USGS
science for a changing world

Prepared in cooperation with the Idaho Department of Environmental Quality

Evaluation of Total Phosphorus Mass Balance in the Lower Boise River, Southwestern Idaho

Scientific Investigations Report 2013–5220

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

Cover: Boise River north channel upstream of Middleton Canal, Idaho. Hydrologists are shown completing an acoustic Doppler current profiler compass calibration (left) and collecting a water-quality sample (right). Photograph taken by Lowell Abbadini, U.S. Geological Survey, August 20, 2012.

Evaluation of Total Phosphorus Mass Balance in the Lower Boise River, Southwestern Idaho

By Alexandra B. Etheridge

Prepared in cooperation with the Idaho Department of Environmental Quality

Scientific Investigations Report 2013–5220

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

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 http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Etheridge, A.B., 2013, Evaluation of total phosphorus mass balance in the lower Boise River, southwestern Idaho: U.S. Geological Survey Scientific Investigations Report 2013–5220, 70 p., *http://dx.doi.org/10.3133/sir20135220*.

ISSN -2328-0328 (online)

Contents

Contents

Figures

Figures

Tables

Conversion Factors, Datums, and Abbreviations and Acronyms

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Area	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
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)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
cubic foot per second per mile [(ft^3/s)/mi]	0.02832	cubic meter per second per kilometer [(m^3/s)/km]
	Mass	
pound avoirdupois per day (lb/d)	0.4536	kilogram per day (kg/d)
pound, avoirdupois, per day per mile [(lb/d)/mi]	0.4536	kilogram per day per kilometer (kg/d/km)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
ton per year (ton/yr)	0.9072	metric ton per year
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
	Volume	
liter (L)	0.2642	gallon (gal)
	Mass	
gram per square meter (g/m^2)	2.05×10^{-4}	pound per square foot (lb/ft^2)
milligram per square meter (mg/m^2)	2.05×10^{-7}	pound per square foot (lb/ft^2)
milligrams per kilogram (mg/kg) (soil)	1	parts per million (ppm) (soil)

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

$$°F=(1.8\times°C)+32.$$

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L)

Conversion Factors, Datums, and Abbreviations and Acronyms

Datums

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

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

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

ADCP	acoustic Doppler current profiler
BFI	base flow index
CVO	Cascades Volcano Observatory (of the U.S. Geological Survey)
EPA	U.S. Environmental Protection Agency
EWI	Equal-Width-Increment (method)
IDEQ	Idaho Department of Environmental Quality
IDWR	Idaho Department of Water Resources
IDWSC	Idaho Water Science Center (of the U.S. Geological Survey)
LRL	laboratory reporting level
NWQL	National Water-Quality Lab (of the U.S. Geological Survey)
ODEQ	Oregon Department of Environmental Quality
OP	orthophosphorus as phosphorus
Reclamation	Bureau of Reclamation
RM	river mile
RPD	relative percent difference
SR-HC	Snake River-Hells Canyon
TDP	total dissolved phosphorus
TMDL	Total Maximum Daily Load
TP	total phosphorus
USGS	U.S. Geological Survey
USGS NFM	U.S. Geological Survey National Field Manual
WWTP	wastewater treatment plant

Evaluation of Total Phosphorus Mass Balance in the Lower Boise River, Southwestern Idaho

By Alexandra B. Etheridge

Abstract

The U.S. Geological Survey (USGS), in cooperation with Idaho Department of Environmental Quality, developed spreadsheet mass-balance models for total phosphorus using results from three synoptic sampling periods conducted in the lower Boise River watershed during August and October 2012, and March 2013. The modeling reach spanned 46.4 river miles (RM) along the Boise River from Veterans Memorial Parkway in Boise, Idaho (RM 50.2), to Parma, Idaho (RM 3.8). The USGS collected water-quality samples and measured streamflow at 14 main-stem Boise River sites, two Boise River north channel sites, two sites on the Snake River upstream and downstream of its confluence with the Boise River, and 17 tributary and return-flow sites. Additional samples were collected from treated effluent at six wastewater treatment plants and two fish hatcheries. The Idaho Department of Water Resources quantified diversion flows in the modeling reach.

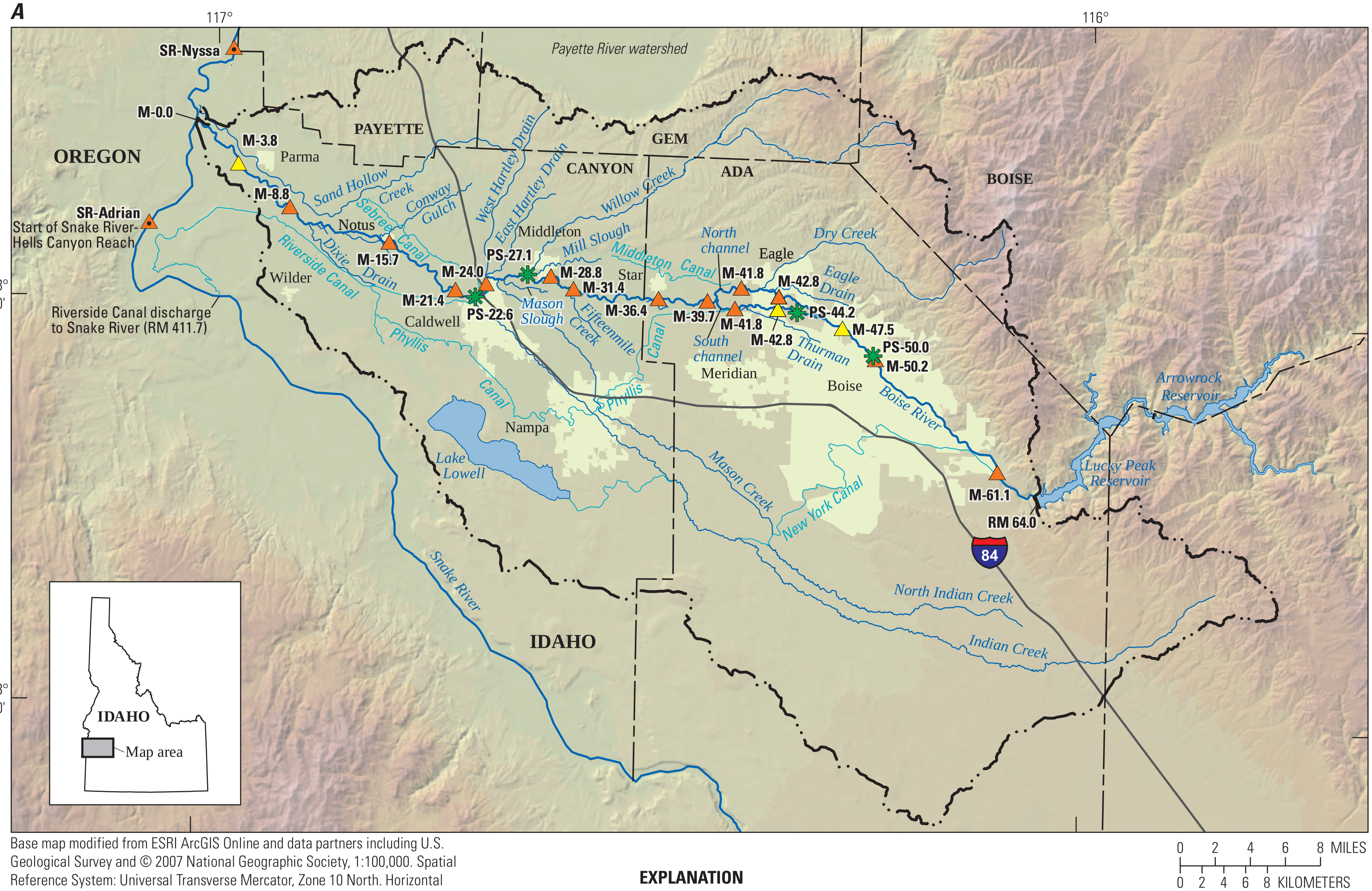
Total phosphorus mass-balance models were useful tools for evaluating sources of phosphorus in the Boise River during each sampling period. The timing of synoptic sampling allowed the USGS to evaluate phosphorus inputs to and outputs from the Boise River during irrigation season, shortly after irrigation ended, and soon before irrigation resumed. Results from the synoptic sampling periods showed important differences in surface-water and groundwater distribution and phosphorus loading. In late August 2012, substantial streamflow gains to the Boise River occurred from Middleton (RM 31.4) downstream to Parma (RM 3.8). Mass-balance model results indicated that point and nonpoint sources (including groundwater) contributed phosphorus loads to the Boise River during irrigation season. Groundwater exchange within the Boise River in October 2012 and March 2013 was not as considerable as that measured in August 2012. However, groundwater discharge to agricultural tributaries and drains during non-irrigation season was a large source of discharge and phosphorus in the lower Boise River in October 2012 and March 2013. Model results indicate that point sources represent the largest contribution of phosphorus to the Boise River year round, but that reductions in point and nonpoint source phosphorus loads may be necessary to achieve seasonal total phosphorus concentration targets at Parma (RM 3.8) from May 1 through September 30, as set by the 2004 Snake River-Hells Canyon Total Maximum Daily Load document. The mass-balance models do not account for biological or depositional instream processes, but are useful indicators of locations where appreciable phosphorus uptake or release by aquatic plants may occur.

Introduction

The U.S. Environmental Protection Agency (EPA) approved a Total Maximum Daily Load (TMDL) for the Snake River-Hells Canyon (SR-HC) reach in 2004 (Idaho Department of Environmental Quality and Oregon Department of Environmental Quality, 2004). TMDLs are required documentation under the Clean Water Act (U.S. Environmental Protection Agency, 2013) for any water body that has been listed as “impaired” with respect to beneficial uses including recreation, water supply, and aquatic habitat. The SR-HC TMDL was developed to address impairment by nuisance algae, nutrients, and other pollutants (U.S. Environmental Protection Agency, 2013). Approved TMDLs establish target amounts or loads of pollutants that a water body can accept from various sources in the watershed. Target loads are established with the goal of attaining beneficial uses that are impaired, and are based on water-quality and discharge information that has been gathered in the watershed.

The Boise River is a major tributary to the Snake River in southwestern Idaho (fig. 1*A*). Under the 2004 SR-HC TMDL, the Boise River and other major tributaries were assigned seasonal concentration-based targets for total phosphorus (TP) that correlate with a seasonal algae target of 14 μg/L in the Snake River as measured by chlorophyll-*a* in phytoplankton (floating algae). Bioavailable phosphorus shows a significant negative correlation with increased algae growth in the Snake River, indicating phosphorus as the limiting nutrient in the Snake River near the confluence of the Boise River (Wood and Etheridge, 2011).

A



Base map modified from ESRI ArcGIS Online and data partners including U.S. Geological Survey and © 2007 National Geographic Society, 1:100,000. Spatial Reference System: Universal Transverse Mercator, Zone 10 North. Horizontal datum is North American Datum of 1983.

EXPLANATION

Boise River watershed boundary

M-3.8 **Main-stem Boise River U.S. Geological Survey streamgage and river mile**

M-61.1 **Main-stem site and river mile**

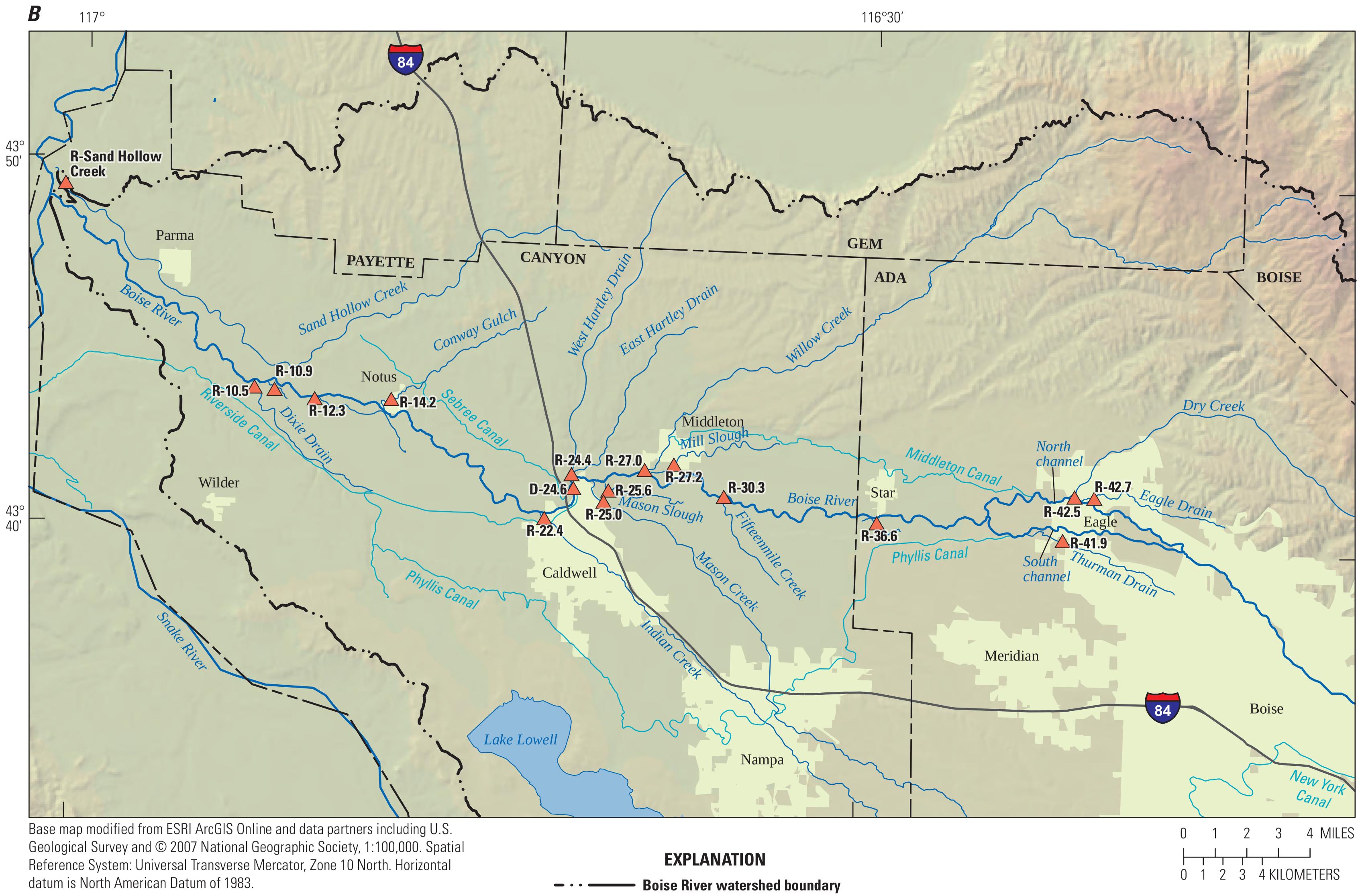
SR-Adrian **Main-stem Snake River**

PS-50.0 **Wastewater treatment plant point source and river mile**

Dam

RM 64.0 **River mile**

Figure 1. Modeling reach for (*A*) main-stem and point-source water-quality sampling sites, (*B*) tributary and drain water-quality sampling sites, and (*C*) groundwater and main-stem biology sampling sites, lower Boise River watershed, southwestern Idaho, August and October 2012, and March 2013.



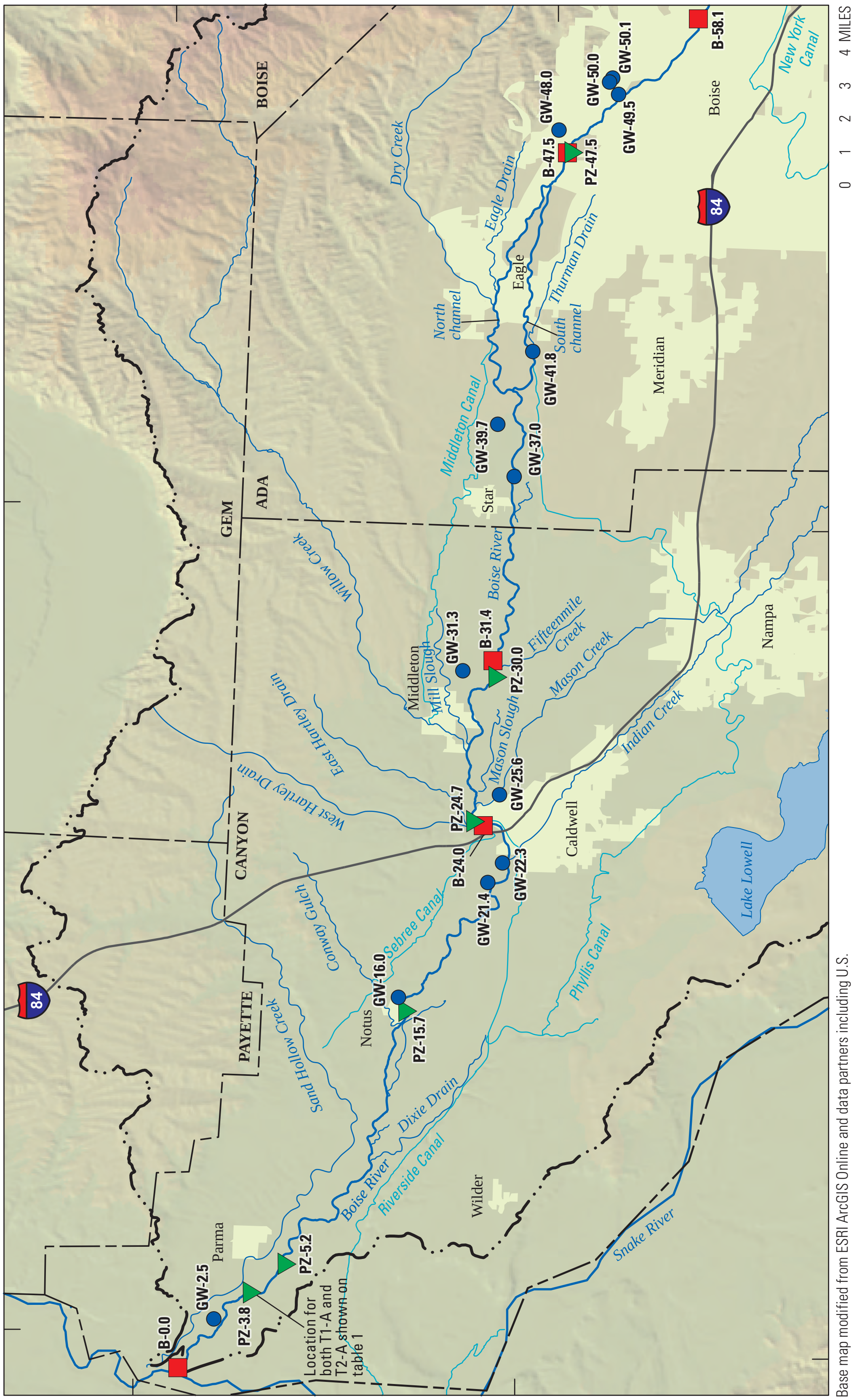
Base map modified from ESRI ArcGIS Online and data partners including U.S. Geological Survey and © 2007 National Geographic Society, 1:100,000. Spatial Reference System: Universal Transverse Mercator, Zone 10 North. Horizontal datum is North American Datum of 1983.

EXPLANATION

Boise River watershed boundary

R-22.4 **Return flow or diversion and river mile (D-24.6,** Riverside Canal Diversion)

Figure 1.—Continued



Base map modified from ESRI ArcGIS Online and data partners including U.S. Geological Survey and © 2007 National Geographic Society, 1:100,000. Spatial Reference System: Universal Transverse Mercator, Zone 10 North. Horizontal datum is North American Datum of 1983.

Figure 1—Continued

Excessive algae growth and subsequent decay can deplete dissolved oxygen crucial for the survival of fish and other aquatic biota, and has resulted in fish kills in Brownlee Reservoir near the downstream end of the SR-HC reach of the Snake River (Myers and others, 2003). According to the 2004 SR-HC TMDL, the May 1 to September 30 growing season was the most critical period to limit algae growth (Idaho Department of Environmental Quality and Oregon Department of Environmental Quality, 2004). Therefore, the TP concentration target at the mouth of the Boise River was set at 0.07 mg/L between May 1 and September 30.

Water-quality conditions in the Boise River sustain periphytic algae growth, but chlorophyll-*a* in phytoplankton has not been detected consistently at concentrations exceeding 14 µg/L (Wood and Etheridge, 2011). However, TP concentrations near the mouth of the Boise River exceed the 0.07-mg/L target year round (MacCoy, 2004; Wood and Etheridge, 2011). Seasonal diversions from the Boise River redistribute TP loads from upstream urban sources to agricultural land throughout the watershed, and agricultural return flows contribute additional TP loads to the Boise River. Although it is useful to understand TP loading from individual point sources and nonpoint source tributaries and drains, the manner in which TP loads are transported through the system as a whole is not well understood. Localized periphyton growth in response to seasonal changes in TP loading also has not been studied in detail.

This study was completed in cooperation with the Idaho Department of Environmental Quality (IDEQ) to support renewed efforts to develop a TP TMDL in the lower Boise River. The Idaho Department of Environmental Quality (2001) stated that nutrients originating in the lower Boise River watershed were not impairing aquatic life or recreational beneficial uses in the lower Boise River; however, nutrients affected beneficial uses downstream in the Snake River and Brownlee Reservoir. In 2009, the EPA denied IDEQ's request to de-list the lower Boise River for TP impairment. That same year, the IDEQ published a lower Boise River implementation plan for TP to establish point and nonpoint source allocations for TP in the lower Boise River and several major tributaries (Idaho Department of Environmental Quality, 2009). The IDEQ listed the Boise River from Middleton (RM 28.8) to the river mouth (RM 0.0) as impaired by TP in the 2010 Integrated Report (Idaho Department of Environmental Quality, 2011). Each of the beneficial uses downstream of Middleton (RM 28.8), including primary- and secondary-contact recreation and cold-water aquatic life, is suspected to be impaired by TP from point and nonpoint sources. In 2013, the IDEQ and the Lower Boise River Watershed Advisory Group agreed to establish a mean periphyton (chlorophyll-*a*) target of 150 mg/m^2 in the lower Boise River as part of TP TMDL development, but the frequency and duration associated with that target was not decided (Idaho Department of Environmental Quality, 2013a).

To evaluate TP loading on a watershed scale, the U.S. Geological Survey (USGS) collected TP samples along a 46-mi reach of the Boise River starting at Veterans Memorial Parkway (River Mile [RM] 50.2) and ending at the Boise River near Parma (RM 3.8) (herein referred to as the "modeling reach") (fig. 1*A*). Water-quality and chlorophyll-*a* in periphyton samples were collected and surface-water discharge was measured during three synoptic sampling periods. The term "synoptic" describes a sampling period that occurs over a relatively short period and under relatively stable hydrologic conditions. Each synoptic sampling period provided a comprehensive snapshot of TP loading in the Boise River. The first synoptic sampling period took place during the week of August 20, 2012, toward the end of irrigation season. The second synoptic sampling period took place just after irrigation season ended during the week of October 29, 2012, and the third synoptic sampling period took place during the week of March 4, 2013, just before the next irrigation season began. Results from each synoptic event were used to develop three TP mass-balance models and to assess spatial and temporal changes in periphyton growth.

A mass-balance model is an analysis of a physical system, in this case the lower Boise River, where the conservation-of-mass concept is applied. Because the Boise River is moving, mass computations are expressed with respect to time as loads in pounds per day. Mass-balance models accounted for TP mass in the Boise River by quantifying discharge and TP concentrations entering and exiting the modeling reach via surface water. Because discharge and TP concentrations were measured only in surface water, an essential function of the mass-balance models was to identify deficits and surpluses of discharge and TP loads that enter or exit the system by other means. Unmeasured gains or losses of discharge were attributed to groundwater exchange. Unmeasured TP loads could have entered or exited the system through groundwater or biogeochemical processes such as uptake and release from aquatic plants. As much as they are useful for evaluating TP loading dynamics along the modeling reach, the TP mass-balance models are useful for understanding sources of unmeasured loads that are otherwise difficult to measure directly.

Two types of mass-balance models were developed for each synoptic event. The first, referred to as the "measured model," used deficits and surpluses resulting from mass-balance accounting to balance or calibrate the model. The measured model represents a static snapshot of TP loading along the modeling reach. The second type of mass-balance model, referred to as the "predictive model," is not static and can be manipulated to evaluate the sensitivity of the modeling reach to changes in TP inputs. The predictive model pairs the groundwater component of discharge with estimated TP concentrations in streamflow gains from groundwater and modeled instream TP concentrations in streamflow losses.

Losses of water from the river to groundwater (streamflow losses) become deficits in TP load and streamflow gains become surpluses in TP load. Instead of prorating a calculated surplus or deficit back into a subreach, as in the measured model, the predictive model attempts to account for surpluses and deficits in surface water TP loads using groundwater TP loads. If groundwater is not the explanation for deficits or surpluses in TP loads, the predictive model is not as successful at predicting main-stem loads, but it retains the ability to implicate biogeochemical sources or sinks for TP loads.

Purpose and Scope

This report describes TP mass-balance modeling results for three synoptic sampling periods in the lower Boise River between Veterans Memorial Parkway (RM 50.2) and Parma (RM 3.8). Input data collected for mass-balance models provided additional information regarding groundwater and surface-water interaction in the modeling reach. Site reconnaissance and analysis of related data were completed to finalize sampling sites within the modeling reach. Site-selection methods are described in detail to document reasons for selecting specific sites and to provide an understanding of the modeling reach. A detailed analysis of model results enabled further evaluation of sources of phosphorus in the lower Boise River during three distinct periods in a given water year (the 12-month period starting October 1 for any given year through September 30 of the following year): (1) during irrigation season, (2) just after irrigation season ends, and (3) just before irrigation season begins. With sources of phosphorus described in context of model results, model sensitivity to changes in these sources was also evaluated. The objectives of this study included:

1. Identification of visible surface-water diversions and return flows in the modeling reach.
2. Comparison of identified diversions and return flows to existing nutrient data to finalize synoptic sampling sites.
3. Completion of three synoptic sampling periods between Veterans Memorial Parkway (RM 50.2) and the mouth of the Boise River at as many as 40 sites in August 2012, October 2012, and March 2013.
4. Determination of seasonal groundwater and surface-water interaction in the modeling reach.
5. Evaluation of potential sources of phosphorus in each subreach using measured and predictive TP mass-balance models.
6. Use of the predictive TP mass-balance model to evaluate sensitivity to point and nonpoint sources of TP.
7. Assessment of periphyton growth at five sampling sites in the study reach (two periphyton sampling sites are outside the modeling reach) (fig. 1*C*) during each synoptic event.

Description of Study Area

The Boise River drains 3,906 mi^2 of land area, but is separated from the upper part of its watershed by a series of dams. The 1,290-mi^2 lower Boise River watershed is in Ada and Canyon Counties between Lucky Peak Dam (RM 64.0) and the confluence with the Snake River (RM 0.0) (fig. 1*A*). Three distinct land uses dominate the lower Boise River watershed. According to the 2006 National Land Cover Dataset (Fry and others, 2011), about one-half the land (54 percent) is in its undeveloped state as woods, forests, grasses, shrubs, and water or wetlands. Land use adjacent to the Boise River is predominantly urban as the river flows through the cities of Boise, Eagle, Meridian, Nampa, and Caldwell, Idaho, and predominantly agricultural downstream of Caldwell. Although the river flows through several cities and towns, 32 percent of the land in the lower Boise River watershed is used for agriculture, whereas 14 percent is urbanized or developed (Fry and others, 2011).

Urban and agricultural land uses have the greatest effect on water quality, including TP contributions, in the Boise River downstream of Lucky Peak Dam (RM 64.0). Upstream of Lucky Peak Dam, land is predominantly forested, and phosphorus loading from human effects is negligible. Phosphorus derived from geologic material upstream of Lucky Peak Dam contributes relatively little phosphorus to the Boise River downstream of Lucky Peak Dam. The median concentration of TP in the Boise River below Diversion Dam (RM 61.1), including a statistical analysis of non-detect results using the Kaplan-Mier method (Helsel, 2005), is 0.02 mg/L ($n = 119$). Downstream of urban and agricultural land uses, the median concentration of TP near the mouth of the Boise River (RM 3.8) is 0.31 mg/L ($n = 776$), more than 15 times the median concentration downstream of Diversion Dam (RM 61.1).

Agricultural land use expanded from the late 1800s through the 1950s when urban expansion became the primary driver for changes in land use (Dion, 1972). In 1906, water for irrigation of crops in the lower Boise River watershed first was diverted on a large scale from the Boise River, after passage of the Federal Reclamation Act of 1902. Between 1906 and 1957, three major dams and reservoirs—Lucky Peak, Arrowrock, and Anderson Ranch—were constructed in the headwaters of the Boise River. Large-scale agricultural production followed, and agricultural operations remain an important economic driver in the lower Boise River watershed. Population growth between 1970 and 2010 averaged 36 percent per decade in Ada and Canyon Counties. Agricultural land has been removed from production to accommodate expanding urban areas in Boise, Eagle, Meridian, Nampa, and Caldwell. The Idaho Association of Soil Conservation Districts reported a loss of 10,930 acres of agricultural land to urban or suburban development between 2001 and 2005 (Scott Koberg, Idaho Soil Conservation Commission, written commun., 2013).

Urban land use continues to expand into formerly agricultural land, but it is uncertain whether agricultural production in the lower Boise River watershed is also decreasing.

Treated wastewater effluent from municipal wastewater treatment plants (WWTPs) is the predominant source of phosphorus from urban lands, whereas fertilizer and manure runoff is a potential source of phosphorus from agricultural land. Septic tanks in rural residential areas can also act as a source of phosphorus to shallow groundwater. Other sources of phosphorus in urban settings include industrial wastewater discharge, domestic fertilizers, and stormwater runoff. The six largest municipal WWTPs discharged an average 50 Mgal/d (77 ft^3/s) of treated effluent to the lower Boise River and its tributaries during sampling periods completed as part of this study. The cities of Boise and Caldwell discharge treated wastewater effluent to the Boise River. Indian Creek, Fivemile Creek (a tributary of Fifteenmile Creek), Sand Hollow Creek, Mill Slough, and Conway Gulch also receive treated effluent from municipal WWTPs (fig. 1*A*). Treated wastewater effluent, whether it originates from domestic or industrial water use, is designated, permitted, and regulated as a point source. Runoff from agricultural fields and pastures is designated as a nonpoint source and is not subject to regulatory control.

Most irrigation water used for agriculture adjacent to the Boise River originates from diversions along the Boise River that occur downstream of treated wastewater effluent releases. The Boise River at Glenwood Bridge (RM 47.5) is 2.5 mi downstream of the first upstream WWTP that discharges treated effluent into the Boise River (Lander WWTP, RM 50.0) (fig. 1*A*). Water diverted from the Boise River upstream of Veterans Memorial Parkway (RM 50.2) generally represents background TP concentrations, and most of any unused irrigation water ultimately drains to Lake Lowell and the Snake River (Bureau of Reclamation and Idaho Department of Water Resources, 2008). Water diverted for irrigation use downstream of Glenwood Bridge shows increasing TP concentrations in the downstream direction and most of the unused irrigation water ultimately drains to the lower Boise River downstream of Glenwood Bridge (MacCoy, 2004). Although an average of 3,100 ft^3/s of water was diverted upstream of Glenwood Bridge during the week of August 20, 2012, the TP load in diverted water was between 200 and 250 lb/d, whereas the TP load in 1,590 ft^3/s of water diverted downstream of Glenwood Bridge during the same week was 1,890 lb/d.

Irrigation practices in the lower Boise River watershed have remained consistent since 1957, when Lucky Peak Dam was completed. Water from the Boise River is diverted for irrigation use between April 15 and October 15 every year. In an average irrigation season, 1.6 million acre-ft of water is diverted from the Boise River and 79,000 acre-ft of water is diverted from the Payette River for agricultural use in the lower Boise River watershed (Bureau of Reclamation and Idaho Department of Water Resources, 2008). About 900,000 acre-ft of irrigation water returns to the Boise River each year through agricultural drains and tributaries, and 29,000 acre-ft are recharged to the shallow aquifer in the lower Boise River watershed (Bureau of Reclamation and Idaho Department of Water Resources, 2008). The net balance of diverted irrigation water from the Boise River (750,000 acre-ft annually) remains in Lake Lowell, returns to the Snake River, or is retained in crops or unsaturated soil. The effects of these irrigation practices and their seasonal recurrence necessitate a more detailed conceptual model of groundwater and surface-water interaction in the lower Boise River watershed.

Conceptual Model of Groundwater and Surface-Water Interaction

Several shallow aquifers underlie the lower Boise River watershed but they have been described as a single hydrologic unit (herein referred to as the “shallow aquifer” or “shallow groundwater”) (Thomas and Dion, 1974). Groundwater in the shallow aquifer, which is the primary source of groundwater that interacts with the Boise River, moves to the west or northwest in the same general direction as the Boise River (Dion, 1972; Petrich, 2004). A groundwater divide exists near the New York Canal, where shallow groundwater north of the canal flows toward the Boise River, and shallow groundwater south of the canal flows toward the Snake River (fig. 1*A*).

Irrigation water in excess of consumptive use has been applied to agricultural land for nearly a century in the lower Boise River watershed (Thomas and Dion, 1974; Berenbrock, 1999; Bureau of Reclamation and Idaho Department of Water Resources, 2008). Widespread crop irrigation began in the 1860s in the lower Boise River watershed and caused drastic changes in groundwater recharge dynamics. Shallow groundwater levels rose tens to hundreds of feet between 1912 and the 1930s, when they stabilized. Continued seasonal application of surface water for irrigation purposes induces seasonal groundwater fluctuations of several feet in shallow groundwater beneath irrigated land (Dion, 1972; Fox and others, 2002; Petrich and Urban, 2004). Shallow groundwater levels generally peak at the end of irrigation season and, because drains and tributaries dewater the shallow aquifer during non-irrigation season, shallow groundwater levels are lowest just before the next irrigation season begins (Baker, 1993; Fox and others, 2002). Shallow groundwater conditions in the lower Boise River watershed have not changed appreciably since at least the 1950s (Berenbrock, 1999).

Discharge in the Boise River varies seasonally in specific stream reaches downstream of Lucky Peak Dam (RM 64.0). Irrigation demand requires relatively high sustained discharge from Lucky Peak Dam to the north and south channel split along the Boise River (RM 42.8) (fig. 1*A*). Water-rights accounting records dating to 1971 have separated the Boise River into three accounting sections for water delivery during irrigation season. The first section is from the Boise River below Diversion Dam (RM 61.1) to the diversion for the

Caldwell Highline Canal (RM 36.3). The second section is from RM 36.3 (just downstream of the sampling site at the Boise River near Star [RM 36.4]; fig. 1*A*) to the Boise River at Notus (RM 15.7), and the third section starts at RM 15.7 and ends at the mouth of the Boise River (fig. 1*A*). Surface-water deliveries in the first upstream accounting section reportedly met the total surface-water irrigation demand in the lower Boise River watershed in 1971 (Thomas and Dion, 1974) because agricultural return flows to the Boise River, in addition to groundwater discharge to the Boise River, sustained sufficient main-stem discharge to meet irrigation demands in the second accounting section along the river. Agricultural return flows and groundwater discharge to the Boise River in the third accounting section also sustained sufficient discharge in the main stem to meet irrigation demand downstream of Notus (RM 15.7). The discharge and recharge distribution reported during irrigation season in 1971 are consistent with discharge balance results for the August 20, 2012 synoptic sampling period.

Surface-water discharge distribution undergoes somewhat of a reversal just after irrigation season ends. Releases from Lucky Peak Dam (RM 64.0) decrease along with discharge in the farthest-upstream accounting section (RMs 61.1–36.3). At the end of irrigation season, discharge in agricultural drains and tributaries tends to surge temporarily before steadily decreasing throughout non-irrigation season. The short-duration surge in discharge in agricultural drains may signal the release of bank storage that occurred with elevated stages in agricultural drains during irrigation season. For the remainder of non-irrigation season, drains and tributaries deliver irrigation water that has percolated through the shallow aquifer during the previous irrigation season and emerged as shallow groundwater discharge. Moving downstream, discharge in the Boise River is augmented with groundwater discharge delivered through agricultural drains and tributaries.

