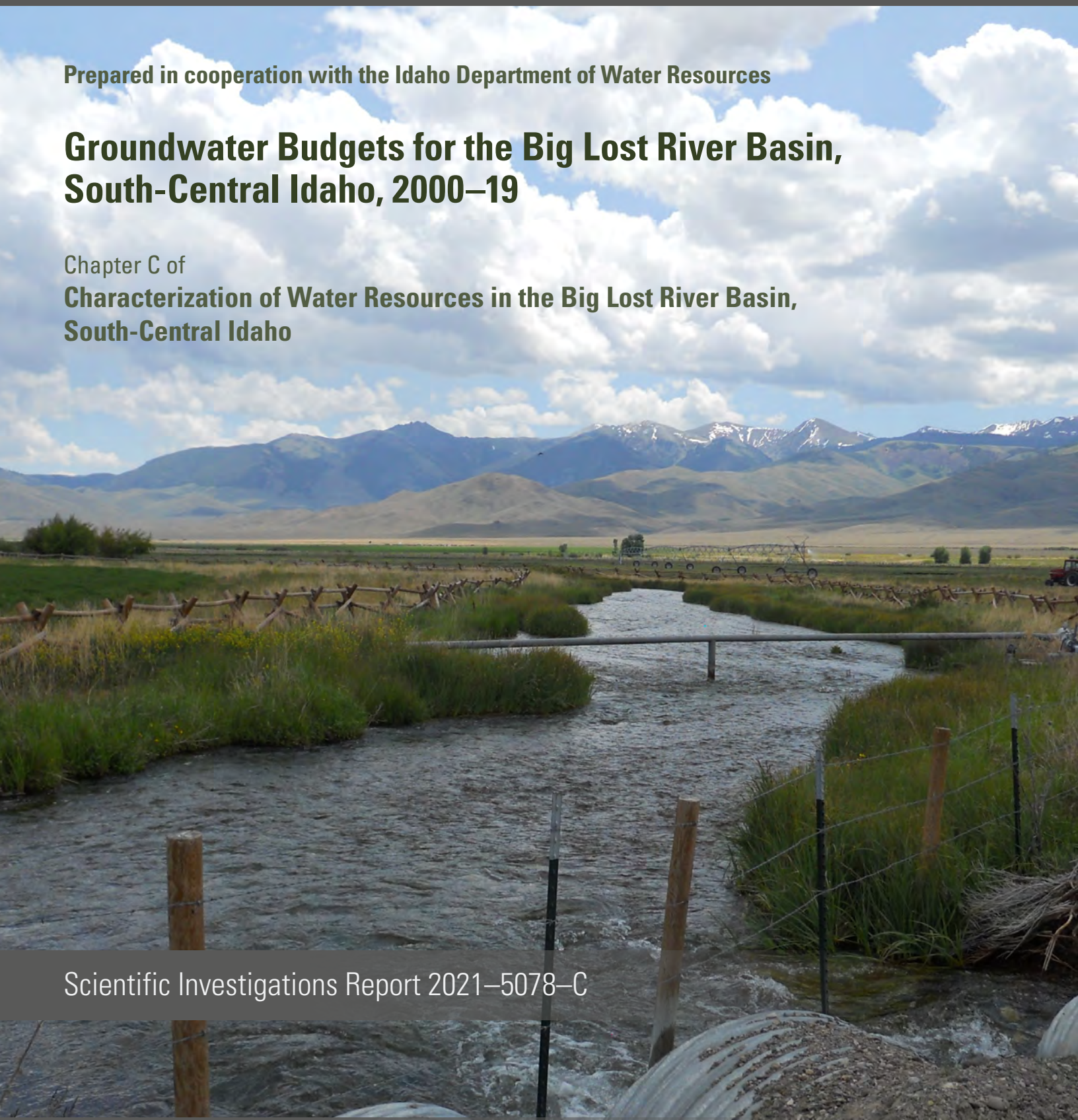
USGS
science for a changing world

Prepared in cooperation with the Idaho Department of Water Resources

Groundwater Budgets for the Big Lost River Basin, South-Central Idaho, 2000–19

Chapter C of
Characterization of Water Resources in the Big Lost River Basin, South-Central Idaho



Scientific Investigations Report 2021–5078–C

U.S. Department of the Interior
U.S. Geological Survey

Cover. Warm Springs Creek, looking downstream (southeast) toward the Lost River Range, south-central Idaho. Photograph by Alexis Clark, Idaho Geological Survey, July 3, 2019.

Groundwater Budgets for the Big Lost River Basin, South-Central Idaho, 2000–19

By Alexis Clark, Idaho Geological Survey

Chapter C of
Characterization of Water Resources in the Big Lost River Basin, South-Central Idaho

Edited by Lauren M. Zinsser, U.S. Geological Survey

Prepared in cooperation with the Idaho Department of Water Resources

Scientific Investigations Report 2021–5078–C

U.S. Geological Survey, Reston, Virginia: 2022

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov/.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this information product, for the most part, is in the public domain, it also may contain copyrighted materials as noted in the text. Permission to reproduce copyrighted items must be secured from the copyright owner.

Suggested citation:
Clark, A., 2022, Groundwater budgets for the Big Lost River Basin, south-central Idaho, 2000–19, chap. C *of* Zinsser, L.M., ed., Characterization of water resources in the Big Lost River Basin, south-central Idaho: U.S. Geological Survey Scientific Investigations Report 2021–5078–C, 111 p., https://doi.org/10.3133/sir20215078C.

ISSN 2328-031X (print)
ISSN 2328-0328 (online)

Preface

This is the third of three reports in a multichapter volume characterizing water resources in the Big Lost River Basin. These reports document the findings of a hydrogeologic investigation of the Big Lost River Basin that was jointly done by the U.S. Geological Survey, Idaho Department of Water Resources, and the Idaho Geological Survey from 2018 through 2021. Chapter A (Zinsser, 2021) describes the hydrogeologic framework of the Big Lost River Basin. It includes a conceptual definition of the hydrogeologic units, a three-dimensional hydrogeologic-framework model, and a description of groundwater occurrence and movement. Chapter B (Dudunake and Zinsser, 2021) describes streamflow gains from and losses to groundwater in the Big Lost River between Mackay Reservoir and south of Arco, Idaho. Streamflow gains and losses were estimated from a series of four surface-water measurement events during pre- and post-irrigation season conditions from 2019 to 2021. Chapter C (this report) describes groundwater budgets for the Big Lost River Basin from 2000 to 2019. The groundwater budgets provide annual estimates for aquifer inflows and outflows. Collectively, these reports present a characterization of water resources in the Big Lost River Basin that will help address current challenges in water-resources management.

Acknowledgments

The author thanks the following organizations and individuals who provided valuable contributions to this work. U.S. Geological Survey staff included Lauren Zinsser for her input and collaboration on this project, James Bartolino and Adel Haj for technical reviews, Roy Bartholomay for Center Director review, Joseph Mangano for figure production, John Osias for editorial review, and Tim Merrick for report coordination. Idaho Department of Water Resources staff included Craig Tesch, Amy Steimke, Jennifer Sukow, David Hoekema, Bill Kramber, Mike McVay, and Cindy Yenter for technical assistance, datasets, and resources throughout the project duration. Lucas Yockey, watermaster for District 34, led an informative field trip. Idaho Geological Survey staff Claudio Berti provided supervisor review, Nate Hopkins supported figure production, Kate Schalck provided editorial review, Jess Starnes provided editorial support, and Christopher Tate provided data support.

Contents

Preface iii
Acknowledgments iv
Abstract 1
Introduction 2
Purpose and Scope 4
Previous Work 4
Study Area 6
Land Use 7
Climate 7
Groundwater Budgets 12
Inflows to the Aquifer 15
Areal Recharge 15
Data Sources, Methods, and Assumptions 16
Areal Recharge Results 17
Tributary Canyon Underflow 18
Data Sources, Methods, and Assumptions 18
Tributary Canyon Underflow Results 24
Seepage from Mackay Reservoir 24
Data Sources, Methods, and Assumptions 24
Mackay Reservoir Seepage Results 25
Recharge of Applied Water 26
Applied Irrigation 26
Data Sources, Methods, and Assumptions 28
Applied Irrigation Recharge Results 29
Canal Seepage 29
Data Sources, Methods, and Assumptions 30
Canal Seepage Recharge Results 34
Managed Aquifer Recharge 36
Data Sources, Methods, and Assumptions 36
Managed Aquifer Recharge Results 36
Municipal Wastewater Treatment Plants 36
Data Sources, Methods, and Assumptions 37
Wastewater Treatment Plant Recharge Results 37
Septic System Effluent 38
Data Sources, Methods, and Assumptions 38
Septic System Effluent Recharge Results 38
Losing and Gaining River Reaches 38
Data Sources, Methods, and Assumptions 38
Losing and Gaining River Reach Results 43
Above Mackay Dam 43
Below Mackay Dam 44

Outflows from the Aquifer 45
Groundwater Pumpage to Canals and Ditches 45
Data Sources, Methods, and Assumptions 45
Groundwater Pumpage to Canals and Ditches Results 45
Groundwater Pumpage 45
Irrigation 46
Data Sources, Methods, and Assumptions 46
Groundwater Pumpage for Irrigation Results 46
Domestic Supply 47
Data Sources, Methods, and Assumptions 47
Groundwater Pumpage for Domestic Supply Results 47
Municipal Supply 47
Data Sources, Methods, and Assumptions 47
Groundwater Pumpage for Municipal Supply Results 47
Groundwater-Budget Residuals 47
Changes in Groundwater Storage 48
Groundwater-Budget Uncertainty and Errors 49
Groundwater Resource Sustainability 50
Suggestions for Groundwater-Budget Use and Future Data Collection 52
Future Data Collection 53
Expanded Reference Datasets 53
Alternative Methodologies 54
Summary and Conclusions 54
References Cited 55
Appendix 1. Land Coverage 63
Appendix 2. Precipitation Data 70
Appendix 3. Areal Recharge 72
Appendix 4. Tributary Canyon Underflow Supporting Detail 76
Appendix 5. Irrigation Efficiency 83
Appendix 6. Surface-Water Diversions and Groundwater Pumpage 84
Appendix 7. Return Surface-Water Flow 90
Appendix 8. Estimated Canal Seepage Details 92
Appendix 9. River-Reach Gain and Loss Assumptions 95
Appendix 10. Evapotranspiration 104

Figures

1. Map showing locations of communities, groundwater-budget extents, aquifer extent, and weather stations, Big Lost River Basin, south-central Idaho....3
2. Map showing irrigated, semi-irrigated, and non-irrigated lands in the Big Lost River Basin, south-central Idaho....8
3. Graph showing total annual precipitation calculated using Parameter-elevation Regressions on Independent Slopes Model (PRISM), Big Lost River Basin, south-central Idaho, 2000–19....12
4. Schematic showing groundwater budget for the Big Lost River Basin, south-central Idaho....13
5. Graph showing average groundwater-budget components, as calculated in this report, for the Big Lost River Basin, south-central Idaho, 2000–19, 2014, and 2017....15
6. Map showing aquifer extent used for areal recharge analysis in the Big Lost River Basin, south-central Idaho....16
7. Graph showing total estimated areal recharge in the Big Lost River Basin by subbasin extent, south-central Idaho, 2000–19....17
8. Map showing tributary drainages evaluated for underflow in the Big Lost River Basin, south-central Idaho....19
9. Graph showing percentage deviation from mean annual storage (1950–2019) for Mackay Reservoir and groundwater-level trends in well IDWR 17 (05N 26E 23CDA1), Big Lost River Basin, south-central, Idaho, 2000–19....26
10. Graph showing estimated recharge from applied irrigation, surface-water diversions, groundwater pumpage, and irrigation requirement in the Big Lost River Basin, south-central Idaho, 2000–19....30
11. Graphs showing estimated consumptive use of irrigated crops and total estimated irrigation recharge compared to total estimated crop requirement, in the Big Lost River Basin, south-central Idaho, 2000–19....31
12. Maps showing water conveyance in the Big Lost River Basin, south-central Idaho....32
13. Graph showing estimated canal seepage in the Big Lost River Basin, south-central Idaho, 2000–19....34
14. Graph showing mean monthly streamflow at streamgages with multi-year records in the Big Lost River Basin, south-central Idaho, 2000–19....39
15. Map showing reaches used to calculate annual gains and losses in the Big Lost River, south-central Idaho....40
16. Graph showing mean annual estimated gains and losses in reaches of Big Lost River, south-central, Idaho, 2000–19....43
17. Graph showing Palmer Drought Severity Index for regions within the Big Lost River Basin, south-central Idaho, 1900–2020....51
18. Graphs showing deviation from mean annual streamflow for U.S. Geological Survey streamgages in the Big Lost River Basin, south-central Idaho, 1950–2019....52

Tables

1. Published groundwater budgets for the Big Lost River Basin, south-central Idaho 5
2. Weather stations, snowpack telemetry (SNOTEL) sites, and snow course sites in the Big Lost River Basin, south-central Idaho.....10
3. Summary of precipitation data, Big Lost River Basin, south-central Idaho 11
4. Estimated annual groundwater budgets for the Big Lost River Basin, south-central Idaho, for average conditions during 2000–19, 2014 (dry), and 2017 (wet).....14
5. Estimated tributary basin underflow for the Big Lost River Basin, south-central Idaho, 2000–19.....20
6. Estimated mean seepage from Mackay Reservoir, south-central Idaho, 2000–19.....27
7. Reported surface-water diversion volumes, calculated delivery factors, and estimated canal and ditch seepage volumes below Mackay Reservoir, Big Lost River Basin, south-central Idaho, 2015–19.....35
8. Managed aquifer recharge total annual volumes for the Big Lost River Basin, south-central Idaho, 2000–19.....37
9. Mean streamflow at streamgages in the Big Lost River Basin, south-central Idaho.....41
10. Calculated mean annual groundwater residuals for the Big Lost River Basin, south-central Idaho, 2000–19.....48

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)

Multiply	By	To obtain
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
inch per day (in/d)	9,721	millimeter per year (mm/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C = (°F – 32) / 1.8.

Datums

Vertical coordinate information, where known, is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum unless otherwise specifically noted.

Abbreviations

AgriMet	agricultural meteorology
ARC	Arco 3 SW (station)
ASCE	American Society of Civil Engineers
BLRID	Big Lost River Irrigation District
CDL	cropland data layer (CropScape)
CHA	Chilly Barton Flat (station)
CIR	crop irrigation requirement
ESPA	eastern Snake River Plain aquifer
ESPAM	Eastern Snake Plain Aquifer Model (formerly referred to as the Enhanced Snake Plain Aquifer Model)
ET	evapotranspiration
GIS	geographic information system
HUC	hydrologic unit code
HSPF	Hydrological Simulation Program
IDWR	Idaho Department of Water Resources
IGS	Idaho Geological Survey
INL	Idaho National Laboratory
MAC	Mackay Ranger Station
MAR	managed aquifer recharge
METRIC	Mapping EvapoTranspiration at high Resolution and Internalized Calibration
MODFLOW	Modular Three-Dimensional Finite-Difference Ground Water Flow Model
NAIP	National Agriculture Imagery Program
NDVI	Normalized Difference Vegetation Index
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
NWS	National Weather Service
PDSI	Palmer Drought Severity Index
POU	place of use
PRISM	Parameter-elevation Regressions on Independent Slopes Model
Q20	20-percent flow exceedance
Q50	median monthly flow duration
Q80	80-percent flow exceedance

R^2	coefficient of determination
Reclamation	Bureau of Reclamation
SNOTEL	snowpack telemetry
SRP	Snake River Plain
SWE	snow water equivalent
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WMIS	water management information system
WRCC DRI	Western Regional Climate Center Desert Research Institute
WWTP	wastewater treatment plant

Groundwater Budgets for the Big Lost River Basin, South-Central Idaho, 2000–19

By Alexis Clark[1]

Abstract

The Big Lost River Basin, located in parts of Butte and Custer Counties in south-central Idaho, supports the communities surrounding the cities of Arco, Leslie, Mackay, and Moore and provides for agricultural resources that depend on a sustainable supply of surface water from the Big Lost River and its tributaries and groundwater from an unconfined aquifer. The aquifer, situated in a structurally controlled intermontane valley, is composed of unconsolidated alluvium, consolidated sedimentary and volcanic rocks, and younger interbedded volcanic rocks.

This report presents two separate groundwater budgets for the aquifer, one above and one below Mackay Dam, as well as a combined groundwater budget for the aquifer within the entire Big Lost River Basin. The budgets span a 20-year period (2000–19), characterizing average conditions, a dry year (2014), and a wet year (2017). The groundwater budgets will help address questions regarding the availability of groundwater supply in the Big Lost River Basin and inform future groundwater modeling. The Idaho Geological Survey has prepared the groundwater budgets as part of a larger hydrogeologic investigation completed by the U.S. Geological Survey and the Idaho Geological Survey in cooperation with the Idaho Department of Water Resources during 2018–21. Other reports describe the hydrogeologic framework and several streamflow-measurement events to evaluate gains and losses on the Big Lost River. Collectively, these reports provide an updated characterization of groundwater resources in the Big Lost River Basin which will help address water resources challenges.

A groundwater budget is a conceptual and numerical accounting of inflow (recharge) to groundwater and outflow (discharge) from groundwater. The predominant sources of recharge to the aquifer include losing river reaches (33 percent), areal recharge (as precipitation less evapotranspiration and surface runoff, comprising about 23 percent of the total inflow), tributary canyon underflow from higher altitudes (20 percent), canal seepage (13 percent), recharge through applied irrigation on fields below the root zone and other minor sources (11 percent), and Mackay Reservoir seepage (less than 1 percent). The primary sources of discharge from the aquifer are groundwater pumpage to meet irrigation demand, domestic supply, and municipal supply (76 percent) and gaining river reaches (24 percent).

The positive or negative difference between the sum of all inflows and outflows is regarded as the residual, representing the change in groundwater storage, groundwater outflow from the basin or subbasins, and uncertainty and errors in the budget. In the Big Lost River Basin, groundwater outflow is at the mouth of the basin below Arco into the eastern Snake River Plain aquifer.

The total mean annual estimated recharge to the Big Lost River Basin was 439,100 acre-feet per year (acre-ft/yr; 607 cubic feet per second [ft^3/s]) for 2000–19, 373,900 acre-ft/yr (516 ft^3/s) in 2014, and 762,100 acre-ft/yr (1,053 ft^3/s) in 2017. The mean annual estimated groundwater discharge from the aquifer was about 112,300 acre-ft/yr (155 ft^3/s) for 2000–19, 153,500 acre-ft/yr (212 ft^3/s) in 2014, and 53,400 acre-ft/yr (74 ft^3/s) in 2017. The estimated mean annual groundwater residual was 326,800 acre-ft/yr (451 ft^3/s) for 2000–19, 220,400 acre-ft/yr (304 ft^3/s) in 2014, and 708,700 acre-ft/yr (979 ft^3/s) in 2017. The mean annual residual above Mackay Dam was 100,400 acre-ft/yr (2000-19), 96,700 acre-ft (2014), and 248,300 acre-ft (2017). The mean annual residual contribution below Mackay Dam, minus any groundwater-flow above Mackay Dam, was 226,400 acre-ft/yr (2000-19), 123,700 acre-ft (2014), and 460,400 acre-ft (2017).

These results are highly sensitive to assumptions about certain budget inflow parameters. In particular, the magnitude of the budget residuals during especially dry and wet periods is amplified by the groundwater-budget terms *tributary streamflow* and *tributary underflow* that contribute appreciable recharge but also have high uncertainty.

The results of the groundwater-budget evaluation describe an interconnected and complex hydrologic response throughout the basin to various climatic and water-use trends. The part of the basin above Mackay Dam typically has a positive groundwater residual derived from snowmelt recharge to tributary canyons and areal recharge in excess of groundwater pumpage for irrigation demand. This supply is used to meet irrigation demand above Mackay Dam and to provide for water supply below Mackay Dam. On average, groundwater inflow from above Mackay Dam to below Mackay Dam, assuming negligible reservoir storage effects,

[1]Idaho Geological Survey

accounts for about 25 percent of the total groundwater recharge below Mackay Dam. Considerable recharge to groundwater below Mackay Dam occurs through seepage from the Big Lost River and canals and ditches. Most groundwater discharge from the aquifer is through irrigation pumping. The water supply below Mackay Dam is highly dependent on available upstream surface-water flows, the magnitude of the groundwater residual from above Mackay Dam, and annual variability in local groundwater conditions.

Introduction

The Big Lost River Basin is a mountainous drainage basin in south-central Idaho that is tributary to the eastern Snake River Plain aquifer (ESPA). The Big Lost River is the prominent river in the basin. The largest population centers are Arco in the southern part of the basin and Mackay just south of Mackay Reservoir (fig. 1). Smaller communities in the lower part of the basin include Moore, Leslie, and Darlington. North of Mackay Reservoir, the basin is sparsely populated near Chilly and Thousand Springs Creek[2].

The Idaho Geological Survey (IGS) prepared groundwater budgets (this document) for the Big Lost River Basin spanning a 20-year period from 2000 to 2019. This work was done jointly with the U.S. Geological Survey (USGS) during 2018–21 in cooperation with the Idaho Department of Water Resources (IDWR) as part of a larger hydrogeologic investigation of the Big Lost River Basin.

The USGS installed five new streamgages in the basin and developed a hydrogeologic framework (Zinsser, 2021). In cooperation with the IDWR, the USGS hosted four, separate streamflow measurement events of the Big Lost River in spring and autumn during 2019–21 (Dudunake and Zinsser, 2021). The IDWR installed 18 new monitoring wells near the Big Lost River as nested well installations incorporated in the existing monitoring well network (IDWR, 2019, 2021a), and they completed a water-quality investigation (Womeldorph and Steimke, 2022). The USGS completed downhole geophysical surveys on eight existing IDWR monitoring wells and two new wells (Zinsser, 2021). The Bureau of Reclamation installed an agricultural meteorology (AgriMet) weather station near Moore, Idaho, brought online in November 2019 (Bureau of Reclamation, 2016).

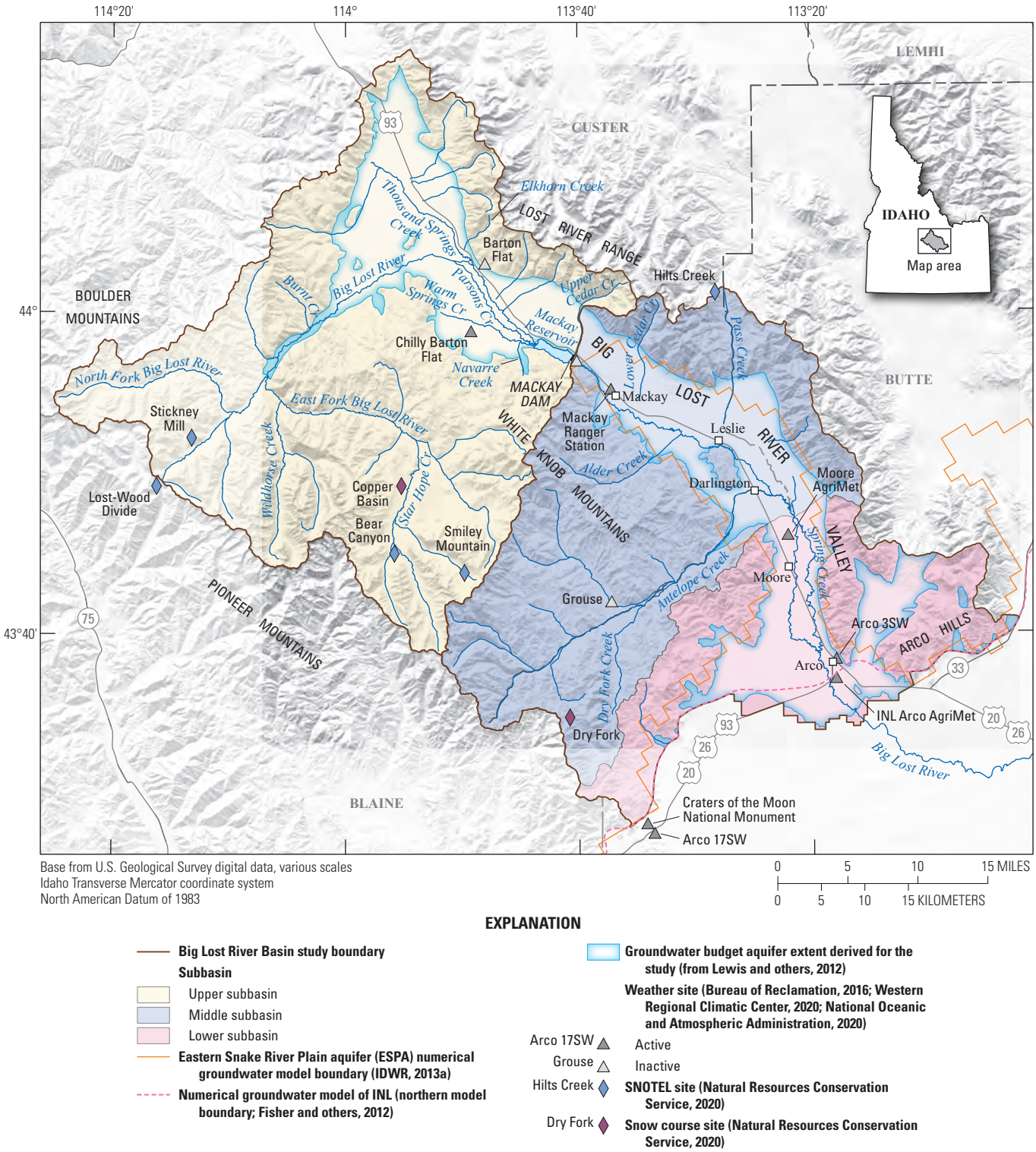
Periodic droughts, declining groundwater-level trends in some parts of the basin, and declining streamflows have prompted implementation of several protective measures including the following:

1. The recognition that surface water and groundwater are interrelated in this basin, leading to the conjunctive management of surface-water and groundwater resources;
2. The transition to higher-efficiency farming methods such as center pivot technology and canal lining;
3. Opportunistic managed aquifer recharge during times of available surface-water supply;
4. Focused hydrologic data collection to better understand the relation between surface-water and groundwater interaction, climatic patterns, and the changes in the aquifer responses over time; and,
5. The undertaking of hydrogeologic investigations, including this study.

Persistent issues and questions regarding future available water resources have prompted this hydrogeologic investigation. Agriculture accounts for the largest use of water supplies in the basin. The predominant crops grown in the Big Lost River Basin include alfalfa and grain crops irrigated primarily by pivot and sprinkler systems that use surface-water and groundwater resources that are hydraulically connected. Water District 34 is authorized by the IDWR to administer the delivery of surface water and groundwater based on water rights in the Big Lost River Basin. Water supply is delivered through a complex system of surface-water diversions and a canal distribution network totaling about 170 miles (mi), nearly 1,700 groundwater extraction wells (including domestic, municipal, and irrigation), and the Mackay Reservoir with an approximate storage capacity of 44,370 acre-feet (acre-ft). Mackay Reservoir above the town of Mackay effectively divides the upper and lower parts of the basin and is used for irrigation. Available water resources below Mackay Reservoir are highly dependent on water availability in the basin above Mackay Reservoir.

The last comprehensive hydrogeologic investigation of the Big Lost River Basin was done by the USGS in the late 1960s (Crosthwaite and others, 1970a). Newer, higher-resolution methodologies for quantifying climatic factors including precipitation and evapotranspiration (historically more difficult to evaluate), direct measurement of surface-water diversions and groundwater pumpage for irrigation, and additional groundwater-level data collected since the last investigation afford greater accuracy in characterizing the hydrogeologic framework and estimating groundwater budgets (this investigation).

[2]The Thousand Springs Creek area in the Big Lost River Basin referred to in this report is not the same Thousand Springs area that serves as a major groundwater discharge for the eastern Snake River Plain aquifer described in Garabedian (1992).



Base from U.S. Geological Survey digital data, various scales
Idaho Transverse Mercator coordinate system
North American Datum of 1983

EXPLANATION

- Big Lost River Basin study boundary
- Subbasin
  - Upper subbasin
  - Middle subbasin
  - Lower subbasin
- Eastern Snake River Plain aquifer (ESPA) numerical groundwater model boundary (IDWR, 2013a)
- Numerical groundwater model of INL (northern model boundary; Fisher and others, 2012)
- Groundwater budget aquifer extent derived for the study (from Lewis and others, 2012)
- Weather site (Bureau of Reclamation, 2016; Western Regional Climatic Center, 2020; National Oceanic and Atmospheric Administration, 2020)
  - Arco 17SW — Active
  - Grouse — Inactive
- Hilts Creek — SNOTEL site (Natural Resources Conservation Service, 2020)
- Dry Fork — Snow course site (Natural Resources Conservation Service, 2020)

Figure 1. Locations of communities, groundwater-budget extents, aquifer extent, and weather stations, Big Lost River Basin, south-central Idaho. IDWR, Idaho Department of Water Resources; INL, Idaho National Laboratory; SNOTEL, Snowpack telemetry.

The ESPA has had declining aquifer storage trends since the mid-1950s (about 13 million acre-ft from 1952 to 2013), leading to its designation in November 2016 by IDWR as a Ground Water Management Area. The Idaho Water Resources Research Institute and IDWR (IDWR, 2013a) constructed a numerical groundwater-flow model (the Enhanced Snake Plain Aquifer Model, or ESPAM) using the Modular Three-Dimensional Finite-Difference Ground Water Flow Model (MODFLOW; Harbaugh and others, 2000). IDWR actively maintains the model, with periodic calibration updates with new datasets, as a tool for simulating surface-water and groundwater interactions and groundwater-flow conditions within the ESPA (Sukow, 2021). The model supports agency and stakeholder water resource and administrative management decisions. The area in the Big Lost River Basin below Mackay Dam is within the ESPAM domain. Groundwater outflow from the Big Lost River Basin goes to the ESPA below the Idaho National Laboratory (INL) facility. The USGS developed a numerical groundwater-flow and contaminant-transport model to represent flow and contaminant pathways below the INL (Ackerman and others, 2010). The northern boundary for the numerical model is within the Big Lost River Basin below Arco (fig. 1). This investigation considered the INL model boundary and additional irrigated lands immediately south of the boundary within the basin. In this report, the groundwater budget and results are presented and used to address the sustainability of groundwater resources and to inform future studies in regard to data collection methods, conceptual model refinement, and numerical groundwater modeling efforts.

Purpose and Scope

The purpose of this report is to present an average groundwater budget determined from a 20-year period (2000–19) and groundwater budgets for an individual dry year (2014) and a wet year (2017). This period is intended to include variability in climatic conditions and water use. The wet and dry years were selected on the basis of average annual precipitation, storage changes in Mackay Reservoir, and groundwater-level trends during the 20-year period. Calendar years, rather than water years, were used unless otherwise indicated. This study period was selected to satisfy technical and administrative objectives outlined in this report. Most years during this period were perceived as having sufficient resolution of key datasets to reduce potential uncertainty in estimating groundwater budgets. Separate groundwater budgets were prepared for two areas ("above Mackay Dam"—or "upper subbasin"—and "below Mackay Dam") that influence the water resources of the basin as a whole. This study does not attempt to quantify the surface-water budget, although surface-water and groundwater interaction factors prominently in the preparation of the groundwater budget.

The groundwater budget was created by (1) examining inflows to the aquifer including areal recharge, tributary canyon underflow, seepage from Mackay Reservoir, and recharge of applied water; (2) examining losing and gaining river reaches; and (3) determining outflows from the aquifer. Groundwater budget residuals, changes in storage, and uncertainty also were examined. Suggestions are provided for how this work may inform future studies, data collection, further conceptual model refinement, or numerical groundwater modeling efforts.

This groundwater budget report is the third of three reports on water resources of the Big Lost River Basin; previous work is published in Zinsser (2021) and Dudunake and Zinsser (2021). Collectively, these works provide an updated characterization of water resources in the basin and provide data and interpretation for water-resources decision making and future groundwater modeling.

Previous Work

Groundwater budgets for the Big Lost River Basin have been published for various periods from 1920 to 2010 (Stearns and others, 1938; Mundorff and others, 1964; Crosthwaite and others, 1970a; Said and others, 2005; Sukow, 2017; Ackerman and others, 2010). This section summarizes investigations that provide a basin-scale, comprehensive treatment of water budgets. The estimated order of magnitude of the total annual average groundwater outflow from the basin from prior investigations ranges from 204,000 to 307,700 acre-feet per year (acre-ft/yr) (table 1).

Variability in the estimated annual water budgets from previous studies is expected, attributable to differences in the datasets used, spatial and temporal extents, methodologies, underlying assumptions, and uncertainty and errors. Comparisons of prior investigations with results from this study should consider the processes reflected in the reported budget results (particularly if outflow is accounted for separately from the estimated change in storage) and the datasets, methods, and assumptions. Therefore, previously developed groundwater budgets may not be directly comparable to those for the current study because of these factors.

Stearns and others (1938) estimated that the average annual groundwater outflow from the basin to the Snake River Plain (SRP) was 226,000 acre-ft/yr for water years (October 1–September 30) 1920–27. This volume was calculated from the total available surface-water supply as streamflow minus crop consumptive demand below Mackay Dam. Available water-supply totals for the basin were estimated from combined streamflow volumes and estimates of inflow from tributary streams below Mackay Dam (fig. 1). Estimated crop consumption was 1.7 acre-ft per acre for areas above and below Mackay Dam.

Table 1. Published groundwater budgets for the Big Lost River Basin, south-central Idaho.

[**Study extent:** ESPA, eastern Snake River Plain aquifer; INL, Idaho National Laboratory. **Abbreviation:** acre-ft/yr, acre-foot per year]

Source	Time period of study	Study extent	Basin discharge (acre-ft/yr)	Comments
Stearns and others, 1938	[1]1920–27	Above and below Mackay Dam	226,000	Groundwater
Mundorff and others, 1964	1921–50	Above Mackay Dam	280,000	Surface water and groundwater
		Below Mackay Dam	60,000	
Crosthwaite and others, 1970a	1944–68	Above and below Mackay Dam	307,700	Groundwater underflow above gauge near Arco
Said and others, 2005	2000	Above and below Mackay Dam	267,000	Surface water and groundwater
Sukow, 2017	1985–2010	ESPA model below Mackay Dam	204,000	Groundwater
Ackerman and others, 2010	1966-90	INL site northern model boundary	261,400	Steady state numerical groundwater-flow model input

[1]Water years (October 1–September 30)

Mundorff and others (1964) reported an average annual outflow of 340,000 acre-ft/yr, combining surface water and groundwater, from the Big Lost River Basin during 1921–50. This work was done as part of a larger study of the SRP. The authors defined water yield as "all the water leaving the basin by surface or groundwater flow," excluding evapotranspiration (Mundorff and others, 1964, p. 43). Separate water budgets in terms of water yield were prepared for areas above Mackay Dam (280,000 acre-ft/yr) and below Mackay Dam (60,000 acre-ft/yr).

Crosthwaite and others (1970a) published the last, most comprehensive groundwater-budget analysis, spanning 1944–68, with an estimated average annual groundwater outflow of 307,700 acre-ft/yr (425 ft^3/s) for the entire basin, leaving the basin at a location above the streamgage near Arco. Separate estimates were compiled for 33 of 44 identified subbasins. Subtotals were reported for separate areas, including 35 ft^3/s (25,340 acre-ft/yr) above Howell Ranch, 75 ft^3/s (54,300 acre-ft/yr) above Mackay Narrows, and 325 ft^3/s (235,290 acre-ft/yr) above the Moore Diversion. These subtotals suggest 75 ft^3/s (54,300 acre-ft/yr) of groundwater underflow above Mackay Dam, 250 ft^3/s (181,000 acre-ft/yr) of groundwater underflow between Mackay Dam and the Moore diversion below the town of Moore, and 100 ft^3/s (72,400 acre-ft/yr) of groundwater underflow between the Moore diversion and Arco. Mean annual precipitation for the basin (1.52 million acre-ft) was determined from an isohyetal map for the study period based on four weather stations (Arco, Chilly Barton Flat, Grouse, and Mackay Ranger Station). The estimated average annual evapotranspiration for the basin was approximately 1.0 million acre-ft. The authors reported that they used an estimated consumptive crop irrigation requirement of 1.2 acre-ft per acre below Mackay Reservoir. The irrigated acres within the basin were 49,000 acres using surface water and 8,500 acres using groundwater; non-irrigated cropland acreage was 18,000 acres. Water yield was quantified by the total average annual input (as precipitation) minus total average annual output (as evapotranspiration), excluding groundwater storage. A map of distributed water yield was used to inform groundwater budgets for individual subbasins.

Using an integrated surface-water and groundwater numerical flow model (Hydrological Simulation Program—FORTRAN [HSPF], together with MODFLOW), Said and others (2005) estimated the total year-2000 groundwater volume leaving the basin at about 267,000 acre-ft. The model simulated unconfined aquifer, transient conditions and incorporated a uniform average precipitation rate. Evapotranspiration was derived from the Jensen and Haise (1963) method based on solar radiation inputs and estimated groundwater pumpage using available electrical power records, and incorporated aquifer and soil parameters. Twelve separate subbasins were defined in the model.

The average annual groundwater budget for the Big Lost River Basin below Mackay Reservoir simulated in ESPAM (version 2.1; IDWR, 2013a) was approximately 204,000 acre-ft/yr for the 1985–2010 period of model calibration (Sukow, 2017). This rate accounts for the change in groundwater storage and reflects groundwater outflow from the basin. The model does not simulate the area above Mackay Dam. The model incorporates aquifer inflow (recharge) and outflow (discharge) water-budget components. Primary sources for recharge to the aquifer include seepage from rivers (as losing reaches), conveyance loss from canals, reservoir seepage, infiltration of precipitation and excess irrigation water, and tributary drainage underflow. The predominant discharge sources include evapotranspiration, groundwater discharge to rivers (as gaining reaches) and springs, pumping

wells, and basin underflow. Surface-water diversions and groundwater pumpage for the Big Lost River Basin were based on Water District 34 records for the period from 1980 to 1996 and were estimated using a mass balance and regression approach for the period from 1997 to 2008. Big Lost River seepage was calculated "using gage data, estimated Antelope Creek inflows, and recorded or estimated diversions" (IDWR, 2013a, p. 67) for the reach between Mackay and the stream gages near Arco.

Ackerman and others (2010) constructed a steady and transient-state groundwater-flow model for INL. This model simulates groundwater outflow from the Big Lost River Basin using a specified flow boundary condition with a uniform rate of 261,400 acre-ft/yr (361 ft^3/s). Ackerman and others (2010) calculated this rate by subtracting simulated streamflow infiltration from the Big Lost River from the basin yield. The basin yield, including groundwater flow and surface-water flow, was determined from the annual average water yield to the SRP from adjacent mountainous areas for water years 1934–80, as defined by Garabedian (1992) and Kjelstrom (1986).

Since previous groundwater-budget estimates were published, new data and newer technologies have become available to evaluate inputs to the water budget, such as precipitation and evapotranspiration. The updated groundwater budget, presented in this report, is intended to convey how the basin has responded to water-use trends and climatic conditions during 2000–19.

Study Area

The Big Lost River Basin is commonly described in terms of an upper area above Mackay Dam and a lower area below the dam such that these areas effectively are treated as two separate hydrologic subbasins (fig. 1). The upper part of the basin is less populated and has less agriculture (averaging about 12,400 acres) compared to the lower part that supports development centered around the Big Lost River, including an extensive network of irrigation canals and ditches, surface-water diversions, and groundwater pumpage for cultivation of about 55,000 acres and the towns of Mackay, Leslie, Moore, and Arco.

The Boulder, Pioneer, and White Knob Mountains form the mountainous uplands on the west side of the Big Lost River Basin. The Lost River Range and Arco Hills form the mountainous uplands on the east side of the Big Lost River Basin.

The Big Lost River is the predominant stream, with headwaters in the north fed by the North Fork of the Big Lost River (draining the Boulder Mountains) and the East Fork of the Big Lost River and its tributaries (draining the Pioneer and White Knob Mountains). From its headwaters, the Big Lost River flows northeast, where the valley widens past Thousand Springs Creek and is characterized by losing river reaches and wetlands. The Big Lost River turns roughly 90 degrees in the Thousand Springs Creek area and flows southeast parallel with U.S. Route 93, with increased agricultural diversions through the central part of the valley (particularly near Parsons and Warm Springs Creeks), to Mackay Reservoir above the town of Mackay.

Bedrock outcropping at Mackay Dam constricts the valley floor and separates the upper and lower part of the basin. Below Mackay Reservoir, the most substantial tributaries are Alder and Antelope Creeks on the west side of the valley. Several drainages enter the basin on the east side of the valley below Mackay Dam, most prominently Upper Cedar, Lower Cedar, and Pass Creeks. Surface flow in these drainage areas is intercepted by extensive alluvial fans (Lewis and others, 2012) associated with high permeability resulting in either no or inconsequential surface discharge to the Big Lost River.

The Big Lost River Basin, as described in this report for the purpose of preparing a groundwater budget, is defined by the watershed bounded by the mountain ranges that surround the aquifer in the valley. A basin scale was selected to account for groundwater underflow from the mountainous areas to the aquifer (fig. 1). The aquifer extent used in this study was informed by surficial geological mapping of Quaternary alluvial and alluvial-fan deposits and Pleistocene glacial deposits (Lewis and others, 2012) predominantly found in the valley.

The groundwater budget is defined by hydrogeologic processes that occur within the aquifer footprint, with the addition of estimated groundwater underflow from the larger watershed boundary. The aquifer extent used in the groundwater budget differs from that presented in the hydrogeologic framework chapter of this report (Zinsser, 2021) based on specific goals for each study. For example, parts of the aquifer within delineated tributary drainages and at higher altitudes were not included in the aquifer boundary for the water budget to avoid overlap with the estimated tributary canyon underflow to the aquifer (see section, "Tributary Canyon Underflow") and the use of the aquifer extent in the areal recharge budget term (see section, "Areal Recharge").

The study area for the groundwater-budget assessment is the Big Lost River Basin (fig. 1) to where it drains into the ESPA below the town of Arco. The area of focus for this study is based on hydrologic unit code (HUC 17040218; U.S. Geological Survey, 2018a) to incorporate surface-water interaction with groundwater in the estimated groundwater budgets. The northern, eastern, and western boundaries of the study area coincide with HUC 17040218 boundaries. The southern boundary of the study includes irrigated acres referred to as "Era Flats" south of Arco and within the INL model boundary but not the full HUC 17040218 extent to the south.

The study area is further subdivided for particular water-budget components. For example, assignment of representative evapotranspiration rates using values derived from nearby weather stations is handled by separating the area below Mackay Dam near the Moore Diversion north of

the town of Moore into a "middle subbasin" above the Moore Diversion and a "lower subbasin" below the Moore Diversion on the basis of HUC 10 boundaries. The terms "middle subbasin" and "lower subbasin" are used throughout this report to designate, respectively, areas above and below the Moore Diversion.

Land Use

Agricultural areas and rangelands factor prominently into the groundwater budget. For example, groundwater-budget components, including areal recharge (see section, "Areal Recharge") and applied irrigation recharge (see section, "Applied Irrigation"), incorporate land use in the estimation of recharge volumes. Different groundwater-budget components account for separate processes (natural and anthropogenic) based on the land-use category and spatial footprint.

The IDWR has created digitized irrigated-lands spatial datasets for the ESPA and other areas within the State, including the Big Lost River Basin, that define "irrigated" and "semi-irrigated" land-use categories (fig. 2) and a "non-irrigated" land-use category (IDWR, 2020a). A separate designation is used for semi-irrigated lands to indicate "generally residential land" (IDWR, 2006). In the Big Lost River Basin, semi-irrigated lands primarily are assigned to towns and rural communities (near farm residences) to include water uses other than for irrigation of crops such as lawn watering. See appendix 1 ("Land Coverage") for further discussion of irrigated-land coverages in addition to other land-coverage datasets—including Cropland Data Layer (CDL) and National Land Cover Database (NLCD) —used in preparation of the groundwater budget.

Preparation of groundwater budgets relies heavily on spatial datasets, with rendering and analyses done using geographic information system (GIS) tools in ArcGIS (Esri, 2018, 2020). This groundwater-budget study incorporates applicable digital data products, to the extent available, with the goal of preserving data representation, accuracy, and reproducibility in estimating water-budget parameters.

Climate

This section provides a brief overview of the climatic conditions in the Big Lost River Basin and summarizes precipitation datasets (2000–19) used in the preparation of the groundwater budget. The climate in the Big Lost River Basin is typical of high desert-mountain conditions. Winter months are often long and cold, and summers are short and hot. Precipitation varies greatly with season and altitude. Temperatures can be less than 0 degrees Fahrenheit (°F) in winter and may exceed 90 °F in summer. Average annual minimum temperatures recorded at five snowpack telemetry (SNOTEL) sites (fig. 1; Natural Resources Conservation Service, 2020) in the Big Lost River Basin during the study period ranged from 21 to 30 °F, and the average annual maximum temperatures ranged from 47 to 52 °F. Higher annual average temperatures were recorded on the valley floor at Arco, ranging from 33 to 54 °F over the study period.

A strong correlation or orographic effect exists between precipitation and altitude (Crosthwaite and others, 1970a; Daly and others, 1994). As is typical of intermontane basins, most annual precipitation occurs as snow at higher altitudes from November to March based on mean monthly snow water equivalent (SWE; median annual SWE of 20–33 inches [in.] during 2000–19 at SNOTEL sites). Less precipitation occurs as snowfall at lower altitudes in the valley (median annual SWE of 7–10 in. during 2000–19 at weather stations). Overall precipitation trends in the Big Lost River Basin indicate higher precipitation above Mackay Dam compared to less precipitation below the dam, particularly below the Moore Diversion.

Precipitation represents the largest component for inflow of water into the basin that informs multiple components of the water budget, including areal recharge (see section, "Areal Recharge"); tributary canyon underflow (see section, "Tributary Canyon Underflow"); seepage from Mackay Reservoir (see section, "Seepage from Mackay Reservoir"); applied irrigation recharge (see section, "Applied Irrigation"); and estimated, unmeasured streamflow used to estimate seepage from Big Lost River reaches (see section, "Losing and Gaining River Reaches"). The time scale (daily or monthly) and spatial resolution of the precipitation datasets (single weather station or an interpolated, gridded raster product) factor into selecting the most appropriate source of precipitation data for a given groundwater-budget component. Therefore, multiple precipitation datasets used for different components are introduced here and described further in appendix 2 ("Precipitation Data").

Precipitation datasets were obtained from the following multiple sources:

- National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) weather stations (National Oceanic and Atmospheric Administration, 2020),
- Western Regional Climatic Center Desert Reach Institute (WRCC DRI) weather stations (Western Regional Climatic Center, 2020),
- AgriMet weather stations (Bureau of Reclamation, 2016),
- U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) SNOTEL sites and snow course locations (Natural Resources Conservation Service, 2020),

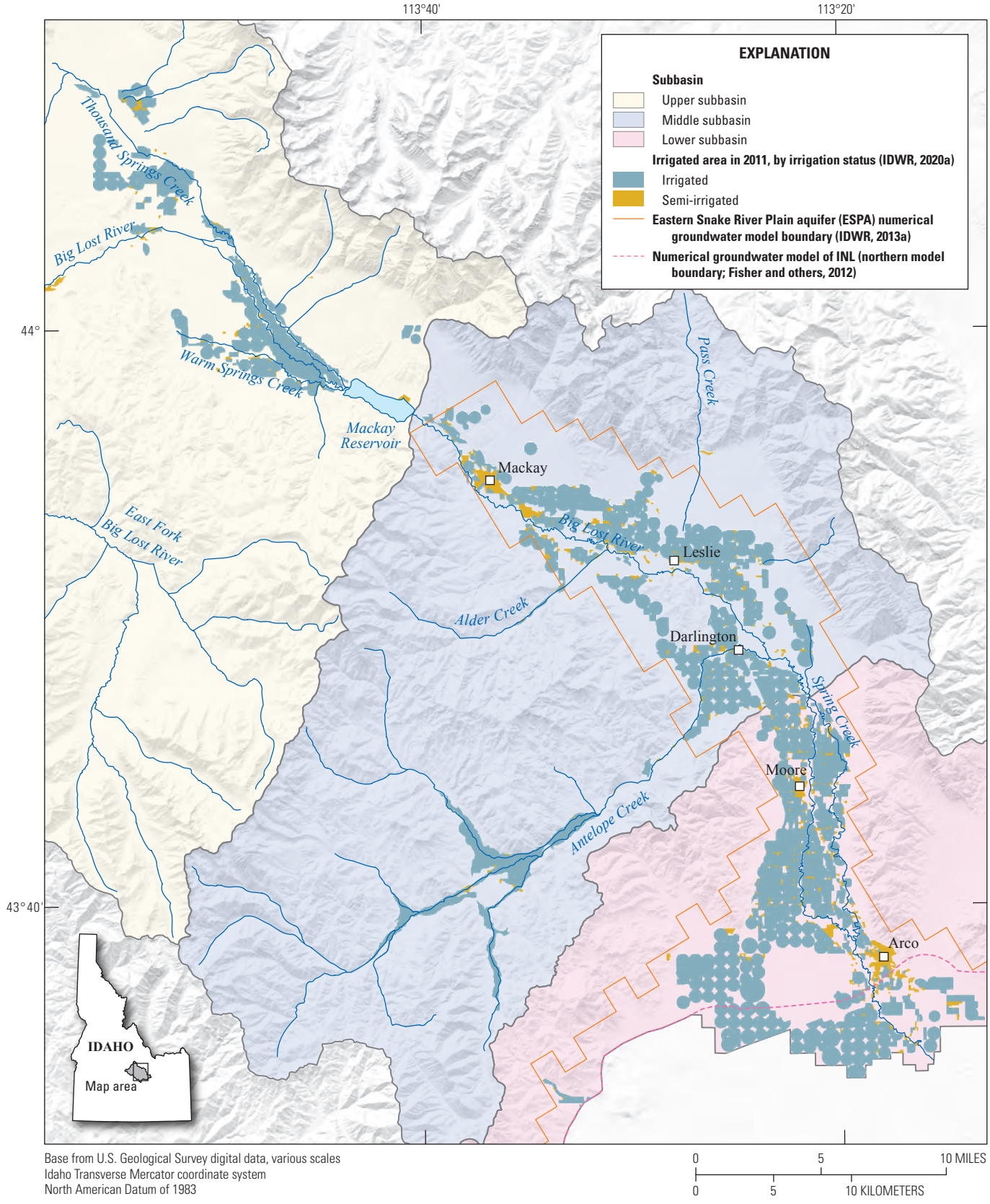


Figure 2. Irrigated, semi-irrigated, and non-irrigated lands in the Big Lost River Basin, south-central Idaho. IDWR, Idaho Department of Water Resources; INL, Idaho National Laboratory.

- NWS weather stations published on the ET_{Idaho} website[3] (Allen and Robison, 2017; University of Idaho, 2018), and
- Monthly Parameter-elevation Regressions on Independent Slopes Model (PRISM) raster grids (PRISM Climate Group, 2020).

Some climate records date back to 1908 (Mackay Ranger Station), and Crosthwaite and others (1970a) reported that the U.S. Weather Bureau first collected temperature and rainfall records at Arco as early as 1894. Seven weather stations, five SNOTEL sites, and two snow course sites (fig. 1; table 2) are active within and near the basin. The Moore AgriMet station, brought online in November 2019, was not included in the groundwater-budget analysis.

Precipitation datasets obtained from NOAA NWS and WRCC DRI and snow datasets obtained from USDA NRCS were used in the preparation of basin-scale precipitation rates and SWE, respectively. PRISM precipitation datasets were used in several groundwater-budget terms including tributary canyon underflow, Mackay Reservoir seepage, applied irrigation recharge, and Big Lost River seepage. Daily precipitation datasets obtained from the ET_{Idaho} website (Allen and Robison, 2017; University of Idaho, 2018) were used in the estimation of areal recharge.

[3]The three weather station locations accessed from the ET_{Idaho} website (Allen and Robison, 2017; University of Idaho, 2018) are the same as the National Weather Service weather stations accessed through the NOAA website (National Oceanic and Atmospheric Administration, 2020) shown on figure 1.

The annual precipitation recorded for the five active SNOTEL sites during the 2000–19 study period (table 3) is within the 1981–2010 normal annual precipitation range distributed across the watershed (8.0–50.4 in/yr) and is consistent with the average annual precipitation reported by Crosthwaite and others (1970a) for 1944–68 (spanning approximately 8 in/yr on the basin floor to 50 in/yr at higher altitudes).

The estimated mean precipitation volume using PRISM monthly datasets (PRISM Climate Group, 2020) for the entire basin was approximately 1,584,400 acre-ft/yr for 2000–19 (fig. 3). The mean annual precipitation for the same period was 890,600 acre-ft/yr (upper subbasin), 500,700 acre-ft/yr (middle subbasin), and 193,200 acre-ft/yr (lower subbasin). The highest total precipitation (2,202,600 acre-ft) occurred in 2017 (wet year). The lowest volume (980,500 acre-ft) was in 2013, contributing to overall dry prior groundwater conditions for the 2014 calendar year. The basin-wide estimated precipitation for 2014 was 1,597,000 acre-ft, closest to the 20-year study average. The average precipitation was 18.5 in/yr for the entire basin, 21.0 in/yr in the upper subbasin, 17.9 in/yr in the middle subbasin, and 12.6 in/yr in the lower subbasin. The reported average annual precipitation for the 1944–68 period of 20.2 in/yr or 1,520,000 acre-ft/yr (Crosthwaite and others, 1970a) is consistent with the 2000–19 annual average precipitation.

Table 2. Weather stations, snowpack telemetry (SNOTEL) sites, and snow course sites in the Big Lost River Basin, south-central Idaho.

[**Station Name:** INL, Idaho National Laboratory; RS, Ranger Station; NM, National Monument; SW, Southwest; NW, Northwest. **Altitude:** The National Oceanic and Atmospheric Administration (NOAA) reports using the vertical datum North American Vertical Datum of 1988 (National Oceanic and Atmospheric Administration, 2018). The U.S Department of Agriculture Natural Resources Conservation Service (USDA NRCS) reports typically using feet above mean sea level (Natural Resources Conservation Service, 2021). No metadata was located on the vertical datum reference for Bureau of Reclamation (Reclamation) agricultural meteorology (AgriMet) and Western Regional Climate Center Desert Research Institute (WRCC DRI) sites. **Agency:** NOAA NWS, NOAA National Weather Service (NWS). **Abbreviations and symbol:** ft, foot; mm-dd-yyyy, month, day, year; NA, not available; —, active through December 31, 2019]

Station name	Station type	Station number	County	Location		Altitude (ft)	Dates in operation		Agency
				Latitude	Longitude		Start date (mm-dd-yyyy)	End date (mm-dd-yyyy)	
INL Arco	Weather	RRCI	Butte	43°37′N	–113°17′W	5,339	03-27-2014	—	Reclamation AgriMet[1]
Arco 3 SW	Weather	100375	Butte	43°36′N	–113°20′W	5,330	08-01-1948	—	WRCC DRI[2]
Arco 17 SW	Weather	WBAN:04126	Butte	43°27′N	–113°33′W	5,920	07-12-2003	—	NOAA NWS[3]
Barton Flat	Weather	100621	Custer	44°03′N	–113°48′W	NA	11-01-1933	12-31-1947	WRCC DRI
Chilly Barton Flat	Weather	101671	Custer	43°59′N	–113°49′W	6,260	08-01-1948	—	WRCC DRI
Chilly Barton Flat[4]	Weather	USC00101671	Custer	43°58′N	–113°49′W	6,260	11-01-1933	—	NOAA NWS
Craters of the Moon NM	Weather	102260	Butte	43°28′N	–113°34′W	5,900	12-01-1958	—	WRCC DRI
Grouse	Weather	103882	Custer	43°42′N	–113°37′W	6,100	08-01-1948	01-30-2004	WRCC DRI
Mackay 4 NW	Weather	105466-8	Custer	43°57′N	–113°40′W	6,000	08-01-1965	10-31-1988	WRCC DRI
Mackay RS	Weather	105462	Custer	43°55′N	–113°37′W	5,900	01-02-1931	—	WRCC DRI
Mackay Lost River RS[4]	Weather	USC00105462	Custer	43°55′N	–113°37’ W	5,897	01-01-1908	—	NOAA NWS
Moore	Weather	MREI	Custer	43°46′N	–113°22′W	5,545	11-05-2019	—	Reclamation AgriMet
Bear Canyon	SNOTEL	320	Custer	43°45’ N	–113°56′W	7,900	10-01-1980	—	USDA NRCS[5]
Hilts Creek	SNOTEL	524	Custer	44° 1′N	–113°28′W	8,000	10-01-1980	—	USDA NRCS
Lost-Wood Divide	SNOTEL	601	Blaine	43°49′N	–114°16′W	7,900	10-01-1981	—	USDA NRCS
Smiley Mountain	SNOTEL	926	Custer	43°44′N	–113°50′W	9,520	09-19-2001	—	USDA NRCS
Stickney Mill	SNOTEL	792	Custer	43°52′N	–114°13′W	7,430	08-12-1980	—	USDA NRCS
Copper Basin	Snow course	13F02	Custer	43°49′N	–113°55′W	7,619	03-31-1936	—	USDA NRCS
Dry Fork	Snow course	13F20	Butte	43°34′N	–113°40′W	7,220	03-01-1961	—	USDA NRCS

[1]Data from Bureau of Reclamation (2016).

[2]Data from WRCC (2020).

[3]Data from NOAA (2020).

[4]Not shown on figure 1.

[5]Data from NRCS (2020).

Table 3. Summary of precipitation data, Big Lost River Basin, south-central Idaho.

[Snowpack telemetry (SNOTEL) site precipitation is based on the sum of reported incremental precipitation. SNOTEL sites are maintained by the U.S Department of Agriculture Natural Resources Conservation Service (USDA NRCS; see table 2). Weather stations are maintained by the Bureau of Reclamation agricultural meteorology (AgriMet), the Western Regional Climate Center Desert Research Institute (WRCC DRI), and the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) (see table 2). Precipitation values are rounded to the nearest tenth of an inch. **Station name:** INL, Idaho National Laboratory; RS, Ranger Station; NM, National Monument; SW, Southwest. **Altitude:** NOAA reports using the vertical datum North American Vertical Datum of 1988 (National Oceanic and Atmospheric Administration, 2018). The USDA NRCS reports typically using feet above mean sea level (Natural Resources Conservation Service, 2021). No metadata was located on the vertical datum reference for AgriMet and WRCC DRI sites. **Abbreviations:** ft, foot; in., inch; precip., precipitation]

Station name	Station type	Calendar years	Altitude (ft)	Mean precip. (in.)	Median precip. (in.)	Minimum precipitation and associated year		Maximum precipitation and associated year	
						Minimum precip. (in.)	Low year	Maximum precip. (in.)	High year
Arco 3 SW	Weather	2000–19	5,330	8.4	9.1	3.5	2013	11.6	2016
Arco 17 SW	Weather	2004–19	5,920	16.3	16.6	8.2	2013	21.7	2005
INL Arco	Weather	2015–19	5,339	10.0	9.7	9.0	2018	11.4	2017
Craters of the Moon NM	Weather	2000–19	5,900	15.2	14.9	7.5	2013	23.4	2017
Chilly Barton Flat	Weather	2000–19	6,260	7.0	7.6	[1]2.5	2008	10.9	2017
Grouse	Weather	2000–03	6,100	8.6	8.6	[1]6.4	2003	10.7	2000
Mackay RS	Weather	2001–19	5,900	9.4	10.0	5.4	2013	12.6	2014
Bear Canyon	SNOTEL	2000–19	7,900	27.8	27.3	17.8	2013	43.4	2017
Hilts Creek	SNOTEL	2000–19	8,000	22.8	23.7	13.5	2013	30.3	2017
Lost-Wood Divide	SNOTEL	2000–19	7,900	28.9	27.7	18.8	2013	43.3	2017
Smiley Mountain	SNOTEL	2002–19	9,520	32.7	33.1	22.2	2013	49.4	2017
Stickney Mill	SNOTEL	2000–19	7,430	18.9	19.6	13.4	2013	28.4	2017

[1]Incomplete dataset.

