F I N A L

Hydrology Assessment of Willard Spur, Great Salt Lake, 2011–2013: Development of Water Quality Standards for Willard Spur

Prepared for

Utah Division of Water Quality

January 2016

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Acknowledgements

The work presented herein was completed with the funding, support, and assistance of the Utah Department of Environmental Quality, Division of Water Quality (UDWQ) as part of UDWQ's Development of Water Quality Standards for Willard Spur project. UDWQ provided all funding and completed the majority of the field efforts that serve as the basis for this assessment. Special thanks to Suzan Tahir and Jim Harris for coordinating and completing this work.

Collaboration among the numerous stakeholders and project partners was also critical to project success. The Willard Spur Science Panel and Steering Committee provided review and important input to the design and completion of this work. The U.S. Geological Survey provided technical support and field monitoring of various sites. The Perry Willard Regional Wastewater Treatment Plant, U.S. Fish and Wildlife Service, Utah Department of Natural Resources, Division of Wildlife Resources, and Weber Basin Water Conservancy District also provided access, input, data, and important assistance with monitoring efforts.

Executive Summary

An extensive effort to document and evaluate the hydrology of Willard Spur reinforced the importance of hydrologic processes in understanding the function of an ecosystem like Willard Spur and potential impacts from the Perry Willard Regional Wastewater Treatment Plant (Plant). Conditions within Willard Spur from 2011 through 2013 were extremely dynamic and driven by wide ranging inflows of surface water from the Bear River, Weber River, and a local east side drainage basin. The year 2011 was a wet year characterized by an almost complete inundation of Willard Spur, water depths of up to 6 feet, and continuous outflow to Bear River Bay throughout the year. The years 2012 and 2013, by contrast, were characterized by a significantly smaller volume of surface water inflow, a complete cutoff of outflow to Bear River Bay when spring runoff was complete, a rapidly shrinking and even disappearing footprint of open water, but then a restoration of outflow to Bear River Bay during the subsequent winter and spring seasons. The range of flood and drought conditions observed during the project's study period provided a unique opportunity to understand this ecosystem.

Surface water inflows were dominated by spring runoff, contributions from the Bear River basin, and in almost all respects the surface water inflows were managed by water users at the fringes of Willard Spur. Water volumes contributed by the Plant were negligible compared to other surface water sources. Groundwater interactions were observed that could explain how surface water inflows from all sources, but in particular from the Plant, often failed to reach the open water impoundment of Willard Spur observed during the summer months of 2012 and 2013.

The mudflats at the western edge of Willard Spur appear to serve as a natural weir that creates an impounded condition during summer months. Increasing surface water inflows, typically beginning at the end of the annual irrigation season (generally in mid-October), likely recharge the local groundwater table, raise the water level of the open water of Willard Spur, reconnect all surface water inflow sources directly to the open water, and then flow out to Bear River Bay through May or June of the subsequent year. A review of historical aerial photography indicates that an impounded condition during summer months followed by outflows during the fall, winter, and spring months is likely a typical annual pattern for Willard Spur. The higher, flushing flows observed during the fall–spring months are likely the most significant factor in preserving Willard Spur's present condition.

Plant effluent that reaches the impounded open water of Willard Spur is likely retained until the higher, flushing flows return in the fall. Plant effluent that reaches the open water during a flowing condition is more likely to be diluted, dispersed, assimilated, and exported to Bear River Bay. A water balance completed for the Plant's effluent provides some perspective on how discharge operations can affect the frequency and volume of the effluent reaching the open water of Willard Spur.

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Acronyms and Abbreviations

ac	acre
ac-ft	acre-foot
BRMBR	Bear River Migratory Bird Refuge
cfs	cubic feet per second
GSL	Great Salt Lake
HCWMA	Harold S. Crane Waterfowl Management Area
NOAA	National Oceanic and Atmospheric Administration
PDSI	Palmer Drought Severity Index
UDWQ	Utah Department of Environmental Quality, Division of Water Quality
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

SECTION 1

Introduction

The hydrologic characteristics of Willard Spur, located within Great Salt Lake's (GSL) Bear River Bay (see Figure 1 for vicinity map), were relatively unknown at the outset of this project. Central to determining the impact of the Perry Willard Regional Wastewater Treatment Plant (Plant) upon Willard Spur was understanding where the effluent would go and how it might affect the ecology of Willard Spur. Would the effluent from the Plant remain within Willard Spur, or would it be diluted and flushed into GSL? This study was designed with the objective of understanding the hydrology of Willard Spur so that, in conjunction with an evaluation of the Plant's potential impact, its influence on Willard Spur's ecology could be determined.

1.1 Background

Construction of the Plant was completed in 2010. The Division of Water Quality (UDWQ) received numerous comments as part of the public notice process for the Plant's Utah Pollutant Discharge Elimination System (UPDES) discharge permit to Willard Spur. Many of these comments expressed concern over the potential impact the effluent could have on the water body. Further, the groups that provided comments also petitioned UDWQ to prohibit all wastewater discharges to Willard Spur or, alternatively, to reclassify Willard Spur to protect the wetlands and current uses of the water.

Although the Utah Water Quality Board denied the petition, the Water Quality Board directed UDWQ to develop a study design to establish defensible protections (for example, site-specific numerical criteria, antidegradation protection clauses, beneficial use changes) for the water body. The Water Quality Board also directed UDWQ to pay for phosphorus reductions at the Plant while the study was conducted. This path forward, developed in conjunction with stakeholders, allowed the Plant to operate while the studies were underway, with reasonable assurances that the effluent would not harm the ecosystem.

Understanding the dynamics and complexity of the Willard Spur food web, how it interweaves with the varying and unique habitat and hydrology, and the role water quality serves as a critical linkage is the challenge that UDWQ's Development of Water Quality Standards for Willard Spur project (Project) begins to address.

1.2 Site Description

Willard Spur is a unique and dynamic ecosystem located in the eastern part of the Bear River Bay of GSL (see Figure 1). Willard Spur encompasses over 11,780 hectares (equivalent to approximately 29,100 acres, or almost 45.5 square miles) of wetlands, with almost 20 percent of that area within the Bear River Migratory Bird Refuge (BRMBR). Its waters are generally bounded on the north by the southern dike of the BRMBR (also known as the D-line Dike), on the east by the natural rise of topography and eventually Interstate 15, and on the south by the northern dikes of Willard Bay Reservoir, the Harold S. Crane Waterfowl Management Area (HCWMA), and Great Salt Lake Minerals. The waters and mudflats of Bear River Bay stretch to the west of Willard Spur. The open waters of GSL are located south of Bear River Bay. This study focuses only on the open waters of Willard Spur as shown in Figure 1.

The unique habitat of Willard Spur varies dynamically throughout any given year and is directly linked to the hydrologic cycle of GSL's watershed. Willard Spur is where GSL's saline waters and fresh water entering from the Bear River and Weber River basins begin to mix when lake levels exceed approximately 4,201.9 feet (CH2M, 2014a; Appendix A[1]). Fresh water entering Willard Spur from the Bear River and Weber River basins makes up an average of 42 percent of the total annual inflow to GSL (HDR Engineering, Inc., 2014). When GSL water levels fall below an elevation of approximately 4,201.9 feet, Willard Spur waters no longer mingle with

[1] Five CH2M HILL technical memorandums cited throughout are also included as appendixes to this report. The appendix designation for each will be given with its standard reference citation.

GSL's saline waters, and Willard Spur's habitat is then controlled largely by the freshwater inflows. GSL was last at an elevation of 4,201.9 feet in July 2000; Willard Spur has since been transitioning into freshwater-dominated wetlands (U.S. Geological Survey [USGS], 2011). As inflows to Willard Spur decrease and water levels in Willard Spur drop, a natural rise in the lake bottom on the western boundary of Willard Spur (locally known as the "sand bar") disconnects the waters of Willard Spur from Bear River Bay and the water body becomes a natural impoundment. This can happen annually depending on available inflows.

The U.S. Fish and Wildlife Service (USFWS) has developed five management categories describing different habitat in the Willard Spur wetlands within the boundaries of the BRMBR (USFWS, 2004). The areal extent of each of these categories depends largely on the hydrology in a given growing season:

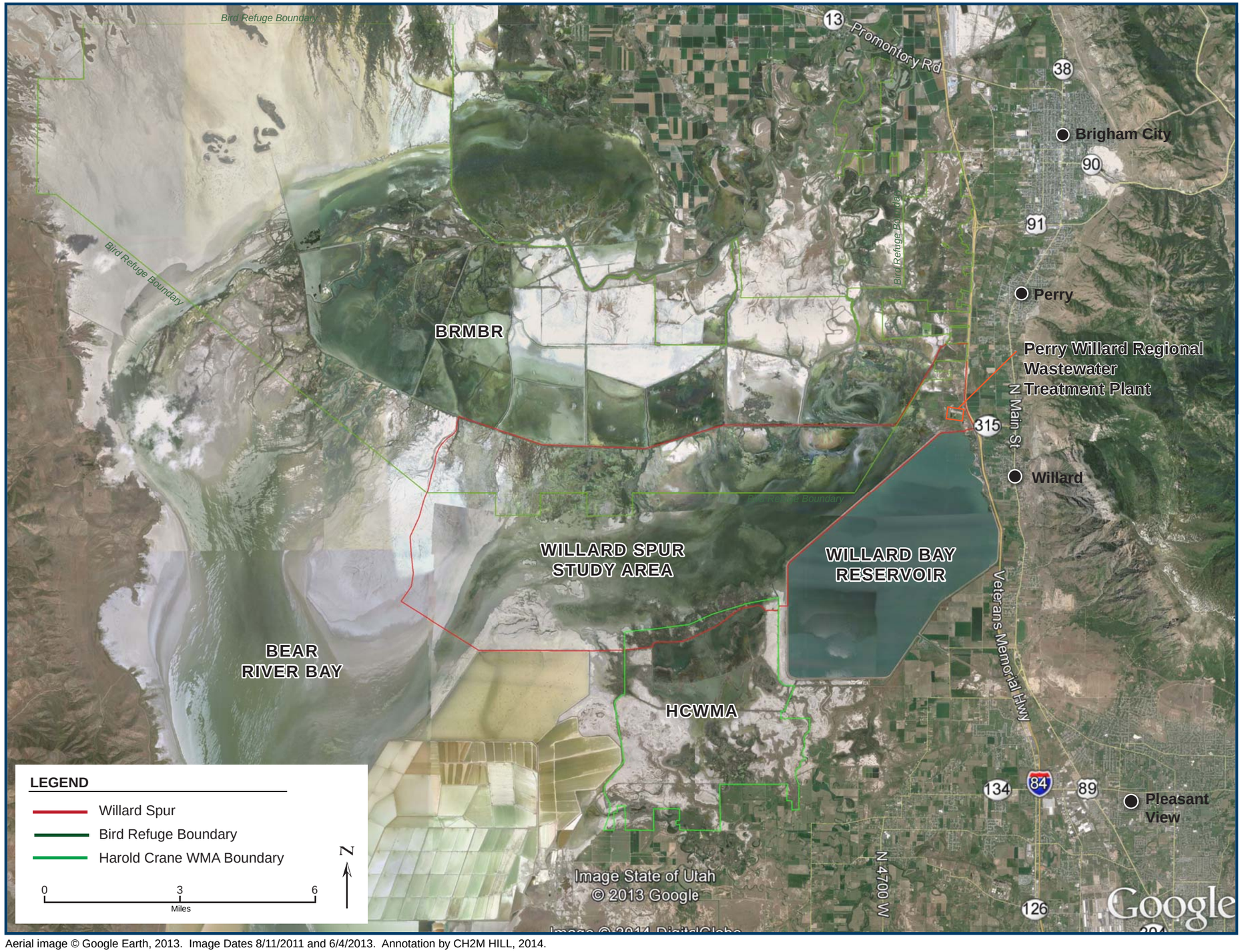
- Deep submergent wetlands (18–24 inches of water, dominated by sago pondweed [*Stuckenia pectinata*] with very little emergent vegetation)
- Shallow submergent wetlands (4–18 inches of water, dominated by sago pondweed with sparse emergent vegetation)
- Mid-depth emergent wetlands (8–12 inches of water, 50 percent emergent vegetation with alkali bulrush [*Schoenoplectus maritimus*] largely in shallower areas and hardstem bulrush [*Schoenoplectus acutus*] in deeper areas, large stands of cattails [*Typha latifolia* and *T. angustifolia*] and phragmites [*Phragmites australis*] possible)
- Shallow emergent wetlands (2–8 inches of water, predominantly alkali bulrush, some stands of cattails, and phragmites)
- Vegetated mudflats (0–2 inches of surface water during high-inflow periods or large precipitation events, highly saline soils, often unvegetated, can support shallow-rooted vegetation such as pickleweed [*Salicornia rubra* and *S. utahensis*], saltgrass [*Distichlis spicata*], and seepweed [*Suaeda calceoliformis* and *S. moquinii*])

The varied habitat that Willard Spur provides is a haven for birds and fish; the immense populations of birds are perhaps what Willard Spur is most well known for. USFWS has documented over 210 bird species that regularly use the adjacent BRMBR, at least 67 of which nest in the area. The vegetation, macroinvertebrates, and fish the wetlands of BRMBR and Willard Spur provide are ideally suited for these migrating populations of waterfowl, shorebirds, and other waterbirds from the Pacific Flyway and Central Flyway. These waters, in conjunction with other waters of GSL, were recognized for their importance to shorebirds as a Western Hemisphere Shorebird Reserve Network Site in 1992 (USFWS, 2004).

1.3 Hydrologic Context

The water depth, surface area, and salinity of Willard Spur vary largely as a result of changes in inflow from precipitation, tributaries, and groundwater, as well as from losses through evaporation. Understanding the watershed's recent hydrologic regime helps to place Willard Spur's response during the study period in context.

The study period (2011–2013) provided a unique opportunity to observe the dynamics of Willard Spur during both very wet and dry periods. One of the indices used by the State of Utah to define and compare cumulative drought events, the Palmer Drought Severity Index (PDSI), indicates that Willard Spur's watershed moved from a very wet period in 2011 into a drought condition during 2012 and 2013. Table 1 and Figure 2 illustrate the PDSI for Utah Climate Division 5 (largely representing the Bear River and Weber River watersheds) (NOAA, 2015). The same pattern is illustrated in terms of Bear River flow rates at Corinne, Utah, and GSL water levels at Saltair as measured by USGS (see Figure 2). An analysis of Bear River flows at Corinne for the time period of 1950-2013 (minus 1957-1963 due to inadequate data) reveals that the annual flow volume in 2011 was in the 84th percentile, while flow volumes in 2012 and 2013 were only in the 29th and 7th percentiles, respectively.



Aerial image © Google Earth, 2013. Image Dates 8/11/2011 and 6/4/2013. Annotation by CH2M HILL, 2014.

Overview Map

FIGURE 1
Vicinity Map of BRMBR and Willard Spur
Flow Measurement Methods at BRMBR

The range of conditions observed during 2011–2013 presented an excellent opportunity for the project to characterize the ecosystem of Willard Spur for wide-ranging conditions.

Table 1. Palmer Drought Severity Index for 2011–2013 for Utah Climate Division 5

Study Period (2011–2013)	PDSI Category
January–March 2011	(+3.0 to +3.9) Very Wet
April–July 2011	(+4.0 and above) Extremely Wet
August 2011 through February 2012	(-1.9 to +1.9) Near Normal
March–April 2012	(-2.0 to -2.9) Moderate Drought
May 2012 through August 2013	(-3.0 to -3.9) Severe Drought
September–December 2013	((-2.0 to -2.9) Moderate Drought

Data from NOAA (2015).

1.4 Document Organization

The remainder of this document is divided in the following sections:

- Section 2 defines the objectives for the overall project and specifically for the hydrology study.
- Section 3 summarizes the considerations, assumptions, and methodology used to evaluate the hydrology of Willard Spur.
- Section 4 summarizes the results of the hydrology study.

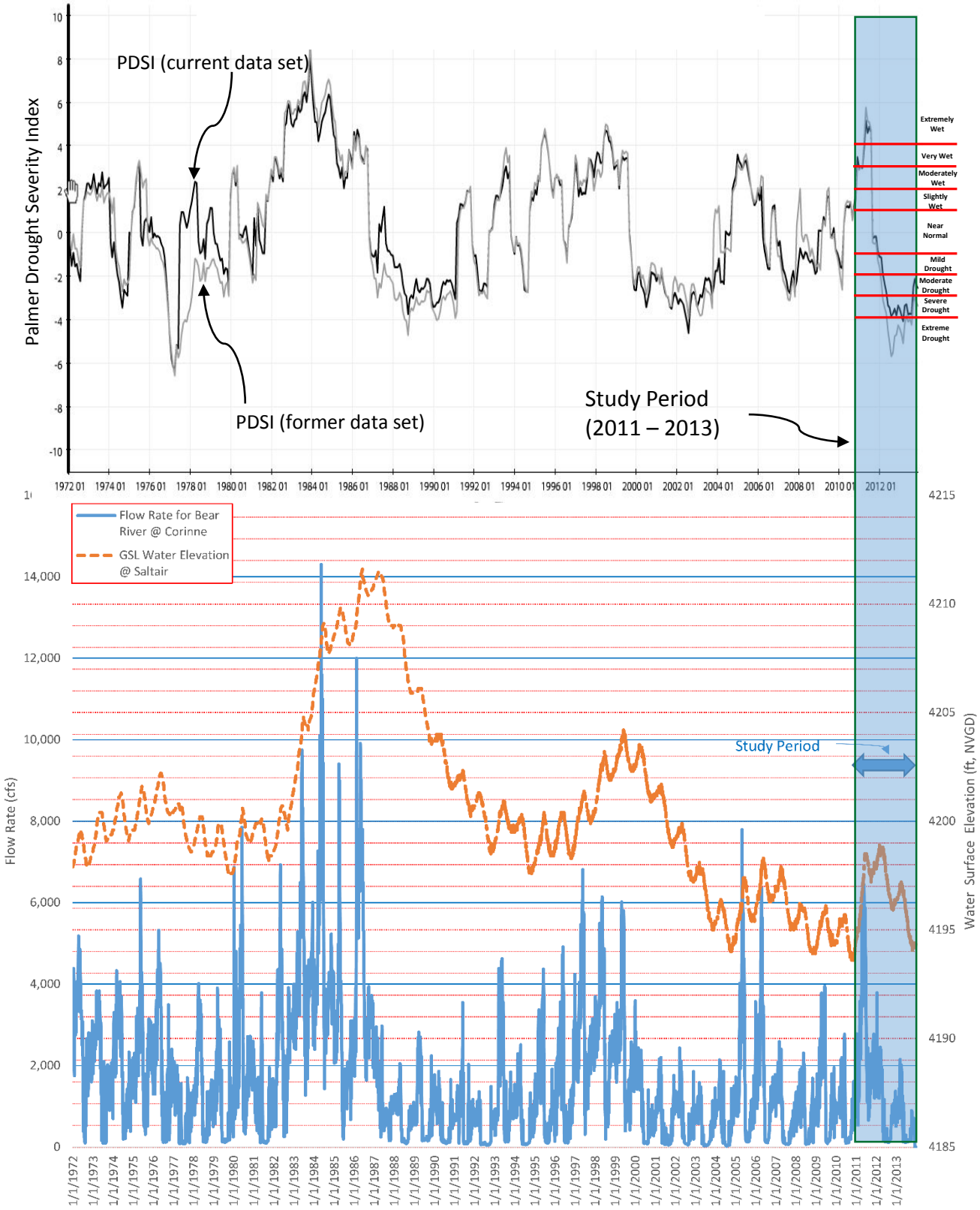


Figure 2. Variations in Palmer Drough Severity Index, Bear River flows, and Great Salt Lake Water Elevations for 1972–2013
Data from NOAA (2015).

