds in the volcanic rocks. The water-bearing deposits are often lenticular in nature, and the deeper deposits are offset by faults resulting in a series of variously connected and isolated aquifers (Planert and Williams 1995). The major aquifers in the County are the north Napa Valley groundwater basin (NNVB) and the Milliken-Sarco-Tulucay groundwater basins (MTSGB). Smaller aquifers include the Carneros groundwater basin (CGB) and small basins within the Putah Creek watershed (Map 15-8). See also Chapter 16, *Groundwater Hydrology*, of the BDR.

NORTH NAPA VALLEY GROUNDWATER BASIN

The largest aquifer in the County is the NNVB, which extends from just north of the City of Napa up the valley floor to the northwestern end of the valley just north of the City of Calistoga. It covers an area of approximately 60 mi^2.

The majority of the valley floor is alluvium, consisting of poorly sorted lenticular stream deposits of sand and gravel interspersed with floodplain deposits of silts and clays. These deposits vary in thickness from over 300 feet at the southern end of the valley to less than 50 feet near Calistoga (United States Geological Society 1973). The alluvium also tends to be thickest near the center of the valley, and the Napa River and decreases in thickness towards the valley margins. Underlying the alluvium in most location are the Sonoma Volcanics, which are believed to be up to 2,000 feet thick. The tuffaceous member of the volcanics, located in the upper half of the deposits, yields moderate amounts of water, while the remaining rocks have relatively low permeabilities and serve as confining units. The Franciscan and Great Valley Complexes on the southern half of the west side of the valley also have low permeability and serve as confining units locally.

Groundwater flow in the NNVB during pre-development conditions was from the valley edges towards the valley axis and southward towards San Pablo Bay. These general flow patterns are obstructed locally by faults along the valley floor. Most of the groundwater occurs within the unconfined surficial deposits, and the storage capacity of these deposits is estimated at 190,000 acre-feet (ac-ft) (Napa County Flood Control and Water Conservation District 1991). Groundwater within the Sonoma Volcanics occurs under both confined and unconfined conditions. No estimate of the storage capacity of these units was found, although wells tapping these rocks generally yield water at much lower rates than from the overlying alluvium. A 1991 study by the Napa County Flood Control and Water Conservation District (NFCWC) estimated that the average annual recharge for the basin from deep percolation, surface tributary flow, and subsurface flow is approximately 26,800 ac-ft/year.

The Natural Resource Conservation Service (NRCS) classified the soils of Napa County into 11 major soil associations, based on landscape units with a distinct pattern of soil composition, relief, and drainage features.

In the year 2000, approximately 37,000 acres of agricultural lands were under irrigation in the Napa Valley floor.

MILLIKEN-SARCO-TULUCAY GROUNDWATER BASIN

The MSTB is located adjacent to the City of Napa along the eastern edge of the valley floor and covers approximately 15 square miles (Map 15-8). The area is distinct from the NNVB because of the high-yielding nature of the Sonoma Volcanics to the east of the Soda Creek fault. To the west of the fault, alluvium is the primary water-bearing material, and to the east of the fault, the volcanics are the primary water-bearing material. Similar to the NNVB, the tuffaceous deposits are the most permeable units of the Sonoma Volcanics. It is estimated that approximately 196,000 ac-ft of water are stored within these units at depths of between 10 and 500 feet below ground surface (Farrar and Metzger 2003). A high point in the impermeable bedrock underlying the tuffaceous rocks acts as a groundwater divide splitting the basin into a north basin containing Milliken and Sarco Creeks and a south basin containing Tulucay Creek. The aquifers are primarily under confined conditions, and average annual recharge is estimated at 5,400 ac-ft/year (Farrar and Metzger 2003).

CARNEROS GROUNDWATER BASIN

The CGB is located in the southwestern portion of Napa County, and very little hydrologic or hydrogeologic information is available for that region. The valley floor consists of Pleistocene terrace deposits and recent alluvium, as well as some Pleistocene Huichica Formation, a member of the Clear Lake Volcanics. The Huichica Formation consists of fluvial deposits of gravel, silt, sand, and clay with interbedded tuff, as well as reworked pumice from the underlying Sonoma Volcanics. The alluvium in this area is generally very thin, with much of its volume located above the saturated zone. Thus, the Huichica Formation is the primary water-bearing material in the basin, although lower well yields indicate that storage capacity is probably much lower than in the two previously described basins (Napa County Flood Control and Water Conservation District 1991).

OTHER GROUNDWATER BASINS

Two regions within the Putah Creek watershed are significant from a hydrogeologic standpoint: Pope Valley and Capell Valley. Pope Valley is located to the northwest of Lake Berryessa, and Capell Valley is located just west of Lake Berryessa in the southern most portion of the upper Putah Creek watershed. Very little hydrogeologic information was available for these areas. Within both of these basins, only the alluvium is considered to be a significant water-bearing unit. The lack of large streams within these basins prevented thick accumulation of alluvium from being deposited, and thus the groundwater storage capacity is fairly limited. In Pope Valley, the alluvium averages 25 to 30 feet thick, consists of silty clayey sands and gravel, and is estimated to contain approximately 7,000 ac-ft of water. Storage within the alluvium and to a lesser extent the fractured bedrock surrounding Capell Valley is even more limited than the above-discussed basins, and it is estimated to be approximately700 ac-ft (Napa County Flood Control and Water Conservation District 1991).

LAND USE INFLUENCE ON REGIONAL-SCALE HYDROLOGY

AGRICULTURAL

In the year 2000, approximately 37,000 acres of agricultural lands were under irrigation in the Napa Valley floor (West Yost & Associates 2005). This agriculture is almost entirely (98%) vineyards and the remaining lands are mostly pastures or orchards and other crops. In 2000, the water demand for wineries and other crops was approximately 1,300 and 32,000 ac-ft per acre (afa), respectively (West Yost & Associates 2005). The values of applied water are likely significantly higher at present due to a relatively rapid rate of land use change to vineyard production from other uses.

In 2001, 2,600 acres of agricultural lands were under irrigation in the Putah Creek and Suisun Creek watersheds. This agriculture is almost entirely (96%) vineyards and the remaining lands are pastures. The vineyards and pastures in the Putah Creek watershed received 3,100 and 500 ac-ft of applied water, respectively, in 2001. In the Suisun Creek watershed, 1,100 acres received irrigation, with 91% of these represented by vineyards and the remainder by other deciduous crops. The vineyards and other deciduous croplands received 1,300 and 400 ac-ft of applied water, respectively, in 2001 (California Department of Water Resources 2001). As in the Napa River watershed, the values of applied water are likely significantly higher at present due to a relatively rapid rate of land use change to vineyard production from other uses.

Water is applied to vineyards in the region for the following three major purposes.

- Irrigation – Vines are irrigated to supplement available precipitation. Most vineyard irrigation is supplied by drip and sprinkler irrigation. Because these methods are efficient and the preferred application of water is to “slightly starve the grapes of water,” they will be considered efficient in the model and therefore unlikely to induce excess runoff or seepage to the groundwater. Irrigation generally occurs from July to September (Graves pers. comm.).

- Frost prevention – During the winter months, temperature inversions can occur in the valleys, creating a freezing layer of air next to the ground. To prevent freezing of the fruit, the vines are sprinkled to create an ice crust on the outside (Napa County Flood Control and Water Conservation District 1991). This application is weather dependent and occurs from December through March.