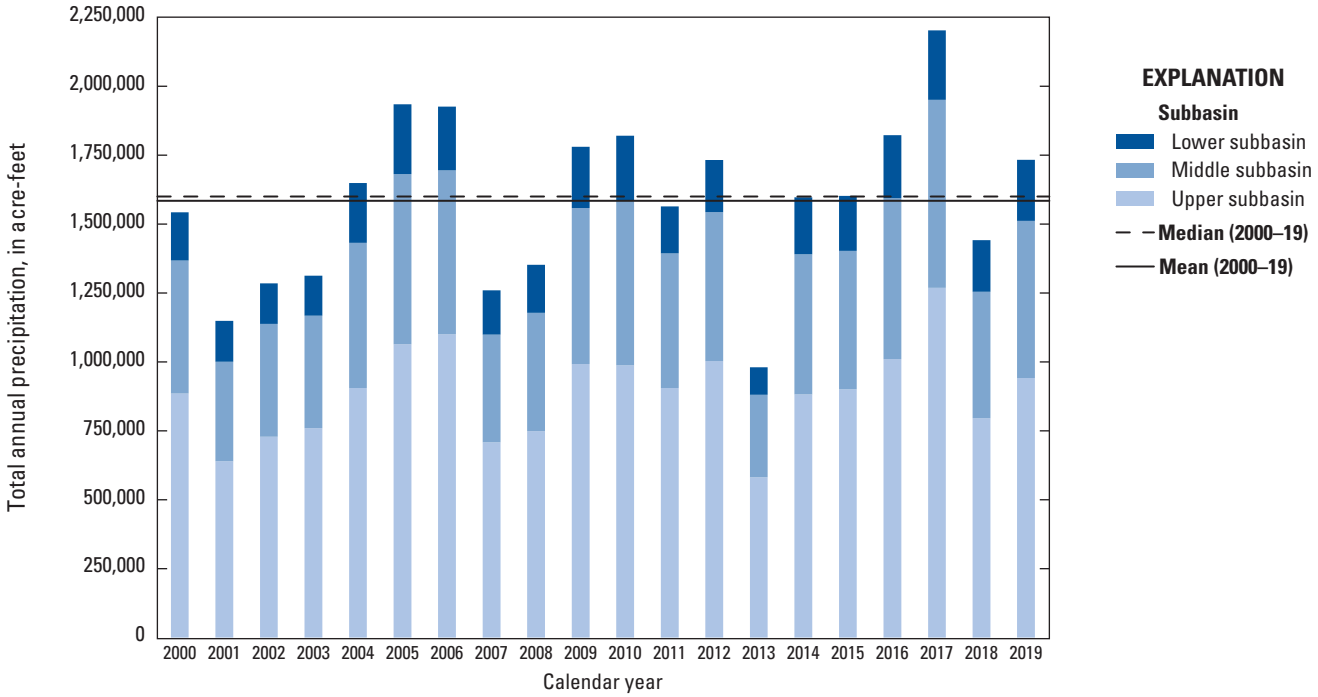


Figure 3. Total annual precipitation calculated using Parameter-elevation Regressions on Independent Slopes Model (PRISM Climate Group, 2020), Big Lost River Basin, south-central Idaho, 2000–19.

Groundwater Budgets

A groundwater budget is an effective way to qualitatively and quantitatively describe a hydrologic system. A groundwater budget is a numerical accounting of the individual components of how groundwater flow enters (as inflow) and exits (as outflow) a hydrologic system. The term "budget" is used because inflows and outflows must balance, plus or minus the change in water storage in the system. In its most simplistic terms, the groundwater budget may be defined as recharge minus discharge equals the change in groundwater storage.

Creation of a groundwater budget includes the following steps:

1. Identifying the predominant inflow and outflow components;
2. Compiling available datasets to document and quantify each inflow and outflow term, and preparing volumetric estimates of each component; and
3. Evaluating the resulting groundwater budget for its relative accuracy and commenting on groundwater resource sustainability, with consideration about the degree of uncertainty and adequacy for its intended use.

More in-depth discussion on groundwater budgets is provided in Healy and others (2007) and Alley and others (1999).

Different approximations of the groundwater budget can be made, depending on the level of hydrologic complexity, the needs of the hydrogeologic study, basin-level or watershed-scale effects, and assumptions. The groundwater budget for the Big Lost River Basin can be represented by individual groundwater inflow and outflow components. Inflow terms are on the left side, and outflow and storage terms are on the right side in equation 1 (after Healy, 2010):

$$\begin{aligned} P + Qsw_{in} + Qgw_{in} = {} & ET^{sw} + ET^{gw} \\ & + ET^{uz} + Qgw_{out} \\ & + RO + Q^{bf} \\ & + \Delta S^{sw} + \Delta S^{snow} \\ & + \Delta S^{gw} + \Delta S^{uz} \end{aligned} \quad (1)$$

where

sw and gw are surface water and groundwater, respectively;
uz is the unsaturated zone;
P is precipitation;
Q is flow (including recharge and discharge);
ET is evapotranspiration;
RO is surface runoff;
Q^{bf} is baseflow as groundwater discharge to streams; and
ΔS is the change in groundwater storage.

In general practice, and for this water-budget study, the separate source terms for evapotranspiration and storage typically are combined since they cannot easily be differentiated (Healy, 2010), condensing the water-budget terms to the equation:

$$P + Qsw_{in} + Qgw_{in} = ET + Qgw_{out} + RO + Q^{bf} + \Delta S \quad (2)$$

where

ET and ΔS reflect the combination of terms defined in equation 1.

For this study, a separate surface-water budget was not prepared, as indicated in equations 1 and 2. However, surface-water inputs such as tributary streamflow and river seepage factor prominently in the groundwater budget because of the close hydraulic connection of surface water and groundwater in the Big Lost River Basin, a condition recognized by previous investigators including Crosthwaite and others (1970a, 1970b). Specific water-budget terms are presented in the context of the aquifer. For example, a gaining streamflow reach reflects groundwater discharge to the stream, with a positive value as a volumetric increase in surface-water flow and a negative value as a volumetric decrease in groundwater. Similarly, a losing streamflow condition arises from streamflow loss through the stream bed (negative) or to the aquifer (positive).

The groundwater budget calculated in this report is shown in the simplified schematic (fig. 4), adapted from Driscoll and Carter (2002), and conveys inflow components in green; outflow terms in orange; and surface water, including interaction with groundwater, in blue. Precipitation is shown in purple as an inflow term (handled separately from the water budget accounting in determining precipitation-derived recharge). Applied water and incidental recharge in figure 4 include the recharge of applied water budget terms: applied irrigation, managed aquifer recharge, and septic system effluent.

The average annual groundwater budget over the entire basin for the study period is summarized in table 4 and figure 5. Groundwater inflow from adjacent basins into the Big Lost River Basin is neglected at the watershed scale. The predominant inflows to groundwater are from losing river reaches, tributary canyon underflow, and areal recharge (as precipitation less evapotranspiration and surface runoff). Most groundwater is discharged from the aquifer through gaining river reaches and pumpage. The residual (total inflows minus total outflows) constitutes the change in groundwater storage and net groundwater discharge from the basin. Some variations may arise owing to unit conversions and rounding.

Groundwater budgets (individual components and residuals) are discussed in sections, "Inflows to the Aquifer," "Losing and Gaining River Reaches," and "Outflows from the Aquifer." Compared to the findings from previous studies (see section, "Previous Work"), the groundwater residual over the study period (as groundwater flow exiting at the mouth of the basin below Arco and changes in groundwater storage) estimated in this investigation shows larger (about 0.05–0.5 times) net average residuals for the entire basin. Differences may arise owing to several factors (including datasets, spatial and temporal extents, methodologies, assumptions, and uncertainty and errors), as described further in section, "Previous Work."

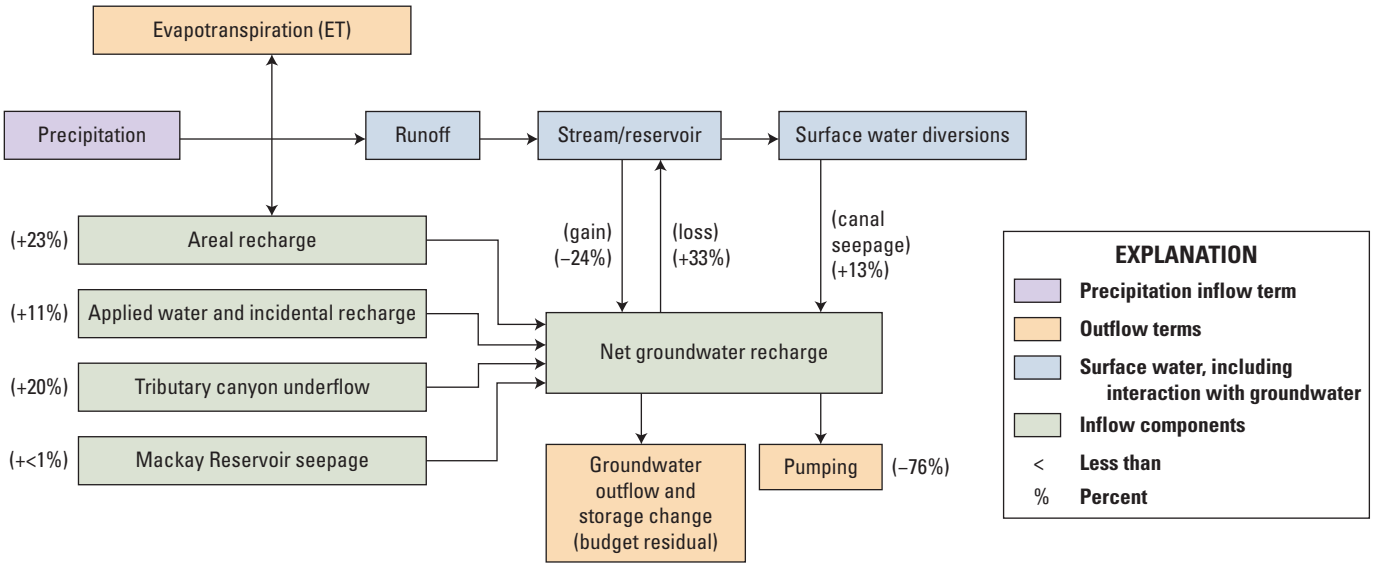


Figure 4. Groundwater budget for the Big Lost River Basin, south-central Idaho. The relative percentage of the total mean annual inflow and outflow (2000–19), as calculated in this report, is provided for each water-budget term. See table 4 for data.

Table 4. Estimated annual groundwater budgets for the Big Lost River Basin, south-central Idaho, for average conditions during 2000–19, 2014 (dry), and 2017 (wet).

[All values in acre feet per year (acre-ft/yr) are rounded up or down to the nearest 100]

Budget component	Entire basin			Above Mackay Dam			Below Mackay Dam		
	2000–19	2014	2017	2000–19	2014	2017	2000–19	2014	2017
Tributary canyon underflow	88,700	87,900	124,200	50,900	49,800	72,100	37,800	38,100	52,100
Areal recharge	99,700	116,200	146,800	36,800	44,200	62,500	62,900	72,000	84,300
Applied irrigation recharge	46,900	15,800	71,700	16,600	5,300	20,700	30,300	10,500	51,000
Canal seepage	55,300	43,000	70,800	19,000	18,600	23,000	36,300	24,400	47,800
Managed recharge (winter)	1,900	0	6,100	100	0	400	1,800	0	5,700
Septic system effluent	200	100	300	0	0	0	200	100	300
Losing river reaches	144,800	109,600	339,900	6,600	0	70,500	138,200	109,600	269,400
Mackay Reservoir seepage	1,600	1,300	2,300	1,600	1,300	2,300	0	0	0
Groundwater inflow (above dam residual)	0	0	0	0	0	0	100,400	96,700	248,300
Groundwater pumpage to canals	8,300	22,400	2,900	0	0	0	8,300	22,400	2,900
Irrigation pumpage	76,000	112,700	49,000	4,200	4,700	3,100	71,800	108,000	45,900
Domestic supply pumpage	500	400	800	100	100	100	400	300	700
Municipal supply pumpage	600	300	700	0	0	0	600	300	700
Gaining river reaches	26,900	17,700	0	26,900	17,700	0	0	0	0
Total inflow (recharge)	439,100	373,900	762,100	131,600	119,200	251,500	407,900	351,400	758,900
Total outflow (discharge)	112,300	153,500	53,400	31,200	22,500	3,200	81,100	131,000	50,200
Difference (residual)	326,800	220,400	708,700	100,400	96,700	248,300	326,800	220,400	708,700

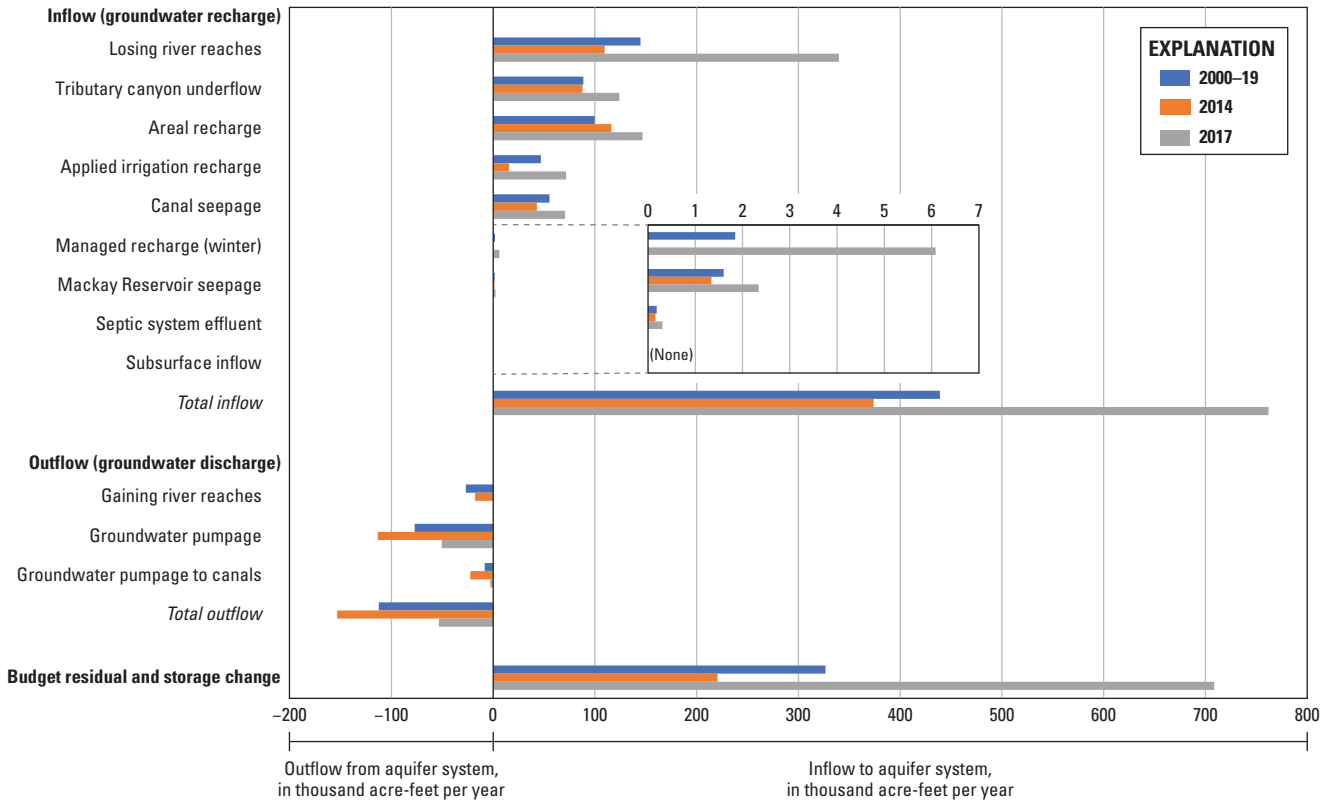


Figure 5. Average groundwater-budget components, as calculated in this report, for the Big Lost River Basin, south-central Idaho, 2000–19, 2014, and 2017. See table 4 for data.

Inflows to the Aquifer

The predominant inflows to the aquifer in the Big Lost River Basin (table 4), from roughly highest to lowest components, include the following:

- Losing river reaches,[4]
- Diffuse areal recharge through infiltration of precipitation from rainfall and snowmelt,
- Tributary canyon underflow,
- Focused recharge from applied irrigation from surface water and groundwater sources,
- Canal seepage,
- Managed recharge during winter months,
- Mackay Reservoir seepage, and
- Septic system effluent recharge.

[4]Gaining reaches are discussed in section, "Losing and Gaining River Reaches" for completeness instead of treated separately in section, "Outflows from the Aquifer."

Areal Recharge

Areal recharge occurs directly on top of the aquifer as defined by the extent of unconsolidated sedimentary deposits. Precipitation (rainfall and snowmelt) is the predominant source of areal recharge to the Big Lost River Basin. Some precipitation infiltrates from the ground surface into the subsurface and reaches (thereby recharging) the water table. Sometimes referred to as deep percolation, this water passes below the root zone of plants in excess of infiltrated water removed by evapotranspiration. The timing and amounts of precipitation, evapotranspiration, and surface runoff control the volume of areal recharge to the aquifer. Conceptually for this groundwater budget, areal recharge occurs on irrigated lands during winter (November–March) and on non-irrigated lands during the full year. Recharge that occurs on irrigated lands during the irrigation season (April–October) is treated as a separate groundwater-budget component as applied irrigation (see section, "Applied Irrigation").

Other forms of recharge from applied irrigation, canal seepage, and losing river reaches within the aquifer domain are addressed in sections, "Applied Irrigation," "Canal Seepage," and "Losing and Gaining River Reaches," respectively. Precipitation that falls within tributary canyons is accounted for in a separate component of the groundwater budget as tributary underflow (see section, "Tributary Canyon Underflow").

Data Sources, Methods, and Assumptions

Areal recharge was calculated in the groundwater budget as recorded precipitation minus actual evapotranspiration minus estimated surface runoff in regions underlain by the aquifer (fig. 6). The aquifer extent is described in section, "Study Area." Areal recharge was handled in the groundwater budget in two ways. One calculation accounted for areal recharge on irrigated lands during winter (November–March), and a second calculation accounted for areal recharge on non-irrigated lands during the full year. Positive values from daily calculations of precipitation minus evapotranspiration minus runoff were summed for each ET_{Idaho} land-cover category (Allen and Robison, 2017; University of Idaho, 2018) as defined in the available NCLD coverage (Multi-Resolution Land Characteristics Consortium, 2019) and were then multiplied by the aquifer area associated with each land-cover type (within upper, middle, and lower subbasins, respectively) to obtain a recharge volume. Total areal recharge was then summed from the results of the two calculations.

Precipitation and evapotranspiration values in datasets from ET_{Idaho} (a searchable database providing evapotranspiration and irrigation data by land-cover type for weather stations across Idaho [Allen and Robison, 2017; University of Idaho, 2018] used in the areal recharge calculation) are highly correlated with altitude and typically do

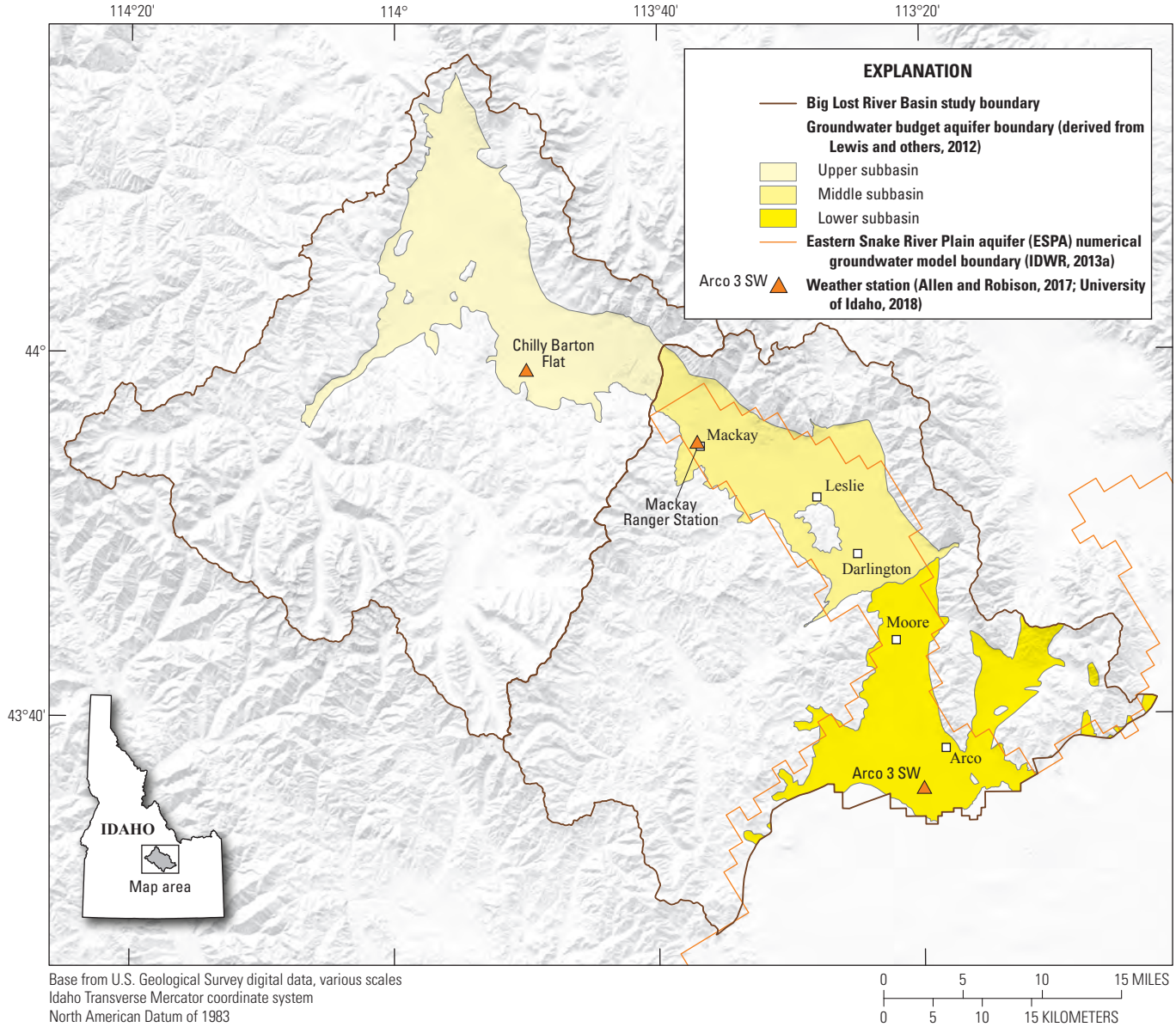


Figure 6. Aquifer extent used for areal recharge analysis in the Big Lost River Basin, south-central Idaho. IDWR, Idaho Department of Water Resources.

not reflect conditions at high altitudes. However, the aquifer extent occurs at lower altitudes in valley areas considered appropriate for the use of ET_{Idaho} datasets.

Three weather stations published on the ET_{Idaho} website (Allen and Robison, 2017; University of Idaho, 2018) are located within the investigation area and are used in areal recharge calculations (Chilly Barton Flat [CHA] above Mackay Reservoir; Mackay Ranger Station [MAC] near the town of Mackay; and Arco 3 SW [ARC] south of the town of Arco). Altitudes are 6,260, 5,910, and 5,330 ft, respectively, for CHA, MAC, and ARC stations. Data for each weather station are assumed to be representative of each respective subbasin in the valley (upper, middle, and lower) in figure 6 based on similar topographic, climatic, and hydrologic factors.

Available daily precipitation, actual evapotranspiration, and estimated runoff datasets for 2000–16 obtained from ET_{Idaho} (Allen and Robison, 2017; University of Idaho, 2018) were used to estimate areal recharge. Some periods had missing data (such as summer 2009). Therefore, the calculated recharge value was based on the average of the recharge value immediately before and after the missing datapoint, or the missing value(s) was assumed to be zero during summer when evapotranspiration is the dominant process with minimal-to-no expected areal recharge. ET_{Idaho} datasets are not available for 2017–19. Therefore, recharge estimates for 2017-19 were based on a linear correlation between precipitation and areal recharge for 2000–16, with a moderate degree of correlation (coefficient of determination, R^2, of about 0.6). Weaker apparent correlation was calculated for evapotranspiration and recharge (R^2 of 0.26 to 0.57, depending on the area). Further details about the datasets and assumptions are provided in appendix 3 (“Areal Recharge”).

In the areal recharge calculations, sources of uncertainty include estimation of surface runoff and deep percolation. Additional uncertainty arises in estimating areal recharge for 2017–19 because of the lack of ET_{Idaho} data during this period.

Areal Recharge Results

The total mean annual estimated areal recharge (table 4; fig. 5) in the Big Lost River Basin was 99,700 acre-ft/yr (2000–19), 116,200 acre-ft in 2014, and 146,800 acre-ft in 2017. The lowest estimated areal recharge for the total basin was 41,000 acre-ft in 2013 (fig. 7), reflecting especially low total precipitation throughout the basin. The mean annual estimated areal recharge (2000–19) was 36,900 acre-ft/yr for the upper subbasin, 32,000 acre-ft/yr for the middle subbasin, and 30,900 acre-ft/yr for the lower subbasin. The relative difference above and below Mackay Dam primarily reflects the size of the area included in the analysis[5], as the recharge rate is relatively similar within the valley throughout the basin (4.4 in/yr above the dam and 4.9 in/yr below the dam). Overall areal recharge volumes represent about 22 percent of the total mean annual inflows in groundwater budget (28 percent above the dam and 21 percent below the dam).

[5]Approximately 100,310 acres above Mackay Dam and 153,220 acres below Mackay Dam (74,850 acres for the middle subbasin and 78,370 acres for the lower subbasin).

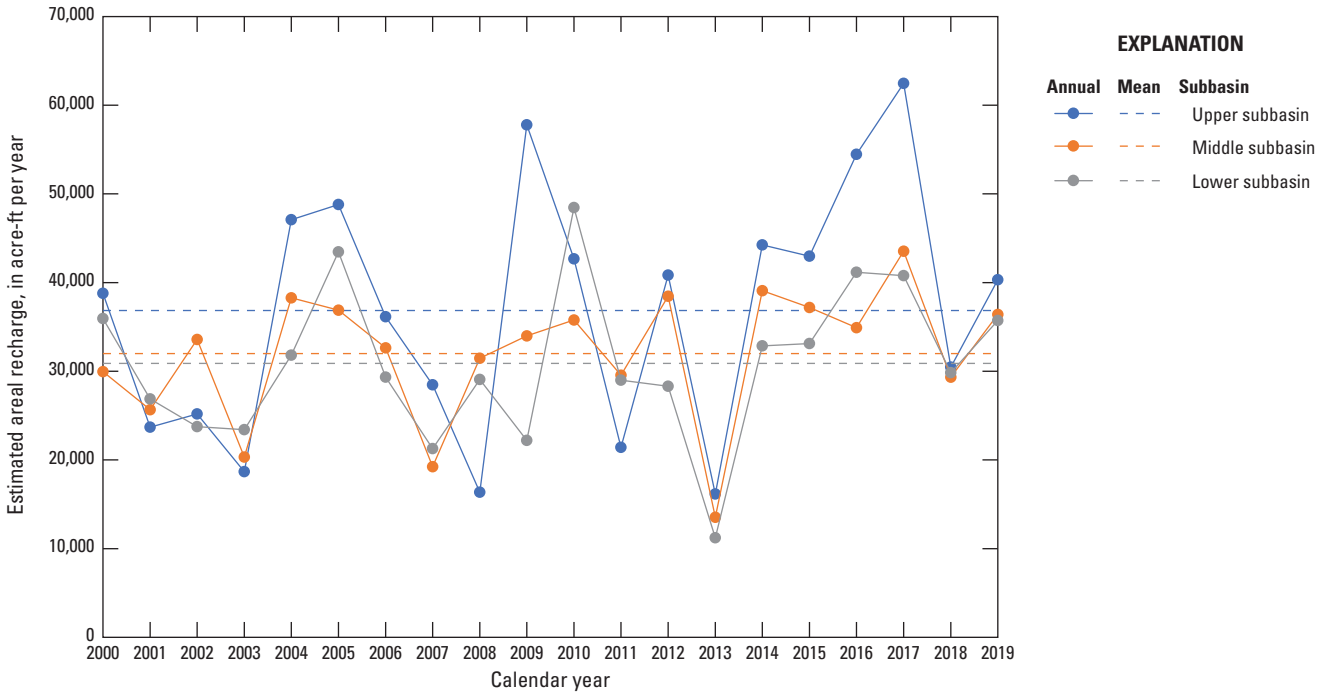


Figure 7. Total estimated areal recharge in the Big Lost River Basin by subbasin extent, south-central Idaho, 2000–19. See table 3.1 in appendix 3, “Areal Recharge,” for data.

Tributary Canyon Underflow

Tributary canyons in intermontane basins can transmit appreciable recharge volumes to lower altitudes or valleys through precipitation that reaches the water table, becoming groundwater underflow. Tributary canyons in the Big Lost River Basin, especially Lower Cedar, Alder, Pass, and Antelope Creeks below Mackay Reservoir, were regarded by Crosthwaite and others (1970a) as a substantial source for the total available water resources. Perennial streams in certain canyons such as Burnt, Elkhorn, Pass, Thousand Springs, and Upper Cedar Creeks above Mackay Dam are well established. However, many tributary canyons, particularly those with incised alluvial fans at the Lost River Range front, do not presently host flowing streams but once had substantial streamflow during the Pleistocene (Pierce and Scott, 1982). The lack of streams or ephemeral streamflow suggests that most, if not all, of the precipitation is infiltrating into the alluvial fan where it presumably recharges the water table and moves downgradient to become inflow to the aquifer used for water supply. Zinsser (2021) discussed the role of sedimentary rocks in the Lost River Range and near the head of Warm Springs Creek in contributing recharge to the alluvial aquifer, supported by the expression of several springs.

Data Sources, Methods, and Assumptions

Because tributary underflow is not measured directly, it must be estimated. Darcy's law (Healy, 2010) is a common method for estimating subsurface throughflow. Darcy's law was used to estimate a mean underflow rate based on assumed properties for each tributary canyon (hydraulic conductivity, saturated cross-sectional area, and hydraulic head). The mean underflow estimates required further adjustments to account for canyon size (done for the smaller canyons with areas of less than about 4 square miles [mi^2]) and for annual variations in the estimated precipitation volume (done for all canyons). Further details and assumptions on the application of Darcy's law to tributary canyons are briefly described in this report section, with supporting information in appendix 4 ("Tributary Canyon Underflow Supporting Detail"). Tributary canyon underflow was estimated for 78 tributary canyons[6] (fig. 8; table 5): 45 above Mackay Dam and 33 below Mackay Dam. Other canyons were excluded owing to their size (less than about 1 mi^2). About one-half of the drainages are minor (less than about 4 mi^2).

The USGS program StreamStats (U.S. Geological Survey, 2016) was used to delineate tributary basin extents and measure drainage areas. StreamStats is a GIS-based, interactive program that incorporates the results of regression analyses used to estimate unmeasured streamflow on ungaged streams (Ries and others, 2017). Additional details about the program are provided in Ries and others (2004). For this project, basin delineation was somewhat subjective but was intended to coincide with the canyon mouth, mapped surface drainage (if present), the aquifer extent, or the ESPA model boundary below Mackay Dam. Saturated thickness was estimated based on evaluation of the depth to water described in nearby well logs (IDWR, 2020b) and inferences from depth-to-water measurements in the IDWR monitoring-well network (IDWR, 2021a).

The estimated mean underflow obtained from Darcy's law required adjustments for the smaller tributary canyons (those with areas less than or equal to 4 mi^2) to address disproportionately higher underflow estimated for smaller canyons compared to larger canyons. This correction was applied following a similar rationale and methodology described in Fisher and others (2016) in which the groundwater table associated with larger canyons with perennial streamflow is believed to not vary considerably over time as opposed to the groundwater table position for smaller canyons with ephemeral or intermittent streamflow conditions. Further details for the adjustments are described in appendix 4 ("Tributary Canyon Underflow Supporting Detail," section "Underflow Correction").

Variable underflow was determined on an annual basis for all the canyons (small and large) using basin-specific PRISM-derived precipitation rates (PRISM Climate Group, 2020). Darcy flow was adjusted either higher or lower based on the deviation from mean annual precipitation within a given canyon. A separate, additional adjustment was made for smaller canyons based on a scaling factor (0.149) developed from the larger canyons as a mean ratio of Darcy flow to the volumetric rate of total annual precipitation (see table 4.1 in appendix 4, "Tributary Canyon Underflow Supporting Detail," section "Underflow Correction"). This scaling factor was calculated using 34 of the larger tributary canyons (with areas greater than about 4 mi^2). The scaling factor was then multiplied by the annual precipitation volume for a given smaller canyon to obtain the estimated underflow for the smaller tributary canyons. Relative assignment of small compared to large canyons was somewhat subjective but was made on the basis of relative breaks in the basin area when plotted on a logarithmic scale. Further details on this methodology are presented in appendix 4 ("Tributary Canyon Underflow Supporting Detail").

The Darcy approach used in this study is highly sensitive to varying estimates of certain parameters such as basin delineation, hydraulic conductivity, saturated aquifer thickness, hydraulic gradient, and canyon width within acceptable parameter bounds. PRISM represents interpolated precipitation rates that may not reflect actual precipitation within a given canyon. The overall magnitude of underflow is sensitive to small changes (within the same order of magnitude) in assumed hydraulic conductivity for tributary drainages. Limited aquifer testing has been done in the basin, introducing uncertainty in estimating tributary underflow owing to the lack of aquifer properties including hydraulic

[6]Elbow and Jepson canyons were combined in a single area for the underflow estimate (fig. 8; table 5).

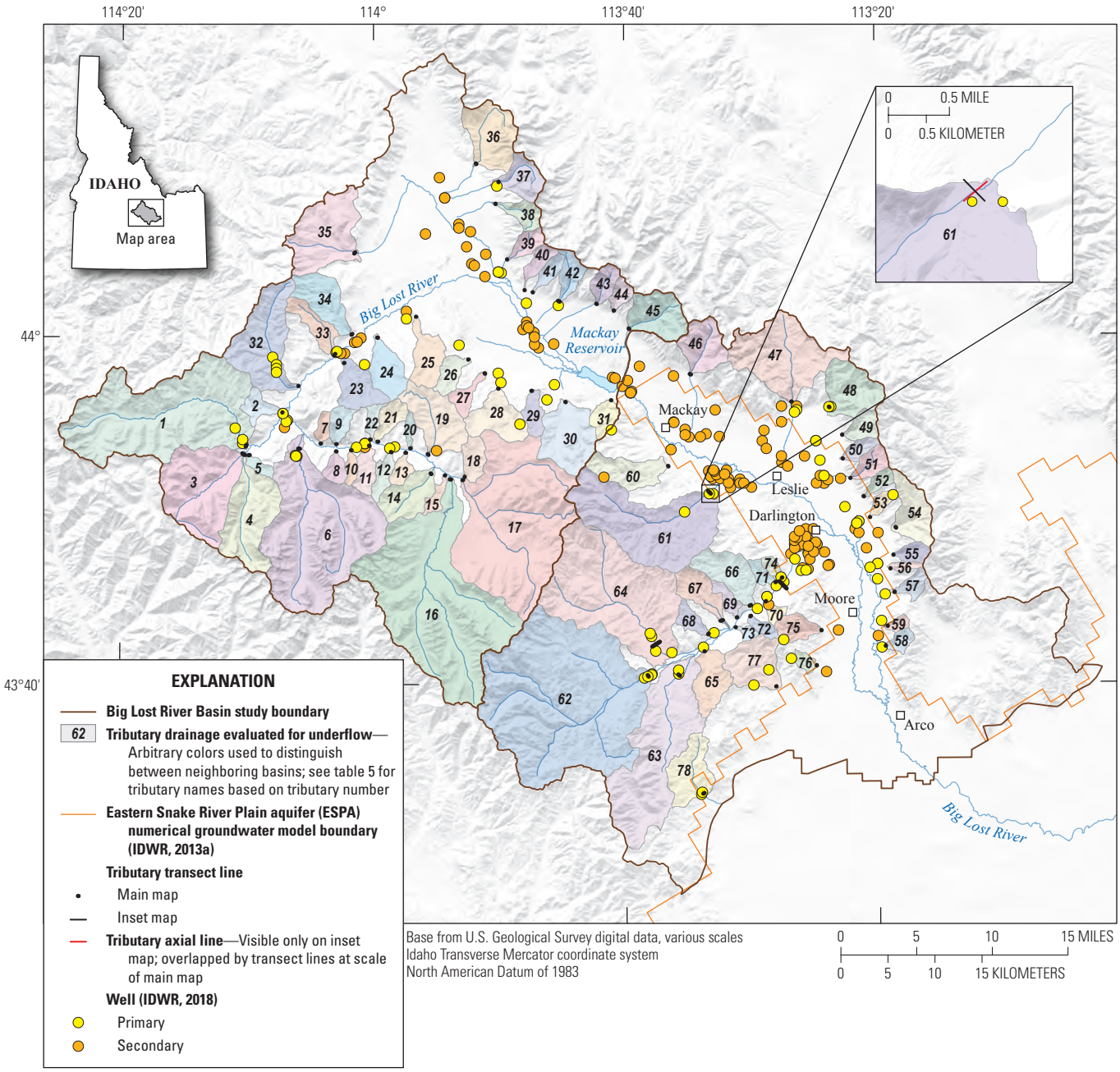


Figure 8. Tributary drainages evaluated for underflow in the Big Lost River Basin, south-central Idaho. IDWR, Idaho Department of Water Resources.

conductivity, transmissivity, and specific yield (or storativity in confined aquifers). Only one aquifer test was identified for use in this investigation. The hydraulic conductivity assumed for the tributary canyons was based on the results of a single test of the aquifer (Bassick and Jones, 1992, described in appendix 4, "Tributary Canyon Underflow Supporting Detail," section "Hydraulic Conductivity") that may be higher than the actual hydraulic conductivity in tributaries characterized by bedrock with lower hydraulic conductivity. Similarly, results are sensitive to assumed canyon width (within the same order of magnitude). Estimated underflow from the larger canyons (such as Dry Fork Creek, the North Fork of the Big Lost River, and Star Hope Creek) may be underestimated in this study because of the consolidation of several, smaller drainage areas into a single area. This approach has the effect of underrepresenting the combined canyon width contributing to the total drainage area of the larger canyon. Therefore, estimated underflow is considered highly uncertain with implications for the overall magnitude of the groundwater budget and residuals.

Table 5. Estimated tributary basin underflow for the Big Lost River Basin, south-central Idaho, 2000–19.

[All values in acre feet per year (acre-ft/yr) are rounded up or down to the nearest 10. Tributary numbers are shown in figure 8. **Abbreviation and symbol:** mi², square mile; #, number]

Tributary name	#	Drainage area (mi²)[1]	Above or below Mackay Dam	Mean annual Darcy flow[2], Q_d, before adjustment (ac-ft/yr)		Mean annual Darcy flow[2], Q_{trib}, adjusted for mean annual precipitation[3] (ac-ft/yr)					
				2000–19		2000–19		2014		2017	
				Low-end	High-end	Low-end	High-end	Low-end	High-end	Low-end	High-end
North Fork Big Lost River drainage											
North Fork Big Lost River (upper drainage)	1	60	Above	990	1,410	990	1,410	960	1,360	1,440	2,040
Deep Creek	2	3	Above	4,070	5,770	410	590	410	590	600	870
Summit Creek	3	26	Above	4,840	6,860	4,840	6,860	4,740	6,720	7,080	10,030
Kane Creek	4	18	Above	1,850	2,620	1,850	2,620	1,790	2,540	2,690	3,810
Unnamed Creek (North Fork)	5	1	Above	5,710	8,090	230	330	230	330	340	500
East Fork Big Lost River drainage											
Wildhorse Creek	6	57	Above	4,960	7,030	4,960	7,030	4,720	6,680	7,120	10,100
Willow Creek (East Fork)	7	2	Above	3,010	4,270	230	330	240	340	350	500
Unnamed Creek 1 (East Fork)	8	2	Above	3,390	4,810	390	570	390	570	600	860
Unnamed Creek 2 (East Fork)	9	3	Above	3,850	5,460	430	620	440	640	640	930
Pole Creek	10	1	Above	3,150	4,470	250	360	250	360	380	550
Deer Creek	11	3	Above	190	270	650	940	640	920	990	1,420
Rider Creek	12	3	Above	480	680	560	800	540	780	840	1,210
Little Boone Creek	13	2	Above	360	510	320	460	320	460	480	700
Fox Creek	14	8	Above	1,170	1,660	1,170	1,660	1,140	1,610	1,740	2,470
Road Creek	15	2	Above	460	650	240	350	240	350	360	530
Star Hope Creek	16	76	Above	740	1,060	740	1,060	710	1,000	1,080	1,520
East Fork Big Lost River (upper drainage)	17	65	Above	120	170	120	2,750	120	2,650	180	4,040
Little Lake Creek	18	4	Above	240	330	590	850	590	850	860	1,240
Boone Creek (East Fork)	19	13	Above	810	1,150	810	1,150	820	1,170	1,190	1,690
Butcher Creek	20	1	Above	1,300	1,840	170	240	170	250	250	360
Castle Creek	21	3	Above	1,050	1,490	540	790	550	800	810	1,170
Stag Creek	22	2	Above	6,280	8,890	250	360	250	370	370	540
White Knob Range (east side above Mackay Dam)											
Bady Creek	23	7	Above	790	1,120	790	1,120	820	1,160	1,170	1,650
Grant Creek	24	7	Above	1,940	2,760	1,940	2,760	2,000	2,840	2,830	4,000

Table 5. Estimated tributary basin underflow for the Big Lost River Basin, south-central Idaho, 2000–19.—Continued

[All values in acre feet per year (acre-ft/yr) are rounded up or down to the nearest 10. Tributary numbers are shown in figure 8. **Abbreviation and symbol:** mi², square mile; #, number]

Tributary name	#	Drainage area (mi²)[1]	Above or below Mackay Dam	Mean annual Darcy flow[2], Q_d, before adjustment (ac-ft/yr)		Mean annual Darcy flow[2], Q_{trib}, adjusted for mean annual precipitation[3] (ac-ft/yr)					
				2000–19		2000–19		2014		2017	
				Low-end	High-end	Low-end	High-end	Low-end	High-end	Low-end	High-end
White Knob Range (east side above Mackay Dam)—Continued											
Rock Creek (White Knob)	25	7	Above	300	430	300	430	310	440	430	610
Garden Creek	26	4	Above	2,680	3,800	440	640	450	650	630	900
Boone Creek (White Knob)	27	3	Above	1,510	2,140	360	510	360	520	510	730
Lehman Creek	28	9	Above	250	350	250	350	250	350	350	500
Hamilton Creek	29	3	Above	10,150	14,390	390	560	400	570	550	800
Navarre Creek	30	13	Above	1,710	2,420	1,710	2,420	1,690	2,400	2,460	3,480
Black Daisy Canyon	31	3	Above	130	180	420	610	440	630	590	860
Northern upper subbasin											
Twin Bridges Creek	32	20	Above	1,190	1,690	1,190	1,690	1,170	1,670	1,760	2,490
Burnt Creek	33	5	Above	2,320	3,280	2,320	3,280	2,330	3,310	3,380	4,800
Pinto Creek	34	9	Above	970	1,380	970	1,380	980	1,380	1,420	2,010
Sage Creek	35	19	Above	1,470	2,090	1,470	2,090	1,480	2,090	2,170	3,080
Lost River Range (above Mackay Dam)											
Willow Creek (Lost River Range)	36	12	Above	2,370	3,360	2,370	3,360	2,370	3,360	3,150	4,470
Rock Creek (Lost River)	37	6	Above	4,980	7,060	4,980	7,060	4,740	6,720	6,530	9,260
Cedar Creek	38	3	Above	11,390	16,140	860	1,250	810	1,170	1,130	1,630
Elkhorn Creek	39	3	Above	4,540	6,430	610	880	580	840	800	1,160
Vance Creek	40	3	Above	2,400	3,400	610	880	570	820	800	1,150
Sawmill Gulch	41	2	Above	3,260	4,630	580	830	530	770	750	1,090
Lone Cedar Creek	42	4	Above	9,720	13,780	920	1,320	850	1,220	1,190	1,720
Jones Creek	43	3	Above	3,170	4,500	880	1,270	810	1,170	1,150	1,660
Pete Creek	44	2	Above	4,020	5,700	620	900	580	830	830	1,190
Upper Cedar Creek	45	10	Above	2,090	2,960	2,090	2,960	1,970	2,790	2,820	4,000
Lost River Range (below Mackay Dam)											
Lower Cedar Creek	46	8	Below	1,480	2,100	1,480	2,100	1,410	2,000	2,070	2,930
Pass Creek	47	24	Below	2,710	3,840	2,710	3,840	2,630	3,730	3,760	5,330
Elbow Canyon and Jepson Canyon	48	11	Below	1,130	1,610	1,130	1,610	1,110	1,580	1,560	2,210

Table 5. Estimated tributary basin underflow for the Big Lost River Basin, south-central Idaho, 2000–19.—Continued

[All values in acre feet per year (acre-ft/yr) are rounded up or down to the nearest 10. Tributary numbers are shown in figure 8. **Abbreviation and symbol:** mi², square mile; #, number]

Tributary name	#	Drainage area (mi²)[1]	Above or below Mackay Dam	Mean annual Darcy flow[2], Q_d, before adjustment (ac-ft/yr)		Mean annual Darcy flow[2], Q_{trib}, adjusted for mean annual precipitation[3] (ac-ft/yr)					
				2000–19		2000–19		2014		2017	
				Low-end	High-end	Low-end	High-end	Low-end	High-end	Low-end	High-end
Lost River Range (below Mackay Dam)—Continued											
Clark Canyon	49	3	Below	3,990	5,650	590	860	590	850	810	1,170
Maddock Canyon	50	2	Below	670	950	350	500	360	520	470	680
Jaggles Canyon	51	3	Below	490	700	540	780	550	800	730	1,060
Big Burnett Canyon	52	2	Below	9,670	13,700	280	410	290	420	380	550
Little Burnett Canyon	53	2	Below	1,200	1,700	240	340	250	360	320	460
Ramshorn Canyon	54	9	Below	2,230	3,170	2,230	3,170	2,280	3,230	3,060	4,330
Anderson Canyon	55	2	Below	4,370	6,190	350	500	360	520	480	690
Limekiln Canyon	56	1	Below	960	1,360	130	190	140	210	190	270
King Canyon	57	2	Below	7,860	11,140	330	470	340	500	450	650
Unnamed Creek 1 (Arco Hills)	58	2	Below	6,610	9,360	200	280	210	310	250	370
Unnamed Creek 2 (Arco Hills)	59	1	Below	2,050	2,910	120	170	130	180	150	220
White Knob Range (east side below Mackay Dam)											
Cliff Creek	60	8	Below	2,000	2,830	2,000	2,830	2,000	2,830	2,750	3,890
Alder Creek	61	37	Below	6,000	8,500	6,000	8,500	5,990	8,490	8,320	11,800
Antelope Creek drainage											
Antelope Creek (upper drainage)	62	93	Below	7,640	10,830	7,640	10,830	7,520	10,670	10,770	15,270
Dry Fork Creek	63	40	Below	3,060	4,340	3,060	4,340	3,100	4,340	4,310	4,410
Cherry Creek	64	52	Below	1,940	2,750	1,940	2,750	1,920	2,720	2,770	3,920
Trail Creek	65	8	Below	1,810	2,570	1,810	2,570	1,920	2,730	2,450	3,470
Marsh Canyon	66	9	Below	2,470	3,500	2,470	3,500	2,580	3,660	3,310	4,690
Unnamed Creek 1 (Antelope)	67	6	Below	1,980	2,810	1,980	2,810	2,030	2,880	2,700	3,830
Unnamed Creek 2 (Antelope)	68	3	Below	880	1,250	310	450	320	470	420	600
Unnamed Creek 3 (Antelope)	69	2	Below	110	160	250	350	260	370	330	470
Unnamed Creek 4 (Antelope)	70	1	Below	5,270	7,460	150	220	160	230	200	290
Unnamed Creek 5 (Antelope)	71	2	Below	4,430	6,270	190	280	210	300	250	370
Unnamed Creek 6 (Antelope)	72	2	Below	560	790	200	280	210	300	270	380
Unnamed Creek 7 (Antelope)	73	1	Below	160	220	100	150	110	160	140	200

Table 5. Estimated tributary basin underflow for the Big Lost River Basin, south-central Idaho, 2000–19.—Continued

[All values in acre feet per year (acre-ft/yr) are rounded up or down to the nearest 10. Tributary numbers are shown in figure 8. **Abbreviation and symbol:** mi², square mile; #, number]

Tributary name	#	Drainage area (mi²)[1]	Above or below Mackay Dam	Mean annual Darcy flow[2], Q_d, before adjustment (ac-ft/yr)		Mean annual Darcy flow[2], Q_{trib}, adjusted for mean annual precipitation[3] (ac-ft/yr)					
				2000–19		2000–19		2014		2017	
				Low-end	High-end	Low-end	High-end	Low-end	High-end	Low-end	High-end
Antelope Creek drainage—Continued											
Unnamed Creek 8 (Antelope)	74	1	Below	350	500	120	170	130	190	150	220
Appendicitis Hill											
Rocky Canyon	75	4	Below	6,300	8,940	460	660	480	700	610	890
Unnamed Creek (Appendicitis Hill)	76	1	Below	260	370	120	180	130	190	150	220
Lower basin											
Newman Canyon	77	10	Below	850	1,200	850	1,200	910	1,280	1,130	1,610
Champagne Creek	78	10	Below	490	690	490	690	490	700	680	960
Total		876		214,350	303,840	88,630	128,660	87,870	127,460	124,180	178,730

[1]Calculated tributary area is based on tributary canyon delineation using StreamStats (U.S. Geological Survey, 2016).

[2]Mean annual Darcy flow in section, "Tributary Canyon Underflow" describes the Darcy flow equation and estimated parameters.

[3]Mean annual precipitation was determined from PRISM datasets (PRISM Climate Group, 2020).

Tributary Canyon Underflow Results

The adjusted tributary basin underflow estimates (table 5) for all the drainages evaluated ranged from approximately 88,600 to 128,700 acre-ft/yr over the 2000–19 study period. Individual terms used in the underflow estimates are summarized in table 4.1 in appendix 4 ("Tributary Canyon Underflow Supporting Detail"). Although the estimated range is relatively narrow, the necessary assumptions and analysis reflect high uncertainty owing to the lack of information for input parameters. The low-end mean adjusted tributary underflow value of 88,700 acre-ft/yr was used in the groundwater budget based on the low-end values for the mean annual adjusted Darcy flow (tables 4 and 5). The highest underflow (nearly 35 percent of the total estimated underflow for the entire basin) is associated with large drainages above Mackay Dam (including Thousand Springs Creek and the North and East Forks of the Big Lost River). About 23 percent of the total is associated with the Antelope Creek drainage below Mackay Dam. This result is expected based on the high correlation between streamflow and basin size, combined with observed stream intermittency (IDWR, 2020c) and the potential for deep recharge to occur at higher altitudes through snowmelt runoff to preferential flow conduits in fractured bedrock and alluvial fans. The mean annual underflow over the 2000–19 study period was approximately 50,900 acre-ft/yr above Mackay Dam and 37,700 acre-ft/yr below Mackay Dam (table 4; 34,700 acre-ft/yr in the middle subbasin and 3,000 acre-ft/yr in the lower subbasin).

Values used in the groundwater budget are based on the low-end range estimated for tributary drainages that use the results of aquifer testing in the Big Lost River Basin (Bassick and Jones, 1992) instead of literature-range reported aquifer properties by Freeze and Cherry (1979). These estimates produce relatively similar hydraulic conductivity (within the same order of magnitude). However, even small variations (about ±25 percent) in the hydraulic conductivity (which can vary by orders of magnitude) result in substantially different estimates of tributary canyon underflow. For context, the assumption of a uniform hydraulic conductivity of 500 feet per day (ft/d) (instead of 1,000 ft/d) reduces tributary underflow by one-half, indicating the high degree of sensitivity to assumed aquifer properties.

Estimated underflow for tributary canyons for this 2000-19 study period (using the low-end value of 88,700 acre-ft/yr) is less than one-half of that estimated by Crosthwaite and others (1970a) whose estimate totaled approximately 192,400 acre-ft/yr for the same approximate areas considered in this study. Some drainages in the Lost River Range and elsewhere were consolidated by Crosthwaite and others (1970a) and are not directly comparable with this study. Therefore, some judgment was necessary when apportioning the results of Crosthwaite and others (1970a). Differences in estimated recharge between the two studies are attributed to variations in methodology and assumed tributary underflow terms.

Seepage from Mackay Reservoir

Mackay Dam, located approximately 3.5 mi north of the town of Mackay, was constructed in 1919 for surface-water impoundment to provide for crop irrigation through an extensive canal system below the dam. The reservoir essentially divides the basin into an upper basin and a lower basin (not to be confused with terminology used throughout this report to distinguish areas below Mackay Dam as middle subbasin and lower subbasin for determining certain groundwater-budget components). The Big Lost River Irrigation District (BLRID) owns and operates Mackay Reservoir. Crosthwaite and others (1970a) reported a storage capacity of 44,370 acre-ft for Mackay Reservoir. BLRID currently reports the reservoir storage capacity is about 43,250 acre-ft (Big Lost River Irrigation District, 2020). Mackay Reservoir is drawn down during most water years during the crop irrigation season, whereas carry-over occurs during particularly wet seasons (such as the 2017–18 irrigation seasons).

The geology near Mackay Reservoir (Lewis and others, 2012) is characterized by the Challis Volcanic Group along the west side of the reservoir, alluvial fan and older sedimentary deposits on the east side, and glacial deposits and alluvium within the valley above the reservoir. Limestone outcrops at the southwestern end of the reservoir, and alluvium and alluvial fan sediments are on the southeastern end (Lewis and others, 2012). Surface inflow to the reservoir is predominantly from the Big Lost River, and Warm Springs and Parsons Creeks. Navarre Creek flows to Warm Springs Creek approximately 1 mi above the reservoir (U.S. Geological Survey, 2018a). No wells have been installed on the west side of the reservoir based on review of the online IDWR well-construction database (IDWR, 2020b).

Leakage through the toe of the dam was reported by Crosthwaite and others (1970a) at about 28,960 acre-ft/yr (40 ft^3/sec) at low stage and 94,120 acre-ft/yr (130 ft^3/s) at high stage. Much of the leakage was reported to return to surface flow below the dam. Stearns and others (1938) also reported seepage below and around Mackay Dam, with seepage return to the river above the "Narrows" where limestone constricts both sides of the valley. Interpretation of seismic mapping through the "Narrows" below Mackay Dam by Crosthwaite and others (1970a) supports constriction owing to limestone bedrock.

Data Sources, Methods, and Assumptions

Recharge to groundwater through seepage from Mackay Reservoir is not directly measured and must be estimated. Nearly continuous daily stage records for Mackay Reservoir have been kept since 1919 (USGS streamgage 13126000). Flow in the Big Lost River about 1.5 mi below Mackay Reservoir (USGS streamgage 13127000) has been continuously gaged since 1903, with some data gaps before 1920. Inflow from the Big Lost River to Mackay Reservoir

was gaged from 1920 to 1959 at USGS streamgage 13125500, with an average inflow of 188,100 acre-ft/yr (ranging from 77,300 to 302,000 acre-ft/yr). Review of the long-term period of record provides additional context for the conditions measured and observed during the 2000–19 study period. USGS streamgage datasets were accessed from the U.S. Geological Survey (2020).

Direct surface-water inflow into Mackay Reservoir from the Big Lost River was not measured during the study period, and flow to the reservoir (as surface runoff and groundwater underflow) from adjacent tributary canyons requires estimation. Inflow was estimated from the residual surface-water balance above Mackay Reservoir.

The method selected for estimating seepage volumes for Mackay Reservoir is adapted from Healy (2010) based on the groundwater-budget relation:

$$Q_{seepgw} = Q_{swout} - Q_{swin} - Q_{trib} - P + E + \Delta S - R_{off} - Q_{inter} \quad (3)$$

where

Q_{seepgw} represents seepage gains and losses from the reservoir, with positive values indicating a net inflow from groundwater to the reservoir and negative values indicating seepage from the reservoir;
Q_{swout} is surface-water outflow from the reservoir;
Q_{swin} is surface-water inflow to the reservoir;
Q_{trib} is estimated mean annual underflow from tributary drainages to the reservoir;
P is precipitation to the reservoir;
E is evaporation from the reservoir;
ΔS is the change in reservoir storage, with positive values indicating a net increase in reservoir storage;
R_{off} is surface runoff reaching the reservoir; and
Q_{inter} is interflow from the unsaturated zone.

Surface-water outflow from Mackay Reservoir (Q_{swout}) was estimated from the average annual streamflow measured at the Big Lost River USGS streamgage below Mackay Reservoir (13127000) plus the Sharp surface-water diversion (IDWR site 13126500; IDWR, 2020d, 2022a), located between the reservoir and USGS streamgage 13127000. Inflow to Mackay Reservoir (Q_{swin}) was calculated from streamflow at USGS streamgage 13127000. The term Q_{trib} is based on estimated mean annual tributary underflow from Pete Creek and Upper Cedar Creek drainages (section "Tributary Canyon Underflow"). The average estimated inflow to the reservoir over the 2000–19 study period (192,720 acre-ft/yr) is very similar to the historical measured average value of 188,120 acre-ft/yr at USGS streamgage 13125500 for 1920–59. Daily reservoir storage records (USGS streamgage 13126000; U.S. Geological Survey, 2020) were compiled to determine the average annual change in reservoir storage (ΔS). Available, published irrigated-land GIS coverages (IDWR, 2020a); draft irrigated-land GIS coverages for 2012–17 (M. Wilkins, IDWR, unpub. data, April 1, 2020)[7]; and available aerial photographs from the National Agriculture Imagery Program (NAIP) over the 2000–19 study period (Natural Resources Conservation Service, 2022) were used to establish the annual footprint of the reservoir for the purpose of estimating precipitation and evaporation used in equation 3. In reality, the surface-area changes observed throughout the irrigation season were small; therefore, any potential errors introduced in the calculation are perceived to be minor. Total annual precipitation (P) to the reservoir was compiled in GIS from annual PRISM raster datasets (PRISM Climate Group, 2020). Total annual evaporation was estimated from ET_{Idaho} values (Allen and Robison, 2017; University of Idaho, 2018) over irrigation and winter seasons for the Chilly Barton Flat weather station for deep open-water systems. ET_{Idaho} values may underestimate evaporation (and, therefore, may increase reservoir seepage) by as much as 50 percent or more compared to the use of available Mapping EvapoTranspiration at high Resolution and Internalized Calibration (METRIC) coverage (IDWR, 2021b) based on a direct comparison of evaporation totals using both data types. However, evapotranspiration is relatively small and is not expected to have a substantial effect on the overall seepage volume. ET_{Idaho} values were used instead of METRIC to include the full year because METRIC data are only available for the irrigation season and calibration is based on well-watered crops. Surface runoff (R_{off}) and inflow from the unsaturated zone (Q_{inter}) are considered negligible and were not included.

Reservoir storage is directly tied to operation of the reservoir to provide for water supply during the irrigation season, including the effects of drawing storage down and carry-over storage during years with surplus supply. Storage management affects the overall accuracy of estimates of reservoir seepage using the water-balance method.

