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Hydrologic Analysis of Fort Leonard Wood, Missouri

Michael L. Follum, Darla C. McVan, Elisabeth M. Jenicek,
and Michael P. Case

August 2015

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Hydrologic Analysis of Fort Leonard Wood, Missouri

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Final report

Approved for public release; distribution is unlimited.

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Units 8609C7, BH01K8, and LG7452

Abstract

This report analyzes the hydrologic ability of Fort Leonard Wood (FLW) in south-central Missouri to sustainably meet its water requirements with natural sources within the boundaries of the installation. This report documents efforts under the Research, Development, Test, and Evaluation project, Integrated Installation Energy, Water, and Waste Modeling. This work was carried out in the second year of a 4-year program that is building on Net Zero Energy to tackle the more complicated problem of reducing energy, waste, and water at the same time through development of the Net Zero Installations (NZI) tool. It also supports the Army's Net Zero Water (NZW) program that seeks to enable Army posts to become self-reliant on basic needs, such as water, therefore becoming more secure and versatile. A definition of water sustainability is first given and then applied to the current sources of water available to FLW. Although this report is specific to FLW, it outlines a framework in which future NZW analyses can be completed for other installations. It is imperative to have an understanding of the water available to an Army post. This helps determine the ability of each installation to sustainably adapt to changing troop levels under a changing climate. The NZW framework of the NZI tool helps installations to understand the amount of water that is available from various sources such as rivers, groundwater, and municipal sources. Through this knowledge, Army staff can properly plan for the future and for emergency operations that may stress the current infrastructure. This report outlines only one piece of NZW, the regional analysis of naturally available water to support the base sustainably.

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Preface

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE) under the Research, Development, Test and Evaluation project, Integrating Installation Energy, Water, and Waste Modeling, via work item codes 8609C7 and BH01K8, Integrated Installation Energy, Water and Waste (EW2) Modeling and work item code LG7452, Computational Framework for Energy, Water, and Waste.

The work was performed by the Hydrologic Systems Branch (HSB) of the Flood and Storm Protection Division (FSPD), U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). The program manager was Dr. Michael P. Case of the Energy Branch of the Facilities Division, U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). Special appreciation is expressed to the installation and other local points of contact for providing information that was invaluable to this study and for reviewing this report. At the time of publication, Dr. Hwai-Ping (Pearce) Cheng was Chief of HSB; Dr. Ty V. Wamsley was Chief of FSPD; William R. Curtis was Technical Director of Flood and Coastal Storm Damage Reduction Program; and José E. Sánchez was the director of CHL.

LTC John T. Tucker III was Acting Commander of ERDC, and Dr. Jeffery P. Holland was Director.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
degrees Fahrenheit	$(F-32)/1.8$	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
miles (U.S. statute)	1,609.347	meters
seconds	864000.0	days
slugs	14.59390	kilograms
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
yards	0.9144	meters

1 Introduction

The U.S. Army is vulnerable to the same issues of water supply and demand that jeopardize water security globally. On Army installations, as is found outside the fenceline, providing the required amount of clean fresh water at the location and time where it is needed is increasingly difficult. The conditions that exacerbate water availability are the aging condition of water infrastructure, general population growth (especially in regions containing key Army installations), increased water demands for energy, and uncertain (but generally agreed on) regional impacts of global climate change. The complexity of water compacts, treaties, and agreements is another challenge for installations. It is anticipated that the impacts of water scarcity will be more severe in certain locations in the coming years, where diminished water supply will be reflected in increasing costs. These global drivers that threaten to compromise water security have fueled an increasing interest in preserving this finite resource.

Over the past decade, Federal legislation and executive orders that stipulate increasingly rigorous water conservation requirements have emerged. The Army adopted these requirements through policy and regulation and advanced the concept even further by establishing challenging targets for installations to achieve Net Zero Water (NZW). NZW is an emerging sustainable buildings concept analogous to Net Zero Energy (NZE). The Army's NZW Installation Vision states that

A Net Zero Water installation limits the consumption of freshwater resources and returns water back to the same watershed so not to deplete the groundwater and surface water resources of that region in quantity or quality (ASA (IE&E) 2011).

Meeting NZW targets can be especially difficult at Army installations, which are often located in regions characterized by a broad spectrum of conditions that affect water availability, security, cost, and the applicability of water-efficient technologies. It is critical for installations to understand both baseline conditions on post and the regional water system that supplies water to the installation. Several types and scales of hydrologic and regional models can provide this vital information. In order for

installations to achieve NZW goals, it will require a holistic approach that includes policy, technology, education, partnering, and a strong command emphasis. A suite of technologies that includes aggressive conservation, rainwater harvesting, and water recycling/reuse can enable buildings to achieve independence from the water *grid*. In addition, it is vital that the energy footprint of water provision and usage be considered so that developing solutions for one resource scarcity issue does not exacerbate another. However, there is no one-size-fits-all solution; an installation Net Zero Water program must be uniquely tailored to the installation's characteristics, which include the regional water system as revealed by hydrologic models.

The Integrated Installation Energy, Water and Waste Modeling research project/work package (NZEW2) was initiated by the ERDC to support attainment of net-zero energy, water and waste. NZEW2 builds on the Net Zero Energy work package to develop planning-scale tools to support Army installations. Driven by Federal policy and Army requirements, the emphasis of the NZEW2 effort is on an integrated approach. Work began in fiscal year 2012 and is scheduled to culminate in 2015 with delivery of an operational integrated modeling system to identify the appropriate technologies, scale, and implementation schedule to meet installation net zero goals.

1.1 Water policy overview

Historically, water conservation policy emerged as a subset of energy policy. On the Federal level this includes public laws and executive orders. Agency policy can be found in Department of Defense (DoD) documents largely mirroring Federal requirements. The Army interprets Law and DoD policy and includes water program requirements in many different programs and documents. Additionally, industry standards and specifications play a key role and are often referenced in Army water policy.

Policy areas that impact water include raw conservation targets, new construction and major renovation performance standards, technology standards, stormwater management, and metering and monitoring requirements.

1.1.1 Federal policy

There are two main pieces of Federal policy currently governing water. These are Executive Order (EO) 13514, Federal Leadership in Environmental, Energy, and Economic Performance, and the Energy Independence and Security Act of 2007 (EISA 2007). EO 13514 superceded the earlier 13423, Strengthening Federal Environmental, Energy and Transportation Management (2007), although some of the provisions of 13423 remain in effect. The Energy Policy Act of 2005 (EPA 2005) required building-level metering in all covered facilities by 2016. (Covered facilities are defined based on size and/or amount of water used.) This requirement also remains in effect though other provisions of EPA 2005 have been strengthened by newer requirements. (Table 1 lists legislative and regulatory water mandate requirements as of May 2013.)

Table 1. Water mandates: legislative and regulatory requirements as of July 2013.

Federal Mandate	Water Topic	Water Performance Target
Executive Order 13123, Jun 1999	Reduce Water through Cost-Effective Efficiency	FEMP Best Management Practices (BMPs)
Executive Order 13423, Jan 2007	Water Consumption	Reduce consumption by 2% annually for 16% total by FY15 (FY07 baseline)
	Water Audits	At least 10% per year every 10 year
	Products and Services	Procurement of water efficiency products and services, WaterSense®
Energy Independence and Security Act of 2007	Covered Facilities (75%)	Comprehensive evaluations, project implementation, and follow-up
	Postconstruction Stormwater	Restore to predevelopment hydrology
Executive Order 13514, Oct 2009	Water Consumption	Reduce consumption by 2% annually for 26% total by FY20 (FY07 baseline)
	Industrial, Landscape, Agricultural	Reduce consumption by 2% annually for 20% total by FY20 (FY10 baseline)
	Water Reuse	Identify, promote, and implement water reuse strategies
	Stormwater Management	Implement and achieve objectives from USEPA
Army Sustainable Design and Development Policy, Oct 2010	New Construction and Renovation	Achieve 30% reduction compared to baseline IAW ASHRAE 189.1-2009 Outdoor use achieve a 50% reduction
Army Campaign Plan	Major Objective 8-3	Eight candidate water metrics

EO 13514 superseded the requirements of EO 13423 in the development of water management plans and implementation of best management practices (BMPs) for water efficiency as identified by the Department of Energy Federal Energy Management Program (FEMP). EO 13423 required a 2% annual reduction in water consumption intensity (gal/sq ft) from a 2007 baseline through the end of FY15 or 16% by the end of FY15. It further required water audits at Federal facilities of at least 10% of facility square footage at least once every 10 years. Finally, it encouraged the procurement and use of water efficient products and services, specifically identifying the U.S. Environmental Protection Agency (USEPA) WaterSense® program as a source of guidance.

Additionally, BMPs were originally developed by FEMP in response to the requirements set forth in EO 13123, Greening the Government Through Efficient Energy Management, which required Federal agencies to reduce water use through cost-effective water efficiency improvements. In response to EO 13423 and to account for recent changes in technology in water-use patterns, the USEPA Water Sense Office updated the original BMPs. The updated BMPs were developed to help agency personnel achieve water conservation goals of EO 13423 and are available at the FEMP web site: http://www1.eere.energy.gov/femp/program/waterefficiency_bmp.html.

The EISA 2007 amends Section 543 of the National Energy Conservation Policy Act, the foundation of most current energy requirements. It adds further water conservation requirements and provides guidance for benchmarking. Under EISA 2007, agencies are required to categorize groups of facilities that are managed as an integrated operation and to identify “covered facilities” that constitute at least 75% of the agency’s facility energy and water use. Each of these covered facilities will be assigned an energy manager responsible for completing comprehensive energy and water evaluations, implementing efficiency measures, and following up on implementation.

EISA 2007 also addresses postconstruction stormwater management for Federal projects, requiring that “The sponsor of any development or redevelopment project involving a Federal facility with a footprint that exceeds 5,000 sq ft (465 m²) shall use site planning, design, construction, and maintenance strategies for the property to maintain or restore, to the maximum extent technically feasible, the predevelopment hydrology of the property with regard to the temperature, rate, volume, and duration of flow.”