Related Studies

Numerous studies have characterized groundwater and surface-water discharge, overall water quality and biotic integrity, and land use in the lower Boise River watershed. The Idaho Department of Health and Welfare (1989) reported that water quality deteriorated in the lower Boise River in the reach from Lucky Peak Dam (RM 64.0) to the confluence with the Snake River (RM 0.0) as a result of municipal wastewater discharges and irrigation return flows. Water quality near Parma was therefore classified as “poor” because of “excessive bacteria, nutrients, sediment, metals, and elevated temperatures.” MacCoy (2004) evaluated water-quality data collected at multiple sites along the Boise River from 1994 to 2002 and determined that TP concentrations increased by more than seven times between Lucky Peak Dam (RM 64.0) and Parma (RM 3.8). Mullins (1998) determined that the largest point source of TP to the Boise River was the West Boise WWTP (RM 44.2), and the largest nonpoint source of TP was Dixie Drain (RM 10.5) (fig. 1*B*, table 1). The Idaho State Department of Agriculture has monitored water quality in major tributaries to the Boise River and detected TP at higher concentrations during irrigation season than during non-irrigation season (Campbell, 2009). Donato and MacCoy (2005) observed the highest orthophosphorus as phosphorus (OP)-to-TP ratios at Parma in November and December and lowest ratios in summer, which was the opposite of patterns observed in the river upstream of agricultural and urban land uses. This suggests that aquatic plants use nutrients in the lower reaches of the river in summer and that dam releases for irrigation supply dilute WWTP effluent.

MacCoy (2004) documented the effects of flow alterations, habitat loss, and poor water quality on lower Boise River biota. In particular, periphyton samples collected annually in late October or early November from 1995 to 2002 showed overall lower concentrations of chlorophyll-*a* in periphyton in 1997 and overall increasing chlorophyll-*a* in periphyton concentrations moving downstream from Diversion Dam (RM 61.1) to Caldwell (RM 24.0). Low concentrations of chlorophyll-*a* in periphyton occurred in 1997 after sustained high discharge during the 1996 spring runoff season scoured the Boise River. Concentrations of chlorophyll-*a* in periphyton at the mouth of the Boise River near Parma (RM 0.0) were less than those monitored upstream, likely because of less light penetration in the more turbid environment at Parma (MacCoy, 2004). Nutrient limitation does not occur in the Boise River near Parma, but the Boise River is phosphorus-limited near Diversion Dam (RM 61.1) and may be nitrogen-limited at Glenwood Bridge (RM 47.5) and near Middleton (RM 31.4) (Mullins, 1998; MacCoy, 2004).

In a study designed to evaluate water-quality conditions in the Snake River upstream and downstream of its confluence with the Boise River, Wood and Etheridge (2011) determined that most measured water-quality parameters and constituents in the Snake River were statistically different upstream and downstream of the confluence with the Boise River. TP concentrations and loads were higher in the Snake River downstream of its confluence with the Boise River than in the Snake River upstream of its confluence with the Boise River. The 2011 study also noted that surrogate models could be a useful tool for representing daily and seasonal variability in water-quality constituents, and for assessing effects of phosphorus reduction measures within the lower Boise River watershed. Chlorophyll-*a* concentrations in phytoplankton in the Boise River near Parma (RM 3.8) generally did not exceed the seasonal (May 1 to September 30) 14-µg/L target or the 30-µg/L target (not to be exceeded more than 25 percent of the time) established for the Snake River. Speciation of phytoplankton also showed that the community commonly was composed of periphytic and epiphytic diatoms that had become suspended in the water column (Wood and Etheridge, 2011).

Table 1. Sites sampled upstream of, downstream of, and within the total phosphorus mass-balance modeling reach in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

[Locations of sites are shown in figure 1. Shaded sites mark upstream and downstream ends of model subreaches. **Site type:** B, biological site; D diversion; GW, groundwater; M, main stem of the Boise River; PS, point-source discharge; PZ, piezometer; R, return flow or tributary; SR, Snake River site. **Samples collected:** Agency that collected samples. Reclamation, Bureau of Reclamation; IDWR, Idaho Department of Water Resources; USGS, U.S. Geological Survey; COB, City of Boise; IPC, Idaho Power Company. **Abbreviations:** WWTP, wastewater treatment plant; North Channel, north channel of the Boise River; South Channel, south channel of the Boise River; ID, Idaho; OR, Oregon; LB, left bank; RB, right bank; RM, river mile; blw, below; Hwy, highway; WL, water-level measurement in piezometer; ft, foot; NA, not applicable; –, no data]

Site name	USGS site No.	River mile	Site type	Samples collected: Discharge	Samples collected: Water-quality	Samples collected: Chlorophyll-*a*	Notes
Boise River below Diversion Dam near Boise, ID	13203510	61.1	M	Reclamation	USGS	–	Not in modeling reach, sampled for baseline surface-water conditions
Boise River at Eckert Road near Boise, ID	13203760	58.1	B	NA	USGS	USGS	
Boise River at Veterans Memorial Parkway at Boise, ID	13205642	50.2	M	USGS	USGS	–	Start of modeling reach
Boise City Sewer Outflow at Boise, ID (Lander WWTP)	13205643	50.0	PS	COB	COB	–	
Riverside Village		47.7	D	IDWR		–	
Boise River at Glenwood Bridge near Boise, ID	13206000	47.5	M, B	USGS	USGS	USGS	
New Dry Creek Canal		46.0	D	IDWR		–	
Loss to North Channel (Boise River North Channel near Eagle, ID)	13206300	45.5	M	USGS	USGS	–	Measured at Boise River North Channel near Eagle, ID at RM 42.8; start of north channel subreach
Ballentyne Canal	–	44.0	D	IDWR	–	–	Diverts from north channel
Lemp Canal	–	44.8	D	IDWR	–	–	Diverts from south channel
Warm Springs Canal	–	44.5	D	IDWR	–	–	Diverts from south channel
West Boise Sewer Outflow near Eagle, ID (West Boise WWTP)	13206303	44.2	PS	COB	COB	–	Returns to south channel
Conway-Hamming Canal	–	43.5	D	IDWR	–	–	Diverts from south channel
Thomas Aiken Canal	–	43.1	D	IDWR	–	–	Diverts from south channel
Mace-Catlin Canal	–	43.1	D	IDWR	–	–	Diverts from south channel
Graham-Gilbert Canal	–	42.9	D	IDWR	–	–	Diverts from south channel
Boise River South Channel at Eagle, ID	13206305	42.8	M	USGS	USGS	–	
Mace-Mace Canal	–	42.8	D	IDWR	–	–	Diverts from north channel
Jon Wroten Canal	–	42.7	D	IDWR	–	–	Diverts from south channel
Eagle Drain at Eagle, ID	13206400	42.7	R	USGS	USGS	–	Returns to north channel
Dry Creek at Eagle, ID	13208000	42.5	R	USGS	USGS	–	Returns to north channel
Barber Pumps	–	42.4	D	IDWR	–	–	Diverts from south channel
Hart-Davis Canal	–	42.1	D	IDWR	–	–	Diverts from north channel
Seven Suckers Canal	–	42.0	D	IDWR	–	–	Diverts from south channel
Thurman Drain at Mouth near Eagle, ID	13208750	41.9	R	USGS	USGS	–	Returns to south channel
Boise River (North Channel) above Middleton Canal, ID	13208600	41.8	M	USGS	USGS	–	End of north channel subreach
Boise River South Channel above Phyllis Canal nr Eagle, ID	13208800	41.8	M	USGS	USGS	–	
Middleton Canal	–	41.5	D	IDWR	–	–	Diverts from north channel
Eagle Island Park	–	41.4	D	IDWR	–	–	Diverts from north channel
Phyllis Canal	–	41.4	D	IDWR	–	–	Diverts from south channel
Little Pioneer Canal	–	41.2	D	IDWR	–	–	Diverts from north channel

Table 1. Sites sampled upstream of, downstream of, and within the total phosphorus mass-balance modeling reach in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.—Continued

[Locations of sites are shown in figure 1. Shaded sites mark upstream and downstream ends of model subreaches. **Site type:** B, biological site; D diversion; GW, groundwater; M, main stem of the Boise River; PS, point-source discharge; PZ, piezometer; R, return flow or tributary; SR, Snake River site. **Samples collected:** Agency that collected samples. Reclamation, Bureau of Reclamation; IDWR, Idaho Department of Water Resources; USGS, U.S. Geological Survey; COB, City of Boise; IPC, Idaho Power Company. **Abbreviations:** WWTP, wastewater treatment plant; North Channel, north channel of the Boise River; South Channel, south channel of the Boise River; ID, Idaho; OR, Oregon; LB, left bank; RB, right bank; RM, river mile; blw, below; Hwy, highway; WL, water-level measurement in piezometer; ft, foot; NA, not applicable]

Site name	USGS site No.	River mile	Site type	Samples collected			Notes
				Discharge	Water-quality	Chlorophyll-*a*	
Boise River below Eagle Island, ID	434050116260100	39.7	M	USGS	USGS	–	–
Eureka No. 1 Canal at Star Road near Star, ID	13209490	36.6	R	USGS	USGS	–	–
Boise River near Star, ID	13210000	36.4	M	USGS	USGS	–	–
Canyon County Canal	–	36.3	D	IDWR	–	–	–
Caldwell Highline Canal	–	36.3	D	IDWR	–	–	–
Otter Mitigation	–	35.7	D	IDWR	–	–	–
Boise River near Middleton, ID	13210050	31.4	M, B	IPC	USGS	USGS	–
Fifteenmile Creek at Mouth near Middleton, ID	13210815	30.3	R	USGS	USGS	–	Includes Meridian WWTP
Boise River at Middleton Road near Middleton, ID	13210820	28.8	M	USGS	USGS	–	–
Mill Slough below Grade Ditch near Middleton, ID	132108247	27.2	R	USGS	USGS	–	Includes Star WWTP
Middleton WWTP on Boise River near Middleton, ID	434149116382200	27.1	PS	COB	COB	–	Discharges to Mill Slough downstream of sample location, treated as direct discharge to Boise River
Willow Creek at Middleton, ID	13210835	27.0	R	USGS	USGS	–	–
Mason Slough near Caldwell, ID	13210849	25.6	R	USGS	USGS	–	–
Mason Creek near Caldwell, ID	13210983	25.0	R	USGS	USGS	–	–
Riverside Canal at HWY 20-26 Xing at Caldwell, ID	132109853	24.6	D	USGS	USGS	–	Measured and sampled upstream of Indian Creek
Hartley Drain near Caldwell, ID	13210988	24.4	R	USGS	USGS	–	Combined East and West Hartley Drains
Sebree Canal	–	24.0	D	IDWR	–	–	–
Campbell Canal	–	24.0	D	IDWR	–	–	–
Boise River at HWY 20-26 Xing near Caldwell, ID	13211000	24.0	M, B	USGS	USGS	USGS	–
Shipley Pumps	–	23.2	D	IDWR	–	–	–
Wagner Pumps	–	23.1	D	IDWR	–	–	–
Caldwell WWTP on Boise River at Caldwell, ID	434038116420900	22.6	PS	COB	COB	–	–
Indian Creek at mouth near Caldwell, ID	13211445	22.4	R	USGS	USGS	–	Includes Nampa WWTP and Nampa fish hatchery
Boise River below WWTP near Caldwell, ID	13211600	21.4	M	USGS	USGS	–	–
Simplot Pumps	–	20.1	D	IDWR	–	–	–
Eureka No. 2 Canal	–	20.1	D	IDWR	–	–	–
Upper Center Point Canal	–	20.1	D	IDWR	–	–	–
McManus and Teater Canal	–	20.0	D	IDWR	–	–	–
Vale Pumps		19.1	D	IDWR	–	–	
Lower Center Point Canal		18.1	D	IDWR	–	–	
Boise River at Notus, ID	13212500	15.7	M	USGS	USGS	–	

Table 1. Sites sampled upstream of, downstream of, and within the total phosphorus mass-balance modeling reach in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.—Continued

[Locations of sites are shown in figure 1. Shaded sites mark upstream and downstream ends of model subreaches. **Site type:** B, biological site; D diversion; GW, groundwater; M, main stem of the Boise River; PS, point-source discharge; PZ, piezometer; R, return flow or tributary; SR, Snake River site. **Samples collected:** Agency that collected samples. Reclamation, Bureau of Reclamation; IDWR, Idaho Department of Water Resources; USGS, U.S. Geological Survey; COB, City of Boise; IPC, Idaho Power Company. **Abbreviations:** WWTP, wastewater treatment plant; North Channel, north channel of the Boise River; South Channel, south channel of the Boise River; ID, Idaho; OR, Oregon; LB, left bank; RB, right bank; RM, river mile; blw, below; Hwy, highway; WL, water-level measurement in piezometer; ft, foot; NA, not applicable]

Site name	USGS site No.	River mile	Site type	Samples collected			Notes
				Discharge	Water-quality	Chlorophyll-*a*	
Conway Gulch at Notus, ID	13212550	14.2	R	USGS	USGS	–	Sampled upstream of Notus WWTP; Notus WWTP did not discharge during study
Baxter Canal		13.3	D	IDWR	–	–	
Unnamed Drain Near Notus, ID	434335116510400	12.3	R	USGS	USGS	–	
Andrews Canal		11.1	D	IDWR	–	–	
Unnamed Drain Near Dixie Drain near Notus, ID	434348116523600	10.9	R	USGS	USGS	–	
Dixie Drain near Wilder, ID	13212890	10.5	R	USGS	USGS	–	
Mammon Pumps		10.0	D	IDWR	–	–	
Boise River at Hwy 95 Xing near Parma, ID	13212900	8.8	M	USGS	USGS	–	
Hass Canal		8.1	D	IDWR	–	–	
Parma Canal		7.5	D	IDWR	–	–	
Island Highline Canal		6.3	D	IDWR	–	–	
Crawforth Pumps		4.3	D	IDWR	–	–	
McConnel Island Canal		3.9	D	IDWR	–	–	
Boise River near Parma, ID	13213000	3.8	M	USGS	USGS	USGS	Chlorophyll-*a* in phytoplankton collected here instead of 13213030; end of modeling reach
Boise River at Mouth near Parma, ID	13213030	0.0	B	NA	–	USGS	
Snake River and Sand Hollow Creek sites outside modeling reach							
Sand Hollow Creek at Mouth near Parma, ID	13213080	NA	R	USGS	USGS	–	Includes Parma WWTP, returns to Snake River downstream of Boise River confluence with Snake River
Snake River near Adrian, OR	13173600	NA	SR	USGS	USGS	–	
Snake River at Nyssa, OR	13213100	NA	SR	USGS	USGS	–	
Point source discharge sampling sites outside modeling reach							
Eagle Island Hatchery Outflow nr Eagle, ID	434038116241200	NA	PS	COB	COB	–	Returns to lakes on Eagle Island
Nampa WWTP on Indian Creek at Nampa, ID	433555116345900	NA	PS	COB	COB	–	Returns to Indian Creek upstream of Sparrow Avenue
Nampa Hatchery at Head of Wilson Drain near Nampa, ID	13211387	NA	PS	COB	COB	–	Returns to Wilson Drain which returns to Indian Creek upstream of mouth
Meridian WWTP near Meridian, ID	433820116261900	NA	PS	COB	COB	–	Returns to Fivemile Creek upstream of its confluence with Fifteenmile Creek

Table 1. Sites sampled upstream of, downstream of, and within the total phosphorus mass-balance modeling reach in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.—Continued

[Locations of sites are shown in figure 1. Shaded sites mark upstream and downstream ends of model subreaches. **Site type:** B, biological site; D diversion; GW, groundwater; M, main stem of the Boise River; PS, point-source discharge; PZ, piezometer; R, return flow or tributary; SR, Snake River site. **Samples collected:** Agency that collected samples. Reclamation, Bureau of Reclamation; IDWR, Idaho Department of Water Resources; USGS, U.S. Geological Survey; COB, City of Boise; IPC, Idaho Power Company. **Abbreviations:** WWTP, wastewater treatment plant; North Channel, north channel of the Boise River; South Channel, south channel of the Boise River; ID, Idaho; OR, Oregon; LB, left bank; RB, right bank; RM, river mile; blw, below; Hwy, highway; WL, water-level measurement in piezometer; ft, foot; NA, not applicable]

Site name	USGS site No.	River mile	Site type	Samples collected			Notes
				Discharge	Water-quality	Chlorophyll-*a*	
Piezometers							
Boise River Piezo 2-LB	433937116164001	47.5	PZ	USGS–WL	USGS	–	Near 13206000, LB near Boise, ID
Boise River Piezo 6B-RB	434140116405602	24.7	PZ	USGS–WL	USGS	–	Near 13211000, RB near Caldwell, Idaho
Boise River Piezo 8-RB	434318116475201	15.7	PZ	USGS–WL	USGS	–	Near 13212500, RB near Notus, Idaho
Boise River T1-F	434612116570901	5.2	PZ	USGS–WL	USGS	–	At Wanstad Road near Parma, Idaho, RB
Boise River T1-A	434706116581601	3.8	PZ	USGS–WL	USGS	–	Near 13213000, 2 ft from RB near Parma, ID
Boise River T2-A	434706116581401	3.8	PZ	USGS–WL	USGS	–	Near 13213000, 180 ft from RB near Parma, ID
Shallow wells							
04N 02E 32ADD1	433832116140201	50.1	GW	–	USGS	–	Near 36th Street and State Street in Boise
04N 02E 32ADB1	433837116141101	50.0	GW	–	USGS	–	Near Veterans Memorial Parkway and State Street in Boise
04N 02E 32CAD1	433820116143401	49.5	GW	–	USGS	–	At Lander WWTP
04N 02E 19CDB1	433954116155801	48.0	GW	–	USGS	–	Near Pierce Park Lane and Castle Drive in northwest Boise
04N 01W 24ACAB2	434026116235602	41.8	GW	–	USGS	–	On south channel upstream of Phyllis Canal diversion
04N 01W 15BADD1	434120116263401	39.7	GW	–	USGS	–	Near confluence of north and south channels
04N 01W 17DDA1	434049116283201	37.0	GW	–	USGS	–	Between Star Road and Linder Road
04N 02W 08ADD1	434200116353201	31.3	GW	–	USGS	–	Near Mill Slough at Duff Lane in Middleton
04N 03W 14CACB2	434057116395901	25.6	GW	–	USGS	–	Near Mason Creek site 13210983
04N 03W 16CBC1	434048116423001	22.3	GW	–	USGS	–	Near ponds and gravel pits on north side of river in Caldwell
04N 03W 17ACA1	434111116424801	21.4	GW	–	USGS	–	Near gravel pit on north side of river in Caldwell
05N 04W 35CCB1	434325116472901	16.0	GW	–	USGS	–	Near Notus
05N 05W 06CBAB2	434758116591702	2.5	GW	–	USGS	–	Near Boise River Mouth

Thomas and Dion (1974) developed a general conceptual model of groundwater and surface-water discharge in the lower Boise River watershed in 1971. Many other reports (Mullins, 1998; Petrich, 2004; Petrich and Urban, 2004; Skinner, 2006; Bureau of Reclamation and Idaho Department of Water Resources, 2008) show consensus among various agencies regarding groundwater and surface-water interaction described in the section, Conceptual Model of Groundwater and Surface-Water Interaction. Each of these reports indicated that discharge in the lower Boise River is sustained year round by groundwater. A reconnaissance-level study of shallow groundwater quality adjacent to the Boise River showed increases in OP concentrations in groundwater in the downstream direction of the Boise River (MacCoy, 2004). The Idaho State Department of Agriculture informed the current conceptual model of groundwater and surface-water interaction with results of phosphorus loading from shallow groundwater to Mason Creek (Fox and others, 2002).

The lower Boise River TP TMDL may be supported further by a phosphorus-trading network. In this system, entities such as farmers or canal operators can remove phosphorus loads that would otherwise enter the Boise River and trade those load reductions to other entities according to their market value. Ross & Associates Environmental Consulting, Ltd. (2000) published a market analysis and a proposed trading framework for TP in the lower Boise River watershed. To explore the potential use of Dixie Drain (RM 10.5; fig. 1*B*) as an offset to remove phosphorus loads that would otherwise discharge to the Boise River, the EPA and the IDEQ completed a mass-balance model of TP in the Boise River (U.S. Environmental Protection Agency and Idaho Department of Environmental Quality, 2012). TP concentration data for surface water were estimated in all but three locations in the modeling reach and discharge was estimated in all but four locations in the modeling reach. Model results showed streamflow gains downstream of Caldwell totaling 207 ft^3/s in August 2000 and 162 ft^3/s in July 2001. The model also estimated a lowered TP concentration relative to background conditions at the Boise River near Parma (RM 3.8) under various scenarios involving phosphorus removal from Dixie Drain (U.S. Environmental Protection Agency and Idaho Department of Environmental Quality, 2012). This report describes results based on the request of the IDEQ that the USGS develop a similar TP mass-balance model using data collected at more than 40 locations during three synoptic sampling periods.

Study Methods

TP mass balance models described in this report relied on input data collected during three sampling periods in the lower Boise River watershed. This section describes the approach to synoptic sampling and site selection. Methods of discharge measurement, water-quality and periphyton sample collection, and laboratory analysis are described. Also described are methods of piezometer installation, measurement of groundwater and surface-water elevations, and survey methods used to assign reference elevations at each site. Consistent data-collection and quality-assurance methods enabled development of two types of mass balance models. This section provides a summary of quality-control sample results and an extensive description of calculations and assumptions made within mass balance models.

Synoptic Sampling

The USGS measured stream discharge and collected water-quality samples during three synoptic sampling periods. Ideally, discharge from Lucky Peak Dam at the upstream end of the lower Boise River watershed would be held steady during each synoptic event, and this generally was the case. Main-stem discharge increases of more than 50 ft^3/s occurred, but generally lasted less than 8 hours before decreasing to discharges within 50 ft^3/s of the measured discharge during sample collection at a given site. These sudden and short-lived increases in discharge occurred upstream of sampling crews and did not propagate to downstream sampling locations before samples were collected.

Site Selection and Sampling Strategy

Surface-water sampling sites were the primary source of information for mass-balance models. The study was originally designed to assess water quality in shallow wells completed at less than 100 ft below land surface near the Boise River. Samples were collected at as many as 13 shallow wells during the first two synoptic events but concentrations of dissolved phosphorus in shallow wells were generally lower than estimated dissolved phosphorus concentrations in groundwater in the modeling reach. Therefore, six piezometers along the Boise River were sampled during the synoptic event in March 2013.

Surface-Water Sites

The USGS collected samples and measured discharge at 16 Boise River sites, and 17 return flows and tributaries to the Boise River as part of this study (table 1; figs. 1*A*, 1*B*). Sand Hollow Creek and the two Snake River sites are outside the modeling reach, but samples were collected to assess TP loads in the Boise River and Sand Hollow Creek relative to TP loads in the Snake River. Samples also were collected at four WWTPs and treated as return flows that discharge directly to the Boise River in the mass-balance model. Two additional WWTPs and two point-source discharges from fish hatcheries were sampled, but were not used directly in the phosphorus mass-balance model because their TP loads either were represented in tributary samples or were discharged into lakes on Eagle Island (in the case of Eagle Island fish hatchery). The Idaho Department of Water Resource (IDWR) provided discharge information for 41 diversions in the modeling reach.

The modeling reach starts at the Boise River at Veterans Memorial Parkway at (RM 50.2) and ends at the Boise River near Parma (RM 3.8). A schematic layout of the modeling reach from upstream to downstream is shown in figure 2. Every site used in the mass-balance model was assigned a river mile based on the point at which it is located along the main stem of the Boise River (herein referred to as “the main stem”). Each main-stem sampling site defines a subreach. For example, the first upstream subreach begins at Veterans Memorial Parkway (RM 50.2) and ends at the Boise River at Glenwood Bridge (RM 47.5), and the next subreach starts with the Boise River at Glenwood Bridge and ends at sampling sites on the north and south channel at Eagle Road (RM 42.8) (table 1).

Main-stem sites generally were selected based on the locations of tributary or return flows (returns) and major diversions. The farthest-upstream main-stem site was the Boise River below Diversion Dam (RM 61.1). Diversion Dam is upstream of the modeling reach but was sampled to establish so-called “baseline” water-quality conditions, or conditions that represent water quality upstream of any urban or agricultural land-use effects. All major return flows or tributaries were sampled and the main stem was sampled upstream and downstream of major returns. Because returns were sampled, more than one return could discharge into the Boise River between main-stem sampling sites as long as a diversion did not occur between any two returns in the same subreach. The IDWR measured discharge in diversions, but water-quality samples were not collected in diversions.

Total phosphorus concentrations in diversions were assumed to be the same as those in the closest main-stem sampling location that would likely represent water-quality conditions in that diversion. For example, the August 2012 TP concentration in the Boise River at Veterans Memorial Parkway (RM 50.2) was 0.015 mg/L. Just downstream of Veterans Memorial Parkway, the Lander Street WWTP (RM 50.0) discharged to the Boise River with a TP concentration of 2.23 mg/L. The Riverside Village diversion (RM 47.7) is downstream of Lander Street WWTP and upstream of the next main-stem sampling site at the Boise River at Glenwood Bridge (RM 47.5). Because the Riverside Village diversion is downstream of the Lander Street WWTP, the TP concentration of water diverted to Riverside Village would likely be similar to the TP concentration at Glenwood Bridge (fig. 2), which was 0.07 mg/L in the August 2012 sample. Additional site selection details are summarized as follows:

1. North and south channel sites were selected immediately downstream of the West Boise WWTP outfall (RM 44.2) and upstream of Eagle Drain (north channel RM 42.7), Dry Creek (north channel RM 42.5), and Thurman Drain (RM 41.9) return flows. The next downstream set of north and south channel sampling sites was selected upstream of the relatively large Middleton Canal (north channel RM 41.8) and Phyllis Canal (RM 41.8) diversions to best characterize water quality in those diversions as well as the north and south channel downstream of the return flows. A site was also selected as close as possible to the confluence of the north and south channels to characterize water quality in the main stem downstream of Eagle Island (RM 39.7).

2. The Boise River near Middleton (RM 31.4) was sampled upstream of the mouth of Fifteenmile Creek (RM 30.3), and the Boise River at Middleton Road (RM 28.8) was sampled downstream of the mouth of Fifteenmile Creek.

3. It was not feasible to collect a main-stem sample between Middleton Road (RM 28.8) and the Boise River at Highway 20-26 crossing in Caldwell (RM 24.0). Five returns discharge into the Boise River in this subreach and the Riverside Canal diversion (RM 24.6) is upstream of the last return flow, Hartley Drain (RM 24.4) (fig. 1*B*). Therefore, samples also were collected from Riverside Canal. The diversion for Sebree Canal (RM 24.0, also known as the Farmer’s Co-op Ditch) is immediately upstream of the Boise River at Highway 20-26 crossing, but downstream of all other return flows in this subreach, so water quality in Sebree Canal was assumed to be the same as water quality in the Boise River at Highway 20-26 crossing.

4. Because of a substandard cross section for discharge measurement at the Boise River at Highway 20-26 crossing (RM 24.0), the measuring and sampling section was moved to RM 24.7, upstream of Hartley Drain (RM 24.4) and Riverside Canal diversion (RM 24.6) for the March 2013 synoptic sampling period. Sebree Canal (RM 24.0) was dry in March 2013, and a discharge of 2.4 ft^3/s was measured and sampled in Riverside Canal (RM 24.6). Hartley Drain was sampled as planned.

5. Indian Creek at the mouth (RM 22.4) was sampled during all three synoptic events. During irrigation season, most of the flow in Indian Creek is diverted to Riverside Canal upstream of the sampling location at the mouth of Indian Creek (fig. 2). Because the mass-balance model requires information on where and how much phosphorus reaches the Boise River, it was appropriate to collect Indian Creek samples at the mouth. Any TP load diverted from Indian Creek to Riverside Canal was accounted for if and when it discharged to the Boise River at points downstream. Indian Creek in its entirety was diverted to Riverside Canal during the October 2012 synoptic event, which is not normally the case during that time of year.

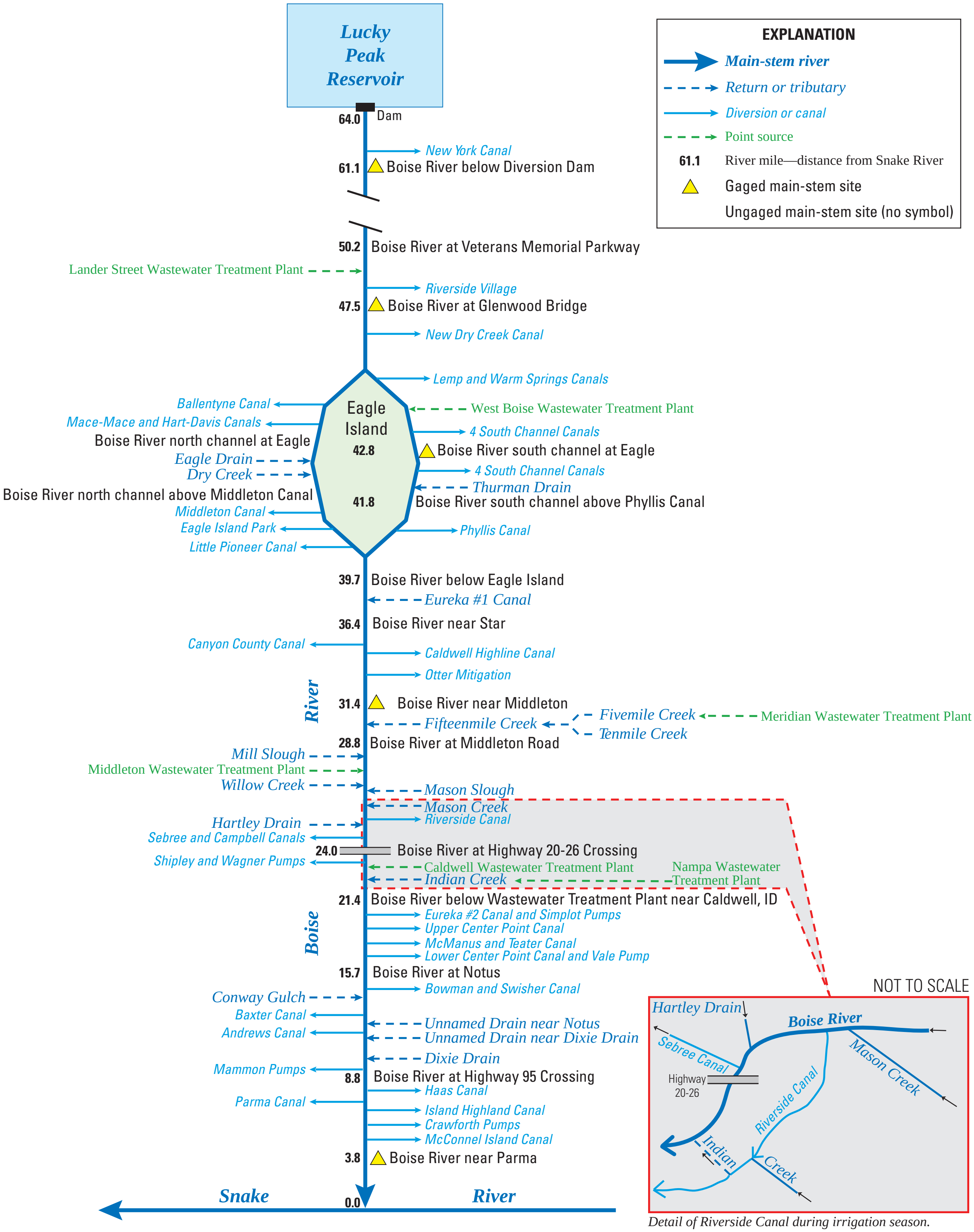


Figure 2. Diversions, drains, and tributaries along the lower Boise River, southwestern Idaho (modified from MacCoy, 2004).

6. It was not feasible to collect a main-stem sample between the Boise River at Notus (RM 15.7) and the Boise River at Highway 95 crossing (RM 8.8). Conway Gulch (RM 14.2), two unnamed drains (RM 12.3 and RM 10.9), and Dixie Drain (RM 10.5) discharge to the Boise River in this subreach. Baxter Canal diversion (RM 13.3) is between Conway Gulch (RM 14.2) and the first upstream unnamed drain (RM 12.3). During the August 2012 synoptic event, 14 ft^3/s of water was diverted from the Boise River into Baxter Canal. Because the TP concentration in the Boise River at Notus was the same as the TP concentration in Conway Gulch (0.32 mg/L), the TP concentration in Baxter Canal was also assumed to be 0.32 mg/L (fig. 2). Andrews Canal (RM 11.1) diverted 20 ft^3/s of water during the August 2012 synoptic event and is between the two unnamed drains (RM 12.3 and RM 10.9). The TP concentration in Andrews Ditch was assumed to be the same as the concentration in the Boise River at Highway 95 crossing (RM 8.8).
7. Sand Hollow Creek near the mouth (not assigned an RM as a discharge to the Snake River; fig. 1*B*) was sampled as a tributary to the Snake River between the mouth of the Boise River (RM 0.0) and the Snake River at Nyssa, Oregon (fig. 1*A*). The Snake River near Adrian, Oregon also was sampled upstream of the mouth of the Boise River, but returns and diversions on the Oregon side of the Snake River were not sampled or measured.

Groundwater Sites

Groundwater was sampled in shallow wells and piezometers in an effort to characterize shallow groundwater concentrations near the lower Boise River. Shallow wells completed at less than 125 ft below land surface were sampled during the first two synoptic events. Dissolved phosphorus concentrations in shallow groundwater samples from the first two synoptic sampling periods were generally lower than estimated groundwater phosphorus concentrations used in predictive mass-balance models. Therefore, seven piezometers completed between 4 and 11 ft below land surface were sampled during the March 2013 synoptic event to improve the understanding of TP concentrations in shallow groundwater (table 1). Existing piezometers were used at the Glenwood Bridge (RM 47.5) and Parma (RM 3.8) streamgages, and at Wanstad Road near Parma (RM 5.2). Three additional piezometers were installed to test assumptions about TP concentrations in groundwater and to validate discharge-balance calculations from the first synoptic event. One piezometer was installed near Middleton (RM 30.0), where discharge-balance results indicated the farthest-upstream location with substantial streamflow gains. The other two piezometers were installed near Caldwell (RM 24.8) and at Notus (RM 15.7) to validate continued gains toward the downstream end of the modeling reach. All piezometers were installed near the bank or in slack water adjacent to the Boise River. Cross-sectional installation of piezometers at Boise River locations was beyond the scope of the project.

Point-Source Discharge Sites

Samples from eight point-source discharge permittees were collected and analyzed for TP (table 1). Those permittees included municipal WWTPs and outfalls from both the Eagle Island and the Nampa fish hatcheries. It was necessary to obtain analytical results and discharge information from point sources that discharged directly to the Boise River or to tributaries downstream of the point at which the tributary was sampled. Such sites included Lander WWTP (RM 50.0) and Caldwell WWTP (RM 22.6), which discharge to the main stem of the Boise River; West Boise WWTP (RM 44.2), which discharges into the south channel of the Boise River; and Middleton WWTP (RM 27.1), which discharges into Mill Slough (RM 27.2) downstream of the USGS sampling location in Mill Slough.

The four remaining point-source discharge samples were not used in the mass-balance model because the facilities do not discharge directly to the Boise River. They were collected from Eagle Island fish hatchery, Nampa WWTP, Nampa fish hatchery, and Meridian WWTP, which discharge to lakes on Eagle Island, Indian Creek, Wilson Drain (a tributary to Indian Creek), and Fivemile Creek (a tributary of Fifteenmile Creek), respectively. The tributary sample in Indian Creek was collected downstream of the confluence of Wilson Drain with Indian Creek and downstream of the Nampa WWTP outfall to Indian Creek (RM 22.4). The tributary sample in Fifteenmile Creek (RM 30.3) was collected downstream of the confluence of Fivemile Creek with Tenmile Creek. Samples were not collected from Star, Kuna, Notus, or Parma municipal WWTPs. Mill Slough was sampled downstream of the WWTP discharge from Star, and Sand Hollow Creek was sampled downstream of the WWTP discharge from Parma. Conway Gulch (RM 14.2) was sampled upstream of the WWTP discharge from Notus, but seasonal Notus WWTP discharges did not occur during any synoptic sampling period.

Water-Quality Sampling

Surface-water and groundwater samples were collected and processed following standard USGS sampling protocols described in the USGS National Field Manual (herein referred to as the “USGS NFM”) (U.S. Geological Survey, variously dated). Depth- and width-integrated water samples were collected according to the Equal-Width-Increment (EWI) method described in the USGS NFM. WWTP samples were collected as 24-hour composite samples and a mean 24-hour discharge was assigned to the outfall. The city of Boise managed the collection of the WWTP samples and compiled

24-hour WWTP flows. WWTP samples were processed and analyzed according to USGS protocols. Surface-water and point-source discharge water-quality samples were analyzed for total phosphorus (TP), total dissolved phosphorus (TDP), total nitrogen, nitrate plus nitrite as nitrogen, ammonia, and dissolved orthophosphorus as phosphorus (OP) at the USGS National Water-Quality Laboratory (NWQL). Water-quality samples collected from surface water also were analyzed for suspended-sediment concentration at the USGS Cascades Volcano Observatory (CVO). Groundwater samples were analyzed for dissolved nutrients at NWQL.