Any uncertainty in the parameters used in the calculation are expected to affect the overall seepage calculation. However, the calculated seepage discussed in section, "Mackay Reservoir Seepage Results" is small; any errors in the groundwater budget, therefore, are expected to be minor as well.

Mackay Reservoir Seepage Results

Over the period of record, the maximum recorded reservoir storage of 46,070 acre-ft occurred on May 14, 1976, and multiple instances of zero storage have been reported. During the study period, the maximum storage (45,750 acre-ft) occurred on May 29, 2005, and the minimum storage (260 acre-ft) was reported on August 7, 2002. Mackay Reservoir storage changes derived from USGS streamgage 13126000 daily reservoir storage datasets (U.S. Geological Survey, 2020) reflect climatic and hydrologic conditions, apparent

[7]At the time of publication, published data were not available from IDWR but files may be requested from M. Wilkins at IDWR Idaho Water Science Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800.

in the deviation from the long-term average annual storage from 1950 to 2019 (fig. 9). Notably, greater negative deviation occurred during 2001–04, attributed to several sequential years with low total precipitation followed by years with relatively average precipitation (2005–09). Years with higher precipitation had correspondingly higher cumulative storage (2010–12 and 2017–19) with an intervening dry period from 2013 to 2015. Observed trends in Mackay Reservoir storage generally correspond with fluctuations in groundwater levels below the reservoir (table 6), such as well IDWR17 (05N 26E 23CDA1; IDWR, 2021a) below Moore with a total depth of 203 feet and undocumented completion interval. Groundwater pumpage was greater during drier years when less surface-water supply was available because of less snowpack. The effect of less recharge on reservoir storage and groundwater levels is indicated in figure 9.

Reservoir seepage, as inflow to groundwater in the water budget, was estimated from Mackay Reservoir, averaging 1,600 acre-ft/yr from 2000 to 2019, with the lowest estimated seepage in 2013 (260 acre-ft/yr) corresponding to a very dry year, and the highest estimated seepage was in 2005 (2,570 acre-ft), reflecting above-normal precipitation. Estimated seepage was 1,340 acre-ft in 2014 and 2,340 acre-ft in 2017 (table 6).

Recharge of Applied Water

Potential sources of recharge of applied water (sometimes referred to as incidental recharge) include applied irrigation (on-farm irrigation), irrigation return flows, irrigation canal seepage, artificial recharge (referred to as managed aquifer recharge in this report), land application of treated wastewater treatment plant discharge (which is not a substantial contribution in the Big Lost River Basin), and a portion of septic system effluent. Each of these sources is considered in the sections that follow. Recharge of applied water from surface water, groundwater, or some combination of the two may occur if the water does not otherwise evaporate or become surface runoff. Diverted surface water or groundwater represents an outflow from surface water and groundwater, respectively. However, the ultimate fate of the applied water may return a part back to the water table.

Applied Irrigation

Applied water in excess of crop demand may become surficial runoff that reaches a stream or river, or it may pass through the root zone and become recharge (Healy, 2010). Cultivated crops require an adequate water supply during the growing season. Precipitation and snowmelt in Idaho typically do not provide sufficient water for crops to grow and mature. Irrigation with surface water or groundwater is needed to satisfy the balance of total water demand for most crops (U.S. Department of Agriculture, 1993). The groundwater

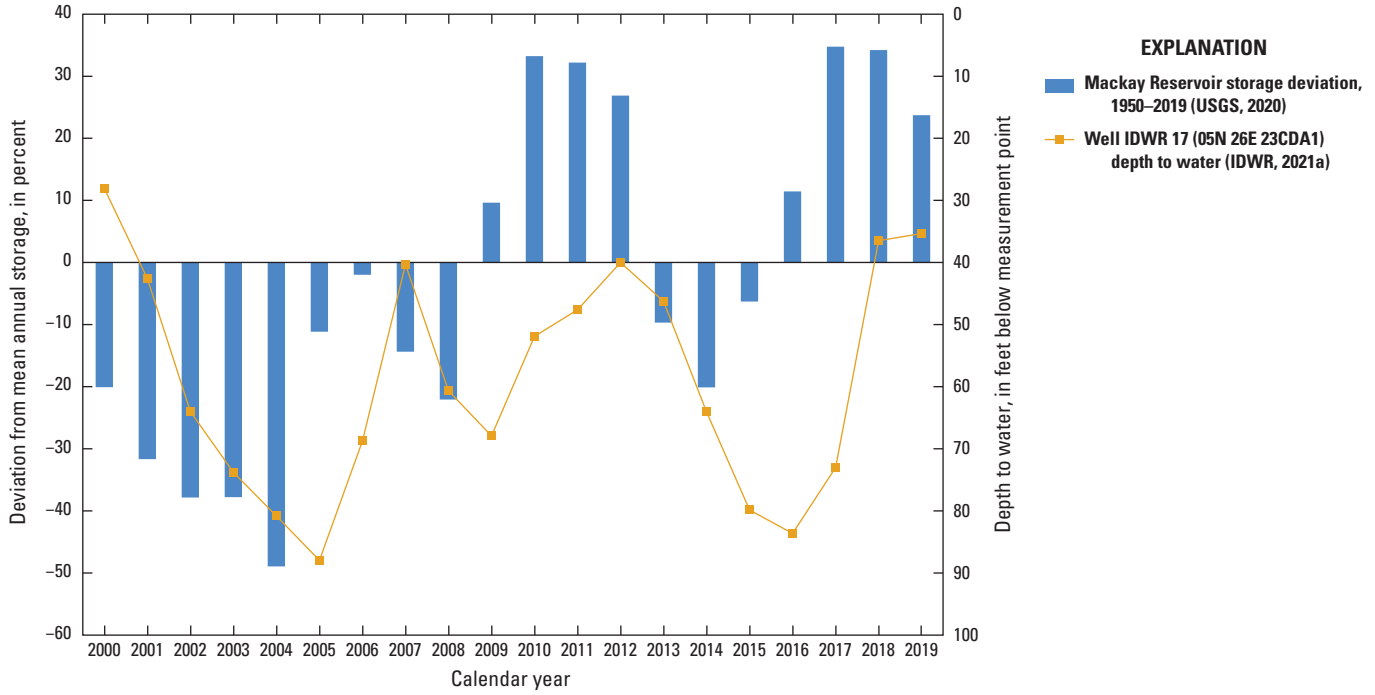


Figure 9. Percentage deviation from mean annual storage (1950–2019) for Mackay Reservoir and groundwater-level trends in well IDWR 17 (05N 26E 23CDA1), Big Lost River Basin, south-central, Idaho, 2000–19. IDWR, Idaho Department of Water Resources; USGS, U.S. Geological Survey. See table 6 for data.

Table 6. Estimated mean seepage from Mackay Reservoir, south-central Idaho, 2000–19.

[All values are in acre-feet per year. **Abbreviations:** *Qseepgw*, seepage gains and losses from the reservoir; *Qswout*, surface-water outflow from the reservoir; *Qswin*, surface-water inflow to the reservoir; *Qtrib*, estimated mean annual underflow from tributary drainages to the reservoir; *P*, precipitation to the reservoir; *E*, evaporation from the reservoir; IDWR, Idaho Department of Water Resources; Δ*S*, the change in reservoir storage]

Year	*Qseepgw* [1]	*Qswout* [2]	*Qswin* [3]	*Qtrib* [4]	*P* [5]	*E* [6]	Δ*S* [7]
2000	–1,750	168,920	161,076	2,282	1,007	1,540	–7,844
2001	–950	125,934	122,947	1,723	785	1,562	–2,986
2002	–1,310	129,259	127,671	1,916	824	1,429	–1,588
2003	–1,090	139,237	139,253	1,934	726	1,567	15
2004	–2,040	121,338	118,462	2,142	1,300	1,407	–2,877
2005	–2,570	196,088	205,821	2,648	1,350	1,425	9,733
2006	–2,440	286,466	288,834	2,669	1,249	1,475	2,368
2007	–1,010	149,289	146,093	1,857	814	1,661	–3,196
2008	–1,460	160,672	158,691	1,911	918	1,366	–1,981
2009	–2,640	216,968	225,134	2,529	1,321	1,207	8,166
2010	–1,920	200,084	206,160	2,480	1,255	1,812	6,076
2011	–1,730	229,871	229,601	2,538	1,000	1,804	–269
2012	–1,370	206,912	205,546	2,480	976	2,089	–1,366
2013	–260	156,328	146,913	1,567	642	1,949	–9,415
2014	–1,340	120,040	117,350	2,102	1,140	1,901	–2,690
2015	–1,300	149,873	153,436	2,060	1,177	1,941	3,564
2016	–2,000	178,251	182,816	2,558	1,292	1,854	4,565
2017	–2,340	397,260	403,264	2,992	1,206	1,854	6,003
2018	–1,190	282,188	282,048	1,949	1,097	1,854	–140
2019	–1,280	235,997	233,299	2,099	1,038	1,854	–2,698

[1]Seepage gains and losses from the reservoir were calculated using equation 3.

[2]Source datasets include measured streamflow below Mackay Dam (USGS streamgage 13127000; U.S. Geological Survey, 2020) and Sharp Ditch surface-water diversions (IDWR, 2020d, 2022a). See section, "Losing and Gaining River Reaches" for details on streamflow measurements. See section, "Applied Irrigation" and appendix 6 ("Surface-Water Diversions and Groundwater Pumpage") for details on surface-water diversions.

[3]Source datasets include daily storage for Mackay Reservoir (USGS streamgage 13126000; U.S. Geological Survey, 2020), measured streamflow below Mackay Dam (USGS streamgage 13127000; U.S. Geological Survey, 2020), and Sharp Ditch surface-water diversions (IDWR, 2020d, 2022a).

[4]See table 4.1 in appendix 4 ("Tributary Canyon Underflow Supporting Detail") for estimated tributary streamflow for Pete Creek and Upper Cedar Creek tributary canyons.

[5]Source precipitation datasets from PRISM (PRISM Climate Group, 2020).

[6]Source evaporation datasets from ET_{Idaho} for deep open water (Allen and Robison, 2017; University of Idaho, 2018). Data processing on non-irrigated lands used annual National Land Cover Database (NLCD) land-use coverages (Multi-Resolution Land Characteristics Consortium, 2019), published irrigated lands coverages (2000–11; IDWR, 2020a), and draft irrigated lands coverages for 2012–17 (M. Wilkins, IDWR, unpub. data, April 1, 2020—data available upon request from IDWR Idaho Water Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800). IDWR has since published irrigated-lands coverages as the "Eastern Snake Plain" for 2012–15, available from them at https://data-idwr.opendata.arcgis.com/pages/gis-data#IrrigatedLands.

[7]Source: Daily storage for Mackay Reservoir (USGS streamgage 13126000; U.S. Geological Survey, 2020).

budget incorporates recharge that occurs on irrigated and semi-irrigated lands during the irrigation season from April 1 to October 31. Most surface-water rights (IDWR, 2022b) in the Big Lost River Basin span from May 1 to October 15, whereas groundwater rights (IDWR, 2022b) typically span from early April to late October (D. Hoekema, IDWR, written commun., 2021). Most recharge occurs on irrigated lands, and some recharge occurs on "semi-irrigated" lands through lawn watering.

Total applied irrigation at the place of use (POU) is considered in the groundwater budget without distinguishing between separate surface-water and groundwater sources. Many irrigation POUs in the Big Lost River Basin are "mixed source," meaning that they have both surface-water and groundwater rights. This practice allows flexibility to irrigate with surface water when sufficient resources are available or with groundwater when surface water is not adequate for meeting irrigation demand (Sukow, 2017).

Mixed-source irrigation has implications when estimating unmeasured pumping in that the efficiencies are expected to differ depending on the source used. Appendix 5 ("Irrigation Efficiency") further describes irrigation efficiency.

Sukow (2017) assessed water rights and irrigation water sources for the Big Lost River Basin as of October 2016. Of the 76,200 total acres designated for permissible POU, 18,000 irrigated acres were above Mackay Dam, and 58,200 acres were below Mackay Dam. Most of the acres above the dam were irrigated solely with surface water (15,100 acres), and the remainder were irrigated using solely groundwater (1,300 acres) and a combination of surface water and groundwater (1,600 acres). Most POUs below Mackay Dam were irrigated with mixed sources (43,200 acres), whereas surface water only was used for 8,300 acres and groundwater only was used for 6,700 acres.

Data Sources, Methods, and Assumptions

Because recharge from applied irrigation cannot be measured directly, it must be estimated. Fisher and others (2016) presented a method for estimating applied irrigation recharge used in the groundwater-flow model of the Wood River Valley. The discussion that follows considers each component of the recharge calculation during the irrigation season, slightly modified from Fisher and others (2016) as follows:

$$Q_{incid} = Div_{SW} + Div_{GW} - Ret_{SW} - Canal_{seep} - \mathrm{CIR} \quad (4)$$

where

Q_{incid} is incidental recharge from applied irrigation water;

Div_{SW} and Div_{GW} are surface-water diversions and groundwater pumpage, respectively;

Ret_{SW} is return surface-water flow to streams and rivers;

$Canal_{seep}$ is canal seepage (from canal and ditch features); and

CIR is the crop-irrigation requirement (as annual evapotranspiration minus annual precipitation) on irrigated and semi-irrigated lands.

Surface-water diversions factor prominently in groundwater budget components and are included in recharge from applied irrigation (this section); canal seepage in section, "Canal Seepage;" and Big Lost River reach seepage in section, "Losing and Gaining River Reaches." A brief introduction is provided here and expanded upon in appendix 6 ("Surface-Water Diversions and Groundwater Pumpage"). IDWR maintains a searchable Water District surface-water diversion database for certain water districts, including Water District 34 (IDWR, 2020d). The database provides total annual volumes of surface-water diversions on the Big Lost River by the point of diversion, accessed for this study. IDWR created and provided a GIS coverage of the locations of surface-water diversions used in this study (D. Hoekema, IDWR, unpub. data, December 4, 2018)[8]. Surface-water diversion locations may be accessed from IDWR's water rights accounting database (IDWR, 2020e). Because most surface-water diversions are for irrigation of crops, the total measured and estimated diversion volumes have been used to estimate recharge of applied water.

Groundwater pumpage as outflow from the aquifer is addressed in sections "Groundwater Pumpage to Canals and Ditches" and "Groundwater Pumpage," including pumpage for irrigation, domestic supply, and municipal supply, and described further in appendix 6. Groundwater pumpage datasets may be accessed from IDWR's online water management information system (WMIS) web page (IDWR, 2020f) but for convenience for this water budget, annual groundwater pumpage records (2010–19) for irrigation and municipal uses were obtained from IDWR staff (C. Yenter, IDWR, written commun., 2018). Reported groundwater pumpage for 2014–19 was used in the groundwater budget components. Pumpage for 2000–13 was estimated using the methods described herein in this report in the above-mentioned sections. Groundwater pumpage for domestic supply was estimated using the methodology described in section "Domestic Supply."

Irrigation efficiency is a consideration when using water from a surface-water source versus a groundwater source; however, this term was not used directly in the groundwater budget calculations. Irrigation efficiency is presented in appendix 5 ("Irrigation Efficiency") for more context as it relates to estimates of unmeasured groundwater pumpage.

Return flows to the Big Lost River were estimated by IDWR (2020c) and measured by PivoTrac Monitoring, a remotely operated monitoring system for irrigation water (http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021)[9]. Measurements were recorded during the study period at two locations below Mackay Reservoir: (1) on the Burnett Ditch at the Burnett TE site above the West Side Ditch (locally known as the Moore Canal) and above the East Side Ditch (locally known as the Eastside Canal), and (2) on the East Side Ditch at East Side Out site, IDWR site 13132350, above the Munsey Ditch and Arco Canal[10]. Details regarding estimated and measured return flows are provided in appendix 7 ("Return Surface-Water Flow"). Terminal points for other canals typically do not directly flow to the Big Lost

[8]At the time of publication, published data were not available from IDWR but may be requested from D. Hoekema at IDWR Idaho Water Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800.

[9]At the time of publication, published data were not available from PivoTrac Monitoring but raw data may be requested from the Water District 34 watermaster, Lucas Yockey, at 208-589-3138.

[10]The PivoTrac Monitoring web page indicates that the East Side Out site is a rectangular weir but does not specify the type of device for the Burnett TE site.

River and, therefore, do not represent a return flow to surface water. However, Darlington Ditch diverts from the Big Lost River, passes Alder Creek, and ultimately intercepts Antelope Creek at an unmeasured location.

Canal seepage is described in section "Canal Seepage" and appendix 8 ("Estimated Canal Seepage Details") but is briefly summarized here because it is a factor in evaluating recharge from applied water. Below Mackay Dam, the canal network lies predominantly within irrigated and semi-irrigated lands. However, parts of the Nielsen and Warm Springs Ditches above Mackay Dam cross non-irrigated lands, where any seepage would be associated with non-irrigated lands instead of irrigated or semi-irrigated lands. Apportionment of the estimated canal seepage based on irrigated lands designation has not been addressed for canal segments spanning non-irrigated areas and could represent a source of focused recharge above Mackay Dam not included in the groundwater budget.

CIR was estimated as a volumetric total for each irrigation season (April 1–October 31) within the 2000–19 study period. Prior soil moisture at the start of the irrigation season may not necessarily be represented, as winter conditions were not included in the CIR analysis. Inclusion of winter evapotranspiration and precipitation effectively reduced CIR in most (but not all) years because of higher winter precipitation amounts compared to winter evapotranspiration, as most vegetation was dormant. METRIC datasets (IDWR, 2021b) were used in 12 of the 20 years, to the extent possible for estimating evapotranspiration. ET_{Idaho}-derived evapotranspiration values (Allen and Robison, 2017; University of Idaho, 2018) were used for years when METRIC coverage was not available. PRISM precipitation datasets (PRISM Climate Group, 2020) were used to estimate precipitation. The methodologies for estimating precipitation and evapotranspiration are presented in appendix 2 ("Precipitation Data") and appendix 9 ("River Reach Gain and Loss Assumptions"), respectively. Irrigated and semi-irrigated land status GIS coverages obtained from the IDWR were processed for available years: 2000, 2002, 2006, and 2008–17 for areas above Mackay Dam and for the middle and lower subbasins below Mackay Dam. Further details regarding additional processing of irrigated-land coverages are provided in appendix 1 ("Land Coverage").

Unmeasured parameters (including surface-water diversions and groundwater pumpage, return flows, and canal seepage) are sources of uncertainty in the estimated recharge of applied water. Any errors or uncertainty in these terms will compound and propagate in the groundwater budget. Groundwater pumpage measurement since 2014 using flow meters affords more accurate volumes calculated during those periods. Limited surface-water diversion measurement above Mackay Dam and for Antelope Creek during 2000–02 introduces uncertainty in the estimated recharge for that period.

Applied Irrigation Recharge Results

The total estimated mean recharge to groundwater from applied irrigation on irrigated and semi-irrigated lands during irrigation seasons in the 2000–19 study period was approximately 46,900 acre-ft/yr; this volume was approximately 11 percent of the groundwater inflow for the entire basin (table 4). The total mean applied irrigation recharge was 16,600 acre-ft/yr (13 percent of the total) above Mackay Dam and 30,300 acre-ft/yr (10 percent of the total) below Mackay Dam (fig. 10). Of the total mean applied irrigation recharge below Mackay Dam, 29,300 acre-ft/yr was estimated for the middle subbasin above the Moore Diversion and 1,000 acre-ft/yr was estimated for the lower subbasin below the Moore Diversion. The high irrigation recharge in 2005 above Mackay Dam (39,500 acre-ft) was driven by the high reported surface-water diversions (78,570 acre-ft) during that year. No recharge occurred in the lower subbasin during most years with the exception of 2002 and 2008–10. The entire basin had less recharge during dry years (fig. 10).

Irrigation recharge in the lower subbasin is particularly sensitive to high surface-water return flows for the East Side Ditch, high canal seepage, and high CIR, with higher magnitude to offset combined surface-water and groundwater diversion volumes based on equation 4. Irrigation recharge is compared to total estimated surface-water diversions and groundwater pumpage and estimated CIR (fig. 11; equation 4), suggesting that periods with increased irrigation recharge are correlated with lower CIR ($R^2 = 0.63$). The degree of correlation increases to 0.76 if 2005 is removed as an outlier (influenced by higher reported surface-water diversions than other years in the study period).

Canal Seepage

An extensive canal network carries irrigation water throughout the Big Lost River Basin (fig. 12). Most of the water is diverted from the Big Lost River, although some canals distribute water sourced from Warm Springs, Alder, and Antelope Creeks. Approximately 40 mi of canals are upstream from Mackay Reservoir, and 130 mi of canals distribute irrigation water below Mackay Reservoir. This total includes the major canals, but not all canals are included in the USGS National Hydrography Dataset (U.S. Geological Survey, 2018a) or ArcGIS coverage of canal locations created by IDWR used in this study (D. Hoekema, IDWR, unpub. data, December 4, 2018)[11].

Most canals are unlined, although a few have been or are in the process of being lined (L. Yockey, Water District 34, oral commun., 2018). Some of the canal water either directly evaporates from the open channel or seeps through

[11]At the time of publication, published GIS coverage was not available from IDWR but may be requested from D. Hoekema at IDWR Idaho Water Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800.

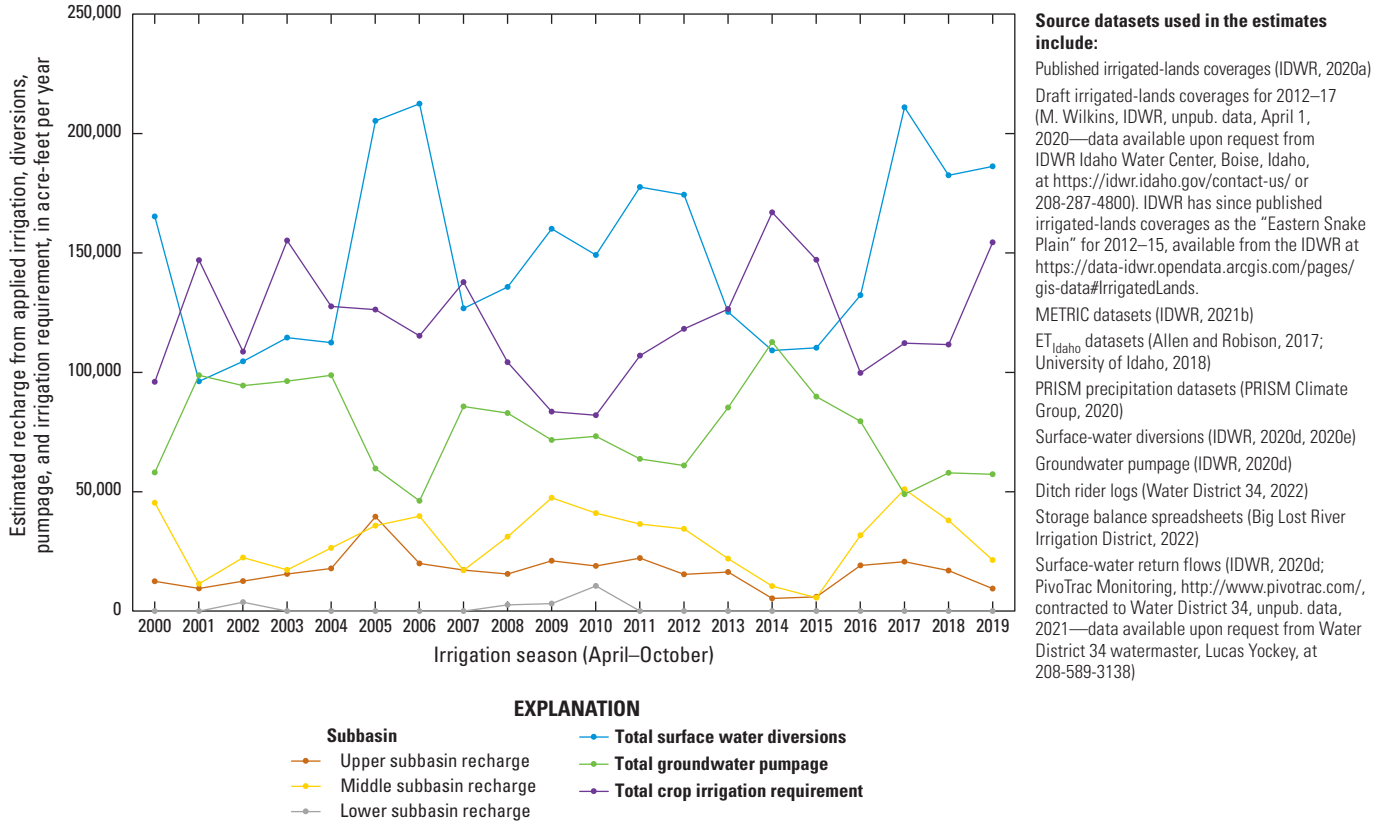


Figure 10. Estimated recharge from applied irrigation, surface-water diversions, groundwater pumpage, and irrigation requirement in the Big Lost River Basin, south-central Idaho, 2000–19. Total surface-water diversions, groundwater pumpage, and the crop irrigation requirement are shown in the figure for context. IDWR, Idaho Department of Water Resources.

the channel. Seepage recharges the aquifer if the water table is below the water surface in the canal (the most typical case in the Big Lost River Basin).

Multiple factors can affect canal seepage rates, including channel geometry and configuration, flow velocity, the type of substrate present, the degree of channel siltation, water-table proximity to the canal bottom and water level fluctuation, water temperature, nearby infiltration or withdrawal of water used for irrigation, microbiological activity, channel vegetation, and channel material saturation (Worstell, 1976; Iqbal and others, 2002). For example, coarse-grained bed material conducts higher seepage compared to finer-grained material. Because of these factors, seepage rates vary over time.

Data Sources, Methods, and Assumptions

Direct measurement of canal seepage rates (including inflow and outflow discharge measurements, ponding tests, or deployed seepage meter studies) has not been done in the Big Lost River Basin. Therefore, indirect methods may be used to estimate the volume of canal seepage. Canal delivery factors are the ratio of the reported delivery volume at the diversion location to the reported delivery volume at the canal headgate. Water District 34 ditch rider logs (Water District 34, 2022) provide the delivery volumes both at the diversion and the headgate[12] and were used to calculate delivery factors for a given canal. For this study, IDWR provided electronic compilations of delivery records as storage balance spreadsheets derived from the ditch rider logs below Mackay Dam for 2015–19 (Big Lost River Irrigation District, 2022) for incorporation into the groundwater budget (D. Hoekema, IDWR, written commun., October 9, 2019; M. Anders, IDWR, written commun., March 4, 2020).

Delivery factor calculations were used, to the extent available, for estimating canal seepage (2015–19). Seepage volumes below Mackay Dam were estimated from the relation between calculated delivery factors using 1 minus the delivery factor as the seepage factor multiplied by the total reported surface-water diversion volumes. The IDWR Water District surface-water diversion database (IDWR, 2020d) was used to compile surface-water diversion volumes used in the canal seepage estimates for the groundwater budget.

[12]Deliveries were reported in units of miner's inches. Miner's inches were converted to cubic feet per second per day by dividing by 50. Units in cubic feet per second per day were converted to acre-feet per year as follows: 1 acre-foot per year = (1 cubic foot per second×60×6,024)/43,560.

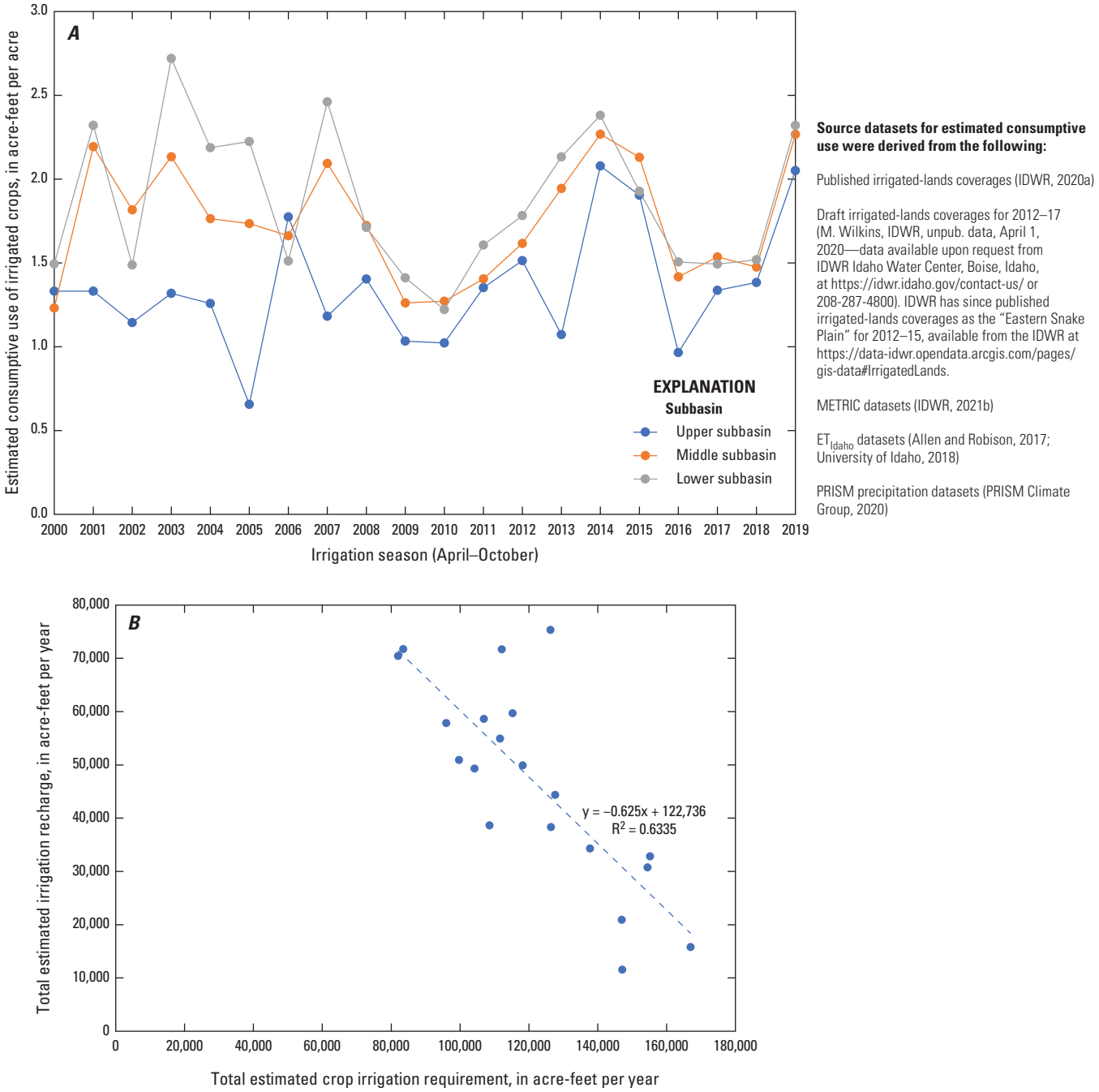


Figure 11. Estimated consumptive use of irrigated crops (*A*) and total estimated irrigation recharge compared to total estimated crop requirement (*B*) in the Big Lost River Basin, south-central Idaho, 2000–19. IDWR, Idaho Department of Water Resources; R^2, coefficient of determination.

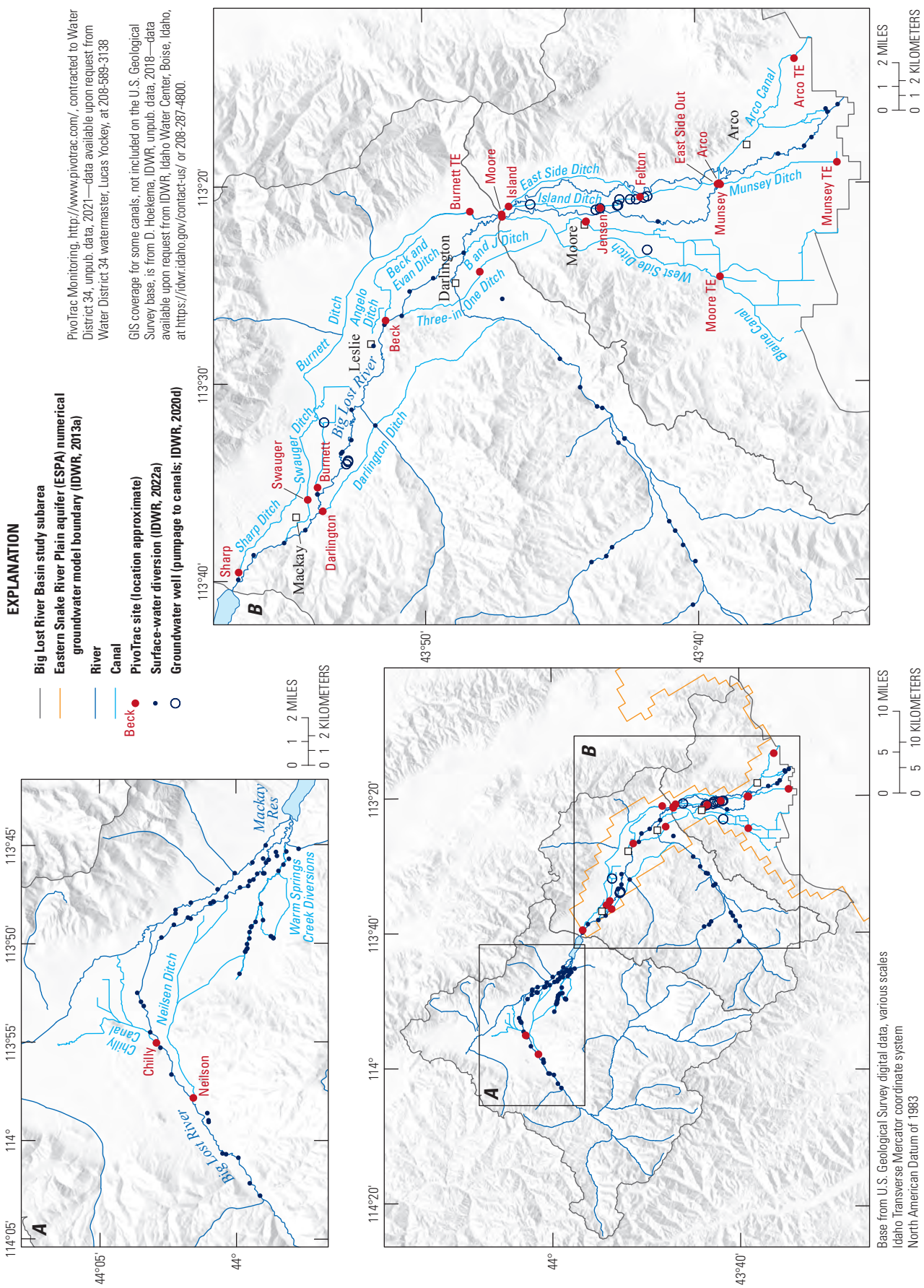


Figure 12. Water conveyance in the Big Lost River Basin, south-central Idaho. IDWR, Idaho Department of Water Resources.

Calculated delivery factor values below Mackay Dam ranged from 0 to 1. A factor of 1 indicates that no loss was reported for a particular diversion; however, this likely does not reflect true losses incurred as most canals are unlined and lose water to seepage. A high delivery factor is expected for deliveries that are close to the diversion point, with minimal conveyance loss (Angelo, Sutter, and Harris-Vaught Ditches) compared to canals with longer segments, deliveries farther along the canal, and with greater, cumulative seepage loss. The reported delivery factor exceeded 1 in a few records, attributed to recorded errors. Those values were removed from canal seepage estimates. This occurrence was very minor overall in the datasets.

Delivery records from ditch rider logs obtained from the IDWR were evaluated for canals and ditches below Mackay Dam during 2015–19 (Water District 34, 2022) but not for prior years within the study period (2000–14)[13]. In the middle subbasin, canal delivery factors were calculated for Three-in-One, Angelo (and combined Sutter, Pehrson, and Harris-Vaught parts of the ditch), B&J, Beck, Burnett, Darlington, Sharp, and Swauger Ditches[14] (fig. 12). Factors were calculated for lower subbasin canals and ditches including Arco Canal, East Side Ditch, West Side Ditch, and Munsey Ditch. Basin totals excluded West Side Ditch (included already in records for "Moore Canal") and Island Ditch (included in East Side Ditch) to avoid double-counting. The mean delivery factor for the 2015–19 period was 0.77 for the middle subbasin above the Moore Diversion and 0.73 for the lower subbasin below the Moore Diversion.

No electronic delivery records were available for canals and ditches above Mackay Dam (Neilsen Ditch, Chilly Canal, Upper Fish Hatchery Canal, and Shoupe Ditch[15]) or for some smaller or infrequently used canals below Mackay Dam, including Blaine Canal. A constant delivery factor of 0.60 was assumed for canals above Mackay Dam. Delivery factors used in the groundwater budget for canals below Mackay Dam without available delivery records were assumed to be within the same range as measured values for the other canals below Mackay Dam with delivery records.

Canal delivery factors for the middle and lower subbasins were correlated with reported surface-water diversions (only for the canals included in the 2015–19 annual delivery reports) to estimate delivery factors for 2000–14. The resulting correlation from linear regression yielded a coefficient of 0.71 for the middle subbasin and 0.62 for the lower subbasin. The relation between individual canal diversion volumes and calculated delivery factors, however, was correlated for some, but not all canals. During the period evaluated from 2015 to 2019, correlation coefficients of 0.60 and greater were apparent for Burnett, Darlington, and Pehrson Ditches, but correlation was not as high for Beck, Harris-Vaught, Sharp, and Swauger Ditches. Similar results were obtained for the lower subbasin canals, with reasonable correlation for Moore Canal (0.93) and Munsey Ditch (0.51) but poor correlation for Arco Canal (0.38) and East Side Ditch (0.31).

Because of the variability in the calculated delivery factors for each canal, the annual mean delivery factor was used to represent all canals for the middle and lower subbasins, respectively, during a given irrigation season (2015–19). Canal seepage estimates for middle and lower subbasins during 2000–14 were based on linear regression analysis of the total reported surface-water diversion volumes (2015–19) and the associated, calculated delivery factors (2015–19). These canal seepage estimates exclude the East Side Ditch, which is handled separately (see app. 8, "Estimated Canal Seepage Details").

The East Side Ditch conveys surface water diverted from the Big Lost River and groundwater inflow from several groundwater wells. The IDWR measures inflow to the canal at East Side In (IDWR site 13132060), and the IDWR measures outflow to the Big Lost River as return flow at East Side Out (IDWR site 13132350). Measured inflows to the East Side Ditch (IDWR, 2020d) and outflows from the East Side Ditch (IDWR, 2020d; http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021[16]) provide for more direct calculation of canal seepage than using estimated diversion factors. Some of the surface water and groundwater seeps from the canal back to the aquifer. Estimated seepage from groundwater represents a small volume and is calculated by multiplying the associated canal delivery factor term (actually as 1 minus the canal delivery factor) by the total reported groundwater pumpage to the canal. The seepage calculation for the East Side Ditch uses a similar methodology as described in section, "Losing and Gaining River Reaches."

Unmeasured canal diversions above Mackay Dam during 2000–02 were estimated based on the linear regression correlation ($R^2 = 0.50$) of measured canal diversions in the upper subbasin for 2003–19 with measured canal diversions in the middle subbasin for 2003–19 (IDWR, 2020d). A delivery factor of 0.60 was assumed for the canals above Mackay Dam to estimate seepage volumes. The use of an assumed, constant seepage rate introduces uncertainty in the estimated canal seepage volume. In reality, seepage is expected to vary over time.

Negative values estimated for total seepage loss in the middle and lower subbasins, arising from reported deliveries at the diversion location in excess of reported deliveries at

[13]Accessing delivery records and compiling delivery factors using hard-copy format for earlier years was beyond the scope of this study. Available records above Mackay Dam may be obtained through Water District 34 by contacting the WD34 watermaster, Lucas Yockey, at 208-589-3138. Available records below Mackay Dam may be obtained through the Big Lost River Irrigation District (BLRID) by contacting the BLRID general manager, Lucas Yockey, at 208-589-3138.

[14]Small segments of the Three-in-One and B&J Ditches extend into the lower subbasin.

[15]Upper Fish Hatchery Canal and Shoupe Ditch are included in the Warm Springs Creek Diversions (fig. 12).

[16]At the time of publication, published data were not available from PivoTrac Monitoring but raw data may be requested from the Water District 34 watermaster, Lucas Yockey, at 208-589-3138.

the headgate, were excluded from computed totals[17]. The total volume of water lost to evaporation is assumed to be relatively minor compared to other losses and, therefore, has not been used in the loss calculations. This assumption is consistent with Wood and others (2014) based on their finding that evaporation losses were low relative to measured seepage volumes during a 2012–13 seepage study of the middle Snake River in southwestern Idaho.

Canal Seepage Recharge Results

Relatively high canal seepage rates are expected for the Big Lost River Basin because of the coarse-grained soil present near the surface and observed in canal channels. Spatial soil datasets were obtained from the USDA NRCS State Soil Geographic database for Idaho coverage based on a 1:250,000 mapping scale (Natural Resources Conservation Service, 2019). The predominant surface soil in the basin is mapped as gravelly loam, with some reported silty loam and very gravelly loam soil.

[17]Three-in-One Ditch in 2015; Angelo, Sutter, Pehrson, and Harris-Vaught Ditches in 2016 and 2019; and Island Canal in 2017.

Canal diversion volumes and delivery factors were compiled for available canal segments by irrigation season for 2015–19 (table 7). Delivery factors were compiled only for the canals presented in table 7. The canal seepage term in the groundwater budget is based on extrapolation of the delivery factors for prior years (2000–14) and reported delivery factors during 2015-19 and includes additional canals for more complete accounting of canal seepage (table 8.1; appendix 8, "Estimated Canal Seepage Details"). Average estimated canal delivery factors below Mackay Dam ranged from 0.43 to 1.00 for this period, with most values ranging from 0.60 to 0.80. Fewer deliveries or diversions were reported in the ditch rider logs for a given canal segment compared to the total diversions reported for a canal in the IDWR Water District surface-water diversion database. The total diversions in the database were used for estimating total canal seepage based on the delivery factors estimated using the logs.

Estimated canal seepage for the 2015–19 period is likely to have higher certainty based on ditch rider field measurements than for the 2000–14 period based on assumed and estimated delivery factors (fig. 13). Estimated seepage for the East Side Ditch is summarized in table 8.2 in appendix 8 ("Estimated Canal Seepage Details").

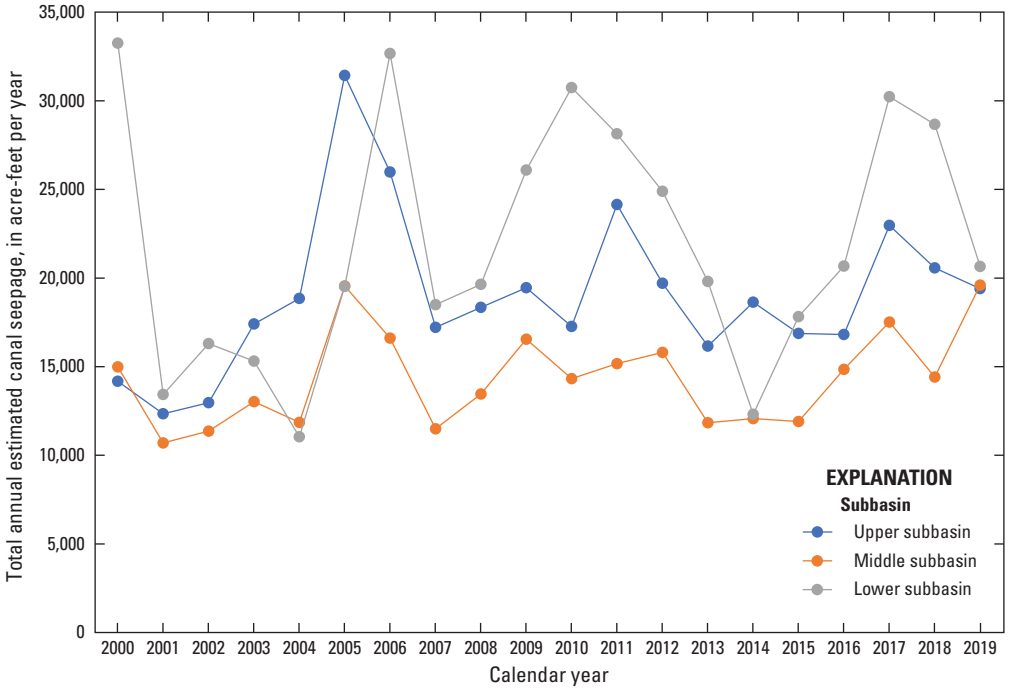


Figure 13. Estimated canal seepage in the Big Lost River Basin, south-central Idaho, 2000–19. See tables 8.1 and 8.2 in appendix 8 ("Estimated Canal Seepage Details") for data.

Table 7. Reported surface-water diversion volumes, calculated delivery factors, and estimated canal and ditch seepage volumes below Mackay Reservoir, Big Lost River Basin, south-central Idaho, 2015–19.

[Estimated seepage volumes in the table are based on the reported diversion volume instead of the delivery total at the headgate, rounded to the nearest ten. Not all canals, ditches, and diversions were reported in the delivery records used for seepage evaluation. Major canals are represented here and shown in figure 12. Italicized numbers were removed from analysis. **Abbreviations and symbol:** acre-ft/yr, acre-foot per year; IDWR, Idaho Department of Water Resources; NA, not available; n/a, not applicable; (-), dimensionless parameter]

Canal or ditch name	Basin location	Diversion volume[1] (acre-ft/yr)					Delivery factor[2] (-)					Seepage volume[1] (acre-ft/yr)				
		2015	2016	2017	2018	2019	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019
Three-in-One Ditch	Middle	241	1,901	7,286	3,634	5,770	NA	NA	0.92	NA	NA	NA	NA	560	NA	NA
Angelo, Sutter, Pehrson, Harris-Vaught Ditches[3]	Middle	432	1,212	4,943	1,487	2,317	0.99	0.89	1.00	NA	0.55	10	*140*	20	NA	*1,040*
B&J Ditch	Middle	107	0	739	0	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Beck Ditch	Middle	1,765	2,424	4,181	2,837	2,950	0.76	0.75	0.78	0.92	0.92	420	610	930	220	240
Burnett Ditch	Middle	10,104	13,208	22,779	19,104	21,135	0.43	0.49	0.71	0.63	0.69	5,750	6,790	6,640	7,020	6,650
Darlington Ditch	Middle	8,008	8,640	14,958	14,867	14,645	0.62	0.62	0.65	0.73	0.69	3,010	3,260	5,260	4,040	4,580
Sharp Ditch	Middle	2,618	2,689	3,495	2,809	2,445	0.83	0.85	0.87	0.88	0.88	440	410	450	330	290
Swauger Ditch	Middle	5,128	4,800	7,263	6,522	5,994	0.78	0.80	0.75	0.90	0.87	1,150	960	1,780	660	800
Total volumes (middle subbasin)		28,403	34,874	65,643	51,260	55,256	n/a	n/a	n/a	n/a	n/a	10,780	12,170	15,640	12,270	13,600
Arco Canal	Lower	672	3,368	11,239	10,394	7,203	0.50	0.57	0.81	0.58	0.84	330	1,440	2,100	4,380	1,180
East Side Ditch	Lower	10,913	15,711	32,100	27,779	20,165	0.66	0.72	0.85	0.72	0.89	3,710	4,380	4,660	7,770	2,270
West Side Ditch	Lower	17,236	22,523	36,656	32,878	36,072	0.47	0.62	0.76	0.68	0.76	9,100	8,660	8,940	10,460	8,690
Munsey Ditch	Lower	5,302	8,924	12,108	10,928	10,437	0.73	0.82	0.85	0.83	0.94	1,420	1,590	1,830	1,880	600
Total volumes (lower subbasin)		34,123	50,525	92,102	81,978	73,877	n/a	n/a	n/a	n/a	n/a	14,560	16,070	17,530	24,490	12,740

[1]See IDWR (2020d, 2020e) for surface-water diversion datasets used in the calculation of diversion and seepage volumes.

[2]See Water District 34 (2022) and Big Lost River Irrigation District (2022) for delivery records used in the calculation of delivery factors.

[3]Angelo, Sutter, Pehrson, Harris-Vaught Ditches are represented as Angelo Ditch in fig. 12.

Seepage represents approximately 14 percent (average 19,000 acre-ft/yr) and 12 percent (average 36,300 acre-ft/yr) of the recharge above and below Mackay Dam, respectively (table 4). The estimated mean annual seepage was 14,400 acre-ft/yr for the middle subbasin and 22,000 acre-ft/yr for the lower subbasin (table 8.1 in appendix 8, "Estimated Canal Seepage Details"). More canals convey water in the lower subbasin (with about 80 total mi estimated for West Side, East Side, and Munsey Ditches, and Arco Canal), as reflected in higher seepage totals. Because canal seepage is correlated with total surface-water diversions, years with high diversions (including 2000, 2005, 2010, and 2016) typically had higher seepage compared to years with lower diversions (such as 2001, 2004 and 2014). Few years with sufficient readily available records were reviewed, creating uncertainty in the estimated delivery factors and seepage volumes.

Managed Aquifer Recharge

Artificial recharge or managed aquifer recharge (MAR) is the intentional land application of water in a pit, depression, or channel feature. The goal of MAR is to replenish storage and increase groundwater levels through recharge of infiltrated water at the surface. MAR is one approach that may be used to address declining groundwater-level trends, stabilize an aquifer, promote conservation, or mitigate for water rights (Idaho Water Resources Board, 2012). The Idaho Water Resources Board and IDWR have implemented a MAR program in the ESPA as part of a comprehensive aquifer-management plan in response to declining groundwater-level trends and to stabilize the ESPA aquifer (Idaho Water Resources Board, 2009).

The Director of the IDWR appoints a watermaster for each active water district in Idaho. Primary duties of the watermaster include tracking daily water distribution, measuring water usage, and maintaining records (IDWR, 2020c). The watermaster prepares annual reports (hereinafter referred to as "watermaster reports"). Based on review of available annual watermaster reports (spanning 2003–19), managed recharge has occurred in the Big Lost River Basin during periods of adequate surface-water supply since at least 2005. Unlined canals and gravel pits are used for managed recharge during irrigation and non-irrigation seasons when surface-water supply is available.

Data Sources, Methods, and Assumptions

MAR records were obtained from annual watermaster reports available from the IDWR online document repository (IDWR, 2020c) for the groundwater-budget study period of 2000–19. MAR occurred in the Big Lost River Basin during 2005 at 30 sites (5 locations above Mackay Reservoir and 25 locations below the reservoir) and during 2006 at 95 sites throughout the basin. Those years were relatively wet, and the available surface-water supply permitted MAR during snowmelt runoff in late spring and early summer. Recharge activities also occurred during 2009–12 and 2017–19 (wet years in the study period).

MAR totals were compiled for the irrigation season (April–October) as a reported diversion in IDWR Water District surface-water diversion database (IDWR,2020d) and the IDWR water rights accounting database (IDWR, 2020e). However, MAR volumes during the non-irrigation season (January–March and November–December) are not tracked in the database and have been compiled separately from available annual watermaster reports (IDWR, 2020c).

Managed Aquifer Recharge Results

Total annual irrigation and non-irrigation season managed recharge (table 8) for the entire Big Lost River Basin ranged from approximately 8,130 acre-ft (in 2012) to 64,780 acre-ft (in 2006). Most recharge activities occurred in the lower subbasin, with comparable recharge in the middle subbasin and, to a lesser extent, in the upper subbasin (less than 1 percent of the inflow for groundwater budget). Managed recharge was reported as an annual total in the 2009 watermaster annual report, so it was assumed to have occurred during the irrigation season.

Municipal Wastewater Treatment Plants

Three municipal wastewater treatment plant (WWTP) facilities in the towns of Mackay, Moore, and Arco are located within the Big Lost River Basin. Most of the basin population, however, lives in rural areas served by individual septic systems (see section, "Septic System Effluent").

Treated effluent from the City of Mackay WWTP is discharged into the Big Lost River (specifically, the Big Lost River–Mackay Dam to Beck and Evan Ditch reach; Idaho Department of Environmental Quality, 2018). The facility design flow is 202 acre-ft/yr (0.28 ft^3/s; U.S. Environmental Protection Agency, 2020).

The Moore Water and Sewer Association operates a containment lagoon wastewater facility, consisting of three separate cells, in the City of Moore. In 2010, Keller Associates determined the average infiltration rate of 0.1102 inches per day (1.14 million gallons per year) based on a seepage study done for two of the three cells in operation at the time (Keller Associates, 2012). Assuming the 2010 infiltration rate is representative for the 2000–19 study period, the annual recharge from the lagoon facility is about 3.5 acre-ft/yr (0.005 ft^3/s).

Treated wastewater from the City of Arco WWTP is land-applied with three pivots approximately 1 mi south of the City of Arco. Recycled, treated water is delivered over 65 acres to crops during the irrigation season. Sewage disposal ponds are adjacent to the pivots. The 2013 reuse permit states that application rates ranged from 920 acre-ft/yr (1.3 ft^3/s) to 1,140 acre-ft/yr (1.6 ft^3/s) over the most recent 3-year

Table 8. Managed aquifer recharge total annual volumes for the Big Lost River Basin, south-central Idaho, 2000–19.

[***Bold italicized*** values have been estimated because there were no available records. **Abbreviations:** acre-ft/yr, acre-foot per year; IDWR, Idaho Department of Water Resources]

Year	Irrigation season[1] (acre-ft/yr)				Winter season[2] (acre-ft/yr)				Calendar year total (acre-ft/yr)
	Upper subbasin	Middle subbasin	Lower subbasin	Total	Upper subbasin	Middle subbasin	Lower subbasin	Total	
2000	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0
2005	3,239	9,243	16,195	28,677	0	0	0	0	28,677
2006	7,317	20,878	36,583	64,778	0	0	0	0	64,778
2007	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0
2009	1,390	11,254	13,182	25,827	***0***	***0***	***0***	***0***	25,827
2010	966	4,269	5,246	10,481	0	0	0	0	10,481
2011	3,164	253	0	3,418	0	843	2,292	3,135	6,552
2012	1,984	2,324	3,800	8,109	0	0	23	23	8,132
2013	0	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0	0
2017	6,803	21,062	0	27,866	411	5,675	0	6,085	33,951
2018	2,345	19,373	22,675	44,393	0	8,531	7,825	16,356	60,749
2019	3,717	17,830	15,689	37,236	1,339	5,338	4,620	11,296	48,532

[1]Annual managed aquifer recharge volumes for the irrigation season were compiled from the IDWR Water District surface-water diversion database (IDWR, 2020d) and IDWR water rights accounting database (IDWR, 2020e).

[2]Annual managed aquifer recharge volumes for winter were compiled from annual watermaster reports (IDWR, 2020c).

period (Idaho Department of Environmental Quality, 2013). The permit indicates that annual reporting of recycled water loading rates are in units of million gallons per month.

Data Sources, Methods, and Assumptions

Available records from 2007 to 2019 for average annual Mackay WWTP facility flow (in million gallons per day) were obtained from USEPA Enforcement and Compliance History Online searchable database (U.S. Environmental Protection Agency, 2020). No records were located for 2000–06. The total annual volume (in acre-ft/yr) was assumed to be representative of the average annual facility flow (in million gallons per day)[18].

Wastewater Treatment Plant Recharge Results

Mackay WWTP flow discharge is relatively consistent from year to year. During 2007–19, excluding 2009, the average annual discharge ranged from 0.0579 million gallons per day (Mgal/d; 65 acre-ft/yr) to 0.1074 Mgal/d (120 acre-ft/yr). The reported 2009 average discharge of 10.68 Mgal/d (11,963 acre-ft/yr) is two orders of magnitude larger than the average values reported for other years and seems to be an error. Therefore, the median discharge for years 2007–08 and 2010–19 (76 acre-ft/yr) was assumed for 2009. These volumes represent a very minor contribution to the Big Lost River and were not included in the groundwater-budget accounting. For example, total measured flows on the Big Lost River were not adjusted for Mackay WWTP discharge in river seepage calculations (see section, "Losing and Gaining River Reaches").

[18]A conversion factor (365×1,000,000)/(7.4805×43,560) was used to convert million gallons per day to acre-feet per year.

WWTP operations for Moore (using wastewater lagoons) and for the City of Arco (using lagoons and land-application) represent a small percentage of the total budget compared to the evaporation effects. Therefore, estimated recharge volumes for these systems are not included in the calculations.

Septic System Effluent

Because of the low population in the Big Lost River Basin, infiltration from septic system effluent was considered a minor contribution to the total groundwater inflow when compared to the total groundwater budget. Rural populations are served with self-supplied domestic wells for indoor and outdoor water supply. Idaho Water Resources Board (2012) reported that domestic uses predominantly are non-consumptive in that most of the water used eventually returns to the subsurface.

Data Sources, Methods, and Assumptions

The IDWR maintains a GIS well database for Idaho, including domestic water wells (IDWR, 2018). At the time the data were accessed in August 2018, the Butte County part of the study area had 247 domestic wells and the Custer County part had 234 domestic wells (defined as domestic in the database). These numbers likely underrepresent the total number of domestic wells that are not identified as "domestic" in the database. The USGS reported water use datasets for Butte and Custer Counties at 5-year intervals from 1985 through 2015. Data were accessed from the USGS National Water Information System (NWIS) web interface (U.S. Geological Survey, 2021). The average per-capita daily domestic use for self-supplied systems spanning the study period (2000–15) was 450 gallons per day (gal/d) in Butte County and 310 gal/d in Custer County. The U.S. Census QuickFacts reported that the number of persons per household was 2.43 in Butte County and 2.28 in Custer County during 2014–18 (U.S. Census Bureau, 2020). The total domestic water use per household (in gallons per day) was estimated by multiplying the number of persons per household in the county by the per-capita, self-supplied water use (in gallons per day per person). Total domestic water use per county was estimated by multiplying the total use per household by the number of domestic wells. Only indoor consumption during winter (January–March and November–December) was included in the estimate to avoid double-counting of lawn and garden watering that occurs during the irrigation season, as accounted for in the estimated recharge of applied water.

Hsieh and others (2007), for the Spokane Valley-Rathdrum Prairie aquifer in Bonner and Kootenai Counties in Idaho, and Bartolino (2009), for the Wood River Valley aquifer system in south-central Idaho, assumed that 95 percent of water discharged to septic systems from indoor water use ultimately infiltrated to the aquifer. Similar methodology used in the Big Wood River water-budget analysis also was applied here for the effluent infiltration assessment of the Big Lost River Basin septic system. One domestic well per household was assumed in the estimate, and the total number of wells and persons per household were assumed to be constant throughout the study period. Per-capita water use data were not published for 2014 and 2017, so mean values were used over the available period of record because the overall contribution of septic system effluent to the overall groundwater budget is small.

Septic System Effluent Recharge Results

The mean total estimated infiltration volumes from septic system effluent were 120 and 75 acre-ft/yr for Butte and Custer Counties, respectively, for the period from 2000 to 2015. The estimated mean inflow was about 200 acre-ft/yr over the 2000–19 study period. This total represents less than 0.01 percent of the total groundwater recharge.

Losing and Gaining River Reaches

A river-reach gains or loses flow as a function of several factors including streambed and subsurface permeability, streamflow, soil moisture conditions, nearby pumping or surface-water diversion and conveyance, and the water-table position relative to the streambed (Healy, 2010). A gaining reach receives groundwater discharge, as an outflow from the aquifer, when the water table is above the water surface in the stream. A losing reach loses flow, potentially recharging the aquifer, when the water table is below the water surface in the stream. At times, the river may be entirely disconnected from the water table. A particular reach may gain at certain times and lose at other times (Winter and others, 1998).