SECTION 2

Objectives

The objective of the Project was to determine appropriate and defensible modifications to Utah's water quality standards to provide long-term protection of Willard Spur's aquatic life uses. Central to achieving this objective was the completion of research to answer two questions:

1. What are the potential impacts of the Plant on Willard Spur?
2. What changes to water quality standards will be required to provide long term protection of Willard Spur as they relate to the proposed Plant discharge?

Research Area Number 2 (CH2M, 2011) focused on understanding the overall hydrology and nutrient loads to Willard Spur to better understand the influence of the Plant's effluent. The Willard Spur Hydrology Study (Study), as documented herein, evaluated the characteristics of inflow, changes in water level and storage volume, and outflow of Willard Spur for the period of 2011 through 2013. This in turn informed an understanding of the ecosystem's dynamics and nutrient balance, potential impacts from the Plant, and the development of long-term protection strategies. Some of the questions that this study attempted to answer include the following:

1. What hydrologic and meteorological data is available for Willard Spur?
2. What are the water sources to Willard Spur? How do flow rates change at these locations throughout the year (that is, what are the individual and combined hydrographs?)?
3. What are the outflow mechanisms and rates of Willard Spur, that is, outflow to Bear River Bay and evapotranspiration?
4. How does the water level change in relation to inflow and outflow? How do water depths and surface area vary spatially and temporally in relation to the water level?
5. What flow regimes should be considered for use in evaluating nutrient cycling and the food web of Willard Spur? What are the flow regimes and conditions that are most critical?
6. Under what conditions does Plant outflow reach Willard Spur? How does this outflow mix with Willard Spur? How large of an area does it influence?

This report summarizes the methods used and the results that were developed, and provides a discussion of key observations.

Water Mass Balance

The only information identified describing the hydrology of Willard Spur at the outset of the project was descriptions provided by members of the public and State agencies who had previously visited the area. Some information was available describing flows released by the Bear River Migratory Bird Refuge (BRMBR), Willard Bay Reservoir, and the HCWMA but the information often did not identify where the flows were released and, more importantly, what occurred specifically within Willard Spur. A plan was developed in 2011 in conjunction with the Willard Spur Science Panel to collect adequate data to characterize the inflow, changes in water level and storage volume, and outflow of Willard Spur to Bear River Bay. This plan was reviewed with the Science Panel, Steering Committee, and other stakeholders and implemented beginning in 2011, continuing through 2013. The plan was not static; the plan changed throughout the study period in response to changing conditions and lessons learned. Appendixes A–E summarize the methods and results of these efforts.

One of the desires of this project from the beginning was to use the information from the various field efforts to develop an approximate water balance for Willard Spur. The water balance, if successful, could be used to validate the hydrologic evaluation, possibly populate a 2D or 3D hydrodynamic model of Willard Spur, and be used to inform a nutrient mass balance for Willard Spur.

3.1 Approach

The mass balance approach used was based upon an equation that balances inflows and outflows with storage within the system (Pierce, 1993; Wanlass, 1996). The equation uses measured surface water inflows and precipitation and estimated surface water storage, evaporation, surface water outflows, and groundwater gains and losses to complete the mass balance. The mass balance can be described as:

$$\text{Inflows - Outflows = Storage or} \qquad \text{(Equation 1)}$$

$$Q_{Sin} + P + Q_{Gin} - Q_{Sout} - E - Q_{Gout} = \Delta S \qquad \text{(Equation 2)}$$

where

Q_{Sin} = surface water inflow
Q_{Sout} = surface water outflow
P = precipitation (on open water surfaces)
E = evaporation (from open water surfaces), or ET = evapotranspiration (from vegetation and open water)
Q_{Gin} = groundwater inflow
Q_{Gout} = groundwater outflow
ΔS = change in surface water storage

Previous water balance analyses completed in the area had assumed that the groundwater flux (Q_{Gout} - Q_{Gin}) was equal to zero (Wanlass, 1996) or that groundwater contributes to the surface water and is captured by surface water gauges (Kadlec and Adair, 1993). Due to the lack of data indicating otherwise, this project also initially assumed that the groundwater flux was zero, thus simplifying Equation 2 into the following water balance equation:

$$Q_{Sin} + P - E - Q_{Sout} = \Delta S \qquad \text{(Equation 3)}$$

It became readily apparent during the second year of the project (2012) that the groundwater flux within Willard Spur was not zero. As no groundwater data were available or collected as part of this project, groundwater was treated as the net flux, or unknown variable, in the equation, and groundwater storage was assumed to be negligible. This made the specific water balance equation used for this project:

$$Q_{Sin} + P - E - Q_{Sout} - \Delta S = Q_{Gout} - Q_{Gin} \quad \text{(Equation 4)}$$

Each component of the water balance equation was either measured directly or estimated from available data collected.

3.2 Inputs to Water Mass Balance Equation

Efforts to document and evaluate the hydrology of Willard Spur reinforced the complexity and importance of hydrologic processes in understanding the function of an ecosystem like Willard Spur. Key observations are summarized below in the context of the attempt to complete a water balance for Willard Spur.

3.2.1 Surface Water Inflows (Q_{Sin})

The project team completed an initial reconnaissance of the study area in late February 2011 to identify potential points of surface water inflows to Willard Spur. Reconnaissance activities included an evaluation of available historical aerial photography, field visits, and meetings with agency personnel responsible for managing the surrounding wildlife management areas. The watershed contributing surface water to Willard Spur was divided into three basins: the Bear River basin to the north (that is, BRMBR drainage), the east side drainage, and the Weber River basin to the south (HCWMA drainage) (see Figure 1). A total of 33 inflow points were monitored by UDWQ and the USGS for the period of April 2011 through November 2013 using various methods and at various intervals, depending upon the site characteristics and volume of inflow (CH2M, 2014b–d; Appendixes B–D). Values for Q_{Sin} typically represent flows at the discharge point from the facility and do not account for gains or losses once the flow enters the mudflats, fringe wetlands, or open water of Willard Spur.

Surface water inflows to Willard Spur demonstrated significant variability year to year. Inflows were significantly higher in 2011 than in 2012 and 2013, as reflected by the PDSI index values illustrated in Figure 2. Underlying hydrologic conditions—for example, soil moisture levels, as well as significant snow accumulation during the 2010–2011 winter—led to significant snowmelt and subsequent inflows to Willard Spur during 2011. A largely opposite scenario presented itself during the winters of 2011–2012 and 2012–2013, resulting in snowmelt and inflows to Willard Spur in 2012–2013 that were significantly less than those observed in 2011. Figure 3 illustrates the total estimated surface water inflow to Willard Spur for all three years in relation to estimated flows in the Bear River at Corinne (as measured by the USGS). It was found that much could be inferred about surface water inflow patterns to Willard Spur from flows in the Bear River at Corinne.

> Surface water inflows to Willard Spur can vary considerably year to year. The year 2011 was a significantly wetter year than both years 2012 and 2013.

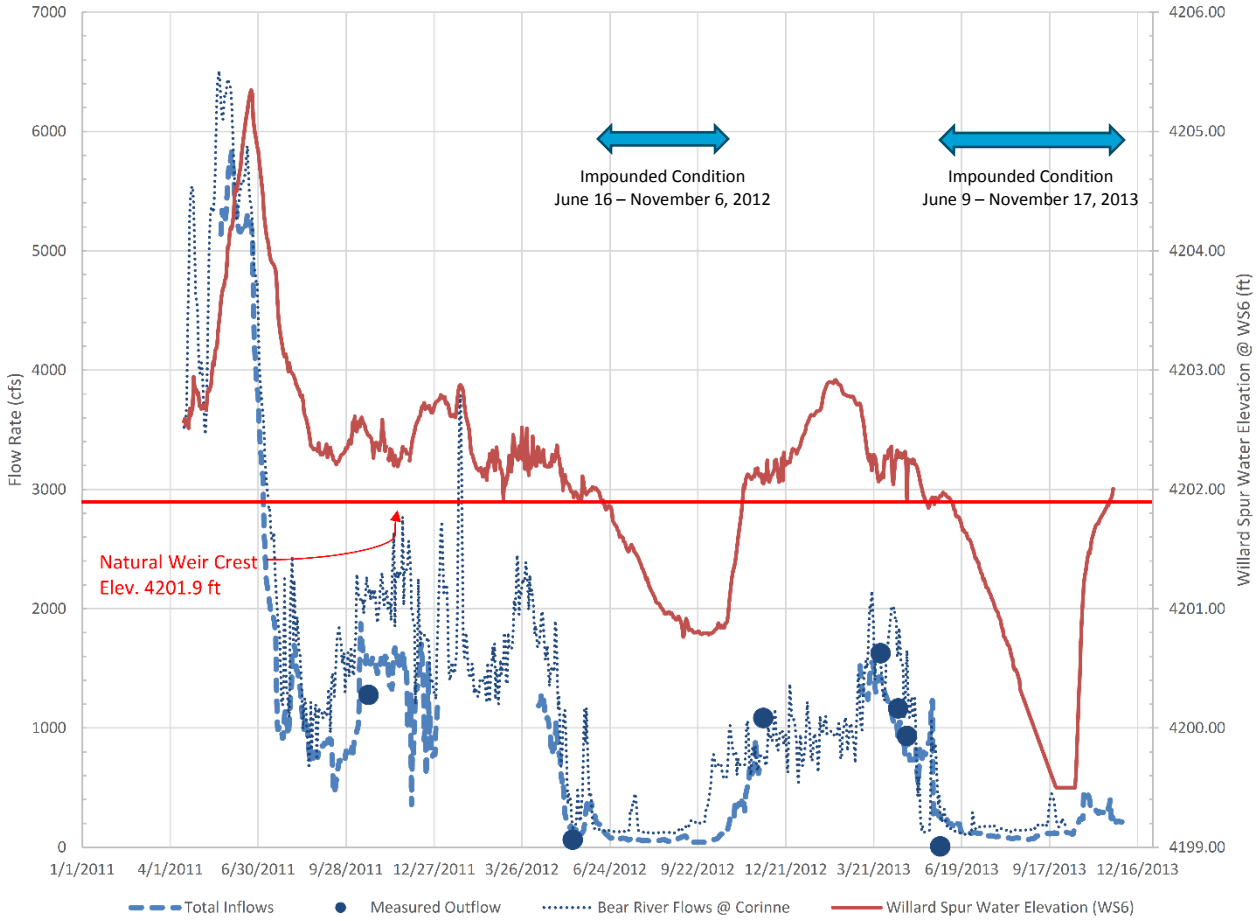


Figure 3. Summary of Measured Inflows and Water Levels in Willard Spur, 2011–2013

Although the total surface water inflow was different year to year, each year followed a similar seasonal pattern:

- A small peak in flow in February–March as snow in the foothills melted
- A larger peak during spring runoff in April–June as snowmelt from the upper watershed reached Willard Spur
- Sharp reduction in inflow in May–September as snowmelt ended and upstream water demands reached their peak
- An increase in and sustained inflow pattern from October–January as upstream water demands decreased significantly

Although annual inflow volumes varied significantly, annual seasonal patterns in the hydrograph were consistent.