EWI method samples were collected with a DH-81 sampler at wadable sites, or a DH-95 hand-line sampler at bridge sites. A 1-L high-density polyethylene bottle and nozzle were used to collect water in the sampler. Water samples were homogenized in a plastic churn splitter. In accordance with methods described in the USGS NFM, the churn and sampling equipment were cleaned in soapy water, rinsed in tap water, and triple rinsed with deionized water at the start of each sampling period. The sampling equipment was rinsed three times with deionized water between sampling sites and rinsed three times with native water just prior to sample collection. Sites were sampled in downstream order starting at the farthest-upstream site.

Unfiltered water samples for total nutrient analysis were acidified with sulfuric acid and were chilled at 4 °C until analysis. Unfiltered suspended sediment samples were homogenized, stored at room temperature, and shipped to the CVO for analysis. Water samples to be analyzed for dissolved nutrients were filtered through 0.45-µm-pore-size capsule filters certified as free from contamination.

Water temperature, specific conductance, pH, turbidity, and dissolved oxygen were measured in the stream at the time of sample collection using a multi-parameter water-quality sonde calibrated according to methods described by Wagner and others (2006). Qualitative stream conditions such as odor, turbidity, and presence of debris, garbage, floating algae, suds, fish kills, and oil also were noted.

Analytical Methods

The USGS NWQL analyzed nutrients according to methods described in Fishman (1993) and Patton and Kryskalla (2003, 2011), and quality-assurance and quality-control protocols described in Pritt and Raese (1995). Suspended-sediment samples were analyzed for concentration and percentage of particles less than 0.0625 mm by the CVO Sediment Laboratory using methods described in Guy (1969) and the American Society for Testing and Materials (2002) method D3977-97. The CVO Sediment Laboratory adheres to quality-control and quality-assurance measures described in Knott and others (1993).

Periphyton and Phytoplankton Sampling

Five main-stem sites were sampled for chlorophyll-*a* in periphyton (benthic algae) and phytoplankton (algae suspended in the water column). The biological sampling sites were selected in historical sampling locations, including the Boise River at Eckert Road (RM 58.1), Boise River at Glenwood Bridge (RM 47.5), Boise River near Middleton (RM 31.4), Boise River at Highway 20-26 crossing near Caldwell (RM 24.0), and the Boise River at the mouth near Parma (RM 0.0) (table 1, fig. 1*C*). Periphyton samples were collected according to standard USGS methods described in Moulton and others (2002) by filtering a measured portion of a composited periphyton sample through a 0.45-µm glass-fiber filter. The filter was wrapped in foil and placed on dry ice or in a freezer until analyzed. Water-column samples for chlorophyll-*a* in phytoplankton were collected using the EWI method, homogenized in a plastic churn splitter, chilled, and analyzed within 24 hours. Chlorophyll-*a* in periphyton, chlorophyll-*a* in phytoplankton, and ash-free dry weight (periphyton biomass) were analyzed by the Bureau of Reclamation (Reclamation) Pacific Northwest Regional Laboratory in Boise, Idaho, according to standard method 10200H (Clesceri and others, 1998).

As part of standard USGS protocols for collecting periphyton samples, substrate type, water depth and velocity, and light availability were measured at each of the five main-stem sampling sites. Depth was measured using a standard wading rod, and water velocity was measured using a velocity meter. Light intensity or photosynthetically active radiation also was recorded at each periphyton and phytoplankton sampling site using a LI-COR® LI-192 underwater light sensor.

Discharge Measurements

The USGS measured discharge at all surface-water sampling sites in the main stem and returns. Measurements were completed according to methods described in Mueller and Wagner (2009) and Turnipseed and Sauer (2010). USGS streamgages with existing stage-discharge ratings were used to provide computed discharge at the time of sample collection as well as a daily mean discharge for the sampling day at five USGS streamgaging stations including the Boise River at Glenwood Bridge near Boise (RM 47.5), the Boise River South Channel at Eagle Road (RM 42.8), Eagle Drain at Eagle (north channel RM 42.7), the Boise River near Parma (RM 3.8), and the Snake River at Nyssa.

Discharge information was also obtained from sources outside the USGS during each synoptic sampling period.

The IDWR provided discharge data for diversions. The Boise River water master of the IDWR measures discharge in diversions weekly from April 1 to October 31 (Idaho Department of Water Resources, 2013) using:

1. a stage-discharge rating (referenced to either a staff plate or a submersible pressure transducer);
2. a Parshall flume;
3. a broad-crested weir; or
4. a contracted rectangular weir (Rex Barrie, Idaho Department of Water Resources, oral commun., July 2012).

The water master does not measure flows in diversions during non-irrigation season because they are physically turned off or shut at head gates and assumed to have zero discharge. The October 2012 synoptic sampling period took place after irrigation season ended, but diversions were measured by the IDWR through October 31. Prior to the March 2013 synoptic event, the USGS visually inspected diversions to confirm zero flow or stagnant water. A streamgage operated by Idaho Power Company (IPC) provided discharge values for the Boise River near Middleton (RM 31.4). The Reclamation Hydromet streamgage system allowed calculation of discharge values for the Boise River below Diversion Dam (RM 61.1). The daily mean Hydromet discharge in the New York Canal was subtracted from the daily mean discharge from Lucky Peak Dam to calculate the daily mean discharge at Boise River downstream of Diversion Dam (Bureau of Reclamation, 2013).

Discharge Measurement Uncertainty

The flow balance approach described in the section, Mass-Balance Models, relied solely on surface-water discharge measurements in the Boise River, returns, diversions, and tributaries. The USGS used two methods to measure flow at sampling sites according to methods described in Mueller and Wagner (2009) and Turnipseed and Sauer (2010). Discharge in tributaries and return flows was measured using a SonTek/YSI FlowTracker® acoustic Doppler velocimeter. Discharge at main-stem sites was measured using one of two acoustic Doppler current profilers (ADCPs) made by Teledyne RDI. The StreamPro® ADCP was used at relatively shallow sites, whereas the Rio Grande® ADCP was used at relatively deep sites such as the Snake River near Adrian, Oregon.

Discharge measurement uncertainty was estimated to assess confidence in calculated streamflow gains and losses along subreaches. Uncertainty was estimated differently depending on the instrument used to complete the discharge measurement. The FlowTracker acoustic Doppler velocimeter calculates uncertainty internally through a statistical technique developed by the USGS, and outputs a statistical uncertainty value in percent at the completion of the measurement (SonTek/YSI, 2009). A 5-percent uncertainty was used for computed discharge from USGS streamgaging stations. Regardless of methods or instrumentation used to compute discharge, a more conservative uncertainty value of 10 percent was assumed for discharge data obtained from the IDWR, the Idaho Power Company, and Reclamation.

Different methods of estimating measurement uncertainty for ADCP measurements were selected based on the number of measurement transects. Uncertainty was estimated according to methods described in Williams (2011) when the measurement was composed of four or more transects. However, most ADCP measurements completed during synoptic events were composed of two transects in accordance with a recently approved USGS requirement regarding ADCP exposure time. In 2011, the USGS Office of Surface Water mandated that moving-boat ADCP measurements have a minimum exposure time of 720 seconds (12 minutes) and an even number of two or more transects (U.S. Geological Survey, written commun., 2011). Prior to the exposure-time mandate, USGS ADCP measurements were required to be composed of at least four transects. With the minimum number of transects now decreased to two, a different method of estimating uncertainty was developed based on an extensive statistical analysis (D.S. Mueller, U.S. Geological Survey, written commun., 2011). Estimates of uncertainty for two-transect ADCP measurements are computed using the coefficient of variation computed by instrument software as follows:

1. Convert the coefficient of variation to percent (for example, 0.021 to 2.1 percent).
2. Round to the nearest whole number (for example, 2.1 percent to 2 percent.
3. If rounding produces 0 percent use an uncertainty of 3 percent.
4. If the rounded number is greater than 0, multiply it by 3.3 (for example, $2 \times 3.3 = 6.6$ percent).
5. Add 0.5 percent for systematic error (for example, $6.6 + 0.5 = 7.1$ percent).

Uncertainty was propagated through each subreach according to methods described in Williams (2011). Propagated uncertainty was multiplied by the discharge at each site to obtain uncertainty in cubic feet per second.

Piezometer Installation and Groundwater and Surface-Water Elevations

Although piezometers used in this study were not portable, piezometer installation followed USGS guidance for installation of portable piezometers provided in Rosenberry and LaBaugh (2008). Galvanized steel pipe with a 3/4-in. inside diameter was crimped at the end and perforated with 1/8-in. holes before being driven into nearshore sediments to a depth of 4–11 ft below land surface. Piezometers were developed using a peristaltic pump until clear water could be pumped sustainably from the piezometer. Measuring points and reference pins used to measure groundwater and surface-water elevations were established according to methods in Cunningham and Schalk (2011) and surveyed according to methods in Rydlund and Densmore (2012). Surface-water elevations at surface-water sites were measured from steel reference pins during each synoptic event. Groundwater elevations in piezometers were measured from measuring points on piezometers. Where present, the surface-water elevation also was measured from the same measuring point on the piezometer to obtain the elevation head difference between groundwater and surface water on site. Efforts to survey piezometer measuring points, reference pins, and the arbitrary streamgage datum at each USGS streamgage in the modeling reach effectively referenced all measured elevations to the North American Vertical Datum of 1988.

Quality Assurance and Quality Control

USGS protocols require quality assurance of instrumentation and observations at each step of site selection, site installation or establishment, data collection, and data review. Quality assurance generally is built into USGS sampling procedures (U.S. Geological Survey, variously dated) and detailed in the Idaho Water Science Center (IDWSC) Quality-Assurance Plan for Water-Quality Activities (M. Hardy, U.S. Geological Survey, written commun., 2008). Equipment preparation, transport, and cleaning were completed as described in the USGS NFM for nutrient and suspended-sediment sample collection. Instrumentation used to record water-quality parameters was calibrated daily according to procedures described in Wagner and others (2006). EWI sampling collection methods were used at all surface-water sites with the exception of those with inadequate discharge to complete a vertical transect. Such conditions required the use of USGS grab-sampling protocols (U.S. Geological Survey, variously dated). Sample processing and preservation for filtered and unfiltered nutrients and suspended sediment also was completed as described in the USGS NFM. Water levels in wells were measured according to methods described in Cunningham and Schalk (2011). Groundwater-quality sites were selected and sampled according to methods described in Lapham and others (1995) and Koterba and others (1995).

Quality assurance also is built into USGS protocols for measuring surface-water discharge (Mueller and Wagner, 2009; Turnipseed and Sauer, 2010). Discharge measurement instrumentation is checked using built-in quality-assurance checks done prior to making a discharge measurement. All discharge measurements are peer reviewed at the science-center level. Quality-assurance protocols for surface-water discharge measurements are further detailed in the IDWSC surface-water quality-assurance plan (M.S. Wood and D.M., Evetts, U.S. Geological Survey, written commun., 2011).

Quality Control Sample Results and Data Validation

Quality-control samples provide information necessary to evaluate the quality, in terms of bias and precision, of analytical results reported for water samples. Quality-control samples were collected according to procedures outlined in the USGS NFM and analyzed concurrently in the laboratory with routine samples. Two types of quality-control samples were collected during each synoptic event. Each of three field crews collected one blank sample and two replicate samples during each synoptic event. Replicate and blank quality-control samples were submitted at a proportion equivalent to at least 10 and 5 percent of the total number of water samples, respectively.

Replicate data can be obtained in different ways to provide an assessment of precision (reproducibility) of analytical results. Replicate samples are two or more samples considered to be essentially identical in composition. Replicate samples can be obtained in the field (field replicate) either by repeating the collection process to obtain two or more independent composite samples (concurrent field replicate), or by splitting a single composite sample into two or more subsamples (split field replicate). The individual replicate samples then are analyzed separately. Likewise, a single sample can be analyzed two or more times in the laboratory to obtain a measure of analytical precision (laboratory replicate). All replicate samples collected as part of this study were split field replicates. Analyses of split field replicates indicate the reproducibility of environmental data that are affected by the combined variability potentially introduced by field and laboratory processes.

The precision of analytical results for a constituent can be determined using the relative percent difference (RPD) between the routine sample result and the replicate result. RPD is calculated using the absolute value of the difference between the result pair, divided by the mean of the result pair, multiplied by 100. Expressing precision relative to a mean concentration standardizes comparison of precision among individual constituents. The data-quality objective used to indicate acceptable precision of results for field replicates was a maximum RPD of 20 percent. Median RPDs for nutrient replicate results ranged from 0 to 1.6 percent, and the median RPD for suspended-sediment replicate results was 6.5 percent. Precision estimates for individual analytes in replicate samples were within the 20-percent RPD limit for 91 of 95 constituent results. The March 7, 2013, replicate TP concentration result in Dixie Drain (RM 10.5) was 0.13 mg/L compared to the routine sample result of 0.10 mg/L (26 percent RPD). The replicate TDP concentration at shallow well 434049116283201 was 0.03 mg/L compared to 0.04 mg/L in the routine sample (29 percent RPD). Two of three replicate suspended-sediment samples collected at the Boise River at Notus (RM 15.7) differed between 23 and 25 percent from the routine sample results. Suspended-sediment concentration results at Notus (RM 15.7) were between 4 and 7 times greater than suspended sediment concentration results in the Boise River upstream or downstream of Notus in August and October 2012. Further evaluation of site-specific conditions at Notus is warranted based on routine and quality-control suspended-sediment results on site. No adjustments were made to analytical data on the basis of replicate analyses.

Three field crews each submitted a deionized-water blank sample during each synoptic event. Blank samples identify the presence and magnitude of contamination that potentially could bias analytical results. Field blanks are aliquots of deionized water that are certified as contaminant free and are processed through the sampling equipment used to collect stream samples. Blanks then are subjected to the same processing (sample splitting, filtration, preservation, transportation, and laboratory handling) as stream samples. Blank samples are analyzed for the same constituents as stream samples to identify whether any detectable concentrations exist.

Analytical results for field blanks indicated no bias in TP, OP, or TDP results, as TP, OP, and TDP were undetected in six blank samples from surface-water sites and three blank samples from groundwater sites. A field blank with constituent concentrations equal to or less than the laboratory reporting level (LRL) for the analytical method indicates that the entire process of sample collection, field processing, and laboratory analysis is presumably free of contamination. If detectable concentrations in field blanks were equal to or greater than twice the LRL, the concentrations were noted during data review. Two blank sample results for total nitrogen were greater than twice the LRL for total nitrogen (both detected at 0.13 mg/L with an LRL of 0.05 mg/L). Both total nitrogen detections occurred during the August synoptic event and were collected by two separate crews using different sets of equipment. Analytical results from field blanks for the next two synoptic events did not reveal a consistent trend suggestive of systematic contamination associated with field practices. Exceedances of twice the LRL may have represented random contamination or error in the calibration of laboratory instruments that was not persistent in the process and was not likely to cause positive bias in the larger population of routine sample results. A consistent pattern in blank detections did not emerge during this short-term study, but during longer-term studies, such a pattern would require collection of blank samples from individual components of the processing sequence to identify the source of contamination.

Routine water-quality sample results also were reviewed after release from the NWQL, CVO, and Reclamation laboratories. Data validation included computing RPDs between any dissolved nutrient result that exceeded the whole-water equivalent nutrient result. Laboratory analyses were rerun on any such RPD that exceeded 10 percent. Periphyton, chlorophyll-*a* in phytoplankton, and suspended-sediment results were reviewed in relation to historical results at the same location for any anomalies.

Mass-Balance Models

Three TP mass-balance models were generated using the results of three synoptic sampling periods. The first synoptic event was during irrigation season in August 2012. The second synoptic event was in late October 2012 after irrigation season ended. The final synoptic event was in early March 2013 prior to spring runoff and before irrigation season began again. Two types of mass-balance models were developed for each of the three synoptic events. Each mass-balance model was generated in an Excel spreadsheet and is arranged from the first upstream site at the top of the spreadsheet, to the last downstream site at the bottom of the spreadsheet. The modeling reach and the top of the spreadsheet begins at the Boise River at Veterans Memorial Parkway (RM 50.2) and ends at the Boise River near Parma (RM 3.8) (fig. 2). Moving downstream, a spreadsheet row was added to the model for each surface-water diversion, return, or tributary according to its location in downstream order along the Boise River. Main-stem sampling locations defined the beginnings and ends of subreaches within the modeling reach. Many equations are provided throughout the section, Mass-Balance Models. If not otherwise stated, equations use values for discharge in cubic feet per second, values for TP concentrations in milligrams per liter, values for distance in miles, and values for TP loads in pounds per day. Variables for equations presented in this section are summarized in table 2. The spreadsheet models and instructions for using the models are provided in appendix 1.

Table 2. Variables described in total phosphorus mass-balance model equations for the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

[**Abbreviations:** ft^3/s, cubic foot per second; $(ft^3/s)/mi$, cubic foot per second per mile; mi, mile; lb/d, pound per day; TP, total phosphorus; $L/ft^3 \times s/d \times lb/mg$, product of liters per cubic foot, seconds per day, and pounds per milligram; (lb/d)/mi, pound per day per mile; mg/L, milligram per liter]

Variable	Defined in equation No.	Units	Description
		Discharge balance	
Q_{gw}	1	ft^3/s	Unmeasured discharge (assumed to be groundwater) gain or loss in a main-stem subreach.
Q_{DS}	1	ft^3/s	Measured main-stem discharge at the downstream end of the subreach.
Q_{US}	1	ft^3/s	Measured main-stem discharge at the upstream end of the subreach.
Q_R	1	ft^3/s	Measured discharge in a return flow or tributary within the subreach.
Q_D	1	ft^3/s	Measured discharge in a diversion within the subreach.
Qgw_{RM}	2	$(ft^3/s)/mi$	Streamflow gain or loss per river mile.
RM_{US}	2	mi	River mile at the upstream end of the subreach.
RM_{DS}	2	mi	River mile at the downstream end of the subreach.
$Qgw_{i \ldots n}$	3	ft^3/s	Streamflow gain or loss at each site represented in the spreadsheet mass-balance model (locations *i* through *n*).
L_{DS}	3	mi	River mile of a consecutive downstream location within a subreach.
L_{US}	3	mi	River mile of a consecutive upstream location within a subreach.
$Qm_{i \ldots n}$	4	ft^3/s	Modeled discharge including groundwater exchange at each site represented in the spreadsheet mass-balance model (locations *i* through *n*).
		Measured mass-balance model	
ΔM	5	lb/d	Unmeasured change in TP load in the subreach.
C_{DS}	5	mg/L	TP sample result at the downstream end of the subreach.
C_{US}	5	mg/L	TP sample result at the upstream end of the subreach.
C_R	5	mg/L	TP sample result in a return flow or tributary within the subreach.
C_D	5	mg/L	Estimated TP concentration in a diversion within the subreach.
F	5	$L/ft^3 \times s/d \times lb/mg$	Conversion factor to convert mg/L × ft^3/s to lb/d equal to 5.3938.
ΔM_{RM}	6	(lb/d)/mi	Unmeasured TP load per river mile.
$\Delta M_{i \ldots n}$	7	lb/d	Unmeasured TP load at each site represented in the spreadsheet mass-balance model (locations *i* through *n*).
Cm_i	8	mg/L	TP sample result at the first upstream site in the modeling reach.
$Cm_{j \ldots n}$	9	mg/L	Modeled main-stem TP concentration at each site represented in the spreadsheet mass-balance model (locations *j* through *n*).
$Qm_{j \ldots n}$	9	ft^3/s	Modeled discharge at each site represented in the spreadsheet mass-balance model (locations *j* through *n*).
$Cm_{k \ldots n}$	10	mg/L	Modeled main-stem TP concentration at a main-stem site.
Mm_i	11	lb/d	Measured TP load at the first upstream site in the modeling reach.
$Mm_{j \ldots n}$	12	lb/d	Modeled TP load at each site represented in the spreadsheet mass-balance model (locations *j* through *n*).
		Predictive mass-balance model	
Cp_i	13	mg/L	TP sample result at the first upstream site in the modeling reach.
$Cgw_{j \ldots n}$	14	mg/L	In gaining reaches, is the estimated TP concentration in groundwater, and in losing reaches, is the modeled TP concentration in the main stem at the previous upstream site.
$Cp_{j \ldots n}$	14	mg/L	Modeled main-stem TP concentration at each site represented in the spreadsheet mass-balance model (locations *j* through *n*).
$Cp_{k \ldots n}$	15	mg/L	Modeled main-stem TP concentration at a main-stem site.
Mp_i	16	lb/d	Measured TP load at the first upstream site in the modeling reach.
$Mp_{j \ldots n}$	17	lb/d	Modeled TP load at each site represented in the spreadsheet mass-balance model (locations *j* through *n*).

Table 2. Variables described in total phosphorus mass-balance model equations for the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.—Continued

[**Abbreviations:** ft^3/s, cubic foot per second; $(ft^3/s)/mi$, cubic foot per second per mile; mi, mile; lb/d, pound per day; TP, total phosphorus; $L/ft^3 \times s/d \times lb/mg$, product of liters per cubic foot, seconds per day, and pounds per milligram; (lb/d)/mi, pound per day per mile; mg/L, milligram per liter]

Variable	Defined in equation No.	Units	Description
			Groundwater concentration estimates
Cgw_{DS}	18	mg/L	Back-calculated groundwater TP concentration at the downstream end of a subreach.
Cgw_{US}	18	mg/L	Back-calculated groundwater TP concentration at the upstream end of a subreach.
$Cgw_{upper\ i \ldots n}$	18	mg/L	Groundwater TP concentration interpolated through the modeling reach upstream of Middleton Road (locations *i* through *n*) based on an estimated 0.25-mg/L TP concentration throughout the lower end of the modeling reach.
			Spreadsheet variables
M_{US}	Spreadsheet[1]	lb/d	Measured TP load at the upstream end of a subreach.
M_D	Spreadsheet[1]	lb/d	Estimated TP load in a diversion within the subreach.
M_R	Spreadsheet[1]	lb/d	Measured TP load in a return flow or tributary within the subreach.
Cgw_{BC}	Spreadsheet[1]	mg/L	Back-calculated TP concentration in groundwater using unmeasured discharge and unmeasured TP load.

[1] Indicates the variable used in the spreadsheet mass-balance models (appendix 1). Variables are not further described in text.

Limitations

The TP mass-balance models are steady-state models that account for changes in water quality and discharge but do not account for changes in phosphorus loads owing to biogeochemical processes. Losses of phosphorus to riparian phreatophytes and losses of water to evapotranspiration in the riparian zone also are not included in the mass-balance models. The TP mass-balance models work under the assumption that all instream phosphorus is delivered from upstream surface water, removed by losses to groundwater, removed by surface-water diversions, added by gains from groundwater, or added by surface-water returns and tributaries. Many small pipe discharges and pumped diversions occur on private land along the Boise River. These discharges and diversions were identified and inventoried but, with the exception of two relatively large unnamed drains identified downstream of Notus (RMs 12.3 and 10.9, fig. 1*B*), were not sampled or measured during synoptic events. Mass-balance models account for unmeasured and unsampled returns and diversions as unmeasured gains or losses in discharge and TP mass. Each mass-balance model is representative only of conditions during the synoptic event that produced the input data. Because synoptic sampling periods did not take place during a storm, the mass-balance models do not represent, measure, or simulate phosphorus inputs from stormwater.

Discharge Balance

The discharge balance approach accounted for all measured surface-water inflows and outflows in each subreach and compared the accounting result to the measured discharge at the end of that subreach. Any unmeasured discharge was assumed to represent an overall streamflow gain from groundwater or loss to groundwater within a subreach. A positive groundwater component is indicative of a gaining stream due to groundwater flow into the stream reach (streamflow gain). A negative groundwater component indicates a losing stream reach and recharge to the shallow aquifer system from the stream (streamflow loss). The total subreach gain or loss then was extrapolated by distance between each site (or spreadsheet model cell) in the subreach based on its river-mile location. In this manner, flows were calibrated to measurements in the main stem using additions or subtractions of groundwater. Streamflow gains from groundwater or losses to groundwater in each subreach were calculated according to the following equations:

$$Q_{gw} = Q_{DS} - \left(Q_{US} + Q_R - Q_D\right), \tag{1}$$

$$Qgw_{RM} = Q_{gw} / \left(RM_{US} - RM_{DS}\right), \tag{2}$$

$$Qgw_{i..n} = Qgw_{RM} \times \left(L_{US} - L_{DS}\right) \quad (3)$$

where

Q_{gw} is the unmeasured gain or loss in the subreach assumed to represent groundwater, in cubic feet per second;

Q_{DS} is the measured main-stem discharge in cubic feet per second at the downstream end of the subreach;

Q_{US} is the measured main-stem discharge in cubic feet per second at the upstream end of the subreach;

Q_R is the measured discharge in cubic feet per second in a return flow or tributary within the subreach;

Q_D is the measured discharge in cubic feet per second in a diversion within the subreach;

Qgw_{RM} is the streamflow gain or loss per river mile in cubic feet per second;

RM_{US} is the river mile at the upstream end of the subreach in miles from the mouth;

RM_{DS} is the river mile at the downstream end of the subreach in miles from the mouth;

$Qgw_{i..n}$ is the streamflow gain or loss in cubic feet per second at each site represented in the spreadsheet mass balance model (locations *i* through *n*);

L_{US} is the location in river miles of a consecutive upstream location in a subreach (for example, spreadsheet row 11); and

L_{DS} is the location in river miles of a consecutive downstream location in a subreach (for example, spreadsheet row 12).

Interpolation of estimated streamflow gains and losses throughout a subreach ensures that measured discharge equals modeled discharge at the end of each subreach. Modeled discharge including streamflow gains or losses was computed at each spreadsheet row or site using the following calculation:

$$Qm_{i...n} = Q_{US} + Q_R - Q_D \pm Qgw_{i..n} \quad (4)$$

where

$Qm_{i...n}$ is the modeled discharge in cubic feet per second including groundwater exchange at each site represented in the spreadsheet mass-balance model.

The propagated uncertainty in cubic feet per second was compared to the unmeasured gain or loss of discharge within each subreach. In cases where propagated uncertainty was less than the unmeasured gain or loss of discharge, the assumed streamflow gain or loss was considered more likely to represent actual conditions.

Discharge Balance Assumptions

The modeling reach was 46.4 mi long, and discharge measurements were made along the reach to gain a similarly large-scale understanding of groundwater exchange. Measurement uncertainty—inherent as systematic error in instrumentation used to measure discharge and random error associated with natural conditions under which discharge is measured—affects measured gains and losses within each subreach. Assumptions made in balancing flow throughout the modeling reach included:

- Unmeasured discharge was assumed to represent groundwater exchange with the Boise River for modeling purposes, but also may represent measurement uncertainty, evapotranspiration in the riparian zone, or unmeasured diversions and returns such as small pipes or residential pumps.
- Unmeasured discharge was assumed to enter or leave the river as groundwater uniformly within each subreach based on distance.
- Return flow from drains and tributaries was treated as surface-water discharge in all three mass-balance models regardless of the concept that it represents groundwater discharge to surface water during non-irrigation season.

Measured Total Phosphorus Mass-Balance Model

Measured phosphorus concentrations and modeled discharge were used to calibrate the "measured" TP mass-balance model. Compared to the "predictive" TP mass-balance model, the measured model makes no assumptions about groundwater concentrations. However, in both models, unmeasured discharge is assumed to represent exchanges with groundwater and those exchanges are assumed to occur uniformly along a given subreach.

After the discharge balance was completed, a similar exercise was completed to balance TP loads in the modeling reach. Measured TP concentrations and measured discharge including gains and losses to groundwater were used to calculate unmeasured TP loads in each subreach. Water-quality samples were not collected in diversions, except in Riverside Canal. Concentrations of TP in diversions were estimated based on nearby measured sample results in the main stem. Unmeasured changes in TP load (ΔM) at the subreach scale were interpolated throughout each subreach based on location and a number representing change-in-load-per-river-mile as follows:

$$\Delta M = \left(Q_{DS} \times C_{DS} \times F\right) - \left(\left(Q_{US} \times C_{US} \times F\right) + \left(Q_R \times C_R \times F\right) - \left(Q_D \times C_D \times F\right)\right), \quad (5)$$

$$\Delta M_{RM} = \Delta M \,/\, \left(RM_{US} - RM_{DS}\right), \quad (6)$$

$$\Delta M_{i..n} = \Delta M_{RM} \times \left(L_{US} - L_{DS}\right) \quad (7)$$

where

ΔM is the unmeasured change in TP load in the subreach in pounds per day;
C_{DS} is the TP sample result in milligrams per liter at the downstream end of the subreach;
C_{US} is the TP sample result in milligrams per liter at the upstream end of the subreach;
F is a conversion factor used to compute loads in pounds per day (5.3938);
C_R is the TP sample result in milligrams per liter in a return flow or tributary within the subreach;
C_D is the estimated TP concentration in milligrams per liter in a diversion within the subreach;
ΔM_{RM} is the unmeasured change in TP load in pounds per day per river mile; and
$\Delta M_{i...n}$ is the unmeasured change in TP load in pounds per day at each site represented in the spreadsheet mass-balance model (locations *i* through *n*).

With unmeasured discharge and unmeasured loads interpolated throughout each subreach in the measured mass-balance model, main-stem TP concentrations and loads could be estimated for each spreadsheet row or site. Given the measured concentration and load at the first upstream site, concentration and load were modeled at subsequent sites downstream as follows:

$$Cm_i = C_{US}, \quad (8)$$

$$Cm_{j..n} = \left(\left(Qm_i \times Cm_i\right) \pm \left(Q_{D \text{ or R}} \times C_{D \text{ or } R}\right) \pm \left(\Delta M_{j..n} \times 1/F\right)\right) / Qm_{j...n}, \quad (9)$$

$$Cm_{k..n} = \left(\left(Qm_j \times Cm_j \right) \pm \left(\Delta M_{k...n} \times 1/F \right) \right) / Qm_{k..n}, \quad (10)$$

$$Mm_i = M_{US}, \quad (11)$$

$$Mm_{j...n} = \left(Qm_j \times Cm_j \times F \right) \quad (12)$$

where

Cm_i is equal to the measured TP concentration in milligrams per liter at the first upstream site in the modeling reach;

$Cm_{j..n}$ is the modeled main-stem TP concentration in millligrams per liter adjacent to each diversion or return represented in the spreadsheet mass-balance model (locations j through n);

$Cm_{k..n}$ is the modeled TP concentration in milligrams per liter at a sampled main-stem site marking the beginning or end of a subreach;

Mm_i is equal to the measured TP load in pounds per day at the first upstream site in the modeling reach;

M_{US} is the measured TP load at the upstream end of the subreach; and

$Mm_{j..n}$ is the modeled TP load in pounds per day at each site represented in the spreadsheet mass-balance model (locations j through n).

Measured Mass-Balance Model Assumptions and Limitations

Because the measured mass-balance model uses modeled discharge, it assumes that any unmeasured discharge enters or leaves the river uniformly throughout each subreach based on river-mile distances. In the measured mass-balance model, it was necessary to estimate TP concentrations in diversions. Loads in diversions were calculated with estimated concentrations and measured discharge. TP concentrations in diversions were assumed to be the same as the TP concentration in the nearest main-stem sampling location, except where a diversion occurred between two return flows prior to collection of the next downstream main-stem sample.

Predictive Total Phosphorus Mass-Balance Model

Like the measured mass-balance model, the predictive mass-balance model incorporates gains and losses from what is assumed to be groundwater. Unlike the measured model, the predictive model does not compute, use, or consider unmeasured TP loads in subreaches and instead makes assumptions about TP concentrations in groundwater. The quantity of groundwater gained or lost within each subreach is the same in the measured model and the predictive model. The estimated quality of groundwater in the predictive mass-balance model is the essential difference separating it from the measured mass-balance model. Because estimates of TP concentrations in groundwater are used in the predictive model, TP loads in groundwater then can be added and removed from the model in gaining and losing reaches. TP concentrations in groundwater are estimated in gaining reaches whereas TP concentrations in losing reaches are assumed to equal the adjacent main-stem TP concentration modeled upstream. Because the predictive model is not balanced with unmeasured loads, users can change TP concentrations in groundwater and returns to evaluate sensitivity to different sources of phosphorus in the modeling reach.

Given the measured TP concentration and flow at the first upstream site in the modeling reach, main-stem TP concentrations at subsequent locations were calculated as follows:

$$Cp_i = C_{US}, \tag{13}$$

$$Cp_{j..n} = \left(\left(Qm_i \times Cp_i\right) \pm \left(Q_{D \text{ or } R} \times C_{D \text{ or } R}\right) \pm \left(Qgw_{j..n} \times Cgw_{j..n}\right)\right) / Qm_{j...n}, \tag{14}$$

$$Cp_{k..n} = \left(\left(Qm_j \times Cm_j\right) \pm \left(Qgw_{k...n} \times Cgw_{j...n}\right)\right) / Qm_{k..n}, \tag{15}$$

$$Mp_i = M_{US} \tag{16}$$

$$Mp_{j..n} = \left(Qm_j \times Cm_j \times F\right) \tag{17}$$

where

Cp_i is equal to the measured TP concentration in milligrams per liter at the first upstream site in the modeling reach;

$Cp_{j...n}$ is the modeled main-stem TP concentration in milligrams per liter adjacent to each diversion or return represented in the spreadsheet mass-balance model (locations j through n);

$Cp_{k...n}$ is the modeled TP concentration in milligrams per liter at a sampled main-stem site marking the beginning or end of a subreach;

$Cgw_{j...n}$ in gaining reaches, is the estimated TP concentration in milligrams per liter, and in losing reaches, is the modeled TP concentration in the main stem at the previous upstream site;

Mp_i is equal to the measured TP load in pounds per day at the first upstream site in the modeling reach; and

$Mp_{j...n}$ is the modeled TP load in pounds per day at each site represented in the spreadsheet mass-balance model (locations j through n).

Groundwater Concentration Estimates

Water in most major tributaries to the Boise River is mostly groundwater discharge during non-irrigation season (Thomas and Dion, 1974; Mullins, 1998; Berenbrock, 1999). An estimated shallow groundwater TP concentration of 0.25 mg/L was used in groundwater from the Boise River at Middleton Road (RM 28.8) to the end of the modeling reach (RM 3.8). Model results showed that most streamflow gains from groundwater were in the Boise River downstream of Middleton Road (RM 28.8). The 0.25-mg/L TP concentration used in the predictive model represents the average of all median historical TP concentrations in tributaries downstream of Middleton Road (RM 28.8) during non-irrigation season. The estimation method assumed the TP concentration in groundwater at the beginning of the modeling reach was 0.01 mg/L, and interpolated by distance to the next estimated groundwater TP concentration downstream. The 0.01-mg/L TP concentration at the upstream end of the modeling reach is based on historical dissolved phosphorus results in piezometers near Glenwood Bridge (RM 47.5). The difference between the baseline groundwater TP concentration assigned to the first upstream site in the modeling reach (0.01 mg/L) and

0.25 mg/L was interpolated by the distance between the Boise River at Veterans Memorial Parkway (RM 50.2) and the Boise River at Middleton Road (RM 28.8) using equation (18) to produce $Cgw_{upper\ i \ldots n}$. Downstream of Middleton Road, all TP concentrations in groundwater were assumed to equal 0.25 mg/L. Because TP concentrations in shallow groundwater increase in the downstream direction of the Boise River (MacCoy, 2004), the predictive mass-balance models also assumed that the TP concentration in groundwater increased uniformly by distance between Veterans Memorial Parkway (RM 50.2) and Middleton Road (RM 28.8) as follows:

$$Cgw_{upper\ i \ldots n} = \left(\left(Cgw_{DS} - Cgw_{US} \right) \ / \ \left(RM_{US} - \mathrm{RM}_{DS} \right) \right) \times \left(L_{US} - L_{DS} \right) \tag{18}$$

where

$Cgw_{upper\ i \ldots n}$ is the groundwater TP concentration in milligrams per liter at sites between Veteran's Memorial Parkway (RM 50.2) and Middleton Road (RM 28.8) (locations *i* through *n*);

Cgw_{DS} is equal to 0.25 mg/L; and;

Cgw_{US} is equal to 0.01 mg/L at Veteran's Memorial Parkway (RM 50.2).