Surface water and groundwater in the Big Lost River Basin are directly connected (Crosthwaite and others, 1970a). The Big Lost River has both gaining and losing characteristics depending on the subreach, and individual reaches may gain or lose seasonally. Reaches near the headwaters of the Big Lost River have both gaining and losing trends, whereas reaches at the southern end of the basin near Arco commonly register no flow during dry years. Operation of Mackay Reservoir during the irrigation season substantially influences flow in the Big Lost River below Mackay Dam. Surface-water-rights administration influences the Big Lost River and some tributary flow regimes, adhering to basin-specific protocols above and below Mackay Reservoir (IDWR, 2004).

Data Sources, Methods, and Assumptions

River-reach gains and losses were calculated from the following relation, modified from California Department of Water Resources, 2020:

$$\begin{aligned}\text{River gain or loss} = {} & \text{Outflow} - \text{Inflow} - \text{Tributary inflow} \\ & + \text{Surface-water diversions} \\ & - \text{Groundwater pumpage to canals} \\ & \text{and ditches} - \text{Return flow}\end{aligned} \quad (5)$$

A positive value indicates a gain to the reach and a loss from the aquifer. A negative value indicates a loss for the reach and gain for the aquifer. Gains and losses are calculated as annual mean values. All units are in cubic feet per second unless otherwise indicated.

The mean annual streamflow for a given stream reach at the downstream streamgage represents the outflow term, and the upstream streamgage represents the inflow term[19]. Tributary inflow represents tributary streams that are either known or inferred to reach the Big Lost River. Reported and estimated surface-water diversions are discussed in appendix 6 ("Surface-Water Diversions and Groundwater Pumpage"). Groundwater that is pumped into canals and ditches for conveyance and ultimately used for irrigation (discussed in section, "Groundwater Pumpage to Canals and Ditches") is handled separately from groundwater pumpage by other wells used for irrigation, domestic supply, and municipal supply (addressed in section, "Groundwater Pumpage"). Surface-water diversions and groundwater pumped into canals and ditches, recorded in units of cubic feet per second per day, were summed over each reach based on available irrigation season records. Mean annual returns to the Big Lost River were included in the reach calculation based on flow accounting for Burnett Ditch and East Side Ditches (Burnett TE and East Side Out, respectively) using PivoTrac Monitoring (http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021)[20] and IDWR Water District surface-water diversion database records (IDWR, 2020d). Return flows were estimated when records were unavailable.

The USGS, Idaho Power, and IDWR monitored streamflow during the study period at several streamgages in the Big Lost River Basin (figs. 14 and 15; table 9). Some streamgages have been monitored continuously for more than 100 years with substantially or entirely complete records during 2000–19. Historically, other streamgages were operated on the Big Lost River and its tributaries but are now inactive (fig. 15). At some streamflow monitoring locations in the Big Lost River Basin, different entities have monitored streamflow (either continuously with a dedicated streamgage or by discrete streamflow measurements) at the same location with the same site identification number. Site attribution in this

[19]The Big Lost River streamgage below Mackay Reservoir (USGS streamgage 13127000) was adjusted for changes in Mackay Reservoir storage for calculation of the mean annual downstream streamflow for determining estimated seepage for the reach immediately above Mackay Reservoir.

[20]At the time of publication, published data were not available from PivoTrac Monitoring but raw data may be requested from the Water District 34 watermaster, Lucas Yockey, at 208-589-3138.

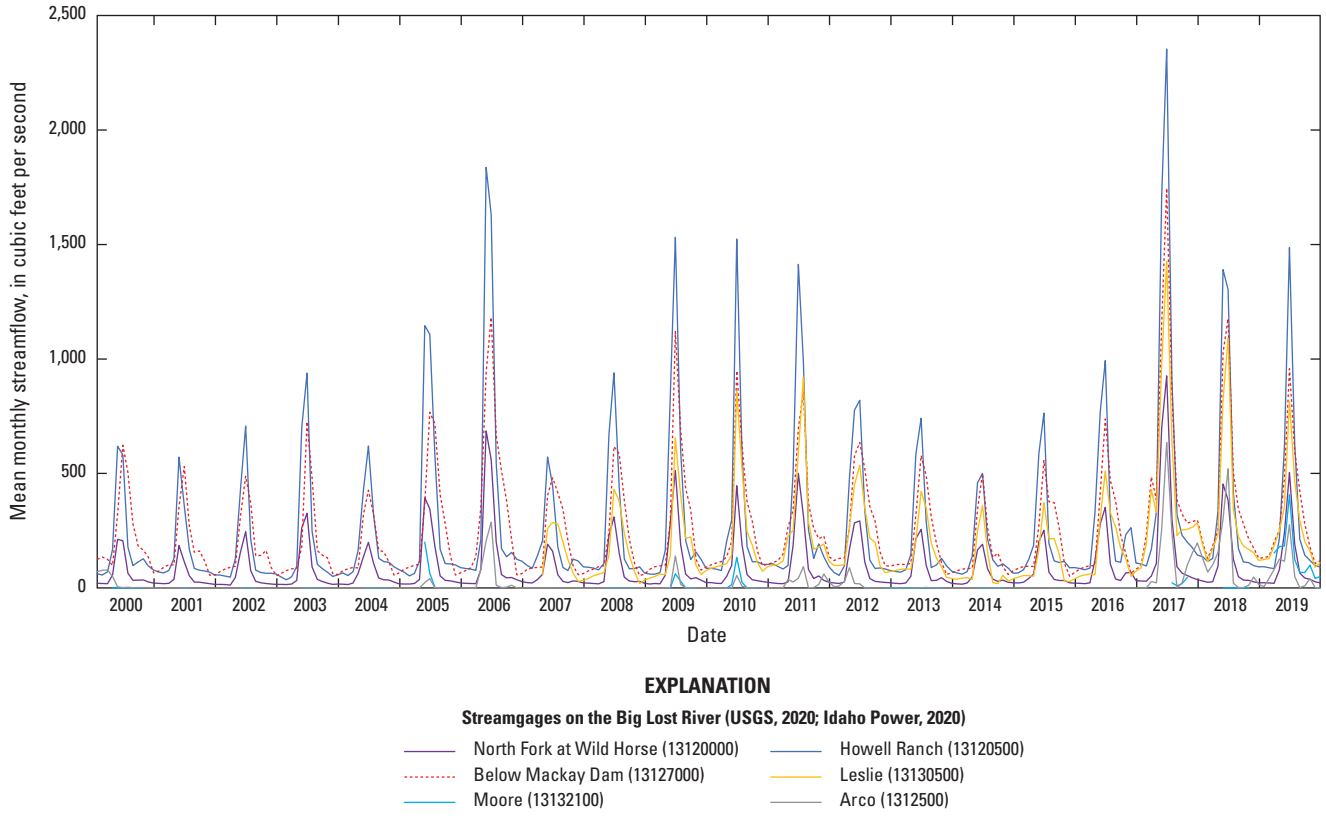


Figure 14. Mean monthly streamflow at streamgages with multi-year records in the Big Lost River Basin, south-central Idaho, 2000–19. USGS, U.S. Geological Survey.

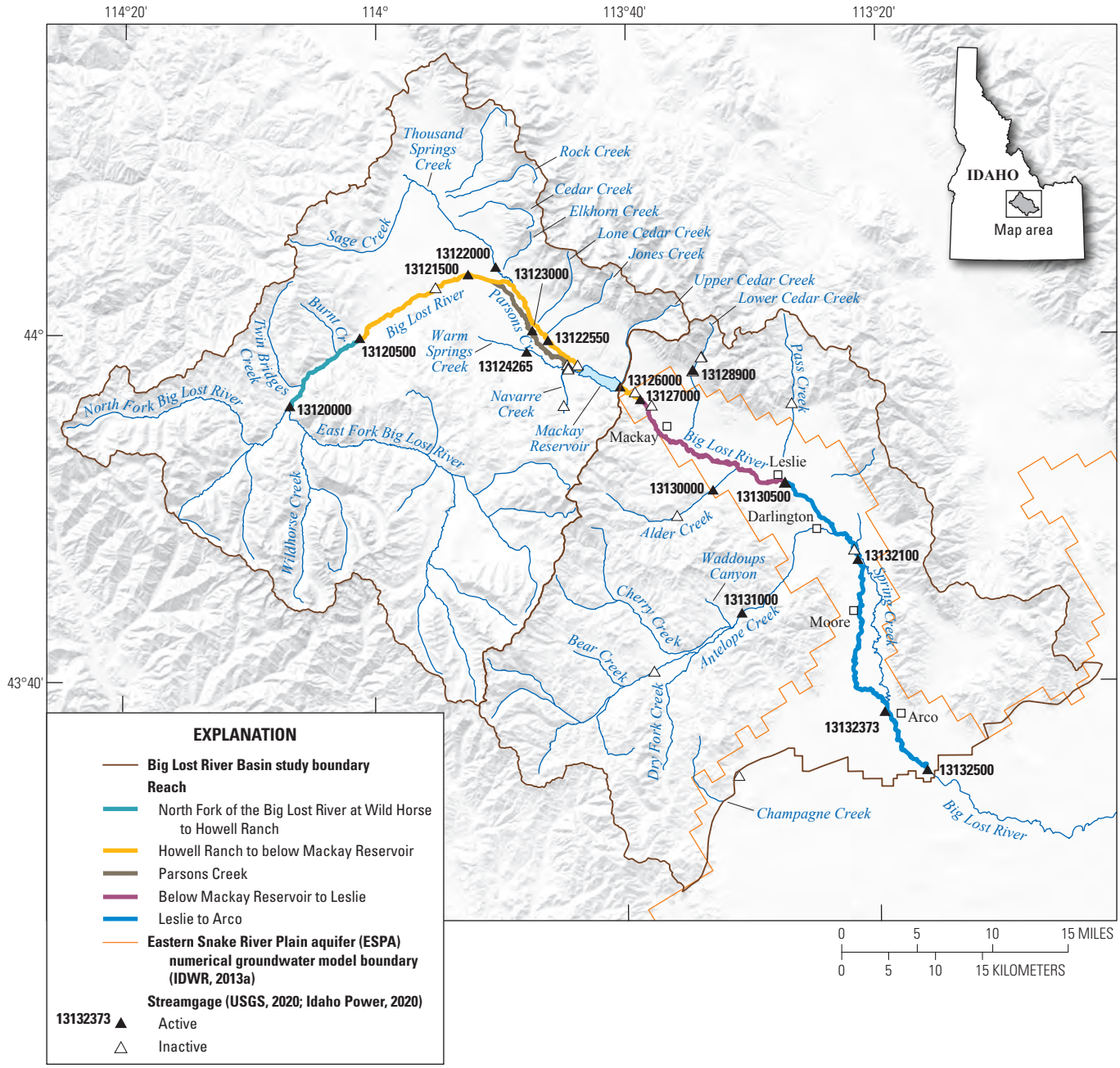


Figure 15. Reaches used to calculate annual gains and losses in the Big Lost River, south-central Idaho. IDWR, Idaho Department of Water Resources; USGS, U.S. Geological Survey.

report is to the entity responsible for data collection during the time period referenced for a given site identification number unless otherwise noted.

Datasets for streamgages monitored by the USGS were accessed from the USGS NWIS web page (U.S. Geological Survey, 2020). Big Lost River at Leslie, Idaho (13130500; hereinafter referred to as the Leslie streamgage) records were accessed from the Idaho Power database (Idaho Power, 2020). Streamgage records for the Big Lost River at Chilly Bridge near Chilly, Idaho (IDWR streamgage 13121500, hereinafter referred to as the Chilly streamgage) and for the Big Lost River below Moore Diversion near Moore, Idaho (USGS streamgage 13132100; hereinafter referred to as the Moore streamgage) from 2003 to 2019 were accessed from the IDWR Water District surface-water diversion database (IDWR, 2020d). Moore streamgage records from 2000 to 2002 were obtained from IDWR staff (J. Sukow, IDWR, unpub. data, January 21, 2020)[21].

[21]At the time of publication, published data were not available from IDWR but files may be requested from J. Sukow at IDWR Idaho Water Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800.

Table 9. Mean streamflow at streamgages in the Big Lost River Basin, south-central Idaho.

[**Abbreviations and symbol:** ab, above; Apr–Oct, April through October; blw, below; Cal./cal., calendar; Dec, December; Div, diversion; IDWR, Idaho Department of Water Resources; ft^3/s, cubic foot per second; Jan–Mar, January through March; Jun–Dec, June through December; May–Jul, May through July; Nov–Dec, November through December; nr, near; POR, period of record in reference to start of the streamgage record and end date for record coinciding with the end of the study period, December 31, 2019 (12-31-2019); Rd, road; USGS, U.S. Geological Survey; —, no data or insufficient data]

Streamgage			Start-end record (month, day, year)	Mean streamflow (POR) (ft^3/s)			Mean streamflow 2000–19 (ft^3/s)				
No.	Name	Entity[1] (POR)		Jan–Mar; Nov–Dec	Apr–Oct	Cal. year	Jan–Mar; Nov–Dec	Apr–Oct	2000–19 cal. years	2014 cal. year	2017 cal. year
13120000	North Fork Big Lost River, Wild Horse nr Chilly	USGS	04-01-1944 to 12-31-2019	25	155	101	23	136	89	58	203
13120500	Big Lost River at Howell Ranch nr Chilly	USGS	05-01-1904 to 12-31-2019	88	459	337	87	401	271	166	562
13121500	Big Lost River at Chilly Bridge nr Chilly	USGS	06-24-1920 to 9-30-1920	—	160	160	—	170	169	67	4
		IDWR	06-10-2014 to 12-31-2019							Jun–Dec	May–Jul
13122000	Thousand Springs Creek nr Chilly	USGS	12-1912 to 02-1913 01-1914 to 09-1914 05-1920 to 09-1922 03-27-2019 to 12-31-2019	9	31	26	—	19	19	—	—
13124265	Warm Springs Creek blw Diversion nr Mackay	USGS	03-26-2019 to 12-31-2019	—	33	36	—	33	36	—	—
13127000	Big Lost River blw Mackay Res nr Mackay	USGS	12-01-1903 to 12-31-2019	120	431	302	104	374	262	162	544
13128900	Lower Cedar Creek ab Div nr Mackay	USGS	08-14-1966 to 09-29-1984 03-26-2019 to 12-31-2019	7	32	22	—	26	22	—	—
13130000	Alder Creek nr Mackay	USGS	04-29-1920 to 09-29-1922 10-25-2018 to 12-31-2019	—	—	23	—	—	8	—	—
13130500	Big Lost River at Leslie	USGS; Idaho Power	05-08-1919 to 10-22-1922 04-09-2007 to 12-31-2019	93	300	221	93	292	212	92	448
13131000	Antelope Creek nr Darlington	USGS	04-29-1913 to 09-29-1922 08-23-2017 to 12-31-2019	38	116	97	37	126	89	—	—
13131500	Pass Creek nr Leslie	USGS	04-30-1920 to 09-30-1922 09-10-2001 to 08-20-2015	6	17	16	—	—	4	—	—
13132100	Big Lost River blw Moore Div nr Moore	IDWR (1994–2018) USGS (2019)	05-02-1994 to 12-31-2019	18	16	16	18	22	21	0	20
13132373	Big Lost River at Arco at Sunset Rd	USGS	03-25-2019 to 12-31-2019	11	102	80	11	102	80	—	—
13132500	Big Lost River nr Arco	USGS	09-01-1946 to- 12-31-2019	57	95	80	12	30	23	0	138

[1]Entity reflects associated agency responsible for collecting and reporting the streamflow data for the respective streamgage during the study period as follows: USGS (U.S. Geological Survey, 2020); IDWR (IDWR, 2020d); Idaho Power (Idaho Power, 2020).

Mean monthly streamflow recorded at streamgages with multi-year records (fig. 14) indicates a pattern of seasonal snowpack runoff, typically peaking during May or June. Howell Ranch (USGS streamgage 13120500) consistently has the highest peak flows in the system (often greater than 1,000 ft^3/s during wet years, with a recorded mean monthly low of 36 ft^3/s in February 2003 and a recorded mean monthly high of 2,353 ft^3/s in June 2017). Downstream flows typically decrease as the Big Lost River loses considerable flow to groundwater, and surface water is diverted for irrigation. At the Moore USGS streamgage (13132100) location, measured and estimated flow often was zero flow because of high losses above the streamgage near Darlington and substantial diversions above the USGS streamgage site at the Moore Canal (IDWR site 13132050) and East Side Ditch (IDWR site 13132060). The Arco USGS streamgage registers flow only during wet years or during seasons with appreciable runoff (during 2000, 2005–06, 2009–12, and 2017–19). The highest mean monthly reported flow at the Arco streamgage during the 2000–19 period occurred in June 2017 (636 ft^3/s).

The USGS, in cooperation with the IDWR, measured streamflow four times on the Big Lost River during the 2019–21 irrigation shoulder seasons (spring and autumn) (Dudunake and Zinsser, 2021) to document Big Lost River gains and losses. The method used for evaluating seepage in the groundwater budget differs from streamflow measurement events in that longer reaches between streamgages compiled over the irrigation season or calendar year (as applicable) are incorporated. This approach differs from the point-based, discrete field measurements that reflect seepage conditions at the time of measurement. As a result, the estimated seepage over these more aggregated reaches and time periods is expected to differ in magnitude and possibly indicate different trends with respect to gaining compared to losing reaches.

The river reaches selected for seepage calculation were determined on the basis of available streamgage locations and sufficient periods of streamflow records for upstream and downstream reach segments (fig. 15). Five primary reaches were evaluated on the Big Lost River for inclusion in the groundwater budget: (1) North Fork of the Big Lost River at Wild Horse (USGS streamgage 13120000) to Howell Ranch (USGS streamgage 13120500), (2) Howell Ranch to below Mackay Reservoir (USGS streamgage 13127000), (3) Parsons Creek, (4) below Mackay Reservoir to Leslie (Idaho Power streamgage 13130500), and (5) Leslie to Arco (USGS streamgage 13132500). Parsons Creek was included to account for Big Lost River flow and surface-water diversions between Howell Ranch and Mackay Reservoir.

Additional reaches (not shown on fig. 15) were evaluated from (1) Howell Ranch to Chilly (IDWR streamgage 13121500), (2) Chilly to just below Mackay Reservoir (USGS streamgage 13127000), and (3) Warm Springs Creek (USGS streamgages 13120805 to 13124265). Data for some years within the study period are not available for all locations, limiting complete assessment of reach gaining and losing trends and volumetric rates. Estimated reach gain and loss for the Chilly Bridge location (IDWR streamgage 13121500) were compiled for 2014 and 2018–19 available datasets. Warm Springs streamgage datasets were available for 2015–19 but not for prior years.

Many tributaries to the Big Lost River (including the East Fork of the Big Lost River; and Twin Bridges, Burnt, Pinto, Thousand Springs, Warm Springs, Alder, and Antelope Creeks) have not been directly monitored or only monitored for brief periods during 2000–19. Further details on streamflow monitoring are provided in appendix 9 ("River Reach Gain and Loss Assumptions"). Historical streamflow measurements outside the study period and insufficient records within the study period were considered but could not be used directly in the river-seepage analysis. Therefore, estimates of tributary streamflow were necessary for adjusting estimates of Big Lost River seepage.

Tributary basins were delineated using the USGS program StreamStats (U.S. Geological Survey, 2016). The program calculates the mean annual flow and median monthly flow-duration (Q50) statistics for each drainage using program-defined regression relations based on drainage area, water storage, and mean annual precipitation. The program also computes flow-duration statistics for 20-percent flow exceedance (Q20) and 80-percent flow exceedance (Q80) (Ries and others, 2017).

Certain assumptions and caveats are necessary because of missing data. For example, streamflow, surface-water return flow, and surface-water diversion data were not available for certain years within the study period for some streamgages and locations. Some records were incomplete during the irrigation season or calendar year.

Estimated tributary inflow to the Big Lost River represents a substantial source of uncertainty with expected implications for the overall groundwater budget. Few data are available to accurately estimate tributary streamflow during the study period. The magnitude and timing of flow reaching the Big Lost River through tributary streams (especially the East Fork of the Big Lost River and Antelope Creek) are major components of the overall water budget. Few records or observations were recorded in annual watermaster reports to indicate whether tributary flows reach the Big Lost River during the irrigation season. The 2014 watermaster report noted that Antelope Creek did not reach the Big Lost River, and the 2008 watermaster report indicated that Antelope Creek flows in 2008 decreased during the irrigation season and ceased to reach the Big Lost River (IDWR, 2020c). Measured flow on Antelope Creek at USGS streamgage 13131000 during August 2017–December 2019 (U.S. Geological Survey, 2020) indicated consistent flow during the irrigation season. This period included wet years. Tributaries likely lose flow, especially during dry years or near the end of the irrigation season, such that flow no longer reaches the Big Lost River. In these cases, estimated tributary flow will overrepresent actual contributions to the Big Lost flows, overestimating seepage.

Conversely, tributaries may reach the Big Lost River during wet years and outside the irrigation season or could provide for year-round flows.

The use of variable streamflow statistics derived from StreamStats (Q20, Q50, or Q80 flow-duration statistics) may not reflect actual conditions. The sensitivity in estimated seepage is highlighted in tables 9.1–9.4 of appendix 9 ("River Reach Gain and Loss Assumptions"), with and without the contribution from tributary streams. The groundwater budget does not consider reach gains and losses on tributaries to the Big Lost River. However, several tributaries (including the North and East Forks of the Big Lost River, and Thousand Springs and Antelope Creeks) have appreciable streamflow. Approaches and assumptions for estimating unmeasured terms are summarized in appendix 9 ("River Reach Gain and Loss Assumptions").

Losing and Gaining River Reach Results

Slight gaining or losing conditions were calculated above Mackay Reservoir, depending on the year, with average gains of about 26,900 acre-ft/yr and average losses of 6,600 acre-ft/yr during 2000–19. Substantial losses of 138,200 acre-ft/yr were calculated consistently below Mackay Reservoir during the study period. Individual reaches are summarized in figure 16 and discussed in sections "Above Mackay Dam" and "Below Mackay Dam." Input terms and estimated seepage results are summarized in appendix 9 (tables 9.1 and 9.2 for reaches above Mackay Dam and tables 9.3 and 9.4 for reaches below the dam). Implications of the interactions between surface water and groundwater are described further in section, "Groundwater Resource Sustainability."

Above Mackay Dam

The Big Lost River above Mackay Dam either gains or loses flow from its headwaters (gaged between the North Fork at Wild Horse and Howell Ranch), loses flow from Howell Ranch to Chilly (IDWR streamgage 13121500), and typically gains or loses flow in the longer reach from Howell Ranch to the Mackay Reservoir (fig. 16).

The reach from the North Fork at Wild Horse to Howell Ranch gained flow of about 6,500 acre-ft/yr from 2000 to 2019, and lost flow of about 8,500 acre-ft in 2014 and 40,800 acre-ft in 2017. Substantial estimated loss was unexpected in 2017 because of high precipitation, with an anticipated high groundwater-table condition, and was attributed to large estimated tributary flow (subtracted in the equation for determining seepage). Estimated streamflow gains and losses in this reach were sensitive to estimated flows for the East Fork of the Big Lost River, as described in appendix 9 ("River Reach Gain and Loss Assumptions"). The East Fork flows into the Big Lost River below the USGS streamgage (13120000) on the North Fork of the Big Lost River at Wild

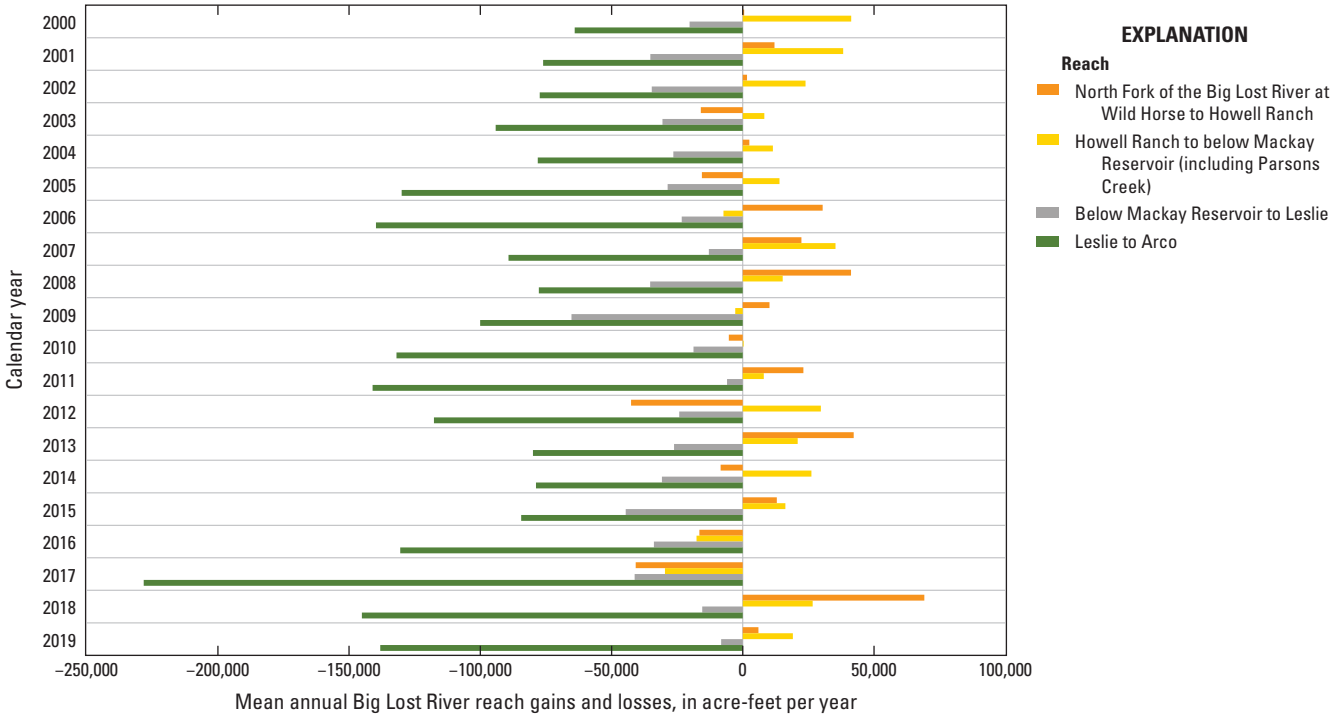


Figure 16. Mean annual estimated gains and losses in reaches of Big Lost River, south-central Idaho, 2000–19. Negative values indicate a loss from the river and a gain to the aquifer. Positive values indicate a gain to the river and a loss from the aquifer. See tables 9.1–9.4 in appendix 9 ("River Reach Gain and Loss Assumptions") for source datasets used in the estimation.

Horse above Howell Ranch. Estimated flow for the East Fork ranged from about 100 ft^3/s during dry years to 400 ft^3/s in 2017 (wet year).

The Big Lost River historically loses flow near Chilly Buttes and Thousand Springs Creek (Crosthwaite and others, 1970a). The estimated seepage loss in the reach from Howell Ranch to Chilly was about 43,200 acre-ft in 2014, 73,700 acre-ft in 2018, and 126,200 acre-ft in 2019. The estimated seepage losses during this study are reasonably consistent with previous findings by Crosthwaite and others (1970a) who reported an average loss of 86,900 acre-ft/yr (120 ft^3/s). However, overall gaining trends were calculated for the reach from Chilly Bridge to Mackay Reservoir in 2014 (69,400 acre-ft), 2018 (100,300 acre-ft), and 2019 (145,300 acre-ft). Although the different estimation periods prohibit an accurate comparison to this study, Stearns and others (1938) also described overall gaining conditions below the Chilly Sinks[22], influenced by groundwater inflow and streamflow contributions from Warm Springs.

The reach from Howell Ranch to Mackay Reservoir overall was slightly gaining (13,900 acre-ft/yr on average during 2000–19), with the highest estimated gain in 2000 (41,300 acre-ft/yr) and the highest loss in 2017 (about 29,600 acre-ft/yr), see fig.16. Crosthwaite and others (1970a) reported average losses during 1944–69 of 120,000 acre-ft/yr (170 ft^3/s). However, Crosthwaite and others (1970a) did not explicitly account for diversions in the estimates. During 2000–19, surface-water diversions between Howell Ranch and Mackay Reservoir averaged nearly 42,000 acre-ft/yr. During 1944–69 in the Crosthwaite and others (1970a) evaluation, the mean annual difference in flow in the Big Lost River between Howell Ranch and Mackay Reservoir was higher (by about 15 ft^3/s [10,900 acre-ft/yr]) than during 2000–19 (approximately 9 ft^3/s [6,500 acre-ft/yr] between Howell Ranch and the Big Lost USGS streamgage below Mackay Reservoir, 13127000). Total estimated tributary flows from Pinto, Thousand Springs, and Warm Springs Creeks, averaged about 22,200 acre-ft/yr during the 2000–19 study period, greatly influencing estimated seepage in this reach. The USGS measured streamflow in Thousand Springs and Warm Springs Creeks from March 2019 to December 2019, with mean streamflows of 19 ft^3/s and 36 ft^3/s, respectively (U.S. Geological Survey, 2020). Because of incomplete annual records in 2019, estimated streamflow was used for the seepage calculations. The total calculated seepage may be either slightly positive or negative depending on the assumed tributary streamflow contributions. For example, use of the adjusted mean annual tributary streamflow results overall in an estimated reach loss, whereas the adjusted median annual streamflow results in an estimated reach gain over the study period.

[22]As described in Stearns and others (1938), the Chilly Sinks extend from T8N, R22E, Section 6, southwest of the village of Chilly, to 9 miles downstream.

Below Mackay Dam

The Big Lost River tends to lose flow below Mackay Reservoir, particularly in the Darlington Sinks area (Crosthwaite and others, 1970a). A 2007 study (Rice and Boyd, 2008) focused on seepage measurement in the Darlington Sinks area, indicating significant reach loses attributed to a local deep water-table condition. A part of the reach above the Moore Diversion consistently has measured gains based on streamflow measurement events that occurred in 2007 (Rice and Boyd, 2008) and 2019 (Dudunake and Zinsser, 2021).

In the reach from Mackay Reservoir to Leslie, the river lost on average 28,100 acre-ft/yr from 2000 to 2019, about 30,800 acre-ft in 2014, and about 41,200 acre-ft in 2017 (fig. 16). Flows on the Big Lost River at Leslie were estimated for 2000–06. Section, "Unmeasured Big Lost River Streamflow Assumptions" in appendix 9 ("River-Reach Gain and Loss Assumptions") provides more details on the estimation techniques. Flow was estimated over the entire study period for Alder Creek, as a tributary to the Big Lost River (section, "Unmeasured Tributary Streamflow Assumptions" in appendix 9), introducing uncertainty to seepage estimates.

The Antelope Creek drainage area (about 236 mi^2) contributes appreciable streamflow to the Big Lost River and groundwater underflow to the alluvial aquifer. Seepage estimates from Antelope Creek, however, are poorly constrained by the lack of continuous streamflow gaging during the 2000–19 study period. Therefore, tributary canyon underflow was estimated for the Antelope Creek drainage (discussed in section, "Tributary Canyon Underflow") to represent the contribution of the drainage to the groundwater budget. Alluvium is mapped within the immediate channel of Antelope Creek, and glacial outwash occurs near the historical USGS streamgage 13130900 around the confluence of Dry Fork Creek and Cherry Creek with Antelope Creek (fig. 15). However, much of the contributing drainage spanning the river reach is within either dacite flows or carbonaceous mudstone or argillite (Skipp and others, 2009), perhaps restricting stream seepage conditions within this reach. Just above USGS streamgage 13131000, the geology changes to cavernous limestone (Skipp and others, 2009) at a fault boundary. Channel material properties of Antelope Creek possibly change at this transition or closer to the alluvial fan at the mouth of the creek, promoting seepage to groundwater with less surface-water expression near the confluence with the Big Lost River. Crosthwaite and others (1970a) estimated 21,700 acre-ft/yr (30 ft^3/s) of flow underground past the streamgage, with flow sinking in the Darlington Sinks area. During this study period, estimated mean annual tributary underflow from the Antelope Creek drainage was 20,200 acre-ft/yr. Discrete streamflow measurements taken from September 1966 to August 1968 in the Antelope Creek reach between Cherry Creek and the downstream Antelope Creek streamgage (Crosthwaite and others, 1970a) indicated slightly gaining

and losing seepage conditions (–44 ft³/s to +15 ft³/s). The lack of measured streamflow for Antelope Creek and disparate time periods of available historical records complicate assessment of gaining and losing trends. The actual volume of Antelope Creek flow that reaches the Big Lost River also has implications for the magnitude of estimated Big Lost River seepage, either by overestimating or underestimating seepage in the Big Lost River.

Between the Leslie and Arco streamgages, the Big Lost River loses significant flow, averaging 110,100 acre-ft/yr over the study period, 78,800 acre-ft in 2014, and 228,200 acre-ft in 2017 (fig. 16). These calculations do not account for the part of the Big Lost River diverted to the East Side Ditch (through East Side In, IDWR site 13132060) that returns to the river (at East Side Out, IDWR site 13132350). Seepage from East Side Ditch is handled as canal seepage in the groundwater budget, described in section, "Canal Seepage" and appendix 8 ("Estimated Canal Seepage Details").

Outflows from the Aquifer

The predominant sources of outflow (discharge) from the aquifer in the Big Lost River Basin include the following:

- Groundwater pumpage to canals and ditches;
- Pumpage for crop irrigation, domestic supply, and municipal supply; and
- Gaining river and stream reaches[23].

Groundwater Pumpage to Canals and Ditches

Wells are used by some irrigators at 18[24] locations below Mackay Reservoir to pump groundwater from the aquifer for discharge into canals and ditches (fig. 12). These wells are referred to in the IDWR Water District surface-water diversion database as "exchange" wells (IDWR, 2020d). This practice is done in the Big Lost River Basin as a cost-saving measure by which groundwater pumped from a shallower depth is piped into a nearby canal or ditch where it is then delivered to the POU, instead of groundwater being pumped from a greater depth beneath the POU at a higher cost. Groundwater is pumped into the East Side Ditch and Island Canal, where it is conveyed to the Big Lost River and then rediverted to the Arco and Munsey Canals and delivered to farm headgates (D. Hoekema, IWDR, written commun., 2021). The exact locations of 4 of the 18 wells were not identified during the study, but most wells are south of the town of Moore (D. Hoekema, IDWR, written commun., 2021). The fate of groundwater extracted by these wells is handled separately, in the groundwater budget, from other wells used for irrigation (see section, "Groundwater Pumpage").

Data Sources, Methods, and Assumptions

Daily and annual pumpage volumes for the wells are available for 2003–19 from the IDWR Water District surface-water diversion database (flagged as "E" for "exchange" wells; IDWR, 2020d). The IDWR staff provided well-pumpage records on the Big Lost River below Mackay Dam during 2000–02 from the IDWR water rights accounting files (J. Sukow, IDWR, unpub. data, January 21, 2020)[25].

Total pumpage volumes by groundwater wells were included in the groundwater-budget calculations as a net outflow from the aquifer. Conceptually, the fate of the extracted groundwater pumped into the Big Lost River channel is that it technically becomes surface flow where it may be diverted, evaporated, or returned to the subsurface through seepage. Pumped volumes are not included in surface-water inflow accounting and are subtracted from river or canal seepage calculations accordingly as the source is from groundwater. Pumpage volumes constitute a minor part of the total groundwater discharge; therefore, any associated uncertainty or errors are expected to have a negligible impact on the overall groundwater budget.

Groundwater Pumpage to Canals and Ditches Results

The reported mean annual groundwater pumpage by wells for use in canals for the entire basin (table 4) was 8,307 acre-ft/yr during 2000–19, ranging from no pumpage (in wet year 2005) to 22,402 acre-ft (in dry year 2014). On average, more than 90 percent of the total annual groundwater pumped from wells occurred below the Moore Diversion, and in 2014, well pumpage volumes exceeded surface-water diversions by nearly 3,000 acre-ft. Lower surface-water supply in 2014 contributed to higher groundwater pumpage totals (see fig. 6.2 in appendix 6, "Surface-Water Diversions and Groundwater Pumpage").

Groundwater Pumpage

Groundwater use in the Big Lost River Basin during 2000–19 primarily was for irrigation of crops. Other uses included domestic supply for household uses and lawn watering, stock watering, and municipal supply. Each groundwater pumpage category is discussed in the sections that follow. Total estimated volumes are for the calendar year.

[23]Also discussed in sections, "Losing and Gaining River Reaches" and "Canal Seepage."

[24]The "Neilsen canal injection" above Mackay Dam is flagged as an exchange well in the IDWR Water District surface-water diversion database. This location is actually a surface-water exchange rather than a groundwater exchange. A portion of the surface water diverted from the Big Lost River is carried by the Neilsen Canal to Warm Springs Creek where it is then rediverted (D. Hoekema, IDWR, written commun., 2021; J. Sukow, IDWR, written commun., 2021).

[25]At the time of publication, published data were not available from IDWR but files may be requested from J. Sukow at IWDR Idaho Water Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800.

Irrigation

The fate of groundwater withdrawn for irrigation of crops essentially is the same as that of diverted surface water applied to crops. A total of 992 water rights in the IDWR online WMIS database (IDWR, 2020f) are listed as having a groundwater source within Water District 34. Not all surface-water diversions and wells necessarily are active.

Data Sources, Methods, and Assumptions

Because direct measurement and reporting of groundwater pumpage were not mandatory until 2014, historical estimates of groundwater pumpage have used consumptive evapotranspiration as a proxy for groundwater pumpage volumes (Crosthwaite and others, 1970a). Power-consumption calculations by Water District 34 also have been used for estimating pumpage that Water District 34 reports to IDWR.

Groundwater pumpage records may be accessed from the IDWR WMIS database (IDWR, 2020f) but for convenience for this water budget, IDWR staff provided groundwater pumpage records collected by Water District 34 for calendar years 2010–19 (C. Yenter, IDWR, written commun., March 5, 2019, and February 13, 2020). Groundwater pumpage during 2010–13 was estimated using power-consumption ratios that may not necessarily reflect actual pumpage volumes (C. Yenter, IDWR, written commun., 2018). Since 2014, direct measurement of groundwater pumpage (excluding small domestic and stock watering uses) in the Big Lost River Basin within part of the lower subbasin has been required through an IDWR final order dated July 10, 2013 (IDWR, 2013b). Annual pumpage during 2014–19 was based on monthly flow totalizer readings or, in some cases, weekly hour meter readings paired with weir measurements for open discharge wells (C. Yenter, IWDR, written commun., 2018). Direct measurement of groundwater pumpage for irrigation is not available for 2000–09, so volumes must be estimated.

Unmeasured pumpage may be estimated from the following relation, modified from Fisher and others (2016):

$$Div_{gw,\,est} = \frac{CIR}{IE} - Div_{gw,\,obs} - Div_{sw} + Ret_{sw} + Canal \quad (6)$$

where

$Div_{gw,est}$ is the estimated unmeasured groundwater pumpage,

CIR is the crop irrigation requirement met by groundwater and surface-water sources for irrigated and semi-irrigated lands over the irrigation season,

IE is irrigation efficiency,

$Div_{gw,obs}$ are measured groundwater pumpage,

Div_{sw} is measured surface-water diversions,

Ret_{sw} is return surface-water flow, and

$Canal$ is estimated canal seepage.

The terms in equation 6 are defined in other sections in this report: CIR in section, "Applied Irrigation"; irrigation efficiency in appendix 5, "Irrigation Efficiency"; surface-water diversions in appendix 6, "Surface-Water Diversions and Groundwater Pumpage"; return surface-water flow in appendix 7, "Return Surface-Water Flow"; and canal seepage in section, "Canal Seepage," and appendix 8, "Estimated Canal Seepage Details." Estimates of unmeasured groundwater pumpage using equation 6 were within the range of values measured for groundwater pumpage during 2014–19 (table 6.3 in appendix 6, "Surface-Water Diversions and Groundwater- Pumpage") based on comparable wet or dry seasons for some but not all years within the study period. The estimated CIR presumably is closer to the actual CIR when estimated unmeasured pumpage is within expected trends. However, a clear, established relation between CIR and reported surface-water diversions and groundwater pumpage is not always apparent, especially above Mackay Dam, so estimates of unmeasured pumpage derived from CIR relations may not yield the expected results. For example, during 2014–19 when surface-water diversions and groundwater pumpage were measured, the percentage of CIR met with surface water (assuming an irrigation efficiency of 0.45) was greater than 100 percent for wet years (such as 2016–18). The percentage of CIR met with groundwater (assuming an irrigation efficiency of 0.85) ranged from 15 to 40 percent.

Because of the uncertainty associated with estimating unmeasured groundwater pumpage using equation 6, pumpage during 2000–13 was estimated for each subbasin using linear regression analysis of measured groundwater diversions (2014–19) with measured surface-water diversions (2014–19). Linear regression indicated a high negative correlation with surface-water diversions (R^2 terms of 0.85–0.93). For comparison, linear regression using power-consumption estimates of pumpage yielded a lower R^2 term of 0.69.

Groundwater Pumpage for Irrigation Results

Total annual estimated and measured groundwater pumpage volumes are summarized in figure 6.1 and tables 6.1–6.3 in appendix 6 ("Surface-Water Diversions and Groundwater Pumpage"), with mean annual estimates in the upper subbasin (4,248 acre-ft/yr), middle subbasin (34,020 acre-ft/yr), and lower subbasin (37,822 acre-ft/yr). The overall trend in meeting the CIR is discussed in appendix 6. In general, when CIR increases, groundwater pumpage increases.

Groundwater pumpage for meeting irrigation demand indicates different characteristics throughout the basin regarding surface-water availability. Above Mackay Dam, surface-water resources are more readily available than below Mackay Dam, as indicated by greater than 90-percent use of surface water and less than 10-percent use of groundwater. Compared to the upper and middle subbasins, the lower subbasin relies the most on groundwater (45 percent, with 55-percent reliance on surface-water; see tables 6.1 and 6.2 in appendix 6). These trends generally are consistent with water

right sources as reported by Sukow (2017), who described sources above Mackay Dam (84 percent surface water, 7 percent groundwater, and 9 percent mixed) and below Mackay Dam (14 percent surface water, 12 percent groundwater, and 74 percent mixed).

Domestic Supply

Domestic supply accounts for a small percentage of the overall groundwater pumpage and the overall groundwater budget because of the sparse population in the Big Lost River Basin. Details were presented in section, "Septic System Effluent" based on assessment of the rural population in Butte and Custer Counties.

Data Sources, Methods, and Assumptions

The same data sources, methodology, and assumptions were applied for estimating domestic pumpage as described in section, "Septic System Effluent."

Groundwater Pumpage for Domestic Supply Results

The estimated total domestic pumpage ranged from about 40 to 70 acre-ft/yr above Mackay Dam, 100 to 200 acre-ft/yr in the middle subbasin, and about 130 to 520 acre-ft/yr in the lower subbasin (table 4). The higher estimate below the Moore Diversion in the lower subbasin is owing to a greater number of persons per household according to available U.S. Census records (U.S. Census Bureau, 2020). Domestic pumpage accounts for 1 percent or less of outflow in the total groundwater budget. Thus, any errors and uncertainty in domestic pumpage totals are expected to be negligible in the budget.

Municipal Supply

The City of Mackay has water rights for four production wells and one spring. Mackay did not use the spring during 2013–19 but reported volumes for the four wells. The City of Arco has water rights for five production wells, although not all wells are used within a given year. Arco reported using two of the five wells during 2013–19.

Both municipalities reported water use by calendar year. Most of the pumpage volumes are based on totalizing flow meters installed at each well, but some of the data are supplied from "alternative" methods. Flow-meter measurements generally are preferred over other methods for estimating pumpage such as rate-time methods using energy-consumption data from power utility records (Hurr and Litke, 1989).

Data Sources, Methods, and Assumptions

Municipal pumpage records were accessed from the IDWR WMIS for the Cities of Mackay and Arco (IDWR, 2020f). Available datasets span 2013–19; no records were available during 2000–12, prior to an order requiring installation of measuring devices for diversions (IDWR, 2013b) that took effect in 2014 for Water District 34. The average reported municipal pumpage totals for 2013–19 were used for 2000–12 estimates. Based on the overall small volume, this assumption was unlikely to affect the overall groundwater-budget volume.

Groundwater Pumpage for Municipal Supply Results

Overall, the total reported volumes and use patterns for municipal pumpage were similar for Mackay and Arco. Mackay pumpage ranged from 113 to 415 acre-ft/yr, and Arco pumpage ranged from 92 to 560 acre-ft/yr, with the highest volumes reported in 2016. Municipal pumpage represents a very small percentage (less than 1 percent) of the total groundwater discharge (table 4).

Groundwater-Budget Residuals

The groundwater-budget residual is the difference between the calculated inflows and outflows, representing three components: groundwater outflow from the basin, changes in groundwater storage, and errors. Groundwater storage is addressed in section, "Changes in Groundwater Storage." Groundwater outflow from above Mackay Dam to below the dam and groundwater outflow from the basin are estimated as a residual from the annual groundwater-budget calculations. Overall, water-budget deficits for certain years are not uniform throughout the entire basin but instead are spatially distributed based on (1) water availability (as either recharge to the aquifer or streamflow available for diversion), (2) relative use of surface water compared to groundwater, and (3) the localized effects of groundwater pumpage.

The total groundwater residual for the Big Lost River Basin was 326,800 acre-ft/yr over the 2000–19 study period, 220,400 acre-ft in 2014, and 708,700 acre-ft in 2017 (table 4). The groundwater residual above Mackay Dam was 100,400 acre-ft/yr during the 2000–19 study period, 96,700 acre-ft in 2014, and 248,300 acre-ft in 2017. Not accounting for the groundwater inflow from above the dam, the contribution to the budget residual below Mackay Dam was 226,300 acre-ft/yr for the study period, 123,700 acre-ft in 2014, and 460,400 acre-ft in 2017 (table 10).

For context, the groundwater residual was about 20 percent of the mean annual precipitation within the entire basin over the study period. This percentage fluctuates in response to climatic and water-use patterns within a given year. During years within the study period (2000–19) with low-to-average precipitation (2001, 2004, 2007–08, and 2013–15), this percentage ranged from 13 to 17. During typical wet years (2005–06, 2009–12, and 2016) the percentage ranged from 22 to 25. The groundwater residual was 32 percent of the total precipitation in 2017, an especially wet year. The magnitude of the residual in 2017 was affected by less groundwater pumpage requirement with higher

available surface-water supply for diversions, resulting in higher applied irrigation recharge and seepage from canals and rivers compared to other years within the study period.

Higher precipitation in 2017 compared to other study years (nearly 40 percent higher than the annual mean over the study period for the entire basin) contributed to higher losing river reaches, tributary canyon underflow, and areal recharge. The lowest groundwater-budget residuals actually occurred in 2013 (table 10) owing to about 38 percent less precipitation compared with the 20-year study average. The low precipitation in 2013 was a significant contributing factor in the observed declines in groundwater levels and reservoir storage in 2014. These trends highlight the influence of climatic and water-use patterns on the budget residuals. The residuals reflect inflow and outflow terms during a specific year without accounting for antecedent conditions. In reality, some delay in groundwater response occurs as stresses reach and propagate through the aquifer.

Table 10. Calculated mean annual groundwater residuals for the Big Lost River Basin, south-central Idaho, 2000–19.

[**Abbreviation:** acre-ft/yr, acre-foot per year]

Year	Total above Mackay Dam (acre-ft/yr)	Total below Mackay Dam (acre-ft/yr)	Total basin (acre-ft/yr)
2000	70,000	213,000	283,000
2001	27,200	128,000	155,200
2002	62,100	157,900	220,000
2003	100,000	142,700	242,700
2004	118,500	158,200	276,700
2005	184,800	300,200	485,000
2006	123,300	308,600	431,900
2007	42,400	124,400	166,800
2008	34,100	185,400	219,500
2009	145,800	284,800	430,600
2010	137,600	298,500	436,100
2011	88,500	261,100	349,600
2012	143,700	258,500	402,200
2013	14,200	111,200	125,400
2014	97,000	123,700	220,700
2015	83,700	174,900	258,600
2016	178,300	267,600	445,900
2017	248,300	460,400	708,700
2018	14,700	291,000	305,700
2019	94,700	275,000	369,700
Mean	100,400	226,300	326,700
Median	95,900	235,750	294,350

Changes in Groundwater Storage

The annual groundwater-budget residual includes annual groundwater outflow leaving the basin, the annual change in groundwater storage, and errors (described in section, "Groundwater-Budget Residuals"). These components of the residual cannot be easily separated during preparation of a groundwater budget. In particular, the budget does not consider antecedent changes in soil moisture, and limited groundwater level data are available to define annual changes in the groundwater table throughout the aquifer. Therefore, the annual change in groundwater storage is difficult to ascertain, but it is an important part of the overall budget residual. This study considered the possible magnitude of the annual change in groundwater storage for additional context when considering the magnitude of groundwater outflow from the Big Lost River Basin.

A groundwater budget-based method for estimating groundwater storage change is only as accurate as the water-budget components. Storage in an unconfined aquifer is described by the term "specific yield," which is the volume of water drained by gravity from a volume of rock (Freeze and Cherry, 1979). Specific yield can vary over time, through gravity drainage and saturation of the aquifer matrix, as the groundwater table fluctuates in an unconfined aquifer. Groundwater levels can vary substantially over time throughout the basin because of seasonal fluctuations in precipitation, evapotranspiration, and pumpage effects. Reported values for specific yield range from approximately 0.01 to 0.3 for different unconsolidated materials (Healy, 2010). Determination of an actual specific yield or storage coefficient for the Big Lost River Basin is limited based on the lack of data and testing.

The water-table fluctuation method provides a relatively simple approach for estimating changes in groundwater storage over time in an unconfined aquifer, assuming that recharge is responsible for increases in the groundwater level. The change in storage is calculated from specific yield multiped by the change in the groundwater level over a specified time period (Healy, 2010). Some automated methods, such as a master recession curve approach, require continuous, daily groundwater-level measurement and precipitation datasets to discern if a precipitation event is responsible for the rise in groundwater levels (Heppner and Nimmo, 2005).

Most monitoring wells in the Big Lost River Basin lack a sufficient record of daily pressure-transducer measurements for the 2000–19 study period. New monitoring wells installed in 2019 by IDWR as part of this investigation (IDWR, 2019) may provide additional data for future analysis. Therefore, annual groundwater altitude changes were estimated to provide a rough approximation of potential aquifer storage changes over the study period. For this analysis, only mean groundwater-level measurements during March and April were used to avoid biasing the estimates with active or residual

nearby pumpage effects or changes in the groundwater altitude owing to applied irrigation water on fields or local canal seepage effects.

Storage changes above Mackay Reservoir cannot be estimated with certainty because limited groundwater-level data were available above Mackay Dam[26], prohibiting the use of traditional methods for estimating the change in aquifer storage using methodologies based on groundwater-level measurements. The analysis does also not include bedrock aquifer-storage changes, which are likely to have low storativity.

For the basin below Mackay Dam, the ordinary kriging interpolation method, with the spherical semi-variogram model (Dixon and Uddameri, 2016; Esri, 2018, 2020), was used to create potentiometric surface maps in ArcGIS based on groundwater levels measured in individual wells to represent average annual conditions. The annual interpolated surfaces from one year to the next were then subtracted to estimate the change in groundwater altitude over the calendar year. The estimated change in aquifer storage was estimated from the volumetric change in the groundwater level multiplied by a range of assumed specific-yield values (0.01–0.3).

The mean annual estimated storage change in the middle subbasin above the Moore Diversion ranged from 1,000 to 32,900 acre-ft/yr over the study period, assuming a low-end specific yield of 0.01 and high-end specific yield of 0.3. Considerable variation in estimated storage was noted between years, often with unexpected results attributed to the method limitations. For example, 2013 was a dry year; however, the estimated change in storage ranged from 15,700 to 472,000 acre-ft, with the high-end value in excess of the estimated groundwater residual of 125,400 acre-ft in 2013 (table 10). This result highlights the uncertainty associated with assessing potential groundwater storage changes using this method.

The mean annual estimated storage change in the lower subbasin below the Moore Diversion ranged from 1,600 to 49,400 acre-ft/yr during the study period, again assuming specific yield ranging from 0.01 to 0.3. Similar trends were observed in the lower subbasin compared to the middle subbasin results in terms of the overall magnitude of change. However, during some years, the storage change was negative in the middle subbasin and positive in the lower subbasin and vice versa.

The calculated mean annual groundwater residual below Mackay Dam was 226,300 acre-ft/yr over the 2000–19 study period (table 10). The total estimated annual groundwater storage change below Mackay Dam (combining the above results for the middle and lower subbasins) over the study period ranged from 2,600 to 82,300 acre-ft/yr. The estimated magnitude of annual groundwater storage change represents from 1 percent to nearly 40 percent of the total budget residual, with considerable uncertainty for the reasons stated in this section.

The results are sensitive to inclusion or exclusion of certain wells. Not all years had complete datasets for a given monitoring well. The lack of monitoring-well coverage both within and outside the basin extents is apparent, as there are no available groundwater altitude data to constrain the interpolation. The lack of available well coverage is especially apparent in the southern part of the lower subbasin. The use of kriged surfaces based on sparse well networks, such as in the Big Lost River Basin, introduces large uncertainty in the estimated change in storage.

Direct comparison of the estimated annual aquifer storage change using groundwater altitudes cannot be made to the groundwater-budget residual estimates (groundwater inflow minus groundwater outflow), as the areas used in the analyses differ between the methods. Rises in groundwater altitudes incorporate a lag time for recharge whereas the aquifer storage change estimated using the water budget assumes instantaneous recharge. This groundwater budget also does not account for any unsaturated zone soil moisture storage effects.

The use of numerical modeling approaches for calculating the change in groundwater storage is preferred over the analytical approach considered here, as numerical models account for antecedent water-table conditions. The mean annual simulated storage change in the ESPA model (spanning the part of the basin below Mackay Reservoir) was a decrease of 16,000 acre-ft/yr from 1985 to 2010, with annual storage changes of more than 100,000 acre-ft modeled during extreme wet or dry years (Sukow, 2017).

The results of the storage-change assessment are regarded as highly uncertain. Use of the water-budget method (equating the change in storage to inflow minus outflow) is subject to the uncertainty, and estimates could benefit from an independent method for evaluating changes in aquifer storage above Mackay Dam. Estimated storage change is sensitive to the assumed specific yield. The results are useful, however, in better understanding the relative proportion of groundwater outflow from the basin to changes in storage in the water-budget residuals.

Groundwater-Budget Uncertainty and Errors

Errors in the groundwater budget may arise from one or more factors including insufficient spatial or temporal datasets, errors in estimated or measured values, an inaccurate conceptual model or equation(s), incorrect assumptions, or unidentified sources of error. Several identified sources of potential errors in the groundwater-budget estimates are addressed throughout this report. Many of these potential errors form the basis of suggestions for future data collection and analyses (see section, "Suggestions for Water-Budget Use

[26]The IDWR groundwater monitoring program consists of three wells in the upper subbasin (07N 23E 02DDA1 [IDWR-3] next to Mackay Reservoir, 08N 22E 05BAA1 [IDWR-2], and 09N 21E 14BBC1 [IDWR-1]).

and Future Data Collection"). Sources of uncertainty with the greatest perceived impact on the groundwater budget are discussed here.

Spatial and temporal averaging and upscaling of datasets to sub-watershed and annual scales, respectively, influence the water-budget terms estimated in this investigation. For example, estimated river-reach gain and loss volumes over larger reaches and for longer periods of time are not expected to yield the same results as direct streamflow-measurement events spanning shorter reaches and over daily time periods. Representing groundwater-budget terms on a monthly or seasonal basis may more accurately depict groundwater inflows and outflows, commensurate with inputs for a numerical groundwater-flow model.

Estimated tributary canyon streamflow and underflow terms are regarded with great uncertainty, perhaps more so than any other variables in the groundwater budget. As indicated in sections, "Tributary Canyon Underflow" and "Losing and Gaining River Reaches," uncertainty is attributed to few supporting datasets and observations during the study period or in previous years. Furthermore, these components account for a large percentage of the overall estimated recharge to the aquifer in the basin (20 percent for tributary underflow and 33 percent for losing river reaches).

Groundwater Resource Sustainability

Alley and others (1999, p. 2) define sustainability as "development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences." Using this definition, sustainability can be addressed through consideration of the effects of drought conditions, climate change, and water-use patterns on groundwater levels and storage change. In Western U.S. intermontane basins such as the Big Lost River Basin, water resource management and administration for meeting irrigation needs are challenged by early snowmelt runoff, variable and lower snowpack, and reservoir storage limitations. Extensive research has been done and continues on these topics; more information is available in Mote (2006), Scalzitti and others (2016), and Qin and others (2020).

Climate variations generally have led to shifting dynamics in the timing of available water resources. In particular, snowmelt runoff throughout the Western U.S. occurs earlier in the season than in the past (Meixner and others, 2016). Clark (2010) evaluated long-term seasonal runoff patterns in snowmelt-dominated watersheds, including Big Lost River Basin streamflow records for the North Fork of the Big Lost River (USGS streamgage 13120000) and the Big Lost River at Howell Ranch (USGS streamgage 13120500). Mann-Kendall trend tests on runoff characteristics indicated that the annual percentage rate of change from 1967 to 2007 was –0.42 and –1.05 ft/yr, respectively, consistent with overall reduced streamflow trends observed elsewhere in the Pacific Northwest. Abatzoglou and others (2014) evaluated seasonal climate variability and change in the Pacific Northwest using linear regression modeling with four separate datasets. This study concluded that water deficits from 1980 to 2012 have resulted from combined factors including decreased summer and autumn precipitation and increased summer potential evapotranspiration despite long-term increased spring precipitation.

Recently, some water users in the Big Lost River Basin have expressed concern regarding the sustainability of groundwater supplies based on declining groundwater-level trends in some parts of the aquifer and declining flows during drought periods in the Big Lost River. In 2016, some water users petitioned the Director of the IDWR to designate the basin as a Critical Ground Water Area (Bernal, 2016) or as a Groundwater Management Area (Broadie, 2017a, 2017b). Both petitions subsequently were withdrawn (Bernal and Broadie, 2017). In 2017, Water District 34 developed a management and aquifer stabilization plan. Protective aquifer measures are discussed in section, "Introduction."

Crosthwaite and others (1970b) previously addressed sustainability of water resources in the Big Lost River Basin in terms of water yield. In the associated study reflecting the period 1944–68, Crosthwaite and others (1970a) estimated that 23 percent of the 650 ft^3/s total water yield (surface water and groundwater) was used consumptively. The remainder was surface-water (12 percent) and groundwater flow leaving the basin (65 percent). Sustainability was addressed by Crosthwaite and others (1970b) by discussing the use of conjunctive management practices among other measures to address drought conditions, flood control, and storage. Further sustainability considerations for the Big Lost River Basin were addressed in Szczepanowski (1982) and Johnson and others (1991).

Some of the Big Lost River Basin volumetric inflow and outflow parameters estimated for 2000–19 have relatively comparable trends to historically reported estimates. For example, the total estimated mean annual precipitation and evapotranspiration for 2000–19 were approximately 1.6 million acre-ft/yr and 1.0 million acre-ft/yr, respectively. Those estimates are consistent with the Crosthwaite and others (1970b) findings of 1.5 million acre-ft/yr of precipitation and 1.0 million acre-ft/yr of evapotranspiration. The estimated average annual consumptive use during 2000–19 (1.7 acre-feet per acre [acre-ft/acre]) is within the range of values reported in previous studies—1.2 acre-ft/acre (Crosthwaite and others, 1970a) below Mackay Reservoir to 2.0 acre-ft/acre reported by Allen and Brockway (1983), as referenced in Johnson and others (1991). This result suggests similar trends over time for meeting CIR.

The Palmer Drought Severity Index (PDSI), developed by Palmer (1965), provides an indication of wet or dry conditions by region based on a water-balance model that considers temperature, precipitation, soil moisture changes, recharge, and runoff. Results often are expressed as a monthly index on a scale from –10 to +10. Positive values indicate

wet conditions and negative values indicate dry conditions. The index represents the departure from the long-term mean moisture supply (Heim, 2002). Heim (2002) and Liu and others (2017), among others, described recognized shortcomings of PDSI, including the inability of the method to adequately characterize drought conditions in "real-time." However, PDSI remains widely used and provides a general indication of drought and climate change (National Center for Atmospheric Research, 2021) and is considered here for context.