EO 13514 expands the water efficiency and conservation requirements of EO 13423 and EISA 2007. This mandate extends EO 13423 2% annual water consumption intensity reduction requirement into FY20, resulting in a total water reduction requirement of 26% from the baseline year of 2007. Additionally, the new rules require a 2% annual reduction for agency industrial, landscaping, and agricultural water consumption through 2020, for a total of 20% water consumption reduction relative to the 2010 base year. EO 13514 also encourages agencies to identify, promote, and implement water reuse strategies that reduce potable water consumption and support objectives identified in the stormwater management guidance issued by the USEPA.

1.1.2 Army policy

Army water policy interprets that of the DoD as well as Federal policy. Documents include Army Regulations (AR), technical standards, policy memos, and general guidance documents. In addition, the Army provides guidance on a range of specific water topics such as metering and setting rates for reimbursable customers.

AR 420-1 (Feb 2008), *Army Facilities Management*, covers energy and water management in Chapter 22-11. This guidance covers conservation guidelines, funding programs, metering and audits, reporting, awareness, and award programs. AR 420-41 (Sep 1990), *Acquisition and Sale of Utilities Services*, calls for water supply and wastewater services to be provided at the lowest life cycle cost (LCC) consistent with installation and mission requirements, efficiency of operation, reliability of service, and environmental considerations. The costs for these services are to be held to a minimum through comprehensive water resource planning, management, and an effective water conservation program, all of which rely heavily upon the adoption of sustainable water technologies. Furthermore, AR 420-41 requires compliance with the Safe Drinking Water Act.

1.1.2.1 Army Campaign Plan

The 2013 Army Campaign Plan addresses water sustainability under Campaign Objective 8, Major Objective 8-3, “Enhance Water Security.” The desired strategic outcome is assured availability of water for all Army missions. Water security is the capacity to ensure that water of suitable quality is provided at a sustained rate sufficient to support all current and future Army missions, as needed. Within Major Objective 8-3, eight

metrics, six of which are proposed, address water efficiency and conservation.

1.1.2.2 Army Energy Security Implementation Strategy

The Army Energy Security Implementation Strategy (AESIS), signed 13 January 2009, addresses both energy and water security. This policy stresses the enhanced operational capability that is supported through achievement of the Army's energy and water goals. Progress toward meeting AESIS metrics is being tracked using the Army Strategic Management System.

1.1.2.3 Army Water Portfolio

The Army's Water Portfolio includes details about the Army Water Vision 2017, DoD and Army water guidance, moving to water security, best management practices and projects, major water programs, and the way ahead. The portfolio is available on the Assistant Chief of Staff, Installation Management (ACSIM), web site at the following URL:

<http://army-energy.hqda.pentagon.mil/>

1.1.2.4 Sustainable Design and Development Policy

The Army's Sustainable Design and Development Policy Update (Environmental and Energy Performance) (1 Oct 2010) updates and supersedes the policy of 8 July 2010. The revision includes incorporation of sustainable development and design principles, following guidance as detailed in American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 189.1-2009. All facility construction projects shall achieve a 30% reduction in indoor potable water use as compared to a baseline using guidance from ASHRAE. In addition, outdoor potable water consumption shall achieve a reduction of 50% from the baseline (Department of the Army [DA] 2010).

1.1.2.5 Standards and codes

Plumbing and building codes influence the adoption of water-efficient products and processes. DoD adopts the International Code Council International Plumbing Code (IPC) as the primary standard for DoD facility plumbing systems. The code has a 3-year development cycle for updates. The process of amending codes is long and labor intensive and

requires the support of water stakeholders. Any additions, deletions, and revisions to the IPC are listed in Appendix A “Supplemental Technical Criteria” of Unified Facilities Criteria 3-420-01, 25 October 2004.

WaterSense® is a USEPA partnership program that certifies water fixtures that meet rigorous criteria in both performance and efficiency. Specifications and criteria are available for bathroom sink faucets, shower heads, toilets, urinals, and landscape irrigation controls. The prerinse spray valve specification is in the public review stage with release anticipated during Fiscal Year 2013.

The U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED®) Green Building Rating System is a voluntary standard for high performance sustainable buildings. LEED® certification validates that a building is a high performing, sustainable structure. Certification also benchmarks a building’s performance to support ongoing analysis over time to quantify the return on investment of green design, construction, systems, and materials. All Military Construction, Army (MCA) projects meeting the Minimum Program Requirements for LEED® certification are to be planned, designed, and built to be Green Building Certification Institute certified at the Silver level or higher. WE 1, the Water Efficient Landscaping credit and WE 3, the Water Use Reduction (30% reduction) credit are required in all MCA projects.

ASHRAE developed Standard 189.1-2009 in conjunction with the USGBC and the Illuminating Engineering Society. This standard is intended to provide minimum requirements for sustainable or green buildings through the general goals of reducing energy consumption, addressing site sustainability, water efficiency, occupant comfort, environmental impact, materials, and resources. The Army adopted the energy and water standards of ASHRAE 189.1-2009 for all new construction and major renovations through the Sustainable Design and Development Policy.

1.1.3 Army Net Zero program

The Army Net Zero program was established in October 2010 by the Honorable Katherine Hammack, Assistant Secretary of the Army, Installations, Energy and Environment. Net Zero was conceived as a force multiplier, that is, a means to steward available resources and to manage costs in order to better support soldiers, families, and civilians. Net Zero also supports resource security and sustainability.

The Army's Net Zero Water Installation Vision states "A Net Zero Water installation limits the consumption of freshwater resources and returns water back to the same watershed so not to deplete the groundwater and surface water resources of that region in quantity or quality over the course of a year."

Definitions and guidance for installations to achieve NZW is provided on the Army Energy Program web site and contained in the Net Zero Water Guidelines:

The net zero water strategy balances water availability and use to ensure sustainable water supply for years to come. This concept is of increasing importance since scarcity of clean potable water is quickly becoming a serious issue in many countries around the world. The continued draw-down of major aquifers results in significant problems for our future. Strategies such as harvesting rain water and recycling discharge water for reuse can reduce the need for municipal water, exported sewage or storm water. Desalination can be utilized to convert briny, brackish or salt water to fresh water so it is suitable for human consumption or irrigation.

To achieve a net zero water installation, efforts begin with conservation followed by efficiency in use and improved integrity of distribution systems. Water is re-purposed by utilizing grey water generated from sources such as showers, sinks, and laundries and by capturing precipitation and storm water runoff for on-site use. Wastewater can be treated and reclaimed for other uses or recharged into groundwater aquifers. Several Army installations are already well down the path to reaching net zero water goals. (ACSIM 2013)

Net Zero installations were selected based on self nomination in April 2011. There are five NZE sites, six NZW sites, and six Net Zero Waste sites. In addition, two installations were designated Net Zero Energy-Water-Waste. The pilot installations are shown on the map in Figure 1.

Figure 1. National map showing Army Net Zero pilot installations.



An initial Net Zero training workshop was held at Fort Detrick, MD, in June 2011. Another workshop was held in Chicago, IL, in January 2012. Individual workshops (energy, water, and waste) were held separately in late FY2012. The purpose of the workshops was to engage with installation resource managers in an information exchange, both to gauge installation progress toward Net Zero goals and to share lessons learned and technology updates.

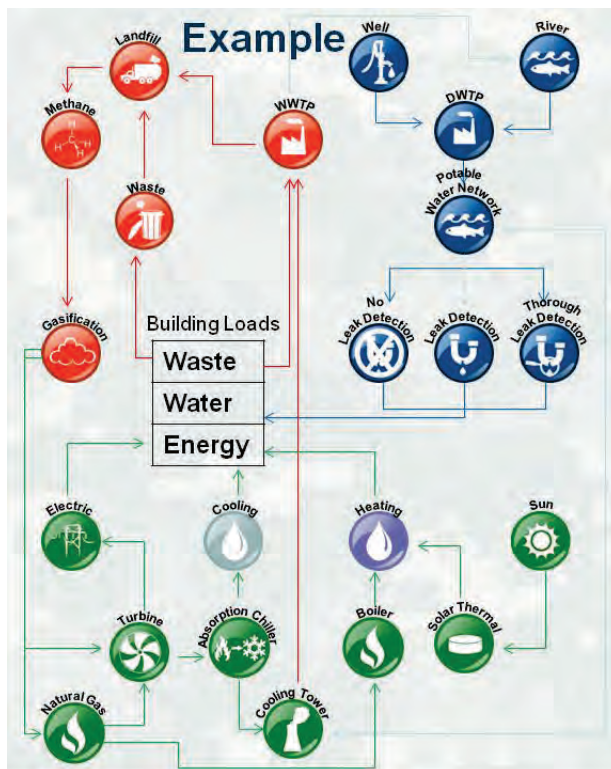
1.2 Modeling for Net Zero Energy, Water, and Waste

1.2.1 Integrated Installation Energy, Water, and Waste Modeling work package

The Integrated Installation Energy, Water, and Waste Modeling work package is part of the FY 2012 Research, Development, Test, and Evaluation program of the Environmental Quality and Installations Business Area. This work package extends over 4 fiscal years. Generally, the first year involves researching currently available models, the next 2-year focus on adapting/developing new models, and the final year completes the tech transfer process.

The purpose of this work package is to develop an integrated modeling capability to support Army and installation master planning for energy, water, and waste (EW2) resource optimization. Figure 2 shows the integrated modeling concept for this work package. EW2 is being built on the existing NZE modeling capability, a project that was completed in FY 2013.

Figure 2. Integrated modeling concepts.



Intrinsic to achieving NZW is consideration for natural water availability. The tiered NZW approach is to limit water use, employ water reuse strategies (through rain water harvesting and recycling of discharge water), and to return water to the source. Balancing water supply and demand while securing a sustainable resource requires knowledge of and experience with modeling on several levels. A series of water modeling strategies are being employed to develop the integrated process. These range from large-scale hydrologic models to building-scale, water-demand calculators.