- Heat prevention – Extreme heat during the summer months can dry grapes. To prevent this, sprinklers apply water to the grapes during periods of excess heat. The evaporating water cools the grapes and prevents them from drying. This application typically occurs from late July through September (Napa County Flood Control and Water Conservation District 1991).

DOMESTIC (RESIDENTIAL), COMMERCIAL, AND INDUSTRIAL LAND USES

Water demand in 2002 for the northern half of the Napa River watershed, including the areas surrounding the Cities of Calistoga, St. Helena, and Yountville, was approximately 840, 1,900, and 531 afa, respectively (West Yost & Associates 2005). Likewise, water demand in the southern half of the watershed, including areas surrounding the City of Napa, was approximately 16,000 afa in 2002 and is estimated to be 6,300 afa in American Canyon in 2003 (West Yost & Associates 2005). The majority (65%) of this demand is for residential use, with 16% for commercial use, 10% for large landscape use, and 9% for industrial use. For the urban component, the majority of the water (89%) is derived from surface water sources, with the remainder coming from groundwater (West Yost & Associates 2005). Much of the urban water from groundwater sources is abstracted at relatively shallow depths, such that these withdrawals likely influence river stages more than the regional groundwater elevations.

Water demand in the Lake Berryessa and Suisun Creek watersheds was on the order of 58,600 ac-ft/year in 1990 and is estimated at 67,800 ac-ft/yr for 2005 (Napa County Flood Control and Water Conservation District 1991). The majority (85%) of this demand is for residential use, with 8% for commercial use, 6% for large landscape use, and 1% for industrial use. For the urban component, the water is derived from groundwater and surface water sources in nearly equal proportions, with 53% coming from surface water and 47% from groundwater. In the Suisun Creek watershed, however, urban water comes almost entirely from surface water sources (<1% from groundwater) (Napa County Flood Control and Water Conservation District 1991). Much of the urban water from groundwater sources is abstracted at relatively shallow depths, such that these withdrawals likely influence river stages more than the regional groundwater elevations.

SURFACE WATER MODEL

The purpose of the surface water modeling phase of the Napa County BDR is to develop an analytical tool that enables the establishment of baseline surface water runoff characteristics for 189 subbasins within Napa County. One of the primary uses for the surface water model will be to assist in the updating of the General Plan by assessing different land use scenarios, and to provide a basis for evaluating environmental conditions and impacts on a program-/landscape-scale. In addition, the surface water model will provide a more complete mapping and understanding of the County's stream network than currently exists, by identifying how streamflow conditions relate to watershed functioning and characteristics.

The MIKE SHE (2005 version) integrated surface-groundwater model (2005 version) and the MIKE 11 hydraulic model (2005 version), developed by DHI Water and Environment, were selected to support the Napa County BDR surface water model. These two models are dynamically linked to allow a complete representation of the hydrologic system. The ability to link these two models provides a well-suited tool for simulating current and future water distribution/conveyance in Napa County and an evaluation instrument to describe how hydrologic conditions change with different land use conditions.

GENERAL MODELING APPROACH AND APPLICATION

The Napa County MIKE SHE surface hydrologic model was constructed as a part of the BDR to support a planned General Plan update. More specifically, the hydrology studies supporting the BDR were designed to establish baseline conditions by which countywide projects and programs could be assessed and evaluated for their benefits, constraints, and potential environmental impacts.

The key processes driving the hydrologic cycle in Napa County are rainfall, evapotranspiration, and surface runoff (Napa County Flood Control and Water Conservation District 1991). One of the main objectives of the BDR surface water model is to create output surface runoff hydrographs and water budget estimates at the subbasin level that can be used as a baseline on which to compare hydrologic outcomes of land use planning scenarios. The focus of the initial modeling effort was to build a comprehensive model that adequately represents the river/channel network and major surface water features throughout Napa County for the purpose of evaluating such land use planning scenarios. The model was also developed to allow the dynamic exchange of river flow with other components of the hydrologic cycle.

The river network, which consists of the main basin river and its tributaries, is modeled in MIKE 11, but can receive inflows from the MIKE SHE overland flow and saturated zone modules. The major surface water features include the major reservoirs, lakes, and wetland areas. These features can be represented in both MIKE SHE and MIKE 11. In MIKE 11, lakes and reservoirs are represented as storage components that are directly linked to the river network, and if necessary controlled by structures. In MIKE SHE, rivers, lakes, and wetlands occupy an area of the landscape that serves as storage and is also part of the hydrologic cycle.

Given that the model will be used as a land use based planning tool, an appropriate representation of the hydrologic components that are affected by land use changes is necessary. Changes in land use may have significant effects on the way water flows through the landscape and on its infiltration and evapotranspiration capacities. In order to accurately simulate these processes, the overland flow, unsaturated flow, and evapotranspiration are spatially distributed in the model and defined by the input data for topography, soil, and vegetation distributions. In addition, the irrigation module in MIKE SHE, as well as surface water and groundwater abstractions, were included in the model to represent the effects of agricultural and urban uses on the water budget/balance equation.

For the surface hydrology model, the simulation of groundwater flow in the saturated zone used an aggregate-parameter linear reservoir option (Figure 15-6). This option for simulating groundwater in the surface water model provides a simple way to add groundwater baseflow to the rivers at the lowest topographic areas within each subbasin modeled. Groundwater flow is controlled by the threshold depths and time constants defined for each interflow and baseflow reservoir.

In the more detailed groundwater analysis (described in Chapter 16, *Groundwater Resources*, of the BDR) the groundwater modeling process was more area-specific and used local groundwater basins with separate MSHE models with three-dimensional groundwater algorithms. Chapter 16 of the BDR


Aerial view of the City of Yountville.


Aerial view South of Napa City.

describes local geology, groundwater use, and application of the three-dimensional groundwater model in MIKE SHE for these basins.

Intended output from the Napa County MIKE SHE surface hydrologic model is monthly water budgets and streamflow for 189 subbasins. As stated above, this information can be displayed in spatial and graphical format for any component of the hydrologic cycle. Therefore, for the application of assessing different land use alternatives, specific changes to each of the input components of the model (as described above) can be displayed and reviewed throughout the simulation period.

Though this model can be run on any time step, it is currently constructed to provide monthly flow results. Due to the constraints of model structure, available data, scale of the model, and limited channel network, it is not an effective tool to determine the physical extent of flooding or local (site-specific) effects of a project. The model can be modified to address any of these questions by changing the model domain and adding data as required. For example, the current cross sections in the models are constructed from a digital elevation model (DEM) or from theoretical curves. If flooding is a concern along a stream, the user would need to change the domain range and grid size in the model, incorporate more detailed surveyed cross sections, include any structures into the channel network, and potentially import a higher resolution DEM (they currently use a 25-ft grid sized DEM for the topography). Once these changes are made, the model can be calibrated for stream roughness and used to predict flooding.

MIKE SHE/MIKE 11 MODEL ATTRIBUTES

The MIKE SHE code is a physically based distributed hydrologic model that simulates the major flow components of the hydrologic cycle, including overland flow, unsaturated flow, evapotranspiration, and saturated flow. Within each of these processes, MIKE SHE offers several different approaches ranging from simple, aggregated (or lumped), and conceptual approaches to advanced, distributed, and physically based approaches. Simple and advanced approaches may be combined, which enables the user to model the hydrological problem with the existing data and time constraints of the project. In addition, MIKE SHE is a modeling domain that is scalable, allowing later development of more detailed models for smaller area-specific issues with minimal adjustment to the data setup. This flexibility will allow the basic countywide hydrologic model (as developed for the BDR) to be adjusted and modified in time as more area-specific data or project needs require analysis.