Predictive Mass-Balance Model Assumptions and Limitations

Assumptions associated with the predictive mass-balance model are summarized as follows:

- Groundwater TP concentrations change uniformly by distance between each estimated groundwater concentration.
- The background TP concentration in groundwater is 0.01 mg/L at the beginning of the modeling reach and increases uniformly by distance to the first estimated groundwater TP concentration at Middleton Road (RM 28.8).
- TP concentrations in shallow groundwater are equal to 0.25 mg/L downstream of Middleton Road (RM 28.8).

Sensitivity Analysis

Three predictive TP mass-balance models were generated from three synoptic sampling periods and used to complete a sensitivity analysis. Twelve input scenarios were designed to evaluate sensitivity of predictive TP mass-balance models to changes in TP concentrations in point sources, nonpoint sources, and unmeasured sources (assumed to be groundwater and relatively small unmeasured diversions and returns). Each simulation applied changes to TP concentrations and kept discharge constant (table 3). Because discharge and loading dynamics during each synoptic event were different, simulations provided a means for evaluating model sensitivity to changes in TP concentrations under generalized seasonal conditions. Assumptions and limitations described in the discharge balance approach and the predictive mass-balance modeling approach also apply in model simulations. Results from model simulations are described under the assumption that the predictive model may represent conditions on a more seasonal scale, such as irrigation season (August), post-irrigation season (late October), and pre-irrigation season (early March). Use of the predictive mass-balance model to simulate outcomes for specific management scenarios assumes that arbitrary changes to TP concentrations have no effect on biogeochemical processes in the modeling reach. Simulations also assume that input conditions could reflect real-world conditions in the future.

Table 3. Summary of simulation inputs to and sources of phosphorus in the predictive total phosphorus mass-balance model of the Boise River, southwestern Idaho.

[Shading indicates no change from measured conditions (red); intermediate goal for source reduction (blue); long-term goal for source reduction (green). **Abbreviations:** RM, river mile; NC, no change from measured concentration; TP, total phosphorus; WWTP, wastewater treatment plant; mg/L, milligram per liter; ID, Idaho]

	Total phosphorus concentration inputs for model simulations by scenario No. (mg/L)											
	1	2	3	4	5	6	7	8	9	10	11	12
Point sources	0.30	0.07	NC	NC	0.30	0.30	0.30	0.30	0.07	0.07	0.07	0.07
Nonpoint sources	NC	NC	0.10	0.07	0.10	0.07	0.10	0.07	0.10	0.07	0.10	0.07
Unmeasured discharge downstream of RM 28.8 TP concentration[1]	NC	NC	NC	NC	0.15	0.15	0.07	0.07	0.15	0.15	0.07	0.07

Sources of phosphorus in the modeling reach

Point sources	River mile
Boise City Sewer Outflow at Boise, ID (Lander WWTP)	50.0
West Boise Sewer Outflow near Eagle, ID (West Boise WWTP)	44.2
Middleton WWTP on Boise River near Middleton, ID	27.1
Caldwell WWTP on Boise River at Caldwell, ID	22.6
Non-point sources	**River mile**
Eagle Drain at Eagle, ID	42.7
Dry Creek at Eagle, ID	42.5
Thurman Drain at Mouth near Eagle, ID	41.9
Eureka No. 1 Canal at Star Road near Star, ID	36.6
Fifteenmile Creek at Mouth near Middleton, ID	30.3
Mill Slough below Grade Ditch near Middleton, ID	27.2
Willow Creek at Middleton, ID	27.0
Mason Slough near Caldwell, ID	25.6
Mason Creek near Caldwell, ID	25.0
Hartley Drain near Caldwell, ID	24.4
Indian Creek at Mouth near Caldwell, ID	22.4
Conway Gulch at Notus, ID	14.2
Unnamed Drain Near Notus, ID	12.3
Unnamed Drain Near Dixie Drain near Notus, ID	10.9
Dixie Drain near Wilder, ID	10.5
Unmeasured discharge[1]	**River mile**
Interpolate from 0.01 mg/L at RM 50.2 to input TP concentration at RM 28.8	50.2–28.8
Constant TP concentration of 0.25 mg/L	28.8–3.8

[1] Unmeasured discharge represents streamflow gains from or losses to groundwater and also may represent small unmeasured diversions or returns.

Water-Quality and Periphyton Sampling Results

Water-quality samples were collected during the weeks of August 20 and October 29, 2012, and March 4, 2013, from shallow wells and piezometers, point-source discharges, agricultural drains and tributaries to the Boise River, and the main stem of the Boise River (figs. 1*A*, 1*B*, and 1*C*; table 1). Time-series discharge hydrographs spanning the three synoptic sampling periods for the Boise River below Diversion Dam (RM 61.1), the Boise River at Glenwood Bridge (RM 47.5), and the Boise River near Parma (RM 3.8) are shown in figure 3. The August sampling period occurred as irrigation deliveries began to decrease; the October sampling period occurred just after irrigation deliveries stopped; and the March sampling period occurred just before irrigation deliveries began again in 2013. Tributaries and return flows to the Boise River contain agricultural runoff during irrigation season and consist primarily of shallow groundwater discharge during non-irrigation season. The conceptual model for groundwater and surface-water interaction provides context for the timing of synoptic sampling periods. Sampling periods represent water-quality and discharge conditions in the lower Boise River when agricultural runoff likely represented a source of TP (August), when diversions were inactive and groundwater discharge through tributaries and drains was relatively large (October), and when groundwater discharge within agricultural drains and tributaries had decreased at the end of non-irrigation season (March).

Total Phosphorus in Surface Water

Concentrations of TP in the main stem of the Boise River relative to tributaries and WWTPs that discharged to the river during the sampling periods are shown in figure 4. All three sampling periods showed a small increase in the main-stem TP concentration downstream of Lander WWTP (RM 50.0) and a large increase in the main-stem TP concentration downstream of West Boise WWTP (RM 44.2). Downstream of the Lander Street WWTP, main-stem TP reached concentrations near (0.06 mg/L) or greater than the 0.07-mg/L target and did not decrease below the target for the remaining 50 mi of the Boise River downstream. With the exception of Thurman Drain (RM 41.9) and two unnamed drains (RM 12.3 and 10.9) between Notus (RM 15.7) and Dixie Drain (RM 10.5), TP concentrations in most tributaries and agricultural drains mimicked TP concentrations in the main stem of the Boise River in August. High TP concentrations in Fifteenmile, Mason, and Indian Creeks (RM 30.3, 25.0, and 22.4, respectively) during the August sampling period suggested that WWTP discharges in Fifteenmile and Indian Creeks act as a source of TP and that agricultural sources of TP exist in the Mason Creek watershed. Dixie Drain (RM 10.5) contributed a TP load of 470 lb/d, but did not act as a concentrated source of TP relative to the Boise River at RM 10.5. Remaining tributaries to the Boise River also had negligible effects on the TP concentration in the Boise River in August (fig. 4).

Compared to results from the August synoptic sampling period, TP concentration results from the October event decreased in Mason Creek (RM 25.0), Mason Slough (RM 25.6), and Conway Gulch (RM 14.2), and increased in Fifteenmile Creek (RM 30.3), Indian Creek (RM 22.4), and the Boise River upstream of Caldwell (RM 24.0). Increased TP concentrations in Fifteenmile and Indian Creeks likely occurred because both creeks received point-source discharge from WWTPs that was no longer diluted by irrigation return water. Urban sources and WWTP effluent also generally increased TP concentrations in the Boise River upstream of Caldwell because they were not diluted by discharge from Lucky Peak Dam (RM 64.0) that was released to meet irrigation demands in August (discharge from the Boise River below Diversion Dam [RM 61.1] represents discharge from Lucky Peak Dam [RM 64.0] within the modeling reach in fig. 3). Lower TP concentrations in Mason Slough (RM 27.2), Mason Creek (RM 25.0), and Conway Gulch (RM 14.2) in late October indicated that agricultural returns in August were sources of TP to the Boise River during irrigation season.

Indian Creek (RM 22.4), which normally contributes a substantial TP load to the Boise River in October, was diverted entirely to Riverside Canal so that maintenance on a head gate could be completed (fig. 2). The TP concentration in 3 ft^3/s of water discharged to the Boise River from Indian Creek in October was 0.54 mg/L. Riverside Canal discharges partially to Dixie Drain (RM 10.5), and any remaining water in Riverside Canal discharges to the Snake River (fig. 1*A*). It is not known how much water from Indian Creek ultimately discharged to Dixie Drain and reached the Boise River in October 2012. The discharge measured in Dixie Drain exceeded discharge recorded in historical discharge measurements made in late October by about 150 ft^3/s, and the TP concentration was about 0.05 mg/L greater than concentrations in historical samples collected in Dixie Drain in late October. The corresponding additional 40 lb/d of TP load in Dixie Drain was less than a typical 500-lb/d load from Indian Creek in late October.

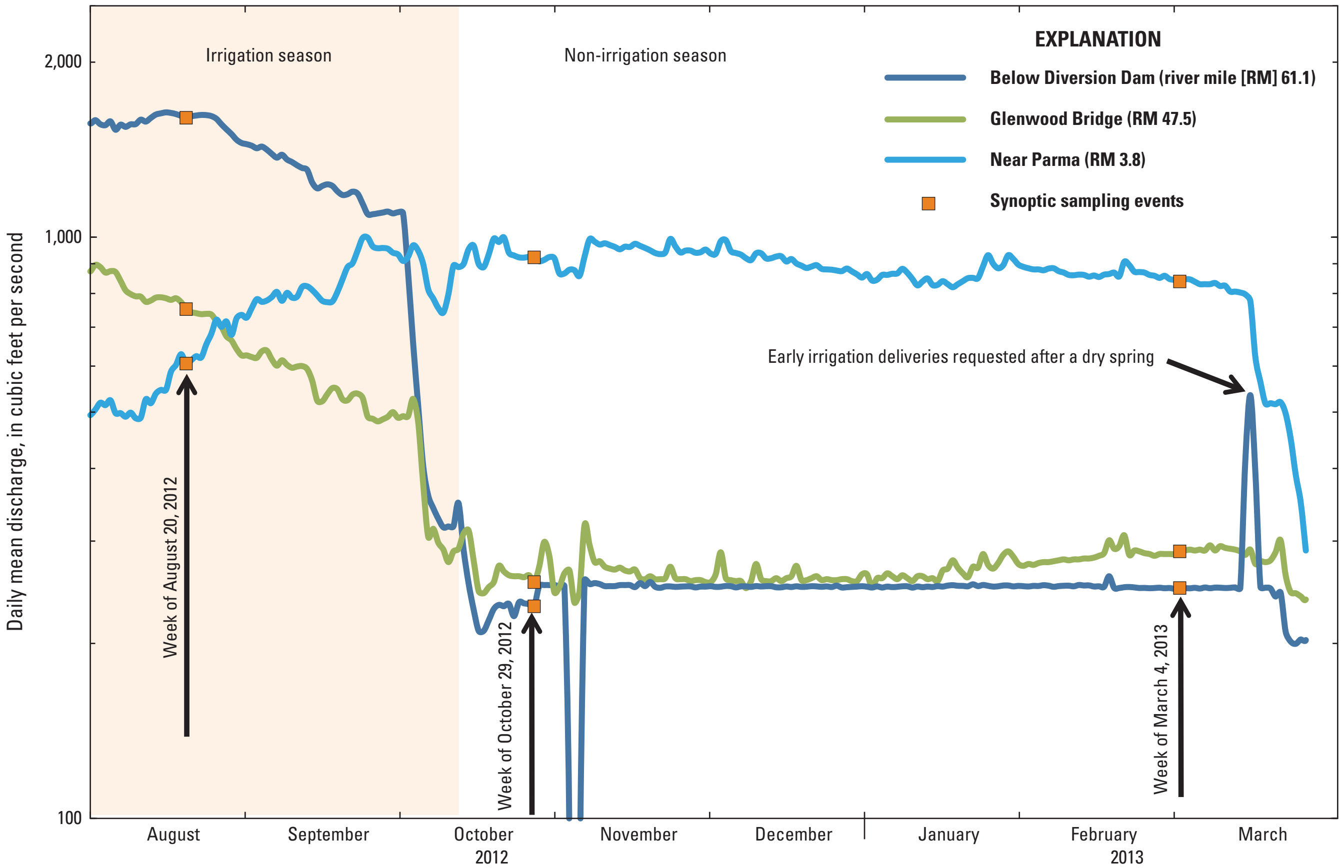


Figure 3. Time-series hydrographs showing discharges at three streamgages in the lower Boise River, southwestern Idaho, August 1, 2012–March 25, 2013.

Compared to TP concentrations in August and October 2012, TP concentrations in March 2013 generally were higher in the Boise River and lower in return flows from tributaries and drains (fig. 4). As the shallow aquifer continued to discharge groundwater during winter, discharge in agricultural drains and tributaries likely decreased steadily as it did at the USGS streamgage at Mason Creek near Caldwell (13210983) during water year 2012. Groundwater discharge from tributaries and drains diluted TP concentrations in the main stem of the Boise River less in March than in late October because groundwater discharge and tributary flows had decreased. TP concentrations in Fifteenmile Creek (RM 30.3) decreased from 0.60 mg/L in October 2012 to 0.12 mg/L in March 2013. TP concentrations in effluent from the Meridian WWTP, a point source in a tributary to Fifteenmile Creek, were also lower (0.14 mg/L) during the March sampling period. In Indian Creek (RM 22.4), TP concentrations decreased from 0.54 mg/L in October to 0.44 mg/L in March. Based on monthly samples collected between 1999 and 2001 (summarized in MacCoy, 2004), TP concentrations in Fifteenmile and Indian Creeks do not follow a seasonal pattern and likely are more dependent on the TP concentration and load in wastewater effluent. The TP concentration in Mason Slough (RM 25.6) was 0.58 mg/L in March 2013, compared to 0.22 mg/L in August 2012 and 0.13 mg/L in October 2012. Cattle were observed in Mason Slough upstream of the sampling location in March, and turbidity was notably higher than during the August or October sampling periods. Of all three synoptic sampling periods, Indian Creek (RM 22.4) followed its natural channel to the Boise River only in March. TP concentrations in Indian Creek were higher than in other tributaries owing to the consistent source of TP from wastewater treatment plants that discharge to Indian Creek. Hartley Drain (RM 24.4) remained a consistent source of TP in the October and March synoptic sampling periods. Point-source discharges are not known to occur in either East Hartley or West Hartley Drains, which combine to form Hartley Drain at the sampling location, but rural residences and pasture land are present directly upstream of the sampling location.

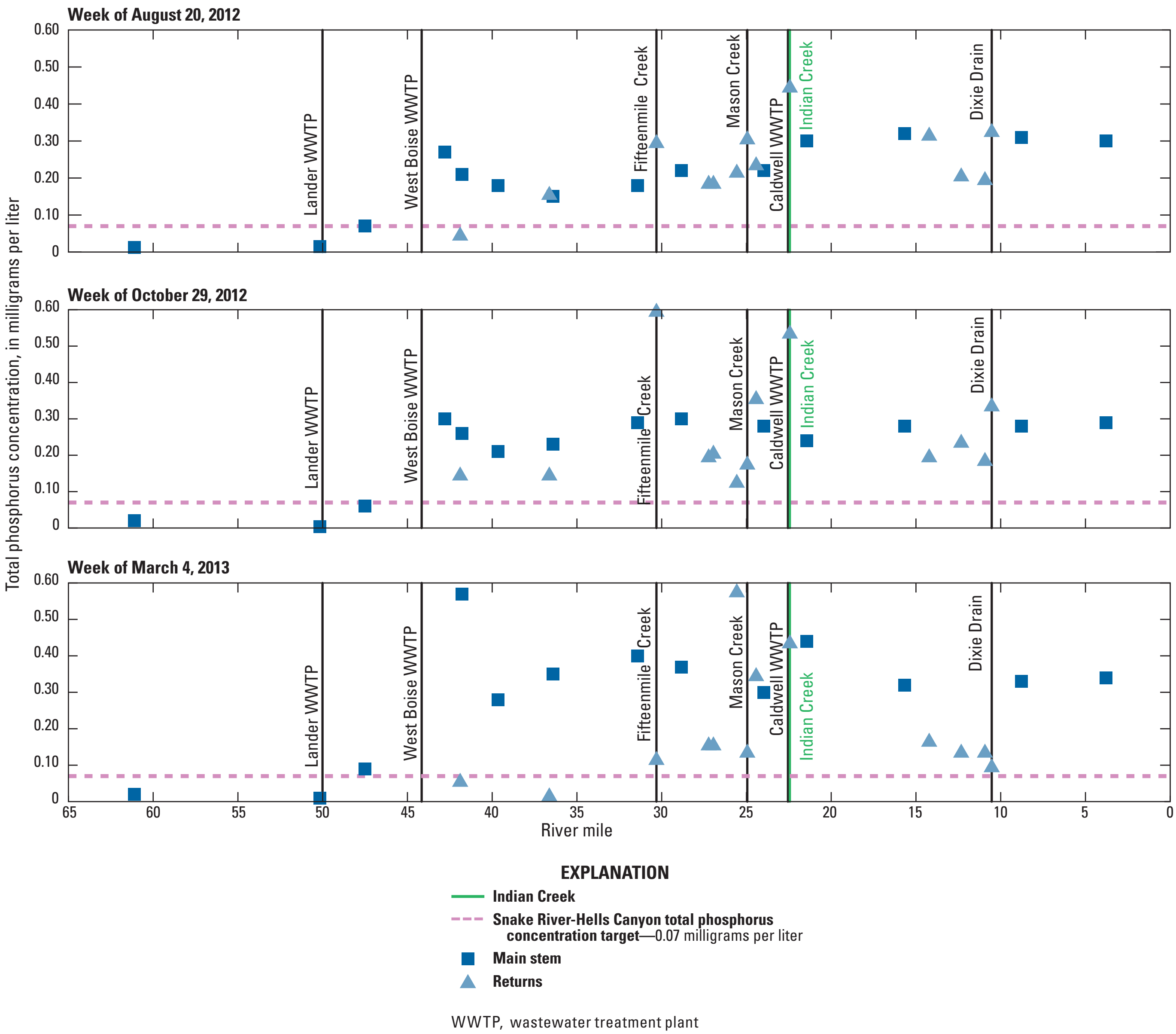


Figure 4. Total phosphorus concentrations in the lower Boise River, southwestern Idaho, from synoptic sampling periods during the weeks of August 20 and October 29, 2012, and March 4, 2013.

Dissolved Phosphorus in Shallow Groundwater

Water-quality samples were collected in 13 shallow groundwater wells and 7 piezometers during this study (fig. 1*C*, table 1). Total depth in shallow wells ranged from 32 to 125 ft below land surface. Piezometers were installed at or near the edges of the Boise River to depths of 4–11 ft below land surface. Samples were collected from shallow wells in late August and late October 2012, and samples were collected from piezometers in early March 2013. Results for groundwater and piezometer OP samples are summarized in table 4. Because phosphorus in groundwater is present primarily in the dissolved state, this section compares measured OP concentrations in shallow groundwater to TP estimates used for groundwater in the predictive TP mass-balance model. The median OP concentration in shallow groundwater wells was 0.04 mg/L, which is consistent with findings in larger datasets that included hundreds of groundwater samples in the lower Boise River watershed and also included wells deeper than 125 ft (Neely and Crockett, 1998). Shallow groundwater sampling results generally did not support mass-balance model estimates of TP concentrations in shallow groundwater and suggested that high OP (>0.04) concentrations do not occur below 35 ft. Samples from piezometers, however, were more consistent with the hypothesis that OP concentrations in groundwater discharging to the Boise River increase moving downstream (fig. 5). The median OP concentration in piezometers sampled during this study was 0.11 mg/L as compared to 0.09 mg/L in samples collected from shallow piezometers in 2001 (MacCoy, 2004).

Samples collected in shallow groundwater and piezometers during this study identified the same source areas in shallow groundwater and piezometers identified in previous studies. Shallow wells on the north side of the Boise River near Veterans Memorial Parkway and adjacent to Lander WWTP (RM 50.0) showed the highest detected OP concentrations in any shallow well or piezometer sampled as part of this study (fig. 1*C*, tables 1 and 4). Neely and Crockett (1998) also reported OP concentrations greater than 0.1 mg/L and as much as 1.6 mg/L in shallow wells northwest of the city of Boise. The 1.6-mg/L OP concentration was the highest concentration detected in 144 shallow wells sampled in the lower Boise River watershed (Neely and Crockett, 1998), and was detected in the same shallow well with the highest OP detected during this study (0.59 mg/L adjacent to Lander WWTP). A reconnaissance of groundwater quality in piezometers installed along the Boise River in 2001 detected OP concentrations greater than 0.3 mg/L near Hartley Drain (RM 24.4) and Parma (RM 3.8) and as much as 1.07 mg/L on the left bank of the Boise River at Notus (RM 15.7) (MacCoy, 2004). Piezometers sampled at the Boise River near Parma (RM 3.8) and at Notus (RM 15.7) in 2013 also showed relatively high OP concentrations (fig. 5, table 4). Concentrations of TP in Hartley Drain remained greater than 0.3 mg/L during non-irrigation season, and OP in a piezometer sampled near Hartley Drain in March 2001 was measured at 0.35 mg/L. The OP concentration of 0.08 mg/L in a newly installed piezometer sampled near Hartley Drain (RM 24.7) in 2013 (table 4) indicated wide spatial variability in groundwater quality.

Data reported in previous studies indicate that the estimated 0.25-mg/L shallow groundwater TP concentration used in the predictive model downstream of Middleton Road (RM 28.8) may be realistic. Dion (1972) reported a median OP concentration of 0.24 mg/L in shallow groundwater wells in the Boise River watershed. Dissolved OP in shallow groundwater likely is a source of phosphorus to the Boise River, but also may be localized, as determined by Fox and others (2002) in a study completed near the mouth of Mason Creek (RM 25.0). Fox and others (2002) reported a 0.33 mg/L average OP concentration in shallow groundwater near the mouth of Mason Creek in 2001. Sampling results for TP concentrations in two monitoring wells on J.R. Simplot Company (Simplot) property near Caldwell averaged between 0.26 and 0.33 mg/L between 2009 and 2012 ($n = 12$). Both Simplot wells were completed 20 ft below land surface about 0.6 mi south of the Boise River (RM 19). The well with an average TP concentration of 0.33 mg/L is located several hundred feet from the Eureka No. 2 Canal (diverted at RM 20.1) (Idaho Department of Environmental Quality, 2013b). Groundwater monitoring data on the Simplot property near Caldwell also shows higher groundwater elevations (leakage) beneath Riverside Canal 1.5 mi downstream of its seasonal confluence with Indian Creek (Idaho Department of Environmental Quality, 2013b) (fig. 2).

A focused study on shallow groundwater (less than 25 ft deep) near agricultural drains and beneath agricultural land may provide a better understanding of the quality of shallow groundwater that discharges to the Boise River and its tributaries. Shallow groundwater between 19 and 25 ft below land surface was hydraulically connected to Mason Creek in 2001 (Fox and others, 2002). OP concentrations in shallow groundwater on site were the source of 10–12 percent of the phosphorus load in Mason Creek from January to May 2001. Fox and others (2002) also determined that higher OP concentrations in shallow groundwater near Mason Creek were positively correlated with a higher water table. A lag in time occurred between application of irrigation water in the Mason Creek watershed and increases in groundwater levels and OP concentrations. A lag in time also occurred between the end of irrigation season and decreases in groundwater levels and OP concentrations (Fox and others, 2002). OP concentrations in groundwater deeper than 100 ft below land surface near Mason Creek averaged 0.04 mg/L (Fox and others, 2002).

Table 4. Dissolved orthophosphorus as phosphorus concentrations in samples collected from shallow wells and piezometers during synoptic sampling periods in the lower Boise River watershed, southwestern Idaho, August and October 2012, and March 2013.

[Complete USGS site names and locations for wells sampled during synoptic sampling periods during weeks of August 20, 2012, October 29, 2012, and March 4, 2013, are provided in table 1 and figure 1*C*. **Total depth**: Well depths provided to accuracy available in drilling logs. Piezometer depths based on field measurements of total depth. **Abbreviations:** GW, groundwater; PZ, piezometer USGS, U.S. Geological Survey; WWTP; wastewater treatment plant; ft, foot; mg/L, milligram per liter; <, less than]

USGS site No.	Site type	River mile	Dissolved orthophosphorus as phosphorus (mg/L)					Total depth (ft)	General location
			Synoptic results			Historical results			
			August	October	March	Low[1]	High[1]		
433832116140201	GW	50.1	–	0.18	–	–	–	40	Downstream of Veterans Memorial Parkway, Boise, Idaho
433837116141101	GW	50.0	–	0.19	–	–	–	49	Downstream of Veterans Memorial Parkway, Boise, Idaho
433820116143401	GW	49.5	0.59	–	–	0.54	1.60	32	Downstream of Veterans Memorial Parkway, Boise, Idaho
433954116155801	GW	48.0	–	0.04	–	–	–	75	Upstream of Glenwood Bridge, Boise, Idaho
433937116164001	PZ	47.5	–	–	<0.01	0.01	0.06	5.60	At USGS gage at Glenwood Bridge, Boise, Idaho
434026116235602	GW	41.8	0.02	0.02	–	0.01	0.02	85	Upstream of Phyllis Canal, Meridian, Idaho
434120116263401	GW	39.7	0.02	0.02	–	–	–	73	Near north and south channel confluence, near Star, Idaho
434049116283201	GW	37.0	0.04	–	–	–	–	75	Upstream of Star, Idaho
434200116353201	GW	31.3	0.04	0.04	–	0.02	0.04	80	Near Middleton, Idaho
434112116354201	PZ	31.2	–	–	0.04			6.15	Near Middleton, Idaho
434057116395901	GW	25.6	0.03	0.03	–	0.03	0.03	125	Near Mason Slough, Caldwell, Idaho
434140116405602	PZ	24.7	–	–	0.08	–	–	5.18	Upstream of Hartley Drain, Caldwell, Idaho
434140116405601	PZ	24.0	Piezometer destroyed after 2001			0.35	0.35	7.5	Near Hartley Gulch, Caldwell, Idaho
434048116423001	GW	22.3	–	0.03	–	–	–	112	Downstream of Confluence with Indian Creek, Caldwell, Idaho
434111116424801	GW	21.4	–	0.04	–	0.03	0.04	79	Near Boise River below Caldwell WWTP, near Caldwell, Idaho
434325116472901	GW	16.0	0.02	0.02	–	–	–	78	Upstream of Notus, Idaho
434318116474601	PZ	15.7	Piezometer destroyed after 2001			0.04	1.07	5.60	At Boise River at Notus, Idaho, left bank
434317116475201	PZ	15.7	–	–	0.14	–	–	4.35	At Boise River at Notus, Idaho, right bank
434612116570901	PZ	4.1	–	–	0.11	0.09	0.10	10.90	At Wanstad Road near Parma, Idaho
434706116581601	PZ	3.7	0.04	0.08	–	0.04	0.15	10.11	Downstream of USGS streamgage near Parma, Idaho
434706116581401	PZ	3.6	–	0.37	0.30	0.29	0.42	11.09	Downstream of USGS streamgage near Parma, Idaho
434758116591702	GW	2.5	–	0.07	–	–	–	45	Downstream of USGS streamgage near Parma, Idaho

[1] From MacCoy (2004) and Neely and Crockett (1998).

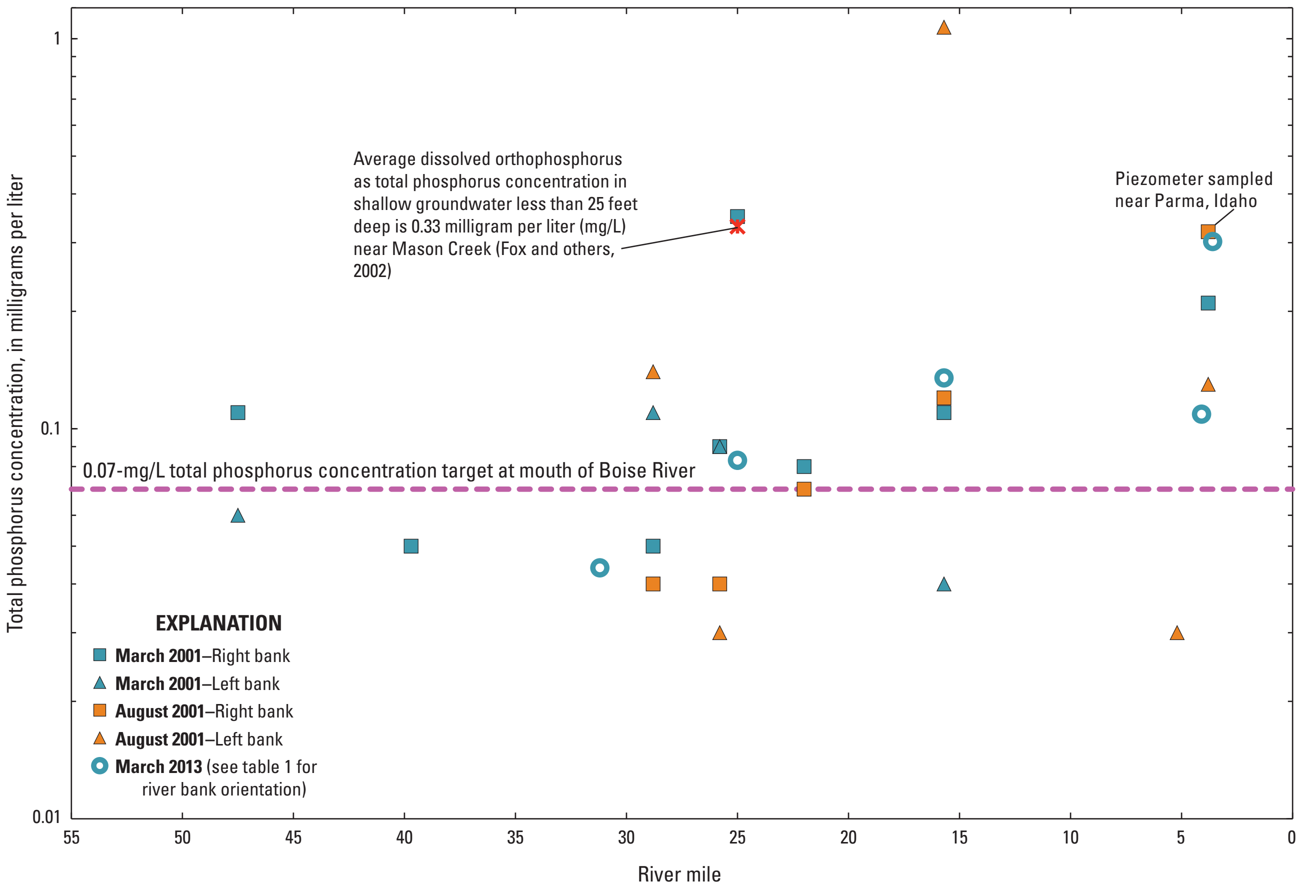


Figure 5. Dissolved orthophosphorus as phosphorus concentrations in piezometers near the Boise River, southwestern Idaho, March and August 2001 (from MacCoy, 2004) and during the week of March 4, 2013.

Periphyton and Phytoplankton Chlorophyll-*a*

Chlorophyll-*a* in periphyton and phytoplankton were analyzed in samples collected from five sites in the Boise River during each synoptic event (table 5). A statistical summary of historical chlorophyll-*a* in periphyton sample results compared to results from the three synoptic sampling periods is shown in figure 6. Chlorophyll-*a* in phytoplankton measures algal productivity in the water column, whereas chlorophyll-*a* in periphyton measures algal productivity on the river bottom. The SR-HC TMDL set a seasonal concentration target (May 1–September 30) in the Snake River for “nuisance algae” at 14 µg/L of chlorophyll-*a* in phytoplankton, and a not-to-exceed (more than 25 percent of the time) concentration target at 30 µg/L of chlorophyll-*a* in phytoplankton. None of the chlorophyll-*a* in phytoplankton samples in the Boise River sites exceeded either Snake River target from May 1 to September 30 (table 5). Chlorophyll-*a* in phytoplankton exceeded the target outside the compliance period, with an early March result of 36.2 µg/L at the Boise River near Parma (RM 3.8). The higher concentration of chlorophyll-*a* in phytoplankton near Parma in March is consistent with findings that diatom blooms in late winter can increase concentrations of chlorophyll-*a* in phytoplankton in the Boise River near Parma and in the Snake River (Wood and Etheridge, 2011).

Table 5. Chlorophyll-*a* concentrations in periphyton and phytoplankton from samples collected in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

[**Light extinction coefficient:** Can be used with measured incident light (in user-specified units) to calculate light intensity at a given depth. The equation necessary to complete this calculation is: $lnI_0 - kz = lnI_z$, where *ln* is the natural log, I_0 is incident light in desired units, *k* is the light extinction coefficient, *z* is depth of the water in desired units, and I_z is light intensity at depth in desired units. **Abbreviations:** ID, Idaho; Hwy, Highway; g/m², gram per square meter; mg/m²; milligram per square meter; µg/L, microgram per liter; ft, foot; ft/s, foot per second; ND, below laboratory detection level; NA, not applicable]

USGS Site No.	River mile	Site name	Week of August 21, 2012					
			Periphyton biomass (g/m²)	Periphyton chlorophyll-*a* (mg/m²)	Phytoplankton chlorophyll-*a* (µg/L)	Mean water depth (ft)	Mean water velocity (ft/s)	Light extinction coefficient
13203760	58.1	Boise River at Eckert Rd near Boise, ID	3	3	1.0	1.04	1.47	0.09
13206000	47.5	Boise River at Glenwood Bridge near Boise, ID	47	147	3.0	0.72	1.37	0.04
13210050	31.4	Boise River near Middleton, ID	10	40	6.4	0.43	2.26	0.07
13211000	24.0	Boise River at Hwy 20-26 Crossing near Caldwell, ID	25	108	6.7	0.27	1.67	0.20
13213030	0.0	Boise River at mouth near Parma, ID	11	63	[1]10.5	0.26	1.20	0.09

USGS Site No.	River mile	Site name	Week of October 29, 2012					
			Periphyton biomass (g/m²)	Periphyton chlorophyll-*a* (mg/m²)	Phytoplankton chlorophyll-*a* (µg/L)	Mean water depth (ft)	Mean water velocity (ft/s)	Light extinction coefficient
13203760	58.1	Boise River at Eckert Rd near Boise, ID	3	4	ND	0.51	2.53	0.06
13206000	47.5	Boise River at Glenwood Bridge near Boise, ID	16	131	3.7	0.80	1.82	0.15
13210050	31.4	Boise River near Middleton, ID	24	219	6.4	0.63	2.22	0.15
13211000	24.0	Boise River at Hwy 20-26 Crossing near Caldwell, ID	25	255	5.6	0.57	2.57	0.14
13213030	0.0	Boise River at mouth near Parma, ID	32	181	[1]9.0	0.67	2.48	0.10

USGS Site No.	River mile	Site name	Week of March 4, 2013					
			Periphyton biomass (g/m²)	Periphyton chlorophyll-*a* (mg/m²)	Phytoplankton chlorophyll-*a* (µg/L)	Mean water depth (ft)	Mean water velocity (ft/s)	Light extinction coefficient
13203760	58.1	Boise River at Eckert Rd near Boise, ID	14	36	4.8	0.59	1.56	NA
13206000	47.5	Boise River at Glenwood Bridge near Boise, ID	33	283	7.3	1.09	1.80	0.08
13210050	31.4	Boise River near Middleton, ID	30	137	19.5	0.53	1.68	0.11
13211000	24.0	Boise River at Hwy 20-26 Crossing near Caldwell, ID	23	211	17.5	0.46	1.87	0.13
13213030	0.0	Boise River at mouth near Parma, ID	16	92	[1]36.2	0.58	2.39	0.13

[1]Depth and width-integrated water sample for chloryphyll-*a* in phytoplankton collected at RM 3.8.