Hydrologic models enable what-if analyses for a given water source. These models can incorporate alternate future scenarios, including climate change projections, to provide information about future water availability. The output from hydrologic models is necessary for both regional water balance models and to evaluate applicability of specific water measures

(rain water capture, condensate collection, aquifer recharge, drilling new wells, etc.). Regional water balance models are vital to understand competing demands for regional resources.

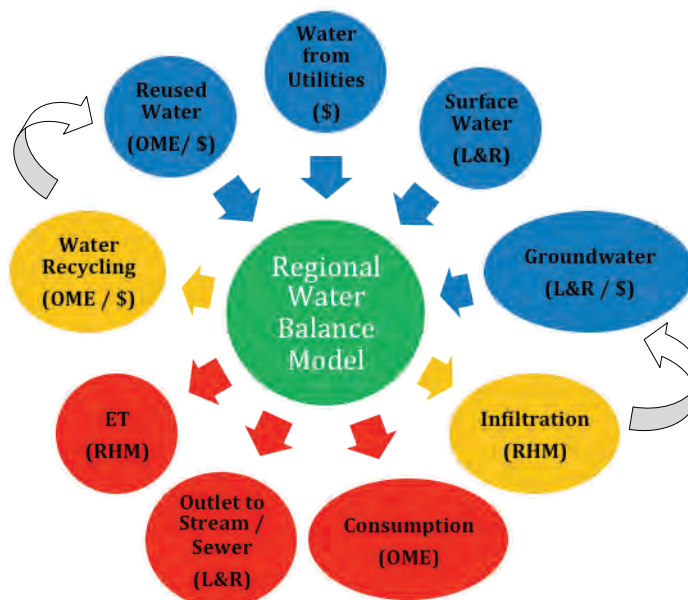
1.2.2 First-year progress

The NZW team focused on evaluating existing water analysis methods and tools during project year 1. In addition, the team evaluated a wide range of water conservation and efficiency measures to evaluate applicability of these measures and to document inputs to life-cycle cost assessment evaluations and interactions with the energy and waste sectors.

The assessed water models included a range of scales: measure, system, installation, watershed, and region. An example of a measure-based model is the River Network shower head calculator. System-scale models include EPANet, used to model water and wastewater distribution system flows. Installation-scale models include those developed for use by civilian communities and utility companies. These include the Demand Side Management Least Cost Planning Decision Support System Model, the Alliance for Water Efficiency Tracking Tool, the Pacific Institute Cost Effectiveness of Water Conservation and Efficiency model, and the CERL Installation Demand Tool. A methodology for conducting a regional water balance was developed as a part of this project and is also documented in the year-1 technical report. The water balance relies on outputs from the other models in order to evaluate the overall sustainability of the regional water system. Figure 3 shows the concept of the regional water balance model. Water sources include ground and surface water (either purchased or self-supplied) and reused water (gray water, reclaimed municipal water, and condensate are a few sources).

The year-1 technical report includes a description of and comparison among the various existing watershed-scale hydrologic models. Some models excel at groundwater-dominated systems where others are intended for surface-water dominated systems. The model documented in this report was created to meet the needs of the Fort Leonard Wood Net Zero Installation analysis.

Figure 3. Regional water balance concept.



1.3 Fort Leonard Wood, MO, case study

Fort Leonard Wood (FLW), MO, is the first installation case study for the developing NZI tool that incorporates net zero water and waste in addition to net zero energy. FLW is a key training installation located in Pulaski County, in the north-central part of the Gasconade River Basin, in south-central Missouri (Mugel and Imes 2003). FLW is approximately 63,000 acres, almost 54,000 acres used as training grounds, host to 237 courses, and an annual throughput of 80,000 trainees (Rexroad 2001). Figure 4 shows the location of FLW.

1.3.1 Role of hydrologic analysis in Net Zero Water (NZW)

The role of the hydrologic analysis in NZW planning is to assess how much water can be sustainably extracted and used from natural water sources within the confines of the installation boundary without adversely affecting ecological systems. It is a goal of NZW to enable installations to use only water generated from within the post boundaries. This may constrain the amount of water available. Water is used and lost if immediately treated and discharged. If managed responsibly, an installation's water sources can be sustained for the indefinite future.

Figure 4. Fort Leonard Wood, MO, and surrounding area.



Most water sources naturally release water and are replenished, creating a dynamic equilibrium (Sophocleous 2000). When human activity withdraws more water than natural sources can replenish, there will be a point in time when the sources are no longer available. A classic example is the Ogallala Aquifer, a part of the High Plains Aquifer System that is located beneath the Great Plains in the mid-western U.S. This aquifer has been drawn down considerably since the 1940's and recharge could not counteract the withdrawals for irrigation (Rosenberg et al. 1999). Eventually, this source will no longer be viable if current pumping practices continue. Hydrologic analyses of Army installations are intended to prevent this type of situation.

Analyses will be completed to estimate the amount of water FLW can withdraw from natural water resources without adversely affecting the surrounding area. Water rights as well as local, state, and national laws may restrict the amount of water that is released to the stream system from the post and how much water may be pumped from the groundwater and surface water systems. These issues are the responsibility of installation staff to evaluate.

1.3.2 Tools used for analysis of natural availability of renewable water resources

Hydrologic models are often used to determine natural fluxes within the water cycle. Advanced hydrologic models such as the Gridded Surface Subsurface Hydrologic Analysis Model (GSSHA) (Downer and Ogden 2004) have the ability to simulate numerous characteristics within the water cycle such as evapotranspiration, infiltration, overland flow, stream flow, groundwater, man-made structures, and snow melt. The limitation of the more advanced models is the amount of time required to develop the model and/or the computational time (how long it takes to run the model).

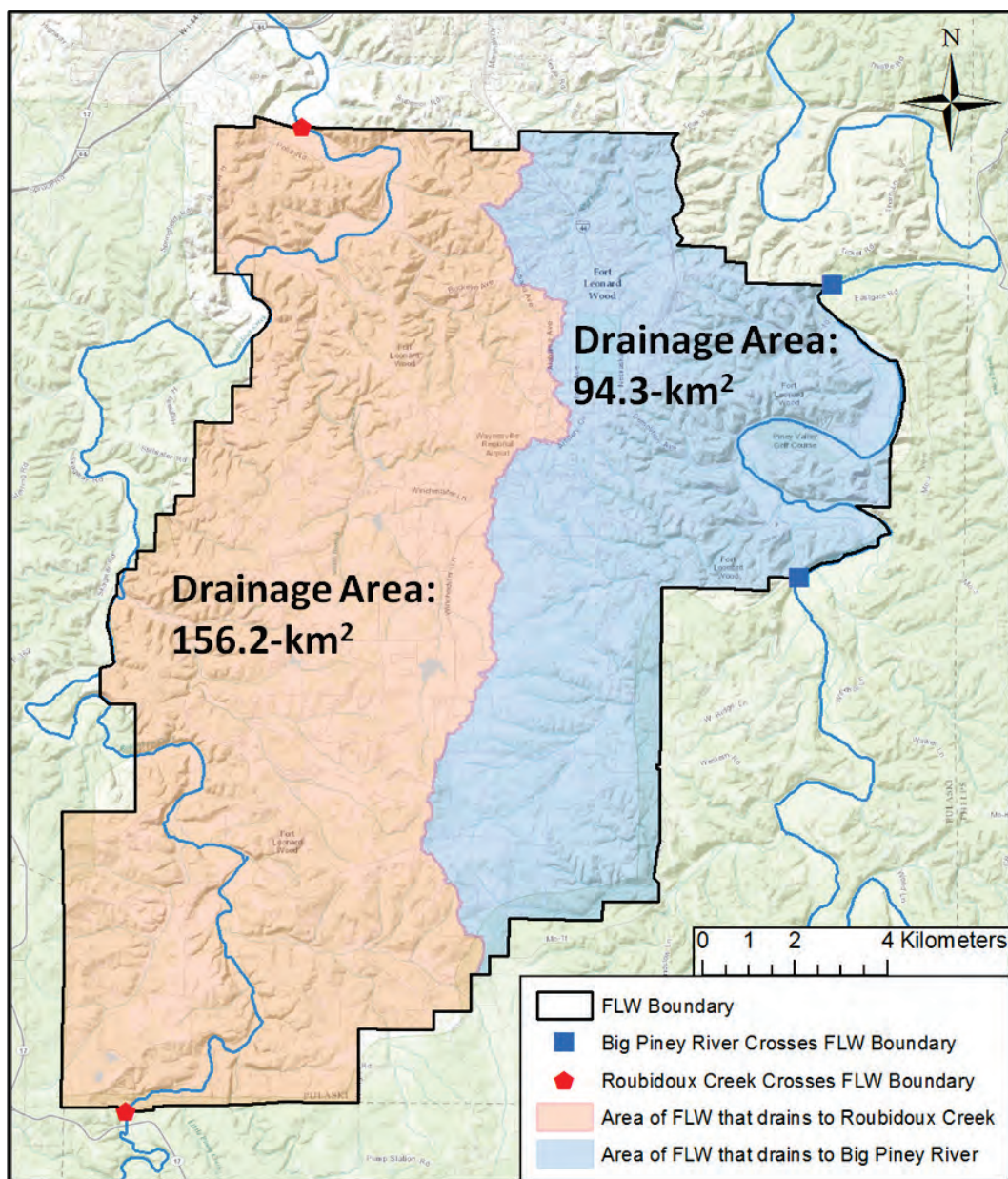
The tool selected in every modeling scenario depends upon the answer required. If a simple answer is required, then a simple model may suffice. If a complex answer is required, then a highly detailed model may be required. For FLW, this is the main question: how much water can the sources within and near FLW indefinitely sustain without adversely affecting the ecological systems?