The Napa County MIKE SHE/MIKE 11 model is a dynamic model that can be refined and expanded as new data becomes available and as new questions are identified. Because the model is currently setup for regional analysis of the Napa County hydrologic system, it can be used to help evaluate alternatives developed as part of the current updating of the Napa County General Plan. In this way, the model can also be used to support a countywide program-level environmental impact report to support the General Plan update, including evaluation of cumulative impacts. The baseline model can also be developed for more localized and site-specific environmental analyses of specific projects. In turn, the development of local information for site-specific projects can then be “returned” or input into the broader countywide model to also improve the accuracy of the regional model.

The model inputs are described individually below.

PRECIPITATION

Rainfall is entered either as constant values or time series and can be distributed in space using stations (for instance, Thiessen polygons) or as cell-by-cell values. Distributing precipitation by stations requires a time series for each station.

For the Napa County MIKE SHE surface hydrology model, rainfall was distributed by stations.

EVAPOTRANSPIRATION (MIKE SHE ET)

Evapotranspiration calculations use meteorological and vegetative data to predict the total evapotranspiration and net rainfall due to interception of rainfall by the canopy, drainage from the canopy to the soil surface, evaporation from the canopy surface, evaporation from the soil surface, and uptake of water by plant roots and its transpiration, based on soil moisture in the unsaturated root zone (DHI 2005). The primary ET model is based on empirically derived equations that follow the work of Kristensen and Jensen (1975).

An alternative modeling approach is to use the simplified ET model that is used in the Two-Layer UZ/ET model. The Two-Layer UZ/ET model divides the unsaturated zone into a root zone, from which ET can occur and a zone below the root zone, where ET does not occur (DHI 2005). The Two-Layer UZ/ET module is based on a formulation presented in Yan and Smith (1994). Its main purpose is to provide an estimate of the actual evapotranspiration and the amount of water that recharges the saturated zone.

For the Napa County MIKE SHE surface hydrology model, the primary ET model was used (Table 15-6).

Table 15-6. Attributes of Model Components

Model Component	Simulates	Flow Dimension	Governing Equation
MIKE SHE UZ and ET	Flow and water content of the unsaturated zone, ET, infiltration, and groundwater recharge	1-D	Simple mass balance approach based on average moisture conditions on root zone
MIKE SHE OL	Overland sheet flow, water depth, and depression storage	2-D	Saint-Venant equation (diffusion wave approximation)
MIKE SHE SZ	Saturated zone (groundwater) flows and water levels	2-D	Linear Reservoir equation
MIKE 11	Fully dynamic river and canal hydraulics (flow and water level)	1-D	Saint-Venant equation (Kinematic or fully dynamic wave approximation)

OVERLAND FLOW (MIKE SHE OL)

The overland-flow component of MIKE SHE includes a two-dimensional finite difference diffusive wave approach using the same two-dimensional mesh as the groundwater component. Overland flow interacts with the river, the unsaturated zone, and saturated groundwater zone.

For the Napa MIKE SHE surface hydrology model, the two-dimensional finite difference diffusive wave was used (Table 15-6).

UNSATURATED ZONE (MIKE SHE UZ)

The unsaturated zone is the link between surface water and groundwater. The unsaturated zone model in MIKE SHE is a vertical soil profile model that interacts with both the overland flow (through ponding from above) and the groundwater model below. The groundwater table is the lower boundary condition for the unsaturated zone. MIKE SHE offers three different approaches to simulate the unsaturated zone, including a simple two-layer root-zone mass balance approach, a gravity flow model, and a full Richards equation model. All three approaches require specification of certain soil properties. Additionally, another feedback exists whereby the unsaturated zone model interacts with MIKE SHE's evapotranspiration model, which calculates actual ET as a function of reference ET, soil moisture, and crop characteristics.

For the Napa MIKE SHE surface water model, the two-layer root-zone mass balance approach was used (Table 15-6).

SATURATED ZONE (MIKE SHE SZ)

The saturated zone (SZ) component of MIKE SHE calculates the saturated subsurface flow using either a fully three-dimensional flow or a simplified linear groundwater algorithm (DHI 2005). The former simulates groundwater flows in a heterogeneous aquifer with shifting conditions between unconfined and confined conditions.

The spatial and temporal variations of the dependent variable (the hydraulic head) is described mathematically by the three-dimensional Darcy equation and solved numerically by an iterative implicit finite difference technique. The SZ component interacts with the other components of MIKE SHE mainly by using the boundary flows from other components implicitly or explicitly as sources and sinks.

For the Napa MIKE SHE surface water model, the simplified linear groundwater algorithm was employed (Table 15-6).

MIKE 11 HYDRAULIC MODEL

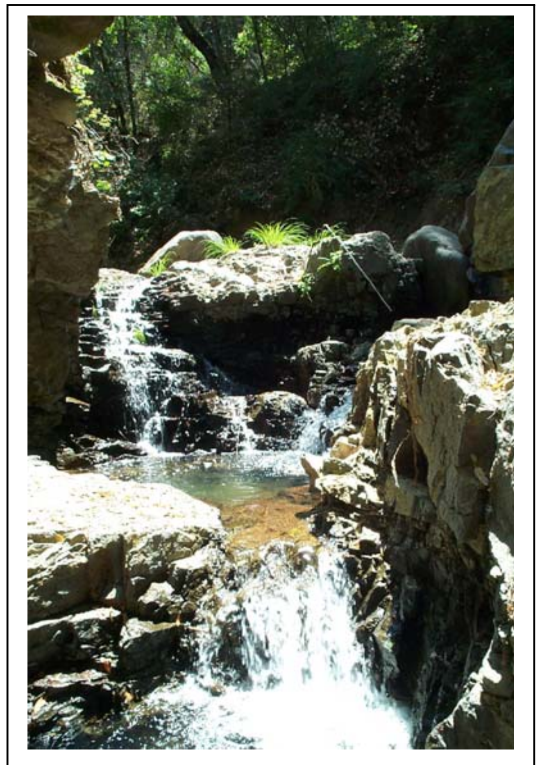
MIKE 11 is a dynamic one-dimensional hydraulic modeling tool used to analyze streamflows that can be integrated with the MIKE SHE surface/groundwater model to simulate the routing of runoff conditions (or groundwater return flows) through a stream network. A MIKE 11 model was developed and used in Napa County to analyze Napa River and tributary streamflows (Zlomke et al. 1999). MIKE 11 supports any level of complexity and offers simulation engines that cover the entire range from simple Muskingum routing to the Higher Order Dynamic Wave formulation of the Saint-Venant equations. In addition, MIKE 11 can simulate flow through control structures and other hydraulic features. MIKE 11 is approved by the Federal Emergency Management Agency (FEMA) for use on projects related to the National Flood Insurance Program. MIKE 11 can be used in combination with MIKE SHE (as conducted for the BDR) or as a stand-alone hydraulic modeling system (as used by the Napa County RCD).

For the Napa MIKE SHE surface water model, the simplified linear groundwater model was employed (Table 15-6).