Figures 4–6 compare surface water inflows from the various sources in 2011 (Figure 4), 2012 (Figure 5), and 2013 (Figure 6). Table 2 summarizes total monthly flow volumes from each basin for the study period. Note that these inflow rates represent estimates at the point where the water leaves the water control structure and enters the Willard Spur boundary and not necessarily what reaches the open water of Willard Spur.

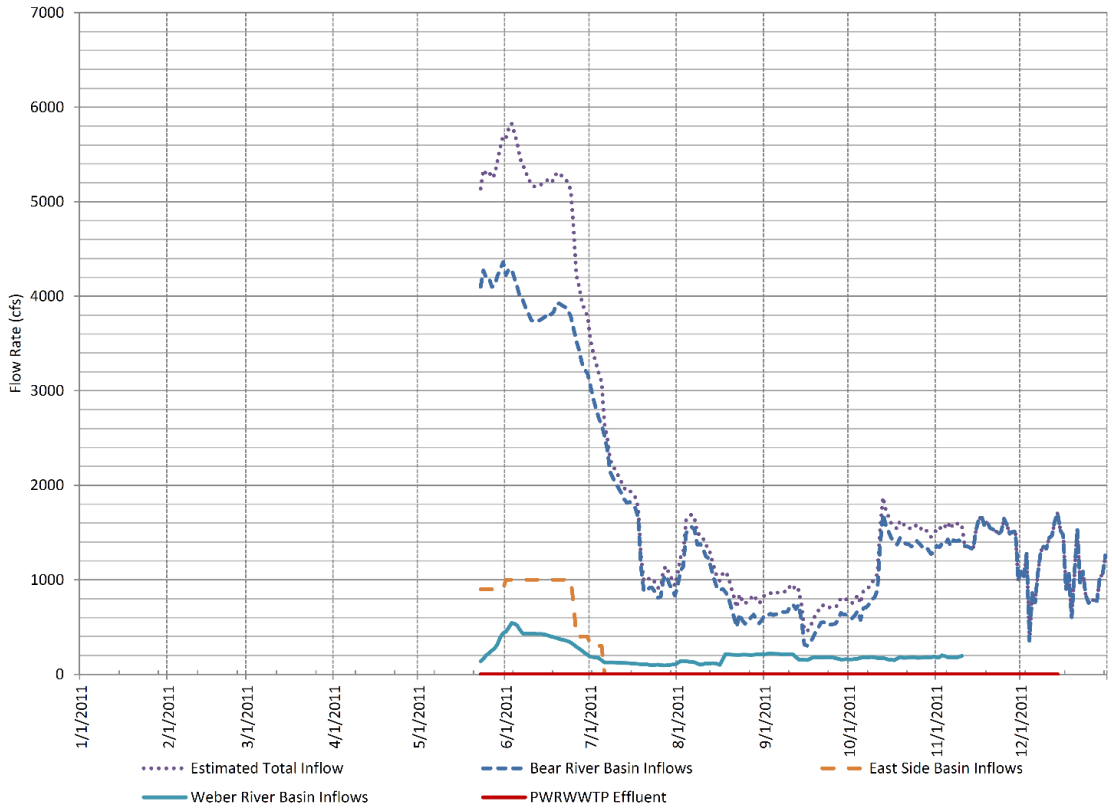


Figure 4. Inflow Hydrograph for Willard Spur, 2011

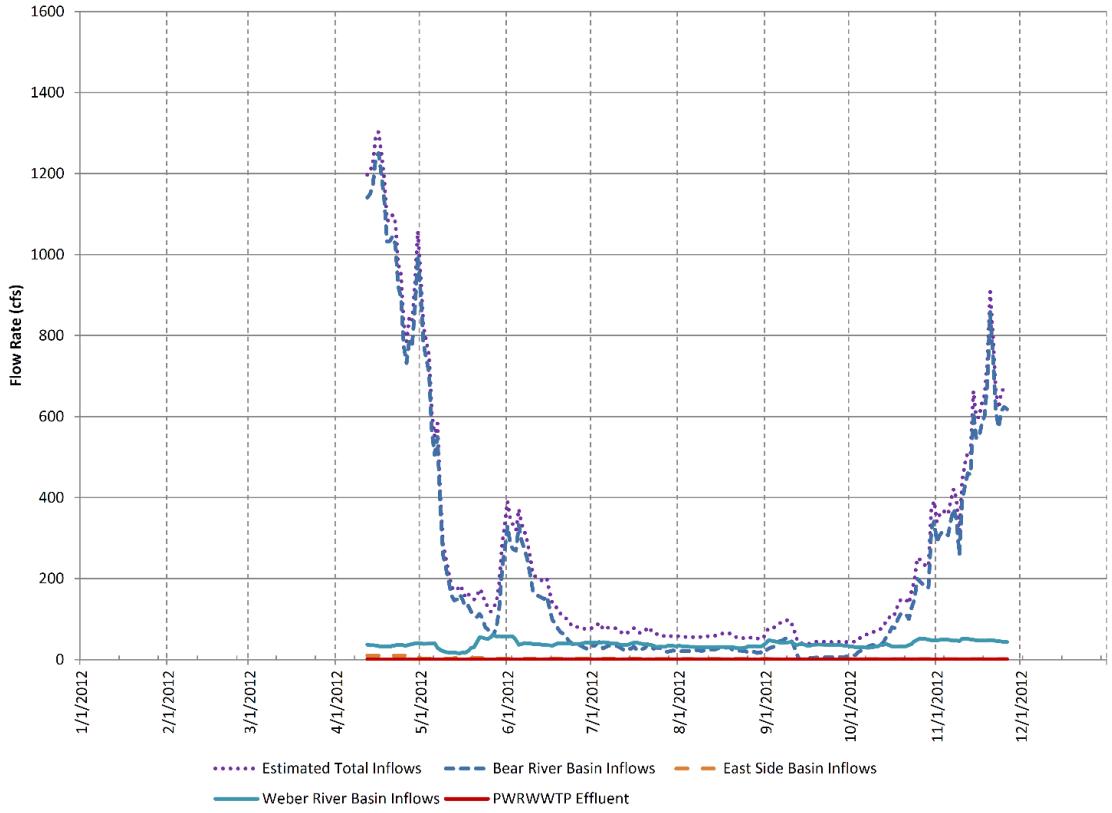


Figure 5. Inflow Hydrograph for Willard Spur, 2012

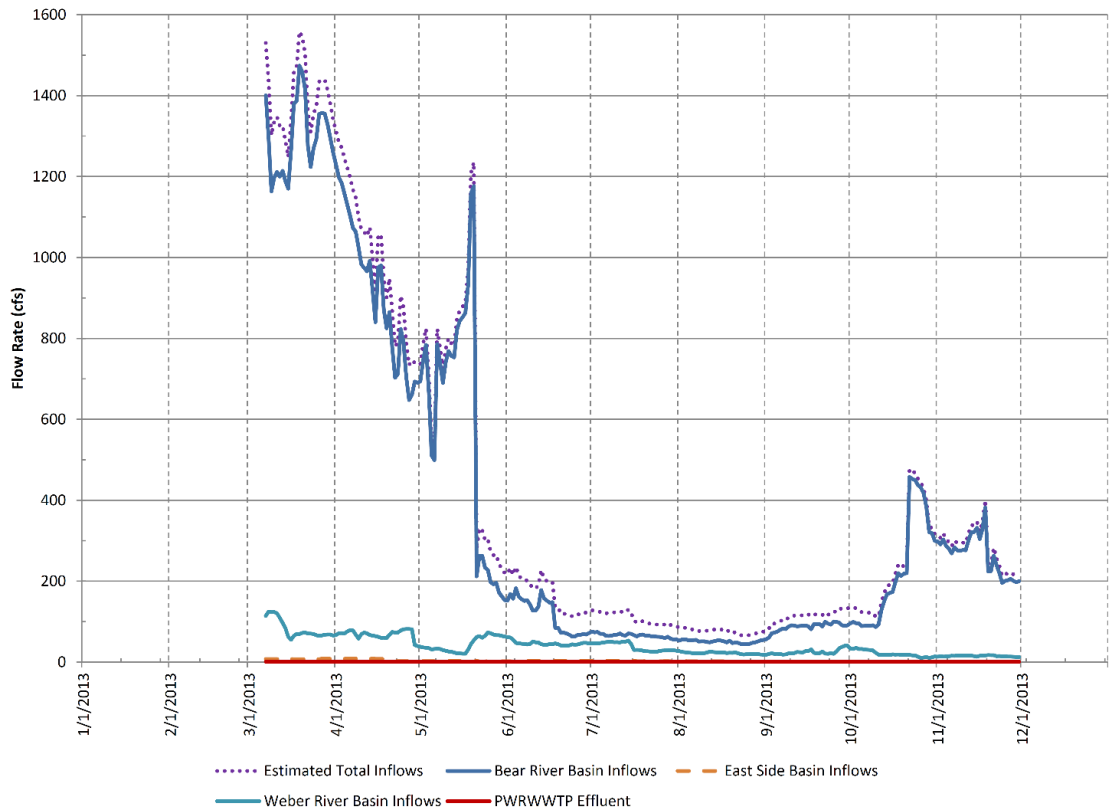


Figure 6. Inflow Hydrograph for Willard Spur, 2013

3.2.1.1 Bear River Basin

There are 11 possible inflow points contributing surface water from the Bear River into Willard Spur through the BRMBR. The UDWQ worked with USGS and USFWS to install flow monitoring stations at each of the 11 outlet structures along the BRMBR's D-line Dike. These stations were operated nearly continuously from April 2011 through November 2013 and were effective in documenting the flow rates and volumes, with the exception of winter flows, for the majority of the inflow to Willard Spur.