To answer this question, all of the available sources of water must be identified. The Missouri Department of Natural Resources and the United States Geological Survey (USGS) possess significant hydrologic data within and near FLW; therefore, a simple hydrologic model will suffice for the purposes of this project. Basic hydrologic equations were used to determine approximately how much water is available to FLW while remaining sustainable. More complex analyses may be performed at a later date, and may be justified, but the approach outlined in this report will give insight into the volume of water naturally and sustainably available to FLW on an annual basis. The method is also simple enough to be easily deployed at any installation for future use.

2 Methods

Water that falls on FLW is transported to one of two principle drainages: Roubidoux Creek and Big Piney River. Both the Big Piney River and Roubidoux Creek drain northward into the Gasconade River. As shown in Figure 5, Roubidoux Creek drains approximately 62.4% of FLW while the Big Piney River drains approximately 37.6 %. Although the two systems are adjacent to each other, they are very different.

Figure 5. FLW drainage divide.



The drainage area of Roubidoux Creek is approximately 427 km² (USGS 2012a) when it enters FLW. Roubidoux Creek is a losing stream as it flows through FLW. This means that the creek is losing water due to infiltration because the water table is lower than the bottom of the stream channel. This region is also dominated by karst topography which affects the creek losing water. Groundwater flow in northern FLW is affected by solution-enlarged fractures and bedding planes. Several large springs located on and off the installation receive water from precipitation recharge and stream loss on FLW (Kleeschulte and Imes 2003).

Big Piney River is a gaining stream as it flows adjacent to FLW near the eastern boundary of the post and through FLW. A gaining stream increases in water volume farther downstream as it gains water from the local aquifer. Big Piney River has a drainage area of approximately 1,450 km² (USGS 2012b) as it nears the southern boundary of FLW. Because the two drainage areas are different, hydrological analysis will be conducted on the two basins individually. The results of the two analyses will be combined to determine the overall hydrologic analysis of FLW as a whole and the amount of sustainable water available to FLW.

2.1 Hydrologic data collection

Water enters FLW through precipitation (P) and inflow (Q_{In}) (inflow can be streamflow, overland flow, and/or groundwater). Water entering FLW is naturally lost to evapotranspiration (ET) and outflow (Q_{Out}) and is also stored in detention basins (ΔSW) and groundwater (ΔGW). The consumptive use (C) at FLW is taken from a combination of surface water (predominantly streamflow) and groundwater (Mugel and Imes 2003). For any finite areas, fundamentals of conservation of mass can be used to determine the amount of water going into, water going out of, and water being stored within the system. Based on this principle, the main equation used to determine the volume of water naturally and sustainably available at FLW is shown below:

$$P + Q_{In} - \Delta SW - \Delta GW - ET - Q_{Out} - C = 0 \quad (1)$$

2.1.1 Precipitation (P)

The average annual precipitation for FLW is approximately 45 in. (1,143 mm), with most falling in the form of rain as opposed to snow (Murrell 2009).

2.1.2 Inflow (Q_{In}) and outflow (Q_{Out})

Both inflow and outflow between FLW and the surrounding region can take many forms: streamflow, overland flow, and groundwater flow. As will be discussed in the following sections, the overland flow between FLW and the region is not significant; however, the interactions of streamflow and groundwater flow between FLW and the region is significant. Studies have shown that the interaction between the stream network and groundwater in this area is highly connective (Imes et al. 1996; Mugel and Imes 2003). It is reasonable to assume that if the stream network were altered, there would be an effect on the groundwater and vice versa. Without highly detailed models and data, it is nearly impossible to determine how water taken from the stream affects the surface and groundwater systems, and the same is true for water pumped from the groundwater system. Therefore, the effects of both the groundwater flow and streamflow will be considered as one entity, with a mass volume going into FLW (Q_{In}) and a mass volume leaving FLW (Q_{Out}). The following are further descriptions of the streamflow, overland flow, and groundwater flow present at FLW.

2.1.2.1 Streamflow

Roubidoux Creek and Big Piney River are the primary discharge areas for precipitation that percolates through the unsaturated zone and recharges the water table in FLW (Imes et al. 1996). Table 2 lists the site names, USGS ID, and dates that flow data were collected for this analysis for upstream and downstream gages along Roubidoux Creek and upstream and downstream gages along Big Piney River.

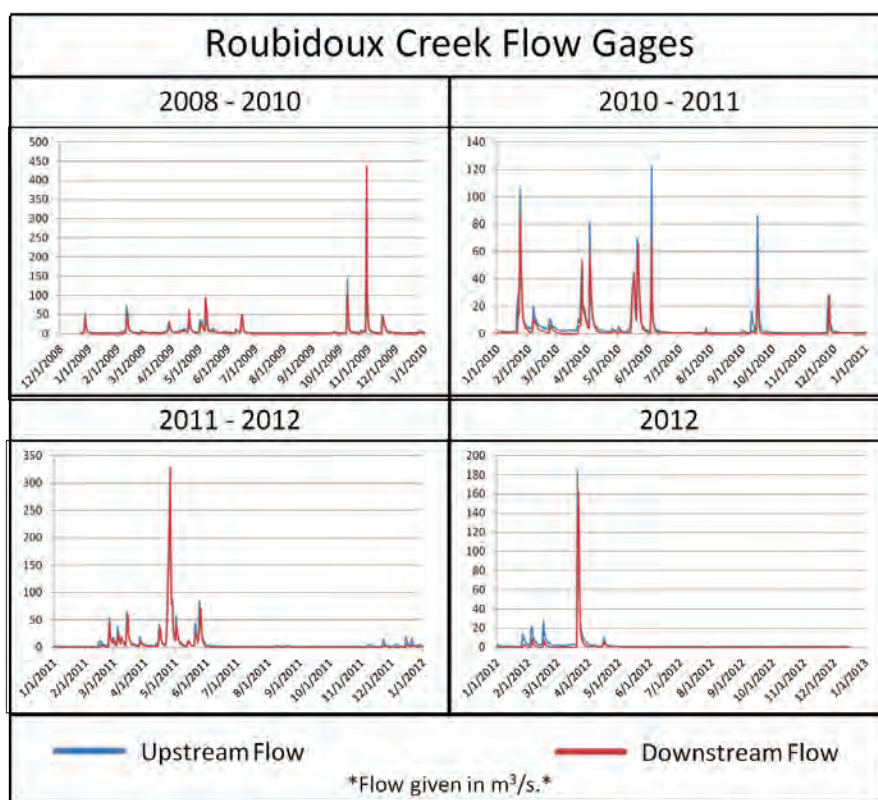
Table 2. Flow data collected near FLW.

Site Name	USGS ID	Start Date	End Date
Roubidoux Creek above Fort Leonard Wood, MO	06928300	12/23/2008	12/17/2012
Roubidoux Creek at Polla Rd below Ft. Leonard Wood, MO	06928420	12/23/2008	12/17/2012
Big Piney River near Big Piney, MO	06930000	12/3/1999	12/17/2012
Big Piney below Fort Leonard Wood, MO	06930060	12/3/1999	12/17/2012

Roubidoux Creek runs on the western and northern boundaries of FLW. It is the smaller of the two waterways and both gains and loses water to the groundwater system (Mugel and Imes 2003). It is an intermittent stream,

which means that it is dry for 7 to 8 miles along the boundary of FLW unless a large amount of runoff occurs (Imes et al. 1996). Roubidoux Creek flow data were obtained at two gage sites upstream and downstream of FLW between December 2008 and December 2012 from USGS (2012a) and USGS (2012c). Figure 6 displays the flow data collected by these two flow gages. This figure clearly shows Roubidoux Creek as a losing stream during intervals when a major rain event occurred in that area. This is demonstrated by the upstream flows being greater than the downstream flows.

Figure 6. Roubidoux Creek flow data, 2008–2012.



The Big Piney River is the larger of the two waterways and is typically a gaining stream from the groundwater system in the area near FLW¹. Big Piney River flow data were obtained at two gage sites near FLW between December 1999 and December 2012 from USGS (2012b) and USGS (2012d). Figures 7 through 9 show the flow data collected by these two flow gages. These figures show the downstream flows are higher than the upstream flows, which characterizes a gaining stream.

¹ Kaden Scott, personal communication, 10 October 2012, Missouri Department of Natural Resources.

Figure 7. Big Piney River flow data, 1999–2004.

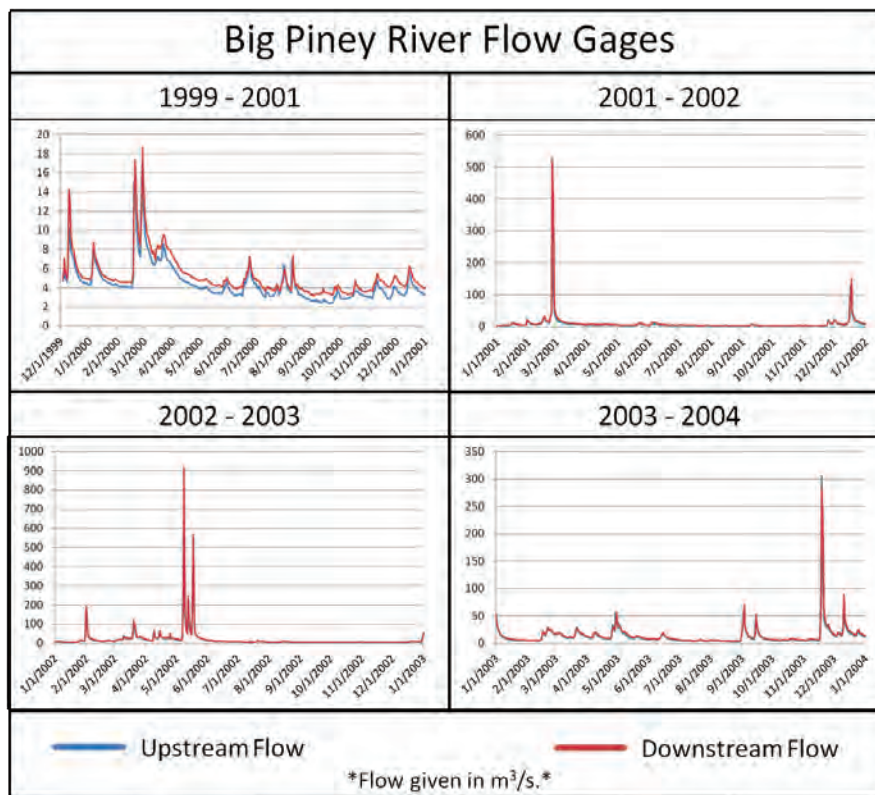


Figure 8. Big Piney River flow data, 2004–2008.