TYPE AND FORMAT OF MODEL OUTPUT

Numerous types of results can be extracted from the MIKE SHE/MIKE 11 model. In MIKE 11, water levels and discharge plots of longitudinal water surface profiles along the river as well as time series graphs can be created and animated from different locations along the streams. In MIKE SHE, spatially distributed and time-varying results can be extracted for all of the components of the hydrologic cycle that were simulated, as well as water balance calculations. The following are specific components of the hydrologic cycle that can be displayed and animated in map view.

- Precipitation rate.
- Rooting depth.
- Leaf area index.
- Crop coefficient.
- Actual evapotranspiration.
- Actual transpiration.
- Actual evapotranspiraton from interception.
- Actual evapotranspiraton from ponded water.
- Canopy interception storage.



Overland flow interacts with the river, the unsaturated zone, and the saturated groundwater zone.

Attributes of agricultural crops influence the hydrologic cycle.

- Depth of overland flow.
- Overland flow in x-direction.
- Overland flow in y-direction.
- Water content in the root zone.
- Infiltration to the unsaturated zone.
- Exchange between unsaturated zone and saturated zone.
- Unsaturated zone deficit.
- Groundwater feedback to the unsaturated zone.
- Total irrigation.
- Irrigation from wells.
- Irrigation from external sources.
- Sprinkler irrigation.
- Dip and sheet irrigation.
- Stream flow.
- Water depth.

In addition, time series plots for any component can be created from any grid cell, and a water budget can be derived from any delineated area.

To standardize and clarify the results for individual subbasins analyzed in Napa County model(s), DHI developed a dedicated post-processor tool in the form of an HTML file to extract results for each of the 189 subbasins modeled. Information on this summary report for each subbasin includes the following: subbasin name; minimum, average, and maximum elevation; soil and vegetation distributions; stream names and lengths; water budget statistics (zone quantities); and monthly flow statistics for each basin outlet. The result is written to an HTML sheet that can be hotlinked in ArcGIS so that a user can click on a subbasin and review the surface hydrologic results. The dedicated results of the post-processor will expedite the analysis of current and planning scenario results. The hydrologic summary includes monthly flow values, yearly statistics, outflow hydrographs, and water budget depths per year. These model results data are available for all of the subbasins simulated in Napa County and are provided in the supporting technical report (*Napa BDR Surface Hydrology Modeling Report*). Representative examples of these modeling results are presented and discussed below.

MODEL STRUCTURE, SCALE, AND MODULES

MODEL STRUCTURE AND SCALE

Napa County covers approximately 728 mi^2. Its drainage network is shaped by a series of northwest-south-southeast trending mountain ranges and intervening valleys that form three hydrologically discreet watersheds: Napa River watershed, Putah Creek/Berryessa watershed, and Suisun Creek watershed. To properly address the hydrologic characteristics of these discreet watersheds, two separate surface hydrology models were constructed for the Napa County BDR: the Napa River watershed model and the Putah Creek/Lake Berryessa model. The Napa River model covers only the Napa River (Napa Valley) watershed and the Putah Creek/Lake Berryessa model includes both the Putah Creek and Suisun Creek watersheds; which can be developed (stand alone) as separate models in the future.

The MIKE SHE model grid cell resolution for both models is 250 meters (820 ft). This means that the overland flow, the unsaturated zone flow, and the evapotranspiration calculations are computed for every 250-meter cell. For the saturated zone calculations, the model is divided into subbasins, which consists of the main tributaries of each of the three watersheds (basins). Delineation of the subbasin boundaries was based on DEMs of the County. There are a total of 189 subbasins in both models. This model provides the County with a comprehensive set of subbasin planning units that are of an appropriate scale to be used for baseline and alternative conditions.

DATA REQUIREMENTS

As described above, the MIKE SHE and MIKE 11 modeling combination is able to represent all of the important processes in the hydrologic cycle. Table 15-7 summarizes the model components and inputs used for the Napa County MIKE SHE surface water model.

Table 15-7. Model Inputs and Parameters Required for each Model Component

Model Component	Model Inputs	Model Parameters
MIKE SHE OL	Topographical map	M = Overland Manning number
	Detention storage areas	D = Detention storage
	Flooded areas (lakes)	
	Bathymetry of flooded areas	
MIKE 11	Digitized river network	M = River Manning number
	River/lake cross-section geometry	
	Control structures	
	Boundary conditions	
MIKE SHE UZ	Soil type spatial distribution	K = infiltration capacity
	Soil physical properties	θs = saturated water content
		θ_{FC} = water content at field capacity
		θ_{WP} = water content at wilting point
MIKE SHE ET	Time series of reference ET	C_{int} = Interception parameter
	Time series of vegetation Leaf Area Index	Kc = Crop coefficient
	Time series of vegetation root depth	
MIKE SHE SZ	Subbasin division	Ki, Kp, Kb = time constants for interflow reservoir, percolation, and baseflow reservoir
	Interflow reservoir division	
	Baseflow reservoir division	Sy = specific yield for interflow and baseflow reservoirs
	Well locations and withdrawal rate	

HYDROLOGIC MODULES

PRECIPITATION

The precipitation input in MIKE SHE can be both time varying and distributed spatially, as specified throughout the model area. For Napa County, only gauge data were available. Typically, a Thiessen polygon method is used to distribute the gauge data over an area. In MIKE SHE, these rainfall polygons are linked to corresponding time-series files that have the gauge data associated with the polygon. For Napa County, the Thiessen polygon approach is insufficient to capture the spatial variation of rainfall because it neglects rainfall variations due to topography, such as the orographic rainfall that occurs along the mountainous areas. To capture the climatic complexity of the area, a combination of the Thiessen polygon method (valley floor) and isohyetal map (valley walls) of Napa County was used. The isohyetal contours from a statewide isohyetal map showing the distribution of average annual precipitation were obtained from California Spatial Information Library. Unlike the Thiessen map, the isohyetal map captures the topographic differences in rainfall.

In the Napa River watershed model, an intersection of the Thiessen map and the isohyetal map was created and resulted in 69 precipitation polygons for the model area (Map 15-9). The annual average of each resulting polygon corresponding to a particular Thiessen area was calculated and compared to the isohyetal value of that area. If the difference exceeded more than 5 inches, the polygons were scaled to match the isohyetal annual average.

In the Putah Creek/Lake Berryessa and Suisun Creek watershed model areas, available precipitation data were much sparser than in the Napa River watershed model area, and precipitation gauge data from the California Department of Water Resources (California Spatial Information Library 1997) were obtained for one location in the watershed near Monticello Dam at the eastern edge of Lake Berryessa. Additional precipitation gauge data were obtained for several locations outside the watershed but relatively close to the watershed boundaries. These data consist of daily precipitation totals for a period of record ranging from 1987 to present for the Atlas Peak (ATL) and Angwin (ANG) stations and 1997 to present for the Berryessa (BER) station.

To develop a precipitation distribution for the Putah Creek/Berryessa model, the statewide isohyetal map was clipped down to the extent of the model area. The data were then simplified by aggregating zones with similar values together to produce a simplified isohyetal map of the model area with four precipitation zones (Map 15-10). Annual precipitation values were then calculated for each of the four zones by taking an area-weighted average of the original precipitation values. The average elevation in each zone was also calculated from a DEM. The annual precipitation totals and average elevations in each zone were compared with the elevations and annual precipitation totals from each of the available precipitation gauges, and a gauge location was chosen for each precipitation zone based on the closest match of average elevation and total annual precipitation.