Of the 10 regions in Idaho, the following 3 regions overlap the groundwater-budget study extent in the Big Lost River Basin: Region 4 (Central Mountains), Region 8 (Northeastern Valleys), and Region 9 (Upper Snake River Plain). Overall, trends apparent in monthly PDSI datasets (National Oceanic and Atmospheric Administration, 2021) spanning 1895–2019 for the three regions in the Big Lost River Basin (fig. 17) generally are consistent with locally observed precipitation, groundwater levels, streamflow, and reservoir storage trends. Severe to extreme drought (values less than –3 on fig. 17) occurred in all or parts of the basin during 2000–04, 2007–08, and 2013–15. Wetter conditions, with values of 3 or greater, were observed in 2006, 2011, and 2017. The extremes were greater for Region 9 in the southern part of the basin than for Regions 4 and 8 in the upper and middle parts of the basin.

Review of mean annual streamflow in the Big Lost River Basin recorded at streamgages with long-term monitoring over decades (fig. 18) indicated an increased pattern of sustained, negative departures over a 70-year period from 1950 to 2019. Streamgages with a sufficiently long, continuous record (table 9) included the North Fork of the Big Lost River at Wild Horse (USGS streamgage 13120000), the Big Lost River at Howell Ranch (USGS streamgage 13120500), the Big Lost River below Mackay Reservoir (USGS streamgage 13127000), and the Big Lost River near Arco (USGS streamgage 13132500). Surface-water diversions above USGS streamgage 13127000 and the combination of diversions and pumping effects above USGS streamgage 13132500 somewhat complicated the interpretation of climatic-related

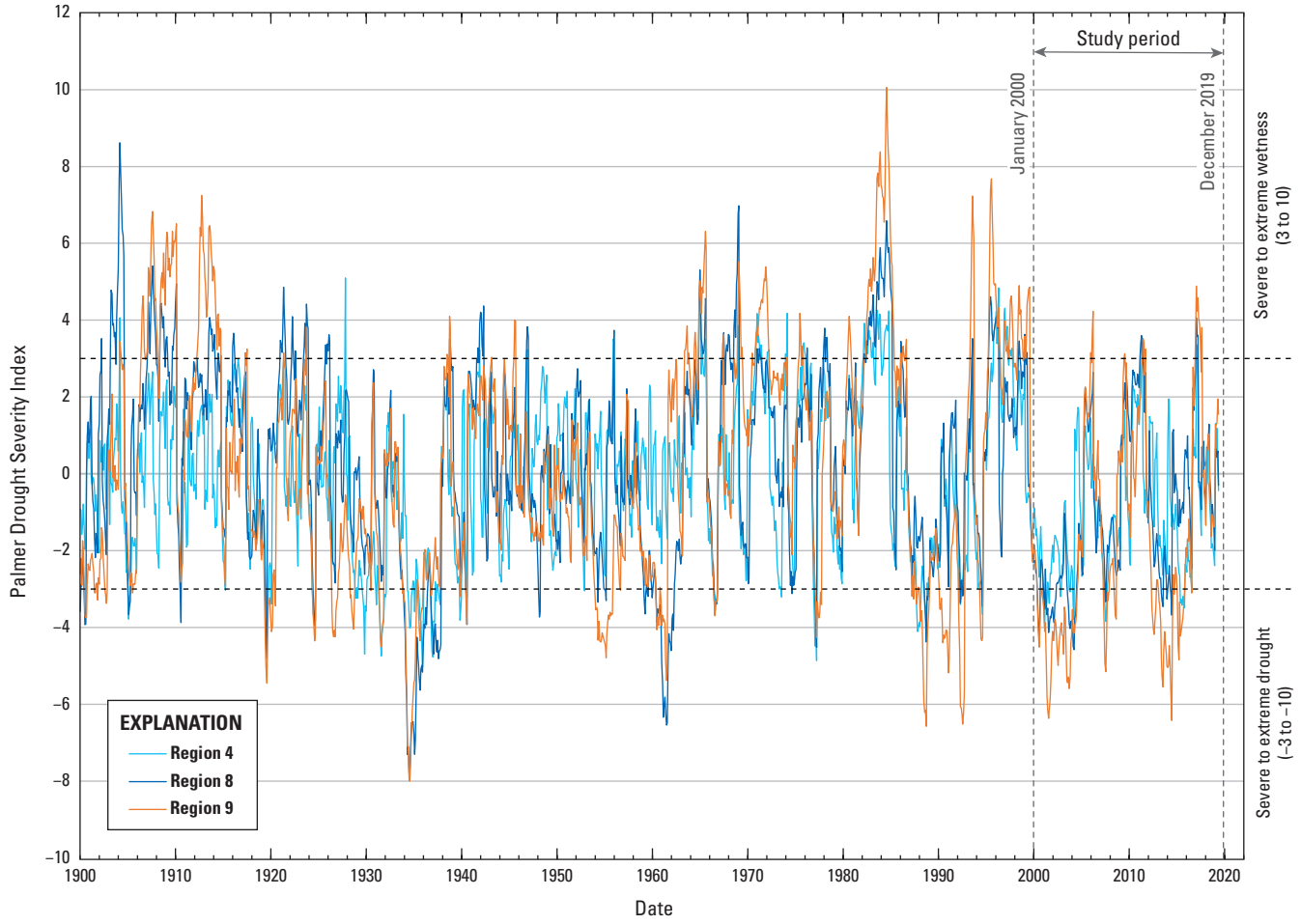


Figure 17. Palmer Drought Severity Index (National Center for Atmospheric Research, 2021) for regions within the Big Lost River Basin, south-central Idaho, 1900–2020. Region 4, Central Mountains; Region 8, Northeastern Valleys; Region 9, Upper Snake River Plain.

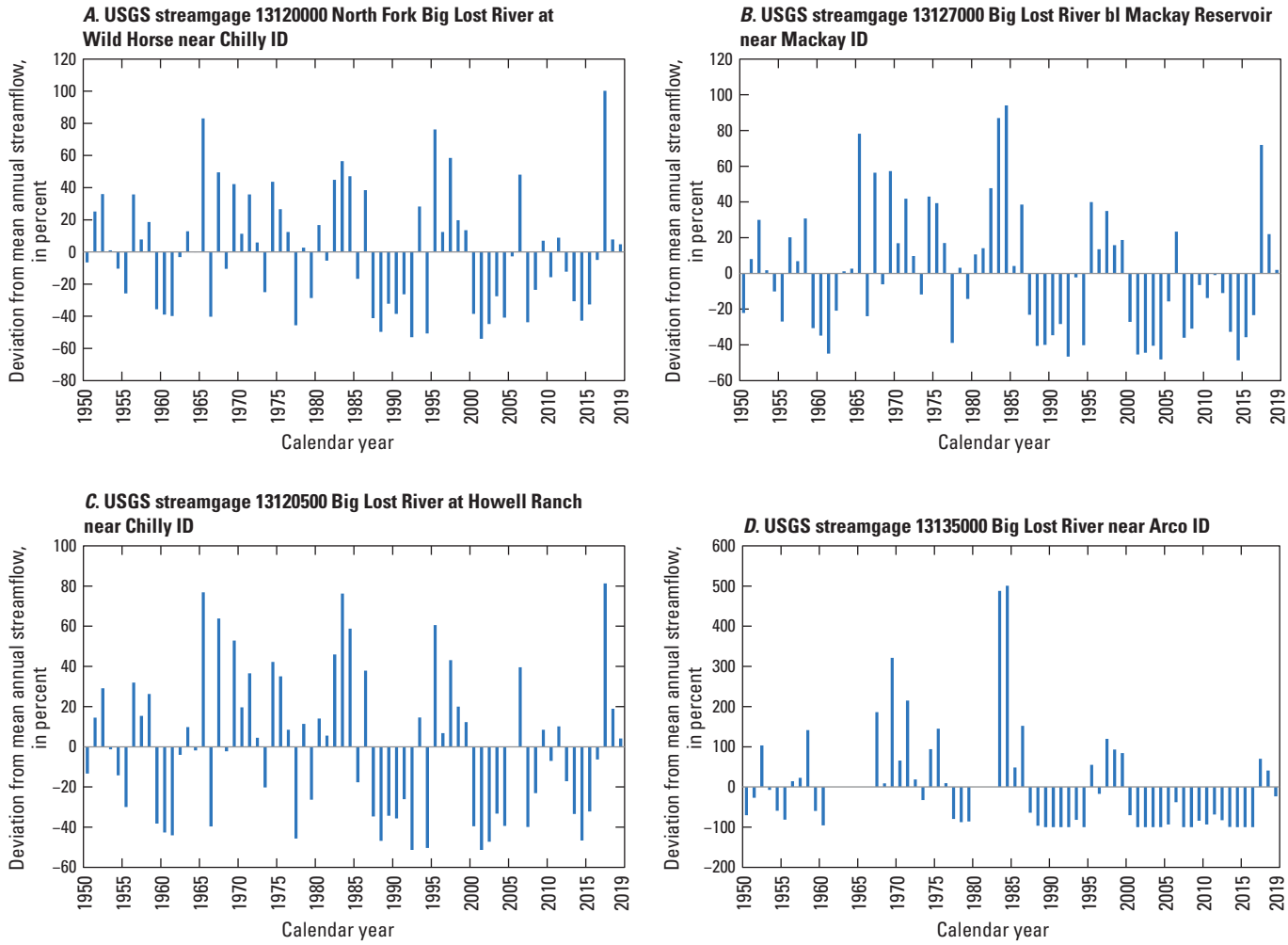


Figure 18. Deviation from mean annual streamflow for U.S. Geological Survey streamgages in the Big Lost River Basin, south-central Idaho, 1950–2019. bl, below; ID, Idaho; USGS, U.S. Geological Survey. Mean annual streamflows are from U.S. Geological Survey (2020).

factors that influence streamflow. However, similar trends were noted for USGS streamgage 13120000, with no nearby pumping or diversions, and USGS streamgage 13120500, with only minimal diversions. On average, about 10 percent less streamflow was recorded for 2000–19 compared to the period of record at USGS streamgages 13120000, 13120500, and 13127000. Note that different vertical scales were used in figure 18 to visualize relative departures as a percentage of the normal. The negative annual departure of 100 percent at the USGS Arco streamgage (13135000) resulted from a mean annual streamflow rate of zero when compared to the long-term mean streamflow.

Aggregate effects of periods of drought conditions (with greater reliance on groundwater for meeting irrigation demand in the Big Lost River Basin during low water years) have resulted in overall declining groundwater-level trends from 1977 to 2016 (about 0.4 feet per year; Sukow, 2017). Review of groundwater-level trends in IDWR monitoring wells since the wet 2016–17 period through 2019 (IDWR, 2021a) indicated appreciable, but not complete, rebound of groundwater levels in many wells throughout the basin. The pattern of wet and dry periods with highly correlated responses in streamflow and groundwater levels is consistent with the findings of previous studies (Crosthwaite and others, 1970a; Johnson and others, 1991).

Suggestions for Groundwater-Budget Use and Future Data Collection

The groundwater budgets prepared during this hydrogeologic investigation may be used to inform other work including ESPA and INL numerical groundwater-flow model refinement and calibration, water-rights accounting and decision-making, and future model development.

Hydrologic and water-quality data collection programs that are in place and that expanded during this investigation are expected to improve overall understanding of the hydrogeology in the Big Lost River Basin. Suggestions for additional activities that focus on improving overall

estimates of groundwater inflows and outflows are grouped in the following categories: (1) future data collection, (2) expanded reference datasets, and (3) implementation of alternative methodologies for estimating groundwater-budget components deemed as major influences for budget accuracy and identified as sources of uncertainty during preparation of this groundwater budget.

Future Data Collection

Future groundwater-budget estimates may be better constrained by streamflow data collected at newly installed USGS streamgages on the Big Lost River and Antelope, Thousand Springs, and Warm Springs Creeks (U.S. Geological Survey, 2020); groundwater-level data from newly installed IDWR monitoring wells (IDWR, 2019, 2021a); and the Bureau of Reclamation AgriMet weather station near Moore (Bureau of Reclamation, 2016). Estimation of unmeasured streamflow and interpolation of climatic conditions over subbasin scales (necessary for development of the groundwater budgets in this investigation) has inherent associated uncertainty, resulting in potential errors in the groundwater budget (described further throughout this report and in section, "Groundwater-Budget Uncertainty and Errors"). Monitoring equipment installed by USGS (U.S. Geological Survey, 2020), IDWR (IDWR, 2021a), and Bureau of Reclamation (Bureau of Reclamation, 2016) during 2018–19 as part of this hydrogeologic investigation and described in this report (see the "Introduction" section) was used to the extent possible during preparation of this groundwater budget; however, most of the study period did not span recent data collected in 2019.

Review of historical datasets further indicates the need for long-term, continuous monitoring of climatic conditions, streamflow, and groundwater levels. Although several discontinued streamgage sites have now been reactivated either though continuous or opportunistic discrete monitoring (Thousand Springs, Alder, Lower Cedar, and Antelope Creeks), many years of data gaps at these locations and other locations not currently monitored (such as the Big Lost River inflow to Mackay Reservoir, and Pass and upper Antelope Creeks) have introduced uncertainty into the groundwater budget. Therefore, long-term continuous data collection (of both streamflow and groundwater levels) is suggested for the newly installed stations to assist future hydrogeologic investigations. Continuation of the current program for synoptic groundwater-level measurement events led by IDWR annually during spring and autumn (IDWR, 2021a) will contribute to better understanding of the groundwater resource.

Measurement of canal delivery volumes on upper subbasin canals (Neilsen and Warm Springs) and electronic compilation of prior records collected below Mackay Reservoir would permit estimation of delivery factors. This information may improve estimates of potential canal seepage, similar to the methodology applied in this investigation to canals in the middle and lower subbasins during 2015–19.

Much of the available surface-water supply and groundwater supply[27] for the entire Big Lost River Basin originates in the upper subbasin. This conclusion is supported by the findings from this investigation and previous studies including Crosthwaite and others (1970a). Considerable uncertainty remains in quantifying tributary streamflow and underflow and areal recharge to groundwater, especially at higher altitudes, because of uncertainty in estimating evapotranspiration and surface runoff. Installation of one or more monitoring wells in the upper subbasin within the inferred direction of groundwater flow, with incorporation in the IDWR monitoring well network program, would permit better assessment of the hydraulic gradient, changes in storage, and interaction with surface water. Future investigation may be warranted to emphasize data collection in areas likely to receive appreciable recharge (specifically mountain-front zones) and improved methodologies to better constrain estimates.

Limited data on aquifer properties such as hydraulic conductivity, transmissivity, saturated aquifer thickness, and specific yield are available. Little aquifer testing has been done to constrain estimated aquifer properties. Although well testing provides an indication of localized conditions near the test well, aquifer testing is suggested to build a catalog of available data because hydraulic conductivity can vary by several orders of magnitude. Multi-well testing would permit evaluation of specific yield.

Expanded Reference Datasets

The development and expansion of certain datasets would improve groundwater-budget estimates, and the following suggestions are included:

1. Any revised or new irrigated-land coverages could be integrated in groundwater-budget updates. Specifically addressing the inclusion of actively irrigated areas near riparian zones or wetlands with an "irrigated" lands classification, updated for prior years and in future coverages, would better constrain estimates of CIR and irrigation recharge.

[27]Surface-water discharge from the upper subbasin, as measured below Mackay Reservoir (USGS streamgage 13127000) plus the change in storage in Mackay Reservoir, accounts for a mean annual discharge of nearly 215,000 acre-ft/yr. This total represents nearly 50-percent more than the mean annual streamflow measured at the Leslie streamgage (152,250 acre-ft/yr from 2007 to 2019) and 1–2 orders of magnitude higher than streamflows at Moore and Arco (registering zero streamflow during dry years). Estimates of groundwater underflow from the upper subbasin over the project study period account for about 16 percent of the total estimated mean annual groundwater outflow from the entire basin.

2. Expanding ET_{Idaho} estimates of evapotranspiration to include years after 2016 could improve evapotranspiration estimates in future groundwater budgets.

3. Compilation of available canal delivery volumes from historical water district files could improve estimates of irrigation efficiency, including the upper subbasin for headgate and on-farm deliveries to determine a representative delivery factor.

Alternative Methodologies

Analytical approaches that incorporate time-series analyses of continuous groundwater levels may improve estimates of recharge when combined with numerical modeling or statistical approaches (Dickinson and others, 2004). These methods evaluate the lag periods in aquifer response to stresses to approximate variable recharge over time, with application for mountain-front recharge-dominated systems, such as the Big Lost River Basin.

Continued numerical groundwater-flow model refinement for the Big Lost River Basin could improve overall estimates of expected groundwater outflow from the basin. Numerical modeling incorporates year-to-year soil-moisture conditions and pumping effects that are not captured in the groundwater-budget approach and with a finer spatial and temporal resolution than permissible with the subbasin groundwater budgets.

Summary and Conclusions

The Idaho Geological Survey prepared separate groundwater budgets for the Big Lost River Basin (above and below Mackay Dam, and the entire basin), located in parts of Butte and Custer Counties in south-central Idaho, as part of a broader hydrogeologic investigation done with the U.S. Geological Survey in cooperation with the Idaho Department of Water Resources. Groundwater budgets were prepared for average annual conditions for 2000–19, including representative dry (2014) and wet (2017) years to bracket the range of expected stresses on the aquifer. The groundwater budgets will help address questions regarding the availability of adequate groundwater supplies for meeting demands and inform future groundwater modeling. This report is one of three reports in a multichapter volume that collectively provide an updated characterization of water resources in the Big Lost River Basin to help address water-resource challenges in the basin.

The Big Lost River Basin supports farming and ranching activities and the communities of Arco, Leslie, Mackay, and Moore that rely on surface-water and groundwater supplies. The basin is susceptible to periodic drought conditions, expressed as declining groundwater-level trends in some parts of the basin and decreased streamflow. The unconfined aquifer is closely connected with surface water and responds dynamically to changes in available precipitation (primarily derived from snowmelt runoff in spring and early summer) and pumping effects. The driest water years were amplified by consecutive years with below-average precipitation (such as 2001–04 and 2013–15). During wet years with carry-over effects (such as 2017–18), the groundwater levels showed appreciable, but not complete, rebound.

The groundwater budget incorporated and quantified general inflows to the aquifer, outflows from the aquifer, and the residual (as inflow minus outflows). The residual represents groundwater flowing out of the basin, the change in groundwater storage, and unaccounted errors in the budget. The predominant inflows consisted of precipitation-derived (areal) recharge, tributary underflow, net recharge from applied irrigation water and canal seepage, and losing river reaches. Major sources of recharge to the aquifer occurred along mountain-front margins and alluvial fans, as tributary canyon underflow, and through river seepage. Minor sources of recharge included inflow from Mackay Reservoir, managed aquifer recharge during winter months, and septic system effluent. Outflow from the aquifer was through discharge to rivers and streams (in gaining reaches) and pumpage for irrigation, and, to a much less extent, through domestic and municipal uses. Groundwater pumping for irrigation represented the largest outflow.

The total mean annual estimated recharge to the aquifer over the entire basin was 439,100 acre-ft/yr (2000–19), 373,900 acre-ft (in 2014), and 762,100 acre-ft (in 2017). Estimated mean annual groundwater discharge from the entire basin (excluding groundwater outflow to the eastern Snake River Plain aquifer) was 112,300 acre-ft/yr between 2000 and 2019, 153,500 acre-ft (in 2014), and 53,400 acre-ft (in 2017). The estimated mean annual groundwater-budget residual for the entire basin during the 2000–19 study period was 326,800 acre-ft/yr, 220,400 acre-ft in 2014, and 708,700 acre-ft in 2017. The mean annual residual above Mackay Dam was 100,400 acre-ft/yr during the 2000-19 study period, 96,700 acre-ft in 2014, and 248,300 acre-ft in 2017. Below Mackay Dam, the total mean annual residual, not accounting for groundwater-flow contributions above Mackay Dam, was estimated at 226,400 acre-ft/yr during the 2000–19 study period, 123,700 acre-ft in 2014, and 460,400 acre-ft in 2017. Recovery of groundwater levels during wet years was apparent in the basin, reflected in groundwater residuals and surface-water and groundwater dynamics. These estimates reflected uncertainty inherent in the source datasets, the necessary simplifying assumptions and methodologies, and errors in preparing the groundwater budgets.

The separate groundwater budgets for the Big Lost River Basin over the 2000–19 study period indicate different hydrologic responses above and below Mackay Dam based on available surface-water and groundwater supplies relative

to irrigation demand and local climatic variations and aquifer properties. The groundwater-budget findings during this investigation suggest the following:

- Above Mackay Dam, combined surface-water and groundwater supplies provide for irrigation needs above the dam and storage in Mackay Reservoir. High precipitation, owing to snow accumulation at high altitudes, contributes to appreciable tributary underflow and areal recharge. Applied irrigation and canal seepage provide for additional recharge to groundwater. These recharge sources are responsible for positive groundwater residuals above Mackay Dam. Most of the groundwater discharge is to gaining river reaches. Some of the groundwater is transferred below the dam through surface-water delivery to canals and as groundwater outflow from the upper part of the basin.
- Below Mackay Dam, losing river reaches and groundwater inflow from the upper subbasin (as the groundwater residual) are responsible for the highest sources of recharge. Lesser, additional recharge is supplied from areal recharge, tributary canyon underflow, canal seepage, and applied irrigation. Surface-water diversions and groundwater pumpage account for most of the net withdrawals of water. Variable surface-water and groundwater supplies below Mackay Dam are attributed to less available precipitation (at lower altitudes) and less flow in the Big Lost River compared to supplies above Mackay Dam. These dynamics place greater reliance on net, available resources from the upper subbasin. The combination of these factors impacts the annual groundwater budgets, with higher recharge and groundwater residuals in wet years and lower recharge and groundwater residuals in dry years.

References Cited

Abatzoglou, J.T., Rupp, D.E., and Mote, P.W., 2014, Seasonal climate variability and change in the Pacific Northwest of the United States: Journal of Climate, v. 27, no. 5, p. 2125–2142, accessed August 3, 2021, at https://doi.org/10.1175/JCLI-D-13-00218.1.

Ackerman, J., Rousseau, J.P., Rattray, G.W., and Fisher, J.C., 2010, Steady-state and transient models of groundwater flow and advective transport, Eastern Snake River Plain aquifer, Idaho National Laboratory and vicinity, Idaho: U.S. Geological Survey Scientific Investigations Report 2010–5123, 219 p., accessed February 20, 2018, at https://doi.org/10.3133/ofr20105123.

Allen, R.G., and Brockway, C.E., 1983, Estimating consumptive irrigation requirements for crops in Idaho: Moscow, Idaho, Idaho Water and Energy Resources Research Institute, University of Idaho, Research Technical Completion Report, 130 p.

Allen, R.G., and Robison, C.W., 2017, Evapotranspiration and consumptive irrigation water requirements for Idaho—Supplement updating the time series through December 2016: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center, Research Technical Completion Report, [variously paged], accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 79 p., accessed November 14, 2018, at https://doi.org/10.3133/cir1186.

Bartolino, J.R., 2009, Ground-water budgets for the Wood River Valley aquifer system, south-central Idaho, 1995–2004: U.S. Geological Survey Scientific Investigations Report 2009–5016, 36 p., accessed July 17, 2018, at https://doi.org/10.3133/sir20095016.

Bassick, M.D., and Jones, M.L., 1992, Aquifer-test results, direction of ground-water flow, and 1984–90 annual ground-water pumpage for irrigation, lower Big Lost River Valley, Idaho: U.S. Geological Survey Water-Resources Investigations Report 92-4006, pl. 1, accessed August 29, 2018, at https://doi.org/10.3133/wri924006.

Bernal, R., 2016, Petition to designate a critical groundwater area in the Big Lost River Basin: Petition submitted to the Idaho Department of Water Resources, docket #P-CGWA-2016-001, 17 p., accessed February 17, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/legal/P-CGWA-2016-001/P-CGWA-2016-001-20160919-Petition-to-designate-the-Big-Lost-River-Basin-as-a-CGWA.pdf.

Bernal, R., and Broadie, M., 2017, Notice of withdrawal of petitions: Document submitted to the Idaho Department of Water Resources, Boise, docket #P-CGWA-2016-001, 3 p., accessed February 17, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/legal/P-CGWA-2016-001/P-CGWA-2016-001-20170620-Notice-of-Withdrawal-of-Petitions.pdf.

Big Lost River Irrigation District, 2020, Big Lost River Irrigation District: Big Lost River Irrigation District web page, accessed June 23, 2020, at http://www.blrid.com/.

Big Lost River Irrigation District, 2022, Storage balance spreadsheets from the Big Lost River Irrigation District, 2015–19: Idaho Department of Water Resources web page, accessed June 22, 2022, at https://idwr.idaho.gov/water-data/projects/big-lost/.

Broadie, M., 2017a, Designation of Big Lost River Basin as a ground water management area (GWMA): Letter submitted to the Idaho Department of Water Resources, Boise, by Big Lost River Ground Water District, Arco, Idaho, docket #P-CGWA-2016-001, 2 p., accessed February 17, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/legal/P-CGWA-2016-001/P-CGWA-2016-001-20170109-Broadie-Letter-re-designation-of-Big-Lost-River-Basin-GWMA.pdf.

Broadie, M., 2017b, Response to petition to create a critical ground water area in the Big Lost River Basin: Letter submitted to the Idaho Department of Water Resources, Boise, by Big Lost River Ground Water District, Arco, Idaho, docket #P-CGWA-2016-001, 2 p., accessed February 17, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/legal/P-CGWA-2016-001/P-CGWA-2016-001-20170123-Response-to-Petition-to-Create-a-CGWA-in-the-Big-Lost-River-Basin.pdf.

Bureau of Reclamation, 2016, AgriMet—Cooperative agricultural weather network: Bureau of Reclamation web page, accessed February 14, 2020, at https://www.usbr.gov/pn/agrimet/agrimetmap/agrimap.html.

California Department of Water Resources, 2020, Draft handbook for water budget development with or without models: Sacramento, California Department of Water Resources, 419 p., accessed December 3, 2020, at https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Data-and-Tools/Files/Water-Budget-Handbook.pdf.

Clark, G.M., 2010, Changes in patterns of streamflow from unregulated watersheds in Idaho, western Wyoming, and northern Nevada: Journal of the American Water Resources Association, v. 46, no. 3, p. 486–497, accessed July 2, 2021, at https://doi.org/10.1111/j.1752-1688.2009.00416.x.

Crosthwaite, E.G., Thomas, C.A., and Dyer, K.L., 1970b, Considerations for water use and management in the Big Lost River Basin, Idaho—A supplemental report: U.S. Geological Survey Open-File Report, 15 p., accessed February 20, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/publications/197006-OFR-Considerations-for-Water-Use-Big-Lost-River-Basin.pdf.

Crosthwaite, E.G., Thomas, C.A., and Dyer, K.L., 1970a, Water resources in the Big Lost River Basin, south-central Idaho: U.S. Geological Survey Open-File Report 70–93, 123 p., accessed February 20, 2022, at https://doi.org/10.3133/ofr7093.

Daly, C., Neilson, R.P., and Phillips, D.L., 1994, A statistical-topographic model for mapping climatological precipitation over mountainous terrain: Journal of Applied Meteorology, v. 33, no. 2, p. 140–158, accessed October 12, 2018, at https://doi.org/10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2.

Dickinson, J.E., Hanson, R.T., Ferre, T.P.A., and Leake, S.A., 2004, Inferring time-varying recharge from inverse analysis of long-term water levels: Water Resources Research, v. 40, no. 7, p. 1–15, accessed May 3, 2020, at https://doi.org/10.1029/2003WR002650.

Dixon, B., and Uddameri, V., 2016, GIS and computation for water resource science and engineering: West Sussex, United Kingdom, John Wiley and Sons, Ltd., 545 p.

Driscoll, D.G., and Carter, J.M., 2002, Hydrology of the Black Hills Area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 02–4094, 150 p., accessed August 28, 2018, at https://doi.org/10.3133/wri024094.

Dudunake, T.J., and Zinsser, L.M., 2021, Surface-water and groundwater interactions in the Big Lost River, south-central Idaho, chap. B *of* Zinsser, L.M., ed., Characterization of water resources in the Big Lost River Basin, south-central Idaho: U.S. Geological Survey Scientific Investigations Report 2021–5078–B, 33 p., accessed October 2, 2021, at https://doi.org/10.3133/sir20215078B.

Esri, 2018, ArcMap, version 10.6.1: Esri software release.

Esri, 2020, ArcMap, version 10.8.1: Esri software release.

Fisher, J.C., Bartolino, J.R., Wylie, A.H., Sukow, J., and McVay, M., 2016, Groundwater-flow model of the Wood River Valley aquifer system, south-central Idaho—Appendix F—Natural groundwater recharge and discharge in the Wood River Valley aquifer system, south-central Idaho: U.S. Geological Survey Scientific Investigations Report 2016–5080, 71 p., accessed July 17, 2018, at https://doi.org/10.3133/sir20165080.

Fisher, J.C., Rousseau, J.P., Bartholomay, R.C., and Rattray, G.W., 2012, A comparison of U.S. Geological Survey three-dimensional model estimates of groundwater source areas and velocities to independently derived estimates, Idaho National Laboratory and vicinity, Idaho: U.S. Geological Survey Scientific Investigations Report 2012–5152 (DOE/ID-22218), 130 p., accessed February 20, 2018, at https://doi.org/10.3133/sir20122152.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Garabedian, S.P., 1992, Hydrology and digital simulation of the regional aquifer system, eastern Snake River Plain, Idaho: U.S. Geological Survey Professional Paper, v. 1408–F, accessed March 14, 2021, at https://doi.org/10.3133/pp1408F.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 2000–92, 121 p., accessed July 5, 2021, at https://doi.org/10.3133/ofr200092.

Healy, R.W., 2010, Estimating groundwater recharge: Cambridge, United Kingdom, Cambridge University Press, 245 p.

Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, Water budgets—Foundations for effective water-resources and environmental management: U.S. Geological Survey Circular 1308, 92 p., accessed July 16, 2018, at https://doi.org/10.3133/cir1308.

Heim, R.R., Jr., 2002, A review of twentieth-century drought indices used in the United States: Bulletin of the American Meteorological Society, v. 83, no. 8, p. 1149–1166, accessed August 6, 2021, at https://doi.org/10.1175/1520-0477-83.8.1149.

Heppner, C.S., and Nimmo, J.R., 2005, A computer program for predicting recharge with a master recession curve: U.S. Geological Survey Scientific Investigations Report 2005–5172, 8 p., accessed May 5, 2021, at https://doi.org/10.3133/sir20055172.

Hsieh, P.A., Barber, M.E., Contor, B.A., Hossain, M.A., Johnson, G.S., Jones, J.L., and Wylie, A.H., 2007, Ground-water flow model for the Spokane Valley-Rathdrum Prairie Aquifer, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho: U.S. Geological Survey Scientific Investigations Report 2007–5044, 78p., accessed February 28, 2018, at https://doi.org/10.3133/sir20075044.

Hurr, R.T., and Litke, D.W., 1989, Estimating pumping time and ground-water withdrawals using energy-consumption data: U.S. Geological Survey Water-Resources Investigations Report 89–4107, 27 p., accessed July 22, 2020, at https://doi.org/10.3133/wri894107.

Idaho Department of Environmental Quality, 2013, Reuse Permit M-029-03: Idaho Department of Environmental Quality web page, accessed July 22, 2020, at https://www.deq.idaho.gov/permitting/issued-permits/?records=100&type=Wastewater+Reuse&sort=nameAscending.

Idaho Department of Environmental Quality, 2018, Final 401 water quality certification NPDES Permit Number ID-002302-7, City of Mackay: Idaho Falls, Idaho Department of Environmental Quality web page, 8 p., accessed February 20, 2022, at https://www2.deq.idaho.gov/admin/LEIA/api/document/download/10537.

Idaho Department of Water Resources [IDWR], 2004, Notice of filing supplemental reports for reporting area 1 (IDWR Basin 34) regarding revision of the following—Period of use (for irrigation water uses), conjunctive management general practices: Idaho Department of Water Resources web page, accessed June 1, 2018, at https://idwr.idaho.gov/wp-content/uploads/sites/2/adjudication/general-provisions-basin-34.pdf.

Idaho Department of Water Resources [IDWR], 2006, 2006 irrigated lands for the Eastern Snake Plain Aquifer (ESPA): Idaho Department of Water Resources web page, accessed July 2, 2021, at https://idwr.maps.arcgis.com/sharing/rest/content/items/0d77f2c29f0a45b0837eca6d9575452b/info/metadata/metadata.xml?format=default&output=html.

Idaho Department of Water Resources [IDWR], 2013a, Enhanced Snake Plain aquifer model version 2.1, January 2013: Idaho Department of Water Resources web page, accessed February 15, 2022, at https://research.idwr.idaho.gov/files/projects/espam/browse/ESPAM_2_Final_Report/ESPAM21FinalReport.pdf.

Idaho Department of Water Resources [IDWR], 2013b, Re final order requiring measuring devices for ground water diversions in Water District No. 34, The Big Lost River: Idaho Department of Water Resources order, accessed September 7, 2018, at https://idwr.idaho.gov/wp-content/uploads/sites/2/legal/orders/2013/20130710-Final-Order-Requiring-Measuring-Devices-WD34.pdf.

Idaho Department of Water Resources [IDWR], 2018, Map and GIS data hub—Groundwater wells: Idaho Department of Water Resources web page, accessed August 2, 2018, at https://data-idwr.opendata.arcgis.com/pages/gis-data#Groundwater.

Idaho Department of Water Resources [IDWR], 2019, Big Lost River well installation: Idaho Department of Water Resources, 23 p., accessed June 10, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/publications/Big-Lost-River-Well-Installation.pdf.

Idaho Department of Water Resources [IDWR], 2020b, Find a well map—Well logs: Idaho Department of Water Resources web page, accessed March 20, 2020, at https://idwr.idaho.gov/wells/find-a-well-map/.

Idaho Department of Water Resources [IDWR], 2020a Map and GIS data hub—Irrigated lands: Idaho Department of Water Resources web page, accessed April 2, 2020, at https://data-idwr.opendata.arcgis.com/pages/gis-data#irrigatedLands.

Idaho Department of Water Resources [IDWR], 2020c, Water District #34 (Big Lost River): Idaho Department of Water Resources document repository, accessed July 13, 2020, at https://idwr.idaho.gov/apps/ExtSearch/RelatedDocsWaterDistrictyearwithyear.asp?water_dist_no=34&wateryear=.

Idaho Department of Water Resources [IDWR], 2020d, Water district surface-water diversion database: Idaho Department of Water Resources database, accessed 2020, at https://idwr.idaho.gov/apps/wm/DiversionDataApplication/AnnualSummary.aspx.

Idaho Department of Water Resources [IDWR], 2020e, Water rights accounting database: Idaho Department of Water Resources web page, accessed May 25, 2022, at https://research.idwr.idaho.gov/apps/Hydrologic/Accounting/.

Idaho Department of Water Resources [IDWR], 2020f, Water management information system: Idaho Department of Water Resources database, accessed July 21, 2020, at https://research.idwr.idaho.gov/apps/WaterManagement/WMIS/PointOfDiversion.aspx.

Idaho Department of Water Resources [IDWR], 2021a, Groundwater data portal—Station overview: Idaho Department of Water Resources database, accessed November 10, 2020, at https://idwr.idaho.gov/water-data/groundwater-levels/.

Idaho Department of Water Resources [IDWR], 2021b, Map and GIS data hub—Evapotranspiration: Idaho Department of Water Resources web page, accessed April 8, 2021, at https://data-idwr.opendata.arcgis.com/pages/gis-data.

Idaho Department of Water Resources [IDWR], 2022a, Map and GIS data hub—Water rights, point of diversion: Idaho Department of Water Resources web page, accessed June 9, 2022, at https://data-idwr.opendata.arcgis.com/pages/gis-data#WaterRights.

Idaho Department of Water Resources [IDWR], 2022b, Water right research: Idaho Department of Water Resources database, accessed May 27, 2022, at https://research.idwr.idaho.gov/apps/waterrights/wrajsearch/wradjsearch.aspx.

Idaho Power, 2020, Leslie gage station (13130500) data: Idaho Power database, accessed March 9, 2020, at https://idastream.idahopower.com/Data/Export.

Idaho Water Resources Board, 2009, Eastern Snake Plain Aquifer (ESPA) comprehensive aquifer management plan, January 2009: Idaho Department of Water Resources web page, accessed July 13, 2020, at https://idwr.idaho.gov/IWRB/water-planning/CAMPs/ESPA/.

Idaho Water Resources Board, 2012, Idaho State water plan: Idaho Department of Water Resources, 80 p., accessed February 20, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/iwrb/2012/2012-State-Water-Plan.pdf.

Iqbal, Z., MacLean, R.T., Taylor, B.D., Hecker, F.J., and Bennett, D.R., 2002, Seepage losses from irrigation canals in southern Alberta: Canadian Biosystems Engineering, v. 44, p. 1.21–1.27, accessed June 23, 2022, at https://library.csbe-scgab.ca/docs/journal/44/c0108.pdf.

Jensen, M.E., and Haise, H.R., 1963, Estimating evapotranspiration from solar radiation: Journal of the Irrigation and Drainage Division, v. 89, no. 4, p. 15–41. [Also available at https://eprints.nwisrl.ars.usda.gov/id/eprint/1248.]

Johnson, G.S., Ralston, D.R., and Mink, L.L., 1991, Ground-water pumping impacts on surface water irrigation diversions from Big Lost River: Prepared for Idaho Department of Water Resources, Boise, Idaho, by Idaho Water Resources Research Institute, University of Idaho, Moscow, 54 p., accessed February 20, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/publications/199112-GWQ-IWRRI-Report-GW-Pumping-Impacts-Big-Lost-River.pdf.

Keller Associates, 2012, Moore, Idaho, Environmental information document: Prepared by Keller Associates, Pocatello, Idaho, for Moore Water and Sewer Association, Moore, Idaho, accessed July 22, 2020, at https://www.deq.idaho.gov/media/856262-moore-water-sewer-asson-ww-improvement-project-eid-0612.pdf.

Kjelstrom, L.C., 1986, Flow characteristics of the Snake River and water budget for the Snake River Plain, Idaho and eastern Oregon: U.S. Geological Survey Hydrologic Investigations Atlas HA-680, scale 1:1,000,000, 2 sheets, accessed June 17, 2022, at https://doi.org/10.3133/ha680.

Lewis, R.S., Link, P.K., Stanford, L.R., and Long, S.P., 2012, Geologic map of Idaho: Idaho Geological Survey Map M-9, scale 1:750,000, accessed August 3, 2018, at https://www.idahogeology.org/product/m-9.

Liu, Y., Zhu, Y., Ren, L., Singh, V.P., Yang, X., and Yuan, F., 2017, A multiscalar Palmer drought severity index: Geophysical Research Letters, v. 44, no. 13, p. 6850–6858, accessed August 6, 2021, at https://doi.org/10.1002/2017GL073871.

Meixner, T., Manning, A.H., Stonestrom, D.A., Allen, D.M., Ajami, H., Blasch, K.W., Brookfield, A.E., Castro, C.L., Clark, J.F., Gochis, D.J., Flint, A.L., Neff, K.L., Niraula, R., Rodell, M., Scanlon, B.R., Singha, K., and Walvoord, M.A., 2016, Implications of projected climate change for groundwater recharge in the western United States: Journal of Hydrology, v. 534, p. 124–138, accessed June 17, 2020, at https://doi.org/10.1016/j.jhydrol.2015.12.027.

Mote, P., 2006, Climate-driven variability and trends in mountain snowpack in western North America: Journal of Climate, v. 19, no. 23, p. 6209–6220, accessed August 3, 2021, at https://doi.org/10.1175/JCLI3971.1.

Multi-Resolution Land Characteristics Consortium, 2019, National Land Cover Database: U.S. Geological Survey database, accessed November 8, 2019, at https://www.mrlc.gov/data.

Mundorff, M.J., Crosthwaite, E.G., and Kilburn, C., 1964, Ground water for irrigation in the Snake River Basin in Idaho: U.S. Geological Survey Water-Supply Paper 1654, 240 p., accessed June 16, 2020, at https://doi.org/10.3133/wsp1654.

National Center for Atmospheric Research, 2021, Climate data—Palmer Drought Severity Index (PDSI): National Center for Atmospheric Research database, accessed August 6, 2021, at https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi.

National Oceanic and Atmospheric Administration, 2018, Vertical datums: National Oceanic and Atmospheric Administration National Geodetic Survey web page, accessed February 28, 2022, at https://www.ngs.noaa.gov/datums/vertical/.

National Oceanic and Atmospheric Administration, 2020, Climate data online: National Oceanic and Atmospheric Administration database, accessed September 11, 2020, at https://www.ncdc.noaa.gov/cdo-web/.

National Oceanic and Atmospheric Administration, 2021, Climate at a glance—Divisional time series: National Oceanic and Atmospheric Administration website, accessed August 4, 2021, at https://www.ncdc.noaa.gov/cag/divisional/time-series.

Natural Resources Conservation Service, 2019, STATSGO2: U.S. Department of Agriculture Natural Resources Conservation Service database, accessed November 4, 2022, at https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm.

Natural Resources Conservation Service, 2020, Snowpack Telemetry (SNOTEL) and snow course data and products: U.S. Department of Agriculture Natural Resources Conservation Service web page, accessed February 15, 2020, at https://www.wcc.nrcs.usda.gov/snow/.

Natural Resources Conservation Service, 2021, Climate station metadata: U.S. Department of Agriculture Natural Resources Conservation Service web page, accessed February 28, 2022, at https://www.nrcs.usda.gov/wps/portal/wcc/home/climateSupport/fieldOfficeGuide/climateStationMetadata/.

Natural Resources Conservation Service, 2022, National Agricultural Imagery Program—Direct data/NAIP download: U.S. Department of Agriculture Natural Resources Conservation Service database, accessed June 17, 2022, at https://datagateway.nrcs.usda.gov/GDGHome_DirectDownLoad.aspx.

Palmer, W.C., 1965, Meteorological drought: U.S. Department of Commerce, Research Paper No. 45, 58 p., accessed August 5, 2021, at https://www.droughtmanagement.info/literature/USWB_Meteorological_Drought_1965.pdf.

Pierce, K.L., and Scott, W.E., 1982, Pleistocene episodes of alluvial-gravel deposition, southeastern Idaho, *in* Bonnichsen, B., and Breckenridge, R.M., eds, Cenozoic geology of Idaho: Idaho Bureau of Mines and Geology, Bulletin 26, p. 685–702, accessed August 16, 2018, at https://www.researchgate.net/publication/265751313_Pleistocene_Episodes_of_Alluvial-Gravel_Deposition_Southeastern_Idaho.

PRISM Climate Group, 2020, PRISM climate data: Corvallis, Oregon State University PRISM web page, accessed November 1, 2020, at https://prism.oregonstate.edu/.

Qin, Y., Abatzoglou, J.T., Siebert, S., Huning, L.S., AghaKouchak, A., Mankin, J.S., Hong, C., Tong, D., Davis, S.J., and Mueller, N.D., 2020, Agricultural risks from changing snowmelt: Nature Climate Change, v. 10, no. 5, p. 459–465, accessed August 3, 2021, at https://doi.org/10.1038/s41558-020-0746-8.

Rice, J.B., and Boyd, K., 2008, Big Lost River Darlington Sinks geomorphology, loss rates, and conceptual alternatives development: Prepared by Rocky Mountain Environmental Associates, Inc., Idaho Falls, Idaho, and Applied Geomorphology, Inc., Bozeman, Montana, for Trout Unlimited, Big Lost River Irrigation District, and Water District #34, 87 p.

Ries, K.G., III, Newson, J.K., Smith, M.J., Guthrie, J.D., Steeves, P.A., Haluska, T.L., Kolb, K.R., Thompson, R.F., Santoro, R.D., and Vraga, H.W., 2017, StreamStats—Version 4: U.S. Geological Survey Fact Sheet 2017–3046, 4 p., accessed September 21, 2018, at https://doi.org/10.3133/fs20173046.

Ries, K.G., III, Steeves, P.A., Coles, J.D., Rea, A.H., and Stewart, D.W., 2004, StreamStats—A U.S. Geological Survey web application for stream information: U.S. Geological Survey Fact Sheet 2004–3115, 4 p., accessed December 2, 2020, at https://doi.org/10.3133/fs20043115.

Said, A., Stevens, D.K., and Sehlke, G., 2005, Estimating water budget in a regional aquifer using HSPF-MODFLOW integrated model: Journal of the American Water Resources Association, v. 41, no. 1, p. 55–66, accessed December 4, 2018, at https://doi.org/10.1111/j.1752-1688.2005.tb03717.x.

Scalzitti, J., Strong, C., and Kochanski, A., 2016, Climate change impact on the roles of temperature and precipitation in western U.S. snowpack variability: Geophysical Research Letters, v. 43, no. 10, p. 5361–5369, accessed August 3, 2021, at https://doi.org/10.1002/2016GL068798.

Skipp, B., Snider, L.G., Janecke, S.U., and Kuntz, M.A., 2009, Geologic map of the Arco 30 × 60 minute quadrangle, south-central Idaho: Idaho Geological Survey, Geologic Map GM-47, scale 1:100,000, accessed November 7, 2018, at https://www.idahogeology.org/product/gm-47.

Stearns, H.T., Crandall, L., and Steward, W.G., 1938, Geology and ground-water resources of the Snake River Plain in southeastern Idaho: U.S. Geological Survey Water-Supply Paper 774, 268 p., accessed June 16, 2020, at https://doi.org/10.3133/wsp774.

Sukow, J., 2017, Groundwater in the Big Lost River Valley: Idaho Department of Water Resources Memorandum, February 6, 2017, 37 p., accessed February 25, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/legal/P-CGWA-2016-001/P-CGWA-2016-001-20170206-IDWR-Staff-Memo-Re-BLRV-by-Jennifer-Sukow.pdf.

Sukow, J., 2021, Model calibration report—Eastern Snake Plain aquifer model version 2.2: Idaho Department of Water Resources, 181 p., accessed February 25, 2022, at https://research.idwr.idaho.gov/files/projects/espam/browse/ESPAM22_Reports/ModelCalibrationRpt/ModelCalibration22_Final.pdf.

Szczepanowski, S.P., 1982, Review of groundwater conditions in the Big Lost River Valley: Idaho Department of Water Resources, 29 p., accessed February 25, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/publications/198212-OFR-gw-conditions-big-lost.pdf.

University of Idaho, 2018, Evapotranspiration and consumptive irrigation water requirements for Idaho: University of Idaho Kimberly Research and Extension Center web page, accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

U.S. Census Bureau, 2020, QuickFacts—Idaho: U.S. Census Bureau web page, accessed June 21, 2020, at https://www.census.gov/quickfacts/fact/table/US/PST045221.

U.S. Department of Agriculture, 1993, Irrigation water requirements, chap. 2 *of* Part 623—National engineering handbook: U.S. Department of Agriculture, 302 p., accessed July 2, 2019, at https://www.wcc.nrcs.usda.gov/ftpref/wntsc/waterMgt/irrigation/NEH15/ch2.pdf.

U.S. Environmental Protection Agency, 2020, ECHO—Enforcement and compliance history online: U.S. Environmental Protection Agency web page, accessed July 20, 2020, at https://echo.epa.gov/facilities/facility-search/results.

U.S. Geological Survey, 2016, StreamStats—Streamflow statistics and spatial analysis tools for water-resources applications: U.S. Geological Survey web page, accessed August 30, 2021, at http://streamstats.usgs.gov.

U.S. Geological Survey, 2018a, National hydrography dataset—Hydrologic unit code (HUC Level 8) 17040218: U.S. Geological Survey web page, accessed November 7, 2018, at https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

U.S. Geological Survey, 2020, National Water Information System—USGS water data for Idaho: U.S. Geological Survey database, accessed June 20, 2020, at https://waterdata.usgs.gov/id/nwis/ and https://doi.org/10.5066/F7P55KJN.

U.S. Geological Survey, 2021, National Water Information System—Web interface—USGS Water use data for Idaho: U.S. Geological Survey database, accessed May 25, 2021, at https://waterdata.usgs.gov/id/nwis/wu.

Water District 34, 2022, Ditch rider logs from Water District 34, 2015–2018: Idaho Department of Water Resources web page, accessed June 22, 2022, at https://idwr.idaho.gov/water-data/projects/big-lost/.

Western Regional Climatic Center, 2020, Recent climate in the West: Western Regional Climate Center web page, accessed February 14, 2020, at https://wrcc.dri.edu/.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water—A single resource: U.S. Geological Survey Circular 1139, 79 p., accessed July 23, 2018, at https://doi.org/10.3133/cir1139.

Womeldorph, G., and Steimke, A., 2022, Surface and ground water quality of the Big Lost River Basin: Boise, Idaho Department of Water Resources, 16 p., accessed July 27, 2022, at https://idwr.idaho.gov/water-date/projects/big-lost/.

Wood, M.S., Williams, M.L., Evetts, D.M., and Vidmar, P.J., 2014, Evaluation of seepage and discharge uncertainty in the middle Snake River, southwestern Idaho: U.S. Geological Survey Scientific Investigations Report 2014–5091, 34 p., accessed February 12, 2019, at https://doi.org/10.3133/sir20145091.

Worstell, R.V., 1976, Estimating seepage losses from canal systems: Journal of the Irrigation and Drainage Division, v. 102, no. 1, p. 137–147, accessed April 30, 2019. https://doi.org/10.1061/JRCEA4.0001080.

Zinsser, L.M., 2021, Hydrogeologic framework of the Big Lost River Basin, south-central Idaho, chap. A *of* Zinsser, L.M., ed., Characterization of water resources in the Big Lost River Basin, south-central Idaho: U.S. Geological Survey Scientific Investigations Report 2021–5078–A, 42 p., accessed September 24, 2021, at https://doi.org/10.3133/sir20215078A.

Appendix 1. Land Coverage

Abbreviations

CDL	cropland data layer (CropScape)
CIR	crop irrigation requirement
ET	evapotranspiration
IDWR	Idaho Department of Water Resources
METRIC	Mapping EvapoTranspiration at high Resolution and Internalized Calibration
NAIP	National Agriculture Imagery Program
NDVI	Normalized Difference Vegetation Index
NLCD	National Land Cover Database
PRISM	Parameter-elevation Regressions on Independent Slopes Model
USDA	U.S. Department of Agriculture

Two sources of vegetation and land-cover data are available for the Big Lost River Basin: cropland data layer (CDL) coverage (CropScape; National Agricultural Statistics Service, 2020a, 2020b) and National Land Cover Database (NLCD) coverage (Multi-Resolution Land Characteristics Consortium, 2019). These coverages were used for preparing estimates of areal recharge, irrigation recharge, and evapotranspiration (ET) for the groundwater budget. The U.S. Department of Agriculture (USDA) National Agricultural Statistics Service prepares CDL datasets for the continental U.S. Datasets are 30-meter (m) resolution "raster-based, geo-referenced crop-specific land cover" (U.S. Department of Agriculture, 2020). CDL coverage is available for most of the basin below Mackay Dam in 2005, and complete coverage is available from 2007 to 2019. No CDL coverage is available for 2000–04 or 2006.

Source CDL files (National Agricultural Statistics Service, 2020a) are not smoothed or filtered, producing a somewhat discontinuous, pixelated effect with the potential for incorrectly representing land cover types, particularly at the transition boundary from one land-use type to another. For convenience, smoothed CDL datasets were obtained from Idaho Department of Water Resources (IDWR) staff (B. Kramber, IDWR, written commun., September 13, 2019; A. Steimke, IDWR, written commun., April 7, 2020) for use in developing the groundwater budget to provide for continuous, complete coverage over the entire study area. Smoothing was done using the zonal statistics majority tool in ArcGIS[1] (Esri, 2018, 2020; P. Blankenau, IDWR, written commun., 2019).

The Multi-Resolution Land Characteristics Consortium distributes NLCD coverage for the entire U.S. Datasets are 30-m resolution, Landsat-based, raster thematic class maps (Homer and others, 2012). NLCD coverage is available for 2001, 2004, 2006, 2008, 2011, 2013, and 2016 (Multi-Resolution Land Characteristics Consortium, 2019). Representative NLCD coverage for 2016 is provided as figure 1.1.

The NLCD and CDL datasets were used in conjunction with datasets from ET_{Idaho}, a searchable database providing evapotranspiration and irrigation data by land-cover type for weather stations across Idaho for determining ET (Allen and Robison, 2017; University of Idaho, 2018). ET_{Idaho} is described further in section, "Areal Recharge," and in appendix 10 ("Evapotranspiration"). Each ET_{Idaho} category was assigned to a NLCD or CDL land-use classification for the Big Lost River Basin (tables 1.1 and 1.2, respectively) using a similar assignment that Bartolino (2009) applied in the Big Wood River Valley water-budget study (with some slight modifications). The Big Wood River Basin is an intermontane basin west of the Big Lost River Basin, so similar climatic, vegetation, and land-use patterns are expected there.

A few ET_{Idaho} categories do not have an NLCD or CDL comparable class (table 1.2). For example, ET_{Idaho} does not have a published ET rate for evergreen forest (or coniferous trees). Review of U.S. Forest Service land-cover datasets (U.S. Forest Service, 2021) indicates a Douglas-fir group is a dominant type of tree at high altitudes. Evergreen forests constitute about 21, 17, and 5 percent of the total non-irrigated lands for areas above Mackay Dam, the middle subbasin, and the lower subbasin, respectively, based on review of 2016 NLCD coverage. Focused research on the ET rates of Douglas fir stands in the Pacific Northwest suggest an ET range of about 370 millimeters per year (mm/yr) (14.57 inches per year [in/yr]) to 430 mm/yr (16.93 in/yr) in one study during 1998–2007 (Jassal and others), 2009).

[1] The 2019 CDL coverage is a draft version based on 2013 irrigated-land data for the zones, as irrigated-land coverage for 2019 was not available during preparation of the water budget.

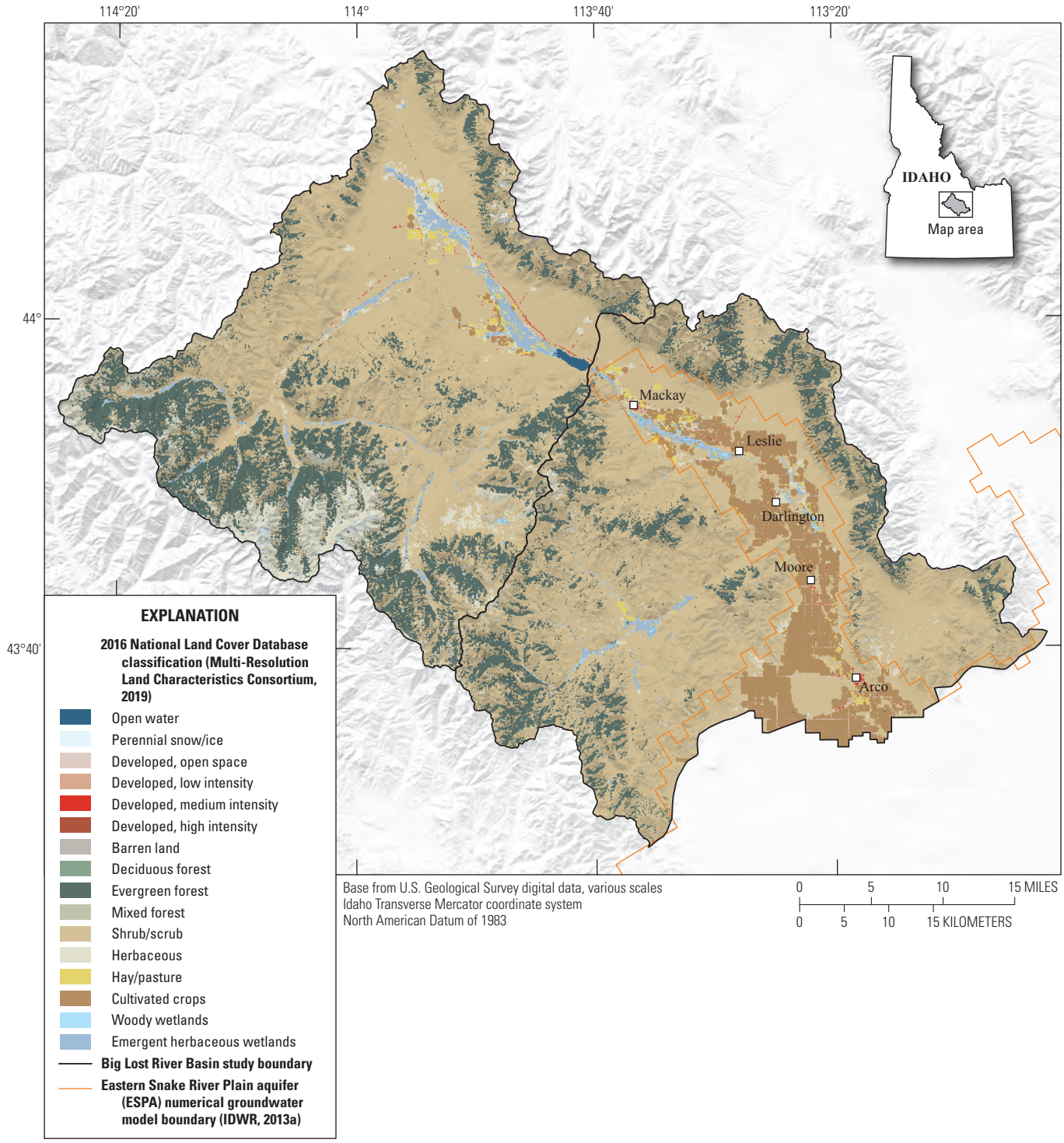


Figure 1.1. National Land Cover Database classifications for the Big Lost River Basin, south-central Idaho, 2016. IDWR, Idaho Department of Water Resources.

Table 1.1. ET_{Idaho} land-class assignments of National Land Cover Database land-cover classes for the Big Lost River Basin, south-central Idaho.

[**Abbreviations and symbol:** ET_{Idaho}, searchable database providing evapotranspiration and irrigation data by land-cover type for weather stations across Idaho; NLCD, National Land Cover Database; —, no corresponding ET_{Idaho} land-use class]

NLCD land-cover class (Multi-Resolution Land Characteristics Consortium, 2019)	Definition	ET_{Idaho} land-use class (Allen and Robison, 2007)
Open water	All areas of open water, generally with less than 25-percent cover, vegetation. or soil.	Open water-shallow systems (ponds, streams); Above Mackay Dam assigned "deep open water" to approximate Mackay Reservoir. Below Mackay Dam assigned "shallow open water.'
Perennial ice/snow	All areas characterized by a perennial cover of ice and (or) snow, generally less than 25 percent of total cover.	—
Developed, open space	Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.	80-percent grass-turf (lawns)—Irrigated, 20-percent impervious cover
Developed, low intensity	Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20–49 percent of total cover. These areas most commonly include single-family housing units.	51-percent grass-turf (lawns)—Irrigated, 49-percent impervious cover
Developed, medium intensity	Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50–79 percent of the total cover. These areas most commonly include single-family housing units.	21-percent grass-turf (lawns)—Irrigated, 79-percent impervious cover
Developed, high intensity	Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses, and commercial/industrial. Impervious surfaces account for 80–100 percent of the total cover.	100-percent impervious cover
Barren land	Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.	Bare soil
Forest, deciduous	Areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.	Cottonwoods

Table 1.1. ET_{Idaho} land-class assignments of National Land Cover Database land-cover classes for the Big Lost River Basin, south-central Idaho.—Continued

[**Abbreviations and symbol:** ET_{Idaho}, searchable database providing evapotranspiration and irrigation data by land-cover type for weather stations across Idaho; NLCD, National Land Cover Database; —, no corresponding ET_{Idaho} land-use class]

NLCD land-cover class (Multi-Resolution Land Characteristics Consortium, 2019)	Definition	ET_{Idaho} land-use class (Allen and Robison, 2007)
Forest, evergreen	Areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.	—
Forest, mixed	Areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. Neither deciduous nor evergreen species are greater than 75 percent of total tree cover.	—
Shrub/scrub	Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20 percent of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.	Sage brush
Grassland, herbaceous	Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80 percent of total vegetation. These areas are not subject to intensive management such as tilling but can be used for grazing.	Range grasses–early short season
Hay/pasture	Areas of grasses, legumes, or grass-legume mixture planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.	Grass pasture; low management above Mackay Dam and middle basin and high management in lower basin
Cultivated crops	Areas used to produce annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20 percent of total vegetation. This class also includes all land being actively tilled.	Alfalfa–less frequent cuttings
Wetlands, woody	Areas where forest or shrub land vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	Cottonwoods
Wetlands, herbaceous	Areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover and the soil or substrate is periodically saturated or covered with water.	Wetlands; large stands above Mackay Dam and narrow stands below Mackay Dam

Table 1.2. ET_{Idaho} land-use class assignment (Allen and Robison, 2017; University of Idaho, 2018) for cropland data layer (CropScape) land-cover classes (National Agricultural Statistics Service, 2020a) for the Big Lost River Basin, south-central Idaho.