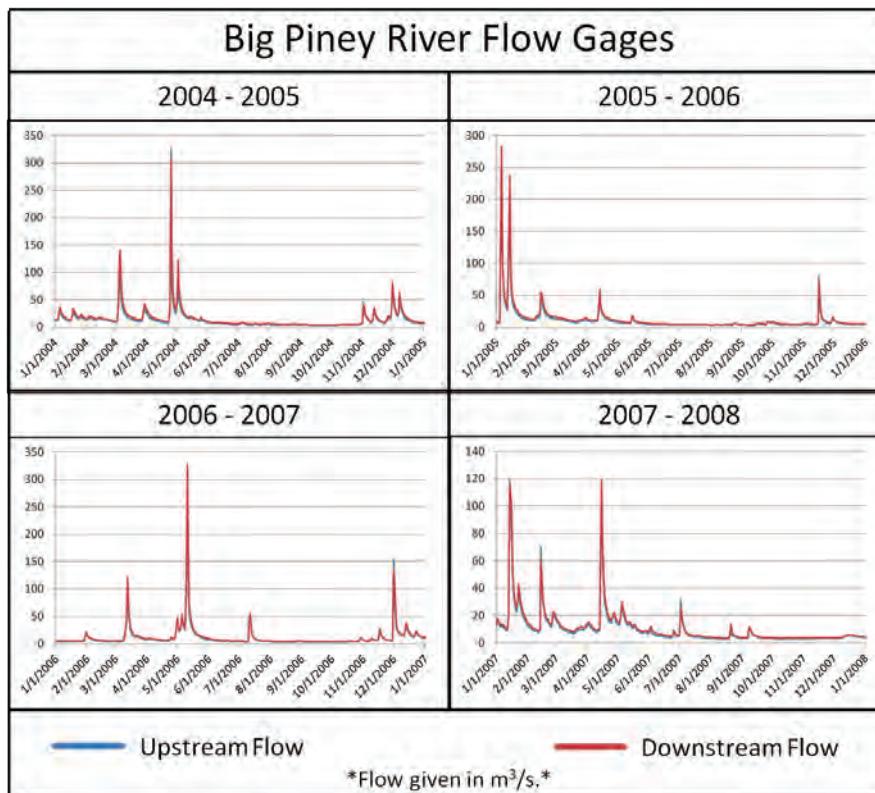
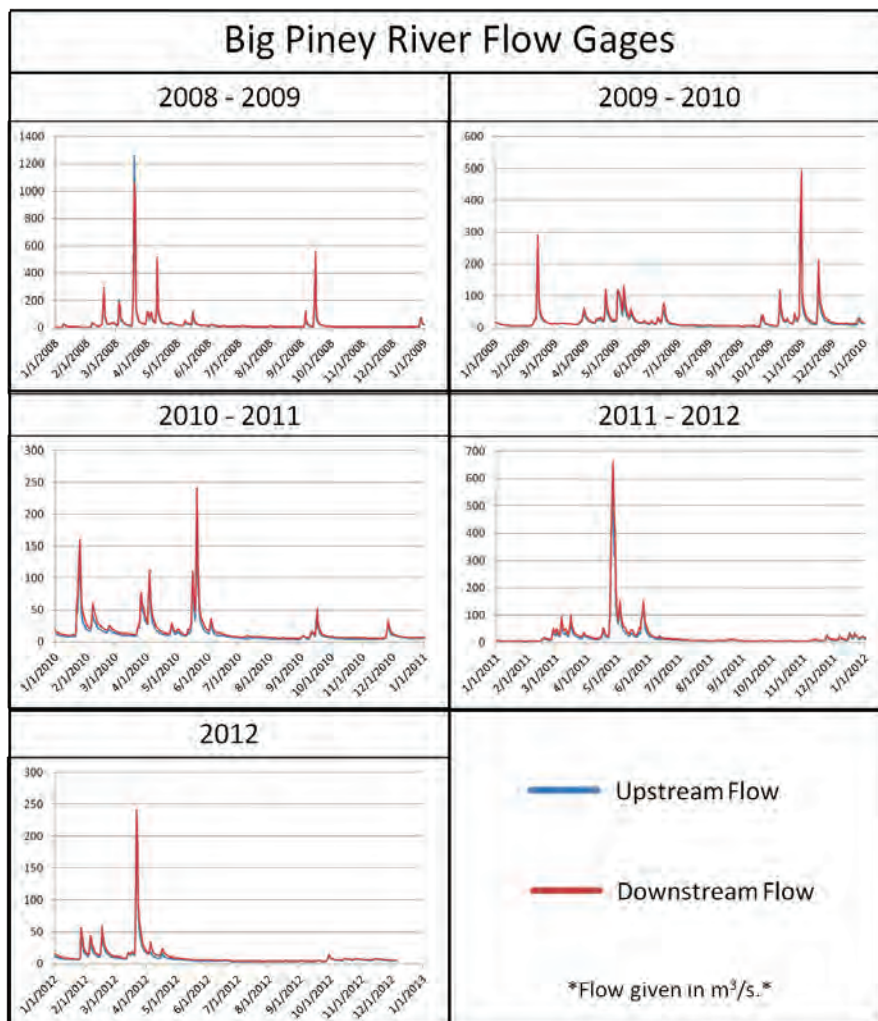


Figure 9. Big Piney River flow data, 2008–2012.



2.1.2.2 Overland flow

It is unlikely that overland flow contributes much volume, either gaining or losing, to the water balance of FLW. Numerous streams drain the area within and near FLW to the Roubidoux Creek and the Big Piney River, leaving inconsequential volumes to run overland from outside the boundary of the base towards the base and vice versa. For this reason, the overland flow volumes entering and leaving FLW will be assumed to cancel out each other and will not be accounted for within the hydrologic analysis.

2.1.2.3 Groundwater flux

Water within groundwater aquifers flows due to potentiometric head gradients. In a confined aquifer, the potentiometric head gradient, or

surface, is a hypothetical surface representing the level to which groundwater would rise if not confined by impermeable material. The potentiometric surface is equivalent to the water table in an unconfined aquifer. There are two significant aquifers near FLW. The unconfined Ozark Aquifer overlies the St. Francois Aquifer, with the St. Francois confining unit impeding the vertical movement of groundwater between the two aquifers (Murrell 2009). Although a few wells obtain water from the St. Francois Aquifer, the Ozark Aquifer is the principal source of groundwater in and around FLW (Imes et al. 1996; Mugel and Imes 2003). Studies have shown that the groundwater in the area is active (Imes et al. 1996; Mugel and Imes 2003).

Both Roubidoux Creek and Big Piney River run adjacent to FLW. The Big Piney River is generally a gaining stream, and therefore the river likely functions as a hydraulic barrier for the top layers of the water table. This means groundwater will flow to the river in the upper levels of the unconfined aquifer, but little groundwater will flow from one side of the river to the other side. Roubidoux Creek is a losing stream, and therefore the assumption cannot be made that it acts like a hydraulic barrier for the top layers of the water table. It is currently unknown, but within the lower levels of the aquifer the groundwater fluxes may move between the base boundary and outside the base. For the purposes of this study, it is assumed that spatially the groundwater fluxes behave similarly to the surface water fluxes in that groundwater does not flow across basin lines. This is a typical assumption when groundwater data is not available to determine the flow directions of the groundwater.

There is not currently a measured estimate of the groundwater flow coming into or out of FLW through groundwater fluxes. Tests have been conducted (Imes et al. 1996; Mugel and Schumacher 2004) on the interactions between the groundwater and the waterways flowing within and near FLW. These tests have shown significant interaction between the groundwater and stream network within the area. Mugel and Imes (2003) stated that the groundwater system loses much more water to the stream network through baseflow (water flowing out of groundwater and into streams) than to pumping from wells. This is significant considering that most of the area around FLW pumps water from the groundwater system as its source of water (Mugel and Imes 2003).

2.1.3 Groundwater (ΔGW) and surface water storage (ΔSW)

As previously discussed in the 2.1.2.3 Groundwater flux section, FLW has significant groundwater storage in the Ozark and St. Francois Aquifers. The groundwater storage volume likely changes due to seasonal patterns, drought periods, and wet periods. The same is true for the surface water storage on FLW in the form of detention ponds and lakes (Imes et al. 1996). The stream system at FLW can also be considered surface water storage that changes due to climatic conditions. Because NZW is typically considered over a long time frame, the net change in groundwater and surface water storage can be assumed to be zero ($\Delta SW + \Delta GW = 0$). This is because the changes due to seasons, drought periods, and wet periods will more than likely cancel out over long periods of time. This also assumes climate stationarity and that wells surrounding the base are not significantly drawing down the aquifer.

2.1.4 Evapotranspiration (ET)

Evapotranspiration is the sum of evaporation and plant transpiration from the land surface into the atmosphere and is a significant loss from the drainage basins. The average annual ET is approximately 30 in. (762 mm) for south-central Missouri (Hu et al. 2005).