EVAPOTRANSPIRATION

For ET calculations in MIKE SHE, reference ET values must be specified. Reference ET is the rate of ET from a reference surface with an unlimited amount of water. For each ET time step, the model tries to meet the reference (or potential ET) from the different storages: canopy, ponded water, and root zone. Like rainfall, reference ET can be time varying and distributed spatially as specified throughout the model area.

In the Napa River watershed model, reference ET was distributed using a Thiessen polygon approach with polygons linked to evapotranspiration records obtained from California Irrigation Management Information System (CIMIS) for stations at Oakville, Carneros, and Angwin (Map 15-11). For the Putah Creek and Suisun Creek models, available ET data were much sparser, and one record was used for the entire model area based on the station located in closest proximity to the model area.

The reduction of the reference ET to actual ET in MIKE SHE is based on a land use/vegetation map and a vegetation database linked to the map. The 86 vegetation types described in Chapter 4, *Biologic* Resources, of the Napa BDR were reclassified to create 15 classes suitable for hydrologic modeling without losing the important vegetative cover distinctions. The following vegetation/land use classes

Evergreen broadleaf woodland was one of the vegetation classes used to model evapotranspiration.

were included: bare ground, coniferous forest, deciduous shrubs, deciduous woodland, developed, eucalyptus woodland, evergreen broadleaf wood, evergreen scrubland, grassland, rock outcrop, unclassified, vineyard, water, and wetlands (Map 15-6). The vegetation database contains the parameters used for the ET calculations such as rooting depth, leaf area index, and crop coefficients. These were considered across the annual cycle and determined for each vegetation class. The parameters were obtained from the parallel biology studies conducted for the BDR as presented in Chapter 4, *Biologic Resources*, of the BDR, but were modified for the hydrology analysis during the calibration process (Table 15-8).

Table 15-8. Leaf Area Index, Rooting Depth, and Crop Coefficient for the General Vegetation Classifications

Vegetation Type	Leaf Area Index	Rooting Depth [mm]	Crop Coefficient (Kc)
Coniferous Forest	5.5	1,230	1.0
Deciduous Shrubland	0.0–2.1	1,710	0.2–1.2
Deciduous Woodland	0.0–5.1	1,710	0.2–1.2
Eucalyptus Woodland	2.4	1,710	1.1
Evergreen Shrubland	2.1	1,710	1.1
Evergreen Broadleaf Woodland	5.7	1,710	1.1
Grassland	0.1–1.7	510	1.0
Mixed Woodland	1.0–6.3	1,710	0.5–1.1
Vineyard	0–1.4	800	0.3–0.7
Wetlands	1.0–6.3	400	0.3–1.2

Source: (Jones & Stokes 2004)

SURFACE RUNOFF/OVERLAND FLOW

The overland component in MIKE SHE uses the two-dimensional diffusive wave approximation of the Saint-Venant equations to calculate flow in the land surface. The main inputs to this component are topography and Manning roughness coefficients for the overland surface. Detention storage is represented in the model primarily by the natural topographic depressions in the DEM. However, constructed storage ponds that occupy a significant area can be added to the model separate from the topography. These areas are given a detention depth below which overland flow cannot occur.

A 25-ft resolution DEM was obtained from the County. The reference vertical datum of the elevation dataset is the North American Vertical Datum (NAVD) of 1988. This DEM provides the basis for defining the topography of the watershed (Maps 15-12 and 15-13) used for the overland flow component of both models. In MIKE SHE, the DEM values are averaged to the model cell size using a bilinear interpolation method.

A spatial distribution of overland flow roughness coefficients was used for both models. This distribution was determined using the land use coverage described above and a combination of references that link Manning roughness coefficient values to each land use category (Table 15-9).

Table 15-9. Overland Flow Roughness Parameters as Classified by Land Use

Land use/vegetation	Manning's Coefficient (s / $m^{1/3}$)
Wetlands	0.22
Water[a]	-
Bare ground	0.011
Coniferous forests	0.5
Grassland	0.2
Deciduous woodland	0.5
Evergreen woodland	0.5
Mixed woodland	0.5
Deciduous shrubland	0.4
Evergreen shrubland	0.4
Developed	0.014
Unclassified[b]	-

Notes:

* Water cells (lakes, ponds, wetlands) were given a rough (high) coefficient to avoid rapid drainage.

* Unclassified cells were considered the same as grassland.

In the Napa River watershed model, a map of detention storage areas was used to describe the numerous storage ponds in the southern area of the model (Map 15-14). Due to the paucity of more detailed information about these ponds, a uniform detention depth of 5 feet was assumed.

UNSATURATED ZONE FLOW

The unsaturated zone flow in the Napa River watershed and Putah Creek and Suisun Creek models was represented using the Two-Layer Water Balance Method. This method uses a simple mass-balance approach to represent the unsaturated zone. The Two-Layer Water Balance method accounts for interception storage changes, surface ponding, water content in the root zone, infiltration, evapotranspiration, and groundwater recharge. Unlike the more complex methods for the unsaturated zone flow in MIKE SHE, this method does not account for the actual relation between the UZ hydraulic conductivity and the soil moisture content. It uses the volumetric moisture contents at saturation (θ_S), at field capacity (θ_{FC}), and at the wilting point (θ_{WP}) to calculate average moisture content in the soil, which is linearly dependent on the depth of the water table. The difference between the moisture content at saturation and at field capacity (θ_S - θ_{FC}) provides an estimate of the storage capacity of the soil, while the difference between the moisture content at field capacity and at the wilting point (θ_{FC} - θ_{WP}) provides an estimate of the amount of water available for transpiration within the root zone.

Infiltration to the unsaturated zone in the Two-Layer Water Balance method is controlled by a time-invariant maximum infiltration rate that can be spatially distributed according to the types of soil. The specified infiltration rate is a calibrated effective parameter rather than a physical soil property. Because it is an effective parameter, the value must be sufficient to represent average response of the unsaturated zone in an area. The actual infiltration to the unsaturated zone is the minimum of the amount of ponded water available, the infiltration rate times the time step, or the available storage volume in the unsaturated zone.

A map representing the distribution of the various soil types in the watershed was obtained from the Natural Resource Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO). The 120 soil types in the soil database for Napa County were aggregated into eight dominant classes based on their relative depth, saturation conductivity, saturation point, wilting point, and field capacity. The soil classes used in the models include clay loam, deep clay, deep fine loam/clay, gravelly loam, loam, rock, undeep loam, and undeep loam/gravel. A database of soil properties was obtained from the NRCS (Lambert and Kashiwagi 1978). The percentage of each of the eight soil type areas occupied by each of the original more-detailed soil types was tabulated, and an area-weighted average property value was calculated using the database values for each parameter of interest. The required input parameters for each type of soil in the model are the soil water content at saturated conditions (θ_S), at field capacity (θ_{FC}), and at wilting point (θ_{WP}), and an infiltration rate (Table 15-10). These parameters were modified during the calibration process.

Table 15-10. Soil Parameters Used in Napa County MIKE SHE Model

Soils	θ_S	θ_{FC}	θ_{WP}	Infiltration Rate [in/hr]
Undeep loam/gravel	0.221	0.187	0.109	1.28
Undeep loam	0.255	0.203	0.094	1.42
Clay loam	0.399	0.295	0.181	0.54
Rock*	-	-	-	-
Deep Clay	0.429	0.348	0.271	0.24
Loam	0.356	0.286	0.173	0.79
Gravelly loam	0.295	0.211	0.123	1.84
Deep fine loam/clay	0.388	0.288	0.187	0.67

Notes:

* Parameters not available.