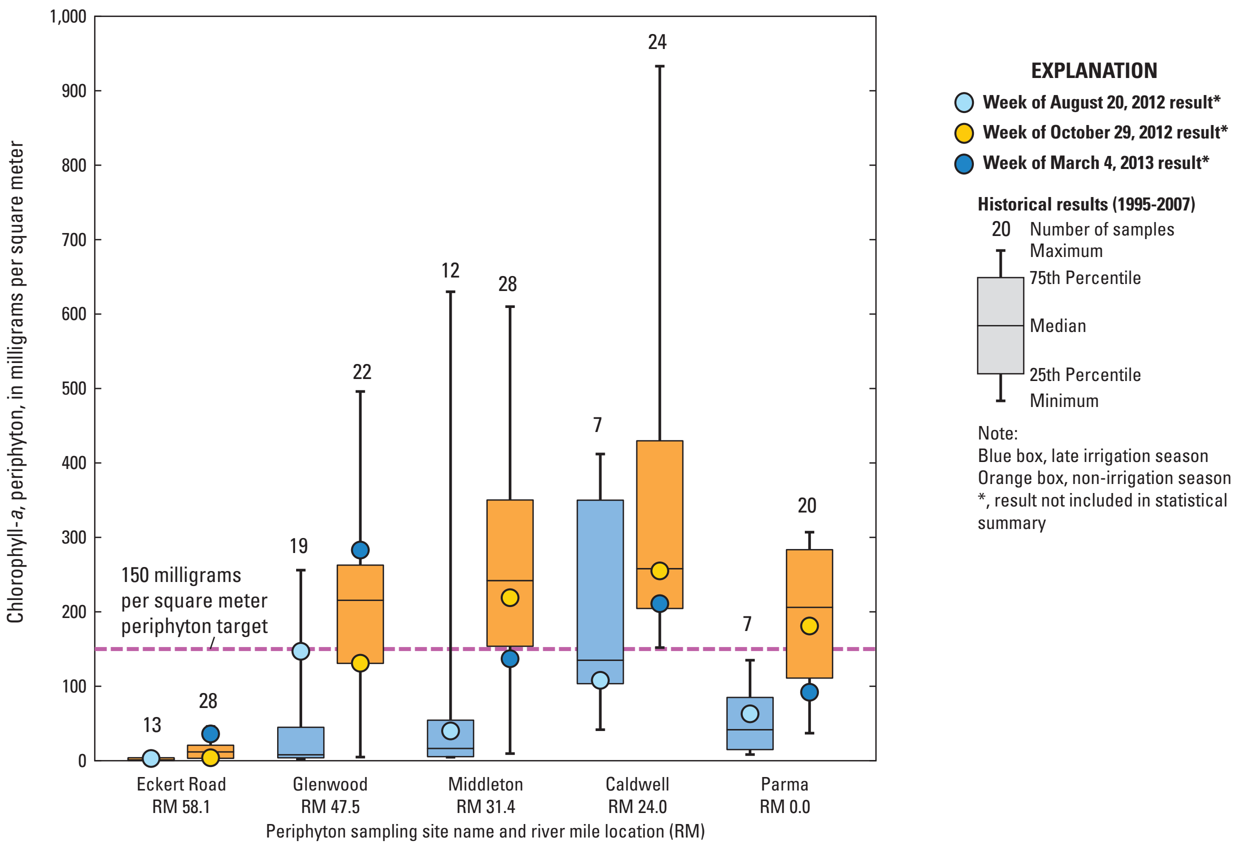


Figure 6. Statistical summary of monitoring results of chlorophyll-*a* in periphyton from lower Boise River, southwestern Idaho, 1995–2007 compared to synoptic sampling periods in August and October 2012, and March 2013.

In 2013, the Lower Boise Watershed Council voted to support an IDEQ proposal to establish a mean benthic chlorophyll-*a* target of 150 mg/m^2 for periphyton growth in the Boise River (Idaho Department of Environmental Quality, 2013a). Although most historical periphyton chlorophyll-*a* data have been collected in the Boise River in late October or November for consistency and to record optimum conditions for periphyton growth, synoptic periphyton sampling provided an opportunity to evaluate periphyton growth in the Boise River during three distinct periods in a given year. Periphyton growth was relatively low in August at four of five Boise River sites, with the exception of Boise River at Glenwood Bridge (RM 47.5) (table 5, fig. 6). Chlorophyll-*a* in periphyton sample results from the October synoptic sampling period are consistent with historical results showing more prolific periphyton growth soon after irrigation season ends (fig. 6). Chlorophyll-*a* in periphyton results in samples collected in late October 2012 exceeded 150 mg/m^2 at the Boise River near Middleton (RM 31.4), in Caldwell (RM 24.0), and near Parma (RM 0.0) (fig. 6). Periphyton samples historically have not been collected in March, as that time of year is not considered a growing season for periphyton. However, monitoring results from the March 2013 synoptic event indicate that chlorophyll-*a* in periphyton results in late winter exceeded 150 mg/m^2 at Glenwood Bridge (RM 47.5) and Highway 20-26 crossing in Caldwell (RM 24.0) (fig. 6). Chlorophyll-*a* in periphyton at Glenwood Bridge (RM 47.5) was near or greater than 150 mg/m^2 during all three synoptic events, with the highest measured result of any site occurring in March 2013 at 283 mg/m^2.

Historical data and data collected during synoptic sampling periods indicate that chlorophyll-*a* in periphyton concentrations: (1) do not exceed 150-mg/m^2 at the Boise River near Eckert Road (RM 58.1), (2) are greater throughout the lower Boise River soon after irrigation season ends, and (3) have the potential to exceed the 150-mg/m^2 target during and after irrigation season at the Boise River at Glenwood Bridge (RM 47.5) and Highway 20-26 crossing (RM 24.0) (figs. 1*C* and 6). Chlorophyll-*a* in periphyton in the Boise River near Middleton (RM 31.4) may exceed 150 mg/m^2 in late October or March, and chlorophyll-*a* in periphyton at the mouth near Parma (RM 0.0) often exceeds 150-mg/m^2 in late October (fig. 6). Concentrations of chlorophyll-*a* in periphyton generally increase with distance downstream of Eckert Road (RM 58.1) to at least Caldwell (RM 24.0), and then periphyton growth becomes limited presumably by lack of available light under relatively turbid conditions near Parma (RM 0.0).

Periphyton monitoring and TP mass-balance results (discussed in the section, Model Results) from the three synoptic sampling periods suggest that the Boise River near Glenwood Bridge (RM 47.5) and near the Highway 20-26 crossing (RM 24.0) may act as a phosphorus sink in late October. Effluent from the Lander WWTP (RM 50.0) may sustain substantial year-round periphyton growth at Glenwood Bridge (RM 47.5). Wastewater discharge with high concentrations of OP can result in increased phosphorus uptake within the aquatic community immediately downstream (Withers and Jarvie, 2008). Periphyton was not monitored immediately downstream of other WWTPs. Monitoring results show phosphorus limitations in the Boise River at Eckert Road (RM 58.1), whereas light limitation owing to high turbidity limits periphyton growth near Parma (RM 0.0). Site-specific relations between light availability; nutrient limitation (if any); phosphorus uptake, retention time, and release; abiotic retention of phosphorus; and nutrient cycling related to macrophyte growth require further study and may be important factors influencing the year-round cycling of phosphorus in the lower Boise River.

Groundwater and Surface-Water Interaction

Groundwater and surface-water interaction was estimated in 13 subreaches along a 46.4-mi reach of the Boise River between Veterans Memorial Parkway (RM 50.2) and Parma (RM 3.8). Surface-water discharge measurements collected during three synoptic sampling periods accounted for surface water in the main stem of the Boise River and in tributaries, point sources, and agricultural return flows and diversions along the Boise River (figs. 1*A*, 1*B*). Any surface-water surplus or deficit in each subreach was attributed to streamflow gains from groundwater or streamflow losses to groundwater. Water in tributaries and drains was treated as surface water in discharge balance calculations even though it may seasonally represent groundwater discharge. Discharge measurement uncertainty was propagated through each subreach, and calculated streamflow gains or losses were considered more accurate where discharge measurement uncertainty was less than the calculated gain or loss to groundwater (fig. 7, table 6). A cumulative streamflow gain was measured in the Boise River during each synoptic sampling period, with the largest overall streamflow gain totaling 485 ft^3/s (10.4 [ft^3/s]/mi) during the week of August 20, 2012. Streamflow gains totaling 174 ft^3/s (3.8 [ft^3/s]/mi) were measured during the week of March 4, 2013, and streamflow gains totaling 91.4 ft^3/s (1.97 [ft^3/s]/mi) were measured during the week of October 29, 2012.

Numerous studies have shown the seasonal nature of surface and groundwater interaction along the lower Boise River. Studies completed in summer 2005, November 1971, and November 1996 support findings in this study from August and October 2012. Modeled groundwater seepage in four piezometer transects between RMs 2 and 4 near Parma showed a gaining river during summer 2005, with the largest modeled seepage rate estimated at 73 (ft^3/s)/mi (Skinner, 2006). The estimated seepage rates averaged 13 (ft^3/s)/mi between RMs 2 and 4 during summer 2005, and the seepage rate calculated between the Highway 95 crossing (RM 8.8) and the Boise River near Parma (RM 3.8) in August 2012 was 8.5 (ft^3/s)/mi. Berenbrock (1999) also measured seepage in November 1996 along three reaches in the lower Boise River. In the reach from the Boise River near Boise (RM 61.8) to the Boise River at Glenwood Bridge (RM 47.5), an 8.17-ft^3/s net streamflow gain occurred in November 1996. A 1.56-ft^3/s net streamflow gain occurred in late October 2012 in a shorter subreach between Veterans Memorial Parkway (RM 50.2) and Glenwood Bridge (RM 47.5). Streamflow gains totaled 17.8 ft^3/s between the Boise River near Star (RM 36.4) and the Boise River at Notus (RM 15.7) in November 1996, and totaled 29.3 ft^3/s in late October 2012. Between the Boise River at Highway 95 crossing (RM 8.8) and the Boise River near Parma (RM 3.8), a 25.6-ft^3/s loss was measured in November 1996, compared to a 6.00-ft^3/s gain in October 2012 with a 106-ft^3/s propagated measurement uncertainty (table 6). In November 1971, Thomas and Dion (1974) determined that the Boise River gained 200 ft^3/s or 3.3 (ft^3/s)/mi between Diversion Dam (RM 61.1) and the mouth (RM 0.0). In late October 2012, the Boise River between Veterans Memorial Parkway (RM 50.2) and Parma (RM 3.8) gained a total of 91.4 ft^3/s or 1.97 (ft^3/s)/mi (table 6).

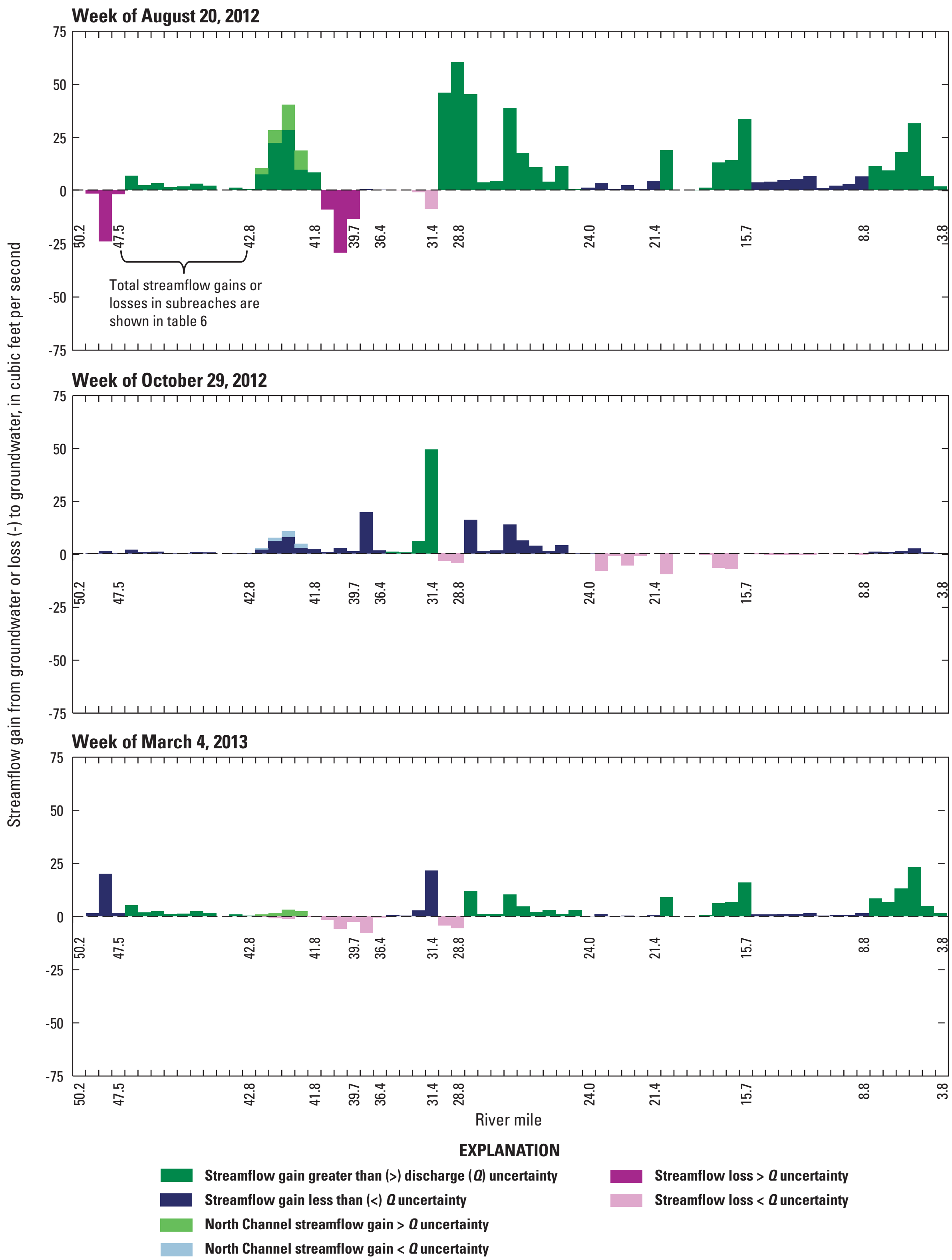


Figure 7. Streamflow gains and losses in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

Table 6. Discharge balances and total phosphorus load balances in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

[**Abbreviations:** ID, Idaho; Hwy, Highway; RM, river mile; ft^3/s, cubic foot per second; lb/d, pound per day; mg/L, milligram per liter; TP, total phosphorus: P, phosphorus NA, neither uptake nor release indicated; –, biogeochemical exchange not indicated]

Upstream subreach site	Reach (RM)		Week of August 20, 2012					
	Beginning	End	Propagated measurement uncertainty (ft^3/s)	Streamflow gain / loss (-) over subreach (ft^3/s)	Load gain / loss (-) over subreach (lb/d)	Theoretical TP concentration (mg/L)	Uptake "U" or release "R"	Can measurement uncertainty rule out P uptake or P release?
Boise River at Veterans Memorial Parkway at Boise, ID	50.2	47.5	47.4	-27.8	-0.19	0.00	NA	–
Boise River at Glenwood Bridge near Boise, ID	47.5	42.8	32.9	21.1	95.0	0.83	R	No
Boise River North Channel at Eagle, ID	42.8	41.8	18.7	29.8	24.9	0.15	NA	–
Boise River South Channel at Eagle, ID	42.8	41.8	37.5	76.1	-86.8	-0.21	U	No
Boise River above Phyllis Diversion near Eagle, ID	41.8	39.7	43.5	-52.0	-53.1	0.19	NA	–
Boise River Below Eagle Island, ID	39.7	36.4	19.6	0.41	-58.5	-26.5	U	No
Boise River near Star, ID	36.4	31.4	29.9	-10.0	32.8	-0.61	R	No
Boise River near Middleton, ID	31.4	28.8	30.6	106	141	0.25	NA	–
Boise River at Middleton Road near Middleton, ID	28.8	24.0	94.9	136	164	0.22	NA	–
Boise River at Hwy 20-26 Crossing near Caldwell, ID	24.0	21.4	85.9	10.9	19.8	0.34	NA	–
Boise River below WWTP near Caldwell, ID	21.4	15.7	45.2	80.4	176	0.41	NA	–
Boise River at Notus, ID	15.7	8.8	39.7	35.8	30.9	0.16	NA	–
Boise River at Hwy 95 Crossing near Parma, ID	8.8	3.8	42.3	78.0	90.5	0.22	NA	–
Totals				485	576			
Gain or loss / RM				10.4	12.4			

Upstream subreach site	Reach (RM)		Week of October 29, 2012					
	Beginning	End	Propagated measurement uncertainty (ft^3/s)	Streamflow gain / loss (-) over subreach (ft^3/s)	Load gain / loss (-) over subreach (lb/d)	Theoretical TP concentration (mg/L)	Uptake "U" or release "R"	Can measurement uncertainty rule out P uptake or P release?
Boise River at Veterans Memorial Parkway at Boise, ID	50.2	47.5	21.7	1.56	-19.6	-2.33	U	No
Boise River at Glenwood Bridge near Boise, ID	47.5	42.8	12.6	5.74	-197	-6.36	U	No
Boise River North Channel at Eagle, ID	42.8	41.8	8.03	6.80	3.1	0.08	NA	–
Boise River South Channel at Eagle, ID	42.8	41.8	36.0	20.8	-16.1	-0.14	U	No
Boise River above Phyllis Diversion near Eagle, ID	41.8	39.7	42.2	4.60	-5.1	-0.21	U	Yes
Boise River Below Eagle Island, ID	39.7	36.4	34.9	21.2	62.9	0.55	R	Yes
Boise River near Star, ID	36.4	31.4	48.7	57.0	205	0.67	R	No
Boise River near Middleton, ID	31.4	28.8	44.3	-7.90	-40.4	0.95	U	No
Boise River at Middleton Road near Middleton, ID	28.8	24.0	61.0	48.5	76.3	0.29	NA	–
Boise River at Hwy 20-26 Crossing near Caldwell, ID	24.0	21.4	62.8	-26.3	-182	1.28	U	No
Boise River below WWTP near Caldwell, ID	21.4	15.7	45.3	-42.0	71.0	-0.31	R	No
Boise River at Notus, ID	15.7	8.8	104	-4.60	-83.5	3.37	U	Yes
Boise River at Hwy 95 Crossing near Parma, ID	8.8	3.8	106	6.00	58.9	1.82	R	No
Totals				91.4	-66.5			
Gain or loss per RM				1.97	-1.43			

Table 6. Discharge mass balances and total phosphorus load mass balances in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.—Continued

[**Abbreviations:** ID, Idaho; Hwy, Highway; RM, river mile; ft^3/s, cubic foot per second; lb/d, pound per day; mg/L, milligram per liter; TP, total phosphorus: P, phosphorus; –, neither uptake nor release indicated; –, no uptake of biogeochemicals or release of phosphorus]

Upstream subreach site	Reach (RM)		Week of March 4, 2013					
	Beginning	End	Propagated measurement uncertainty (ft^3/s)	Streamflow gain / loss (-) over subreach (ft^3/s)	Load gain / loss (-) over subreach (lb/d)	Theoretical TP concentration (mg/L)	Uptake "U" or release "R"	Can measurement uncertainty rule out P uptake or P release?
Boise River at Veterans Memorial Parkway at Boise, ID	50.2	47.5	29.1	23.2	-31.3	-0.25	U	No
Boise River at Glenwood Bridge near Boise, ID	47.5	42.8	12.9	16.0	182	2.11	R	No
Boise River North Channel at Eagle, ID	42.8	41.8	7.00	7.70	-0.87	-0.02	U	No
Boise River South Channel at Eagle, ID	42.8	41.8	29.1	-3.47	-73.5	3.93	U	Yes
Boise River above Phyllis Diversion near Eagle, ID	41.8	39.7	29.4	-10.4	-318	5.67	U	No
Boise River Below Eagle Island, ID	39.7	36.4	16.7	-8.49	108	-2.36	R	No
Boise River near Star, ID	36.4	31.4	36.2	25.0	136	1.01	R	No
Boise River near Middleton, ID	31.4	28.8	36.5	-10.2	-51.0	0.93	U	Yes
Boise River at Middleton Road near Middleton, ID	28.8	24.0	21.8	30.6	-42.1	-0.26	U	No
Boise River at Hwy 20-26 Crossing near Caldwell, ID	24.0	21.4	30.9	2.00	297	7.5	R	No
Boise River below WWTP near Caldwell, ID	21.4	15.7	31.3	38.0	-360	-1.76	U	No
Boise River at Notus, ID	15.7	8.8	35.4	7.36	152	3.83	R	No
Boise River at Hwy 95 Crossing near Parma, ID	8.8	3.8	51.9	57.0	147	0.48	R	No
Totals				174	145			
Gain or loss per RM				3.8	3.1			

Watershed-scale groundwater-budget calculations and groundwater-elevation maps show that within the Boise River flood plain alluvium, shallow groundwater discharges year round to the lower Boise River (Berenbrock 1999; Bureau of Reclamation and Idaho Department of Water Resources, 2008). Beyond the flood plain but still within the lower Boise River watershed, groundwater recharge from application of irrigation water generally occurs during irrigation season, whereas groundwater discharge from irrigated lands generally occurs during non-irrigation season (Bureau of Reclamation and Idaho Department of Water Resources, 2008). Fox (2006) calculated the vertical and horizontal hydraulic conductivity of the alluvial aquifer near the Boise River below Diversion Dam (RM 61.1) at 72 and 180 ft/d, respectively. Compared to gains from the highly conductive shallow aquifer (including groundwater discharged through tributaries and drains), streamflow gains from or losses to bank storage along the Boise River likely are negligible, as are cumulative losses to phreatophytes in the riparian zone (Cardiff and others, 2009; Johnson and others, 2013).

If irrigation of agricultural lands in the Boise River watershed did not occur, the river probably would maintain lower flows during the winter. The Bureau of Reclamation and Idaho Department of Water Resources (2008) reported that the shallow aquifer beneath irrigated farmland in the lower Boise River watershed received an average of 1,012,000 acre-ft in annual recharge from on-farm infiltration or canal seepage in the mid-1990s. Much of this groundwater recharge from irrigation subsequently is discharged through agricultural drains and tributaries to the Boise River (618,000 acre-ft/yr) or contributed as base flow to the Boise River (233,000 acre-ft/yr). During the mid-1990s, a reported 29,000 acre-ft/yr of irrigation water was added as groundwater storage within the shallow aquifer (Bureau of Reclamation and Idaho Department of Water Resources, 2008). Groundwater budgets developed in 1996 and 2000 for the shallow aquifer in the lower Boise River watershed (Urban, 2004) generally agree with values presented by the Bureau of Reclamation and Idaho Department of Water Resources (2008).

Groundwater discharge to the Boise River shows a different seasonal pattern than groundwater discharge to Boise River tributaries and drains. However, groundwater discharge is tied closely to the start and end of irrigation season throughout the watershed. The amount of discharge in a river derived from groundwater discharge is called the base flow index (BFI). The closer the river BFI is to 1, the larger the percentage of river discharge derived from groundwater. The BFI in the lower Boise River was modeled at 0.68 (Wolock, 2003), and the modeled BFI was verified using data from USGS streamgages at Glenwood Bridge (13206000; RM 47.5) and the Boise River near Parma (13213000; RM 3.8), and data from the Reclamation streamgage at the Boise River below Diversion Dam (13203510; RM 61.1). BFI estimates are not feasible during irrigation season because diversions along the Boise River continually redistribute discharge throughout the watershed. Rainfall runoff data for the lower Boise River and daily mean streamflow data between August 1, 2012, and March 25, 2013, provided information necessary to evaluate the BFI in the lower Boise River during non-irrigation season in water year 2012 (fig. 8). Although BFI estimates are not realistic prior to October 20, 2012 because irrigation diversions remained active along the lower Boise River, they are shown in figure 8 to illustrate the rapid transition in discharge distribution that occurs as irrigation season ends. BFI estimates presented in this report assume all discharge at the Boise River below Diversion Dam (RM 61.1) is "runoff" from releases at Lucky Peak Dam (RM 64.0). The peak BFI (0.73) in the Boise River occurred on October 19, 2012, soon after diversions along the river stopped. As non-irrigation season progressed, the BFI steadily decreased to 0.59 on March 14, 2013, before operations at Lucky Peak Dam (RM 64.0) began to change the discharge distribution dynamics in the lower Boise River watershed (fig. 8).

The steady decrease in BFI between October 19, 2012, and March 14, 2013, is consistent with the conceptual model of groundwater and surface-water interaction in the Boise River wherein the shallow aquifer is dewatered slowly by agricultural drains and tributaries during the non-irrigation season. The discharge at Parma also steadily decreased from a median daily flow statistic of 962 ft^3/s on October 19 to a median daily statistic of 824 ft^3/s on March 14 (based on 36 years of record). Compared to a BFI between 0.68 and 0.71 during the week of October 29, 2012, synoptic discharge measurements showed that groundwater represented 69 percent of the discharge at Parma (RM 3.8) during the week of October 29, 2012. Compared to a BFI between 0.60 and 0.62 during the week of March 4, 2013, synoptic discharge measurements showed that groundwater represented 66 percent of the discharge at Parma.

In contrast, the computed BFI for Mason Creek remained steady at 0.84 during non-irrigation season in water year 2012 when a USGS streamgage was in operation near the mouth (13210983; RM 25.0). (Runoff data were obtained from Purdue University [2013], and daily mean discharge data were obtained from the U.S. Geological Survey [2013]). Although daily mean discharge steadily decreased, the percentage of water in Mason Creek represented by groundwater discharge in Mason Creek remained the same during non-irrigation season (except during rain events). The contrasting seasonal patterns in BFI in the lower Boise River and Mason Creek show groundwater-surface-water exchange conditions typical of non-irrigation season.

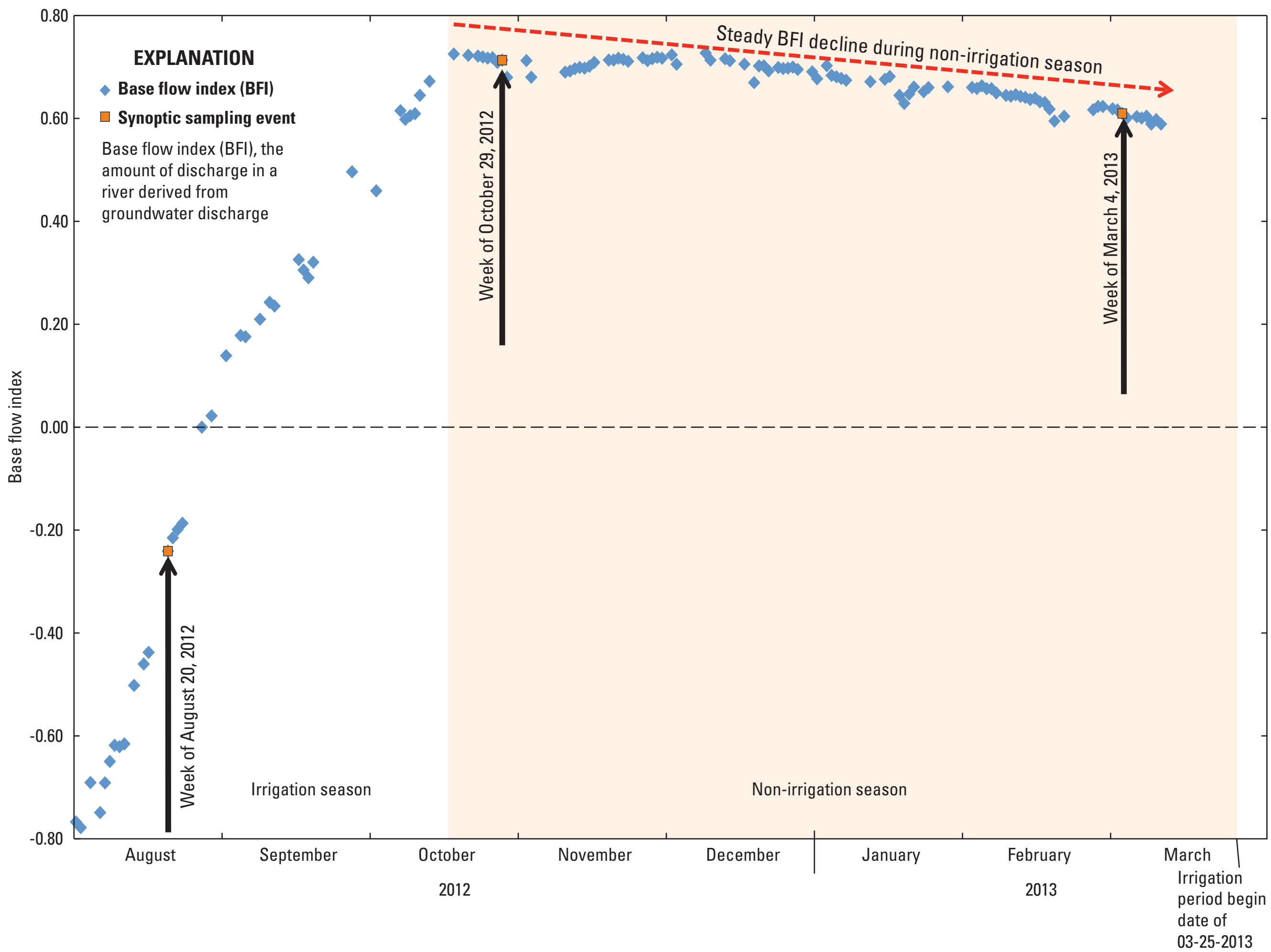


Figure 8. Base flow index in the lower Boise River, southwestern Idaho, August 1, 2012–March 25, 2013.

Shallow Groundwater Elevations

Seven shallow piezometers installed adjacent to the Boise River were used to measure the shallow groundwater elevation relative to the elevation of the Boise River between November 2012 and April 2013 (fig. 1C). Vertical head gradients between the shallow groundwater and the Boise river indicated varying seepage conditions and amounts, but generally did not support findings from the large-scale assessment of groundwater exchange during synoptic sampling periods. The farthest-upstream piezometer, Boise River Piezo 2-LB near the Boise River at Glenwood Bridge (RM 47.5), indicated groundwater discharge to the Boise River (streamflow gains) in all but the December measurement. The next six downstream piezometers all indicated discharge from the river to the groundwater (streamflow losses), except for the January measurement at the piezometer Boise River Piezo 6B-RB near the Boise River at Highway 20-26 crossing (RM 24.7).

The two piezometers at the most downstream location near the Boise River near Parma (RM 3.8) are aligned perpendicular to the Boise River, allowing for a horizontal gradient to be determined. Piezometer T1-A was located 2 ft from the right river bank and piezometer T2-A was located 180 ft from the right river bank (table 1, fig. 1C). Paired measurements in the two piezometers were collected monthly from December 2012 to April 2013, and groundwater elevations in the two piezometers were used to determine the direction of shallow groundwater flow. In early December, groundwater elevations in the two piezometers indicated groundwater flow away from the river or a losing system. Groundwater elevations in the two piezometers near Parma were equal in early January 2013, and indicated a gaining system in late February, early March, and late April. The indication of groundwater movement toward the river from February to late April supports findings from the large-scale assessment of groundwater exchange in the Boise River during the March 2013 synoptic sampling period. The results of this study suggest that the primary source of groundwater discharge to the Boise River, the shallow alluvial aquifer, may be best characterized by larger-scale assessments of horizontal flow gradients in shallow groundwater (less than 25 ft deep).

Model Results

Mass-balance modeling of TP for the three synoptic sampling periods showed variable results. This section summarizes mass-balance modeling results rounded to 3 significant digits. The spreadsheet mass-balance models developed for all three synoptic sampling periods are available in appendix 1. Each of the three TP mass-balance models is limited in that it is a static representation of conditions during one sampling period, but the sampling periods were selected to assess three variable hydrologic regimes during the water year. The August model represents conditions during irrigation season, when TP from point and nonpoint sources enters the Boise River as surface water. The October model represents conditions immediately after irrigation season ends, when diversions and agricultural returns are no longer leaving or entering the Boise River as surface water. The March model represents conditions in perennial tributaries, when TP typically decreases to the low range of concentrations observed in a given year.

Each model also characterizes the groundwater and surface-water interaction in the Boise River and provides insight into the seasonal role of groundwater as a nonpoint source of phosphorus. The models treat tributary return flows as surface water although tributaries are thought to drain the shallow aquifer during non-irrigation season (Thomas and Dion, 1974; Petrich, 2004). Any discussion of “groundwater” in this section refers to main-stem streamflow gains or losses that cannot be accounted for in surface-water returns including tributary returns during the non-irrigation season. Streamflow gains and losses quantified in this manner accounted for a large portion of the TP load at the Boise River near Parma (RM 3.8) in August, but did not account for a large portion of the TP load at the Boise River near Parma in October or March. However, if tributary returns during the non-irrigation season are assumed to represent groundwater draining a shallow aquifer that is seasonally recharged by irrigation water, groundwater is an important source of TP loads in all three models.

Two types of mass-balance models were developed for each synoptic event. Unmeasured loads were assigned to “groundwater” for modeling purposes, but also could have come from unmeasured diversions, returns, or biogeochemical processes. Unmeasured returns were scouted from Caldwell (RM 24.0) to the mouth of the Boise River during irrigation season, and two large unnamed drains (RM 12.3 and 10.9) were located and included in the model. Other unmeasured returns were noted as insignificant and likely were inactive during the non-irrigation season.

The measured mass-balance models do not contain inputs for instream uptake or release of phosphorus, but rather are balanced to provide insight into areas where these processes could be occurring. Quantified uncertainties of discharge measurements allowed further inspection of the range of estimated streamflow gains or losses in each subreach. Streamflow gains and losses were adjusted by their measurement uncertainties within the spreadsheet models to assess whether revisions to streamflow gains or losses could realistically account for unmeasured gains or losses in TP loads. The assessment was conducted after calculating a theoretical groundwater TP concentration using revised gains or losses in streamflow and TP loads. If a theoretical groundwater TP concentration was negative or greater than 0.45 mg/L in any subreach, it was considered unrealistic and uptake or release of phosphorus was further supported. The results of this exercise are summarized in table 6 and figure 9.

August Model

During irrigation season, more than 50 diversions and returns exchange surface water with the main stem of the Boise River throughout the modeling reach (fig. 2). Large diversions including Phyllis Canal (RM 41.4), Riverside Canal (RM 24.6), and Sebree Canal (RM 24.0) remove substantial TP loads from the Boise River and redistribute the loads throughout myriad drains, furrows, gullies, lateral canals, and natural tributaries to the Boise River. The August model does not account for the origin of phosphorus in each return or tributary to the Boise River. Even if phosphorus acted conservatively throughout the modeling reach, TP loads could not be mathematically summed during irrigation season because diversions repeatedly redistribute large TP loads throughout the modeled watershed and several thousand cubic feet per second of discharge is conveyed to the watershed from the Payette River and New York, Ridenbaugh, Farmers Union, and Settler’s Canals outside the modeling reach. The amount of phosphorus applied to and taken up by crops on agricultural fields during irrigation season also is unmeasured. However, the August model shows the relative magnitude of TP loads in diversions and return flows and their effects on TP concentrations in the Boise River. Understanding the dynamics in TP loading and the resulting main-stem TP concentration helps in identifying where engineering controls or best management practices could best achieve the 0.07-mg/L TP target at the mouth of the Boise River.