2.1.5 Consumptive use (C)

FLW obtains approximately 98% of its drinking water from a pumping station located on the Big Piney River near Sandstone Spring (Mugel and Imes 2003; Murrell 2009; Conti and CH2MHill 2010). This water, as well as approximately 2% which comes from groundwater pumps, is treated at a water treatment plant on the premises of FLW (Conti and CH2MHill 2010). After consumptive use, the water is once again treated and released to Dry Creek on the northern part of the installation (Murrell 2009). Dry Creek flows northward until it drains into the Big Piney River approximately 3.7 stream miles away from the northern boundary of FLW. Dry Creek is a losing stream, with water lost to groundwater showing up in nearby springs (Mugel and Schumacher 2004). The only nonpotable usage of water on the base is the golf course, which pumps unknown volumes of water directly from the Big Piney River (Conti and CH2MHill 2010). According to Conti and CH2MHill (2010), the water treatment plant at FLW has the capacity to treat ~5 million gallons per day (MGD), but typically treats between 2.6 and 2.8 MGD, an average of 2.7 MGD. From 1993 to 1997, the amount of water

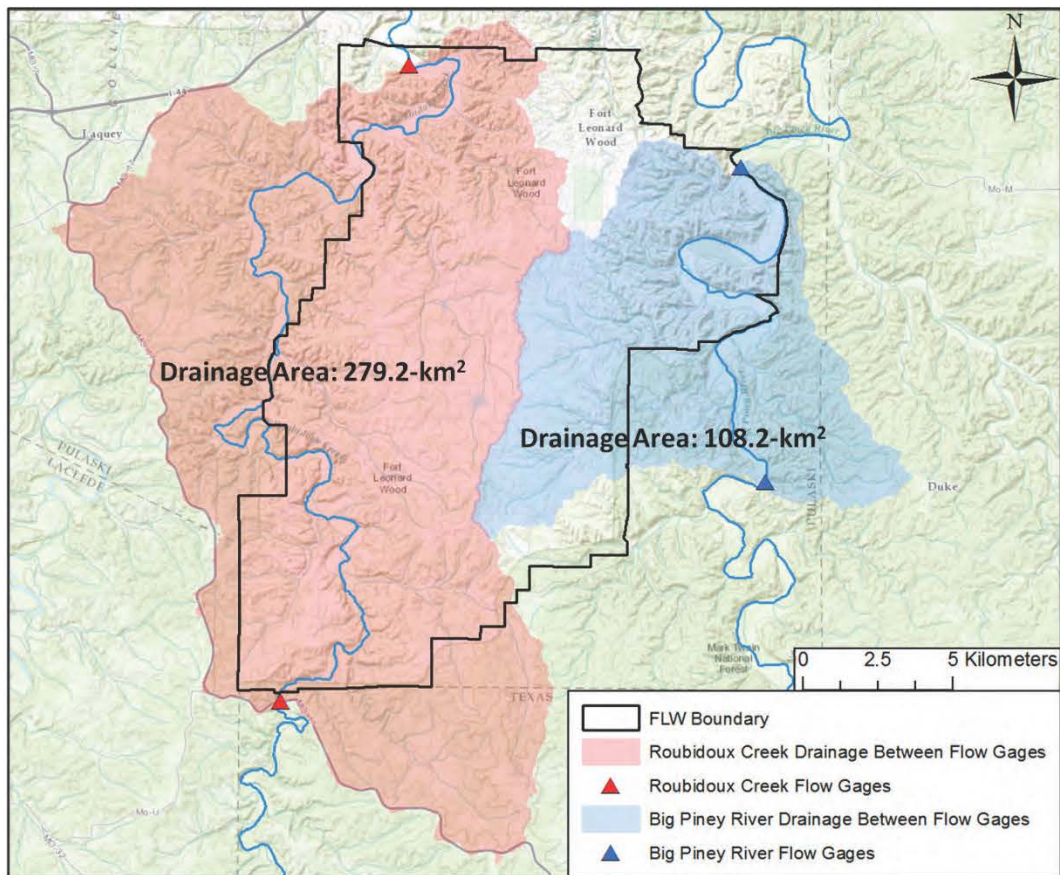
pumped from the Big Piney River at FLW ranged between 3.11 and 3.65 MGD, an average of 3.38 MGD. For the formulation used in this project, water that is returned to either the surface water network (including Dry Creek) or the groundwater is considered a part of the outflow (Q_{out}).

2.2 Spatial data collection

Elevation data (Gesch et al. 2002; Gesch 2007) for the area were gathered from the USGS National Map Viewer site (<http://nationalmap.gov/viewer.html>) at a resolution of approximately 10 m.

Using basic functions within ArcGIS (Environmental Systems Research Institute [ESRI] 2011), flow direction and flow accumulation maps were created for the area within and surrounding FLW. Based on these maps, the areas of FLW that drains to either Roubidoux Creek or Big Piney River were determined and are presented in Figure 5. Drainage areas between the stream gage located along the Big Piney River and Roubidoux Creek were also determined and are shown in Figure 10. The stream gages along Roubidoux Creek and Big Piney River capture approximately 87.2% of the drainage from within the FLW boundary. The other 12.8% drains into either Roubidoux Creek or Big Piney River but is not captured by the stream gages. Analyses will be completed for the areas captured by the gages along the Roubidoux Creek and Big Piney River. The gages act as domain boundary conditions where information is known and hydrologic flow analyses can be completed. The analyses will be conducted based on each drainage area, and the results can be applied to the entire base.

Figure 10. Drainage area between flow gages.

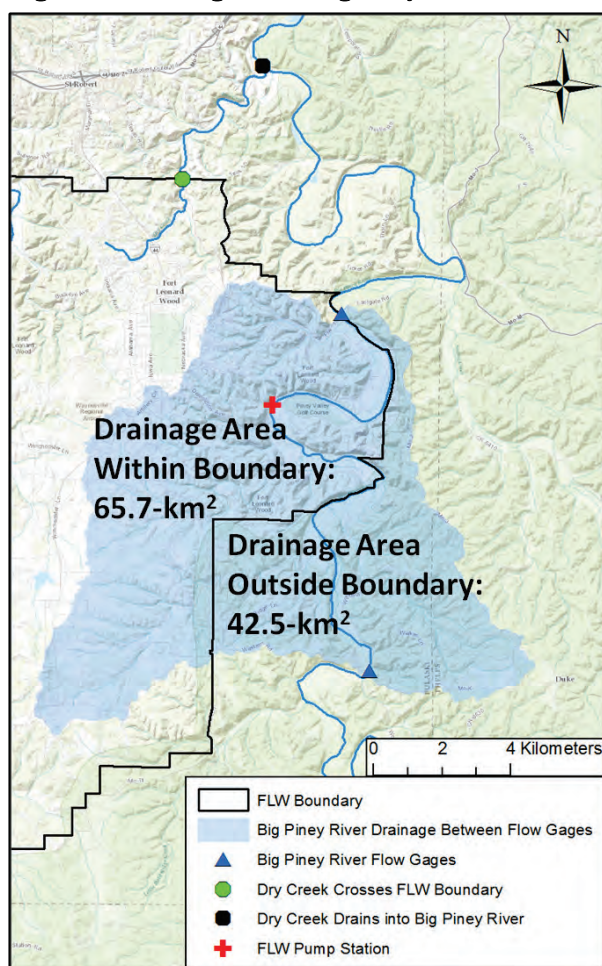


3 Results/Analyses

3.1 Big Piney River analysis

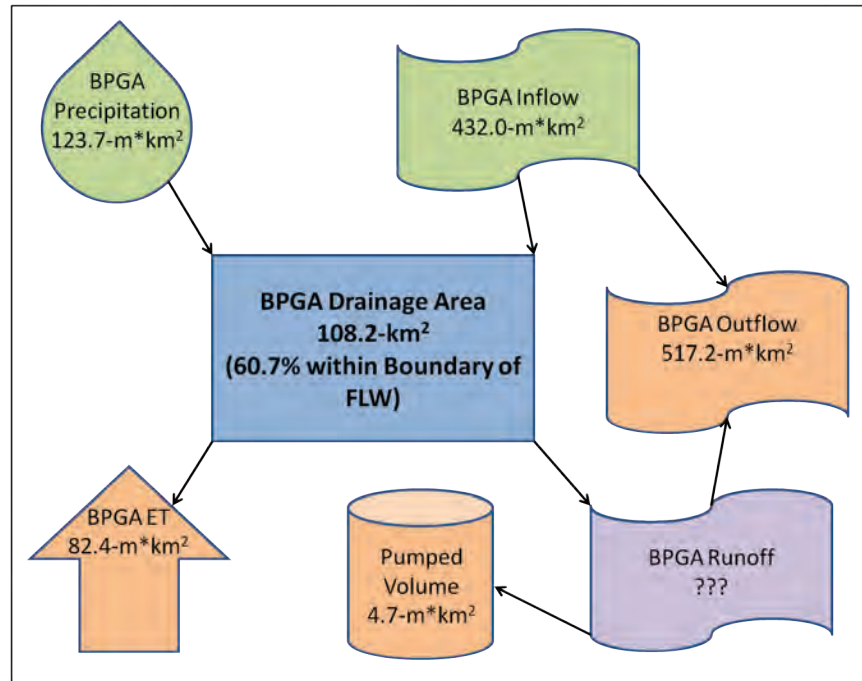
Figure 11 shows the two flow gages along the Big Piney River are located near the boundary of the FLW installation. Furthermore, the area where FLW pumps water from the Big Piney River is located between the two gage points. The drainage area between the two gage points is approximately 108.2 km², with FLW encompassing approximately 65.7 km² of that area. Between December 1999 and December 2012, the average flow at the upstream gage along the Big Piney River was 13.7 m³ · s⁻¹ while the downstream gage was 16.4 m³ · s⁻¹. The drawdown from the pump at FLW is approximately 3.38 MGD, which computes to an average of 0.15 m³ · s⁻¹.

Figure 11. Drainage of the Big Piney River near FLW.



The schematic in Figure 12 shows the annual net inputs and outputs to the drainage area between the two gage points along the Big Piney River. This area will be referred to as the Big Piney Gaged Area (BPGA). Equations 2 through 6 show how the annual volumes of water for each component of the NZW Equation 1 and shown in the schematic are calculated.