The terms θ_S, θ_{FC}, and θ_{WP} refer to the saturation point, field capacity, and wilting point, respectively.

SATURATED FLOW

The flow in the saturated zone in the Napa River watershed and Putah Creek/Lake Berryessa watershed models was simulated using the simplified linear groundwater algorithm in MIKE SHE. The linear reservoir module provides an alternative to the physically based, fully distributed groundwater model, which requires more data and more computational time. The combined lumped/physically distributed model was primarily developed for applications such as the Napa County model to provide assessment of water balance, simulation of runoff for ungauged catchments, and prediction of hydrological effects of land use changes. Detailed groundwater movement is not necessary for the surface water budgets representing Napa County. Therefore, the simplified linear groundwater algorithm was used to simulate the influence of the groundwater saving model construction effort and computational time when running scenarios. More completely physically based integrated surface water groundwater models are being developed for areas of the County that currently or potentially could use significant portions of groundwater.

In the simplified linear groundwater algorithm, the entire basin is subdivided into subbasins, and within each subbasin the saturated zone is represented by a series of interdependent, shallow interflow reservoirs, which usually represent different topographical zones plus deep baseflow reservoir that contribute to stream baseflow. If a river is present in the subbasin, water will be routed through the linear reservoirs as interflow and baseflow and subsequently added as lateral flow to the river parts located in the lowest topographical zone. As a result, the infiltrating water from the unsaturated zone may either contribute to the baseflow or move laterally as interflow towards the stream. Water held in the part of the baseflow reservoirs beneath the lowest interflow zone may be allowed to contribute to the root zone when the soil moisture is below field capacity.

The parameters specified for each groundwater reservoir are depth, threshold depth for flow, the specific yield, and a time constant. These parameters are basically unknown for ungauged basins, but a fair estimate can be obtained from an evaluation of the hydrogeological conditions, from gauged basins with similar subsurface conditions, and/or model calibration.

As previously mentioned, the model areas were subdivided into 189 subbasins delineated based on surface water drainages basins (Maps 15-15 and 15-16). In the Napa River watershed model, there are 102 such basins with an average drainage area of 3.8 mi^2, and in the combined Putah Creek/Lake Berryessa and Suisun Creek watershed models, there are 87 basins with an average drainage area of 6.0 mi^2.

The Napa River watershed model was divided into 11 baseflow reservoirs, each with between one and three interflow reservoir divisions (Map 15-17). Each baseflow reservoir acts like a separate groundwater unit, whereas the interflow reservoirs are allowed to flow from the topographically highest to the lowest within a subbasin. The baseflow reservoirs were divided to create more flexibility for parameter adjustment in the groundwater model, thus optimizing the calibration results. Each of these reservoirs includes all of the subbasins in the following areas.

Surface flow in the stream network was modeled in MIKE 11.

- Northeast mountains upstream of the St. Helena United States Geological Society (USGS) surface water gauge.
- Northwest mountains upstream of the St. Helena USGS surface water gauge.
- North valley upstream of the St. Helena USGS surface water gauge.
- The Lake Hennessey watershed.
- Central eastern mountains between the St. Helena and Napa USGS surface water gauges.
- Central western mountains between the St. Helena and Napa USGS surface water gauges.
- Central valley between the St. Helena and Napa USGS surface water gauges.
- Milliken-Sarco-Tulucay groundwater basin.
- Southeast mountains downstream of the Napa USGS surface water gauge.
- Southwest mountains downstream of the Napa USGS surface water gauge.
- South valley downstream of the Napa USGS surface water gauge.

Aerial view of Lake Hennessy.

In the Putah Creek/Lake Berryessa and Suisun Creek models, only one baseflow reservoir was specified for each of the model areas, because the lack of precipitation and streamflow data prevented differentiation of groundwater properties in greater detail. For each subbasin described above, two interflow reservoirs were used to represent the steep and flat areas in the basin. Delineation of the two zones was based on a 15% slope criterion as determined from the DEM (Map 15-18).

STREAMFLOW

Surface flow in the stream network was modeled in MIKE 11. The main data required are boundary conditions, channel and lake geometry, and control structure geometry and operations. MIKE SHE acts as a dynamic boundary condition that exchanges overland flows and groundwater baseflows with MIKE 11.

RIVER NETWORK

The stream network was extracted from a 1-meter resolution DEM elevation dataset for the Napa River watershed model and from a 25-ft resolution DEM for the Putah Creek/Lake Berryessa and Suisun Creek models. The resulting extensive river network was then simplified to include the main stream in each of the 189 subbasins. To maintain a relatively uniform drainage density, two or three principle tributaries were included in the network for some of the larger subbasins (Maps 15-19 and 15-20).

CROSS SECTIONS

Cross sections were extracted from the highest resolution DEM available for the model area, unless survey data were available. For the Napa River watershed model, the 1-m grid cell size allowed for direct extraction of the cross-section data. A total of 843 cross sections were used in this model.

For the Putah Creek/Lake Berryessa and Suisun Creek models, the cross sections were cut from a 25-ft resolution DEM. These cross sections reasonably represent the floodplain topography, but do not adequately represent the channel morphology. To provide better accuracy, representative channel cross sections were imbedded into the DEM extracted cross sections of the floodplain topography. The representative channel dimensions were derived using an empirical relationship that relates the upstream drainage area to average channel width and depth for streams in the San Francisco Bay region (Dunne and Leopold 1978). As a test of the accuracy of this relationship, channel widths and depths were measured from surveyed cross sections in the Napa River watershed and plotted against upstream drainage area. The relation was then compared to the one derived by Dunne and Leopold, and the two datasets agreed reasonably well. A total of 570 and 90 cross sections were used in the Lake Berryessa model and Suisun Creek model, respectively.

BOUNDARY CONDITIONS

Boundary conditions in MIKE 11 are required for all the unconnected branch ends. In the Napa River watershed model, all of the upstream boundaries are closed (i.e., no-flow boundaries) and defined by the upper topographic limits of the watershed. The downstream boundary is the last point of the Napa River included in the model, which is at the county line. Tidal water levels were available from the Mare Island Navy Shipyard National Oceanic and Atmospheric Administration station. In addition, reservoir abstractions and lake evaporation were included as boundary conditions.

Stream gauge data within the Putah Creek/Lake Berryessa model area were available along Putah Creek, upstream of Lake Berryessa and the study area. Outflow data from the reservoir were also available. The discharge data for Putah Creek upstream of the model area were used as an inflow boundary condition. Figure 15-7 shows a hydrograph of this inflow boundary. The outflow from the reservoir was used as a downstream boundary condition for the model.

LAKES AND RESERVOIRS

A map of the principal lakes and reservoirs in Napa County was obtained from Jones & Stokes. This data were clipped to include only the five largest lakes in the Napa River watershed: Kimball Reservoir, Bell Canyon Reservoir, Lake Hennessey, Rector Reservoir, and Milliken Reservoir (Map 15-21); and the two largest lakes in the Lake Berryessa watershed: Lake Curry and Lake Berryessa (Map 15-22).

The river network was modified by placing a single channel running through the center of the lakes and channels connecting to upstream and downstream tributaries along each arm of the lakes.