As illustrated in Figures 4–6 and Table 2, the Bear River represented the most significant source of inflow for Willard Spur for all three years of the study period. Inflows from the BRMBR to Willard Spur are highly dependent upon flows in the Bear River upstream of the BRMBR and upon the USFWS's water management objectives at BRMBR. Although the project was not able to monitor all Bear River flows passing through the BRMBR into both Bear River Bay and Willard Spur, it appears that the majority of spring runoff flows from the Bear River is diverted through BRMBR and into Willard Spur.

> The Bear River represented the most significant source of inflow for Willard Spur. The delivery of these inflows was dependent upon the management objectives and operations at the BRMBR.

Table 2. Estimated Water Deliveries to Willard Spur from Three Sources

	Month							
Year	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**
From the Bear River Basin through BRMBR								
Average Monthly Flow Rate (cfs)								
2011	—	—	3,809	1,673	950	574	1,155	1,452

Table 2. Estimated Water Deliveries to Willard Spur from Three Sources

	Month							
Year	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**
2012	1,010	269	144	29	23	18	98	493
2013	918	582	117	66	51	87	221	266
Total Monthly Delivery (ac-ft)[a]								
2011	—	—	226,677	102,851	58,388	34,177	71,027	86,431
2012	—	16,565	8,547	1,788	1,392	1,046	6,022	—
2013	54,646	35,814	6,984	4,048	3,125	5,160	13,571	15,827
From the East Side Basin								
Average Monthly Flow Rate (cfs)								
2011	—	—	892	50	2	1	1	1
2012	10	3	2	2	1	1	1	1
2013	6	2	3	3	2	1	1	1
Total Monthly Delivery (ac-ft)[a]								
2011	—	—	53,084	3,044	95	86	85	66
2012	—	169	142	109	89	63	75	—
2013	376	141	166	164	104	60	62	69
From the Weber River Basin through HCWMA								
Average Monthly Flow Rate (cfs)								
2011	—	—	394	121	162	186	172	185
2012	35	36	41	38	31	39	37	48
2013	69	43	46	38	22	25	21	15
Total Monthly Delivery (ac-ft)[a]								
2011	—	—	23,415	7,430	9,940	11,040	10,597	3,677
2012	—	2,237	2,430	2,313	1,927	2,296	2,275	—
2013	4,098	2,670	2,753	2,344	1,367	1,461	1,278	887
Total Estimated Water Deliveries to Willard Spur								
Total Monthly Delivery (ac-ft)[a]								
2011	—	—	303,176	113,325	68,423	45,303	81,709	90,173
2012	—	18,972	11,120	4,210	3,409	3,406	8,372	—
2013	59,120	38,625	9,902	6,555	4,596	6,682	14,912	16,783

cfs, cubic feet per second; ac-ft, acre-foot.
[a] Months without data for all days are not included.

Inflows to Willard Spur from the BRMBR are dominated by spring runoff flows because the USFWS uses its canals to bypass peak flows and sediment loads in the Bear River to Willard Spur. Summer inflows during average/dry years sharply decline in July, are typically only in locations where the BRMBR is targeting specific habitat objectives, and do not appear to always reach the open waters of Willard Spur. These summer periods of low inflow from the Bear River correlate with periods where Willard Spur exhibited an impounded condition. The project was unable to monitor winter inflows to Willard Spur due to ice, but observations indicate that significant inflows to Willard Spur from BRMBR were sustained during the winter months and were consistent with flows in the Bear River. A cursory review of current water management practices with USFWS indicates that the USFWS does have the flexibility to convey additional waters to Willard Spur if BRMBR objectives are revisited and Bear River flows are adequate.

> There were no inflow contributions from the Plant to the open water of Willard Spur during summer months when Willard Spur water levels were low and effluent was discharged to a wetland or pasture area.

CH2MHILL (2014b; Appendix B) details methods used and results from monitoring inflows from these 11 locations for the period 2011–2013.

3.2.1.2 East Side Basin

There are three possible sources of inflow from the east side of Willard Spur:

- Local runoff
- Perry Willard Regional Wastewater Treatment Plant
- Willard Bay Reservoir (see Figure 1)

The Plant provided data documenting its effluent flow rates and location of discharge, and the Weber Basin Water Conservancy District provided data documenting releases from the Willard Bay Reservoir. UDWQ supplemented these data with measured flows in various ditches and the Willard Bay outlet structure and Outlet Channel.

While inflow from the East Side Drainage Basin is generally negligible, it represents in part the wastewater effluent of concern and potentially includes significant flows from the Willard Bay Reservoir. The Willard Bay Reservoir contributed significant flow to Willard Spur during the spring of 2011 but did not provide substantial flows after that.

> Surface water inflows from the east side of Willard Spur appear to typically be negligible and dependent upon water levels in Willard Spur.

Local runoff and irrigation return flows are negligible and likely reach the open waters of Willard Spur only during spring runoff and when water levels in Willard Spur are high. Evaporation and, more significantly, infiltration rates appear to be high in periods when water levels in Willard Spur are low, thus these runoff and irrigations flows as well as Plant effluent may only reach the open waters of Willard Spur when inflows to and water levels in Willard Spur are high. It does appear that water from the Willard Bay Outlet Channel reaches the open water on a more frequent basis due to what appears to be a dredged channel and apparent leakage from the Willard Bay outlet structure. This may facilitate Plant effluent reaching the open water of Willard Spur from the Willard Bay Outlet Channel more frequently than if the effluent were discharged onto the pastures and wetlands on the east side of Willard Spur. Willard Spur water levels and the surface area over which the effluent spreads were the two most significant factors controlling the quantity of effluent reaching Willard Spur. CH2M (2014c; Appendix C) details the methods used and results from monitoring inflows from these various locations for the period 2011–2013.

3.2.1.3 Weber River Basin

The second most significant source of inflow to Willard Spur was from the Weber River basin via HCWMA (see Figures 4–6 and Table 2). The UDWQ worked with the Utah Department of Natural Resources, Division of Wildlife Resources (UDWR), to monitor flows through 16 weirs that deliver water to the HCWMA's impoundments and Willard Spur. Additionally, UDWQ installed two flow-monitoring stations in HCWMA's bypass drain to document flow rates and volumes contributed to Willard Spur. These stations were operated nearly continuously from April 2011 through November 2013 and were effective in documenting the flow rates and volumes for the majority of these inflows to Willard Spur.

Unknown groundwater interactions likely play a significant role in determining how much of available surface water inflows reach the open water during critical summer impounded conditions.

A significant peak flow from HCWMA observed during 2011 was a result of flood flows diverted from the Weber River basin to HCWMA to minimize flooding in Weber County. Flows through HCWMA are generally consistent throughout the summer, likely due to the dominance of irrigation return flows delivered to HCWMA. While HCWMA appears to be a consistent source of water to the mudflats of Willard Spur, the percentage of the water that reaches the open water of Willard Spur appears to depend upon water levels in Willard Spur and evaporation and infiltration rates in the mudflats north of HCWMA.

UDWR's water management practices at HCWMA closely reflect its priority of providing habitat while protecting/maintaining its facilities. UDWR uses available water to first keep its impoundments full. Excess water spills out from the impoundments to Willard Spur and/or are bypassed around the impoundments via the Bypass Drain (to the east) and mudflats (to the west). CH2M (2014d; Appendix D) provides a detailed summary of methods used and results from monitoring inflows from HCWMA for the period 2011–2013.

3.2.1.4 Actual Inflow Contributions to the Open Water of Willard Spur

It was assumed in 2011 and into 2012 that all water flowing from each of the three basins contributed to the open waters of Willard Spur. This was likely true throughout 2011 as water levels in Willard Spur were generally high enough to flood the mudflats of Willard Spur. As water levels receded in 2012, however, it was observed that water in many locations flowed onto the mudflats but then never did reach the open water. Water released from western management units of BRMBR in 2013 were even observed to bypass the impoundment of Willard Spur and flow directly westward toward Bear River Bay.

Surface water inflows from HCWMA represented a consistent summer base flow to the mudflats of Willard Spur.

Studies completed in 2013 confirmed this phenomenon during the dry summer months and developed estimates for infiltration rates for various open water levels in Willard Spur. These studies focused primarily upon the fate of effluent from the Plant that was discharged onto the pasture and wetlands on the east side of Willard Spur (CH2M 2014c; Appendix C). The project was unable to characterize how much of the inflow from BRMBR and HCWMA that spread out across the mudflats reached the open water when Willard Spur water levels were low. Detailed and frequent aerial photography to map the spread (that is, surface area) of water across the mudflats will likely be needed to achieve this.

3.2.2 Precipitation (*P*)

Daily precipitation (*P*) values were calculated using USGS precipitation records from its meteorological station at BRMBR's Unit 5C Outlet (Station ID 412522112053801) and supplemented by records from the Utah Climate Center for the Brigham City Wastewater Treatment Plant weather station (Station ID

USC00420928) located 7 miles northeast of the USGS station. The USGS station was operated from May 5, 2011, through April 3, 2013. Gaps in the USGS record were supplemented with data from the Brigham City station that were available for January 1, 2011, through December 31, 2013. It was assumed that the precipitation at these stations was the same as the average over the Willard Spur study area. Precipitation was applied only to the open water surface of Willard Spur for the purposes of the water balance. Precipitation on surrounding mudflats was assumed to infiltrate and contribute to the groundwater. No corrections were applied to the data.