[**Abbreviations and symbol:** CDL, cropland data layer (CropScape); ET_{Idaho}, searchable database providing evapotranspiration and irrigation data by land-cover type for weather stations across Idaho; —, no corresponding ET_{Idaho} land-use class]

CDL data layer	ET_{Idaho} assignment
Alfalfa	Alfalfa less frequent
Barren	Bare soil
Barley	Spring grain irrigated
Corn	Sweet corn late
Developed/open space	Grass turf irrigated (80 percent)
Developed/low intensity	Grass turf irrigated (51 percent)
Developed/medium intensity	Grass turf irrigated (21 percent)
Developed/high intensity	100-percent impervious
Evergreen forest[1]	—
Fallow/idle cropland	Mulched soil
Grass/pasture[2]	Grass pasture low/high management
Herbaceous wetlands[3]	Wetlands large/narrow stands
Oats	Spring grain irrigated
Open water[4]	Open water shallow/deep
Other hay/non-alfalfa	Grass hay
Peas	Peas seed
Potatoes	Potatoes late
Shrubland	Sagebrush
Spring wheat	Spring grain irrigated
Sod/grass seed	Grass pasture high management
Triticale	Winter grain rainfed
Winter wheat	Winter grain rainfed
Woody wetlands	Cottonwoods

[1]ET_{Idaho} does not have comparable evapotranspiration values for coniferous forests.

[2]Assumed low management above Mackay Dam and the middle subbasin and high management in the lower subbasin.

[3]Large stands were assumed to be present above Mackay Dam and narrow stands were assumed to be present below Mackay Dam.

[4]Deep water was assumed to be present above Mackay Dam and shallow water was assumed to be present below Mackay Dam.

The NLCD does not differentiate the crop type (designated as "cultivated crops"), so assumptions were necessary for assigning representative crop types. The relative percentage of each crop type to the overall number of irrigated acres was compiled for the available CDL coverages (2007–19). The same proportion was assumed for cultivated crops in the 2000–06 coverages for estimating ET during those years. Constant percentages were assumed for the middle and lower subbasins based on overall consistent trends in the CDL coverages[2]. The crop mix reported in CDL files above Mackay Dam changed over time. At times, alfalfa was the dominant crop, whereas more acres had grass pasture in other years. Although the apparent correlation between the percentage of acres in alfalfa to the precipitation trends was not strong (coefficient of determination [R^2] factor of 0.35), the percentage of alfalfa was adjusted for 2000–06 based on whether years appeared to be relatively wet or dry. Compared to an assumption that alfalfa (with less frequent cutting) represents all crop types, redistribution of assumed ET rates for a proxy crop mix overall resulted in better agreement with the expected seasonal trends and improved the overall estimates of crop irrigation requirement (CIR) and unmeasured groundwater withdrawal for irrigation (as discussed in section, "Groundwater Pumpage").

References to published ET rates for coniferous forests similar to those in the Big Lost River Basin were not available. Therefore, coniferous forest ET was assigned based on the linear regression relation with Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation (PRISM Climate Group, 2020) and Mapping EvapoTranspiration at high Resolution and Internalized Calibration (METRIC) ET (IDWR, 2021b) at higher altitude (R. Allen, University of Idaho, written commun., 2021). The use of monthly datasets compiled over the irrigation season (April–October) resulted in poor correlation (R^2 of 0.1 or less). Direct comparison of monthly METRIC and PRISM may produce better agreement in estimated ET at high altitudes. ET was assumed to be zero for coniferous forests during winter because of snow cover, with sublimation assumed to be the dominant process.

Annual averages of about 12,400 and 55,000 acres were actively irrigated above and below Mackay Dam, respectively, during 2000–19. The number of actively irrigated and semi-irrigated acres varied somewhat with the given irrigation season depending on actual irrigation practices and land conversion (such as urban development, fallow irrigated lands, or the retirement of previously irrigated lands). Furthermore, the interpretation of which lands are actively irrigated may change over time. Overall, irrigated acreage was relatively constant from 2000 to 2010 and 2011 to 2017. However, the increase

[2]In the middle subbasin, the assumed percentages were 70-percent alfalfa (as less frequent cutting), 14-percent barley (assigned as a spring grain requiring irrigation), and 16-percent grass pasture (assumed low instead of high management). Similarly, in the lower subbasin, assumed percentages were 64-percent alfalfa (as less frequent cutting), 26-percent barley (assigned as a spring grain requiring irrigation), and 9-percent spring wheat (assigned as a spring grain requiring irrigation).

in acreage classified as "irrigated" and "semi-irrigated" above and below Mackay Reservoir from 2010 to 2011 (by about 12,800 acres) and sustained during subsequent years is apparent in figure 1.2*A* and 1.2*B*, respectively[3]. Irrigated-land coverages during 2000–10 likely underrepresent actual irrigated and semi-irrigated acres based on review of subsequent assignment of irrigated and semi-irrigated lands during 2011–17.

Bottom pasture lands in the riparian corridor along the Big Lost River above Mackay Reservoir (about 4,800 acres) and along Antelope Creek (about 7,950 acres), not classified as irrigated before 2011, accounted for most of the approximately 12,800-acre increase. The change was not likely attributed to changes in irrigation practices but instead to the interpretation of what constituted irrigated lands (D. Hoekema and J. Sukow, IDWR, written commun., 2020).

For irrigated-land coverage development, the IDWR uses available aerial photography, water rights, and satellite-based imagery sources including the National Agricultural Imagery Program (NAIP), METRIC, Normalized Difference Vegetation Index (NDVI), NLCD, and CDL in delineating land-use classifications (M. Wilkins, IDWR, written commun., 2020). Irrigated-land coverages are available for most of the years in the study period (2000, 2002, 2006, and 2008–17). Irrigated-land coverages for 2012–17 used in this study are draft versions prepared by IDWR in April 2020 (M. Wilkins, IDWR, unpub. data, April 1, 2020)[4] and may not reflect their final interpretation. IDWR has since published irrigated-lands coverages as the "Eastern Snake Plain" for 2012–15, available from the IDWR at https://data-idwr.opendata.arcgis.com/pages/gis-data#IrrigatedLands. The use of surrogate years for missing years is described further in appendix 10 ("Evapotranspiration").

In order for the overall water budget to balance, assumptions had to be made about additional irrigated and semi-irrigated acres that may have been actively irrigated during 2000–10 but the irrigation of which was not reflected in the published datasets of irrigated and semi-irrigated lands. Bottomlands and riparian areas above Mackay Reservoir and

[3]Slight variations between the initial and updated versions in total acres shown for 2011–17 reflect the use of either polygon-derived (final) versus raster-derived areas, typically within ±50 acres. No adjustments were made to 2011-17 datasets.

[4]At the time of publication, published data were not available from IDWR but files may be requested from M. Wilkins at IDWR Idaho Water Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800.

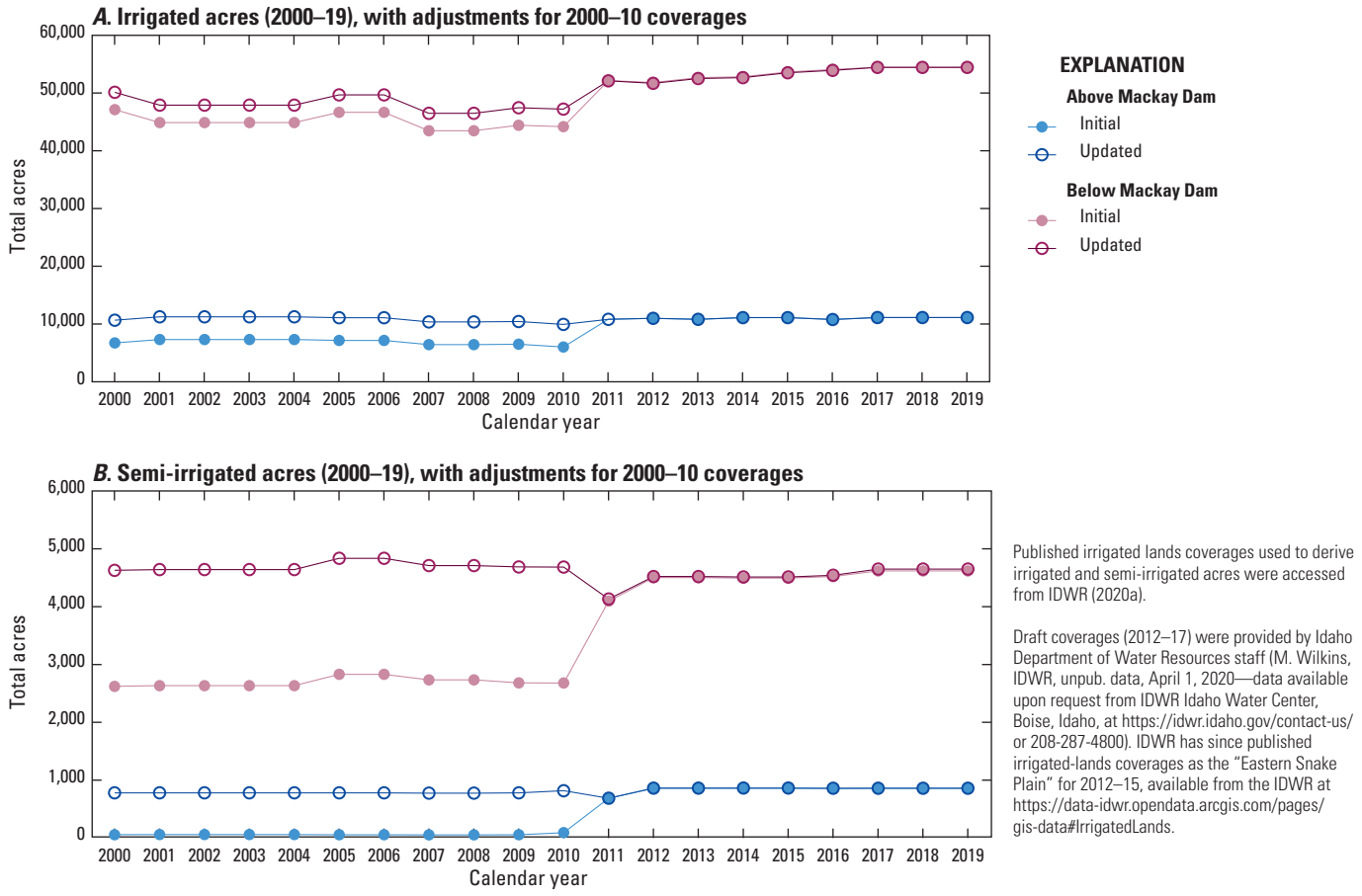


Figure 1.2. Irrigated acres (*A*) and semi-irrigated acres (*B*), in the Big Lost River Basin, south-central, Idaho, 2000–19, with adjustments for 2000–10 coverages.

areas along the Antelope Creek drainage classified as "irrigated" in 2013 (an especially dry year) were added to the 2000–10 irrigated-land dataset for processing precipitation and ET data. Similarly, the published semi-irrigated land-use classification for 2000–10 primarily included towns but not farms. Therefore, the additional semi-irrigated acres included in the draft 2013 coverage were included in the 2000–10 dataset used to process precipitation and ET data. The assumption that 2013 irrigated-land status reflects prior years may not be valid for all years. Overall, this compensation resulted in better agreement between the 2000–10 totals for precipitation, ET, and CIR and the 2011–17 results.

The number of acres assigned a "semi-irrigated" status increased from 2010 to 2011, attributed to inclusion of additional parcels previously classified as "non-irrigated" before 2011 (fig. 1.2). Above Mackay Reservoir, less than 60 acres were semi-irrigated during 2000–10, about 690 acres were semi-irrigated in 2011, and 860 acres were semi-irrigated during 2012–17. Below Mackay Reservoir, semi-irrigated acreage ranged slightly from 2,620 to 2,830 acres during 2000–10, with about 4,100 acres in 2011, and 4,500–4,620 acres during 2012–17.

References Cited

Allen, R.G., and Robison, C.W., 2007, Evapotranspiration and consumptive irrigation water requirements for Idaho: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center, 260 p., accessed July 17, 2018, at http://www.kimberly.uidaho.edu/ETIdaho/.

Allen, R.G., and Robison, C.W., 2017, Evapotranspiration and consumptive irrigation water requirements for Idaho—Supplement updating the time series through December 2016: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center, Research Technical Completion Report [variously paged], accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

Bartolino, J.R., 2009, Ground-water budgets for the Wood River Valley aquifer system, south-central Idaho, 1995–2004: U.S. Geological Survey Scientific Investigations Report 2009–5016, 36 p., accessed July 17, 2018, at https://pubs.usgs.gov/sir/2009/5016/sir20095016.pdf.

Esri, 2018, ArcMap, version 10.6.1: Esri software release.

Esri, 2020, ArcMap, version 10.8.1: Esri software release.

Homer, C.H., Fry, J.A., and Barnes, C.A., 2012, The National Land Cover Database: U.S. Geological Survey Fact Sheet 2012–3020, 4p., accessed July 17, 2018, at https://pubs.usgs.gov/fs/2012/3020/.

Idaho Department of Water Resources [IDWR], 2021b, Map and GIS data hub—Evapotranspiration: Idaho Department of Water Resources web page, accessed April 8, 2021, at https://data-idwr.opendata.arcgis.com/pages/gis-data.

Jassal, R.S., Black, T.A., Spittlehouse, D.L., Brummer, C., and Nesic, Z., 2009, Evapotranspiration and water use efficiency in different-aged Pacific Northwest Douglas-fir stands: Agricultural and Forest Meteorology, v. 149, no. 6–7, p. 1168–1178, accessed January 25, 2021, at https://www.sciencedirect.com/science/article/pii/S0168192309000422.

Multi-Resolution Land Characteristics Consortium, 2019, National land cover database: U.S. Geological Survey database, accessed November 8, 2019, at https://www.mrlc.gov/data.

National Agricultural Statistics Service, 2020a, CropScape—Cropland data layer: U.S. Department of Agriculture National Agricultural Statistics Service database, accessed February 20, 2020, at https://nassgeodata.gmu.edu/CropScape/.

National Agricultural Statistics Service, 2020b, CropScape and cropland data layers—FAQs—Section 3, FAQ 23: U.S. Department of Agriculture National Agricultural Statistics Service database, accessed February 20, 2020, at https://www.nass.usda.gov/Research_and_Science/Cropland/sarsfaqs2.php#Section3_22.0.

PRISM Climate Group, 2020, PRISM climate data: Corvallis, Oregon State University PRISM web page, accessed November 1, 2020, at https://prism.oregonstate.edu/.

University of Idaho, 2018, Evapotranspiration and consumptive irrigation water requirements for Idaho: University of Idaho Kimberly Research and Extension Center web page, accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

U.S. Department of Agriculture, 2020, CropScape—Cropland data layer: U.S. Department of Agriculture Ag data commons database, accessed July 15, 2020, at https://data.nal.usda.gov/dataset/cropscape-cropland-data-layer.

U.S. Forest Service, 2021, National Forest type dataset: U.S. Forest Service database, accessed January 2021, at https://data.fs.usda.gov/geodata/rastergateway/forest_type/index.php.

Appendix 2. Precipitation Data

Abbreviations

AgriMet	agricultural meteorology
ET	evapotranspiration
IDWR	Idaho Department of Water Resources
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
SNOTEL	snowpack telemetry
SWE	snow water equivalent
WRCC DRI	Western Regional Climate Center Desert Research Institute

The Bureau of Reclamation maintains an agricultural meteorology (AgriMet) weather station network throughout the Pacific Northwest (Bureau of Reclamation, 2016). This network collects temperature, precipitation, and evapotranspiration (ET) parameters using satellite-based telemetry. The National Oceanic and Atmospheric Administration (NOAA; National Oceanic and Atmospheric Administration, 2020) and the Western Regional Climate Center Desert Research Institute (WRCC DRI; Western Regional Climatic Center, 2020) collect temperature, precipitation, snowfall, snow depth, and number of growing degree days. WRCC DRI and NOAA stations (Chilly Barton Flat) and WRCC DRI station (Mackay Ranger Station) and NOAA station (Mackay Lost River Ranger Station) seem to overlap based on essentially the same station coordinates[1] (fig. 1; table 2). Meteorological records including daily precipitation for National Weather Service (NWS) weather stations (Chilly Barton Flat, Mackay Ranger Station, and Arco 3 SW) are published on the ET_{Idaho} website in association with evapotranspiration records for various land-cover types (Allen and Robison, 2017; University of Idaho, 2018).

Five snowpack telemetry (SNOTEL) sites (fig. 1; table 3) are located within or near the Big Lost River Basin (Natural Resources Conservation Service, 2020). Automated SNOTEL sites in the basin record temperature, precipitation, and snow depth at altitudes ranging from 7,430 to 9,520 feet. Sites also report snow water equivalent (SWE) totals, representing the amount of water released from snowpack melt. SWE is calculated from the weight of snow measured on snow pillows, snow density, and snow depth (Natural Resources Conservation Service, 2020). Two snow course sites (Natural Resources Conservation Service, 2020) are located within the Big Lost River Basin (fig. 1; table 2). The Natural Resources Conservation Service manually monitors snow course sites semimonthly during winter (at or close to the start of the month) for snow depth and SWE (Natural Resources Conservation Service, 2020).

Monthly total precipitation data were obtained for the 2000–19 study period for the Big Lost River Basin as Parameter-elevation Regressions on Independent Slopes Model (PRISM) raster coverages at 4-kilometer (km) grid resolution (PRISM Climate Group, 2020). For convenience, the Idaho Department of Water Resources (IDWR) provided 2000–18 PRISM datasets used in the groundwater budget[2] (B. Kramber, IDWR, written commun., September 13, 2019). PRISM data for 2019 was accessed from the PRISM Climate Group web page (PRISM Climate Group, 2020) and resolved to the project spatial extent and coordinate system. PRISM incorporates available climate and SNOTEL site datasets in a gridding algorithm that uses a digital elevation model to generate a weighted climatic parameter value for each grid cell. Daly and others (2008) and Daly and Bryant (2013) described the methodology and application of PRISM. For this analysis, monthly PRISM raster datasets were summed over each calendar year, irrigation season (April–October), and winter season within the same calendar year (January–March and November–December). Rasters were then masked to upper, middle, and lower subbasin extents[3] in ArcGIS (Esri, 2018, 2020). Total precipitation volumes were computed for each extent.

Resampling of 4-km PRISM precipitation datasets to 30-m cell resolution at the study boundary scale introduced some small differences in the magnitude of precipitation for certain datasets (used in tributary-basin underflow estimates). Bilinear interpolation[4] was used to resample the

[1]The NOAA NWS sites (Chilly Barton Flat and Mackay Lost River Ranger Station) are not shown in figure 1.

[2]The IDWR reported projecting the source PRISM data to the North American Datum of 1983 Idaho Transverse Mercator projection, converting units to millimeters x 100, using bilinear resampling with cell size of 3,990 meters (m), and registering the PRISM raster data to the same spatial extents as available for surrogate Mapping EvapoTranspiration at high Resolution and Internalized Calibration (METRIC) raster coverages (xy registration points of 15 m). The Idaho Transverse Mercator projection (IDWR, 2022c) was used for this project.

[3]A uniform buffer of one-half the diagonal of a cell (approximately 2,828 m) was applied around the outer perimeter of the PRISM rasters before masking datasets to subbasin coverages in ArcGIS. Use of a buffer prevented null cell regions within the basin boundary. Rasters were converted to polygons for basin-scale and subbasin-scale analysis. For tributary drainage basin analysis, PRISM rasters at 4-km resolution were resampled to 30-m resolution using bilinear resampling. Selected testing done on raster resampling, using the nearest technique, resulted within less than 0.01-percent difference in the results.

[4]Bilinear interpolation uses the four adjacent cell centers for applying a weighted average to the new cell value and is recommended for continuous data, such as elevation, instead of discrete data (Esri, 2019). However, downscaling cell size using the nearest technique may better preserve the source data values. Comparison testing between these methods indicated less than 0.01-percent difference in estimated precipitation.

source 4-km PRISM grid to 30-m to avoid over-estimating or under-estimating precipitation at the margins of the study boundary owing to inclusion or exclusion of parts of 4-km cells. Resampling to 30-m cell size also was done to allow direct overlay with other raster datasets, such as METRIC, for calculating ET within buffered areas around irrigated lands. Most notably, abrupt changes in precipitation values between adjacent cells in the source dataset that tend to occur at the higher altitudes resulted in the greatest differences when resampled. Any bias introduced by resampling the grid size seems small. As a test case, Pass Creek canyon was evaluated for 2017 precipitation using 4-km and 30-m cell resolution, resulting in 1-percent difference. Other tributary basins, including Thousand Springs Creek and East Fork of the Big Lost River, were tested with less than 0.01-percent difference. This difference is regarded as negligible but discussed here for completeness.

References Cited

Allen, R.G., and Robison, C.W., 2017, Evapotranspiration and consumptive irrigation water requirements for Idaho—Supplement updating the time series through December 2016: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center, Research Technical Completion Report, [variously paged], accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

Bureau of Reclamation, 2016, AgriMet—Cooperative agricultural weather network: Bureau of Reclamation web page, accessed February 14, 2020, at https://www.usbr.gov/pn/agrimet/agrimetmap/agrimap.html.

Daly, C., and Bryant, K., 2013, The PRISM climate and weather system—An introduction: Corvallis, Oregon State University PRISM website, 5 p., accessed June 23, 2020, at https://prism.oregonstate.edu/documents/PRISM_history_jun2013.pdf.

Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J., and Pasteris, P.P., 2008, Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States: International Journal of Climatology, v.28, no. 15, p. 2031–2064., accessed September 8, 2022, at https://doi.org/10.1002/joc.1688.

Esri, 2018, ArcMap, version 10.6.1: Esri software release.

Esri, 2019, Cell size and resampling in analysis: Esri web page, accessed February 20, 2022, at https://desktop.arcgis.com/en/arcmap/10.6/extensions/spatial-analyst/performing-analysis/cell-size-and-resampling-in-analysis.htm.

Esri, 2020, ArcMap, version 10.8.1: Esri software release.

Idaho Department of Water Resources [IDWR], 2022c Idaho Transverse Mercator projection: Idaho Department of Water Resources web page, accessed June 12, 2022, at https://idwr.idaho.gov/gis/idtm/.

National Oceanic and Atmospheric Administration, 2020, Climate data online: National Oceanic and Atmospheric Administration database, accessed September 11, 2020, at https://www.ncdc.noaa.gov/cdo-web/.

Natural Resources Conservation Service, 2020, Snowpack Telemetry (SNOTEL) and snow course data and products: U.S. Department of Agriculture Natural Resources Conservation Service web page, accessed February 15, 2020, at https://www.wcc.nrcs.usda.gov/snow/.

PRISM Climate Group, 2020, PRISM climate data: Corvallis, Oregon State University PRISM web page, accessed November 1, 2020, at https://prism.oregonstate.edu/.

University of Idaho, 2018, Evapotranspiration and consumptive irrigation water requirements for Idaho: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center web page, accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

Western Regional Climatic Center, 2020, Recent climate in the West: Western Regional Climate Center web page, accessed February 14, 2020, at https://wrcc.dri.edu/.

Appendix 3. Areal Recharge

Abbreviations

ET	evapotranspiration
GIS	geographic information system
IDWR	Idaho Department of Water Resources
METRIC	Mapping EvapoTranspiration at high Resolution and Internalized Calibration
NDVI	Normalized Difference Vegetation Index
PRISM	Parameter-elevation Regressions on Independent Slopes Model
USGS	U.S. Geological Survey

Weather station datasets published in the ET_{Idaho} database[1] (Allen and Robison, 2017; University of Idaho, 2018) provide daily recorded precipitation, actual evapotranspiration (ET), and estimated surface runoff (in millimeters per day), used in the calculation of areal recharge. ET values in ET_{Idaho} are calculated for specific crop and land-cover types based on the American Society of Civil Engineers standardized Penman-Monteith reference ET relation (Allen and Robison, 2007). ET_{Idaho} does not include parameters for evergreen forests, which constitute less than 1 percent of total lands in the Big Lost River Basin at high altitudes (within the non-irrigated lands used for evaluating areal recharge). Zero recharge was assumed to be associated with this land cover because of lack of available estimates; however, the effects are assumed to be negligible in the groundwater budget. Land-cover assignment is described in appendix 1 ("Land Coverage"), and ET is discussed in appendix 10 ("Evapotranspiration").

Surface runoff has not been measured directly in the Big Lost River Basin and must be estimated. Stream expression is not particularly well developed along the western margins of the Lost River Range (U.S. Geological Survey, 2018a), perhaps suggesting that most of the excess precipitation recharges the water table instead of becoming runoff. Many drainages (for example, the western Lost River Range) are characterized by coarse unconsolidated sediments (sand and gravel) associated with alluvial fans (Pierce and Scott, 1982), promoting direct infiltration.

ET_{Idaho} (Allen and Robison, 2017; University of Idaho, 2018) calculates runoff from precipitation using the U.S. Department of Agriculture Natural Resources Conservation Service curve number method. This method requires daily precipitation and daily soil-water balance and accounts for local soil and vegetation properties as a function of infiltration potential, adjusted for prior moisture conditions (Allen and Robison, 2007). One drawback of the method is that for many crops grown in the Big Lost River Basin, the typical runoff is less than 0.5 inches, a runoff rate for which curve number methods are less accurate (Maidment 1993). Allen and Robison (2007) acknowledge the uncertainty associated with estimating runoff. Deep percolation below the root zone (in millimeters per day) is estimated in ET_{Idaho} and is regarded as recharge to the subsurface from the remainder of precipitation in excess of the soil infiltration capacity (Allen and Robison, 2007). Despite these limitations, ET_{Idaho} provides the most comprehensive estimates of runoff and percolation available for the basin.

Calculations were made at a daily time step to capture discrete precipitation and runoff events. Estimating recharge on an annual or seasonal basis potentially misses prior soil-moisture conditions, introducing uncertainty in the results. Therefore, daily periods were used, consistent with the rationale outlined by Bartolino (2009) for the Wood River Valley aquifer and Bartolino (2007) for the Spokane Valley-Rathdrum Prairie aquifer recharge investigations. Daily recharge was then summed by subbasin over either annual or winter periods, depending on the specific area (table 3.1). Areal recharge was calculated for the full calendar year on non-irrigated lands overlying the aquifer. Areal recharge was calculated during winter on irrigated lands using the same procedure outlined in Fisher and others (2016) for the Wood River Valley. No estimates of areal recharge were made for semi-irrigated lands, with assumed relatively minor recharge because of the overall small area. Recharge that occurs on semi-irrigated lands during the irrigation season is addressed in section, "Applied Irrigation." Because ET_{Idaho} published datasets were not available for 2017–19, areal recharge was estimated using linear regression for each subbasin by correlating total precipitation on all lands over the calendar year (Allen and Robison, 2017; University of Idaho, 2018) with the estimated areal recharge for 2000–16. The degree of correlation was about 0.58 for the upper subbasin, 0.62 for the middle subbasin, and 0.59 for the lower subbasin.

The information presented below is intended to provide more context but ultimately was not incorporated in the estimates of areal recharge used in the groundwater budget because of the limitations described herein for the Big Lost River Basin. Halford and Mayer (2000) recommend using multiple approaches for estimating recharge owing to uncertainties associated with particular methods. This approach is preferred for this investigation; however, a combination of factors limits the application of some conventional analytical methods, including water-table fluctuation analysis based on groundwater levels and streamflow hydrograph recession analysis. For example, the Idaho Department of Water Resources (IDWR) monitors and maintains two monitoring

[1] Searchable database providing evapotranspiration and irrigation data by land-cover type for weather stations across Idaho.

Table 3.1. Areal recharge by subbasin in the Big Lost River Basin, south-central Idaho, 2000–19.

[***Bold italicized*** values are estimated using linear regression analysis (2000–16) of precipitation on all lands for the full year with estimated areal recharge by subbasin. All values are in acre-feet per year. **Abbreviations and symbol:** NLCD, National Land Cover Database; IDWR, Idaho Department of Water Resources; —, not available]

Year	Upper subbasin[1]			Middle subbasin[1]			Lower subbasin[1]		
	Irrigated lands (winter)	Non-irrigated lands (full year)	Total	Irrigated lands (winter)	Non-irrigated lands (full year)	Total	Irrigated lands (winter)	Non-irrigated lands (full year)	Total
2000	1,401	37,380	38,781	4,324	25,628	29,952	7,771	28,178	35,949
2001	2,034	21,653	23,687	4,565	21,111	25,676	7,580	19,307	26,887
2002	2,074	23,114	25,189	5,597	27,988	33,585	4,509	19,242	23,751
2003	628	18,050	18,678	3,601	16,735	20,336	4,686	18,723	23,408
2004	1,886	45,198	47,084	4,602	33,672	38,274	4,955	26,851	31,806
2005	1,497	47,301	48,797	6,137	30,746	36,883	9,928	33,536	43,464
2006	2,047	34,099	36,146	3,972	28,666	32,637	6,115	23,229	29,345
2007	1,805	26,669	28,473	2,738	16,509	19,247	1,187	20,089	21,276
2008	1,507	14,866	16,372	7,432	24,044	31,475	8,070	21,013	29,083
2009	2,510	55,267	57,777	3,776	30,208	33,985	4,710	17,498	22,209
2010	2,013	40,653	42,667	6,812	28,979	35,791	10,061	38,395	48,456
2011	569	20,857	21,426	4,813	24,743	29,556	3,326	25,675	29,002
2012	4,832	36,006	40,838	8,918	29,552	38,470	7,447	20,856	28,302
2013	521	15,648	16,169	1,827	11,720	13,548	2,624	8,610	11,234
2014	2,866	41,377	44,243	5,629	33,461	39,090	5,685	27,186	32,871
2015	2,519	40,449	42,968	6,392	30,805	37,197	6,074	27,048	33,122
2016	2,254	52,198	54,452	4,302	30,617	34,919	8,548	32,625	41,172
2017	—	—	***62,461***	—	—	***43,547***	—	—	***40,789***
2018	—	—	***30,457***	—	—	***29,336***	—	—	***29,842***
2019	—	—	***40,315***	—	—	***36,405***	—	—	***35,733***

[1]Supporting datasets used in the areal recharge calculations include the following sources, described in section "Areal Recharge" and appendix 3 ("Areal Recharge"). Precipitation, evapotranspiration, and runoff datasets were obtained from ET_{Idaho} (Allen and Robison, 2017; University of Idaho, 2018). Geographic information system coverages for "irrigated-lands" and "non-irrigated lands" were derived from published irrigated-lands coverages (2000–11) accessed from IDWR (2020a) and draft irrigated land coverages (2012–17; M. Wilkins, IDWR, unpub. data, April 1, 2020—data available upon request from IDWR Idaho Water Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800). IDWR has since published irrigated-lands coverages as the "Eastern Snake Plain" for 2012–15, available from the IDWR at https://data-idwr.opendata.arcgis.com/pages/gis-data#IrrigatedLands. NLCD coverages were accessed from Multi-Resolution Land Characteristics Consortium (2019). The derived aquifer extent used in the calculations was based on surficial geological mapping (Lewis and others, 2012).

wells with long-term data above Mackay Reservoir. However, additional wells are necessary to use the water-table fluctuation approach for estimating recharge. Streamflow recession analysis may not produce reliable results in systems with snowmelt-dominated runoff (Rutledge, 1998). Determination of an appropriate runoff volume is further complicated, especially below Mackay Dam, by sustained periods without flows in the Big Lost River (at Moore and Arco), numerous surface-water diversions throughout the basin, and operation of Mackay Reservoir.

Recharge and discharge areas were visualized in a geographic information system through raster analyses by subtracting monthly Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation datasets (PRISM Climate Group, 2020) from available monthly Mapping EvapoTranspiration at high Resolution and Internalized Calibration (METRIC; IDWR, 2021b) or Normalized Difference Vegetation Index (NDVI) ET datasets (U.S. Geological Survey, 2017; obtained for convenience from IDWR staff [B. Kramber, IDWR, written commun., June 19, 2019]), compiled during the irrigation season (April–October). The results for 2013 conditions are shown in figure 3.1. METRIC data are available only during the irrigation season, and METRIC is not calibrated for non-irrigated lands. PRISM also is only available for monthly rather than daily periods. Because of these limitations, these datasets were used for visualization and qualitative assessment of potential areas for preferential recharge but not for estimating areal recharge rates or volumes.

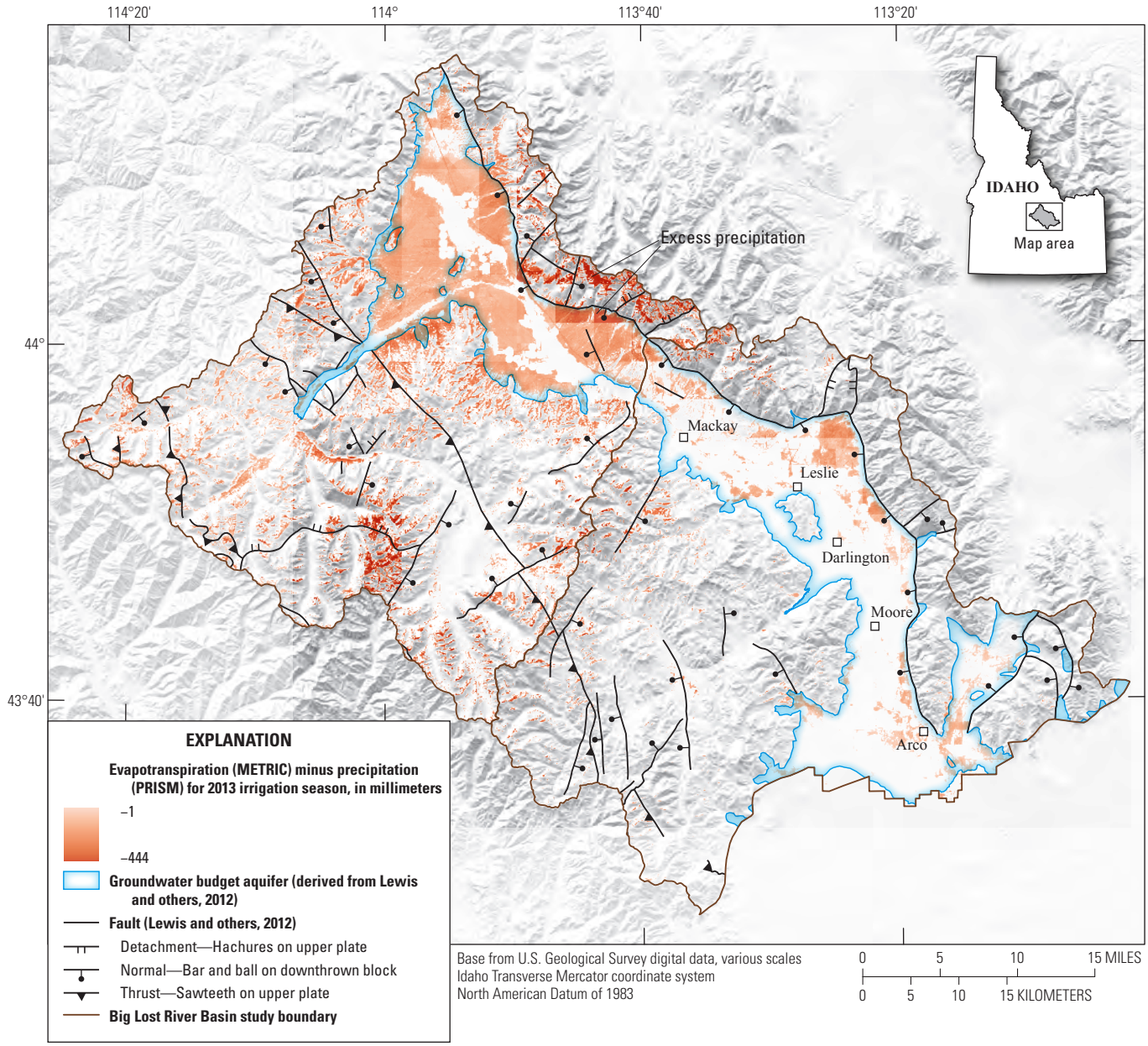


Figure 3.1. Spatial distribution of areal recharge in the Big Lost River Basin, south-central Idaho, April–October 2013. METRIC, Mapping EvapoTranspiration at high Resolution and Internalized Calibration (IDWR, 2021b); PRISM, Parameter-elevation Regressions on Independent Slopes Model (PRISM Climate Group, 2020). IDWR, Idaho Department of Water Resources.

The METRIC and PRISM dataset subtraction results in positive and negative values. Positive values (METRIC minus PRISM) indicate areas with excess ET (as described in section, "Applied Irrigation") and have been removed from figure 3.1. However, negative values in figure 3.1 suggest areas with excess precipitation, with the potential for recharging the aquifer. Recharge primarily occurs within non-irrigated lands in the following three zones: (1) high altitudes, mostly in the upper subbasin, that receive large volumes of precipitation as snow; (2) the alluvial fan interface between the mountains and the basin floor associated with higher permeability compared to surrounding bedrock; and (3) along certain stream and river reaches during especially wet years. The spatial distribution of cells with precipitation in excess of ET shows potential preferential recharge zones that spatially coincide with high altitudes, alluvial fan sediments, and certain regional faults (Lewis and others, 2012), especially along segments of the Lost River Fault at the base of the Lost River Range associated with the alluvial fan transition. These factors support a correlation between precipitation and altitude and suggest a possible strong influence of local geological conditions on aquifer recharge.

References Cited

Allen, R.G., and Robison, C.W., 2007, Evapotranspiration and consumptive irrigation water requirements for Idaho: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center, 260 p., accessed July 17, 2018, at http://www.kimberly.uidaho.edu/ETIdaho/.

Allen, R.G., and Robison, C.W., 2017, Evapotranspiration and consumptive irrigation water requirements for Idaho—Supplement updating the time series through December 2016: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center, Research Technical Completion Report, [variously paged], accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

Bartolino, J.R., 2007, Assessment of areal recharge to the Spokane Valley—Rathdrum Prairie aquifer, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho: U.S. Geological Survey Scientific Investigations Report 2007–5038, 38 p., accessed November 28, 2018, at https://doi.org/10.3133/sir20075038.

Bartolino, J.R., 2009, Ground-water budgets for the Wood River Valley aquifer system, south-central Idaho, 1995–2004: U.S. Geological Survey Scientific Investigations Report 2009–5016, 36 p., accessed July 17, 2018, at https://doi.org/10.3133/sir20095016.

Fisher, J.C., Bartolino, J.R., Wylie, A.H., Sukow, J., and McVay, M., 2016, Groundwater-flow model of the Wood River Valley aquifer system, south-central Idaho—Appendix F—Natural groundwater recharge and discharge in the Wood River Valley aquifer system, south-central Idaho: U.S. Geological Survey Scientific Investigations Report 2016–5080, 71 p., accessed July 17, 2018, at https://doi.org/10.3133/sir20165080.

Halford, K.J., and Mayer, G.C., 2000, Problems associated with estimating ground water discharge and recharge from stream-discharge records: Ground Water, v. 38, no. 3, p. 331–342, accessed December 11, 2018, at https://doi.org/10.1111/j.1745-6584.2000.tb00218.x.

Idaho Department of Water Resources [IDWR], 2020a Map and GIS data hub—Irrigated lands: Idaho Department of Water Resources web page, accessed April 2, 2020, at https://data-idwr.opendata.arcgis.com/pages/gis-data#irrigatedLands.

Idaho Department of Water Resources [IDWR], 2021b, Map and GIS data hub—Evapotranspiration: Idaho Department of Water Resources web page, accessed April 8, 2021, at https://data-idwr.opendata.arcgis.com/pages/gis-data.

Lewis, R.S., Link, P.K., Stanford, L.R., and Long, S.P., 2012, Geologic map of Idaho: Idaho Geological Survey Map M-9, scale 1:750,000, accessed August 3, 2018, at https://www.idahogeology.org/product/m-9.

Maidment, D.R., 1993, Handbook of hydrology: New York, McGraw-Hill, Inc., 1,424 p.

Multi-Resolution Land Characteristics Consortium, 2019, National land cover database: U.S. Geological Survey database, accessed November 8, 2019, at https://www.mrlc.gov/data.

Pierce, K.L., and Scott, W.E., 1982, Pleistocene episodes of alluvial-gravel deposition, southeastern Idaho, *in* Bonnichsen, B., and Breckenridge, R.M., eds, Cenozoic geology of Idaho: Idaho Bureau of Mines and Geology, Bulletin 26, p. 685–702, accessed August 16, 2018, at https://www.researchgate.net/publication/265751313_Pleistocene_Episodes_of_Alluvial-Gravel_Deposition_Southeastern_Idaho.

PRISM Climate Group, 2020, PRISM climate data: Corvallis, Oregon State University PRISM web page, accessed November 1, 2020, at https://prism.oregonstate.edu/.

Rutledge, A.T., 1998, Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records—Update: U.S. Geological Survey Water-Resources Investigations Report 98–4148, 43 p., accessed May 3, 2020, at https://doi.org/10.3133/wri984148.

University of Idaho, 2018, Evapotranspiration and consumptive irrigation water requirements for Idaho: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center web page, accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

U.S. Geological Survey, 2017, Landsat Normalized Difference Vegetation Index web page, accessed June 9, 2022, at https://www.usgs.gov/landsat-missions/landsat-normalized-difference-vegetation-index.

U.S. Geological Survey, 2018a, National hydrography dataset—Hydrologic unit code (HUC Level 8) 17040218: U.S. Geological Survey web page, accessed November 7, 2018, at https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

Appendix 4. Tributary Canyon Underflow Supporting Detail

Abbreviations

GIS	geographic information system
IDWR	Idaho Department of Water Resources
NAIP	National Agriculture Imagery Program
PRISM	Parameter-elevation Regressions on Independent Slopes Model
USGS	U.S. Geological Survey

This section provides additional context for the application of Darcy's law and the underflow-correction method used in estimating tributary canyon underflow, described in section, "Tributary Canyon Underflow." The equations presented here are the same as those described in Fisher and others (2016) for the Big Wood River groundwater-flow model, and deviations from the methodology are highlighted.

Darcy's law is based on the following relation (Healy, 2010):

$$Q_d = K A_{sat} \frac{dh}{dz} \quad (4.1)$$

where

Q_d is the mean underflow rate,
K is hydraulic conductivity,
A_{sat} is the saturated cross-sectional area of the canyon, and
dh is the change in the hydraulic head over "dz" depth (the hydraulic gradient).

Little to no information on hydraulic conductivity and aquifer thickness is available for tributary canyons in the Big Lost River Basin, creating considerable uncertainty in underflow estimates. Furthermore, the network of wells with groundwater-level measurements and hydraulic gradient estimates above Mackay Dam is sparse, creating additional uncertainty about the hydraulic gradient.

Few wells have been completed within or near tributary canyons. These canyons tend to be remote, rugged, and generally pose difficulty for accessing water resources. Many tributary canyons are characterized by bedrock at or near the ground surface or the presence of thin unconsolidated sediments. Nearly 210 well logs obtained from the Idaho Department of Water Resources (IDWR) online well-construction database (IDWR, 2020b) were reviewed to evaluate lithology and aquifer extent[1]. However, wells do not fully penetrate the saturated aquifer thickness, and many are either completed in bedrock or across the unconsolidated deposit/bedrock interface. Individual terms used in the tributary canyon underflow estimate are summarized in table 4.1.

Hydraulic Conductivity

Hydraulic conductivity can and does vary over several orders in magnitude as a function of the subsurface medium and fluid properties (Freeze and Cherry, 1979). Saturated aquifer thickness also varies spatially and temporally. No wells were identified (fig. 8) that fully penetrate the full thickness of units, and the position of the water table typically is not well known in tributary drainages because of the lack of wells and groundwater-level data. Direct aquifer testing and well information are limited in the Big Lost River Basin. Application of estimated properties measured at one location may not be representative of another location. Variability is expected within tributary drainages that may reflect shallow alluvium underlain by bedrock that likely is not representative of aquifer properties in the valley.

The U.S. Geological Survey (USGS; Bassick and Jones, 1992) tested wells near the White Knob Mountain interface with the alluvium and colluvium units constituting the aquifer (referred to as the "Well Orchard," about 2 mi south of the town of Moore). One well (04N 26E 5BAD2) was pumped continuously at an average rate of 2,300 gallons per minute for 25 hours with monitoring of water levels in the test well and in eight nearby wells. The reported transmissivity ranged from 61,000 square feet per day (ft²/d) to 330,000 ft²/d, and the reported storage coefficient ranged between 0.0006 and 0.02. These values are consistent with unconsolidated alluvial sediments of clay, silt, sand, and gravel in a semi-confined to unconfined aquifer system, although they seem closer to semi-confined or confined storativity of about 0.005–0.00005 (Freeze and Cherry, 1979). Bassick and Jones (1992) reported that transmissivity values ranging from 130,000 to 200,000 ft²/d were "most probable." Estimates of hydraulic conductivity and saturated aquifer thickness were not reported in the study. However, the aquifer in the test area was described as thinning, and a negative hydraulic barrier was discovered during the test that was suggestive of a bedrock boundary condition.

[1] Wells are designated as "primary" or "secondary" in figure 8 based on the relative well location to the tributary canyon.

Table 4.1. Estimated terms for tributary canyon underflow, Big Lost River Basin, south-central Idaho, 2000–19. See figure 8 for tributary canyon locations.

[**Abbreviations and symbol:** Trib, tributary; Precip, precipitation; acre-ft/yr, acre-feet per year; m, meters; m^2, square meters; m^3/d, cubic meters per day; mm/yr, millimeters per year; (-), dimensionless; IDWR, Idaho Department of Water Resources; PRISM, Parameter-elevation Regressions on Independent Slopes Model.]

Tributary name	Tributary number	Trib area[1] A_b (m^2)	Basin size	Width[2] w (m)	Saturated thickness[3] d (m)	Saturated area[4] A_{sat} (m^2)	Hydraulic gradient[5] $\Delta h/\Delta l$ (-)	Darcy flow[6] Q_d (m^3/d)	Precip rate[7] P (mm/yr)	Precip flow[8] Q_p (m^3/d)	Flow ratio[9] r (-)	Final underflow[10] Q (m^3/d)	Final underflow[10] Q (acre-ft/yr)
Alder Creek	61	9.6×10^7	Large	395	12	3,785	0.018	20,267	525	134,028	0.159	20,267	5,997
Anderson Canyon	55	6.0×10^6	Small	17	47	638	0.076	14,752	483	7,924	2.009	1,181	349
Antelope Creek (upper drainage)	62	2.4×10^8	Large	186	17	2,453	0.035	25,811	599	362,883	0.074	25,811	7,638
Bady Creek	23	1.8×10^7	Medium	30	17	401	0.022	2,679	435	21,220	0.132	2,679	793
Big Burnett Canyon	52	4.7×10^6	Small	56	34	1,466	0.073	32,664	492	6,382	5.197	951	281
Black Daisy Canyon	31	8.3×10^6	Small	22	13	224	0.006	434	419	9,574	0.047	1,427	422
Boone Creek (White Knob Range)	27	7.1×10^6	Small	39	10	306	0.055	5,110	418	8,089	0.685	1,205	357
Boone Creek (East Fork)	19	3.3×10^7	Medium	112	7	618	0.015	2,753	495	44,074	0.065	2,753	815
Burnt Creek	33	1.3×10^7	Medium	183	5	767	0.033	7,830	466	16,181	0.509	7,830	2,317
Butcher Creek	20	2.8×10^6	Small	41	7	227	0.064	4,387	504	3,838	1.193	572	169
Castle Creek	21	8.9×10^6	Small	64	7	355	0.033	3,541	509	12,339	0.297	1,839	544
Cedar Creek	38	8.9×10^6	Small	34	34	895	0.141	38,487	801	19,586	2.009	2,919	864
Champagne Creek	78	2.6×10^7	Medium	136	10	1,066	0.005	1,640	386	27,211	0.064	1,640	485
Cherry Creek	64	1.4×10^8	Large	948	4	2,949	0.007	6,562	479	177,363	0.039	6,562	1,942
Clark Canyon	49	8.6×10^6	Small	28	15	335	0.132	13,468	566	13,490	1.047	2,010	595
Cliff Creek	60	2.1×10^7	Medium	54	10	427	0.052	6,748	495	28,416	0.242	6,748	1,997
Deep Creek	2	7.8×10^6	Small	10	30	227	0.199	13,761	434	9,290	1.601	1,384	410
Deer Creek	11	8.8×10^6	Small	47	2	57	0.038	654	613	14,782	0.046	2,203	652
Dry Fork Creek	63	1.0×10^8	Large	230	9	1,541	0.022	10,338	465	131,772	0.082	10,338	3,059
East Fork Big Lost River (upper drainage)	17	1.7×10^8	Large	75	7	412	0.003	415	605	280,951	0.002	415	123
Elbow Canyon and Jepson Canyon	48	2.8×10^7	Medium	61	6	292	0.043	3,835	575	45,548	0.087	3,835	1,135
Elkhorn Creek	39	7.1×10^6	Small	22	23	404	0.125	15,326	717	13,874	1.142	2,068	612
Fox Creek	14	2.2×10^7	Medium	107	7	588	0.022	3,955	592	35,224	0.117	3,955	1,170
Garden Creek	26	9.1×10^6	Small	23	21	387	0.077	9,059	402	10,057	0.979	1,499	443
Grant Creek	24	1.7×10^7	Medium	80	10	647	0.033	6,571	445	21,313	0.322	6,571	1,944
Hamilton Creek	29	8.1×10^6	Small	68	27	1,472	0.076	34,298	394	8,738	4.083	1,302	385
Jaggles Canyon	51	8.8×10^6	Small	9	15	105	0.052	1,657	506	12,300	0.142	1,833	542
Jones Creek	43	8.6×10^6	Small	56	10	437	0.081	10,728	729	19,896	0.557	2,965	877
Kane Creek	4	4.8×10^7	Medium	152	15	1,822	0.011	6,246	691	90,147	0.072	6,246	1,848

Table 4.1. Estimated terms for tributary canyon underflow, Big Lost River Basin, south-central Idaho, 2000–19. See figure 8 for tributary canyon locations.—Continued

[**Abbreviations and symbol:** Trib, tributary; Precip, precipitation; acre-ft/yr, acre-feet per year; m, meters; m^2, square meters; m^3/d, cubic meters per day; mm/yr, millimeters per year; (-), dimensionless; IDWR, Idaho Department of Water Resources; PRISM, Parameter-elevation Regressions on Independent Slopes Model.]

Tributary name	Tributary number	Trib area[1] A_b (m^2)	Basin size	Width[2] w (m)	Saturated thickness[3] Δl (m)	Saturated area[4] A_{sat} (m^2)	Hydraulic gradient[5] $\Delta h/\Delta L$ (-)	Darcy flow[6] Q_d (m^3/d)	Precip rate[7] P (mm/yr)	Precip flow[8] Q_p (m^3/d)	Flow ratio[9] r (-)	Final underflow[10] Q (m^3/d)	Final underflow[10] Q (acre-ft/yr)
King Canyon	57	6.3×10^6	Small	36	46	1,292	0.067	26,548	431	7,462	3.724	1,112	329
Lehman Creek	28	2.3×10^7	Medium	37	2	44	0.063	836	434	27,167	0.535	836	247
Limekiln Canyon	56	2.6×10^6	Small	11	30	268	0.040	3,251	461	3,035	1.246	452	134
Little Boone Creek	13	5.2×10^6	Small	62	7	339	0.012	1,213	500	7,188	0.179	1,071	317
Little Burnett Canyon	53	4.4×10^6	Small	12	30	282	0.047	4,059	449	5,346	0.815	797	236
Little Lake Creek	18	9.9×10^6	Small	22	2	26	0.102	799	490	13,291	0.063	1,981	586
Lone Cedar Creek	42	9.6×10^6	Small	184	10	1,444	0.075	32,860	756	20,753	1.632	3,093	915
Lower Cedar Creek	46	2.2×10^7	Medium	129	3	277	0.059	5,005	806	48,573	0.108	5,005	1,481
Maddock Canyon	50	5.7×10^6	Small	18	30	432	0.017	2,256	502	7,917	0.295	1,180	349
Marsh Canyon	66	2.3×10^7	Medium	151	5	591	0.046	8,340	408	25,922	0.338	8,340	2,468
Navarre Creek	30	3.5×10^7	Medium	41	29	927	0.020	5,771	527	50,085	0.116	5,771	1,708
Newman Canyon	77	2.6×10^7	Medium	28	10	220	0.043	2,871	349	24,746	0.122	2,871	849
North Fork Big Lost River (upper drainage)	1	1.6×10^8	Large	203	16	2,523	0.004	3,358	652	279,643	0.012	3,358	994
Pass Creek	47	6.3×10^7	Large	44	40	1,370	0.022	9,156	599	100,170	0.632	9,156	2,709
Pete Creek	44	5.6×10^6	Small	30	21	501	0.089	13,583	718	14,150	0.990	2,109	624
Pinto Creek	34	2.2×10^7	Medium	105	5	440	0.024	3,280	474	29,044	0.118	3,280	970
Pole Creek	10	3.6×10^6	Small	65	12	590	0.059	10,660	572	5,702	1.946	850	251
Ramshorn Canyon	54	2.2×10^7	Medium	89	15	1,063	0.023	7,547	507	30,846	0.600	7,547	2,233
Rider Creek	12	7.4×10^6	Small	54	2	64	0.082	1,613	625	12,602	0.134	1,878	556
Road Creek	15	4.6×106	Small	36	7	197	0.026	1,549	437	5,515	0.298	822	243
Rock Creek (Lost River Range)	37	1.6×10^7	Medium	49	20	767	0.072	16,830	764	33,565	0.573	16,830	4,980
Rock Creek (White Knob Range)	25	1.8×10^7	Medium	17	9	126	0.027	1,020	400	19,327	0.058	1,020	302
Rocky Canyon	75	1.0×10^7	Small	33	39	1,021	0.068	21,305	381	10,449	2.111	1,557	461
Sage Creek	35	4.9×10^7	Large	149	9	1,036	0.016	4,983	482	64,193	0.081	4,983	1,474
Sawmill Gulch	41	5.8×10^6	Small	17	23	307	0.118	11,030	722	13,042	0.916	1,944	575
Stag Creek	22	4.3×10^6	Small	76	16	958	0.073	21,206	474	5,626	3.950	838	248
Star Hope Creek	16	2.0×10^8	Large	141	7	774	0.011	2,516	33,857	401,631	0.007	2,516	744
Summit Creek	3	6.6×10^7	Large	175	30	4,114	0.013	16,365	10,378	123,115	0.139	16,365	4,842
Trail Creek	65	2.0×10^7	Medium	33	15	397	0.051	6,118	1,623	19,253	1.454	6,118	1,810

Table 4.1. Estimated terms for tributary canyon underflow, Big Lost River Basin, south-central Idaho, 2000–19. See figure 8 for tributary canyon locations.—Continued

[**Abbreviations and symbol:** Trib, tributary; Precip, precipitation; acre-ft/yr, acre-feet per year; m, meters; m^2, square meters; m^3/d, cubic meters per day; mm/yr, millimeters per year; (-), dimensionless; IDWR, Idaho Department of Water Resources; PRISM, Parameter-elevation Regressions on Independent Slopes Model.]

Tributary name	Tributary number	Trib area[1] A_b (m^2)	Basin size	Width[2] w (m)	Saturated thickness[3] Δd (m)	Saturated area[4] A_{sat} (m^2)	Hydraulic gradient[5] $\Delta h/\Delta L$ (-)	Darcy flow[6] Q_d (m^3/d)	Precip rate[7] P (mm/yr)	Precip flow[8] Q_p (m^3/d)	Flow ratio[9] r (-)	Final underflow[10] Q (m^3/d)	Final underflow[10] Q (acre-ft/yr)
Twin Bridges Creek	32	5.2×10^7	Large	30	18	433	0.030	4,023	513	73,631	0.056	4,023	1,191
Unnamed Creek 1 (Antelope)	67	1.6×10^7	Medium	245	6	1,173	0.019	6,704	430	18,905	0.372	6,704	1,984
Unnamed Creek 2 (Antelope)	68	6.6×10^6	Small	100	6	479	0.020	2,982	387	7,023	0.447	1,047	310
Unnamed Creek 3 (Antelope)	69	5.5×10^6	Small	37	6	175	0.007	371	368	5,571	0.072	830	246
Unnamed Creek 4 (Antelope)	70	3.3×10^6	Small	42	34	1,125	0.052	17,793	371	3,403	5.509	507	150
Unnamed Creek 5 (Antelope)	71	4.4×10^6	Small	78	29	1,775	0.028	14,958	360	4,369	3.602	651	193
Unnamed Creek 6 (Antelope)	72	4.2×10^6	Small	81	2	97	0.064	1,879	390	4,469	0.444	666	197
Unnamed Creek 7 (Antelope)	73	2.4×10^6	Small	11	2	14	0.129	536	367	2,378	0.229	354	105
Unnamed Creek 8 (Antelope)	74	3.2×10^6	Small	53	2	64	0.061	1,193	306	2,719	0.461	405	120
Unnamed Creek (Appendicitis Hill)	76	3.4×10^6	Small	17	4	59	0.049	893	297	2,795	0.373	417	123
Unnamed Creek 1 (Arco Hills)	58	4.9×10^6	Small	43	36	1,214	0.060	22,323	331	4,441	8.839	662	196
Unnamed Creek 2 (Arco Hills)	59	2.9×10^6	Small	24	15	276	0.083	6,933	332	2,624	1.652	391	116
Unnamed Creek 1 (East Fork)	8	5.9×10^6	Small	52	12	469	0.080	11,469	550	8,944	1.370	1,333	394
Unnamed Creek 2 (East Fork)	9	7.5×10^6	Small	34	12	313	0.136	13,023	474	9,805	1.355	1,461	432
Unnamed Creek (North Fork)	5	3.8×10^6	Small	131	30	3,086	0.021	19,281	499	5,221	3.897	778	230
Upper Cedar Creek	45	2.5×10^7	Medium	82	14	882	0.026	7,053	784	58,432	0.126	7,053	2,087
Vance Creek	40	6.6×10^6	Small	13	23	228	0.116	8,099	658	13,774	0.666	2,053	607
Wildhorse Creek	6	1.5×10^8	Large	180	73	10,313	0.005	16,768	776	313,757	0.345	16,768	4,962
Willow Creek (East Fork)	7	4.0×10^6	Small	54	12	494	0.068	10,173	479	5,258	2.001	784	232
Willow Creek (Lost River Range)	36	3.2×10^7	Medium	78	12	748	0.035	8,008	533	46,016	0.768	8,008	2,370

[1]Tributary area was based on tributary canyon delineation using StreamStats (U.S. Geological Survey, 2016).