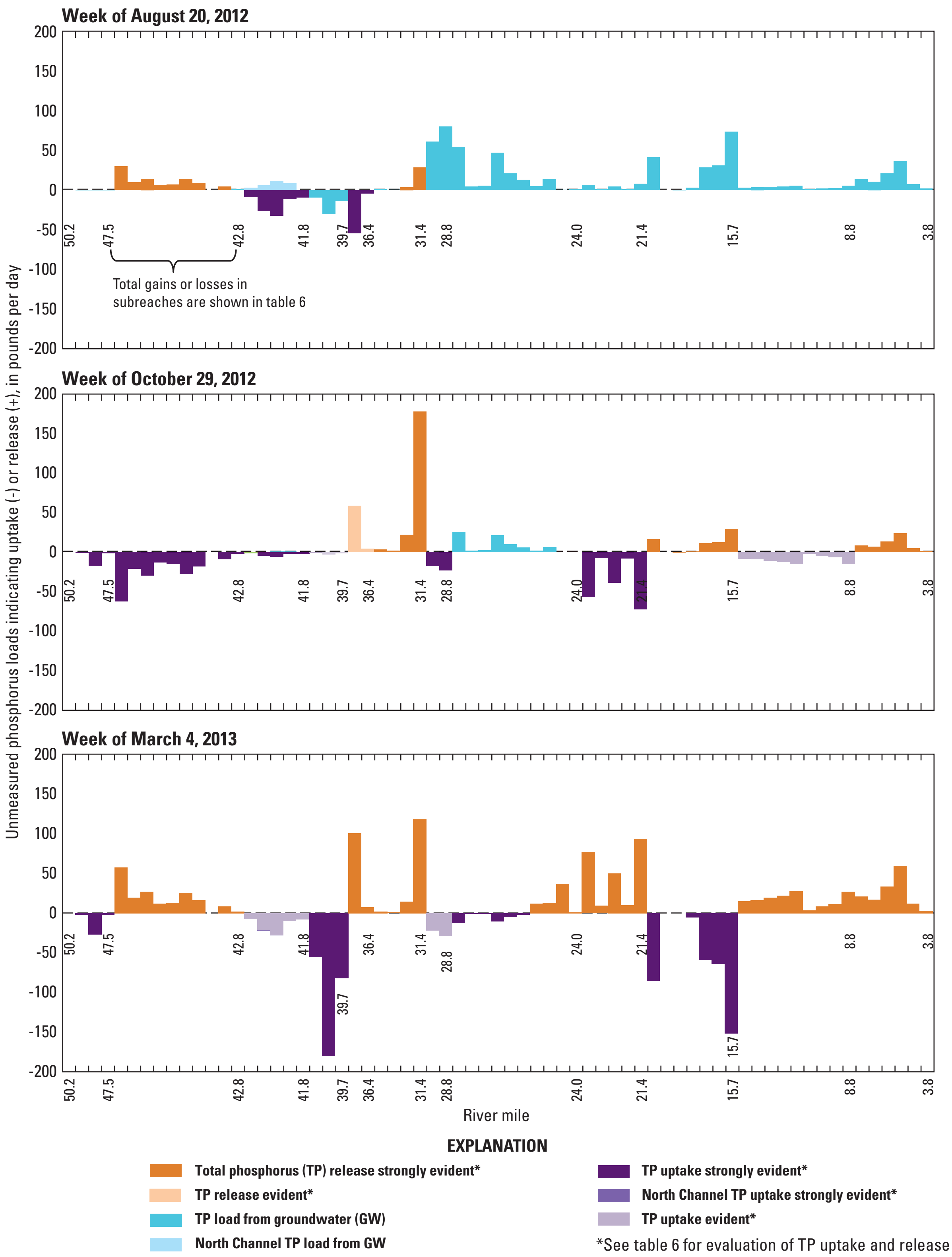


Figure 9. Unmeasured total phosphorus loads in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

Discharge Balance

Main-stem discharge measurements used to develop the August model indicated a substantial cumulative streamflow gain of 485 ft^3/s (fig. 10, table 6). Reaches with gains and losses greater than measurement uncertainties as propagated through a given subreach are shown in figure 7. Discharge balances (streamflow gains or losses) used to model total discharge in the modeling reach are summarized in table 6. All but two of the calculated streamflow gains were greater than propagated measurement uncertainty in subreaches downstream of the Boise River near Middleton (RM 31.4). The modeled discharge and accumulated streamflow gains downstream of RM 31.4 are shown in figure 10. Most streamflow gains occurred downstream of the Boise River near Middleton (RM 31.4). The measured discharge at the Boise River near Parma (RM 3.8) was 624 ft^3/s during the August synoptic event, with groundwater accounting for 78 percent of the discharge. Some of the 485-ft^3/s gain from groundwater likely was irrigation water derived from the seasonally elevated water table (Thomas and Dion, 1974).

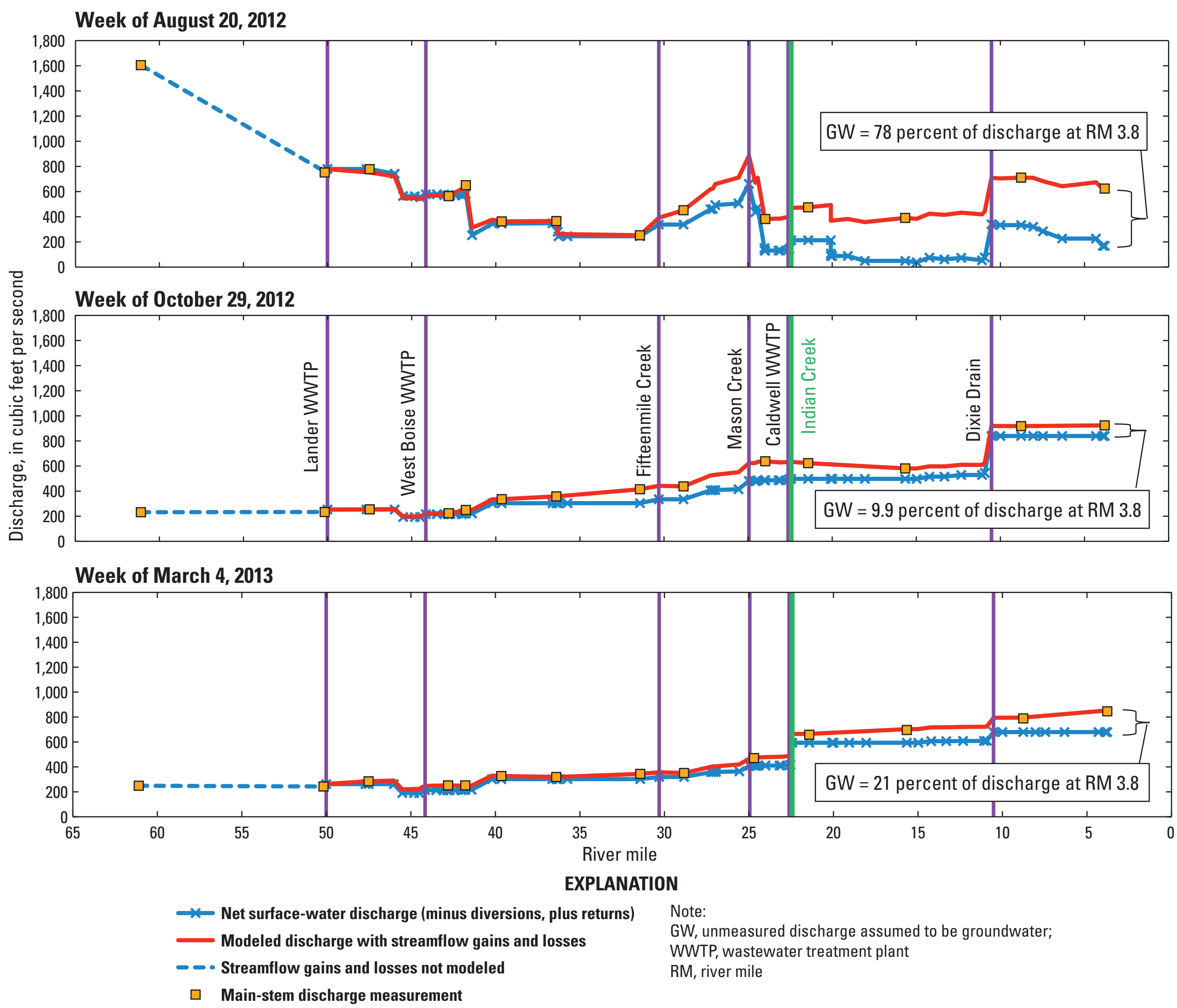


Figure 10. Discharge balance and measured main-stem discharge, lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

Measured Total Phosphorus Mass-Balance Model

Point and nonpoint sources influenced TP concentrations in the Boise River in the August mass-balance models. Surface water from point and nonpoint sources in the modeling reach contributed a total TP load of 2,320 lb/d, and diversions removed a total TP load of 1,890 lb/d. The net result was a gain of 430 lb/d of TP from surface water. The addition of 576 lb/d of TP from unmeasured sources (assumed to be groundwater) resulted in a TP load of 1,010 lb/d (rounded to 3 significant digits) in the Boise River near Parma (RM 3.8) (table 7). Returns from Fifteenmile Creek (RM 30.3), Mason Creek (RM 25.0), Indian Creek (RM 22.4), and Dixie Drain (RM 10.5) increased the TP concentration in the Boise River slightly in August, and remaining agricultural returns had a negligible effect on the main-stem TP concentration (fig. 11*A*, table 7). However, the inflows of Fifteenmile Creek, Mill Slough (RM 27.2), Willow Creek (RM 27.0), Mason Slough (RM 25.6), and Mason Creek between the Boise River near Middleton (RM 31.4) and the Riverside Canal diversion (RM 24.6) increased the TP load from 250 to 1,120 lb/d (fig. 11*B*). The addition of 470 lb/d of TP from Dixie Drain (RM 10.5) increased the main-stem TP load to 1,200 lb/d, the highest modeled main-stem TP load in August. Point sources that discharged directly to the Boise River including Lander WWTP (RM 50.0), West Boise WWTP (RM 44.2), Middleton WWTP (RM 27.1), and Caldwell WWTP (RM 22.6) accounted for 923 lb/d of TP and caused the largest increases in main-stem TP concentrations (fig. 11*A*). Including WWTP discharges from the cities of Meridian and Nampa that discharge into Fivemile Creek (a tributary of Fifteenmile Creek [RM 30.3]) and Indian Creek (RM 22.4), respectively, a total point source TP load of 1,440 lb/d was measured during the August synoptic sampling period (table 8). Point source TP loading in the lower Boise River watershed exceeded the measured TP load at the Boise River near Parma during the week of August 20, 2012 (table 7).

Large increases in main-stem TP concentrations occurred downstream of WWTPs, whereas relatively small increases in main-stem TP concentrations occurred downstream of some tributaries and drains (fig. 11*A*). However, TP loads from several tributaries and drains sharply increased TP loads in the Boise River (fig. 11*B*). Wherever large increases in TP load are observed with small or negligible changes in main-stem TP concentrations, a potential exists for dilution of main-stem TP concentrations. Fifteenmile Creek (RM 30.3), Mill Slough (RM 27.2), Mason Creek (RM 25.0), Indian Creek (RM 22.4), and Dixie Drain (RM 10.5) each have the potential to dilute TP concentrations in the main stem of the Boise River if decreases in TP concentrations are achieved in the drains during irrigation season. Diluted inflow from the north channel showed its potential to decrease TP concentrations when the inflow mixed with the more concentrated south channel (RM 40.2) (fig. 11*A*).

Riverside Canal plays a critical role in TP load distribution in the lower Boise River watershed downstream of Caldwell (fig. 2). During irrigation season, photographs (Fox and others, 2002) show a sediment plume from Mason Creek (RM 25.0) moving along the left bank of the Boise River before being diverted to Riverside Canal (RM 24.6). As a result, Mason Creek affects water quality in Riverside Canal more than it affects water quality in the Boise River during irrigation season. The measured TP load in Riverside Canal just downstream of the Riverside Canal diversion was 302 lb/d in August, slightly more than the 259-lb/d TP load from Mason Creek (appendix 1, table 7). About 2 mi downstream of the Riverside Canal diversion from the Boise River (composed mostly of water from Mason Creek), Riverside Canal and Indian Creek merge into one channel for a short distance before most water from Indian Creek is diverted to Riverside Canal (fig. 2). Less than 0.5 mi downstream of its conveyance into Riverside Canal, Indian Creek reaches its confluence with the Boise River (RM 22.4). Non-irrigation season discharge from Indian Creek to the Boise River typically is between 150 and 250 ft^3/s, whereas during the August sampling, only 69.7 ft^3/s is discharged to the Boise River from Indian Creek (appendix 1). During irrigation season, Indian Creek at the mouth (RM 22.4) is composed of a mixture of water from Indian Creek, Mason Creek, and the Boise River (fig. 2). Several miles downstream of the Nampa WWTP point-source discharge to Indian Creek, and upstream of the confluence of Indian Creek with Riverside Canal, the USGS measured a 466-lb/d instantaneous TP load in August. The instantaneous TP load measured at the mouth of Indian Creek (RM 22.4) showed that 169 lb/d of TP ultimately discharged to the Boise River (at RM 22.4) (figs. 1*A* and 2). Riverside Canal started with 302 lb/d of TP originally diverted from the Boise River to the Riverside Canal (RM 24.6), and received an additional 297 lb/d of TP from Indian Creek. Riverside Canal water downstream of Indian Creek contained both point and nonpoint sources of TP, and acted as a source of TP in the lower Boise River watershed downstream of Caldwell regardless of its return pathway to the Boise River. Some of Riverside Canal water discharges to Dixie Drain 2.9 mi southwest of Notus (RM 15.7), and the remaining water discharges directly to the Snake River (RM 411.7) or supplies irrigation water to laterals and canals south of Parma, Idaho (fig. 1*A*).

TP loads in other diversions also are important in moving TP from the Boise River to meet irrigation demands, and also may be composed of phosphorus that originated partly from point-source discharges upstream. Mass-balance models do not account for TP transport from diversions upstream to groundwater or returns downstream. Diversions between Veterans Memorial Parkway (RM 50.2) and Caldwell (RM 24.0) removed 1,250 lb/d of TP for irrigation use downstream. Middleton Canal (RM 41.5) and Phyllis Canal (RM 41.4) diverted 51 percent of the TP loads in the north and south channels, respectively. Riverside Canal (RM 24.6) and Sebree Canal (RM 24.0) removed 718 lb/d of TP and Indian Creek (RM 22.4) conveyed another 297 lb/d to Riverside Canal in August (appendix 1).

Table 7. Summary of total phosphorus mass balance results in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

[**MTD**: Measured or total discharge. **TPL**: Total phosphorous loads. **MATPC**: Measured or average total phosphorous concentrations. **Abbreviations:** RM, river mile; ft^3/s, cubic foot per second; lb/d, pound per day; mg/L, milligram per liter; <, less than; NA, not applicable; "-", negative; WWTP, wastewater treatment plant]

Source	Week of August 20, 2012			Week of October 29, 2012			Week of March 4, 2013		
	MTD (ft^3/s)	TPL (lb/d)	MATPC (mg/L)	MTD (ft^3/s)	TPL (lb/d)	MATPC (mg/L)	MTD (ft^3/s)	TPL (lb/d)	MATPC (mg/L)
Start of modeling reach (RM 50.2)	759	61.4	0.02	234	5.10	<0.01	243	13.1	0.01
Point sources (including Meridian WWTP and Nampa WWTP)	84.0	1,440	3.18	76.8	1,050	2.53	72.5	1,220	3.12
Diversions	-1,590	-1,890	0.22	NA	NA	NA	NA	NA	NA
All tributaries, WWTP loads removed	888	880	0.18	527	456	0.16	362	236	0.12
Unmeasured	485	576	0.22	91.4	-66.5	-0.14	174	145	0.15
Predictive model groundwater	485	562	0.21	91.4	27.1	0.05	174	142	0.15
End of modeling reach (RM 3.8)	624	1,010	0.30	924	1,450	0.29	846	1,550	0.34
Fifteenmile Creek (RM 30.3) (including Meridian WWTP)	92.8	150	0.30	30.9	100	0.60	17.2	11.1	0.12
Mason Creek (RM 25.0)	155	259	0.31	66.1	64.2	0.18	44.7	33.8	0.14
Indian Creek[1] (RM 22.4) (including Nampa WWTP)	69.7	169	0.45	3.00	8.59	0.54	177	420	0.44
Dixie Drain[1] (RM 10.5)	264	470	0.33	294	539	0.34	70.3	37.9	0.10
Tributaries (excluding Fifteenmile, Mason, and Indian Creeks and Dixie Drain)	309	347	0.21	155	169	0.20	73.9	76.1	0.19
Snake River at Adrian	5,500	1,480	0.05	7,680	1,240	0.03	7,050	2,660	0.07
Sand Hollow Gulch (drains to Snake River)	169	319	0.35	62.0	66.9	0.20	38.7	18.8	0.09
Snake River at Nyssa	6,280	3,050	0.09	8,840	2,860	0.06	8,010	3,890	0.09

[1]Indian Creek was diverted into Riverside Canal and discharged partially to Dixie Drain during the week of October 29, 2012.

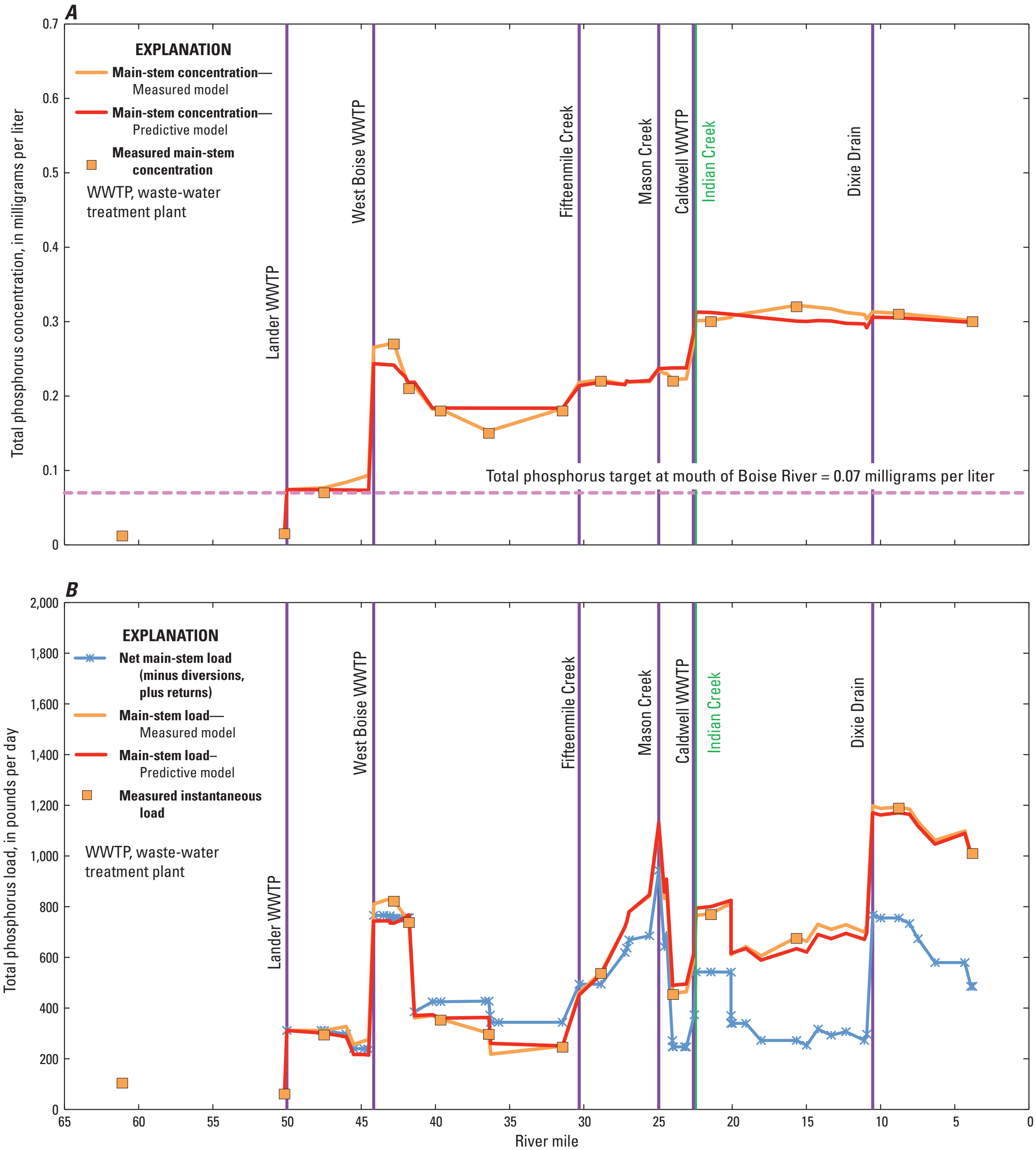


Figure 11. Modeled and measured main-stem (*A*) total phosphorus concentrations and (*B*) total phosphorus loads, lower Boise River, southwestern Idaho, during the week of August 20, 2013.

Table 8. Summary of point-source total phosphorus loading in the lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

[**Abbreviations:** TP, total phosphorus; Mgal/d, million gallons per day; ft^3/s, cubic foot per second; lb/d, pound per day; mg/L, milligram per liter; NA, not applicable; ~, approximately; <, less than]

USGS site No.	Wastewater treatment plant	River mile	Week of August 20, 2012			
			Effluent discharge		TP concentration	TP load
			(Mgal/d)	(ft^3/s)	(mg/L)	(lb/d)
13205643	Lander Street[1]	50.0	13.5	20.8	2.23	251
13206303	West Boise[1]	44.2	14.8	22.9	4.28	528
433820116261900	Meridian	NA	6.14	9.50	0.24	12.3
434149116382200	Middleton[1]	27.1	0.65	1.01	3.23	17.6
433555116345900	Nampa	NA	11.0	16.9	5.51	504
434038116420900	Caldwell[1]	22.6	8.31	12.9	1.83	127
Total			54.4	84.0		1,440
As percentage of the Boise River near Parma (RM 3.8)				13.5		143
	Hatchery					
13211387	Nampa	NA	NA	NA	0.06	NA
434038116241200	Eagle Island	NA	NA	<10	0.03	NA

USGS site No.	Wastewater treatment plant	River mile	Week of October 29, 2012			
			Effluent discharge		TP concentration	TP load
			(Mgal/d)	(ft^3/s)	(mg/L)	(lb/d)
13205643	Lander Street[1]	50.0	12.6	19.4	0.93	97.1
13206303	West Boise[1]	44.2	15.0	23.2	3.97	496
433820116261900	Meridian	NA	5.16	7.98	1.67	71.9
434149116382200	Middleton[1]	27.1	NA	~1	3.62	19.5
433555116345900	Nampa	NA	10.9	16.9	3.88	352
434038116420900	Caldwell[1]	22.6	5.40	8.35	0.37	16.8
Total			49.1	75.8		1,050
As percentage of the Boise River near Parma (RM 3.8)				8.2		72
	Hatchery					
13211387	Nampa	NA	NA	NA	0.07	NA
434038116241200	Eagle Island	NA	NA	<10	0.03	NA

USGS site No.	Wastewater treatment plant	River mile	Week of March 4, 2013			
			Effluent discharge		TP concentration	TP load
			(Mgal/d)	(ft^3/s)	(mg/L)	(lb/d)
13205643	Lander Street[1]	50.0	12.2	18.8	1.54	157
13206303	West Boise[1]	44.2	14.6	22.6	4.76	580
433820116261900	Meridian	NA	4.86	7.52	0.14	5.48
434149116382200	Middleton[1]	27.1	NA	~1	5.11	27.6
433555116345900	Nampa	NA	8.97	13.9	4.50	337
434038116420900	Caldwell[1]	22.6	5.60	8.67	2.36	111
Total			46.2	71.5		1,220
As percentage of the Boise River near Parma (RM 3.8)				8.5		79
	Hatchery					
13211387	Nampa	NA	NA	NA	1.35	NA
434038116241200	Eagle Island	NA	NA	<10	0.03	NA

[1]Discharges directly into Boise River.

Groundwater discharge to the Boise River represented a substantial source of TP in August. Measured mass-balance model results identified two subreaches where theoretical TP concentrations in groundwater were higher than TP concentrations in the Boise River (table 6, fig. 11*A*). Between RMs 31.4 and 28.8, the theoretical TP concentration in groundwater discharge equaled 0.25 mg/L relative to 0.18 mg/L measured in the Boise River near Middleton (RM 31.4). Between RM 21.4 and RM 15.7, the theoretical TP concentration in groundwater discharge equaled 0.41 mg/L relative to 0.32 mg/L measured in the Boise River at Notus (RM 15.7) (table 6). MacCoy (2004) reported an OP concentration of more than 1 mg/L in groundwater near the left bank of the Boise River at Notus (RM 15.7) in August 2001 (fig. 5). A confined animal feeding operation exists on the left bank of the Boise River at Notus Bridge (RM 15.7), and a strong manure odor emanated from shallow pools along the left bank of the Boise River during synoptic sampling. Of the remaining reaches where streamflow gains occurred, increases in main-stem TP loads also occurred, but main-stem TP concentrations did not increase (fig. 9, fig. 11*A*). The total unmeasured TP load in August was 576 lb/d, or 57 percent of the modeled load at Parma. This total is assumed to quantify the TP load contribution from groundwater and unmeasured returns.

Sources of discharge and TP that cannot be attributed to surface water were considered as groundwater for modeling purposes. "Groundwater" loads that cannot be accounted for with corresponding "groundwater" discharge also could represent phosphorus uptake or release by aquatic plants and riparian phreatophytes. Phosphorus uptake or release likely occurred in four subreaches in the August model (table 6). The two subreaches indicating phosphorus uptake were from the Boise River south channel at Eagle Road (RM 42.8) to the Boise River south channel upstream of Phyllis Diversion (RM 41.8), and from the Boise River downstream of Eagle Island (RM 39.7) to the Boise River near Star (RM 36.4) (fig. 9, table 6). Both subreaches indicated a streamflow gain coincident with a loss in TP load (fig. 11*A*). The two subreaches indicating release of phosphorus were from Glenwood Bridge (RM 47.5) to Eagle Road (RM 42.8), and from the Boise River near Star (RM 36.4) to the Boise River near Middleton (RM 31.4) (fig. 9, table 6). Compared to overall TP loads gained from groundwater, biogeochemical release and uptake may have played a minor role in TP loading dynamics in the August model.

Predictive Mass-Balance Model

Discharge balance calculations for the August 2012 model indicated 485 ft^3/s of unmeasured discharge, which was attributed to groundwater inflow for modeling purposes. The August predictive mass-balance model estimated TP concentrations in groundwater to balance deficits and surpluses in unmeasured TP loads. Compared to the 576-lb/d TP load gain computed in the measured model, estimated groundwater concentrations in streamflow gains accounted for a 562-lb/d TP gain in the predictive model (table 7). The predictive model estimated groundwater TP concentrations using a prorated increase ranging from 0.01 mg/L at Veterans Memorial Parkway (RM 50.2) to a constant 0.25 mg/L between the Boise River at Middleton Road (RM 28.8) and the Boise River near Parma (RM 3.8). This estimate of groundwater TP concentrations accounted for 97 percent of the variability in measured main-stem TP concentrations (fig. 12). The statistically significant ability of the August predictive model to estimate TP concentrations in the main stem of the Boise River suggests that the discharge balance calculations and groundwater TP concentration estimates may be reasonably accurate. August model results also suggest that biogeochemical processes, which are not included in static mass-balance models, may have had a limited effect on main-stem TP concentrations in August 2012.

October Model

The late-October sampling period was selected to characterize conditions soon after irrigation season ended in the lower Boise River watershed. Mass-balance accounting during non-irrigation season is simplified because surface-water diversions do not remove water and associated TP loads from the Boise River. Historically, tributary discharge increases slightly immediately after irrigation season ends and then decreases through the winter. Minimum tributary flows typically occur in late winter or early spring. The steady decrease in tributary discharge to the Boise River during non-irrigation season coincides with a steady decrease in shallow groundwater elevations (Fox and others, 2002). Water in the tributaries likely is a mixture of shallow groundwater and bank storage discharging to stream channels. During the October sampling period, Indian Creek was diverted entirely to Riverside Canal. Normally, Riverside Canal is unused (dry) and Indian Creek discharges to the Boise River during the winter months, so the modeling results may not represent normal conditions downstream of Indian Creek during non-irrigation season.

Discharge Balance

The Boise River gained a total of 91.4 ft^3/s from groundwater over the modeling reach in the October model—about, 9.9 percent of the total discharge in the Boise River near Parma (RM 3.8) (fig. 10). Between Veterans Memorial Parkway (RM 50.2) and the Boise River near Middleton (RM 31.4), the Boise River gained 118 ft^3/s. Downstream of the Boise River near Middleton (RM 31.4), the October model indicated losses to groundwater totaling 26.3 ft^3/s (table 6). A gain of 57.0 ft^3/s between the Boise River near Star (RM 36.4) and the Boise River near Middleton (RM 31.4) was the only streamflow gain greater than propagated measurement uncertainty (fig. 7, table 6).

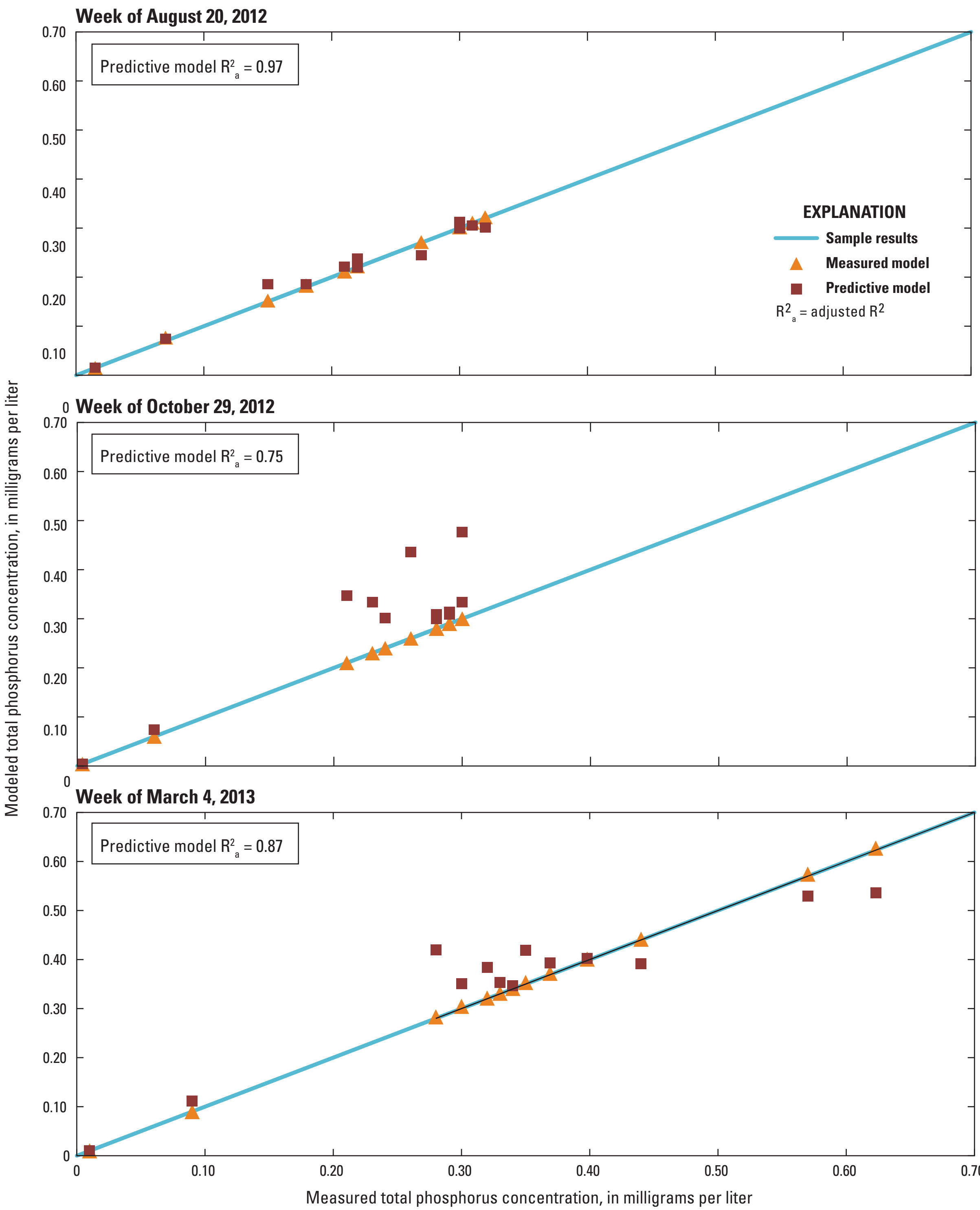


Figure 12. Summary of measured and predictive mass-balance model results for total phosphorus, lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

Thomas and Dion (1974) determined that nearly all the water in the Boise River during non-irrigation season is from groundwater discharge. Water discharging to the river from many of the drains and tributaries during non-irrigation season has been characterized as groundwater (Thomas and Dion, 1974; Mullins, 1998; Fox and others, 2002). However, for modeling purposes, tributary discharge was accounted for as surface water. In October, if all the discharge from tributaries was assumed to represent groundwater discharge, 69 percent of the discharge at the Boise River near Parma (RM 3.8) was groundwater, 25 percent originated from Lucky Peak Dam (RM 64.0), and 6 percent was wastewater effluent discharged directly to the Boise River.

Measured Total Phosphorus Mass-Balance Model

Propagated measurement uncertainty generally exceeded streamflow gains and losses in the October model. Although the Boise River gained a total of 91.4 ft^3/s in the modeling reach, the measured mass-balance model indicated an overall loss of 66.5 lb/d of TP (table 7). Lower confidence in streamflow gains and losses does not discount the effects of biogeochemical processes evident in the October mass-balance models. Out of 13 subreaches, mass-balance accounting indicated phosphorus uptake in 7 subreaches, phosphorus release in 4 subreaches, and neither biogeochemical uptake nor release of phosphorus in 2 subreaches (table 6). In the seven subreaches indicating phosphorus uptake, 544 lb/d of TP was lost with a 6.09-ft^3/s loss to groundwater. In the four subreaches indicating phosphorus release, 398 lb/d of TP was gained with a 42.2-ft^3/s gain from groundwater (table 6).

Unmeasured losses in TP loads exceeded unmeasured gains in TP loads and could not be accounted for using computed streamflow losses. Cumulative unmeasured losses in TP loads reduced TP loads by 5 percent at Parma (RM 3.8). The two most substantial losses of TP occurred between the Boise River at Glenwood Bridge (RM 47.5) and the south channel of the Boise River at Eagle Road (RM 42.8) and between the Boise River at Highway 20-26 crossing (RM 24.0) and the Boise River downstream of the Caldwell WWTP (RM 21.4) (fig. 9, table 6). The mass-balance model implies that TP uptake exceeds the quantity of TP loaded to the Boise River between Glenwood Bridge (RM 47.5) and the south channel at Eagle Road (RM 42.8) (figs. 13*A* and 13*B*). The calculated streamflow gain of 7.3 ft^3/s upstream of the south channel at Eagle Road probably underestimates the actual streamflow gain by at least 52 ft^3/s. Regardless, the substantial loss of TP coinciding with a gain from groundwater indicates phosphorus uptake. Cumulatively, uptake was more important than groundwater exchange in October.

The three most substantial TP releases occurred between the Boise River near Star (RM 36.4) and the Boise River near Middleton (RM 31.4), between the Boise River downstream of the Caldwell WWTP (RM 21.4) and the Boise River at Notus (RM 15.7), and between the Boise River at Highway 95 crossing (RM 8.8) and the Boise River near Parma (RM 3.8) (fig. 9, table 6). Measured model results indicate that biogeochemical TP releases between RM 36.4 and RM 31.4 may have increased main-stem TP concentrations to a greater degree than did return flows from Fifteenmile Creek (RM 30.3) in October (fig. 13*A*, tables 6 and 7). Stream-gaging records from the Boise River near Parma (RM 3.8) provide additional evidence of phosphorus release to the water column. Macrophytes affect the stage-discharge relation throughout the summer at Parma as they grow on the instream control that determines stage. The effect steadily decreases from late October to late December or January as macrophytes decay. This change in the stage-discharge relation also occurs at the streamgage on the Boise River near Middleton (Mike Campbell, Idaho Power Company, written commun., 2013). Macrophyte decay can release dissolved OP to the water column (Withers and Jarvie, 2008), and likely is the source of TP releases measured downstream of Star, Idaho (RM 36.4) and Highway 95 crossing (RM 8.8) in October.

Loading dynamics in late October were different from those in August because water was not diverted from the Boise River for irrigation use and releases from Lucky Peak Dam (RM 64.0) decreased (figs. 3 and 13*B*). However, the 0.29-mg/L TP concentration near the mouth of the Boise River was essentially unchanged from August (0.30 mg/L) (table 7). Discharge below Diversion Dam (RM 61.1) decreased from 1,605 ft^3/s in August to 232 ft^3/s in late October (fig. 10). Water from Lucky Peak Reservoir likely dilutes TP concentrations in the modeling reach upstream of Caldwell (RM 24.0) in August, whereas dilution is limited in October because of the diminished discharge from Lucky Peak Dam. As a result, TP concentrations in the Boise River in late October (fig. 13*A*) generally were higher than in August (fig. 11*A*) upstream of Caldwell (RM 24.0). The highest measured TP load occurred at 1,450 lb/d near Parma (RM 3.8) (fig. 13*B*, table 7).

Point sources discharging directly to the Boise River contributed 629 lb/d or 43 percent of the 1,450-lb/d surface-water TP load near Parma (RM 3.8) in October (table 8). WWTPs for the cities of Meridian and Nampa contributed an additional 424 lb/d of TP to the Fivemile Creek (a tributary of Fifteenmile Creek) and Indian Creek for a total point-source TP load of 1,050 lb/d or 72 percent of the measured TP load at Parma (RM 3.8) (tables 7 and 8). As in August, the largest increases in TP concentrations occurred downstream of WWTP sources in October (fig. 13*A*).