3.2.3 Evapotranspiration (*ET*)

Evapotranspiration (*ET*) losses for Willard Spur were calculated from estimated surface areas of open water, emergent vegetation, and reported daily reference evapotranspiration rates (ET_{ref}) from the Utah Climate Center for the Brigham City Wastewater Treatment Plant weather station (Station ID USC00420928). Data were available for January 1, 2011, through December 31, 2013. Annual ET_{ref} rates at the Brigham City Wastewater Treatment Plant weather station were 44.14 inches for 2011, 50.69 inches for 2012, and 46.57 inches for 2013.

3.2.3.1 Open Water

Evapotranspiration rates (*ET*) were calculated for the open water surface areas of Willard Spur using Equation 5 according to Allen et al. (1998) and Jensen (2010):

$$E = K_w \times ET_{ref} \qquad \text{(Equation 5)}$$

Allen et al. (1998) suggest an open water coefficient (K_w) value of 1.05 for open water depths of less than 2 meters. Jensen (2010) suggests a K_w value of 1.10 as better representing evaporation from shallow water depths. Although using the available ET_{ref} data, average daily water levels and water surface areas (CH2M, 2014a; Appendix A), and a K_w of 1.10 does not address the changing salinity of Willard Spur, it does provide a reasonable estimate of evaporation from the open water of Willard Spur. If increasing salinity levels observed during the summer months were incorporated, evaporation from the open water would likely be less.

Figure 7 compares estimated open water evaporation rates for Willard Spur for the period 2011–2013 with evaporation estimates made from historical pan evaporation data at BRMBR for the period 1948–1983 (Kadlec and Adair, 1993). Estimated open water evaporation rates for this study are below the historical average as measured at BRMBR; however, they are higher (46.8 in./yr for 2011–2013) than reported by Hill et al. (2011) as an average annual open water shallow evaporation rate at the Snowville, Utah, National Weather Service station (38.81 in./yr). This station is located approximately 50 miles northwest of Willard Spur, near the Idaho border.

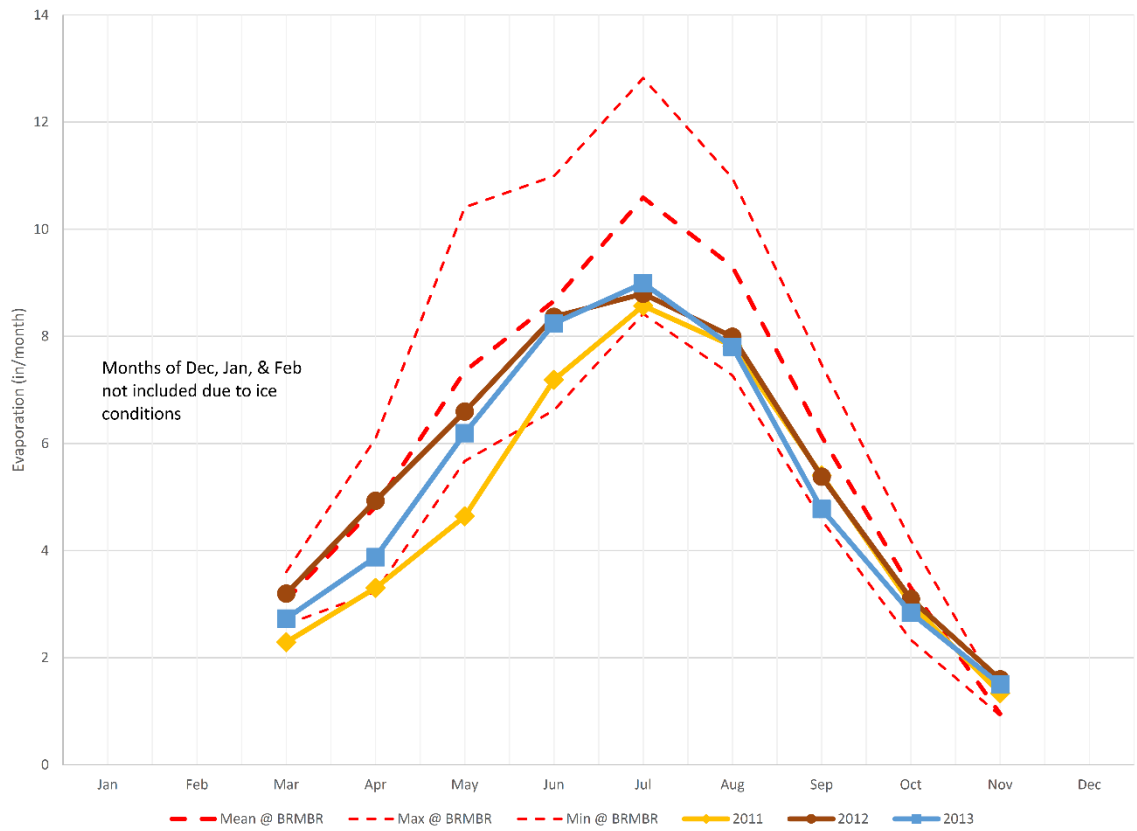


Figure 7. Comparison of Estimated Open Water Evaporation Rates for Willard Spur with Historical Record at BRMBR

3.2.3.2 Emergent Vegetation

ET from the emergent vegetation within the Willard Spur study area was estimated using a "crop" or "cover" coefficient (*Kc*) as described by Allen et al. (1998) for a large stand of cattails and modified by Allen and Robison (2007) and Hill et al. (2011) for a large stand of cattails/bulrush. The modified method accounts for the actual period between "greenup" in the spring and the full cover period until the first killing frost. The surface area of vegetation was considered constant during the study period and was estimated from vegetation mapping provided by Downard et al. (2013). It was assumed that the emergent vegetation had adequate water and was not in a stressed condition.

As with evaporation estimates, computed *ET* rates for the emergent vegetation areas of Willard Spur were higher (annual average of sum of monthly *ET* for June–October = 33.1 inches) than those estimated for large wetlands (22.4 inches) and narrow wetlands (31.5 inches) by Hill et al. (2011) for the Snowville National Weather Service station. Computed *ET* rates for Willard Spur were not adjusted, as methods used are consistent with Hill et al. (2011), use actual and localized meteorological data, and are more consistent with *ET* rates previously estimated for the BRMBR.

3.2.3.3 Adjacent Mudflats

Consideration was given to *ET* rates from adjacent saturated and partially hydrated mudflats according to Chadwick et al. (1983). *ET* losses from these mudflats were not included in the water mass balance because they would be based upon highly uncertain assumptions regarding contributing mudflat areas and groundwater levels. Inclusion of these *ET* losses would also require significant groundwater input to Willard Spur to offset these losses in the water mass balance. These groundwater inflows do not appear to be consistent with available information.

3.2.4 Surface Water Outflow (Q_{Sout})

Surface water entering Willard Spur flows generally westward, through an outflow channel north and west of Great Salt Lake Minerals' evaporation basins, and into Bear River Bay. Outflow appears to be controlled by a natural weir at the western end of Willard Spur with an elevation of approximately 4,201.9 feet. The outflow channel is extremely wide, greater than 1 mile in width, and flows are extremely shallow, generally less than 12 inches deep. Outflows were measured on eight different occasions during 2011–2014 and spanned flows from 8 to 2,665 cfs. A rating curve was developed from these data to allow the estimating of outflow rates using water level data collected at sites WS-2, WS-6, and WS-12 (see Figure 8). The outflow rating curve is considered accurate for outflows up to 2,665 cfs and where estimated water surface elevations in Willard Spur are not impacted by ice conditions. Thus, the equation for the rating curve at WS-6 could be used generally during the months of April–October (see Figure 8).

> Significant outflows from Willard Spur to Bear River Bay occurred during winter and spring months of each year regardless of whether outflows were cut off during the summer.

Figure 9 illustrates the total inflow to Willard Spur, estimated outflows based upon water surface elevations at monitoring site WS-6, and actual flow measurements. Figure 10 summarizes data from historical satellite imagery and illustrates the years in which Willard Spur experienced an impounded period during the summer. It is important to note that the condition observed in 2011, where Willard Spur flowed into Bear River Bay throughout the year, was a very infrequent event. It appears to be more typical that Willard Spur becomes an impoundment during the summer and then experiences higher, flushing flows during the winter and spring (see also Figures 3 and 9). Willard Spur was observed to be an impoundment for the dates of June 16, 2012 – November 6th, 2012, and June 9th, 2013 – November 17th, 2013. Water level elevations indicate that Willard Spur may also have been an impoundment for much of May 2013, however this was not verified in the field. CH2M (2014e; Appendix E) summarizes the methods and results from UDWQ's efforts to estimate surface water outflows from Willard Spur. Table 3 details observations and estimates related to the impounded condition.

Table 3. Summary of Characteristics of Willard Spur Impounded Conditions

Pool Elevation (ft)	Frequency (Total Days with Water Elevation Less than Pool Elevation, Total of 952 Days in Study)		Surface Area (ac)	Volume (ac-ft)	Approximate Distance of Pool from End of Dredged Willard Bay Outlet Channel (ft)	Observed Sources of Surface Water Inflow	Infiltration Observations	Comments
	No. of Days	Percentage						
4199.50	20[a]	2.1	0	0				Pool is gone, observed in 2013
4200.00	4[a]	4.9	789	197	6,900	None	Significant infiltration, all surface water disappears	Smallest Pool Elevation Observed in Satellite Imagery
4200.50	71[a]	7.5	1,562	785	2,800	None	Infiltration observed	Somewhere between 4200.50 and 4200.00 is when the outfall channel disconnected/connected to the pool in 2013
4200.55								Minimum pool elevation observed in 2012
4200.75	81	8.5	2,939	1,348	500	High potential from HCWMA & BRMBR (Google Earth images 11/2/02 and 8/24/04)	Infiltration observed	At 4200.75–4201.00, the pool is only hundreds of feet from the end of the dredged channel
4201.00	160	16.8	3,770	2,186	300	High potential from HCWMA & BRMBR (Google Earth images 11/2/02 and 8/24/04)	Infiltration observed	—
4201.50	231	24.3	6,083	4,650	0	All sources	None observed	—
4201.90	314	33.0	9,735	7,774	0	All sources	None observed	Natural Weir elevation, outflow begins

[a] Estimated, as limit of water level gauge at WS6 was 4200.52 ft.