[2]Canyon width determination aided by review of National Agricultural Imagery Program aerial photography (Natural Resources Conservation Service, 2022), U.S. Geological Survey digital elevation model (U.S. Geological Survey, 2018b) and geological mapping of alluvium (Skipp and others, 2009; Lewis and others, 2012).

[3]Saturated thickness was informed by well logs (IDWR, 2020b) and depth to groundwater datasets (IDWR, 2021a).

[4]Saturated area was a calculated value. See appendix 4 ("Tributary Canyon Underflow Supporting Detail"), section "Saturated Cross-Sectional Area."

[5]Hydraulic gradient aided by review of U.S. Geological Survey digital elevation model (U.S. Geological Survey, 2018b).

[6]Darcy flow was a calculated value. See appendix 4, equation 4.1. Hydraulic conductivity used in the calculation was determined from Bassick and Jones, 1992.

[7]Precipitation rate was determined from PRISM precipitation datasets (PRISM Climate Group, 2020).

[8]Precipitation flow was calculated from the product of the precipitation rate and the tributary area.

[9]Flow ratio was a calculated value. See appendix 4.

[10]Final underflow was a calculated value as the Darcy flow adjusted for underflow corrections as described in appendix 4.

To apply the results of the "Well Orchard" well testing to estimated parameters for tributary basin underflow calculations, assumptions were made regarding the likely depth to bedrock, saturated aquifer thickness, and hydraulic conductivity. Available information on wells included in the test was assessed from the USGS National Water Information System database (U.S. Geological Survey, 2020). However, most of the wells used during the test do not have associated well-completion or well-depth information. Available well logs near the "Well Orchard" well test were accessed from the IDWR well-construction database (IDWR, 2020b) to augment aquifer details[2].

Hydraulic conductivity was calculated (in feet per day) by dividing the mean transmissivity (in square feet per day) derived from the "Well Orchard" testing by the assumed mean saturated aquifer thickness (in feet). Saturated aquifer thickness was estimated from the difference between the reported depth to water and the total well depth. However, the thickness likely is greater as bedrock was not encountered in the wells, with the exception of well 04N 26E 5BAA1 at a depth of 245 feet (ft). Available depth-to-water measurements also were not consistent over time (spanning the 1960s to the 1990s) but generally were from 70 to 120 ft. The mean hydraulic conductivity estimated from the test was 1,000 feet per day (ft/d), assuming an average saturated aquifer thickness of 160 ft, and mean transmissivity was estimated at 165,500 ft^2/d. This estimated hydraulic conductivity was used as the low-end value for estimated tributary canyon underflow because it represents a basin-specific data point. Estimated tributary underflow calculated with this hydraulic conductivity value ultimately was used in the groundwater budget.

Hydraulic conductivity reported in the literature for various unconsolidated deposit grain sizes expected in tributary canyons was used for comparison purposes as the high-end estimated value. Typical hydraulic conductivity values of 1×10^{-6} to 1×10^{-2} meters per second (0.28–2,834 ft/d) reported in Freeze and Cherry (1979) for sand and gravel were used to bracket underflow analysis. The mean value of 1,400 ft/d selected for the comparison was not used in the final groundwater budget but is consistent with the aquifer test-derived value selected for the groundwater budget.

Saturated Cross-Sectional Area

The saturated cross-sectional area near the mouth of all canyons is assumed to be a "U-shape" in the form of a half-ellipse using this equation (Fisher and others, 2016):

$$A_{sat} = \frac{\pi w \Delta d}{4} \quad (4.2)$$

where

π is the ratio of a circle's circumference to its diameter, "pi" (approximately 3.14159);
w is the tributary canyon width in feet; and
Δd is the saturated thickness, in feet.

Canyon width was measured in the geographic information system (GIS) along a transect line (fig. 8; table 4.1), aided by visual inspection of available National Agriculture Imagery Program (NAIP; Natural Resources Conservation Service, 2022), a grayscale (hillshade) representation in GIS of the USGS National Elevation Dataset 1/3 arc-second digital elevation model (U.S. Geological Survey, 2018b), and geologic mapping of alluvium (Skipp and others, 2009; Lewis and others, 2012). Actual widths may differ from those estimated, but any errors in the saturated cross-sectional areas of small tributary canyons are expected to be small. However, representation of canyon width for the large tributary canyons was subjective, with high perceived uncertainty and large potential errors.

Saturated thickness is defined from the water table to the top of bedrock. This parameter is uncertain as the depth to water and top of bedrock typically are not known in the tributary canyons. The depth to water was assumed for each canyon (table 4.1) based on evaluation of the depth to water recorded in nearby well logs (IDWR, 2020b) and inferences from potentiometric surface maps constructed for 2014 and 2017 using March and April depth-to-water measurements in the IDWR monitoring well network (IDWR, 2021a). Both of these data sources pose uncertainty in estimating the depth to water. Well-log records reflect conditions at the time of well completion and may not be representative of more recent groundwater-level trends or at locations other than in the well. Extrapolation of the potentiometric surface map of the aquifer to tributary canyons may not reflect true conditions. Saturated aquifer thickness was highly uncertain but was estimated using best available data.

Hydraulic Gradient

Hydraulic gradient must be estimated because of the lack of adequate well coverage and monitoring of groundwater levels near tributary canyons. Following the approach in Fisher and others (2016), axial lines along the profile of each canyon were drawn perpendicular to the transect in GIS, as discussed in section, "Saturated Cross-Sectional Area" (fig. 8). Land-surface altitudes from the digital elevation model were used to approximate the change in hydraulic head over the axial line length, assuming that the slope of the water table follows topography. This assumption is reasonable for canyons with perennial streams (Fisher and others, 2016). Some canyons host perennial or ephemeral streams; however, rapid infiltration on alluvial fans at the Lost River Range front, without

[2]Wells were located in T5N, R26E, Sec 32 (Well Identifiers [IDs] 436483 and 320305) and in T4N, R26E, Sec 5 (Well IDs 361983, 367664, and 348315).

clear evidence of stream expression, may invalidate the assumption that the altitude of the canyon floor coincides with the water table.

Underflow Correction

During preliminary estimates of underflow using Darcy's equation, disproportionately higher estimates of underflow were noted for smaller drainages compared to larger ones. Fisher and others (2016) described a similar result when estimating underflow for the Big Wood River Valley groundwater-flow model, attributed to ephemeral streamflow conditions associated with smaller drainages. The same methodology used for correcting estimated underflow for the Big Wood River model (Fisher and others, 2016) was adopted for the Big Lost River Basin analyses for small drainages (4 square miles [mi^2] or less). This size correction was not applied to estimated underflow for canyons larger than 4 mi^2. A separate correction was applied to all of the tributary canyons for annually-adjusted precipitation volumes. The largest tributaries comprising several, small-order streams that feed into drainages (including the North and East Forks of the Big Lost River and Antelope Creek) were further subdivided into small tributaries. Subdivision was necessary to better represent total canyon widths and to avoid underestimating tributary underflow for the large tributaries. A size correction was not applied to the largest tributaries.

The underflow correction for small tributary canyons, described in Fisher and others (2016), assumes that all precipitation infiltrates and recharges the aquifer. This assumption seems reasonable because the Wood River and Big Lost River are intermontane basins. The western flank of the Lost River Range is without appreciable stream expression; however, local conditions promoting surface runoff instead of infiltration may invalidate this assumption.

Average annual precipitation for each tributary canyon was calculated using precipitation rates derived from Parameter-elevation Regressions on Independent Slopes Model (also known as PRISM; PRISM Climate Group, 2020). Corresponding precipitation volumes (Q_p) were calculated by multiplying the mean annual precipitation rate by the drainage area. For each drainage area, a ratio of the Darcy underflow estimate (Q_d) to the mean precipitation (Q_p) volume was calculated as Q_d/Q_p. Separate calculations for Darcy underflow were made using lower (1,000 ft/d) and higher (1,400 ft/d) estimates of hydraulic conductivity to bracket the range for potential underflow derived from one well test done in the "Well Orchard" area in the middle subbasin (Bassick and Jones, 1992) and from literature-reported mean values for sand and gravel (Freeze and Cherry, 1979). A mean underflow ratio was obtained for the 34 largest basins (table 4.1). A mean ratio of 0.149 for the largest basins (based on the lowest hydraulic conductivity) was then multiplied by the precipitation volume to adjust the estimated basin underflow for the smallest basins. A mean ratio of 0.215 (based on the highest conductivity) was used for comparison but was not advanced in the groundwater budget.

References Cited

Bassick, M.D., and Jones, M.L., 1992, Aquifer-test results, direction of ground-water flow, and 1984–90 annual ground-water pumpage for irrigation, lower Big Lost River Valley, Idaho: U.S. Geological Survey Water-Resources Investigations Report 92-4006, pl. 1, accessed August 29, 2018, at https://doi.org/10.3133/wri924006.

Fisher, J.C., Bartolino, J.R., Wylie, A.H., Sukow, J., and McVay, M., 2016, Groundwater-flow model of the Wood River Valley aquifer system, south-central Idaho—Appendix F—Natural groundwater recharge and discharge in the Wood River Valley aquifer system, south-central Idaho: U.S. Geological Survey Scientific Investigations Report 2016–5080, 71 p., accessed July 17, 2018, at https://doi.org/10.3133/sir20165080.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Healy, R.W., 2010, Estimating groundwater recharge: Cambridge, United Kingdom, Cambridge University Press, 245 p.

Idaho Department of Water Resources [IDWR], 2020b, Find a well map—Well logs: Idaho Department of Water Resources web page, accessed March 20, 2020, at https://idwr.idaho.gov/wells/find-a-well-map/.

Idaho Department of Water Resources [IDWR], 2021a, Groundwater data portal—Station overview: Idaho Department of Water Resources database, accessed November 10, 2020, at https://maps.idwr.idaho.gov/agol/GroundwaterLevels/.

Lewis, R.S., Link, P.K., Stanford, L.R., and Long, S.P., 2012, Geologic map of Idaho: Idaho Geological Survey Map M-9, scale 1:750,000, accessed August 3, 2018, at https://www.idahogeology.org/product/m-9.

Natural Resources Conservation Service, 2022, National Agricultural Imagery Program, Direct data/NAIP download: U.S. Department of Agriculture Natural Resources Conservation Service database, accessed June 17, 2022, at https://datagateway.nrcs.usda.gov/GDGHome_DirectDownLoad.aspx.

PRISM Climate Group, 2020, PRISM climate data: Corvallis, Oregon State University PRISM web page, accessed November 1, 2020, at https://prism.oregonstate.edu/.

Skipp, B., Snider, L.G., Janecke, S.U., and Kuntz, M.A., 2009, Geologic map of the Arco 30 × 60 minute quadrangle, south-central Idaho: Idaho Geological Survey, Geologic Map GM-47, scale 1:100,000, accessed November 7, 2018, at https://www.idahogeology.org/product/gm-47.

U.S. Geological Survey, 2016, StreamStats—Streamflow statistics and spatial analysis tools for water-resources applications: U.S. Geological Survey web page, accessed August 30, 2021, at http://streamstats.usgs.gov.

U.S. Geological Survey, 2018b, USGS 3D Elevation Program Digital Elevation Model: U.S. Geological Survey web page, accessed November 7, 2018, at https://elevation.nationalmap.gov/arcgis/rest/services/3DEPElevation/ImageServer.

U.S. Geological Survey, 2020, National Water Information System—Web interface—USGS water data for Idaho: U.S. Geological Survey database, accessed June 20, 2020, at https://waterdata.usgs.gov/id/nwis and https://doi.org/10.5066/F7P55KJN.

Appendix 5. Irrigation Efficiency

Abbreviations

CIR	crop irrigation requirement
IDWR	Idaho Department of Water Resources

Irrigation efficiency is defined as the ratio of crop irrigation requirement (CIR) to the water diverted from surface-water and groundwater sources. Unmeasured groundwater pumpage can be estimated using irrigation efficiency (see equation 6 in section, "Groundwater Pumpage"). Irrigation efficiency was considered during preparation of the groundwater budget. However, because of uncertainties in estimating this parameter, unmeasured groundwater pumpage was estimated through linear regression analysis of measured groundwater pumpage (2014–19) with measured surface-water diversions (2014–19). Discussion of irrigation efficiency is presented in this appendix for completeness.

Irrigation using surface water tends to be less efficient than irrigation using groundwater. The methods used for water conveyance and water application are factors in the conveyance loss. For example, surface water is conveyed through canals that mostly are unlined and leak, resulting in typical net irrigation efficiencies, accounting for conveyance and field application, of about 50–60 percent (Brouwer and others, 1989). Groundwater is transported through pipes, minimizing conveyance losses, with expected net irrigation efficiencies of about 75–95 percent (Phocaides, 2007). The IDWR estimates an average irrigation efficiency of about 0.70–0.75 based on consumptive use and commonly used irrigation methods in Idaho (IDWR, 2015).

Irrigation efficiency was determined above Mackay Dam (that is, in the "upper subbasin") and for two areas below Mackay Dam (above and below the Moore Diversion, referred to as "middle subbasin" and "lower subbasin," respectively). Estimated irrigation efficiency from 2014 to 2019 (spanning the period when groundwater pumpage was measured using totalizing flowmeters; table 6.1 in appendix 6, "Surface-Water Diversions and Groundwater Pumpage") seems to be strongly correlated with evapotranspiration, with typical coefficient of determination (R^2) factors greater than 0.90, but less correlated with precipitation and CIR (typical R^2 factors of about 0.2–0.3 or less). Measured groundwater pumpage was negatively correlated with measured surface-water diversions for the available records during 2014–19, with approximate R^2 correlation coefficients of 0.87, 0.84, and 0.93 for the upper, middle, and lower subbasins, respectively. This result was consistent with the description of water use presented in Crosthwaite and others (1970a) and Sukow (2017) because surface water typically is used when surface-water supply is sufficient in meeting CIR, followed by groundwater use when surface-water supply alone is unable to satisfy irrigation demand.

The calculated annual irrigation efficiency for 2014–19 (when surface-water diversion and groundwater pumpage records were available) based on estimated CIR was 0.24–0.53 for the upper subbasin, 0.40–0.77 for the middle subbasin, and 0.58–0.91 for the lower subbasin. Higher irrigation efficiencies (0.75–0.95 range) are expected for irrigation with groundwater. Better estimates of irrigation efficiency could be obtained by developing separate estimates for each water source (surface water, groundwater, or mixed). However, this groundwater budget did not consider separate CIR and irrigated acres based on source water types. An aggregate irrigation efficiency could be used to estimate unmeasured groundwater pumpage during 2000–13 based on the total CIR and irrigated and semi-irrigated acres regardless of the source water. However, unmeasured groundwater pumpage for irrigation during 2000-13 used in the actual groundwater budget calculation was based on linear regression with reported surface-water diversions during 2014–19 (see section "Groundwater Pumpage").

References Cited

Brouwer, C., Prins, K., and Heibloem, M., 1989, Irrigation water management—Irrigation scheduling: Rome, Italy, Food and Agriculture Organization, Training Manual No. 4, [variously paged], accessed March 4, 2021, at https://www.fao.org/3/t7202e/t7202e00.htm.

Crosthwaite, E.G., Thomas, C.A., and Dyer, K.L., 1970a, Water resources in the Big Lost River Basin, south-central Idaho: U.S. Geological Survey Open-File Report 70–93, 123 p., accessed June 23, 2022, at https://doi.org/10.3133/ofr7093.

Idaho Department of Water Resources [IDWR], 2015, Consumptive use: Idaho Department of Water Resources web page, accessed July 5, 2021, at https://www.arcgis.com/sharing/rest/content/items/7c82d0245ce1447d97572e7f5a1ddd1d/info/metadata/metadata.xml?format=default&output=html.

Phocaides, A., 2007, Handbook on pressurized irrigation techniques: Food and Agriculture Organization of the United Nations, accessed May 5, 2021, at https://www.fao.org/3/a1336e/a1336e.pdf.

Sukow, J., 2017, Groundwater in the Big Lost River Valley: Idaho Department of Water Resources Memorandum, February 6, 2017, 37 p., accessed February 25, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/legal/P-CGWA-2016-001/P-CGWA-2016-001-20170206-IDWR-Staff-Memo-Re-BLRV-by-Jennifer-Sukow.pdf.

Appendix 6. Surface-Water Diversions and Groundwater Pumpage

Abbreviations

ET	evapotranspiration
IDWR	Idaho Department of Water Resources
R^2	coefficient of determination
USGS	U.S. Geological Survey

Surface-water diversions and groundwater pumpage are used in groundwater-budget components including (1) inflows to the aquifer (recharge from irrigation [see section, "Applied Irrigation"], canal seepage [see section, "Canal Seepage"]; (2) Big Lost River seepage [see section, "Losing and Graining River Reaches"]); and (3) outflows from the aquifer as groundwater pumpage to certain canals and ditches and for irrigation, domestic supply, municipal supply (see section, "Outflows from the Aquifer"). Surface-water diversions and groundwater pumpage are necessary for satisfying irrigation demand in the Big Lost River Basin. During particularly wet years when adequate surface water is available for meeting irrigation demand, surface-water diversions tend to be greater than during dry years and used first, with less reliance on groundwater pumping (described in section, "Groundwater Pumpage"). The opposite trend is apparent during dry years, which are associated with less available streamflow and higher groundwater extraction than during wet years.

Some irrigation demand is met by a mix of surface water and groundwater, as some water rights allow use of both sources. Inferring the same source distribution as reported in Sukow (2017), about 84 percent of crop production above Mackay Dam uses surface water only, 7 percent uses only groundwater, and 9 percent uses mixed sources. The percentages below Mackay Reservoir are 14 percent with surface water only, 12 percent with groundwater only, and 74 percent mixed sources. Storage in Mackay Reservoir is used as supply below the reservoir during the irrigation season when sufficient storage is available. The difference in the reliance on surface water compared to groundwater sources throughout the basin indicates that surface water is more abundant above the reservoir, supported by measured streamflow at streamgages (U.S. Geological Survey, 2020) and estimated higher available precipitation compared to below the reservoir.

Several factors influence the amount of water diverted for irrigation including precipitation, evapotranspiration (ET), soil-moisture conditions, and economic factors. This investigation accounts for climatic variables but does not consider possible economic supply and demand that may influence the types of crops grown, the number of irrigated acres, and diversion volumes.

A total of 115 surface-water diversions within the basin are tracked in the Idaho Department of Water Resources (IDWR) Water District surface-water diversion database (IDWR, 2020d) and water rights accounting database (IDWR, 2020e), 63 of which are above Mackay Reservoir and 52 of which are below the reservoir (fig. 12). Not all diversions are used during a given irrigation season. Most diversions above the reservoir are from the Big Lost River (35), with fewer diversions from Warm Springs Creek (21), Pole Stackyard Creek (6), and Navarre Creek (1). Most diversions below the reservoir are from the Big Lost River (35), with the remainder from Antelope Creek (11), Cherry Creek (4), Alder Creek (1), and Bear Creek (1). The Big Lost River Irrigation District is the only irrigation district with surface-water diversions from the Big Lost River. Minor diversions for other tributaries not tracked in IDWR Water District surface-water diversion and water rights accounting databases are reported in annual watermaster reports (IDWR, 2020c); these tributaries include Lone Cedar and Rock Creeks above Mackay Dam and Lower Cedar, Pass, and Champagne Creeks below Mackay Dam.

Daily and annual surface-water diversion records were available for 2003–19 (IDWR, 2020d). The IDWR Water District surface-water diversion database flags surface-water diversions as "D" and pumping from a surface-water source as "P." The IDWR staff provided surface-water diversion records on the Big Lost River below Mackay Dam for 2000–02 from IDWR's water rights accounting files (J. Sukow, IDWR, unpub. data, January 21, 2020)[1].

Records from 2000 to 2002 do not include surface-water diversions on Antelope Creek or above Mackay Dam. Therefore, unmeasured diversions above Mackay Dam during 2000–02 were estimated based on a linear regression relation ($R^2 = 0.76$) between measured surface-water diversions above Mackay Dam for 2003–19 (IDWR, 2020d), and the average annual streamflow at Howell Ranch (U.S. Geological Survey [USGS] streamgage 13120500; U.S. Geological Survey, 2020) during 2003–19, excluding 2005 as an outlier. Antelope Creek unmeasured diversions during 2000–02 were estimated using a similar linear regression approach between measured diversions on Antelope Creek (2003–19, excluding 2005 as an apparent outlier) and all measured surface-water diversions on the Big Lost River below Mackay Dam (without tributary diversions) during the same time period (IDWR, 2020d). The resulting R^2 term (0.32) used in the estimate of unmeasured diversions on Antelope Creek (2000–02) showed poor correlation. Total surface-water diversion volumes were calculated as the sum of flagged "D" and "P" values over each irrigation season, including some reported off-season diversions.

[1]At the time of publication, published data were not available from IDWR but files may be requested from J. Sukow at IDWR Idaho Water Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800.

Diversions not included in the IDWR databases for minor tributary drainages were compiled from available annual watermaster reports for 2003–19 (IDWR, 2020c).

Surface-water diversions account for approximately 67 percent of the total volume supplied for irrigation in the Big Lost River Basin based on measured and estimated surface-water diversions and reported and estimated groundwater pumpage from all sources including pumpage to certain canals and ditches and for irrigation, domestic supply, and municipal supply for 2000–19 (tables 6.1 for upper and middle subbasins, 6.2 for the lower subbasin, and 6.3 for the entire basin). Surface water provides for the highest percentage of overall crop irrigation needs above Mackay Dam (more than 90 percent), 65 percent in the middle subbasin above the Moore Diversion, and about 55 percent in the lower subbasin below the Moore Diversion. Although the proportion of irrigation needs met by surface water differs throughout the basin, the total volumes of surface water diverted are similar (averaging about 47,600 acre-feet per year [acre-ft/yr] above Mackay Dam (table 6.1), 59,000 acre-ft/yr in the middle subbasin (table 6.1), and 43,000 acre-ft/yr in the lower subbasin (table 6.2). Total estimated and measured annual surface-water diversions and groundwater pumpage for the entire basin are provided in table 6.3.

Table 6.1. Estimated and measured annual surface-water diversions and groundwater pumpage, upper subbasin and middle subbasin, in the Big Lost River Basin, south-central Idaho. 2000-19.

[***Bold italicized*** values are estimated for surface-water diversions in the upper subbasin (2000–02), groundwater pumpage in the upper and middle subbasins (2000–13), and, therefore, total diversions (2000-13). Groundwater pumpage includes pumpage to canals and ditches and pumpage for irrigation, domestic supply, and municipal supply. All table values are in acre-feet per year. **Abbreviation and symbol:** IDWR, Idaho Department of Water Resources; –, not provided]

Year	Upper subbasin					Middle subbasin				
	Surface water[1]	Percent	Ground-water[2]	Percent	Total diversions	Surface water[1]	Percent	Ground-water[2]	Percent	Total diversions
2000	***35,435***	86	***5,994***	***14***	***41,428***	61,099	**65**	***33,078***	***35***	***94,177***
2001	***30,849***	82	***6,657***	***18***	***37,506***	36,505	**45**	***43,907***	***55***	***80,412***
2002	***32,423***	83	***6,429***	***17***	***38,852***	39,684	**48**	***42,507***	***52***	***82,191***
2003	43,527	90	***4,823***	***10***	***48,350***	48,466	**56**	***38,640***	***44***	***87,107***
2004	47,113	92	***4,304***	***8***	***51,417***	44,539	**52**	***40,369***	***48***	***84,909***
2005	78,569	100	***0***	***0***	***78,569***	79,489	**76**	***24,981***	***24***	***104,470***
2006	64,954	97	***1,722***	***3***	***66,677***	79,202	**76**	***25,107***	***24***	***104,309***
2007	43,034	90	***4,894***	***10***	***47,928***	44,050	**52**	***40,585***	***48***	***84,635***
2008	45,865	91	***4,484***	***9***	***50,349***	51,195	**58**	***37,439***	***42***	***88,634***
2009	48,624	92	***4,085***	***8***	***52,709***	68,203	**69**	***29,950***	***31***	***98,153***
2010	43,174	90	***4,874***	***10***	***48,048***	56,991	**62**	***34,887***	***38***	***91,878***
2011	60,368	96	***2,386***	***4***	***62,754***	61,067	**65**	***33,092***	***35***	***94,159***
2012	49,263	93	***3,993***	***7***	***53,256***	66,072	**68**	***30,888***	***32***	***96,961***
2013	40,394	88	***5,276***	***12***	***45,670***	43,842	**52**	***40,676***	***48***	***84,518***
2014	46,586	91	4,654	9	51,240	45,423	50	46,130	50	91,553
2015	42,196	90	4,745	10	46,942	44,851	55	37,218	45	82,069
2016	42,028	89	5,416	11	47,443	55,468	62	33,402	38	88,870
2017	57,420	95	3,051	5	60,471	92,784	80	22,626	20	115,410
2018	51,421	94	3,381	6	54,802	76,872	77	22,426	23	99,298
2019	48,499	93	3,789	7	52,288	83,398	79	22,498	21	105,895
Minimum	30,849	82	0	0	37,506	36,505	45	22,426	20	80,412
Maximum	78,569	100	6,657	18	78,569	92,784	80	46,130	55	115,410
Mean	47,587	92	4,248	8	51,835	58,960	65	34,020	35	92,980
Median	46,226	–	4,569	–	50,795	56,230	–	34,144	–	91,716

[1]Surface-water diversions datasets (2000-19) were accessed from IDWR (2020d, 2020e) except for surface-water diversions (2000-02) in the upper subbasin, which were estimated using methods described in section, "Canal Seepage.

[2]Groundwater pumpage datasets for irrigation, domestic, and municipal uses (2014–19) accessed from IDWR (C. Yenter, IDWR, unpub. data, March 5, 2019, and February 13, 2020—data available upon request from IDWR Salmon Field Office, Salmon, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800). Groundwater pumpage to canal datasets accessed from IDWR (2020d).

Table 6.2. Estimated and measured annual surface-water diversions and groundwater pumpage, lower subbasin, in the Big Lost River Basin, south-central Idaho. 2000-19.

[***Bold italicized values*** are estimated for groundwater pumpage (2000–13) and, therefore, total diversions in the lower subbasin (2000–13). Groundwater pumpage includes pumpage to canals and ditches and pumpage for irrigation, domestic supply, and municipal supply. All table values are in acre-feet per year. **Abbreviation and symbol:** IDWR, Idaho Department of Water Resources; –, not provided.]

Year	Lower subbasin				
	Surface water[1]	Percent	Groundwater[2]	Percent	Total diversions
2000	68,743	78	***18,999***	22	***87,742***
2001	28,871	37	***48,177***	63	***77,048***
2002	32,494	42	***45,526***	58	***78,020***
2003	22,515	30	***52,829***	70	***75,343***
2004	20,814	28	***54,073***	72	***74,887***
2005	47,269	58	***34,713***	42	***81,983***
2006	68,295	78	***19,327***	22	***87,622***
2007	39,728	50	***40,232***	50	***79,960***
2008	38,669	49	***41,007***	51	***79,676***
2009	43,282	53	***37,631***	47	***80,913***
2010	48,953	59	***33,481***	41	***82,434***
2011	56,127	67	***28,231***	33	***84,358***
2012	59,014	69	***26,119***	31	***85,132***
2013	41,025	51	***39,283***	49	***80,308***
2014	17,161	22	61,848	78	79,009
2015	23,210	33	47,867	67	71,078
2016	34,815	46	40,694	54	75,509
2017	60,893	72	23,267	28	84,160
2018	54,199	63	32,083	37	86,282
2019	54,337	64	31,049	36	85,386
Minimum	17,161	22	18,999	22	71,078
Maximum	68,743	78	61,848	78	87,742
Mean	43,021	55	37,822	45	80,843
Median	42,154	–	38,457	–	80,611

[1]Surface-water diversions datasets (2000-19) were accessed from IDWR (2020d, 2020e) except for surface-water diversions (2000-02) in the upper subbasin, which were estimated using methods described in section, "Canal Seepage."

[2]Groundwater pumpage datasets for irrigation, domestic, and municipal uses (2014–19) accessed from IDWR (C. Yenter, IDWR, unpub. data, March 5, 2019, and February 13, 2020—data available upon request from IDWR Salmon Field Office, Salmon, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800). Groundwater pumpage to canal datasets accessed from IDWR (2020d).

Groundwater wells[2] are used to withdraw groundwater from the shallow aquifer for discharge to a canal. These wells are addressed in section, "Groundwater Pumpage to Canals and Ditches."

Measured groundwater pumpage and methods for estimating unmeasured groundwater pumpage (including the relation between crop irrigation requirement and pumpage and the high correlation between surface-water diversions and groundwater pumpage) are described in section, "Groundwater Pumpage." The highest surface-water diversions occurred during the wettest years (2005, 2006, and 2017) when supply was more readily available. Similarly, the lowest diversions occurred in the driest years (2001–04 and 2013–15). Groundwater supply was used to augment surface-water supplies during dry years, as indicated in figure 6.1.

General trends of water use for meeting irrigation demand during 2000–19 (fig. 6.2) are consistent with previous findings (Johnson and others, 1991) in that, during average

[2]The term "exchange wells" is used in the IDWR Water District surface-water diversion database.

Table 6.3. Total estimated and measured annual surface-water diversions and groundwater pumpage, in the Big Lost River Basin, south-central Idaho. 2000-19.

[***Bold italicized*** values are estimated for groundwater withdrawal for the entire basin (2000–13) and total diversions (2010–13). Groundwater pumpage includes pumpage to canals and ditches and pumpage for irrigation, domestic supply, and municipal supply. All table values are in acre-feet per year. **Abbreviation and symbol:** IDWR, Idaho Department of Water Resources; –, not provided]

Year	Total basin				
	Surface water[1]	Percent	Groundwater[2]	Percent	Total diversions
2000	165,277	74	***58,071***	26	***223,347***
2001	96,225	49	***98,741***	51	***194,966***
2002	104,601	53	***94,463***	47	***199,063***
2003	114,508	54	***96,292***	46	***210,800***
2004	112,466	53	***98,746***	47	***211,213***
2005	205,327	77	***59,694***	23	***265,021***
2006	212,452	82	***46,156***	18	***258,608***
2007	126,811	60	***85,711***	40	***212,522***
2008	135,729	62	***82,930***	38	***218,659***
2009	160,108	69	***71,667***	31	***231,775***
2010	149,118	67	***73,242***	33	***222,360***
2011	177,563	74	***63,709***	26	***241,272***
2012	174,349	74	***61,000***	26	***235,349***
2013	125,261	60	***85,235***	40	***210,496***
2014	109,170	49	112,632	51	221,802
2015	110,258	55	89,831	45	200,088
2016	132,310	62	79,512	38	211,822
2017	211,097	81	48,944	19	260,041
2018	182,492	76	57,891	24	240,383
2019	186,233	76	57,336	24	243,569
Minimum	96,225	49	46,156	18	194,966
Maximum	212,452	82	112,632	51	265,021
Mean	149,568	67	76,090	33	225,658
Median	142,424	–	76,377	–	222,081

[1]Surface-water diversions datasets (2000-19) were accessed from IDWR (2020d, 2020e) except for surface-water diversions (2000-02) in the upper subbasin, which were estimated using methods described in section, "Canal Seepage."

[2]Groundwater pumpage datasets for irrigation, domestic, and municipal uses (2014–19) accessed from IDWR (C. Yenter, IDWR, unpub. data, March 5, 2019, and February 13, 2020—data available upon request from IDWR Salmon Field Office, Salmon, Idaho, https://idwr.idaho.gov/contact-us/ or 208-287-4800). Groundwater pumpage to canal datasets accessed from IDWR (2020d).

water years, mean flows in the Big Lost River measured below Mackay Reservoir (USGS streamgage 13127000; U.S. Geological Survey, 2020) exceeded surface-water diversions and groundwater pumpage. During particularly dry years or several drought years in succession, such as 2001–04 and 2014, overall surface-water diversions and groundwater pumpage exceeded the available surface-water supply. Conversely, during particularly wet years, such as 2005–06 and 2017–19, total diversions were much less than available surface-water supply, as the crop irrigation demand does not increase with available supply. The mean annual streamflow volume shown in figure 6.2 was not compensated for the Sharp diversion above the streamgage or for storage changes in Mackay Reservoir.

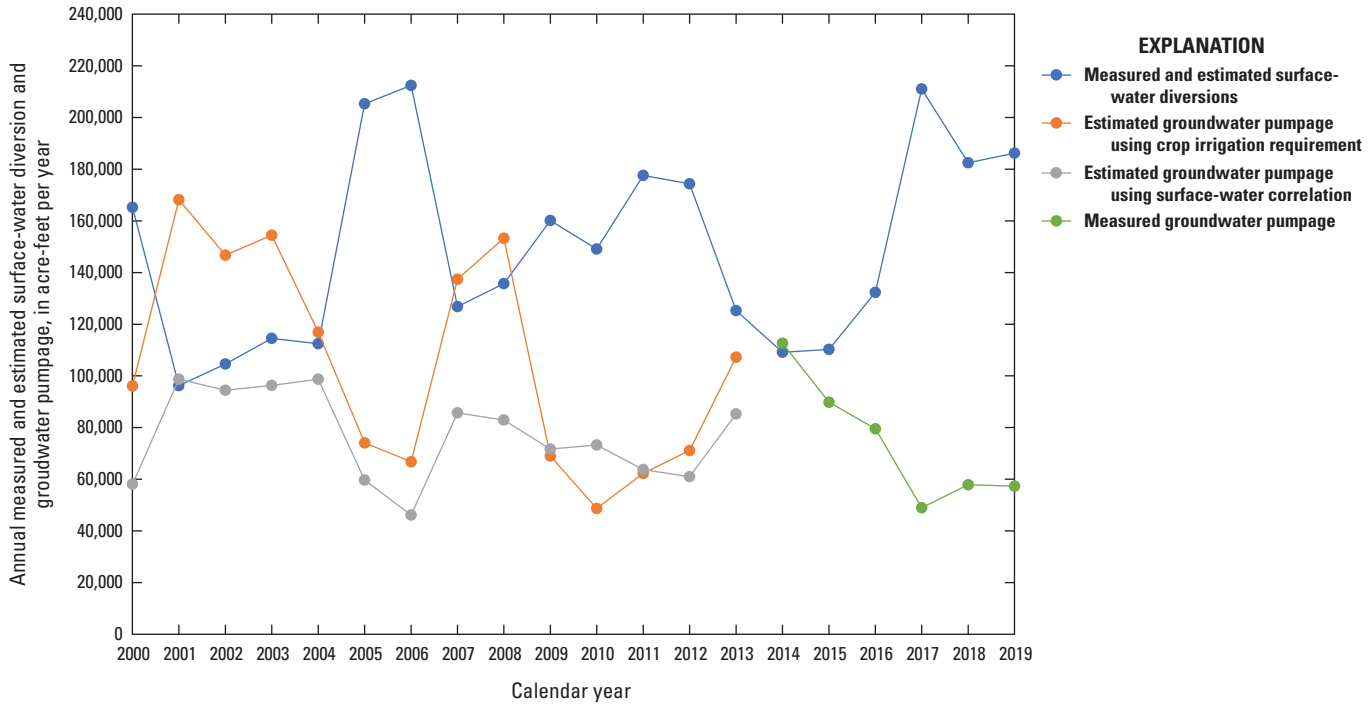
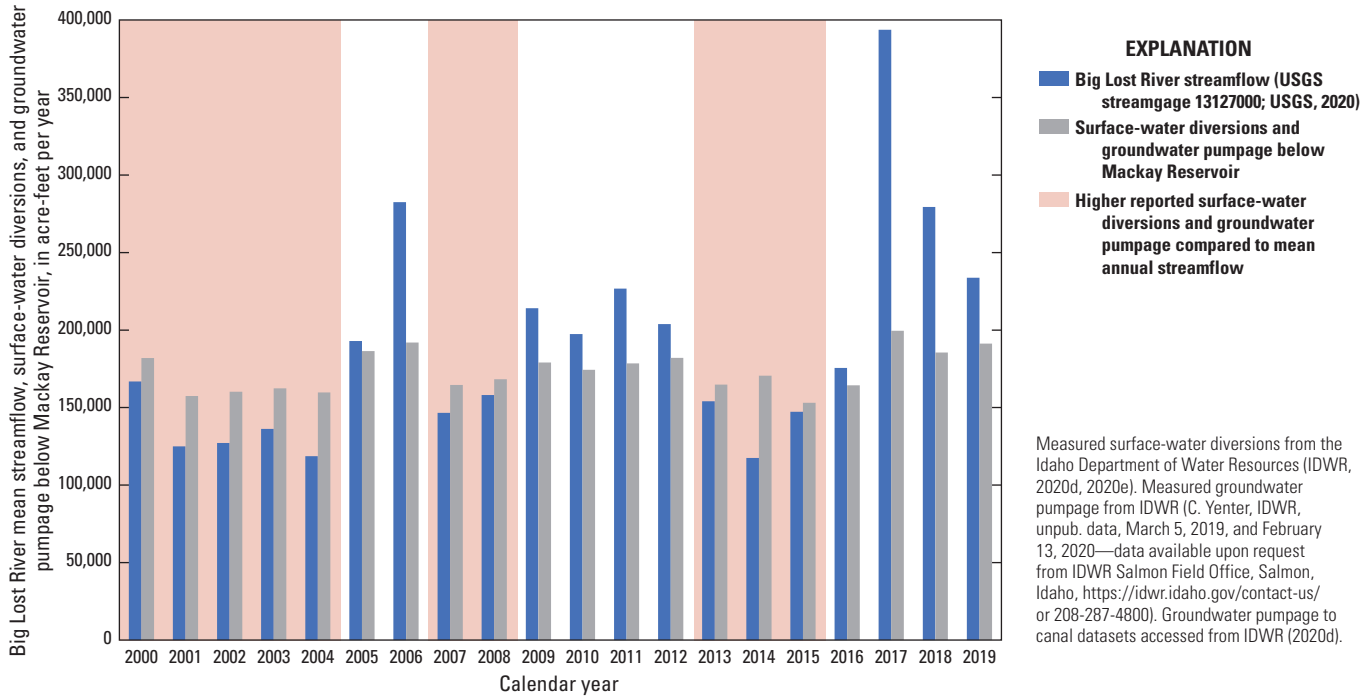


Figure 6.1. Annual measured and estimated surface-water diversion and groundwater pumpage in the Big Lost River Basin, south-central Idaho, 2000–19. See tables 6.1–6.3 for data.



Measured surface-water diversions from the Idaho Department of Water Resources (IDWR, 2020d, 2020e). Measured groundwater pumpage from IDWR (C. Yenter, IDWR, unpub. data, March 5, 2019, and February 13, 2020—data available upon request from IDWR Salmon Field Office, Salmon, Idaho, https://idwr.idaho.gov/contact-us/ or 208-287-4800). Groundwater pumpage to canal datasets accessed from IDWR (2020d).

Figure 6.2. Total mean annual streamflow, Mackay streamgage (U.S. Geological Survey [USGS] streamgage 13127000) and measured and estimated surface-water diversions and groundwater pumpage below Mackay Reservoir in the Big Lost River Basin, south-central Idaho, 2000–19.

References Cited

Idaho Department of Water Resources [IDWR], 2020c, Water District #34 (Big Lost River): Idaho Department of Water Resources document repository, accessed July 13, 2020, at https://idwr.idaho.gov/apps/ExtSearch/RelatedDocsWaterDistrictyearwithyear.asp?water_dist_no=34&wateryear=.

Idaho Department of Water Resources [IDWR], 2020d, Water District surface-water diversion database: Idaho Department of Water Resources database, accessed 2020, at https://idwr.idaho.gov/apps/wm/DiversionDataApplication/AnnualSummary.aspx.

Idaho Department of Water Resources [IDWR], 2020e, Water rights accounting database: Idaho Department of Water Resources database, accessed May 25, 2022, at https://research.idwr.idaho.gov/apps/Hydrologic/Accounting/.

Johnson, G.S., Ralston, D.R., and Mink, L.L., 1991, Ground-water pumping impacts on surface water irrigation diversions from Big Lost River: Prepared for Idaho Department of Water Resources, Boise, Idaho, by Idaho Water Resources Research Institute, University of Idaho, Moscow, 54 p., accessed February 20, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/publications/199112-GWQ-IWRRI-Report-GW-Pumping-Impacts-Big-Lost-River.pdf.

Sukow, J., 2017, Groundwater in the Big Lost River Valley: Idaho Department of Water Resources Memorandum, February 6, 2017, 37 p., accessed February 25, 2022, at https://idwr.idaho.gov/wp-content/uploads/sites/2/legal/P-CGWA-2016-001/P-CGWA-2016-001-20170206-IDWR-Staff-Memo-Re-BLRV-by-Jennifer-Sukow.pdf.

U.S. Geological Survey, 2020, National Water Information System—Web interface—USGS water data for Idaho: U.S. Geological Survey database, accessed June 20, 2020, at https://waterdata.usgs.gov/id/nwis and https://doi.org/10.5066/F7P55KJN.

Appendix 7. Return Surface-Water Flow

Abbreviations

ET	evapotranspiration
IDWR	Idaho Department of Water Resources
METRIC	Mapping EvapoTranspiration at high Resolution and Internalized Calibration
PRISM	Parameter-elevation Regressions on Independent Slopes Model

Return surface-water flows factor into groundwater-budget calculations including the recharge of applied irrigation water (see section, "Applied Irrigation"), canal seepage (see section, "Canal Seepage"), and Big Lost River seepage (see section, "Losing and Gaining River Reaches"). During the 2000-19 study period, measurements of return surface-water flows to the Big Lost River were available at two locations (fig. 12): one location on the Burnett Canal at the Burnett TE site during 2016–19 and another location at East Side Out (Idaho Department of Water Resources [IDWR] site 13132350) during 2015–19. Measured and estimated surface-water return flows to the Big Lost River at those locations are based on PivoTrac Monitoring (http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021)[1] return flow datasets. The IDWR Water District surface-water diversion database reported return flows for East Side Out during 2003–10 and 2012–19 (IDWR, 2020d). No published estimates were available for East Side Out during 2000–02 and 2011. No information was available for years prior to 2016 for Burnett TE.

Available PivoTrac Monitoring datasets were accessed from the PivoTrac Monitoring web page (http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021)[2]. Precise coordinates for the PivoTrac Monitoring systems were not provided on the PivoTrac Monitoring website. Therefore, locations were approximated from satellite imagery of the monitoring system locations and Google Earth Pro satellite imagery (Google LLC, 2020).

PivoTrac Monitoring data are recorded in units of cubic feet per second per day based on communication with IDWR staff (D. Hoekema, IDWR, written commun., 2021). Total irrigation return flow measured at the Burnett TE site ranged from 506 acre-ft (in 2017) to 2,458 acre-ft (in 2018). The measured flow at the East Side Out site ranged from 8,424 acre-ft (in 2015) to 18,376 acre-ft (in 2018). Measurements of return flow at these two locations likely underrepresent the actual total return flow because of unmeasured return locations. For other years within the study period without return flow measurements, estimated returns were based on correlation with measured canal diversions[3].

Irrigation surface-water return flow at Burnett TE in the middle subbasin was estimated based on an average 7-percent return of canal diversions during 2016–19 applied to 2000–15. This assumption may overestimate or underestimate actual return flows. Return flow at East Side Out (IDWR site 13132350) in the lower subbasin was estimated during missing years (2000–02 and 2011) based on a linear regression correlation with reported surface-water diversions to the East Side Ditch at 13132060[4] (IDWR, 2020d).

Excess applied irrigation water also may flow to ditches as an unmeasured source of potential recharge. This recharge may occur along ditches, canal corridors, and right-of-way easements, coincident with spatial distribution of precipitation minus evapotranspiration (ET), indicating that potential recharge is available. Similar to the relation of Mapping EvapoTranspiration at high Resolution and Internalized Calibration (METRIC) ET (IDWR, 2021b) minus Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation (PRISM Climate Group, 2020; see app. 3, fig. 3.1 at the basin-scale), potential areas of focused irrigation recharge are visible at the individual-raster-cell scale.

[1]At the time of publication, published data were not available from PivoTrac Monitoring but raw data may be requested from the Water District 34 watermaster, Lucas Yockey, at 208-589-3138.

[2]At the time of publication, published data were not available from PivoTrac Monitoring but raw data may be requested from the Water District 34 watermaster, Lucas Yockey, at 208-589-3138.

[3]East Side Ditch diversions were well correlated with measured return flows (coefficient of determination [R^2]=0.72) during 2015–19. Burnett and Swauger Canal diversions were not correlated with measured return flows (R^2 = 0.002) during 2016–19; therefore, 7-percent of the canal diversions were assumed to be for return flows based on the mean return-flow rate for 2016–19.

[4]Reported East Side Out surface-water return flows used in the estimation of return flow at East Side Out were weakly correlated (R^2 =0.37) with East Side Ditch diversions over the available period of record. PivoTrac measurements during 2015–19 were better correlated with East Side Ditch diversions (R^2=0.72) but were not used based on the shorter, available period of record for PivoTrac measurements.

References Cited

Google LLC, 2020, Google Earth Pro, version 7.3.3.7786: Google LLC software release.

Idaho Department of Water Resources, 2021b [IDWR], Map and GIS data hub—Evapotranspiration: Idaho Department of Water Resources web page, accessed April 8, 2021, at https://data-idwr.opendata.arcgis.com/pages/gis-data.

Idaho Department of Water Resources, 2020d [IDWR], Water district surface-water diversion database: Idaho Department of Water Resources database, accessed 2020, at https://idwr.idaho.gov/apps/wm/DiversionDataApplication/AnnualSummary.aspx.

PRISM Climate Group, 2020, PRISM climate data: Corvallis, Oregon State University PRISM web page, accessed November 1, 2020, at https://prism.oregonstate.edu/.

Appendix 8. Estimated Canal Seepage Details

Abbreviation

IDWR Idaho Department of Water Resources

This appendix provides estimated seepage volumes for canals considered in the study (table 8.1) with separate estimates for the East Side Ditch for the 2000–19 study period (table 8.2). Canal seepage is discussed in section, "Canal Seepage." Operation of the East Side Ditch includes groundwater pumpage deliveries to the East Side Canal (fig. 12), with a calculation used separate from that used for the other canals in the Big Lost River Basin.

Estimated canal seepage volumes for the East Side Ditch are based on measured and estimated return flows at East Side Out, measured flows at East Side In, and pumped groundwater introduced as inflow to the East Side Ditch, some of which seeps beneath the channel (see section, "Canal Seepage," and appendix 7, "Return Surface-Water Flow"). Negative values in table 8.2 indicate a losing reach condition for all years in the study period. East Side Out return flows for 2003–10 and 2012–14 were reported in the IDWR Water District surface-water diversion database (IDWR, 2020d), and PivoTrac Monitoring (http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021)[1] reported measured return flows for 2015–19. Return flows for other years in the study period for East Side Out were estimated based on correlation with reported surface-water diversions for East Side In. Surface-water diverted to East Side In and groundwater pumpage to the East Side Ditch during 2003–19 were reported in the IDWR Water District surface-water diversion database and were provided by IDWR staff for 2000–02 (J. Sukow, IDWR, unpub. data, January 21, 2020)[2].

[1]At the time of publication, published data were not available from PivoTrac Monitoring but raw data may be requested from the Water District 34 watermaster, Lucas Yockey, at 208-589-3138.

References Cited

Big Lost River Irrigation District, 2022, Storage balance spreadsheets from the Big Lost River Irrigation District, 2015-2019: Idaho Department of Water Resources web page, accessed June 22, 2022, at https://idwr.idaho.gov/water-data/projects/big-lost/.

Idaho Department of Water Resources [IDWR], 2020d, Water District surface-water diversion database: Idaho Department of Water Resources database, accessed 2020, at https://idwr.idaho.gov/apps/wm/DiversionDataApplication/AnnualSummary.aspx.

Idaho Department of Water Resources [IDWR], 2020e, Water rights accounting database: Idaho Department of Water Resources database, accessed May 25, 2022, at https://research.idwr.idaho.gov/apps/Hydrologic/Accounting/.

Water District 34, 2022, Ditch rider logs from Water District 34, 2015-2018: Idaho Department of Water Resources web page, accessed June 22, 2022, at https://idwr.idaho.gov/water-data/projects/big-lost/.

[2]At the time of publication, published data were not available from IDWR but may be requested from J. Sukow at IDWR Idaho Water Center, Boise, Idaho, at https://idwr.idaho.gov/contact-us/ or 208-287-4800.

Table 8.1. Estimated canal seepage by subbasin in the Big Lost River Basin, south-central Idaho, during the 2000–19 study period.

[***Bold italicized*** values are estimated. See table 8.2 for East Side Ditch estimated seepage during the study period. **Abbreviations and symbol**: acre-ft/yr, acre-feet per year, (-), dimensionless parameter; IDWR, Idaho Department of Water Resources.]

Year	Upper subbasin			Middle subbasin			Lower subbasin		
	Total surface-water diversion[1] (acre-ft/yr)	Seepage factor[2] (-)	Seepage volume[3] (acre-ft/yr)	Total surface-water diversion[4] (acre-ft/yr)	Seepage factor[5] (-)	Seepage volume[3] (acre-ft/yr)	Total surface-water diversion[4] (acre-ft/yr)	Seepage factor[5] (-)	Seepage volume[3] (acre-ft/yr)
2000	***35,435***	***0.40***	***14,174***	61,099	***0.25***	***14,990***	68,743	***0.24***	***33,253***
2001	***30,849***	***0.40***	***12,340***	36,505	***0.29***	***10,704***	28,871	***0.39***	***13,430***
2002	***32,423***	***0.40***	***12,969***	39,684	***0.29***	***11,365***	32,494	***0.38***	***16,304***
2003	43,527	***0.40***	***17,411***	48,466	***0.27***	***13,029***	22,515	***0.37***	***15,316***
2004	47,113	***0.40***	***18,845***	44,539	***0.27***	***11,854***	20,814	***0.40***	***11,044***
2005	78,569	***0.40***	***31,428***	79,489	***0.25***	***19,558***	47,269	***0.24***	***19,522***
2006	64,954	***0.40***	***25,982***	79,202	***0.21***	***16,617***	68,295	***0.09***	***32,673***
2007	43,034	***0.40***	***17,214***	44,050	***0.26***	***11,493***	39,728	***0.30***	***18,499***
2008	45,865	***0.40***	***18,346***	51,195	***0.26***	***13,460***	38,669	***0.29***	***19,646***
2009	48,624	***0.40***	***19,449***	68,203	***0.24***	***16,555***	43,282	***0.23***	***26,095***
2010	43,174	***0.40***	***17,270***	56,991	***0.25***	***14,331***	48,953	***0.22***	***30,744***
2011	60,368	***0.40***	***24,147***	61,067	***0.25***	***15,176***	56,127	***0.15***	***28,138***
2012	49,263	***0.40***	***19,705***	66,072	***0.24***	***15,811***	59,014	***0.16***	***24,892***
2013	40,394	***0.40***	***16,158***	43,842	***0.27***	***11,833***	41,025	***0.29***	***19,801***
2014	46,586	***0.40***	***18,634***	45,423	***0.27***	***12,071***	17,161	***0.42***	***12,312***
2015	42,196	***0.40***	***16,879***	44,851	0.27	***11,904***	23,210	0.41	***17,817***
2016	42,028	***0.40***	***16,811***	55,468	0.27	***14,855***	34,815	0.32	***20,674***
2017	57,420	***0.40***	***22,968***	92,784	0.19	***17,520***	60,810	0.18	***30,236***
2018	51,421	***0.40***	***20,568***	76,872	0.19	***14,419***	54,199	0.30	***28,671***
2019	48,499	***0.40***	***19,399***	83,398	0.24	***19,609***	54,337	0.14	***20,650***

[1]Surface-water diversions (2000–02) in the upper subbasin were estimated using methods described in section, "Canal Seepage." Diversion datasets (2003–19) were accessed from IDWR (2020d, 2020e).

[2]Seepage factors for the upper subbasin were assumed based on an assumed 60-percent delivery factor and 40-percent seepage factor for all canals in the upper subbasin.

[3]Seepage volumes were estimated using the methods described in section, "Canal Seepage."

[4]Surface-water diversion datasets (2000–19) for the middle and lower subbasins were accessed from IDWR (2020d, 2020e).

[5]Seepage factors (2000-14) for the middle and lower subbasins were estimated using the methods described in section, "Canal Seepage." Seepage factors (2015–19) were calculated from ditch rider log datasets (Water District 34, 2022; Big Lost River Irrigation District, 2022).

Table 8.2. Estimated East Side Ditch seepage in the Big Lost River Basin, south-central Idaho, during the 2000–19 study period.

[All pumped groundwater seepage and seepage values in ***bold italics*** are estimated. The reported diversion for the East Side Ditch in January 2014 seems to be anomalous. All values in the table are in acre-feet per year.]

Year	East Side Out return flow (13132350)[1]	East Side In (13132060)[2]	Surface-water diversions[3]	Groundwater pumpage to canals[3]	Pumped groundwater seepage	Seepage
2000	***12,992***	21,366	0	10,737	***2,577***	***–16,534***
2001	***10,074***	9,741	0	4,098	***1,598***	***–2,166***
2002	***10,509***	11,471	0	5,058	***1,922***	***–4,099***
2003	11,909	12,926	0	9,636	***3,565***	***–7,088***
2004	9,629	6,471	0	9,916	***3,967***	***–2,792***
2005	11,249	19,441	0	0	***0***	***–8,192***
2006	15,061	36,716	0	5,495	***495***	***–26,655***
2007	14,219	12,676	0	11,827	***3,548***	***–6,736***
2008	12,462	16,345	0	6,650	***1,928***	***–8,604***
2009	12,834	26,214	0	3,719	***855***	***–16,243***
2010	6,115	21,378	0	5,772	***1,270***	***–19,764***
2011	16,139	33,904	0	2,542	***381***	***–19,926***
2012	19,746	28,625	0	8,164	***1,306***	***–15,738***
2013	14,751	14,095	0	12,206	***3,540***	***–8,010***
2014	7,329	5,500	14	12,111	***5,087***	***–5,181***
2015	8,424	10,913	0	9,925	***4,069***	***–8,345***
2016	11,620	15,711	0	8,136	***2,604***	***–9,623***
2017	15,277	32,100	0	2,873	***517***	***–19,178***
2018	18,376	27,779	0	4,472	***1,341***	***–12,534***
2019	10,147	20,165	0	3,283	***460***	***–12,842***
Mean	12,443	19,177	1	6,831	***2,052***	***–11,513***

[1]East Side Out return flow datasets were accessed from IDWR (2020d) during 2003–10 and 2012–19 from PivoTrac Monitoring (http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021; data available upon request from Water District 34 watermaster, Lucas Yockey, at 208-589-3183) for 2015–19.

[2]East Side In flows were accessed from IDWR (2020d).

[3]Surface-water diversion and groundwater pumpage to canal datasets were accessed from IDWR (2020d).

Appendix 9. River-Reach Gain and Loss Assumptions

Abbreviations

IDWR	Idaho Department of Water Resources
PRISM	Parameter-elevation Regressions on Independent Slopes Model
Q20	20-percent flow exceedance
Q50	median monthly flow duration
Q80	80-percent flow exceedance
R^2	coefficient of determination
USGS	U.S. Geological Survey

This appendix describes the methods used for estimating unmeasured surface-water diversions, return flows, and streamflow for incorporation in river-reach seepage calculations. River seepage is described in section, "Losing and Gaining River Reaches." Supporting details on return flows are presented in appendix 7 ("Return Surface-Water Flow"). The locations of canals, surface-water diversions, and return flow sites are shown on fig. 12. Locations of associated streamgage sites are shown on fig. 15. Annual estimated seepage for the 2000–19 study period is summarized by reach (tables 9.1 and 9.2 for reaches above Mackay Dam and tables 9.3 and 9.4 for reaches below Mackay Dam).

Unmeasured Surface-Water Diversions and Return Flow Assumptions

Estimation of surface-water diversions when records were unavailable is addressed in appendix 6 ("Surface-Water Diversions and Groundwater Pumpage"). These unmeasured volumes constitute a minor term in the estimated river seepage.

PivoTrac Monitoring-measured surface-water return flows, when available, were accessed from the PivoTrac Monitoring website (http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021)[1] and used in the seepage calculations. Return-flow data are available for Burnett TE and East Side Out (Idaho Department of Water Resources [IDWR] site 13132350) locations. When PivoTrac Monitoring data were unavailable, the IDWR Water District surface-water diversion database records (IDWR, 2020d) were used. Return-flow estimation methods are described in section, "Recharge of Applied Water," and appendix 7 ("Return Surface-Water Flow").

Unmeasured Big Lost River Streamflow Assumptions

Streamflow at the Idaho Power Leslie streamgage 13130500 (Idaho Power, 2020) was estimated for 2000–06 before available streamflow measurements were recorded. High positive correlation (coefficient of determination [R^2] = 0.96) with streamflow in the Big Lost River below Mackay (U.S. Geological Survey [USGS] streamgage 13127000; U.S. Geological Survey, 2020) from 2007 to 2019 was used for estimating streamflow. Estimated streamflow for the Leslie streamgage was used in the groundwater budget during 2000–02 instead of streamflow reported in the IDWR water rights accounting database (IDWR, 2020e), which indicated zero streamflow during those years.

[1]At the time of publication, published data were not available from PivoTrac Monitoring but raw data may be requested from the Water District 34 watermaster, Lucas Yockey, at 208-589-3138.

Table 9.1. Estimated seepage, North Fork of the Big Lost River (USGS streamgage 13120000) to Howell Ranch (USGS streamage 13120500), in the Big Lost River above Mackay Dam, south-central Idaho, 2000–19.

[All values in ***bold italics*** are estimated. Groundwater budget includes seepage using tributary flows. All table values are in acre-feet per year. Negative seepage values indicate a losing reach condition and positive values indicate a gaining reach condition. **Abbreviations:** USGS, U.S. Geological Survey; IDWR, Idaho Department of Water Resources]

Year	Howell Ranch (13120500)[1]	North Fork of the Big Lost River at Wild Horse (13120000)[1]	Diversions[2]	East Fork of the Big Lost River	Twin Bridges Creek	Burnt Creek	Seepage without Twin Bridges and Burnt Creeks	Seepage with Twin Bridges and Burnt Creeks
2000	135,831	45,149	***1,072***	***88,676***	***2,317***	***240***	***3,078***	***521***
2001	109,218	33,836	***1,072***	***62,485***	***1,695***	***167***	***13,969***	***12,107***
2002	118,352	40,507	***1,072***	***75,259***	***1,858***	***191***	***3,658***	***1,610***
2003	149,757	53,261	973	***110,154***	***3,046***	***294***	***–12,685***	***–16,025***
2004	136,151	43,516	553	***88,080***	***2,370***	***246***	***5,108***	***2,492***
2005	224,930	71,473	1,440	***165,441***	***4,589***	***449***	***–10,544***	***–15,581***
2006	313,313	108,896	674	***169,326***	***4,886***	***470***	***35,765***	***30,409***
2007	134,841	41,357	590	***69,752***	***1,826***	***187***	***24,323***	***22,310***
2008	172,663	56,205	973	***74,036***	***1,976***	***204***	***43,395***	***41,215***
2009	243,548	78,699	705	***150,692***	***4,282***	***421***	***14,862***	***10,158***
2010	208,877	61,963	1,122	***148,611***	***4,352***	***425***	***–575***	***–5,352***
2011	247,439	80,012	1,510	***141,663***	***3,802***	***371***	***27,273***	***23,101***
2012	186,003	64,514	1,319	***160,550***	***4,415***	***423***	***–37,742***	***–42,580***
2013	149,476	50,952	1,633	***56,189***	***1,537***	***158***	***43,968***	***42,272***
2014	119,906	42,084	1,542	***85,318***	***2,276***	***241***	***–5,954***	***–8,470***
2015	152,333	49,493	906	***88,203***	***2,319***	***243***	***15,544***	***12,982***
2016	210,417	69,873	1,062	***153,437***	***4,260***	***424***	***–11,830***	***–16,514***
2017	407,088	147,184	1,400	***290,972***	***10,046***	***1,100***	***–29,668***	***–40,814***
2018	267,055	79,227	1,220	***116,229***	***3,343***	***338***	***72,820***	***69,139***
2019	233,919	77,054	923	***147,096***	***4,293***	***449***	***10,691***	***5,948***
Mean	196,048	64,760	1,088	***122,109***	***3,474***	***352***	***10,273***	***6,446***

[1]Streamflow datasets were accessed from U.S. Geological Survey (2020).