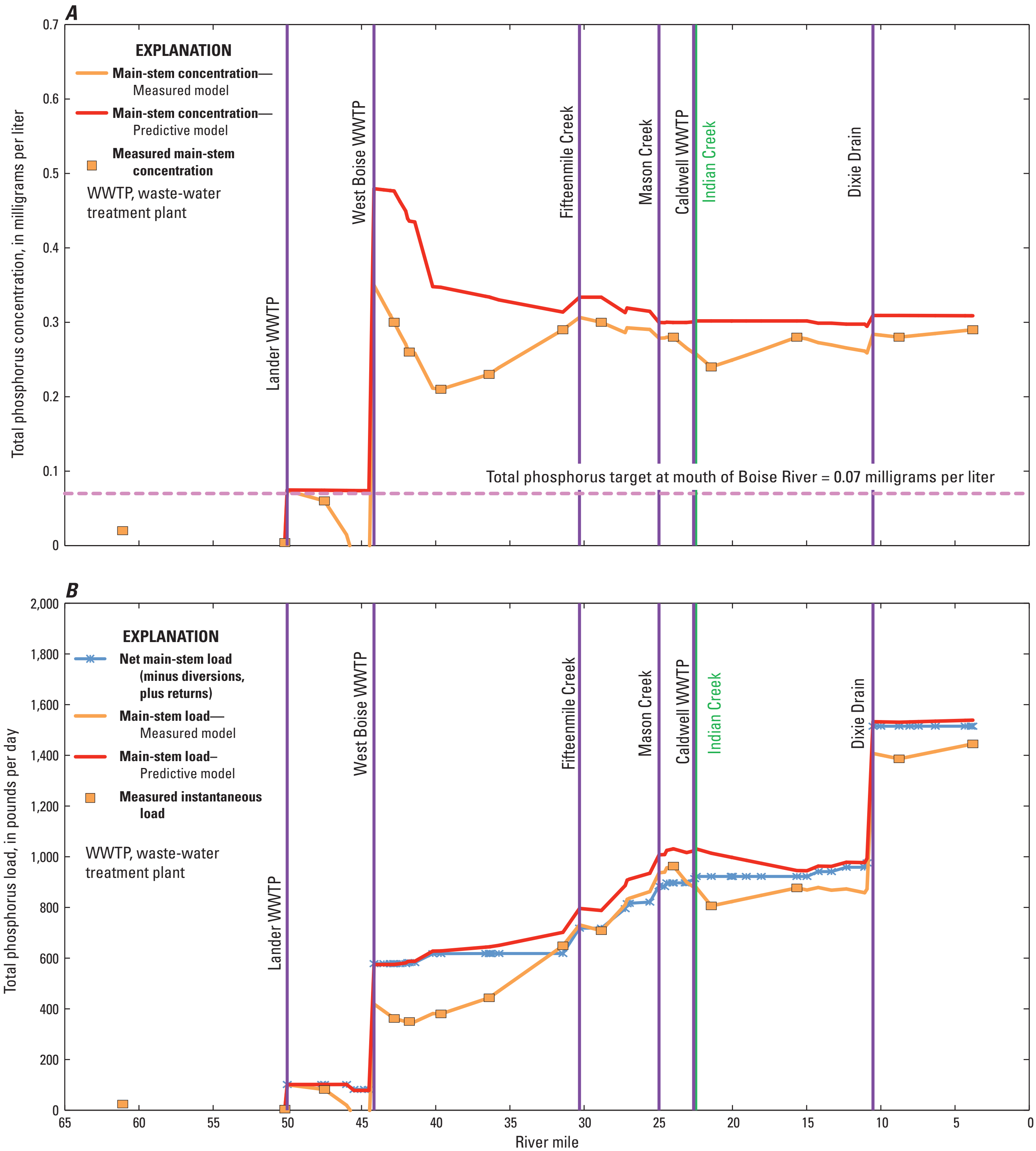


Figure 13. Modeled and measured main-stem (*A*) total phosphorus concentrations, and (*B*) total phosphorus loads, lower Boise River, southwest Idaho, during the week of October 29, 2012.

TP concentrations increased from background concentrations at Veterans Memorial Parkway (RM 50.2) to 0.07 mg/L downstream of the Lander WWTP (RM 50.0), and then to 0.35 mg/L downstream of the West Boise WWTP (RM 44.2). Without the mechanism responsible for removing 197 lb/d of TP (assumed in part to be phosphorus uptake by aquatic plants) between the Boise River at Glenwood Bridge (RM 47.5) and the south channel of the Boise River at Eagle Road (RM 42.8), the net surface-water TP load downstream of West Boise WWTP was 579 lb/d (fig. 13*B*). This suggests that, under the right conditions, aquatic plants readily consume bioavailable OP downstream of both WWTPs in Boise, where the phosphorus-limited river water becomes phosphorus enriched (fig. 9). Effluent from Middleton and Caldwell WWTPs had negligible effects on TP concentrations in the Boise River.

Tributaries containing point-source TP loads contributed 45 percent of the total TP load measured at Parma (RM 3.8) in October. Fifteenmile Creek (RM 30.3), which receives effluent from Meridian WWTP, contributed 100 lb/d of TP, and increased the main-stem TP concentration from 0.29 to 0.31 mg/L (figs. 13*A*, 13*B*). Indian Creek receives effluent from Nampa WWTP and likely would have affected the main-stem TP concentration at RM 22.4 had it not been diverted entirely to Riverside Canal during the synoptic sampling period in late October (fig. 2). Rather than discharging to the Boise River at RM 22.4, any water from Indian Creek that reached the Boise River flowed 12 mi downstream in Riverside Canal and discharged to Dixie Drain (RM 10.5) (fig. 1*A*). Based on historical measurements at the mouth in late October, Indian Creek discharges an average of 254 ft^3/s to the Boise River at a TP concentration of 0.51 mg/L, resulting in an average TP load of 655 lb/d. Dixie Drain receives discharge from Riverside Canal, and discharged 294 ft^3/s to the Boise River, almost double its historical average in late October. The combined average TP loading from Indian Creek and Dixie Drain historically was 940 lb/d when Indian Creek was allowed to follow its natural course to the Boise River in late October. In late October 2012, Dixie Drain contributed 539 lb/d of TP to the Boise River (table 7), suggesting that some loss of TP load occurred between the diversion of Indian Creek to Riverside Canal and the return of some Indian Creek water through Dixie Drain farther downriver (fig. 1*A*). Whether the loss was a result of conveyance of TP loads through groundwater or lateral drains and canals that ultimately discharge to the Snake River is not known. Any time lag between potential losses to shallow groundwater under this practice and those losses manifesting as gains in TP loads upstream of Parma also is not known.

Excluding Fifteenmile Creek, Indian Creek, and Dixie drain, which contained wastewater effluent in October 2012, tributaries that did not receive wastewater effluent contributed a total of 221 ft^3/s and a combined TP load of 233 lb/d—16 percent of the total surface-water TP load in the Boise River near Parma (RM 3.8) (table 7). Surface water from the north channel diluted main-stem TP concentrations from 0.30 to 0.26 mg/L at RM 41.8. Mill Slough (RM 27.2) and Mason Creek (RM 25.0) contributed a total flow of 137 ft^3/s, with TP concentrations of 0.20 and 0.18 mg/L, respectively; both diluted TP concentrations in the Boise River. Willow Creek (RM 27.0), Mason Slough (RM 25.6), Conway Gulch (RM 14.2), and two unnamed drains (RM 12.3 and 10.9) had negligible effects on modeled TP concentrations in the Boise River, especially in context with unmeasured gains and losses in TP loads indicative of biogeochemical phosphorus exchange. Though its effect on modeled TP concentrations also was negligible, Hartley Drain contributed 7.5 ft^3/s of surface water with a relatively high TP concentration of 0.36 mg/L (appendix 1).

Predictive Total Phosphorus Mass-Balance Model

Using estimated groundwater TP concentrations that increase from 0.01 mg/L at Veterans Memorial Parkway (RM 50.2) to a constant 0.25-mg/L between the Boise River at Middleton Road (RM 28.8) and the Boise River near Parma (RM 3.8) (table 3), the October predictive model accounts for 75 percent of the variability in measured main-stem TP concentrations (fig. 12). Although statistically significant, consistent overestimates of TP concentrations and loads in the October predictive model produce non-normal residuals when compared to measured data. Positive bias in the predictive model indicated that biogeochemical processes, which are not accounted for in the predictive model, likely had the overall effect of reducing main-stem TP concentrations in October 2012. Both the measured and predictive October models suggest that calculated streamflow gains between RM 50.2 and RM 42.8 were underestimated. Predictive model results provided more accurate estimates of main-stem TP concentrations and loads downstream of the Boise River near Middleton (RM 31.4) when calculated streamflow gains between RM 50.2 and 42.8 were adjusted upward using the discharge measurement uncertainty. Predictive model results verify that overestimated TP concentrations and loads downstream of RM 31.4 are not so much an indicator of prevalent phosphorus uptake in the lower part of the modeling reach as they are a result of underestimated streamflow gains in the upper part of the modeling reach.

March Model

The late-October and the early-March synoptic sampling periods took place during non-irrigation season. The March mass-balance model compared nonpoint sources of TP just before irrigation resumed to nonpoint sources of TP just after irrigation ended in late October. When irrigation deliveries and returns remain inactive, shallow groundwater levels decline as shallow groundwater discharges to tributaries and drains (Thomas and Dion, 1974; Fox and others, 2002).

Releases from Lucky Peak Dam (RM 64.0) in late winter are used to sustain flows of at least 250 ft^3/s at the Boise River near Middleton or released to prevent overfilling of Lucky Peak Reservoir during wet years. Synoptic sampling took place in early March to avoid the possibility of large releases from Lucky Peak Dam (RM 64.0) that would have prevented measurement of low-flow conditions at the end of non-irrigation season.

Discharge Balance

Higher confidence associated with streamflow gains that exceeded measurement uncertainty benefited the March model. Discharge balance in the March model resulted in a cumulative 174-ft^3/s gain from groundwater—21 percent of the discharge measured at the Boise River near Parma (RM 3.8) (fig. 10). Of a cumulative 174-ft^3/s gain in the March modeling reach, 149 ft^3/s or 87 percent occurred in subreaches where propagated measurement uncertainty was less than the modeled streamflow gain (table 6). Eighty-six percent of the 174-ft^3/s gain occurred downstream of the Boise River near Star (RM 36.4) (fig. 7).

The March synoptic event took place when water in tributaries and drains represents primarily groundwater discharge (Mullins, 1998). All mass-balance models treat returns and tributary inflows as surface water. If water in tributaries in March is assumed to represent groundwater discharge, 66 percent of the total discharge measured in the Boise River near Parma (RM 3.8) was groundwater. Twenty-nine percent of the total discharge at Parma originated from Lucky Peak Reservoir, and 6 percent represents effluent from WWTPs that discharge directly to the main stem.

Measured Total Phosphorus Mass-Balance Model

The measured mass-balance model, developed with sampling results from early March 2013, showed a cumulative streamflow gain of 174 ft^3/s and a cumulative TP load gain of 145 lb/d. Mass-balance accounting in all 13 subreaches suggested biogeochemical phosphorus uptake or release (table 6; figs. 9 and 14*B*). In six subreaches where mass-balance accounting indicated phosphorus release, the Boise River gained a total of 1,020 lb/d of TP load with a corresponding total gain of 98.9 ft^3/s from groundwater. In the seven reaches where mass-balance accounting indicated phosphorus uptake, 877 lb/d of TP load was lost with a 75.4-ft^3/s streamflow gain from groundwater (table 6; figs. 9 and 14*B*). Gains and losses in TP loads in specific subreaches were much larger than the cumulative net gain of 145 lb/d from unmeasured sources.

The two largest losses in TP loads occurred from the north and south channels at RM 41.8 to the confluence of the north and south channels at RM 39.7, where 318 lb/d were lost, and from the Boise River downstream of the Caldwell WWTP (RM 21.4) to the Boise River at Notus (RM 15.7), where 360 lb/d were lost (table 6). The TP concentration in the Boise River decreased from 0.57 to 0.28 mg/L between RM 41.8 and RM 39.7, and from 0.44 to 0.32 mg/L between RM 21.4 and RM 15.7 (fig. 14*A*).

Of the six subreaches indicating phosphorus release, two were downstream of WWTPs where phosphorus uptake occurred in the October sampling period (table 6, fig. 9). The subreach from Glenwood Bridge (RM 47.5) to the south channel at Eagle Road (RM 42.8) includes the point-source discharge from West Boise WWTP (RM 44.2). This subreach showed minimal streamflow gains in October and March, and was responsible for 197 lb/d of phosphorus loss in October in contrast to 182 lb/d of phosphorus gain in March. Apparent phosphorus uptake in October mitigated the effect of West Boise WWTP effluent on main-stem TP concentrations in October (figs. 13*A*, 13*B*), and apparent phosphorus release worsened the effect of West Boise WWTP effluent on main-stem TP concentrations in March (figs. 14*A*, 14*B*). A similar trend was observed downstream of the Caldwell WWTP (RM 22.6) (fig. 9). Between the Caldwell WWTP outfall (RM 22.6) and the Boise River below Caldwell WWTP (RM 21.4), the TP load in March increased by 150 lb/d and the TP concentration increased by 0.14 mg/L with a 1-ft^3/s gain from groundwater (figs. 14*A*, 14*B*). Large gains and losses in TP loads in different subreaches throughout the March modeling reach affected TP concentrations and loads on a subreach scale and could not have been solely the result of groundwater exchange. March TP load balance results indicate that algae and macrophyte growth and decay likely are considerable sinks and sources of phosphorus at varying locations in the Boise River at different times of year.

Total phosphorus concentrations in the March mass-balance model were higher overall than in models developed from either of the other synoptic sampling periods (fig. 14*A*). WWTPs discharging effluent directly to the Boise River increased main-stem TP concentrations and accounted for 629 lb/d or 56 percent of the TP load in the Boise River near Parma (RM 3.8). WWTPs for the cities of Meridian and Nampa contributed an additional 342 lb/d of TP to the Fivemile Creek (a tributary of Fifteenmile Creek) and Indian Creek for a total point-source TP load of 1,220 lb/d or 79 percent of the measured TP load at Parma (RM 3.8) (table 8). Indian Creek (RM 22.4) includes effluent from Nampa and Kuna WWTPs, and contributed 420 lb/d of TP in March. Fifteenmile Creek (RM 30.3) includes effluent from Meridian WWTP, and was not a source of TP in the main stem during the March synoptic sampling period because the 0.12-mg/L TP concentration was lower than the 0.31-mg/L median historical TP concentration measured in Fifteenmile Creek in late winter ($n = 11$).

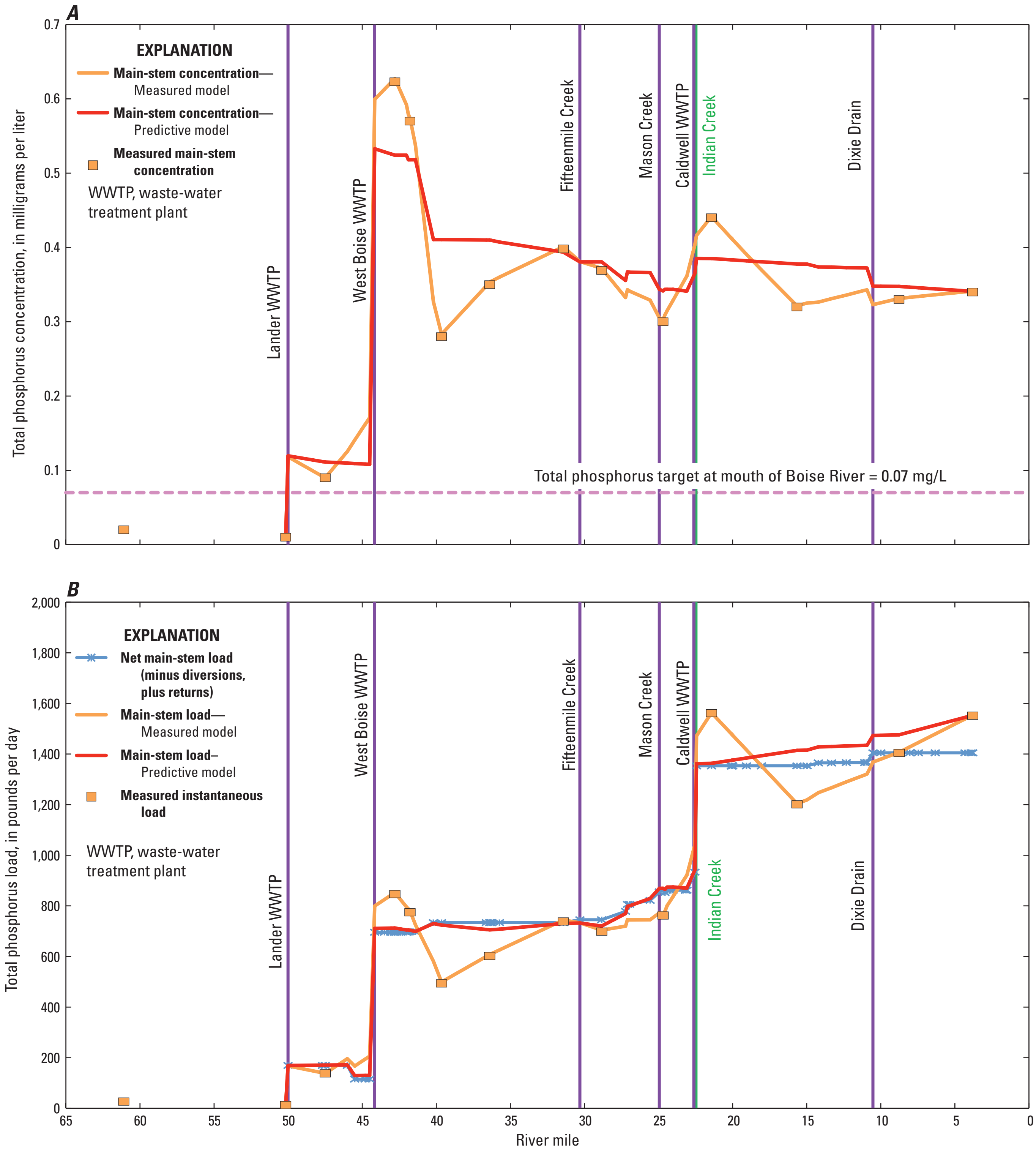


Figure 14. Modeled and measured main-stem (*A*) total phosphorus concentrations, and (*B*) total phosphorus loads, lower Boise River, southwestern Idaho, during the week of March 4, 2013.

Tributaries excluding Fifteenmile Creek (RM 30.3) and Indian Creek (RM 22.4) contributed 148 lb/d, or 10 percent of the modeled TP load in the Boise River near Parma in March. TP concentrations in Mason Slough (RM 25.6) and Hartley Drain (RM 24.4) were higher than the modeled TP concentration in the Boise River, but their effect on the main-stem TP concentration was negligible because they contributed a combined total discharge of less than 10 ft^3/s. Mill Slough (RM 27.2), Mason Creek (RM 25.0), Conway Gulch (RM 14.2), and Dixie Drain (RM 10.5) were the primary sources of surface water contributed by tributaries other than Indian Creek and Fifteenmile Creek, and each of them effectively diluted TP concentrations in the main stem (fig. 14*A*). Unmeasured phosphorus loads in the measured model contributed 145 lb/d or 9 percent of the modeled TP load at Parma. The measured model showed that cumulative gain in TP loads throughout the modeling reach could not be attributed solely to streamflow gains, suggesting that phosphorus released from decaying aquatic plants was a source of phosphorus in March.

Predictive Total Phosphorus Mass-Balance Model

Estimated groundwater concentrations in the March predictive model indicated that groundwater exchange was not as important as biogeochemical phosphorus exchange. Groundwater contributed 142 lb/d of TP in the predictive model, and unmeasured TP loads equaled 145 lb/d in the measured model (table 7). The March predictive TP mass-balance model explained 87 percent of the variability in main-stem TP sample results (fig. 12), but was unsuccessful in accounting for gains and losses in TP loads on a subreach scale. In subreaches where the predictive model underestimated TP concentrations and loads, release of phosphorus may have occurred. In subreaches where the predictive model overestimated TP concentrations and loads, phosphorus uptake may have occurred. “Groundwater” TP concentration estimates used in the predictive model during periods of minimal groundwater exchange generally are more aptly described as an estimation of the cumulative effect of biogeochemical processes.

The August model and groundwater monitoring results support an overall increase in groundwater TP concentrations moving downstream through the modeling reach, but groundwater concentrations used in the March predictive model may have been estimated high given March monitoring results from shallow piezometers. Fox and others (2002) also reported steady decreases in shallow groundwater TP concentrations throughout non-irrigation season at Mason Creek. Because streamflow gains and losses were small on a subreach scale, lowering estimated groundwater concentrations from a constant 0.25 mg/L to a lower constant TP concentration in the modeling reach downstream of Middleton Road (RM 28.8) had little effect on predicted main-stem TP loads and concentrations in the October and the March models. The calculated overall TP concentration of unmeasured sources of phosphorus was 0.22 mg/L in August, negative in October, and 0.15 mg/L in March (table 7). Although biogeochemical processes most likely confounded predictive model results in October and March, residuals in estimated TP concentrations from the March model were unbiased. Paired with an overall unmeasured TP concentration of 0.15 mg/L (table 7), March predictive model results suggest that phosphorus concentrations in groundwater may decrease between August and March. The calculated overall TP concentration of tributaries in October (0.16 mg/L) and March (0.12 mg/L) represented a better estimate for groundwater concentrations during non-irrigation season because tributaries act as drains for shallow groundwater during non-irrigation season (table 7).

Sources of Phosphorus

Phosphorus export within watersheds is influenced by land use. Particulate phosphorus commonly is associated with surface-water runoff from agricultural land, whereas point sources in urban and industrial land-use areas tend to discharge OP (Jarvie and others, 2006). Particulate phosphorus may play a role in TP loading in the lower Boise River watershed, but it must transition to the bioavailable form (OP) to support elevated levels of algae growth. Manure and agricultural fertilizers also can contribute OP in surface-water runoff and groundwater discharge to streams and drains (Sharpley and others, 1996; Domagalski and Johnson, 2011), especially in streams and drains with a large base-flow component (Tesoriero and others, 2009).

Nonpoint Sources

Water-quality results for TP, OP, TDP, and suspended sediment were useful in evaluating agricultural sources of phosphorus from drains and tributaries. TDP results indicate that nearly all the dissolved phosphorus in the Boise River is OP. The relations of suspended sediment concentrations and river miles to OP-to-TP ratios (OP:TP) (figs. 15*A*, 15*B*) were determined using the Spearman’s rho correlation coefficient (Helsel and Hirsch, 2002). The relation between river mile and OP:TP was statistically significant (Spearman’s rho equal to -0.41, $p\text{-value} = 0.11$) for samples collected from the Boise River during the August synoptic event, but not for the samples collected during the October or March synoptic events. A statistically significant negative correlation between OP:TP and suspended sediment concentrations (Spearman’s rho equal to -0.53, $p = 0.04$) also was present for the August samples, but was absent in October and March.

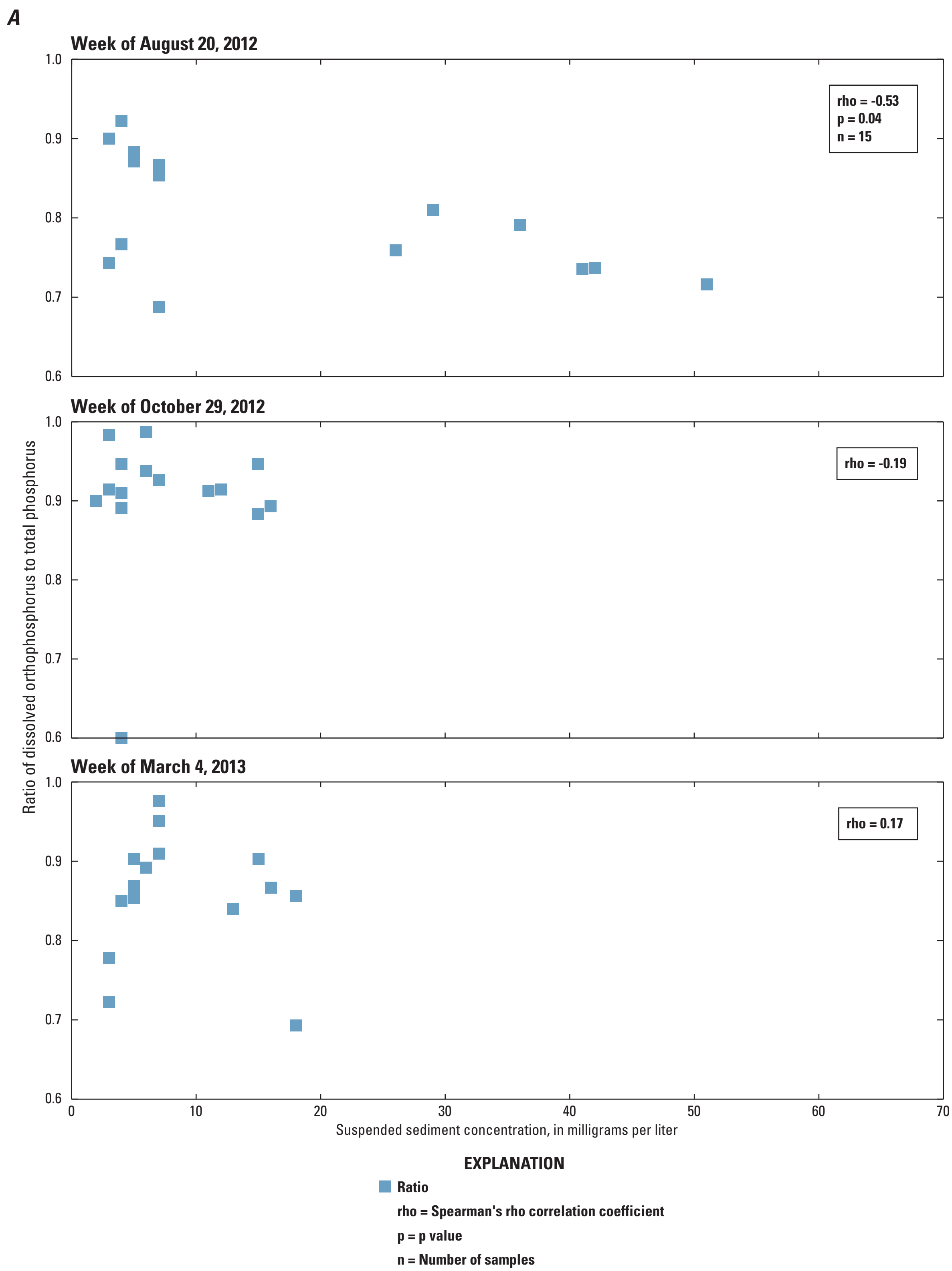


Figure 15. Dissolved and total phosphorus ratios compared to (*A*) suspended sediment concentration, and (*B*) river mile, lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

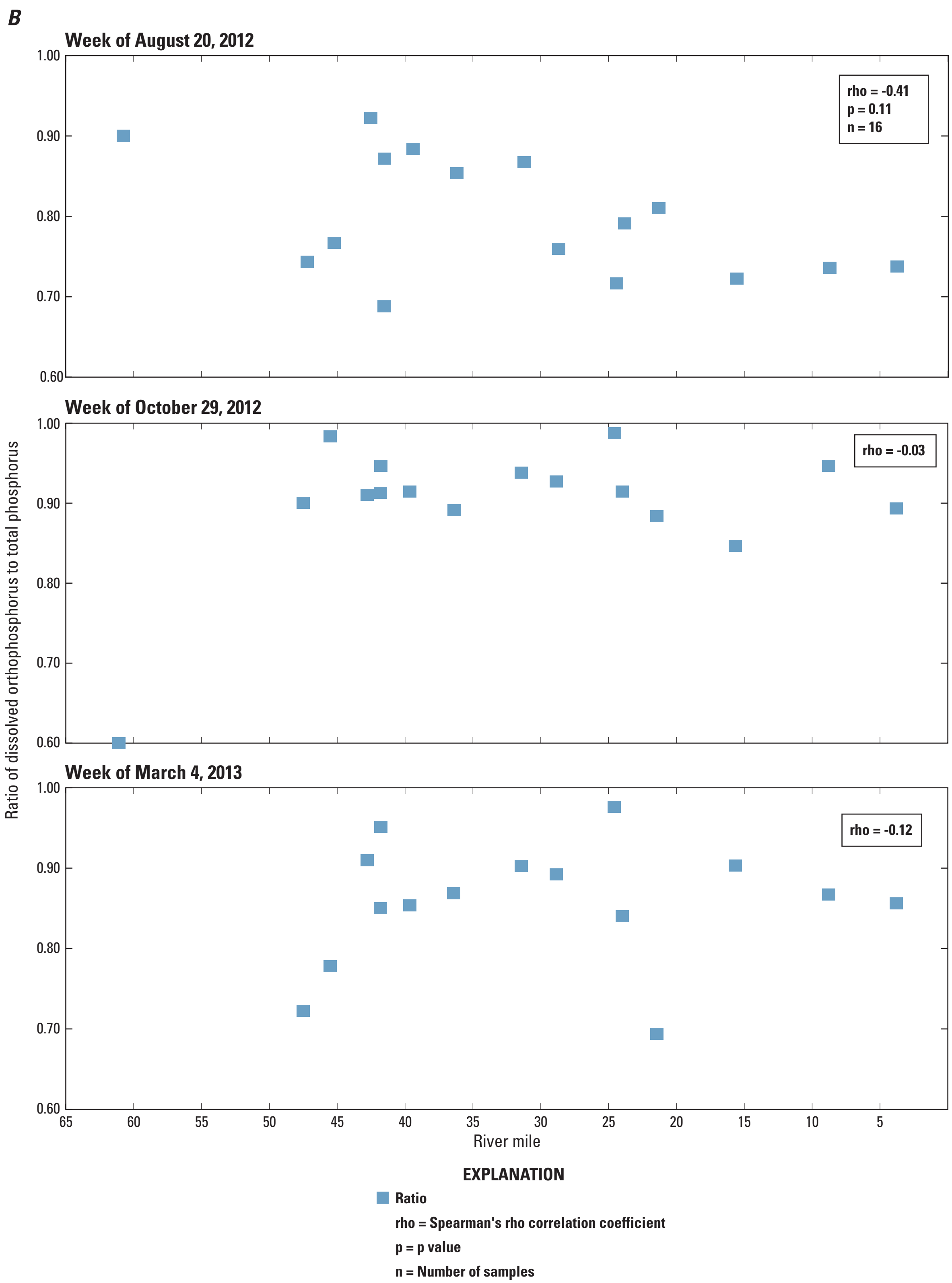


Figure 15.—Continued

The evaluation of OP:TP relative to river mile and suspended sediment concentrations in the Boise River suggests that particulate phosphorus is positively correlated with suspended sediment in the downstream direction during irrigation season and that agricultural sources of particulate phosphorus constitute progressively more of the phosphorus load in a downstream direction.

Agricultural runoff also can contain OP (Sharpley and others, 2002). Monitoring in the Mason Creek watershed during 2000, 2001, 2008, 2011, and 2012 has provided a comprehensive dataset with which to test assumptions about agricultural runoff in the lower Boise River watershed. A study in 2001 showed that soil phosphorus concentrations in soil less than 6 in. deep averaged 14 mg/kg in two locations along Mason Creek (Fox and others, 2002). A study by Vadas and others (2005) indicated that OP runoff in cropped fields with soil phosphorus concentrations of 14 mg/kg, as analyzed in the 2001 study (Fox and others, 2002), could yield concentrations of 0.11–0.67 mg/L of OP in surface runoff. The OP concentration in Mason Creek was 0.65 mg/L during a runoff period in January 2012, when agricultural fields were fallow (uncropped), suggesting that the low end of estimated OP concentrations in runoff from cropped fields in production is a good estimate for conditions near the mouth of Mason Creek (RM 25.0).

Based on monitoring results from Mason Creek near the mouth (RM 25.0) and the Boise River near Parma (RM 3.8), runoff from fallow agricultural fields during winter storm events might provide a large phosphorus load to agricultural drains and the lower Boise River. Historical data from the Boise River near Parma (RM 3.8) confirms that periods of winter rain can generate daily TP loads constituting at least 10 percent of the total annual TP load during a period of several days. Since 1994, the total annual TP load at Parma has been estimated to average between 300 and 400 tons/yr (Donato and MacCoy, 2005; Wood and Etheridge, 2011). In January 1971, winter rain resulted in the highest TP concentration sampled at Parma. Discharge in the Boise river reached 4,400 ft^3/s, with a TP concentration of 3.9 mg/L, resulting in a TP load of 46 tons/d. A similar period of rain in February 1979 resulted in a TP load of 16 tons/d.

With the exception of Dry Creek (RM 42.5), all the tributaries and drains sampled as part of this study are perennial. Tributaries and drains contain base flow and surface runoff from agricultural land during irrigation season and storm events, but otherwise maintain perennial flow solely from groundwater discharge (Bureau of Reclamation and Idaho Department of Water Resources, 2008). Diversions and returns occur below WWTP effluent discharges in Fivemile Creek (upstream of its confluence with Tenmile Creek to form Fifteenmile Creek at RM 30.3, fig. 2) and Indian Creek (RM 22.4). However, some basic calculations were completed after subtracting point-source TP loads and discharges from Fifteenmile and Indian Creeks. The resulting overall mean TP concentration in all tributaries in the lower Boise River watershed was 0.18 mg/L during the week of August 20, 2012, 0.16 mg/L during the week of October 29, 2012, and 0.12 mg/L during the week of March 4, 2013. Without downward percolation of irrigation water through phosphorus-amended soil, mass-balance models showed that TP in agricultural drains (and groundwater discharge) steadily decreased during non-irrigation season. Without the addition of relatively dilute TP concentrations in agricultural drains and tributaries during non-irrigation season, main-stem TP concentrations likely would be higher.

Calculations completed using March mass-balance model results show that nonpoint-source TP load reductions during irrigation season may reduce the overall mean concentration of TP in tributaries. Lower TP concentrations in major tributaries during irrigation season, including Fifteenmile Creek (RM 30.3), Mason Creek (RM 25.0), Indian Creek (RM 22.4), and Dixie Drain (RM 10.5), may result in dilution of TP concentrations in the Boise River as long as collective tributary discharge is maintained. Point-source load reductions in tributaries where point source discharges occur also would reduce the overall mean concentration of TP in tributaries.

Point Sources

Monitoring results from each synoptic sampling period indicate that TP from WWTPs dominated phosphorus loading within the watershed (tables 7 and 8). In particular, TP loads from Lander, West Boise, and Nampa WWTPs constituted between 88 and 90 percent of the total point-source TP loads measured from six municipal WWTP permittees during the three sampling periods (table 8). Despite agricultural phosphorus loading during irrigation season, some of the phosphorus in tributaries, drains, and canals likely originated from point sources that were diverted to supply irrigation water. Phyllis Canal, Indian Creek, and Riverside Canal exemplify water bodies that are used to convey point-source TP loads to irrigated land. The water-quality sample from the south channel of the Boise River immediately upstream of the Phyllis Canal diversion contained 0.18 mg/L OP and 0.21 mg/L TP in August. Phyllis Canal is outside most agricultural areas and downstream of Lander and West Boise WWTPs, indicating that non-agricultural sources of OP probably account for most of the OP in Phyllis Canal. The Nampa WWTP discharged 504 lb/d of TP to Indian Creek during the August synoptic sampling period. Riverside Canal diverts and redistributes most of the discharge from Indian Creek to irrigated land throughout the lower Boise River watershed downstream of Caldwell during irrigation season. Mass-balance models do not account for the fate of any particular TP load, but the redistribution of point-source loads in Phyllis Canal and Indian Creek to irrigated lands downstream may act as a TP source to shallow groundwater, return flows, and ultimately the Boise River.

During non-irrigation season, point-source TP loads are more easily tracked through the lower Boise River watershed because diversions and canals are inactive. Irrespective of TP loads gained and lost to apparent biogeochemical exchange, point sources contributed more than 70 percent of the TP load measured at Parma (RM 3.8) in October and March (table 8). Point-source TP loads exceeded the TP load at Parma in August. Mass-balance models showed that point-source loads may later materialize as nonpoint source loads from decaying aquatic plants immediately downstream of WWTP discharges (fig. 9). Empirical measurements of phosphorus cycling through aquatic plants and bed sediment would provide more insight into indirect TP loading from aquatic environments immediately downstream of WWTPs. Differentiating between point-source TP loads and nonpoint-source TP loads downstream of Fifteenmile Creek (RM 30.3) also is difficult without empirical data regarding soil phosphorus levels, geochemistry in the unsaturated zone beneath irrigated lands, and sediment runoff from agricultural fields. Environmental tracers may provide the best indication of whether OP originated from agricultural land use or urban land use.