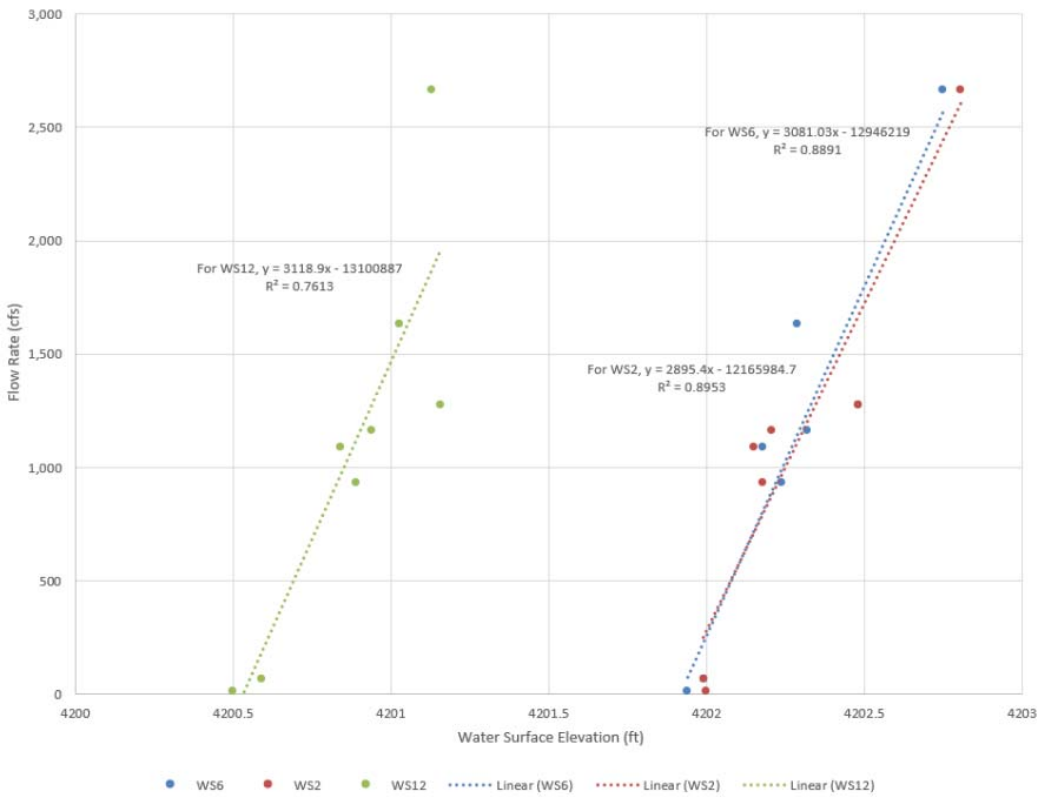


Figure 8. Rating Curve for Outflow from Willard Spur at WS-2, WS-6, and WS-12 for Outflows up to 2,665 cfs

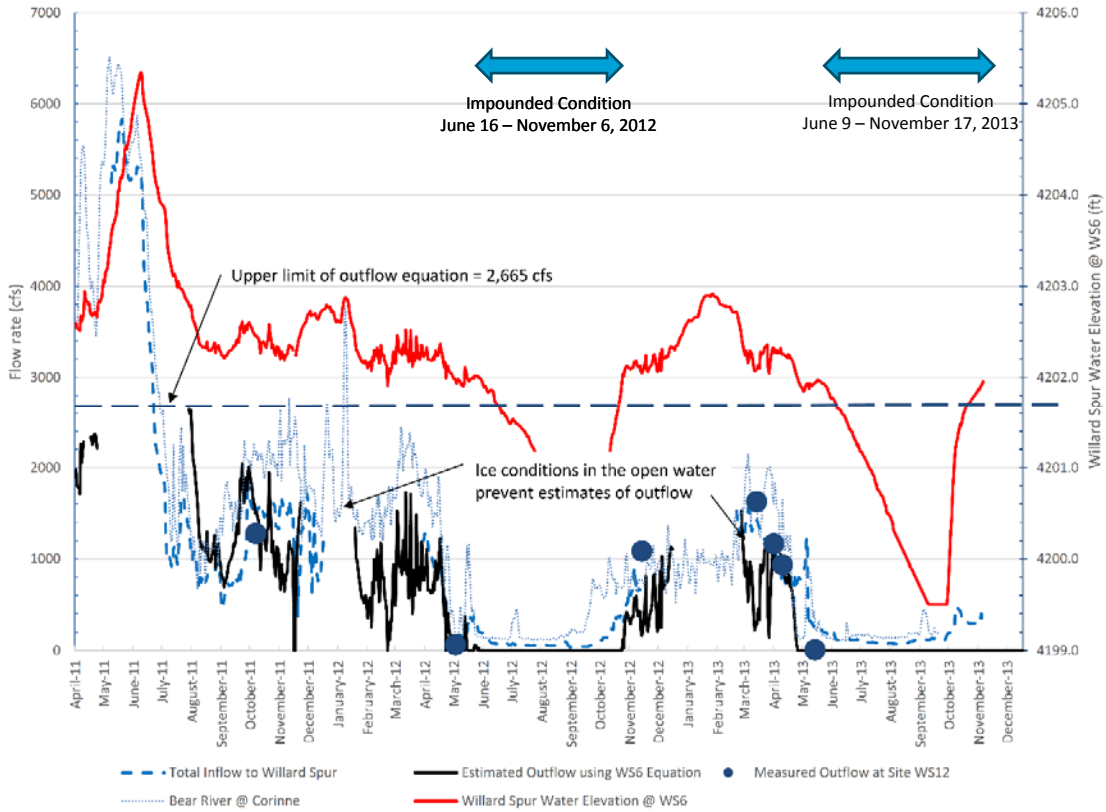


Figure 9. Estimated Outflow from Willard Spur to Bear River Bay, 2011 through 2013

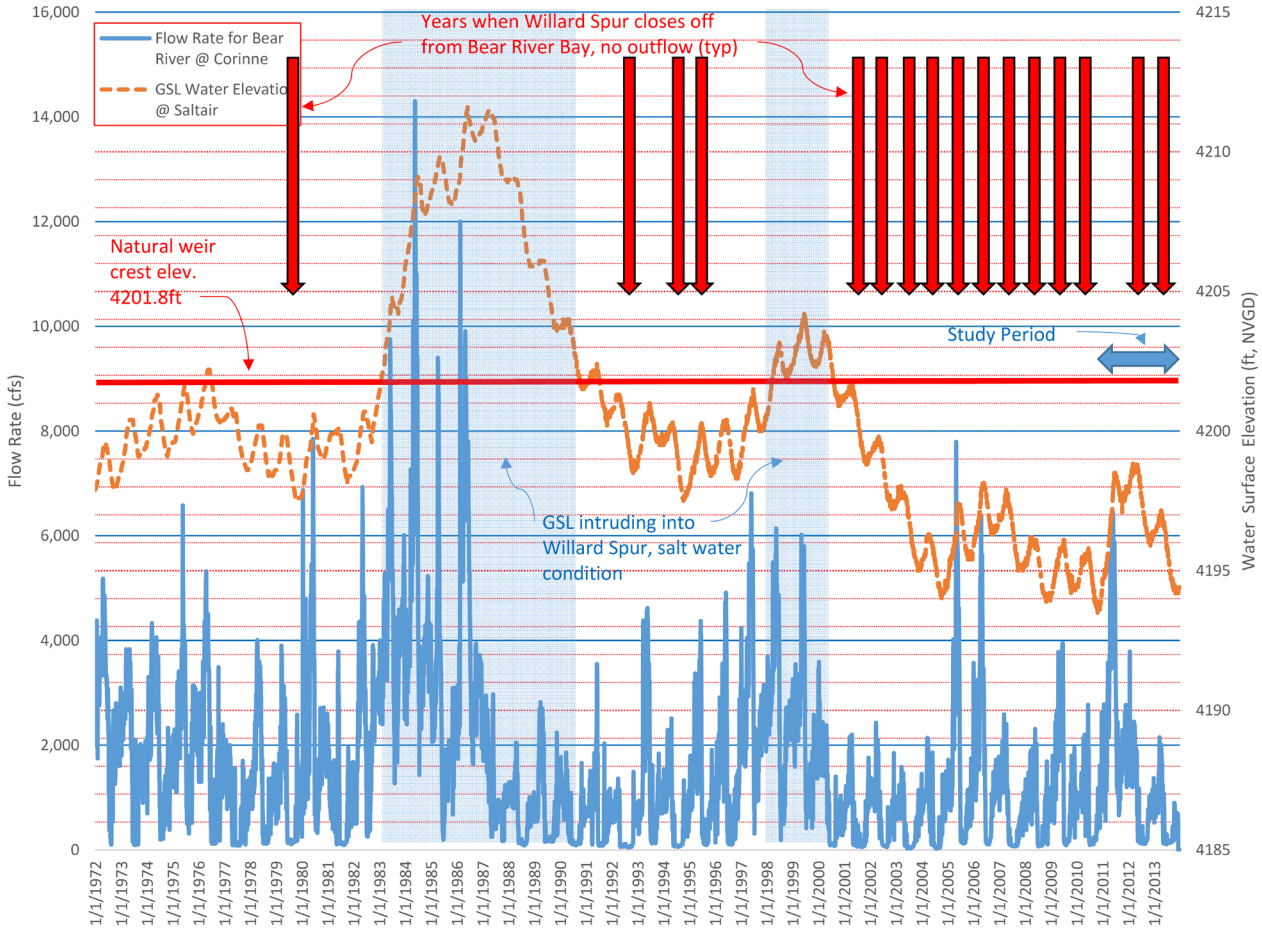


Figure 10. Timeline Illustrating the Relationship between GSL Water Elevations, Bear River Flows, and Willard Spur's Natural Outlet Weir

3.2.5 Surface Water Storage (ΔS)

UDWQ and USGS monitored water levels at the BR-11, WS-2, WS-6, and WS-12 water level gauge stations for 2011–2013 as described in CH2M (2014a; Appendix A). Each station was surveyed annually; resulting water surface elevations correlated well between stations. Digitized water boundaries, oblique aerial photographs taken by John Luft of UDWR, field observations and photographs, and water level data collected as part of the project were reconciled with available BIO-West bathymetric data to create a new map of inundated areas for water surface elevations as measured at WS-6 (see Figure 11). Water surface areas for elevations above 4,201.9 feet are estimates of inundated areas made from available aerial photography when water was flowing out of Willard Spur and when GSL water levels were not creating a backwater effect. Curves of water level vs. storage curve and of water level vs. water surface area were also developed from the water level data and available topography, aerial photographs, and field observations. The relationships between water level and water surface area and volume were essential elements of the water mass balance. Methods used and the curves are included in CH2M (2014a; Appendix A).