[2]Surface-water diversion datasets were accessed from IDWR (2020d).

Table 9.2. Estimated seepage, Howell Ranch (USGS streamgage 13120500) to below Mackay Reservoir (USGS streamgage 13127000), in the Big Lost River above Mackay Dam, south-central Idaho, 2000–19.

[All values in ***bold italics*** are estimated. Groundwater budget includes seepage using tributary flows. All values in the table are in acre-feet per year. Negative seepage values indicate a losing reach condition and positive values indicate a gaining reach condition. **Abbreviations:** USGS, U.S. Geological Survey; IDWR, Idaho Department of Water Resources]

Year	Big Lost River below Mackay Reservoir (13127000)[1]	Howell Ranch (13120500)[1]	Inflow at Mackay Dam[2] (calculated)	Diversions[3]	Pinto Creek	Thousand Springs Creek	Warm Springs Creek	Seepage without tributaries	Seepage with tributaries
2000	166,785	135,831	–11,900	***35,435***	***761***	***7,888***	***4,510***	***54,489***	***41,330***
2001	125,025	109,218	1,045	***30,849***	***537***	***5,804***	***3,131***	***47,701***	***38,229***
2002	127,215	118,352	–6,840	***32,423***	***617***	***6,364***	***3,537***	***34,446***	***23,928***
2003	136,262	149,757	4,514	36,471	***952***	***12,066***	***6,304***	***27,491***	***8,169***
2004	118,678	136,151	2,120	40,800	***778***	***8,288***	***4,932***	***25,447***	***11,449***
2005	192,984	224,930	8,080	66,994	***1,427***	***17,294***	***10,414***	***43,129***	***13,994***
2006	282,593	313,313	–3,650	57,640	***1,514***	***18,833***	***10,271***	***23,270***	***–7,347***
2007	146,563	134,841	–4,962	39,408	***602***	***6,809***	***3,408***	***46,168***	***35,348***
2008	158,050	172,663	1,705	39,553	***652***	***7,087***	***3,738***	***26,646***	***15,169***
2009	214,110	243,548	12,400	42,903	***1,341***	***17,307***	***10,127***	***25,865***	***–2,910***
2010	197,374	208,877	600	39,693	***1,355***	***17,483***	***9,660***	***28,790***	***293***
2011	226,776	247,439	1,000	52,849	***1,195***	***15,728***	***8,258***	***33,187***	***8,007***
2012	203,830	186,003	–4,248	42,780	***1,368***	***16,180***	***9,060***	***56,359***	***29,751***
2013	154,056	149,476	–8,110	33,517	***507***	***5,689***	***2,861***	***29,988***	***20,931***
2014	117,527	119,906	4,140	38,441	***771***	***8,522***	***4,749***	***40,202***	***26,161***
2015	147,272	152,333	–1,270	36,754	***781***	***8,608***	***4,792***	***30,423***	***16,242***
2016	175,586	210,417	10,790	36,096	***1,358***	***18,025***	***10,267***	***12,055***	***–17,594***
2017	393,734	407,088	–271	51,716	***3,184***	***39,901***	***24,644***	***38,091***	***–29,637***
2018	279,410	267,055	–3,010	41,960	***1,089***	***15,118***	***8,478***	***51,305***	***26,619***
2019	233,533	233,919	3,580	42,075	***1,453***	***15,763***	***8,956***	***45,270***	***19,098***
Mean	189,868	196,048	286	41,918	***1,112***	***13,438***	**7,605**	***36,016***	***13,861***

[1]Streamflow datasets were accessed from U.S. Geological Survey (2020).

[2]Mackay Dam inflow calculations were based on Mackay Reservoir storage datasets (USGS streamgage 13127000) accessed from the U.S. Geological Survey (2020) and surface-water diversion datasets (IDWR site 13126500), and from IDWR (2020d).

[3]Surface-water diversion datasets were accessed from IDWR (2020d).

Table 9.3. Estimated seepage, below Mackay Reservoir (USGS streamgage 13127000) to Leslie (Idaho Power streamgage 13130500), in the Big Lost River below Mackay Dam, south-central Idaho, 2000–19.

[All values in ***bold italics*** are estimated. Groundwater budget includes seepage using tributary flows. All values in the table are in acre-feet per year. Negative seepage values indicate a losing reach condition and positive values indicate a gaining reach condition. **Abbreviations:** USGS, U.S. Geological Survey; IDWR, Idaho Department of Water Resources]

Year	Leslie streamgage[1]	Below Mackay Reservoir streamgage[2]	Diversions[3]	Groundwater pumpage to canals[3]	Alder Creek	Seepage without Alder Creek	Seepage with Alder Creek
2000	***117,288***	166,785	35,191	958	***5,219***	***–15,025***	***–20,244***
2001	***77,737***	125,025	16,383	664	***3,818***	***–31,376***	***–35,194***
2002	***79,811***	127,215	17,886	1,070	***4,432***	***–30,278***	***–34,709***
2003	***88,380***	136,262	24,362	0	***7,072***	***–23,520***	***–30,592***
2004	***71,726***	118,678	25,989	0	***5,488***	***–20,963***	***–26,450***
2005	***142,102***	192,984	33,289	0	***11,022***	***–17,594***	***–28,616***
2006	***226,970***	282,593	43,284	0	***10,899***	***–12,340***	***–23,239***
2007	109,766	146,563	29,242	1,716	***4,141***	***–8,824***	***–12,965***
2008	101,714	158,050	26,774	1,595	***4,524***	***–30,743***	***–35,267***
2009	126,101	214,110	33,161	502	***10,047***	***–55,229***	***–65,275***
2010	158,010	197,374	30,865	451	***9,937***	***–8,837***	***–18,774***
2011	197,177	226,776	32,448	0	***8,857***	***2,849***	***–6,008***
2012	154,033	203,830	36,036	687	***9,935***	***–14,283***	***–24,217***
2013	108,551	154,056	24,800	3,070	***3,221***	***–22,947***	***–26,167***
2014	66,380	117,527	27,271	2,269	***5,287***	***–25,533***	***–30,820***
2015	85,869	147,272	23,316	1,561	***5,391***	***–39,226***	***–44,617***
2016	124,927	175,586	27,330	307	***10,301***	***–23,554***	***–33,854***
2017	324,165	393,734	49,518	0	***21,139***	***–20,050***	***–41,189***
2018	230,369	279,410	41,606	69	***7,967***	***–7,483***	***–15,450***
2019	192,147	233,533	43,481	0	***10,370***	***2,095***	***–8,275***
Mean	139,161	189,868	31,112	746	***7,953***	***–20,143***	***–28,096***

[1]Streamflow datasets were accessed from Idaho Power (2020).

[2]Streamflow datasets were accessed from U.S. Geological Survey (2020).

[3]Surface-water diversion and groundwater pumpage datasets were accessed from IDWR (2020d).

Table 9.4. Estimated seepage, Leslie (Idaho Power streamgage 13130500) to Arco (USGS streamgage 13132500), in the Big Lost River below Mackay Dam, south-central Idaho, 2000–19.

[All values in ***bold italics*** are estimated. Groundwater budget includes seepage using tributary flows. All values in the table are in acre-feet per year. Negative seepage values indicate a losing reach condition and positive values indicate a gaining reach condition. **Abbreviations:** USGS, U.S. Geological Survey; IDWR, Idaho Department of Water Resources]

Year	Arco streamgage[1]	Leslie streamgage[2]	Diversions[3]	Groundwater pumpage to canals[3]	Burnett TE return flow[4]	East Side Out return flow (13132350)[5]	Antelope Creek (13131000)[1]	Seepage without Antelope Cr.	Seepage with Antelope Cr.
2000	17,580	***117,288***	75,503	0	***1,639***	***12,992***	***25,229***	***–38,837***	***–64,065***
2001	0	***77,737***	31,058	0	***728***	***10,074***	***18,560***	***–57,481***	***–76,041***
2002	0	***79,811***	35,204	0	***673***	***10,509***	***21,579***	***–55,789***	***–77,367***
2003	0	***88,380***	39,528	0	***1,023***	11,909	***32,372***	***–61,783***	***–94,155***
2004	0	***71,726***	31,399	0	***1,041***	9,629	***27,083***	***–50,997***	***–78,080***
2005	3,995	***142,102***	73,852	0	***1,659***	11,249	***52,823***	***–77,162***	***–129,985***
2006	36,642	***226,970***	119,005	0	***2,130***	15,061	***51,239***	***–88,515***	***–139,753***
2007	0	109,766	56,521	0	***1,397***	14,219	***20,419***	***–68,861***	***–89,280***
2008	0	101,714	60,005	0	***1,229***	12,462	***22,311***	***–55,400***	***–77,712***
2009	9,273	126,101	78,390	0	***1,628***	12,834	***47,129***	***–52,901***	***–100,029***
2010	3,830	158,010	76,857	0	***1,458***	6,115	***47,041***	***–84,897***	***–131,938***
2011	18,494	197,177	95,844	0	***1,688***	*16,139*	***40,377***	***–100,667***	***–141,043***
2012	10,049	154,033	94,910	0	***1,711***	19,746	***47,132***	***–70,531***	***–117,663***
2013	305	108,551	58,946	0	***1,044***	14,751	***14,872***	***–65,094***	***–79,966***
2014	0	66,380	26,065	6,739	***1,146***	7,329	***26,103***	***–52,699***	***–78,802***
2015	0	85,869	36,642	0	***1,066***	8,424	***25,736***	***–58,718***	***–84,453***
2016	0	124,927	55,630	0	1,217	11,620	***48,370***	***–82,134***	***–130,504***
2017	100,189	324,165	106,363	0	506	15,277	***94,831***	***–133,395***	***–228,226***
2018	82,880	230,369	89,052	0	2,458	18,376	65,860	***–79,270***	***–145,131***
2019	45,134	192,147	91,832	0	2,349	10,147	70,413	***–67,678***	***–138,090***
Mean	16,419	139,161	66,630	337	1,390	12,443	39,974	***–70,140***	***–110,114***

[1]Streamflow datasets were accessed from U.S. Geological Survey (2020).

[2]Streamflow datasets were accessed from Idaho Power (2020).

[3]Surface-water diversion and groundwater pumpage datasets were accessed from IDWR (2020d).

[4]Burnett TE return flow datasets were accessed from PivoTrac Monitoring (http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021; data available upon request from Water District 34 watermaster, Lucas Yockey, at 208-589-3183).

[5]East Side Out return flow datasets were accessed from IDWR (2020d) during 2003–10 and 2012–19 and from PivoTrac Monitoring (http://www.pivotrac.com/, contracted to Water District 34, unpub. data, 2021; data available upon request from Water District 34 watermaster, Lucas Yockey, at 208-589-3183) for 2015–19.

The Moore streamgage location (IDWR site 13132100 and USGS streamgage 13132100) ultimately was not selected for river-seepage analysis because of insufficient available data during the study period. Substantial flow was diverted from the Big Lost River to the Moore Canal (IDWR site 13132050) and East Side Ditch (IDWR site 13132060) above the Moore streamgage location. The Moore Canal and East Side Ditch measured diversions and estimated streamflow at the Moore streamgage (IDWR site 13132100)[2] were reported in the IDWR Water District surface-water diversion database (IDWR, 2020d) and in the IDWR water rights accounting database (IDWR, 2020e) in diversion units of cubic feet per day instead of in flow units of cubic feet per second. Flow rates at the Moore streamgage (USGS streamgage 13132100) installed by the USGS in 2019 (U.S. Geological Survey, 2020) were reported in cubic feet per second, resulting in different estimated mean flows for 2019 when compared to the total annual flow in the diversion database[3]. The mean streamflow for the period from March 25, 2019, to December 31, 2019, reported by the USGS at the Moore streamgage, was 135.6 cubic feet per second (ft^3/s; 98,200 acre feet per year [acre-ft/yr]). This flow was substantially greater than reported in IDWR records during prior years at IDWR site 13132100. Before streamgage instrumentation in 2019, data reported for the Moore location typically reflected the irrigation season but not other times when flow might occur. Records indicate that values were either measured, estimated, or interpolated. Estimates of Big Lost River flows at Moore were not reported for 2006, 2007, 2011, and 2015. Some flow likely occurred during wet years such as 2006 and 2011 or outside the irrigation season. Measured flow at the downstream USGS Arco streamgage (13132500) in wet years suggests that unmeasured flow likely occurred at Moore during wet years and non-irrigation periods.

Unmeasured Tributary Streamflow Assumptions

Flows historically were monitored by the USGS on Antelope Creek at two streamgage locations: 13130900 above Cherry and Dry Fork Creeks from 1966 to 1974, and 13131000 below the confluence of Waddoups Canyon at the current streamgage site, intermittently from 1913 to 1922 and again from 2017 to present. Alder Creek was monitored at USGS streamgage 13129800 from 1966 to 1968, and USGS streamgage 13130000 was active from 1920 to 1922 and again from 2018 to present. Warm Springs Creek was monitored at USGS streamgage 13124500 from 1919 to 1959 and at the current USGS streamgage 13124265 from 2019 to the present. The west channel of Warm Springs Creek was monitored at USGS streamgage 13125000 from 1919 to 1959. Pass Creek was monitored at USGS streamgage 13131500 intermittently from 1920 to 1922 and again from 2002 to present. Streamgage datasets may be accessed from the USGS (U.S. Geological Survey, 2020). Crosthwaite and others (1970a) summarized miscellaneous streamflow measurements (1966–68) at several gaged and ungaged stream locations. Although historical conditions may not reflect the 2000–19 study period, available datasets were reviewed to provide a general indication of the timing and magnitude of potential flows.

StreamStats (U.S. Geological Survey, 2016) flagged some results returned during tributary basin delineation as having one or more parameters outside the range of the basin characteristics for the sites used to develop the supporting regression equations, causing the results to be extrapolated. Hortness and Berenbrock (2001) prepared regression equations for the Big Lost Basin as part of an evaluation of ungaged tributary basins using three streamgages (North Fork of the Big Lost River at Wild Horse, Big Lost River at Howell Ranch, and Lower Cedar Creek), with a reported median (Q50) standard error range of –55 to +120 percent. Therefore, estimates of unmeasured streamflow within the Big Lost River Basin may include appreciable errors related to the regression equations.

Total annual precipitation derived from Parameter-elevation Regressions on Independent Slopes Model (PRISM; PRISM Climate Group, 2020) was compiled for the same tributary drainage areas, and the deviation from the average precipitation from 2000 to 2019 was used to estimate annual streamflow by adjusting accordingly the predicted StreamStats (U.S. Geological Survey, 2016) median streamflow. Use of the mean annual streamflow estimate typically either overestimated or underestimated streamflow compared to measured streamflow. However, few years were available to evaluate trends. Therefore, a flow-duration statistic (20-percent flow exceedance [Q20], Q50, or 80-percent flow exceedance [Q80]) was assigned to a given year based on the relative wet-, average-, or dry-year conditions, respectively. Years 2000–02, 2004, 2007–08, and 2013–15 overall were dry (assigned the Q80 statistic), 2017 was assigned as the Q20 statistic, and the remainder of the years were assigned the Q50 statistic. Comparison of estimated to measured streamflow and the mean annual flow duration curves over the respective available period of record for the North Fork at Wild Horse and Howell Ranch USGS streamgages (U.S. Geological Survey, 2020) was used to guide assignment of annual flow-duration statistics. This assignment was somewhat subjective and likely did not reflect actual, unmeasured flows. However, the estimated tributary streamflow was well correlated (R^2 of about 0.74–0.87)

[2]A measuring device was installed by IDWR at IDWR site 13132100 in 2016 but was removed in 2017 because of flooding concerns (D. Hoekema, IDWR, written commun., 2021).

[3]Measured and estimated diversions and streamflow were converted to acre feet per year for the water budget. Daily diversions were summed over the calendar year and converted from units of cubic feet per second per day to acre-feet per foot per year as 1 acre foot year = (cubic feet per second per day×60×60×24)/43,560. Mean annual stream streamflow is converted from units of cubic feet per second to acre-feet year as 1 acre-foot per year = (cubic feet per second x 60×60×24×365)/43,560.

with measured streamflow at USGS streamgages at the North Fork at Wild Horse (13120000), Howell Ranch (13120500), and below Mackay Reservoir (13127000).

Precipitation and streamflow seem to be somewhat correlated from 2000 and 2019 (R^2=0.58) based on linear regression of the North Fork at Wild Horse USGS streamgage average annual streamflow, with total annual precipitation over the drainage area. The adjusted median estimated streamflow, using variable flow-duration statistics for the North Fork of the Big Lost River at Wild Horse, seems to reasonably match measured streamflow during the study period (fig. 9.1).

Historical streamflow measurements were compared with estimated streamflow for several tributary streams including Alder, Antelope, Thousand Springs, and Warm Springs Creeks and the East Fork of the Big Lost River, below the diversions (fig. 9.2). Different vertical scales in figure 9.2 are used to emphasize comparison of measured and estimated streamflow.

The results of the river-seepage analysis (tables 9.1 and 9.2 for reaches above Mackay Dam and tables 9.3 and 9.4 for reaches below Mackay Dam) indicate the uncertainty in estimating unmeasured tributary flows. The effects of surface-water diversions, such as within the Antelope Creek drainage, may bias the results. The groundwater budget reflects inclusion of the estimated flows; however, estimated seepage is presented without tributary contribution for comparison, which may represent relatively dry-year conditions in the study period. Future monitoring of tributary flows (such as Thousand Springs and Antelope Creeks) at streamgage locations installed by the USGS as part of this study (U.S. Geological Survey, 2020) should reduce uncertainty associated with representation in any future water budgets.

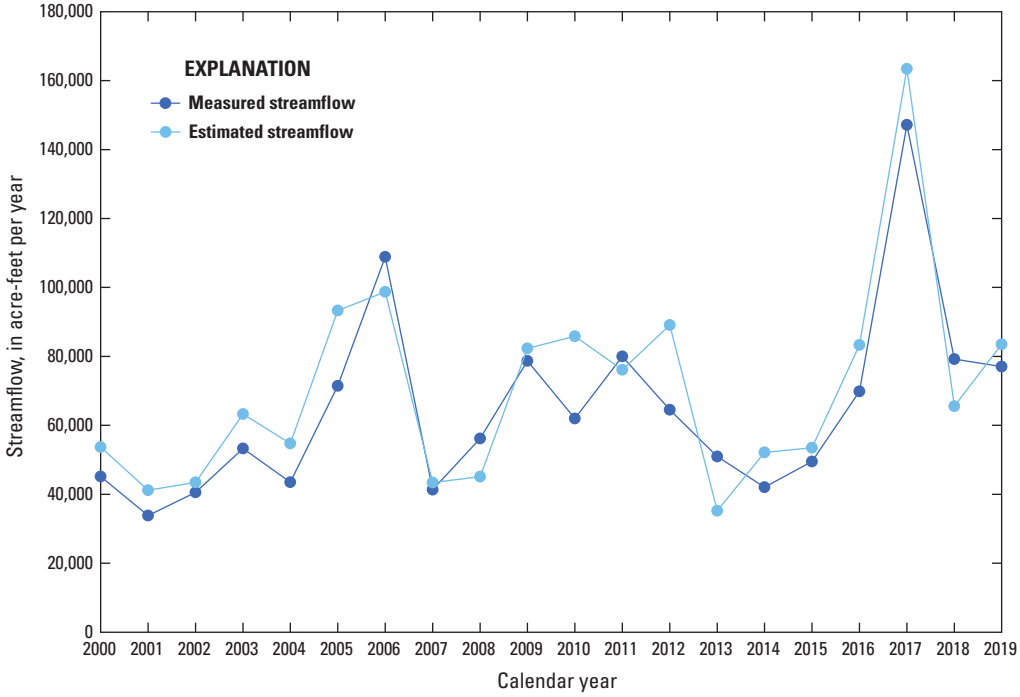


Figure 9.1. Measured and estimated mean annual streamflow at North Fork Big Lost River at Wild Horse (U.S. Geological Survey streamgage 13120000; U.S. Geological Survey, 2020), 2000–19.

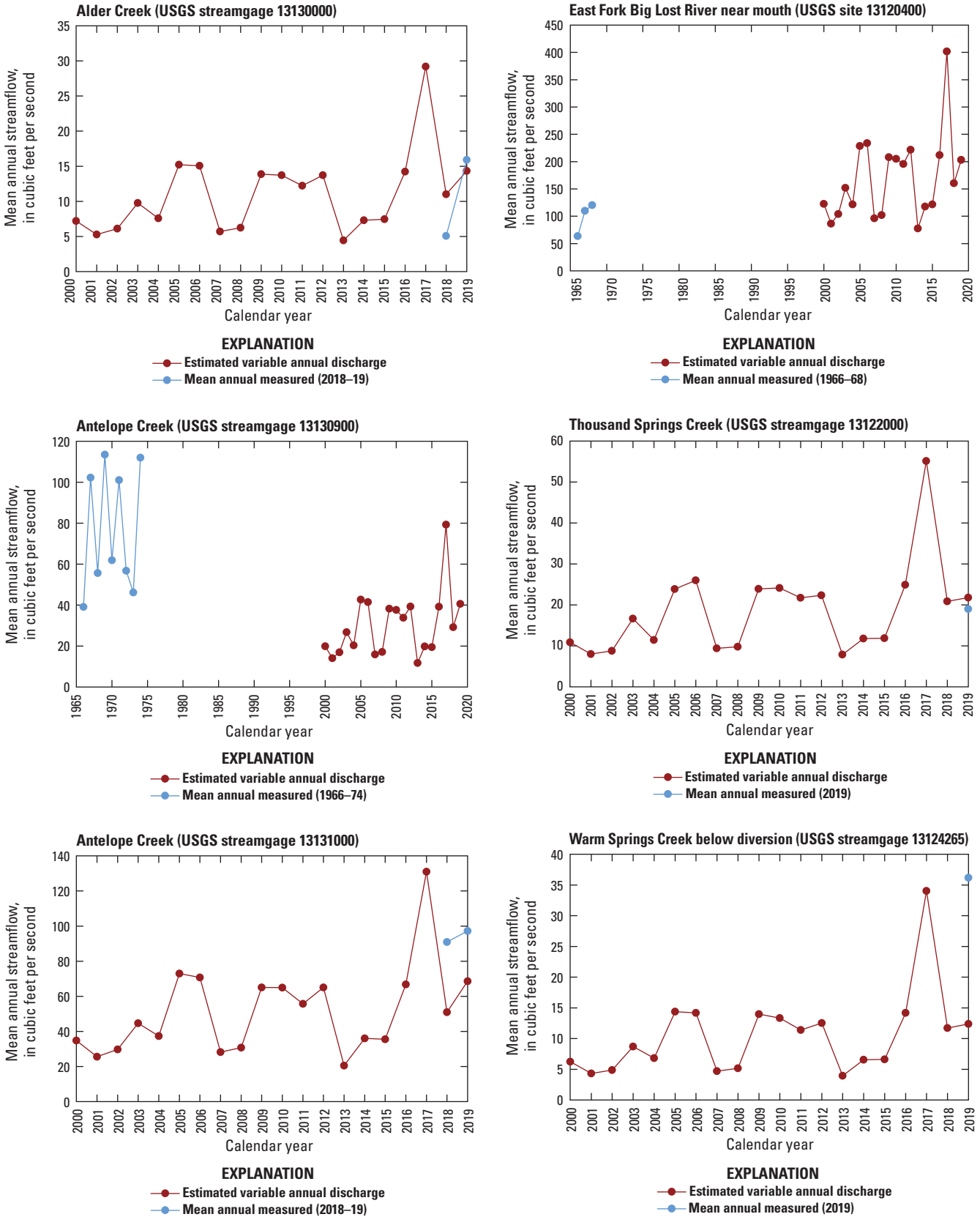


Figure 9.2. Measured and estimated tributary streamflow for the Big Lost River Basin, south-central Idaho, 2000–19. Measured values from U.S. Geological Survey, 2020. USGS, U.S. Geological Survey.

References Cited

Crosthwaite, E.G., Thomas, C.A., and Dyer, K.L., 1970a, Water resources in the Big Lost River Basin, south-central Idaho: U.S. Geological Survey Open-File Report 70-93, 123 p., accessed February 20, 2022, at https://doi.org/10.3133/ofr7093.

Hortness, J.E., and Berenbrock, C., 2001, Estimating monthly and annual streamflow statistics at ungaged sites in Idaho: U.S. Geological Survey Water-Resources Investigations Report 01–4093, 37 p., accessed September 7, 2018, at https://doi.org/10.3133/wri014093.

Idaho Department of Water Resources [IDWR], 2020d, Water District surface-water diversion database: Idaho Department of Water Resources database, accessed 2020, at https://idwr.idaho.gov/apps/wm/DiversionDataApplication/AnnualSummary.aspx.

Idaho Department of Water Resources [IDWR], 2020e, Water rights accounting database: Idaho Department of Water Resources web page, accessed May 25, 2022, at https://research.idwr.idaho.gov/apps/Hydrologic/Accounting/.

Idaho Power, 2020, Leslie gage station (13130500) data: Idaho Power database, accessed March 9, 2020, at https://idastream.idahopower.com/Data/Export.

PRISM Climate Group, 2020, PRISM climate data: Corvallis, Oregon State University PRISM web page, accessed November 1, 2020, at https://prism.oregonstate.edu/.

U.S. Geological Survey, 2016, StreamStats—Streamflow statistics and spatial analysis tools for water-resources applications: U.S. Geological Survey web page, accessed August 30, 2021, at http://streamstats.usgs.gov.

U.S. Geological Survey, 2020, National Water Information System—Web interface—USGS water data for Idaho: U.S. Geological Survey database, accessed June 20, 2020, at https://waterdata.usgs.gov/id/nwis and https://doi.org/10.5066/F7P55KJN.

Appendix 10. Evapotranspiration

Abbreviations

ARC	Arco 3 SW (station)
CDL	cropland data layer (CropScape)
CHA	Chilly Barton Flat (station)
CIR	crop irrigation requirement
ESPAM	Eastern Snake Plain Aquifer Model (formerly referred to as the Enhanced Snake Plain Aquifer Model)
ET	evapotranspiration
IDWR	Idaho Department of Water Resources
MAC	Mackay Ranger Station
METRIC	Mapping EvapoTranspiration at high Resolution and Internalized Calibration
NDVI	Normalized Difference Vegetation Index
NLCD	National Land Cover Database

Evapotranspiration (ET) is used in the preparation of several groundwater-budget components including areal recharge (see section, "Areal Recharge"), recharge from applied irrigation water (see section, "Applied Irrigation"), and in estimates of unmeasured groundwater pumpage (see section, "Groundwater Pumpage"). ET includes evaporation and plant transpiration processes and is controlled by several factors including weather (solar radiation, humidity, and wind speed), vegetation type and growth stage, soil conditions, available moisture, and other factors (Jensen and Allen, 2016). ET represents a significant contribution of water lost from groundwater to the atmosphere. Actual ET varies considerably throughout the year, with higher rates during the irrigation season and lower rates during autumn and winter when plants are dormant and snow covers much of the ground surface. Typical rates for highly consumptive crops, such as alfalfa, in the Big Lost River Basin can range from about 450 to 1,100 millimeters per year (mm/yr) at the Arco weather station (fig. 1), based on the data sources and measurement techniques discussed herein.

Estimated ET values include all land-use categories (irrigated, semi-irrigated, and non-irrigated; Idaho Department of Water Resources [IDWR], 2020a) over the full calendar year, irrigation season (April–October), and winter (January–March and November–December). The total estimated mean ET for the Big Lost River Basin was 1,015,200 acre-feet per year (acre-ft/yr) over the 2000–19 investigation period, 972,300 acre-feet (acre-ft) in 2014 (dry year), and 1,102,400 acre-ft in 2017 (wet year), making ET an important process for reducing potential recharge. The lowest total ET occurred in 2008 (691,800 acre-ft), and the highest total ET occurred in 2015 (1,381,700 acre-ft). The median annual ET (1,014,800 acre-ft) for the entire basin was close to the average annual ET during 2000–19 (fig. 10.1).

Vegetation in the Big Lost River Basin includes cultivated crops on irrigated lands (primarily alfalfa, hay, and other grain crops) and natural rangeland vegetation typical of high-desert dry climates and wet, localized riparian corridors or wetlands next to rivers and canals on non-irrigated lands. Deciduous and coniferous forests are typical at high altitudes.

Actual ET, instead of potential ET, is used in the groundwater-budget calculations. Various methods have been used in hydrologic investigations for estimating actual ET at the basin scale throughout the Western U.S. for typical crop and land covers. Allen and others (2007) described approaches based on energy balance methods, temperature methods, and satellite-based energy balance methods. Satellite-based energy balance methods are used here.

The following two types of data sources for actual ET are available for the Big Lost River Basin: (1) weather station ET data published through a searchable database providing evapotranspiration and irrigation data by land-cover type for weather stations across Idaho (ET_{Idaho}; Allen and Robison, 2017, and University of Idaho, 2018); and (2) remotely sensed datasets, METRIC ET (IDWR, 2021b) and the Normalized Difference Vegetation Index (NDVI) ET datasets (U.S. Geological Survey, 2017; obtained for convenience from IDWR staff [B. Kramber, IDWR, written commun., June 19, 2019]). The emphasis for METRIC calibration is on irrigated agriculture for well-watered reference crops such as alfalfa (Allen and others, 2013), as METRIC is not specifically calibrated for non-irrigated land-cover types including rangeland and grasslands (R. Allen, University of Idaho, written commun., 2020). Allen and others (2013) provided further details regarding calibration of METRIC.

ET for a reference crop (alfalfa) is calculated in ET_{Idaho} by relating latent heat flux to net radiation, soil heat flux density, specific heat of dry air, air density, and air and surface resistance terms (Jensen and Allen, 2016). Daily actual ET datasets were accessed from the ET_{Idaho} web page (University of Idaho, 2018) for Chilly Barton Flat (CHA), Mackay Ranger Station (MAC), and Arco 3 SW (ARC) weather stations (fig. 1). ET values then were summed over monthly and calendar year periods. Irrigation season (April–October) and winter season (January–March, November, and December) periods were compiled separately.

Shrublands constitute much of the vegetation on non-irrigated lands and were assigned representative ET values based on ET_{Idaho}-published sagebrush rates (Allen and Robison, 2017; University of Idaho, 2018). However, uncertainty arises from the need to select ET_{Idaho} categories that do not clearly correspond with National Land Cover Database

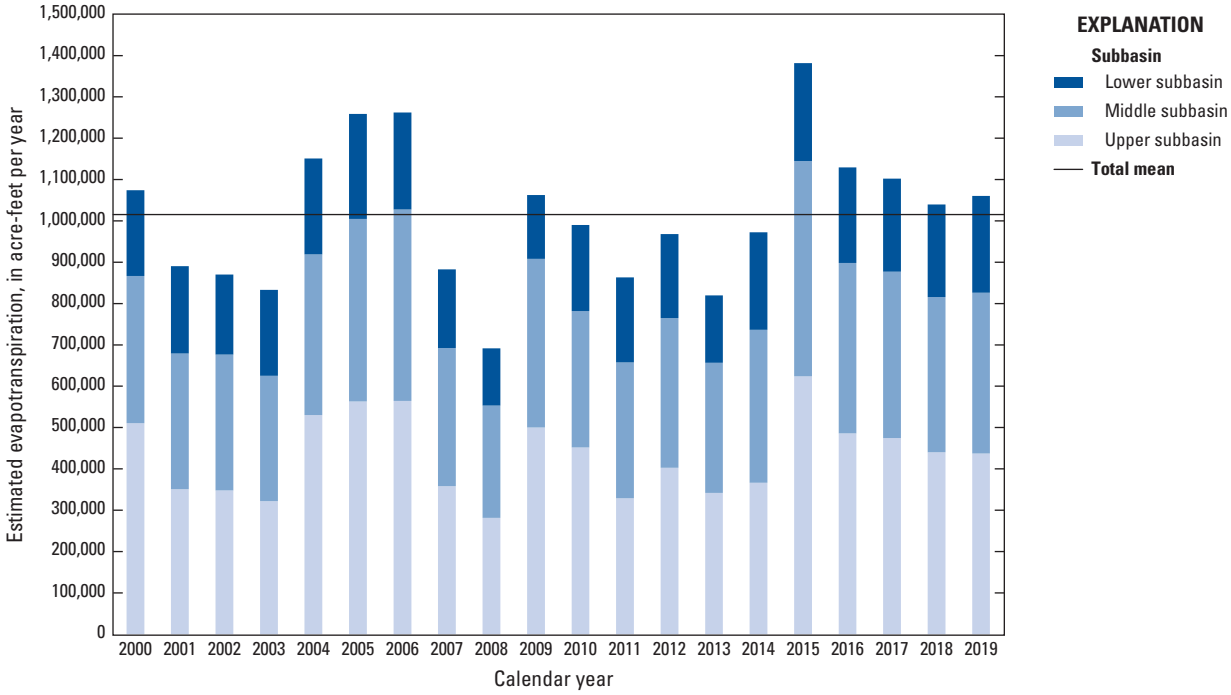


Figure 10.1. Total annual evapotranspiration, Big Lost River Basin, south-central Idaho, 2000–19. See table 10.1 for data sources used in calculations and tables 10.2 and 10.3 for evapotranspiration volumes.

(NLCD; Multi-Resolution Land Characteristics Consortium, 2019) or cropland data layer (CDL, CropScape; National Agricultural Statistics Service, 2020a, 2020b) classifications. Further discussion of assumptions used to assign NLCD and CDL classifications to ET_{Idaho} classes is provided in appendix 1 ("Land Coverage").

The second source of ET data is remotely sensed, Landsat-based digital raster products available as monthly METRIC[1] and NDVI[2] 30-meter (m) resolution rasters over the irrigation season (April–October). METRIC and NDVI data offer several advantages over ET_{Idaho} in that land cover does not need to be explicitly known or approximated, and coverages provide for a high degree of spatial and temporal resolution and accuracy appropriate for basin-scale water resource applications. Allen and others (2007) described METRIC application in Idaho hydrogeologic studies including water-resource planning, groundwater budgets, water-rights compliance monitoring, aquifer-depletion scenarios, and numerical groundwater-flow models, among other uses. NDVI data, available for 2014 in the Big Lost River Basin, was used in the absence of METRIC coverage.

The preferred approach for estimating ET for this study used METRIC (or NDVI) datasets during the irrigation season, to the extent available, and ET_{Idaho}-derived actual ET values based on either CDL or NLCD land-use classification when METRIC was not available and for winter months. CDL is preferred over NLCD for irrigated and semi-irrigated lands because it represents crop-specific land covers. NLCD is preferred for non-irrigated lands. Preferences are informed by reported accuracy associated with the land-cover data (National Agricultural Statistics Service, 2019).

Few years have coincident METRIC data, irrigated-land datasets, and NLCD and CDL coverages available for the same year. METRIC and NDVI datasets are not available for all years in the study period. ET_{Idaho} data spans 2000–16 (Allen and Robison, 2017; University of Idaho, 2018); published ET values are not available for 2017–19. Therefore, 2016 ET_{Idaho} values were used to represent 2017–19 ET (table 10.1). Missing daily ET_{Idaho} rates for actual ET (particularly during July 2009) were assigned either average values for the closest dates or the average of prior and subsequent years (2008 and 2010 for this example).

[1]This method uses an image-processing algorithm to calculate monthly and seasonal ET as a residual of the surface energy balance equation relating latent energy consumed by ET to net radiation and sensible heat flux terms (conducting from the ground and convecting into the atmosphere). The METRIC method was adapted from the Surface Energy Balance Algorithm for Land (SEBAL) for use in mountainous terrain (Allen and others, 2005) and is calibrated for well-watered vegetation types (irrigated crops and wetlands). Allen and others (2013) described limitations when applying METRIC in situations outside of the model's calibration parameters; for example, in dry, upland areas, in bare soil conditions, or during winter months when most vegetation tends to be dormant.

[2]NDVI uses red-band and near-infrared-band reflectance values to calculate the vegetation indices, with values ranging from -1.0 to +1.0. Vegetative cover is indicated by positive, increasing values (Glenn and others, 2011).

Table 10.1. Assignment of irrigated lands for the water-budget analysis of the Big Lost River Basin, south-central Idaho, 2000–19.

[**ET_{Idaho}:** Searchable database (Allen and Robison, 2017; University of Idaho, 2018) providing evapotranspiration and irrigation data by land-cover type for weather stations across Idaho. The use of CDL or NLCD datasets corresponds with ET_{Idaho}-derived ET as opposed to METRIC-derived ET.: **Abbreviations:** CDL, cropland data layer (CropScape); METRIC, Mapping EvapoTranspiration at high Resolution and Internalized Calibration; NLCD, National Land Cover Database; NDVI, Normalized Difference Vegetation Index

Year	Irrigated lands dataset	Irrigation season	Winter land cover	ET_{Idaho}
2000	2000	2000 METRIC	2001 NLCD	2000
2001	2002	2001 NLCD	2001 NLCD	2001
2002	2002	2002 METRIC	2001 NLCD	2002
2003	2002	2004 NLCD	2004 NLCD	2003
2004	2004	2004 NLCD	2004 NLCD	2004
2005	2006	2006 NLCD[1,2]	2006 NLCD	2005
2006	2006	2006 METRIC	2006 NLCD	2006
2007	2008	2007 CDL	2007 CDL	2007
2008	2008	2008 METRIC	2008 CDL	2008
2009	2009	2009 METRIC	2009 CDL	2009
2010	2010	2010 METRIC	2010 CDL	2010
2011	2011	2011 METRIC	2011 CDL	2011
2012	2012	2012 CDL	2012 CDL	2012
2013	2013	2013 METRIC	2013 CDL	2013
2014	2014	2014 NDVI[3]	2014 CDL	2014
2015	2015	2015 METRIC	2015 CDL	2015
2016	2016	2016 METRIC	2016 CDL	2016
2017	2017	2017 METRIC	2017 CDL	2016[7]
2018	2017[4]	2018 METRIC	2018 CDL	2016[7]
2019	2017[5]	2019 CDL[6]	2019 CDL	2016[7]

[1]CDL coverage for 2005 covers only the southern part of the basin. CDL datasets were obtained from National Agricultural Statistics Service (2020a, 2020b).

[2]NLCD datasets were accessed from Multi-Resolution Land Characteristics Consortium (2019).

3NDVI datasets were accessed from U.S. Geological Survey (2017).

[4]2018 was drier than 2017 but Mackay Reservoir storage was comparable to that of 2017.

[5]2019 precipitation, snow accumulation, and reservoir storage are similar to that of 2012.

[6]METRIC datasets for 2019 were not available in time for inclusion in the water budget. METRIC datasets were accessed from the IDWR (2021b).

[7]ET_{Idaho} values were not available after 2016.

Table 10.2. Total estimated annual evapotranspiration volumes on irrigated and semi-irrigated lands in the Big Lost River Basin, south-central Idaho, 2000–19.

[See table 10.1 for evapotranspiration data sources. All units are in acre-feet per year for calendar years 2000–19 over the irrigation season (April–October) and winter (January–March and November–December)]

Year	Irrigated lands						Semi-irrigated lands					
	Upper subbasin		Middle subbasin		Lower subbasin		Upper subbasin		Middle subbasin		Lower subbasin	
	Irrigation season	Winter	Irrigation season	Winter	Irrigation season	Winter	Irrigation season	Winter	Irrigation season	Winter	Irrigation season	Winter
2000	20,298	1,053	41,137	3,761	57,608	6,140	738	87	2,415	350	2,315	369
2001	17,955	837	56,567	2,568	74,987	4,693	703	65	3,892	246	4,637	310
2002	16,941	975	50,254	2,530	52,114	3,803	567	73	3,707	236	3,584	253
2003	19,095	700	56,470	2,258	78,210	3,506	637	49	3,673	220	4,911	243
2004	22,450	1,265	57,011	2,751	72,857	4,555	884	90	3,505	194	4,632	293
2005	14,675	652	58,266	2,962	75,841	4,220	795	64	4,128	265	5,164	295
2006	26,621	956	57,329	3,202	58,350	4,755	1,195	73	3,849	286	3,472	328
2007	15,845	889	55,947	3,462	70,806	1,633	750	66	3,765	292	4,489	126
2008	17,417	826	44,736	3,676	46,108	3,030	658	57	2,097	301	1,871	217
2009	20,501	1,267	49,819	4,018	55,612	4,431	796	92	3,023	318	3,043	271
2010	17,755	873	46,710	3,830	47,899	5,983	874	126	2,903	279	2,241	341
2011	21,042	495	53,031	3,007	60,573	3,381	760	32	1,929	147	2,557	164
2012	20,720	1,127	51,613	4,966	60,214	4,546	873	111	2,398	334	2,638	223
2013	17,188	735	57,458	2,322	68,050	2,491	645	59	2,057	167	1,842	143
2014	30,831	1,224	78,056	4,562	80,855	4,257	1,689	106	5,054	277	4,784	240
2015	30,068	1,135	77,357	4,072	72,615	4,354	1,618	84	4,634	258	3,452	241
2016	20,255	1,346	60,594	4,900	64,377	6,655	756	108	2,335	325	1,923	322
2017	22,475	1,559	59,749	4,980	60,931	6,568	826	109	2,344	311	2,111	306
2018	23,104	1,512	58,941	5,081	63,814	6,596	928	109	2,478	336	2,298	329
2019	28,996	1,592	75,085	5,141	80,404	6,442	1,154	111	4,098	362	4,246	395
Mean	21,212	1,051	57,307	3,702	65,111	4,602	892	84	3,214	275	3,310	270

Table 10.3. Total estimated annual evapotranspiration volumes on non-irrigated lands in the Big Lost River Basin, south-central Idaho, 2000–19.

[See table 10.1 for evapotranspiration data sources. All units are in acre-feet per year for calendar years 2000–19 over the irrigation season (April–October) and winter (January–March and November–December)]

Year	Upper subbasin		Middle subbasin		Lower subbasin	
	Irrigation season	Winter	Irrigation season	Winter	Irrigation season	Winter
2000	443,257	44,885	267,774	41,093	113,463	27,441
2001	299,107	32,361	236,716	28,188	103,167	23,394
2002	292,211	37,113	244,536	27,240	114,334	19,784
2003	277,372	24,289	215,063	25,190	102,386	18,740
2004	460,072	45,698	295,742	29,147	131,499	18,257
2005	515,346	31,464	345,908	30,383	148,743	19,591
2006	498,323	37,144	365,643	32,861	146,133	21,862
2007	307,869	33,025	238,416	32,213	104,042	9,247
2008	231,997	30,587	185,329	35,588	70,713	16,563
2009	425,494	51,833	310,344	40,801	70,351	20,615
2010	381,957	50,265	239,035	37,211	122,305	29,303
2011	285,627	21,049	242,084	28,170	122,859	16,158
2012	325,866	53,986	252,692	50,106	113,497	22,100
2013	295,733	27,623	231,309	21,451	78,354	12,196
2014	278,659	53,936	241,496	40,546	124,044	21,711
2015	549,370	41,430	400,222	34,536	135,956	20,259
2016	409,012	54,515	301,831	42,342	133,504	24,319
2017	395,449	54,471	292,756	42,241	130,869	24,337
2018	345,124	69,503	257,471	51,102	126,442	24,534
2019	335,931	69,590	252,790	51,266	117,852	24,788
Mean	367,689	43,238	270,858	36,084	115,526	20,760

Estimated annual ET volumes (table 10.2 for irrigated and semi-irrigated lands; table 10.3 for non-irrigated lands; table 10.4 for the entire basin; fig. 10.1) highlight spatial and temporal differences in ET for each part of the basin (upper, middle, and lower subbasins) with respect to irrigated, semi-irrigated, and non-irrigated lands for irrigation and winter seasons over each calendar year. Total ET does not include buffered areas (described in section, "Evapotranspiration Buffers"), which are already accounted for in the non-irrigated lands estimate. Higher overall mean annual ET in the upper subbasin (434,200 acre-ft/yr) compared to the middle subbasin (371,500 acre-ft/yr) and the lower subbasin (209,600 acre-ft/yr) is attributed to the larger area for the upper subbasin[3]. However, the total combined ET in the middle and lower subbasins is greater than the total ET in the upper subbasin, primarily owing to more crop production with higher ET rates below the dam (1.1 acre-ft/acre in the middle and lower subbasins compared to 0.9 acre-ft/acre in the upper subbasin). In recent years, 10,000 to11,000 acres have been irrigated in the upper subbasin compared to about 54,000 acres combined in the middle and lower subbasins, table 10.2 (IDWR, 2020a).

Total ET exceeded total precipitation during 2013 and 2015 in the middle subbasin (15,600 and 19,100 acre-ft, respectively). In the lower subbasin, ET exceeded precipitation (by as much as 63,700 acre-ft in 2013) during all but the wettest years (2008–09 and 2017). Other wet years (2005 and 2016) had small deficits. Higher ET conditions during 2015 are attributed to higher-than-average ET on non-irrigated lands, primarily because of high ET for sagebrush reported in ET_{Idaho} datasets (Allen and Robison, 2017; University of Idaho, 2018). Precipitation greatly exceeded ET in the upper subbasin during the entire study period (average of 456,400 acre-ft/yr).

Several assumptions applied during ET processing influenced overall estimates. These factors and necessary assumptions may have led either to overestimation or underestimation of actual ET:

[3]The total estimated acres using the ArcGIS geometry tool (Esri, 2018, 2020) are as follows: upper subbasin (509,800 acres), middle subbasin (335,930 acres), and lower subbasin (183,600 acres).

Table 10.4. Total estimated annual evapotranspiration volumes in the Big Lost River Basin, south-central Idaho, 2000–19.

[See table 10.1 for evapotranspiration data sources. All units are in acre-feet per year for calendar years 2000–19 over the irrigation season (April–October) and winter (January–March and November–December]

Year	Total basin		
	Irrigation season	Winter	Year
2000	949,005	125,179	1,074,184
2001	797,731	92,663	890,394
2002	778,247	92,008	870,255
2003	757,816	75,195	833,011
2004	1,048,651	102,249	1,150,900
2005	1,168,865	89,896	1,258,761
2006	1,160,915	101,467	1,262,382
2007	801,929	80,953	882,882
2008	600,925	90,846	691,771
2009	938,984	123,646	1,062,630
2010	861,678	128,211	989,889
2011	790,462	72,603	863,065
2012	830,510	137,498	968,009
2013	752,635	67,187	819,822
2014	845,469	126,859	972,328
2015	1,275,291	106,369	1,381,661
2016	994,587	134,833	1,129,420
2017	967,509	134,882	1,102,392
2018	880,600	159,102	1,039,702
2019	900,556	159,687	1,060,243
Mean	905,118	110,067	1,015,185

1. The choice of proxy years for selecting an approximate irrigated-land coverage when a particular year did not have a defined coverage contributed to uncertainty in the representation of ET and associated inputs to the groundwater budget including crop irrigation requirement (CIR), areal recharge, and recharge from applied irrigation. For example, 2017 irrigated lands were used to estimate ET for 2018 and 2019, and surrogate years were applied to many of the earlier years in the study.

2. Extrapolation of ET_{Idaho} values during 2016 to subsequent years during the study (2017–19) may have introduced errors in estimated ET. ET_{Idaho} values were not available during those years.

3. Improved ET estimates might be obtained by using correlations between precipitation and ET at finer time scales, such as daily or monthly periods.

4. A single ET value determined from ET_{Idaho} (without lapsed temperature compensation) was applied to represent the entire area when gridded METRIC data were not available. Assumptions also were made about specific crop types and irrigation practices.

5. The use of ET_{Idaho} values for specific weather stations may not be representative at all locations, particularly if climate conditions varied from those collected at Chilly, Mackay, and Arco weather stations used to estimate ET when METRIC coverage was not available.

6. Translation of land-use classification to ET_{Idaho}-specific land-cover types may have introduced sources of error related to incorrect classification (either in the source NLCD or CDL datasets or in the interpretation and assignment of ET rates using ET_{Idaho}). The results during earlier years in the study period (including 2000–07 with less METRIC coverage) may have been especially affected based on necessary assumptions. Assumptions about certain types of crops grown and farming practices may not reflect actual conditions.

Evapotranspiration Buffers

The irrigation drift phenomenon is apparent when comparing METRIC ET datasets, CDL and NLCD land-use classifications, and to some extent, aerial photographs. For example, METRIC ET datasets show elevated values (typically greater than about 400 millimeters) adjacent to some irrigated fields. Wind may cause applied irrigation to drift beyond the field. Ideally, this additional ET could be directly attributed to irrigation practices that could then be used to estimate groundwater pumpage and CIR volumes. However, actual applied irrigation is only one potential component of the elevated ET effects that may also include evaporation owing to cooler air temperatures next to irrigated fields or differences in Landsat satellite-based sensor resolution used in preparing METRIC datasets (McVay, 2018).

Elevated ET just beyond the irrigated fields may be readily distinguished from the surrounding areas, such as bare soil or shrubland with lower ET compared to crops, or may be less easily distinguished from wetlands with higher ET. CDL land-use classifications on some non-irrigated lands include crops (such as alfalfa, barley, and potatoes) and "other hay/non alfalfa" or "grass/pasture." Similarly, NLCD land-cover types within non-irrigated lands adjacent to irrigated fields include "cultivated crops" and "hay/pasture," suggesting that irrigation is occurring beyond the irrigated fields. Aerial imagery (National Agricultural Imagery Program, or NAIP[4], or Google Earth imagery [Google LLC, 2020]) sometimes supports

[4]NAIP datasets may be accessed from the U.S. Department of Agriculture Natural Resources Conservation Service at https://datagateway.nrcs.usda.gov/GDGHome_DirectDownLoad.aspx.

designation of these land-use categories associated with irrigation effects, but obvious confirmation of irrigation may not be apparent in the aerial photographs, perhaps depending on when the photograph was taken relative to when crops were actually grown and visual interpretation of actively cultivated compared to fallow fields.

One method for estimating the additional ET volumes within "non-irrigated" areas surrounding irrigated fields uses a buffer zone around the irrigated lands. Buffers were assigned around irrigated lands to estimate additional ET effects that occur beyond irrigated fields on "non-irrigated" lands. Different approaches are used for estimating ET on irrigated and semi-irrigated compared to non-irrigated lands. METRIC-derived values are used, when available, for irrigated and semi-irrigated lands. ET_{Idaho}-derived values are used for non-irrigated lands (Allen and Robison, 2017; University of Idaho, 2018). ET calculated within the buffered areas is added to ET determined for irrigated lands for the purposes of estimating total CIR. Overall, ET in buffered areas (just beyond the irrigated fields) represents 2–12 percent higher ET (average of 5 percent higher ET) compared to estimated ET without including the buffered radius.

An ideal buffer radius would only include those areas with elevated ET effects attributed to irrigation. The irregular distribution of elevated ET adjacent to irrigated fields and uncertainty about the background land-use type requires some assumptions. The Big Lost River Basin below Mackay Dam is included in the Eastern Snake Plain Aquifer Model (ESPAM; IDWR, 2013a). The model represents ET effects on irrigated lands using METRIC datasets, when available during the irrigation season, incorporating additional ET within a 90-m buffer surrounding irrigated lands[5] (McVay, 2018; J. Sukow, IDWR, written commun., 2019). To be consistent with ESPAM, a 90-m buffer was selected for comparing ET attributed to CDL or NLCD coverages for irrigated lands. For comparison, an alternative buffer was evaluated for 2009 and 2011 that included all non-irrigated areas that had crops or hay as assigned land-use types, without a fixed buffer using NLCD land-use types, with resulting ET volumes within 2–8 percent of the 90-m buffer results.

The groundwater budget includes estimated ET on all lands, including irrigated, semi-irrigated, and non-irrigated lands, during irrigation and winter seasons. Buffered ET for the irrigation season was used to estimate CIR and unmeasured irrigation pumpage. A clear method is not apparent for separating actual irrigation effects from atmospheric and thermal imagery residual effects. Therefore, irrigation pumpage and CIR likely are underestimated to some degree. The additional ET occurring within the buffer zone likely reflects the upper-end estimate of potential irrigation pumpage and CIR. A sensitivity assessment was done when estimating unmeasured irrigation pumpage using unbuffered and buffered ET, respectively, to represent low-end and high-end potential groundwater pumpage volumes.

Other land-use categories (including wetlands, forests, and developed areas) were excluded from the buffers. Underlying "background" areas were excluded from the buffer analysis. For example, if the CDL or NLCD land-use class indicated that a crop was grown, the corresponding METRIC or ET_{Idaho} value was assigned by subtracting ET for the underlying land-use type (assumed to be shrubland because this seems to be the most prevalent land-use type). Therefore, estimated additional ET within buffer areas possibly does not reflect the additional actual ET that occurred associated with irrigation practices if the "background" land-use type was a type other than shrubland (especially wetlands).

Total estimated ET typically is 5 percent higher with ET buffers than without them and ranges from 2 to 16 percent. During most years, however, the difference is less than 5 percent of the total ET.

Consumptive-Use Discussion

The spatial and temporal distribution of recharge from irrigation of crops resulted in different estimates of consumptive use for the upper, middle, and lower subbasins (fig. 11). Consumptive use was calculated as the ratio of estimated CIR to irrigated acres, ranging from 0.66 acre-feet (ft) per acre in 2005 in the upper subbasin (considered an outlier because of high reported surface-water diversion) to 2.72 acre-ft per acre in 2003 in the lower basin and averaging 1.7 acre-ft per acre overall for the entire basin. This range suggests that the estimated CIR is not representative during certain years, perhaps because of (1) underlying assumptions used in estimating ET during earlier years in the study when METRIC coverage was not available, (2) the use of proxy years when irrigated-land coverages were not available, (3) the use of draft irrigated-land coverages for 2012–17, or (4) some combination of these factors. Typically, the estimated consumptive use in this study ranged from 1.0 acre-foot per year per acre (acre-ft/yr per acre) (during particularly wet years) to 2.5 acre-ft/yr per acre, consistent with the IDWR-reported consumptive use for the Big Lost River Basin of 2.5 acre-ft/yr per acre (rounding to the nearest 0.5 acre-ft/yr per acre and inclusive of several tributary basins to the ESPA) used in water-rights administration.

[5]The IDWR reports that a 90-m buffer is used to represent the resolution difference of 90 x 90 m between the METRIC maximum thermal band pixel dimension (120 x120 m) and the METRIC shortwave pixel dimension (30x30 m).

References Cited

Allen, R.G., Burnett, B., Kramber, W., Huntington, J., Kjaersgaard, J., Kilic, A., Kelly, C., and Trezza, R., 2013, Automated calibration of the METRIC-Landsat evapotranspiration process: Journal of the American Water Resources Association, v. 49, no. 3, p. 563–576, accessed July 17, 2018, at https://doi.org/10.1111/jawr.12056.

Allen, R.G., and Robison, C.W., 2017, Evapotranspiration and consumptive irrigation water requirements for Idaho—Supplement updating the time series through December 2016: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center, Research Technical Completion Report [variously paged], accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

Allen, R.G., Tasumi, M., and Morse, A., 2005, Satellite-based evapotranspiration by METRIC and Landsat for Western states water management: Presented at the Bureau of Reclamation Evapotranspiration Workshop, February 8–10, 2005, Fort Collins, Colorado, 20 p., accessed July 17, 2018, at https://doi.org/10.1061/40792(173)556.

Allen, R.G., Tasumi, M., Morse, A., Trezza, T., Wright, J.L., Bastiaanssen, W., Kramber, W., Lorite, I., and Robison, C.W., 2007, Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Applications: Journal of Irrigation and Drainage Engineering, v. 133, no. 4, p. 395–406, accessed July 16, 2018. https://doi.org/10.1061/(ASCE)0733-9437(2007)133:4(395).

Esri, 2018, ArcMap, version 10.6.1: Esri software release.

Esri 2020, ArcMap, version 10.8.1: Esri software release.

Glenn, E.P., Neale, C.M.U., Hunsaker, D.J., and Nagler, P.L., 2011, Vegetation index-based crop coefficients to estimate evapotranspiration by remote sensing in agricultural and natural ecosystems: Hydrological Processes, v. 25, no. 26, p. 4050–4062, accessed August 10, 2021. https://doi.org/10.1002/hyp.8392.

Google LLC, 2020, Google Earth Pro, version 7.3.3.7786: Google LLC software release.

Idaho Department of Water Resources [IDWR], 2013a, Enhanced Snake Plain aquifer model version 2.1, January 2013: Idaho Department of Water Resources web page, accessed February 15, 2022, at https://research.idwr.idaho.gov/files/projects/espam/browse/ESPAM_2_Final_Report/ESPAM21FinalReport.pdf.

Idaho Department of Water Resources [IDWR], 2020a, Map and GIS data hub—Irrigated lands: Idaho Department of Water Resources web page, accessed April 2, 2020, at https://data-idwr.opendata.arcgis.com/pages/gis-data#irrigatedLands.

Idaho Department of Water Resources [IDWR], 2021b, Map and GIS data hub—Evapotranspiration: Idaho Department of Water Resources web page, accessed April 8, 2021, at https://data-idwr.opendata.arcgis.com/pages/gis-data.

Jensen, M.E., and Allen, R.G., 2016, Evaporation, evapotranspiration, and irrigation water requirements (2nd ed.): Reston, Virginia, American Society of Civil Engineers, 744 p.

McVay, M., 2018, Evapotranspiration for the Enhanced Snake Plain aquifer model version 2.2—Draft: Idaho Department of Water Resources, 31 p., accessed February 24, 2022, at https://research.idwr.idaho.gov/files/projects/espam/browse/ESPAM22_Reports/ETDesignDoc/.

Multi-Resolution Land Characteristics Consortium, 2019, National Land Cover Database: U.S. Geological Survey database, accessed November 8, 2019, at https://www.mrlc.gov/data.

National Agricultural Statistics Service, 2019, CropScape and cropland data layers—FAQs: U.S. Department of Agriculture National Agricultural Statistics Service database, accessed January 9, 2019, at https://www.nass.usda.gov/Research_and_Science/Cropland/sarsfaqs2.php.

National Agricultural Statistics Service, 2020b, CropScape and cropland data layers—FAQs—Section 3, FAQ 23: U.S. Department of Agriculture National Agricultural Statistics Service database, accessed February 20, 2020, at https://www.nass.usda.gov/Research_and_Science/Cropland/sarsfaqs2.php#Section3_22.0.

National Agricultural Statistics Service, 2020a, CropScape—Cropland data layer: U.S. Department of Agriculture National Agricultural Statistics Service database, accessed February 20, 2020, at https://nassgeodata.gmu.edu/CropScape/.

University of Idaho, 2018, Evapotranspiration and consumptive irrigation water requirements for Idaho: Moscow, Idaho, University of Idaho Kimberly Research and Extension Center web page, accessed March 10, 2021, at http://data.kimberly.uidaho.edu/ETIdaho/.

U.S. Geological Survey, 2017, Landsat Normalized Difference Vegetation Index web page, accessed June 9, 2022, at https://www.usgs.gov/landsat-missions/landsat-normalized-difference-vegetation-index.

For more information about the research in this report, contact
Director, Idaho Water Science Center
U.S. Geological Survey
230 Collins Road
Boise, Idaho 83702-4520
https://www.usgs.gov/centers/idaho-water-science-center

Manuscript approved on August 25, 2022

Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Tacoma Publishing Service Center

USGS

Clark—**Groundwater Budgets for the Big Lost River Basin, South-Central Idaho, 2000–19**—Scientific Investigations Report 2021–5078–C

ISSN 2328-031X (print)
ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20225078C