Figure 12. Annual water balance schematic of Big Piney River drainage between gage sites.



$$\begin{aligned} \text{BPGA Precipitation} &= 1,143 \text{ mm} \cdot \text{yr}^{-1} * 108.2 \text{ km}^2 \\ &= 123.7 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1} \end{aligned} \quad (2)$$

$$\begin{aligned} \text{BPGAET} &= 762 \text{ mm} \cdot \text{yr}^{-1} * 108.2 \text{ km}^2 \\ &= 82.4 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{BPGA Inflow} &= 13.7 \text{ m}^3 \cdot \text{s}^{-1} * 31,536,000 \text{ s} \cdot \text{yr}^{-1} \\ &= 432.0 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1} \end{aligned} \quad (4)$$

$$\begin{aligned} \text{BPGA Outflow} &= 16.4 \text{ m}^3 \cdot \text{s}^{-1} * 31,536,000 \text{ s} \cdot \text{yr}^{-1} \\ &= 517.2 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1} \end{aligned} \quad (5)$$

$$\begin{aligned} \text{Pumped Volume} &= 3.38 \text{ MGD} * 365 \text{ days} \cdot \text{yr}^{-1} \\ &= 4.7 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1} \end{aligned} \quad (6)$$

A reasonable assumption for this drainage is that only runoff water generated within the premises of the base can be used. To determine this, the runoff water generated in the BPGA must be calculated. Estimates of annual volumes for precipitation, ET, river inflow, river outflow, and water pumped are shown in Equations 2-6. The volume of runoff generated from the BPGA is a function of the river inflow, river outflow, and the volume pumped from the river between the two gage sites. As discussed previously, runoff in this area is generated from both surface runoff as well as precipitation percolating through the groundwater system and into the river. Equation 7 shows how the runoff is calculated between the upstream and downstream Big Piney River gage sites.

$$\begin{aligned}\text{BPGA Total Runoff} &= \text{BPGA Outflow}(517.2) - \\ &\quad \text{BPGA Inflow}(432.0) + \\ &\quad \text{Pumped Volume}(4.7) \\ &= 89.9 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1}\end{aligned}\tag{7}$$

The amount of water available for runoff within the BPGA is equivalent to the difference between precipitation and ET over the same area. Equation 8 shows the amount of water available to runoff from this area.

$$\begin{aligned}\text{BPGA Available Runoff} &= \text{BPGA Precipitation}(123.7) - \\ &\quad \text{BPGA ET}(82.4) \\ &= 41.3 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1}\end{aligned}\tag{8}$$

Because the BPGA Runoff is considerably greater than the BPGA Available Runoff, water coming from outside the BPGA is being released into the BPGA area. This further emphasizes that the groundwater in this area is very active. As will be discussed later in this report, much of this water may come from the Roubidoux Creek drainage area within FLW.

A low estimate on the annual volume of water available to FLW from the Big Piney River drainage is $36.0 \text{ m} \cdot \text{km}^2$, as shown in Equation 9. This estimate proportions the BPGA Available Runoff, which was analyzed over a 108.2 km^2 area, to the drainage area that resides within the FLW boundary (94.3 km^2 , see Figure 5).

FLW BPR Low Estimate

$$\begin{aligned}
 &= \text{BPGA AvailableRunoff} (41.3) * \frac{94.3 \text{ km}^2}{108.2 \text{ km}^2} \\
 &= 36.0 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1}
 \end{aligned} \tag{9}$$

A high estimate on the annual volume of water available to FLW from the Big Piney River drainage is $78.4 \text{ m} \cdot \text{km}^2$, as shown in Equation 10. This estimate accounts for the drainage area that resides within the FLW boundary (94.3 km^2) and considers the BPGA Runoff volume, which is shown to gain water from areas outside of the BPGA.

FLW BPR High Estimate

$$\begin{aligned}
 &= \text{BPGA TotalRunoff} (89.9) * \frac{94.3 \text{ km}^2}{108.2 \text{ km}^2} \\
 &= 78.4 \text{ m km}^2 \text{ yr}^{-1}
 \end{aligned} \tag{10}$$

3.2 Roubidoux Creek analysis

Figure 13 shows the two gages along the Roubidoux Creek are located near the boundary of the FLW installation. The drainage area between the two gage points is approximately 279.2 km^2 , with FLW encompassing approximately 152.7 km^2 of that area. Between December 2008 and December 2012, the average flow at the upstream gage along Roubidoux Creek was $5.2 \text{ m}^3 \cdot \text{s}^{-1}$ while the downstream gage was $3.8 \text{ m}^3 \cdot \text{s}^{-1}$. Approximately $1.4 \text{ m}^3 \cdot \text{s}^{-1}$ is lost between the two gages along Roubidoux Creek.

The schematic in Figure 14 shows the annual net inputs and outputs to the drainage area between the two gage points along Roubidoux Creek. This drainage area will be referred to as the Roubidoux Creek Gaged Area (RCGA). Equations 11 through 14 show how the annual volumes of water for each component of the NZW Equation 1 and shown in the schematic are calculated.

$$\begin{aligned}
 \text{RCGA Precipitation} &= 1,143 \text{ mm} \cdot \text{yr}^{-1} * 279.2 \text{ km}^2 \\
 &= 319.1 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1}
 \end{aligned} \tag{11}$$

$$\begin{aligned}
 \text{RCGA ET} &= 762 \text{ mm} \cdot \text{yr}^{-1} * 279.2 \text{ km}^2 \\
 &= 212.8 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1}
 \end{aligned} \tag{12}$$

Figure 13. Roubidoux Creek drainage network near FLW.

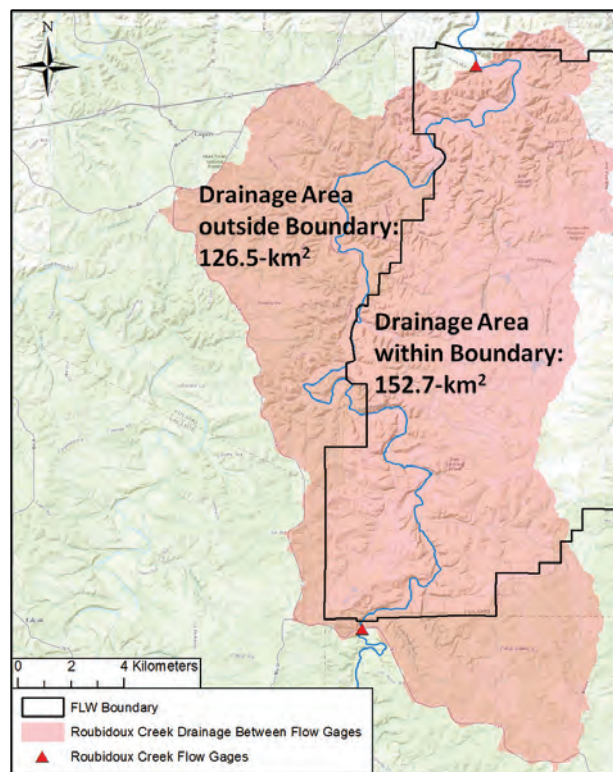
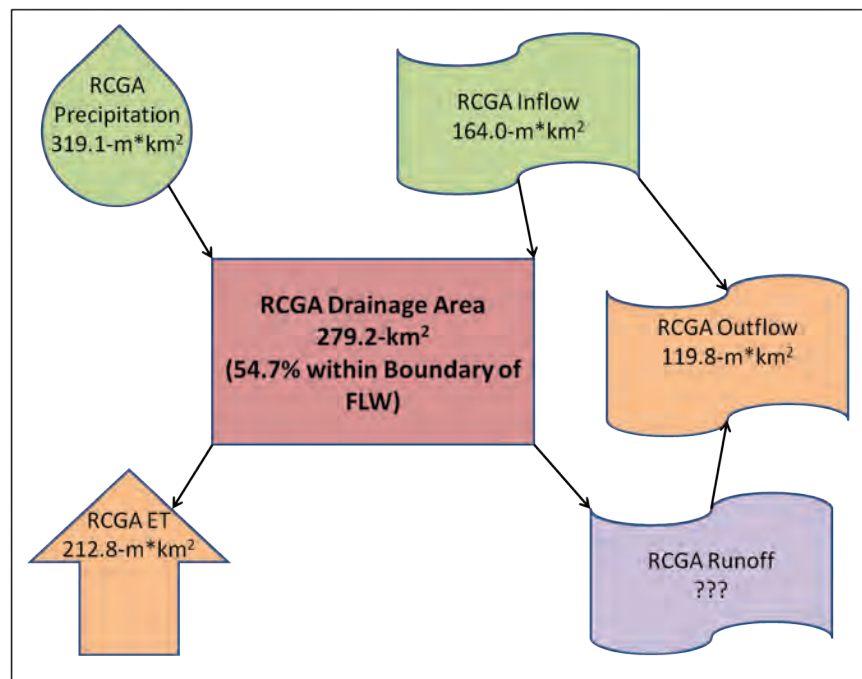


Figure 14. Annual water-balance schematic of Roubidoux Creek Drainage between gage sites.



$$\begin{aligned}\text{RCGA Inflow} &= 5.2\text{m}^3 \cdot \text{s}^{-1} * 31,536,000\text{s} \cdot \text{yr}^{-1} \\ &= 164.0\text{m} \cdot \text{km}^2 \cdot \text{yr}^{-1}\end{aligned}\quad (13)$$

$$\begin{aligned}\text{RCGA Outflow} &= 3.8\text{m}^3 \cdot \text{s}^{-1} * 31,536,000\text{s} \cdot \text{yr}^{-1} \\ &= 119.8\text{m} \cdot \text{km}^2 \cdot \text{yr}^{-1}\end{aligned}\quad (14)$$