Bathymetric survey data were not readily available or included, for the purpose of simulating the principal lakes included in the models, including Kimball Reservoir, Bell Canyon Reservoir, Lake Hennessey, Rector Reservoir, Milliken Reservoir, Lake Berryessa, and Lake Curry. For Lake Hennessey and Lake Berryessa, the available stage-storage relationship was used to create the cross-sections representing the lakes. For the Kimball, Bell Canyon, Rector, and Milliken Reservoirs, cross sections were cut from the DEM. Although these methods are approximate and lake depths almost certainly vary from one location to another, it does provide a means of properly simulating the lake volumetrically was taken from summary statistics sheets from the U.S. Bureau of Reclamation where available. In the absence of dam geometry data, geometry was extracted from the DEM (Maps 15-12 and 15-13). Operational rules were implemented to control the gates associated with the dam structures and adjustments to these rules were made during calibration.

IRRIGATION AND ABSTRACTIONS

MIKE SHE has a flexible time variant and spatially distributed irrigation module. It allows the user to extract water from different sources in the model (or from an external source) and to apply the available water based on different types of crop water demand criteria. The user is also able to decide whether the irrigation water is applied as additional rainfall (sprinkler), to the ground surface (drip), or in specified model cells where they can flow to other cells (sheet irrigation).

The agricultural areas in the land use/vegetation map described above are not differentiated into types of agriculture. However, another map of Napa County vineyards was obtained from California Department of Water Resources (CDWR) (2004) and used for calculating the irrigation requirements. Since most of the agricultural land in the County is vineyards, this map was used to specify the cells in the model to be irrigated, and the irrigation water applied is the estimated irrigation water for vineyards. Only general irrigation estimates were available, so there was no information on the local variations or the sources of irrigation. Because of the limited data, irrigation water was applied from an external source in the absence of surveyed bathymetric information.

To accurately simulate water levels within the seven reservoirs included in the models, control gate hydraulic structures representing dams were implemented. Dam geometry information for Monticello Dam (Lake Berryessa) was based on the available estimates. This water is then taken from the model by adding groundwater pumping.

Data for surface water abstractions was also limited. Monthly water use distributions for the City of Napa, the City of Calistoga, and American Canyon were obtained from the California Department of Water Resources. In addition, the 1991 report for the *Water Resources Study for the Napa County Region* lists the existing and projected water needs for different regions in the County and the safe and firm yield for the various water sources (Napa County Flood Control and Water Conservation District 1991). Combining these pieces of information, monthly time series files were created and linked to the surface water reservoirs as outflow point source boundaries.

CALIBRATION

Model calibration is a critical step in developing the hydrology analysis. The goal of the calibration for the surface water model is to provide a reasonable estimate of the water balance at the regional and subbasin level throughout a long-term simulation period. The accuracy of the total inflows and outflows to and from the surface water system is reflected on how well the observed runoff volumes compare to the simulated.

To calibrate the models, simulated discharge volumes (model results) were compared to actual observed streamflow data at a number of available calibration target locations. The calibration targets were chosen based on data availability. The chosen simulation period (1/1/2000–12/31/2003) is the period for which data for precipitation, evaporation, and streamflow each existed contemporaneously. The difference between the actual discharge observed along the river and the model-simulated output was evaluated at each target in the corresponding location in the model. The total volume error should be less than 10% for most areas, such that:

$$[\Sigma(Q_{obs}) - \Sigma\ (Q_{sim})]/\ \Sigma(Q_{obs}) < 0.1$$

where Q_{obs} is the range of observed or measured discharge or water level, and Q_{sim} is the simulated value.

For the Napa River watershed model, surface water calibration data for the simulation period 1999–2003 are available for nine locations. The USGS has average daily discharge data at two locations along the Napa River, one near the City of St. Helena and another further downstream near the City of Napa. The Napa County RCD has stream water levels and discharge at Huichica Creek, Salvador Creek, Carneros Creek, and Milliken Creek. Additional data include inflow (Conn Creek, Sage Creek, and Chiles Creek) and outflow data (releases) for Lake Hennessey provided by the City of Napa. Map 15-19 shows the locations of the various discharge station locations.

The available hydrologic data from the eastern County areas were limited and consisted of reservoir stage data above Monticello Dam on the southeastern edge of Lake Berryessa, as well as reservoir storage, inflow, and outflow data. Stream gauge data are available at two locations along Putah Creek: one downstream of Monticello Dam and the study area, and the other upstream of Lake Berryessa and the study area (Map 15-20). Additional historical (1961–1980) discharge data are available at five locations in the study area. Modifications to the hydrologic system over the past few decades have likely altered flow conditions, making it difficult to compare this historical discharge data to modern flows. However, in the absence of more recent data from within the watershed, a comparison of simulated monthly flows to the historical mean monthly flows allows for a preliminary evaluation of model results. Since limited data were available for the Putah Creek/Lake Berryessa model area, many of the parameters used in this model were determined through calibration of the Napa River watershed model.

Most of the agricultural land in the County is vineyards.

A computer model of the hydrologic cycle is a simplification of the real-world physical system.

INITIAL RESULTS

The Napa County MIKE SHE models will allow the display and animation of any modeled component. Below is an example that uses preliminary results from the entire Napa Valley MIKE SHE model in order to show the distribution, magnitude, and interconnection between hydrologic components. Though the Napa Valley MIKE SHE model is used for the example, the same can be conducted with results from the Lake Berryessa and Suisun Creek MIKE SHE models. In addition, areas within the model can be defined and results can be extracted from those as well. Complete presentation of surface water modeling results are provided in the *Napa County Hydrology Technical Report*.

Between the three Napa County MIKE SHE surface hydrology models, 189 subbasins have been identified and modeled. To expedite the extraction of information, a post-processor has been developed that generates an HTML file with subbasin name; minimum, average, and maximum elevation; soil and vegetation distributions; stream names and lengths; water budget statistics (zone quantities); and monthly flow statistics for each basin outlet. These summary reports are intended to help compare subbasins in different locations within the basin. A second example using three subbasins from around the County illustrates how the post-processed results can be used to understand the hydrologic cycle around the basin.

SAMPLE WATERSHED ANALYSIS

Viewing the spatial and temporal variability is important for understanding the hydrologic zones and how they interact. For example, the simulated precipitation distribution from the Napa Valley MIKE SHE model for February 14, 2000 (Figure 15-8). Maximum precipitation in the valley was 141 mm/day and occurred in the headwaters of Sugar Loaf Canyon. Minimum precipitation in Napa Valley was 11 mm/day, occurring in the southwest corner of the study area. These results can be animated to see how the precipitation changes throughout the basin over the simulation period.

Another effective means of analyzing results is to view a select component or selected components for the same day. For July 22, 2000, the simulated actual evapotranspiration, water content in the UZ, and total irrigation are depicted in Figures 15-9, Figure 15-10, and Figure 15-11, respectively. In these figures, areas of greater total irrigation agree spatially with areas of greater actual evapotranspiration and waster content. Valley floors depict the greatest values in these while the valley walls exhibit lower values.

Time series are available from every cell as well as from any point in the stream channel network. Preliminary results from the simulation indicate that the Napa Valley MIKE SHE model simulates the timing and magnitude of streamflow in response to a storm event and during baseflow conditions (Figure 15-12). Volumetric comparison of the two records indicates that the observed flow passes 64,000 af-yr and the simulated flow passes 62,000 af-yr thus the model under predicts volume by 3.4%; well within the measurement error of the stream measurements.