Unmeasured Sources

Mass-balance models, especially in March, indicated that aquatic plants, bed sediment, or both likely exist as sources and sinks for phosphorus along the Boise River. The October model showed an overall unmeasured loss of TP loads with an overall streamflow gain. The loss of TP load likely was the result of phosphorus uptake by aquatic plants. The measured and the predictive March models showed that the overall gain in TP load in March likely was the result of phosphorus release from decaying aquatic plants. Because municipal WWTPs discharge phosphorus predominantly in the form of OP, nuisance algal growth occurs more readily downstream of wastewater effluent inputs (Jarvie and others, 2006). Periphyton monitoring results from the Boise River at Glenwood Bridge (RM 47.5) support this finding. In controlled experiments reported within a small stream, as much as 70 percent of OP released from a WWTP was retained in aquatic plants and 40 percent of OP consumed by aquatic plants was later released (Stutter and others, 2010). TP mass-balance model results for the lower Boise River showed that OP sequestered in aquatic plants downstream of point sources later can become a nonpoint source of phosphorus (fig. 9).

Phosphorus in shallow groundwater acts as a year-round source in the lower Boise River. The fate of point sources compared to nonpoint sources of TP in irrigation water that percolates downward into shallow groundwater is poorly understood. Many small, unmeasured diversions and returns active during irrigation season, and apparent phosphorus uptake and release during non-irrigation season, confounded groundwater TP load estimates in mass-balance models. The 0.25-mg/L estimated groundwater TP concentration used in predictive-model subreaches that gained the most groundwater was similar to the overall 0.22-mg/L TP concentration derived from August measured-model results (table 7). Results from historical piezometer monitoring (MacCoy, 2004), results from Simplot shallow monitoring wells near the Boise River (Idaho Department of Environmental Quality, 2013b), and results from shallow monitoring wells near Mason Creek (Fox and others, 2002) also suggest that estimated TP concentrations in groundwater may be accurate in the August predictive model. Excluding the base-flow component present in agricultural tributaries and drains, but including small unmeasured diversions and returns, TP from groundwater constituted 57 percent of the measured load at Parma during the week of August 20, 2012.

Unlike the August mass-balance model, the October and March mass-balance models suggested that substantial biogeochemical phosphorus exchange may have occurred in the Boise River. Because tributaries and drains represent shallow groundwater discharge during non-irrigation season, computed TP concentrations in tributaries that do not contain WWTP loads are a good measure of shallow groundwater TP concentrations in non-irrigation season. These concentrations were estimated at 0.16 and 0.12 mg/L in October and March, respectively (table 7). A theoretical groundwater TP load was calculated using 91.4 ft^3/s with a TP concentration of 0.16 mg/L in October, and 174 ft^3/s with a TP concentration of 0.12 mg/L in March. Theoretical groundwater TP loads and TP loads from agricultural drains and tributaries assumed to represent groundwater discharge contributed an estimated 37 percent of the measured load at Parma (RM 3.8) during the week of October 29, 2012, and 22 percent of the measured load at Parma during the week of and March 4, 2013. Because shallow groundwater monitoring results can have wide spatial variability (Fox and others, 2002; MacCoy, 2004, Idaho Department of Environmental Quality, 2013b) and because groundwater exchange with the lower Boise River has been quantified on a watershed scale (Thomas and Dion, 1974; Berenbrock, 1999; Petrich, 2004; Bureau of Reclamation and Idaho Department of Water Resources, 2008), similarly large-scale assessments or TP loads in groundwater likely are the best means of understanding TP loading from groundwater in the lower Boise River watershed.

Sensitivity Analysis

The August predictive model is the best tool available to assess sensitivity to point and nonpoint sources of phosphorus in the lower Boise River. With phosphorus uptake and release evident in October and March, the predictive model may not provide realistic subreach scale results. Estimates of groundwater concentrations downstream of Middleton Road (RM 28.8) could be adjusted to those estimated in agricultural drains during October and March (table 7) as a baseline (no change) scenario in October and March mass-balance models. Nevertheless, predictive models in October and March will overestimate or underestimate TP concentrations in subreaches where biogeochemical phosphorus exchange likely occurs. Predictive models cannot account for load reductions in irrigation source water if and when that water returns to the lower Boise River at some point farther downstream. The spreadsheet mass-balance models are available for use as an attachment to this report (appendix 1).

Results of sensitivity analyses are summarized in table 9. TP input concentrations are shown (in milligrams per liter) for scenarios 1 through 12, and results for each scenario are summarized for each predictive model (August, October, and March). Scenario results at three locations—Phyllis Canal (RM 41.8), the Boise River near Parma (RM 3.8), and the Snake River at Nyssa—are also shown in table 9. The Snake River between Adrian and Nyssa, Oregon, is outside the modeling reach, but model results were used to estimate effects of Boise River TP loads on the Snake River in tables 7 and 9 and appendix 1. Although the sensitivity analyses provide some information about effects of TP source reductions on TP concentrations in the Boise River and the Snake River, they are not indicative of a system-wide response to reductions specific to point sources, nonpoint sources, phosphorus release or uptake, or groundwater. Nonpoint-source TP loads in surface water are most relevant during irrigation season, and the August model shows the most sensitivity to nonpoint source load reduction in tributaries and drains (table 9). Because nonpoint sources may contain TP loads originating from point sources, and because TP concentrations in groundwater mimic main-stem concentrations, the August model requires TP reductions in groundwater, nonpoint, and point sources to achieve the 0.07-mg/L TP target at Parma (RM 3.8). Scenarios 5 and 9 indicate that the August model is sensitive to point-source load reductions resulting in an effluent TP concentration of 0.30 mg/L, and scenarios 6 and 10 indicate that the August model is not sensitive to point-source load reductions resulting in effluent at a TP concentration of 0.07 mg/L. Although scenarios 8 and 12 are the only two that meet the 0.07-mg/L TP target at the mouth of the Boise River, scenarios 5 and 9 likely indicate the best expected short-term outcome for TP load reductions from all source areas in the lower Boise River watershed during irrigation season (table 9).

In October and March, the model is equally sensitive to nonpoint and point-source reductions. However, any reductions achieved during irrigation season will likely reduce TP concentrations in groundwater and nonpoint source surface-water discharge (representative of groundwater discharge) during non-irrigation season. Because low-flow conditions persist in the upper half of the modeling reach during non-irrigation season, releases from Lucky Peak Dam (RM 64.0) are not available to dilute point-source contributions. Coupled with phosphorus uptake, not shown in the predictive model, scenarios 7 and 8 might represent typical conditions in October when point-source reductions are implemented during irrigation season (table 9). Model sensitivity analysis in October also shows little difference in percent load reductions at Parma with point-source effluent at 0.30 mg/L compared with 0.07 mg/L of TP. Year-round load reductions from point sources that discharge to Indian Creek may result in decreased TP concentrations in groundwater and agricultural drains between Caldwell (RM 24.0) and Parma (RM 3.8), and those decreases are not accounted for in the predictive model.

In March, phosphorus release from decaying aquatic plants was evident, and the resulting gain in TP load is not accounted for in the predictive model. Phosphorus limitation is not as likely to occur downstream of WWTPs discharging effluent year round at 0.30 mg/L. Aquatic plants may cycle nutrients on varying time scales, acting at times as a phosphorus sink and at other times as a phosphorus source. All three models were sensitive to specific source reductions relative to existing conditions, but were not as sensitive to incremental step decreases between 0.07 and 0.30 mg/L for point sources, 0.07 and 0.15 mg/L for groundwater, and 0.07 and 0.10 mg/L for nonpoint source surface water. The predictive model used in sensitivity analyses cannot estimate changes in TP loads resulting from changes in biogeochemical processes. Biogeochemical processes may react to load reductions at varying degrees in different areas of the Boise River. Biogeochemical processes also will change reliably with the occurrence of high- and low-flow water years.

Table 9. Summary of sensitivity analysis results for predictive total phosphorus mass-balance model scenarios, lower Boise River, southwestern Idaho, August and October 2012, and March 2013.

[Shading indicates no change from measured conditions (red); intermediate goal for source reduction (blue); long-term goal for source reduction (green). **Bold** highlighted values indicate scenarios where the total phosphorus target is achieved in the Boise River near Parma, Idaho. **Abbreviations:** NC, no change; RM, river mile; TP, total phosphorus; mg/L, milligram per liter; lb/d, pound per day; WWTP, wastewater treatment plant]

		Total phosphorus concentration inputs for model simulations by scenario No. (mg/L)											
		1	2	3	4	5	6	7	8	9	10	11	12
Point sources		0.30	0.07	NC	NC	0.30	0.30	0.30	0.30	0.07	0.07	0.07	0.07
Nonpoint sources		NC	NC	0.10	0.07	0.10	0.07	0.10	0.07	0.10	0.07	0.10	0.07
Unmeasured discharge[1] downstream of RM 28.8		NC	NC	NC	NC	0.15	0.15	0.07	0.07	0.15	0.15	0.07	0.07
August scenarios[2]	**NC**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
TP concentration upstream of Phyllis Canal (RM 41.8) (mg/L)	0.22	0.04	0.03	0.22	0.22	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.02
TP load (lb/d)	776	136	89	776	776	125	125	116	116	79	79	70	70
Percent load reduction		82	89	0	0	84	84	85	85	90	90	91	91
TP concentration at Parma (RM 3.8) (mg/L)	0.3	0.27	0.27	0.17	0.15	0.11	0.10	0.09	**0.07**	0.11	0.09	0.08	**0.07**
TP load	1,010	919	909	576	516	381	320	264	234	370	310	284	224
Percent load reduction		9	10	43	49	62	68	74	77	63	69	72	78
TP concentration at Snake River at Nyssa (mg/L)	0.08	0.08	0.08	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
TP load (lb/d)	2,800	2,720	2,710	2,370	2,310	2,180	2,120	2,090	2,030	2,170	2,110	2,080	2,020
Percent load reduction		3	3	15	18	22	24	25	28	23	25	26	28
October scenarios[2]	**NC**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
TP concentration upstream of Phyllis Canal (RM 41.8) (mg/L)	0.44	0.06	0.02	0.44	0.43	0.06	0.06	0.05	0.05	0.02	0.02	0.02	0.02
TP load (lb/d)	588	79	32	587	586	74	74	72	71	27	26	25	24
Percent load reduction		87	95	0	0	87	87	88	88	95	96	96	96
TP concentration at Parma (RM 3.8) (mg/L)	0.31	0.21	0.2	0.2	0.18	0.09	**0.07**	0.08	**0.07**	0.08	**0.06**	**0.07**	**0.05**
TP load	1,540	1,060	1,010	980	898	451	368	406	323	394	311	350	267
Percent load reduction		31	34	36	42	71	76	74	79	74	80	77	83
TP concentration at Snake River at Nyssa (mg/L)	0.06	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03
TP load (lb/d)	2,900	2,420	2,360	2,340	2,250	1,800	1,710	1,750	1,670	1,740	1,650	1,690	1,610
Percent load reduction		17	19	19	22	38	41	40	42	40	43	42	44
March scenarios[2]	**NC**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
TP concentration upstream of Phyllis Canal (RM 41.8) (mg/L)	0.53	0.05	0.02	0.53	0.53	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02
TP load (lb/d)	720	74	27	720	720	74	74	74	74	27	27	27	27
Percent load reduction		90	96	0	0	90	90	90	90	96	96	96	96
TP concentration at Parma (RM 3.8) (mg/L)	0.35	0.19	0.18	0.27	0.25	0.09	0.08	0.08	**0.06**	0.08	**0.07**	**0.06**	**0.05**
TP load	1,590	864	807	1,220	1,160	416	356	351	291	359	299	294	234
Percent load reduction		46	49	23	27	74	78	78	82	77	81	82	85
TP concentration at Snake River at Nyssa (mg/L)	0.1	0.08	0.08	0.09	0.09	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
TP load (lb/d)	4,310	3,580	3,520	3,940	3,880	3,130	3,070	3,070	3,010	3,070	3,010	3,010	2,950
Percent load reduction		17	18	9	10	27	29	29	30	29	30	30	32

[1]Unmeasured discharge represents streamflow gains from or losses to groundwater and also may represent small unmeasured diversions or returns.

[2]If the TP measured concentration in a specific tributary or drain was less than that prescribed in a scenario, the TP concentration remained unchanged in that tributary or drain. Diversions and returns occur between the Nampa WWTP and the mouth of Indian Creek and between the Meridian WWTP and the mouth of Fifteenmile Creek. Therefore, no changes to the Nampa and Meridian WWTPs were applied and Indian and Fifteenmile Creeks were treated as "nonpoint sources."

Areas of Further Study

Phosphorus loading to the Boise River from nonpoint sources is evident, but is not easily quantified. Geochemical properties of unsaturated and saturated zones beneath agricultural land play an important role in subsurface phosphorus transport. More comprehensive data on phosphorus application to agricultural land and soil phosphorus concentrations would be helpful to determine the amount of TP loading directly attributable to agricultural activities. Phosphorus movement through the subsurface has been determined to occur rapidly when irrigation water is applied over soil in an unsaturated zone that is already saturated with respect to sorption potential of orthophosphorus as phosphorus (OP). Agricultural nutrient runoff models also may be useful for quantifying phosphorus loading from nonpoint sources. Surrogates for TP and OP developed using continuous turbidity and discharge could provide useful information for characterizing the spatial and temporal loading of phosphorus from tributaries and in the Boise River.

Phosphorus uptake and release due to biogeochemical processes has been shown to occur, but also is poorly understood in the lower Boise River. A controlled study in the Boise River downstream of a point source could provide insight into phosphorus cycling in the Boise River and the timing of uptake versus release. Phosphorus retention and uptake in an aquatic ecosystem can be measured but has not been studied in the lower Boise River. Studies of gross primary production, temperature, light availability, dissolved oxygen, turbidity, and relative fluorescence would be beneficial in understanding the influence of biogeochemical processes on phosphorus cycling in the Boise River.

Larger-scale assessments of groundwater exchange with the lower Boise River and its tributaries similar to those completed in Mason Creek would be helpful. A previous study determined that shallow groundwater is primarily irrigation water applied during the growing season. Irrigation water that has percolated downward to shallow groundwater is discharged to agricultural drains and subsequently to the Boise River. Environmental tracers have proven useful in sourcing groundwater recharged within 10 years. Tracers added to irrigation water also may be helpful in determining percolation rates and recharge from nonpoint sources to drains and tributaries.

Use of irrigation water with OP originally discharged to the Boise River and tributaries from wastewater treatment plants is unavoidable, but the fate of point-source OP as it moves through the vast network of agricultural drains, canals, laterals, crops, and soils in the lower Boise River watershed is difficult to determine. Use of boron, present in detergents, as a tracer of effluent discharge has been documented in 54 agricultural drainages in the United Kingdom. Analysis of boron in water-quality samples collected as part of ongoing monitoring may help to identify water discharged from WWTPs. Analysis of isotopes of oxygen bound in phosphate molecules also may be helpful in sourcing water TP in the Boise River.

Summary

Mass-balance models based on results from synoptic sampling were useful in assessing groundwater and surface-water exchange and total phosphorus (TP) loads in the lower Boise River at three distinct times of the year. During the week of August 20, 2012, cumulative unmeasured discharge (assumed to represent groundwater exchange) in the modeling reach (river miles [RMs] 50.2–3.8) represented 78 percent of the discharge in the Boise River near Parma (RM 3.8). During the weeks of October 29, 2012, and March 4, 2013, groundwater discharge to the Boise River accounted for only 9.9 and 21 percent of the discharge measured in the Boise River near Parma, respectively. However, groundwater discharge to agricultural drains and tributaries to the Boise River during non-irrigation season accounted for an additional 59 percent of the total discharge near Parma in October, and an additional 45 percent of the total discharge at Parma in March. TP loads in groundwater constituted 57 percent of the TP load at Parma in August. Excluding WWTP loads, tributaries and drains sustained by groundwater discharge accounted for 31 percent of the load at Parma in October, and 15 percent of the load at Parma in March. Unmeasured discharge, assumed to represent streamflow gains and losses, was not sufficient to explain all the unmeasured gains or losses in TP loads in October and March, but correlated well with streamflow gains and unmeasured gains in TP loads in August. Estimated groundwater TP concentrations used in the August predictive model explained 97 percent of variability in measured TP loads used to calibrate the August measured model. However, estimated groundwater TP concentrations were not as useful at describing measured variability in TP loads in October and March, when biogeochemical processes confounded predictive model estimates. Periphyton uptake of phosphorus may have accounted for the unmeasured loss of TP loads in October, whereas phosphorus release from decaying aquatic plants may have accounted for unmeasured gains of TP loads in March.

Point-source loads may contribute to nonpoint source loads during irrigation season because water for irrigation is diverted from the Boise River and tributaries downstream of point-source discharges and subsequently returned as groundwater, irrigation return flow, or both. It is not known whether TP from point sources in irrigation water is taken up by crops or adsorbed to unsaturated soil. Based on TP sample results from the Boise River at Diversion Dam (RM 61.1) and the Boise River at Veterans Memorial Parkway (RM 50.2), diversions upstream of Lander wastewater treatment plant (RM 50.0) diverted between 200 and 250 pounds per day of TP and 3,100 cubic feet per second of streamflow in large canals upstream of the modeling reach including New York, Ridenbaugh, Settler's, and Farmers Union Canals. The first major canal downstream of point source discharges in the modeling reach (RMs 50.2–3.8) in the city of Boise is Phyllis Canal (RM 41.4), and it diverted more than 300 pounds per day of TP during the August synoptic event. Overall, diversions downstream of point sources and nonpoint sources in the modeling reach diverted 1,890 pounds per day of TP during the August synoptic event. During August, total point source discharges of TP exceeded the TP load measured at the Boise River near Parma. The phosphorus deficit in August may be from crop uptake or infiltration of irrigation water into the unsaturated zone. Even during non-irrigation season in October and March, data suggested that more than 70 percent of the TP loads measured in the Boise River near Parma are attributable to point sources.

During the August synoptic event, more than 500 pounds per day of TP was discharged to Indian Creek from the Nampa wastewater treatment plant. Most of the TP load was diverted from Mason (RM 25.0) and Indian Creeks (RM 22.4) to Riverside Canal, where it subsequently was used for irrigation. Dixie Drain (RM 10.5), which receives water from the Riverside Canal, would be an ideal location to evaluate the effect of TP load reduction from point and nonpoint sources in the downstream end of the lower Boise River watershed. Indian Creek, Riverside Canal, and Dixie Drain each represent an opportunity for TP source management that could induce system-wide reductions in TP concentrations downstream of Caldwell (RM 24.0). Mason Creek (RM 25.0), Fifteenmile Creek (RM 30.3), and the quality of water in Phyllis Canal (RM 41.4) also represent opportunities for managing TP that could reduce concentrations in the Boise River and tributaries upstream of Caldwell.

Sensitivity analysis of the predictive model results indicated that load reductions from point and nonpoint sources were necessary to achieve a TP target concentration of 0.07 milligram per liter (mg/L) at the mouth of the Boise River. The models were more sensitive to intermediate goals for TP load reductions. Treating wastewater effluent to achieve a TP concentration of 0.07 mg/L did not substantially reduce TP concentrations compared to treating wastewater effluent to achieve a TP concentration of 0.30 mg/L. Scenarios in which TP concentrations in nonpoint source tributaries were held at either 0.10 or 0.07 mg/L also did not show large differences in percent load reduction at the mouth of the Boise River. Scenarios in which TP concentrations in unmeasured discharge (groundwater) were set to 0.07 mg/L in August showed an additional 12 percent load reduction as compared to unmeasured discharge TP concentrations set to 0.15 mg/L, but the October and March models were not sensitive to reductions in groundwater TP concentrations to less than 0.15 mg/L.

Mass-balance models indicate that point sources contribute to TP loads in irrigation water, and ultimately to the TP load attributed to nonpoint sources. Data from Mason Creek also show that implementation of agricultural best management practices may be helpful to reduce nonpoint source loads during irrigation season and storm events. Use of the predictive mass-balance model to simulate outcomes for specific management scenarios assumes that arbitrary changes in TP concentrations from point and nonpoint sources have no effect on biogeochemical processes in the modeling reach. Simulations also assume that input conditions could represent real-world conditions.

Mass-balance models assume conservative behavior to account for changes in water-quality constituents and stream discharge. The mass-balance models also assume that phosphorus is either delivered from upstream sources, removed by losses to groundwater and (or) diversions, or added by groundwater and (or) returns. The models do not account for biogeochemical processes that may result in the uptake or release of phosphorus. However, the models strongly indicate segments in the Boise River where uptake and (or) release of phosphorus may be occurring.

References Cited

American Society for Testing and Materials, 2002, Standard test methods for determining sediment concentration in water samples, method #ASTM D3977-97: West Conshohocken, Penn., American Society for Testing and Materials, accessed October 21, 2013, at www.astm.org.

Baker, Steve, 1993, Ground-water conditions in the area northeast of Kuna, west-central Ada County, Idaho: Boise, Idaho Department of Water Resources, 15 p.

Berenbrock, Charles, 1999, Streamflow gains and losses in the lower Boise River basin, Idaho, 1996–97: U.S. Geological Survey Water-Resources Investigations Report 99–4105, 25 p.

Bureau of Reclamation, 2013, Water year report format: Bureau of Reclamation Pacific Northwest Region Web site, accessed September 18, 2013, at http://www.usbr.gov/pn/hydromet/yearrpt.html.

Bureau of Reclamation and Idaho Department of Water Resources, 2008, A distributed parameter water budget data base for the lower Boise Valley: Bureau of Reclamation and Idaho Department of Water Resources, 110 p.

Busenberg, Eurybiades, Plummer, L.N., Bartholomay, R.C., and Wayland, J.E., 1999, Chlorofluorocarbons, sulfur hexafluoride, and dissolved permanent gases in ground water from selected sites in and near the Idaho National Engineering and Environmental Laboratory, Idaho, 1994–97: U.S. Geological Survey Open-File Report 98-274, 72 p.

Campbell, Kirk, 2009, Water quality monitoring report, lower Boise River and Snake River tributaries, April 24 through October 9, 2008: Idaho State Department of Agriculture Technical Report Summary W-29, 4 p.

Cardiff, M., Barrash, W., Kitanidis, P., Malama, B., Revil, A., Straface, S., and Rizzo, E., 2009, A potential-based inversion of unconfined steady-state hydrologic tomography: Groundwater, v. 47, no. 2, p. 259–270.

Clesceri, L.S., Greenberg, A.E., and Eaton, A.D., eds., 1998, Standard methods for the examination of water and wastewater (20th ed.): Washington, D.C., American Public Health Association, 1,325 p.

Cunningham, W.L., and Schalk, C.W., comps., 2011, Groundwater technical procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods, book 1, chap A1, 151 p. (Also available at http://pubs.usgs.gov/tm/1a1/.)

Dion, N.P., 1972, Some effects of land-use changes on the shallow ground-water system in the Boise-Nampa area, Idaho: Idaho Department of Water Administration Water Information Bulletin no. 26, 47 p.

Domagalski, J.L., and Johnson, H.M., 2011, Subsurface transport of orthophosphate in five agricultural watersheds, USA: Journal of Hydrology, v. 409, p. 157–171.

Donato, M.M., and MacCoy, D.E., 2005, Phosphorus and suspended sediment load estimates for the lower Boise River, Idaho, 1994–2002 (version 2.00): U.S. Geological Survey Scientific Investigations Report 2004-5235, 30 p.

Fishman, M.J., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open-File Report 93-125, 217 p.

Fox, J., Carlson, R., Campbell, K., and Bahr, G., 2002, Ground and surface-water interaction related to nutrients within Mason Creek agricultural drain, Canyon County, Idaho: Boise, Idaho State Department of Agriculture, 120 p.

Fox, J.J., 2006, Analytical modeling of fully penetrating pumping tests at the Boise Hydrogeophysical Research Site for aquifer parameters and wellbore skin: Boise, Idaho, Boise State University, M.S. thesis, 132 p.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J., 2011, Completion of the 2006 National Land Cover Database for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 77, no. 9, p. 858–864.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, 58 p. (Also available at http://pubs.usgs.gov/twri/twri5c1/.)

Helsel, D.R., 2005. More than obvious—Better methods for interpreting nondetect data: Environmental Science and Technology, v. 39, no. 20, p. 419A–423A, accessed September 10, 2013, at http://pubs.acs.org/doi/pdf/10.1021/es053368a.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations Report, book 4, chap. A3, 510 p. (Also available at http://pubs.usgs.gov/twri/twri4a3/.)

Idaho Department of Environmental Quality, 2001, Lower Boise River nutrient subbasin assessment: Boise, Idaho Department of Environmental Quality, 57 p. plus apps., accessed November 4, 2013, at http://www.deq.idaho.gov/media/450530-_water_data_reports_surface_water_tmdls_boise_river_tribs_boise_river_nutrient.pdf.

Idaho Department of Environmental Quality, 2009 Lower Boise River implementation plan total phosphorus: Boise, Idaho Department of Environmental Quality, 162 p.

Idaho Department of Environmental Quality, 2011, Idaho's 2010 integrated report—Final: Boise, Idaho Department of Environmental Quality, 102 p.

Idaho Department of Environmental Quality, 2013a, Benthic chlorophyll-a target recommendation for the lower Boise River total phosphorus TMDL: Boise, Idaho Department of Environmental Quality, Memorandum from Troy Smith to the Lower Boise Watershed Council, 3 p.

Idaho Department of Environmental Quality, 2013b, Staff analysis for reuse permit I-008-05, J.R. Simplot Company, Caldwell plant—Industrial wastewater: Boise, Idaho Department of Environmental Quality, Memorandum from Valerie A. Greear to R. Todd Crutcher, August 1, 2013, 19 p.

Idaho Department of Environmental Quality and Oregon Department of Environmental Quality, 2004, Snake River-Hells Canyon total maximum daily load (TMDL): Idaho Department of Environmental Quality, Boise, and Oregon Department of Environmental Quality, Pendleton, 638 p., accessed November 30, 2011, at http://www.deq.idaho.gov/media/454498-snake_river_hells_canyon_entire.pdf.

Idaho Department of Health and Welfare, 1989, Idaho water quality status report and nonpoint source assessment 1998: Boise, Idaho Department of Health and Welfare, Division of Environmental Quality [variously paged].

Idaho Department of Water Resources, 2013, Water rights accounting: Idaho Department of Water Resources Web site, accessed September 18, 2013, at http://maps.idwr.idaho.gov/wraccounting/default.aspx.

Jarvie, H.P., Neal, C., and Withers, P.J.A., 2006, Effluent phosphorus—A greater risk to river eutrophication than agricultural phosphorus?: Science of the Total Environment, v. 360, p. 246–253.

Johnson, B., Malama, B., Barrash, W., and Flores, A.N., 2013, Recognizing and modeling variable drawdown due to evapotranspiration in a semiarid riparian zone considering local differences in vegetation and distance from a river source: Water Resources Research, v. 49, no. 2, p. 1030–1039, doi:10.1002/wrcr.20122.

Knott, J.M., Glysson, G.D., Malo, B.A., and Schroeder, L.J., 1993, Quality assurance plan for the collection and processing of sediment data by the U.S. Geological Survey, Water Resources Division: U.S. Geological Survey Open-File Report 92-499, 18 p.

Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95-399, 113 p.

Lapham, W.W., Wilde, F.D., and Koterba, M.T., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Selection, installation, and documentation of wells, and collection of related data: U.S. Geological Survey Open-File Report 95-398, 69 p.

MacCoy, D.E., 2004, Water-quality and biological conditions in the lower Boise River, Ada and Canyon Counties, Idaho, 1994–2002: U.S. Geological Survey Scientific Investigations Report 2004-5128, 80 p.

Moulton, S.R., II, Kennen, J.G., Goldstein, R.M., and Hambrook, J.A., 2002, Revised protocols for sampling algal, invertebrate, and fish communities as part of the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 02-150, 75 p.

Mueller, D.S., and Wagner, C.R., 2009, Measuring discharge with acoustic Doppler current profilers from a moving boat: U.S. Geological Survey Techniques and Methods, book 3, chap. A22, 72 p. (Also available at http://pubs.water.usgs.gov/tm3a22.)

Mullins, W.H., 1998, Water-quality conditions of the lower Boise River, Ada and Canyon Counties, Idaho, May 1994 through February 1997: U.S. Geological Survey Water-Resources Investigations Report 98-4111, 32 p. (Also available at http://pubs.er.usgs.gov/publication/wri984111.)

Myers, Ralph, Harrison, Jack, Parkinson, S.K., Hoelscher, Brian, Naymik, Jesse, and Parkinson, S.E., 2003, Pollutant transport and processing in the Hells Canyon Complex: Boise, Idaho Power Company Technical Report Appendix E.2.2-2, 218 p., accessed November 30, 2011, at http://www.idahopower.com/pdfs/Relicensing/hellscanyon/hellspdfs/techappendices/Water%20Quality/e22_02_appendices.pdf.

Neely, K.W., and Crockett, J.K., 1998, Ground water quality characterization and initial trend analysis for the Treasure Valley shallow and deep hydrogeologic subareas: Boise, Idaho Department of Water Resources Information Bulletin No. 50, Part 3, 78 p.

Patton, C.J., and Kryskalla, J.R., 2003, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Evaluation of alkaline persulfate digestion as an alternative to Kjeldahl digestion for determination of total and dissolved nitrogen and phosphorus in water: U.S. Geological Survey Water-Resources Investigations Report 03-4174, 33 p., accessed March 2013, at http://nwql.usgs.gov/Public/pubs/WRIR03-4174/WRIR03-4174.pdf.

Patton, C.J., and Kryskalla, J.R., 2011, Colorimetric determination of nitrate plus nitrite in water by enzymatic reduction, automated discrete analyzer methods: U.S. Geological Survey Techniques and Methods, book 5, chap. B8, 34 p. (Also available at http://pubs.usgs.gov/tm/05b08/.)

Petrich, C.R., 2004, Simulation of ground water flow in the lower Boise River Basin: Prepared for Idaho Department of Water Resources, University of Idaho, Idaho Water Resources Research Institute, 130 p.

Petrich, C.R., and Urban, S.M., 2004, Characterization of ground water flow in the lower Boise River Basin: Prepared for Idaho Department of Water Resources, University of Idaho, Idaho Water Resources Research Institute, and Scott M. Urban, Idaho Department of Water Resources, 148 p.

Pritt, J.W., and Raese, J.W., eds., 1995, Quality assurance/quality control manual—National Water Quality Laboratory: U.S. Geological Survey Open-File Report 95–443, 35 p.

Purdue University, 2013, WHAT—Web-based hydrograph analysis tool: West Lafayette, Indiana, Purdue University Web site, accessed September 20, 2013, at https://engineering.purdue.edu/~what/.

Rosenberry, D.O., and LaBaugh, J.W., 2008, Field techniques for estimating water fluxes between surface water and ground water: U.S. Geological Survey Techniques and Methods, book 4, chap. D2, 128 p. (Also available at http://pubs.usgs.gov/tm/04d02/.)

Ross & Associates Environmental Consulting, Ltd., 2000, Lower Boise River effluent trading demonstration project—Summary of participant recommendations for a trading framework: Prepared for the Idaho Division of Environmental Quality, 38 p.

Rydlund, P.H., Jr., and Densmore, B.K., 2012, Methods of practice and guidelines for using survey-grade global navigation satellite systems (GNSS) to establish vertical datum in the United States Geological Survey: U.S. Geological Survey Techniques and Methods, book 11, chap. D1, 102 p. with appendixes. (Also available at http://pubs.usgs.gov/tm/11d1/.)

Sharpley, A.N., Daniel, T.C. , Sims, J.T., and Pote, D.H., 1996. Determining environmentally sound soil phosphorus levels: Journal of Soil and Water Conservation, v. 51, no. 2, p. 160–166.

Sharpley, A.N., Kleinman, P.J.A, McDowell, R.W., Gitau, M., and Bryant, R.B., 2002, Modeling phosphorus transport in agricultural watersheds—Processes and possibilities: Journal of Soil and Water Conservation, v. 57, no. 6, p. 425–439.

Skinner, K.D., 2006, Estimating streambed seepage using heat as a tracer on the lower Boise River, Canyon County, Idaho: U.S. Geological Survey Scientific Investigations Report 2005-5215, 16 p.

SonTek/YSI, 2009, FlowTracker handheld ADV technical manual, firmware version 3.7, software version 2.30: San Diego, Calif., SonTek/YSI, 116 p.

Stutter, M.I., Demars, B.O.L., and Langan, S.J., 2010, River phosphorus cycling—Separating biotic and abiotic uptake during short-term changes in sewage effluent loading: Water Research, v. 44, p. 4425–4436.

Tesoriero, A.J., Duff, J.H., Wolock, D.M., Spahr, N.E., and Almendinger, J.E., 2009, Identifying pathways and processes affecting nitrate and orthophosphate inputs to streams in agricultural watersheds: Journal of Environmental Quality, v. 38, p. 1892–1900.

Thomas, C.A., and Dion, N.P., 1974, Characteristics of streamflow and ground-water conditions in the Boise River Valley, Idaho: U.S. Geological Survey Water-Resources Investigations Report 74-38, 56 p.

Turnipseed, D.P., and Sauer, V.B., 2010, Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods, book 3, chap. A8, 87 p. (Also available at http://pubs.usgs.gov/tm/tm3-a8/.)

U.S. Environmental Protection Agency and Idaho Department of Environmental Quality, 2012, The U.S. Environmental Protection Agency proposes to modify national pollutant discharge elimination system (NPDES) permit to discharge pollutants pursuant to the provisions of the Clean Water Act to west Boise wastewater treatment facility, city of Boise, Idaho: U.S. Environmental Protection Agency Fact Sheet, 54 p., accessed November 20, 2013, at http://www.epa.gov/region10/pdf/permits/npdes/id/west_boise_dixie_mod_fs_id0023981_091312.pdf.

U.S. Environmental Protection Agency, 2013, Clean Water Act (CWA): U.S. Environmental Protection Agency Web site, accessed October 21, 2013, at http://www.epa.gov/oecaagct/lcwa.html.

Urban, Scott, 2004, Water budget for the Treasure Valley aquifer system, for the years 1996 and 2000: Treasure Valley Hydrologic Project research report prepared by Scott Urban, Idaho Department of Water Resources, 57 p.

U.S. Geological Survey [various dated], National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A9. (Also available at http://pubs.water.usgs.gov/twri9A.)

U.S. Geological Survey, 2013, USGS 13210983 Mason Creek near Caldwell, Idaho: U.S. Geological Survey National Water Information System Web page, accessed September 20, 2013, at http://waterdata.usgs.gov/nwis/nwisman/?site_no=13210983&agency_cd=USGS.

Vadas, P.A., Kleinman, P.J.A., Sharpley, A.N., and Turner, B.L., 2005, Relating soil phosphorus to dissolved phosphorus in runoff—A single extraction coefficient for water quality modeling: Journal of Environmental Quality, v. 34, p. 572–580.

Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods, book 1, chap D3, 51 p., plus 8 attachments. (Also available at http://pubs.water.usgs.gov/tm1d3.)

Williams, M.L., 2011, Seasonal seepage investigation on an urbanized reach of the lower Boise River, southwestern Idaho, water year 2010: U.S. Geological Survey Scientific Investigations Report 2011-5181, 24 p.

Withers, P.J.A., and Jarvie, H.P., 2008, Delivery and cycling of phosphorus in rivers—A review: Science of The Total Environment, v. 400, nos. 1–3, p. 379–395.

Wolock, D.M., 2003, Base-flow index grid for the conterminous United States: U.S. Geological Survey Open-File Report 03-263, digital data set, accessed September 11, 2013, at http://water.usgs.gov/GIS/metadata/usgswrd/XML/bfi48grd.xml.

Wood, M.S., and Etheridge, A.B., 2011, Water-quality conditions near the confluence of the Snake and Boise Rivers, Canyon County, Idaho: U.S. Geological Survey Scientific Investigations Report 2011-5217, 70 p., http://pubs.usgs.gov/sir/2011/5217/.

Appendix 1. Spreadsheet Mass-Balance Models

Spreadsheet mass-balance models were developed for all three synoptic sampling periods completed as part of this study. Unlike the preceding report and accompanying tables and figures, numbers provided in appendix 1 spreadsheets are not rounded to three significant digits. Each of the three predictive models can be utilized to assess outcomes of various input scenarios as compared to static measured model results. Spreadsheet passwords and instructions for running scenarios using the predictive model are included in the digital files.

The spreadsheet mass-balance model files are available online at http://pubs.water.usgs.gov/sir20135220/.

Publishing support provided by the U.S. Geological Survey
Publishing Network, Tacoma Publishing Service Center

For more information concerning the research in this report, contact the
Director, Idaho Water Science Center
U.S. Geological Survey
230 Collins Road
Boise, Idaho 83702
http://id.water.usgs.gov

Etheridge—**Evaluation of Total Phosphorus Mass Balance in the Boise River, Southwestern Idaho**—Scientific Investigations Report 2013–5220

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/20135220