As applied to BPGA, a reasonable assumption for the RCGA drainage is that only runoff water generated within the premises of the base can be used. To determine this, the runoff water generated in the RCGA must be calculated. Estimates of annual volumes for precipitation, ET, river inflow, and river outflow are shown in Equations 11–14. The volume of runoff generated from the RCGA is a function of the river inflow and river outflow. As previously discussed, runoff in this area is generated from both surface runoff as well as precipitation percolating through the groundwater system and into the river. Equation 15 shows how the runoff is calculated between the upstream and downstream Roubidoux Creek gage sites.

$$\begin{aligned}\text{RCGA Total Runoff} &= \text{RCGA Outflow}(119.8) - \\ &\quad \text{RCA Inflow}(164.0) \\ &= -44.2\text{m} \cdot \text{km}^2 \cdot \text{yr}^{-1}\end{aligned}\quad (15)$$

Because RCGA Runoff is a negative value, it is inferred that Roubidoux Creek loses water as it flows through RCGA. Mugel & Imes (2003) found that Roubidoux Creek lost considerable amounts of water in certain areas and determined that the water lost to the groundwater system often resurfaced in areas downstream. This is largely due to the karst topography in this region. The amount of water annually available for runoff within the RCGA is equivalent to the difference between precipitation and ET over the same area. Equation 16 shows the amount of water available to runoff from the RCGA area.

$$\begin{aligned}\text{RCGA Available Runoff} &= \text{RCGA Precipitation}(319.1) - \\ &\quad \text{RCGA ET}(212.8) \\ &= 106.3\text{m} \cdot \text{km}^2 \cdot \text{yr}^{-1}\end{aligned}\quad (16)$$

Because the RCGA Available Runoff is considerably greater than the RCGA Runoff, water within RCGA is being released and lost to surrounding areas. The water is probably being lost downstream through groundwater

movement, as was found by Mugel & Imes (2003) that other parts of Roubidoux Creek were also lost through groundwater movement. The water could also be moving through the groundwater to the Big Piney River, which was shown in the Big Piney River Analysis section to be gaining water from drainages outside BPGA. More tests would have to be completed to verify this, and it is probably only infiltrated water at the farthest east boundary of RCGA that would end up in the Big Piney River. Most infiltrated water closer to Roubidoux Creek flows through the groundwater downstream as was shown to occur in other parts of Roubidoux Creek (Mugel and Imes 2003).

At the most extreme, an argument can be made that within FLW boundaries, water is lost from Roubidoux Creek and is transported through groundwater to Big Piney River. This is an unrealistic scenario but will serve as the premise for determining a conservative or low estimate on the annual volume of water available to FLW from the Roubidoux Creek drainage. In this case, because water is lost to the groundwater system while flowing through RCGA, FLW would have to make up approximately $24.7 \text{ m} \cdot \text{km}^2$, as shown in Equation 17. This estimate proportions the RCGA Total Runoff, which was analyzed over a 279.2 km^2 area, to the drainage area that resides within the FLW boundary (156.2 km^2 , see Figure 5).

FLWRC Low Estimate

$$\begin{aligned} &= \text{RCGA Total Runoff}(-44.2) * \frac{156.2 \text{ km}^2}{279.2 \text{ km}^2} \\ &= -24.7 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1} \end{aligned} \quad (17)$$

A high estimate on the annual volume of water available to FLW from the Roubidoux Creek drainage is $59.5 \text{ m} \cdot \text{km}^2$, as seen in Equation 18. This estimate accounts for the drainage area that resides within the FLW boundary (156.2 km^2) and considers the RCGA Available Runoff Volume, which is shown to not overcome the losses occurring within Roubidoux Creek as it flows through RCGA. As Figure 6 shows, Roubidoux Creek is intermittent, and therefore if consistent water is required from the Roubidoux Creek drainage, it would need to be pumped from the groundwater.

FLW RC High Estimate

$$\begin{aligned}
 &= \text{RCGA Available Runoff} (106.3) * \frac{156.2 \text{ km}^2}{279.2 \text{ km}^2} \\
 &= 59.5 \text{ m} \cdot \text{km}^2 \cdot \text{yr}^{-1}
 \end{aligned} \tag{18}$$

A more feasible estimate for the annual volume of water available to FLW from the Roubidoux Creek drainage is $0.0 \text{ m} \cdot \text{km}^2$. As previously mentioned, Roubidoux Creek is intermittent and cannot be relied upon as a consistent source of water unless the water is taken from the groundwater. More tests would have to be completed at FLW to determine if pumping $59.5 \text{ m} \cdot \text{km}^2$ of water annually from the groundwater, which is the high estimate, will adversely affect (1) the groundwater table, (2) ecological factors, (3) downstream users of Roubidoux Creek, and (4) availability of water in the Big Piney River. It is also unrealistic for FLW to annually have to replenish $24.7 \text{ m} \cdot \text{km}^2$ of water, the FLW Roubidoux Creek Low Estimate, to make up the water lost within Roubidoux Creek. This loss of water is shown to occur in other parts of the creek and is most likely a part of the natural balance.

3.3 Entire Fort Leonard Wood (FLW) analysis

As previously mentioned, FLW can be split into two distinct drainages: Roubidoux Creek and Big Piney River. Sustainable-use water from Roubidoux Creek drainage is estimated at 0.0 m km^2 annually. Sustainable-use water available from Big Piney River drainage is estimated annually between 36.0 and $78.4 \text{ m} \cdot \text{km}^2$. Currently, best estimates indicate FLW uses approximately $4.7 \text{ m} \cdot \text{km}^2$ of water annually. Based on this analysis, FLW should continue to utilize the water resources available within the Big Piney River drainage. Further analysis can be made to determine sustainability of water on a seasonal scale using the same data but accounting for seasonal shifts in precipitation and evapotranspiration.

4 Conclusions

The FLW installation has abundant natural water resources in both groundwater and surface water. Even with abundant resources, it is imperative that FLW continue to use these resources wisely to ensure that they will be available for the foreseeable future. This report analyzes the current resources available to FLW as well as produces estimates of annual usage from these sources that will enable FLW to rely on them for decades to come.

To determine estimates of sustainable use of water resources, FLW was divided into two basins: Roubidoux Creek drainage which is approximately 62.4% of FLW and Big Piney River drainage which is approximately 37.6% of FLW. The surface water and groundwater interaction in this area of south-central Missouri is very active due to the karst topography; therefore, any change in groundwater will directly affect the surface water and vice versa. Because of this, it is assumed that the movement of surface water and groundwater between each drainage area and the surrounding area can be adequately represented as a single process. Using existing flow data as well as referenced estimates of precipitation and evapotranspiration, regional water analyses were completed on both drainages. Based on these analyses, estimates of sustainable water use for each drainage area were calculated.

It is determined that no water can sustainably be taken from the Roubidoux Creek drainage. Roubidoux Creek is intermittent, and the stream loses water to the groundwater system as it flows through FLW. Groundwater could be pumped from the Roubidoux Creek drainage, but more information must be gathered on whether doing so will cause adverse effects on downstream constituents, local ecology, and other local water resources such as the Big Piney River.

The Big Piney River is where FLW currently obtains ~98% of its potable water. The water is treated and returned to the Big Piney River via Dry Creek on the northern boundary of FLW. Estimates of annual sustainable yield from the Big Piney River ranged between 36.0 and 78.4 m · km², with the lower limit being more realistic because it will result in the average inflow and outflow to be identical as the river flows through FLW.

With current annual usage of water at FLW being approximately $4.7 \text{ m} \cdot \text{km}^2$, which is well below the sustainable yield from the Big Piney River, it is reasonable to assume that future expansions of FLW would not adversely affect the current drainage. Changes in the climate would impact the amount of water that is available; however, it is believed that any changes in the climate would have to be extremely severe to adversely affect FLW.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE August 2015			2. REPORT TYPE Technical Report		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Hydrologic Analysis of Fort Leonard Wood, Missouri					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Michael L. Follum, Darla C. McVan, Elisabeth M. Jenicek, and Michael P. Case					5d. PROJECT NUMBER	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER Work Units 8609C7, BH01K8, and LG7452	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Coastal and Hydraulics Laboratory U.S. Army Engineer Research and Development Center 3909 Halls Ferry Road Vicksburg, MS 39180-6199					8. PERFORMING ORGANIZATION REPORT NUMBER ERDC TR-15-4	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Engineer Research and Development Center 3909 Halls Ferry Road, Vicksburg, MS 39180-6199					10. SPONSOR/MONITOR'S ACRONYM(S)	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT This report analyzes the hydrologic ability of Fort Leonard Wood (FLW) in south-central Missouri to sustainably meet its water requirements with natural sources within the boundaries of the installation. This report documents efforts under the Research, Development, Test, and Evaluation project, Integrated Installation Energy, Water, and Waste Modeling. This work was carried out in the second year of a 4-year program that is building on Net Zero Energy to tackle the more complicated problem of reducing energy, waste, and water at the same time through development of the Net Zero Installations (NZI) tool. It also supports the Army's Net Zero Water (NZW) program that seeks to enable Army posts to become self-reliant on basic needs, such as water, therefore becoming more secure and versatile. A definition of water sustainability is first given and then applied to the current sources of water available to FLW. Although this report is specific to FLW, it outlines a framework in which future NZW analyses can be completed for other installations. It is imperative to have an understanding of the water available to an Army post. This helps determine the ability of each installation to sustainably adapt to changing troop levels under a changing climate. The NZW framework of the NZI tool helps installations to understand the amount of water that is available from various sources such as rivers, groundwater, and municipal sources. Through this knowledge, Army staff can properly plan for the future and for emergency operations that may stress the current infrastructure. This report outlines only one piece of NZW, the regional analysis of naturally available water to support the base sustainably.						
15. SUBJECT TERMS Big Piney River Fort Leonard Wood MO			Hydrologic analysis Net-Zero water program Roubidoux Creek		Water balance Watershed	
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 43	19a. NAME OF RESPONSIBLE PERSON Darla C. McVan	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) (601) 634-2869	