Finally, MIKE SHE generates a water budget for the entire model area for the simulation period (Figure 15-13). Preliminary results from the 4-year simulation period (1999–2003) indicate that of the water entering the subbasin, roughly 47% leaves as ET, 29% as streamflow, and 20% pumped as groundwater. The remaining is a net gain in the groundwater storage of 4%.

SUBBASIN COMPARISONS

The characteristics and preliminary results from the Carneros, Butts, and East Fork Wooden Valley Creek subbasins are shown in Figure 15-14, Figure 15-15 and Figure 15-16, respectively. These three subbasins range in size from 8.59 to 10.59 mi^2, exhibit similar elevations ranges of around 1,470 ft, but have different median elevations of 479, 817, and 1,004 ft for the Carneros, Wooden Valley, and Butts Creek subbasins, respectively. The Carneros Creek subbasin is evergreen broadleaf woodland, grass, and vineyard with deep fine loam, gravelly loam, and loam soils. Butts Creek subbasin is predominately evergreen shrubland with mostly gravelly loam and some loam, undeep loam, and rock soils. In East Fork Wooden Valley subbasin, deciduous woodland predominates with some evergreen broadland woodland and grassland with clay loam and loam soils.

The preliminary results suggest that elevation and location have a positive correlation with precipitation received. Carneros, the lowest subbasin, receives the least precipitation at 32.8 inches. Butts Creek subbasin, located in the northern reaches of the valley, receives more that 10 inches more annually.

December experiences the maximum runoff for each subbasin. Carneros and East Fork Wooden Valley subbasins have similar magnitude peak flows for the wet year (around 71 cfs), while Butts is significantly lower at 29 cfs. Because Butts Creek subbasin receives the most rain and is the largest drainage, it can be observed that the soils and vegetation influence the streamflow. The gravelly loam promotes infiltration, allowing water to be stored in the ground. The runoff is then augmented later in the season by the higher percentage of groundwater flow to the stream (baseflow).

Evaporation is negatively correlated to baseflow recharge. Carneros Creek subbasin has a relative evaporation rate of 43% of the total precipitation and only sends 18.9% of the total precipitation to the subsurface. Conversely, Butts Creek subbasin has 32% of the total precipitation and only sends 47% of the total precipitation to the subsurface. Higher soil infiltration rates in Butts Creek subbasin and vegetation with higher crop coefficients in Carneros Creek are the major causes of this difference.

Using these basin parameters and summary results, the Napa County MIKE SHE models can be used to determine the factors that most influence stream flow, which can then be incorporated into the basin planning.

MODEL ASSUMPTIONS AND LIMITATIONS

A computer model of the hydrologic cycle is a simplification of the real-world physical system. The model is intended to represent the significant functions and inter-relations that occur in the natural system. However, no model can represent all the intricate details of the processes and inter-relations that could occur in a real-world system. Limitations of the MIKE SHE/MIKE 11 model arise from the inherent limitations of numerical models, the lack of input and calibration data, and inaccuracies associated with available data.

Fully distributed, integrated surface and ground water models are designed for answering physically based questions such as flood propagation and attenuation, flood extent, ground water-surface water interactions distributed over the landscape, stage within the river, and impacts associated with land use changes. However, they are limited by the modeling scale and available data for the simulations.

The Napa County surface water model was developed to determine the hydrologic response to land use change on a monthly basis. The stream network uses representative channel network for channel geometry. Given the limited detail associated with the cross section, flood inundation and water surface profiles should not be used in flood hazard or flood management studies. If the flood inundation is wanted, the Napa County surface water models could be used to determine flooding extent by replacing the representative cross sections with surveyed cross sections and incorporating local stage or discharge data for calibration. That being said, it is believed that the model developed does provide suitable precision and accuracy to evaluate and assess land use change scenarios for their general hydrologic impacts.

The accuracy of model results depends on the quantity and quality of the input data. Data limitations for the Napa County surface water models include a lack of comprehensive stream gauge data across the County for calibration, uncertainty associated with the direct precipitation across the entire County, limited concurrent period of surface water flow and precipitation to reflect the natural climatic variability, and representative cross-sections and bathymetric data. These limitations can be addressed by collection of additional data as feasible or as dictated by the specific issue to be addressed.

CONCLUSIONS AND REPORT UPDATE RECOMMENDATIONS

SURFACE WATER HYDROLOGY

There are three principal watersheds in Napa County: Napa River watershed, Putah Creek/Lake Berryessa watershed, and Suisun Creek watershed. Annual precipitation in the County varies significantly from year to year. In general, precipitation increases from south to north and with increasing elevation, and average annual precipitation varies by more than a factor of three throughout the County, from 22.5 to 75 in/yr (California Spatial Information Library 1997). Precipitation is lowest in the southern portions of the County and in the vicinity of Lake Berryessa, at about 22.6 in/yr. In addition to watersheds and precipitation, the other primary factors that affect surface hydrology in Napa County are the stream network, evapotranspiration, vegetation, and land use.

Because the factors that affect surface water hydrology are generally relatively stable in that drastic changes occur only over long periods, this chapter of the BDR does not need to be frequently updated. This chapter should be reviewed and updated as necessary every 5 years or when significant changes occur in federal, state, or local policies governing surface water hydrology in Napa County.

SURFACE WATER MODEL

A surface water model has been developed in MIKE SHE/MIKE 11 that simulates the major components of the hydrologic system active in Napa County. In developing the model, the components that influence the hydrologic cycle have been identified, as described in the previous paragraph, and their effects on runoff quantified. For the 1999–2003 simulation period, comparison of the simulated and observed instantaneous flow rates and monthly flow volumes and the models compare favorably at stream gauges throughout the basin. The model is sensitive to changes in land use and can be used for determining the effects of changes in land use planning.

If the model is to be used for purposes other than regional or local hydrology, additional data of the study area may need to be collected and input into the model. The primary data limitation is lack of stream gauge data to calibrate the model. Collection of additional stream gauge data is necessary to improve calibration.

The Napa County MIKE SHE/MIKE 11 model is a dynamic model that can be refined and expanded as data becomes available and as new questions are identified. As the model is currently setup for regional analysis of the Napa County hydrologic system it can be used to help evaluate alternatives developed as part of the current updating of the Napa County General Plan. As described above, with adequate local data, the baseline model can also be developed for more localized and site specific environmental analyses of specific projects. In turn, the development of local information for site-specific projects can then be "returned" or input into the broader countywide model to also improve the accuracy of the regional model.

RECOMMENDATIONS FOR FUTURE DEVELOPMENT AND REFINEMENT OF THE MODEL

- Install more stream gauges. Currently, there are six working stream gauges for the Napa Valley watershed and none in the Putah Creek/Lake Berryessa and Suisun model areas. Stream gauges are important for calibration of the model. Site-specific recommendations are included in the supporting technical report (*Napa BDR Surface Hydrology Modeling Report*).

- Continue to populate the model with current spatial and time series data as they become available. As this is a planning model, it is recommended that this data be updated annually and as warranted by additional studies.

If the model is to be used for purposes other than regional or local hydrology, additional data of the study area may need to be collected and input into the model.

- Evaluate the possibility of procuring and using local detailed RADAR based precipitation data.
- After an extensive search for bathymetric data, a simplified geometry was used to represent bathymetry of reservoirs and lakes in the river network.

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