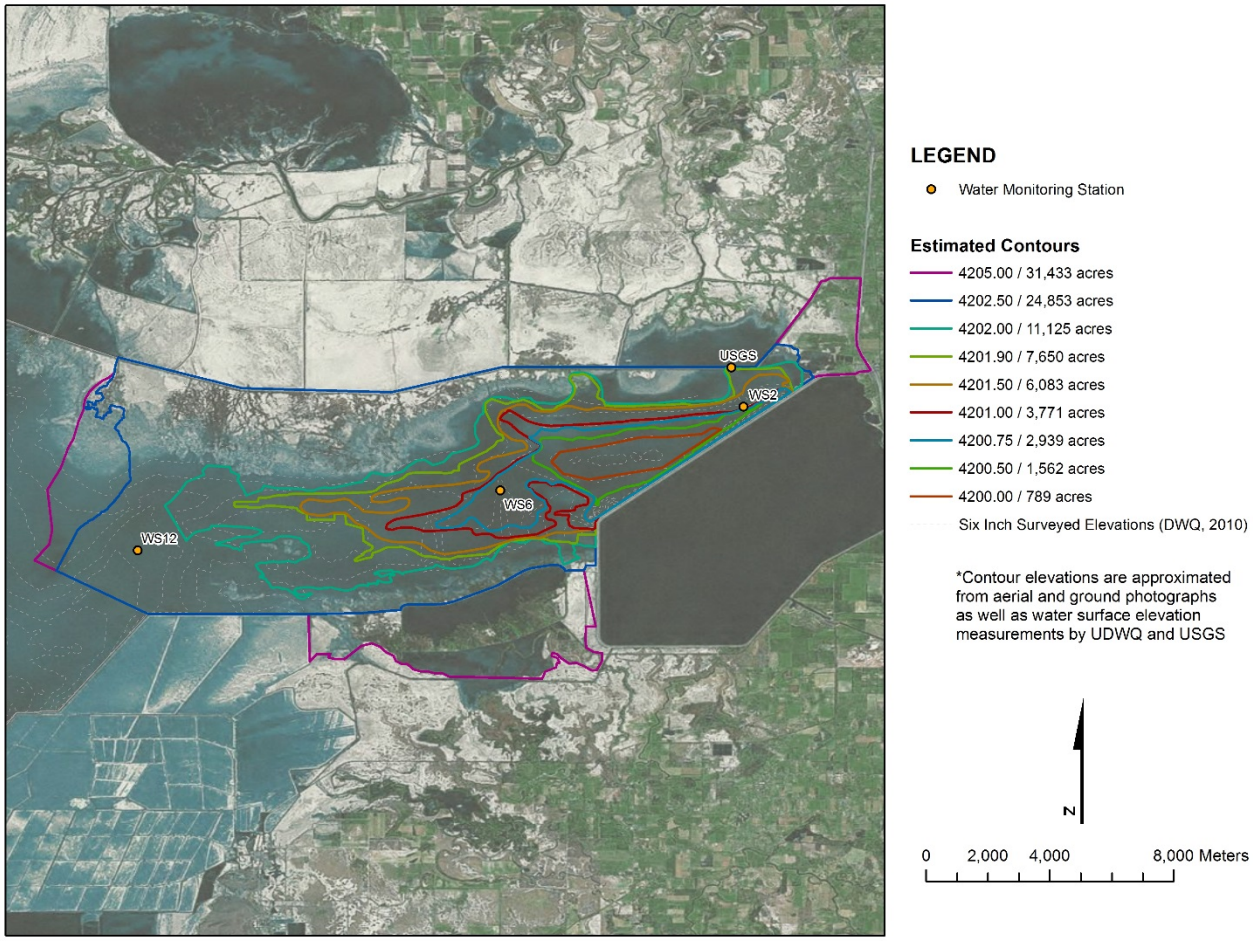


Figure 11. Map of Inundated Areas for Various Water Surface Elevations at WS-6

3.2.5.1 Groundwater Flux (Q_{Gout} - Q_{Gin})

Estimating the groundwater flux for Willard Spur was not included in monitoring plans for this project. A review of the literature and discussions with stakeholders had found that there was a lack of site-specific data and agreement that surface waters generally gained water from the aquifer in this region of GSL. Previous studies considered either the groundwater flux to be zero—that is, gains matching losses (Wanlass, 1996)—or that groundwater contributes to the surface water and is captured by surface water gauges (Kadlec and Adair, 1993). Numerous existing springs on both the east and west sides of Interstate 15 adjacent to Willard Spur do indicate that there are groundwater resources not included in the Bear River gauge at Corinne, but for lack of data these were assumed to be captured by this project's surface water–gauging effort. Thus no resources were deployed as part of this project to monitor and evaluate the groundwater flux to Willard Spur. It was assumed to be a net zero flux.

Field observations in 2013, however, began to indicate that the groundwater flux within Willard Spur may be a more significant and much more complex factor than initially considered:

- Inflows from various surface water sources around the perimeter of Willard Spur were not reaching the open water due to significant infiltration. For example:
  - UDWQ completed an evaluation of a pasture receiving the Plant's effluent on the east side of Willard Spur during July and August 2013. This evaluation seemed to confirm that the majority of the effluent was infiltrating when Willard Spur water levels were low (CH2M, 2014c; Appendix C).

  - Field observations in October 2013 noted that the normal deep pool area of Willard Spur had completely dried up, yet there was inflow observed from both BRMBR and HCWMA that simply did not reach that area. Evaporation alone could not account for why these inflows did not reach the normal deep-pool area.

- Groundwater influence upon the open water area of Willard Spur was also noted:
  - Piezometers installed by the University of Utah in their Willard Spur test plots in 2013 indicated that the open water of Willard Spur may have been losing water to infiltration on June 27, 2013, and gaining water from groundwater sources on July 30, 2013 (Pierson, 2014, personal communication).
  - Inflow volumes measured from all surface water sources to Willard Spur during the months of May–October 2012 were almost 40 percent less than inflow volumes during the same months in 2013. However, Willard Spur was able to maintain an open water area during 2012 while completely drying up in 2013. Evaporative losses alone cannot explain this difference.

While sparse and inconclusive, these data and observations indicate that there may be a localized groundwater flux that could be a factor in the water mass balance for Willard Spur.

Rather than assuming that the groundwater flux was negligible, an attempt was made to use the water balance to estimate this flux (Daniels et al., 2000). Measured and estimated values were developed for each of the variables in Equation 4 to estimate the net groundwater flux (Q_{Gout} - Q_{Gin}). Results for this analysis are discussed in Section 3.3.

3.3 Results from the Water Mass Balance

Calculating a water mass balance for an ecosystem like Willard Spur requires the following:

- A complete and correct data set to describe each of the variables within Equation 2
- The assumption that water within the system is conserved; that is, water cannot be created or disappear spontaneously

In other words, we should be able to describe how water is entering, being stored within, and exiting the system through measurements and/or calculations assuming that the sum of water moving through the system is zero. Once the data are incorporated into the mass balance equation, results are used to determine the unknown variable and identify where uncertainties lie or where more study is required. Adjustments to one or more data sets can then be made to balance or calibrate the mass balance based upon an understanding of the system's dynamics and processes.

Previous studies had assumed that groundwater interactions within the area of Willard Spur represented a net zero flux thus simplifying the mass balance by eliminating groundwater as a variable in the equation (see Equation 3). What was observed during the course of this study, however, was that the groundwater flux is most likely not zero. Thus, rather than allowing the project team to evaluate how and where to attribute any uncertainty and error in measurements within the known variables, the project team had to weigh those uncertainties along with the completely unknown variable representing the groundwater flux (see Equation 4). This made it exceptionally difficult to evaluate any other uncertainties in the data, especially when there were other variables without data to describe them (for example, outflow measurements for flows that exceeded 2,665 cfs).

The mass balance was developed using Equation 4 with the groundwater flux as the unknown variable. This approach uses the groundwater flux to balance the mass balance equation for each month; that is, the sum of all of the other variables results in the groundwater flux. This results in a fair estimate of the groundwater flux with the understanding that these estimates also include any unknown uncertainty or error in measurements or calculations of the other variables. Known uncertainties were addressed as

discussed above (for example, estimates of inflows, evapotranspiration, and outflows), and a mass balance is not provided where the uncertainties could not be reconciled (as discussed below).

Data describing each of the variables were formatted and incorporated into a monthly water mass balance for the months of September 2011 and April–October of 2012 and 2013 (see Figure 12). The factors that limited the months where the mass balance could be computed include the following:

- Monitoring stations were first deployed in April 2011; however, not all stations were deployed until the end of May 2011. The first full month with a complete data set was June 2011.
- Outflow estimates are limited to flows less than 2,665 cfs (see discussion in Section 3.2.4). As a result, outflows as well as the groundwater flux were unknown variables for all months in 2011 except for September. Having two unknown variables, outflows and groundwater flux, within the mass balance equation precluded useful results, and mass balance results are not shown for these months.
- Ice conditions observed during winter and early spring months did not allow for accurate water surface level measurements. This affected inflow measurements and outflow estimates for these months; thus they were not included.

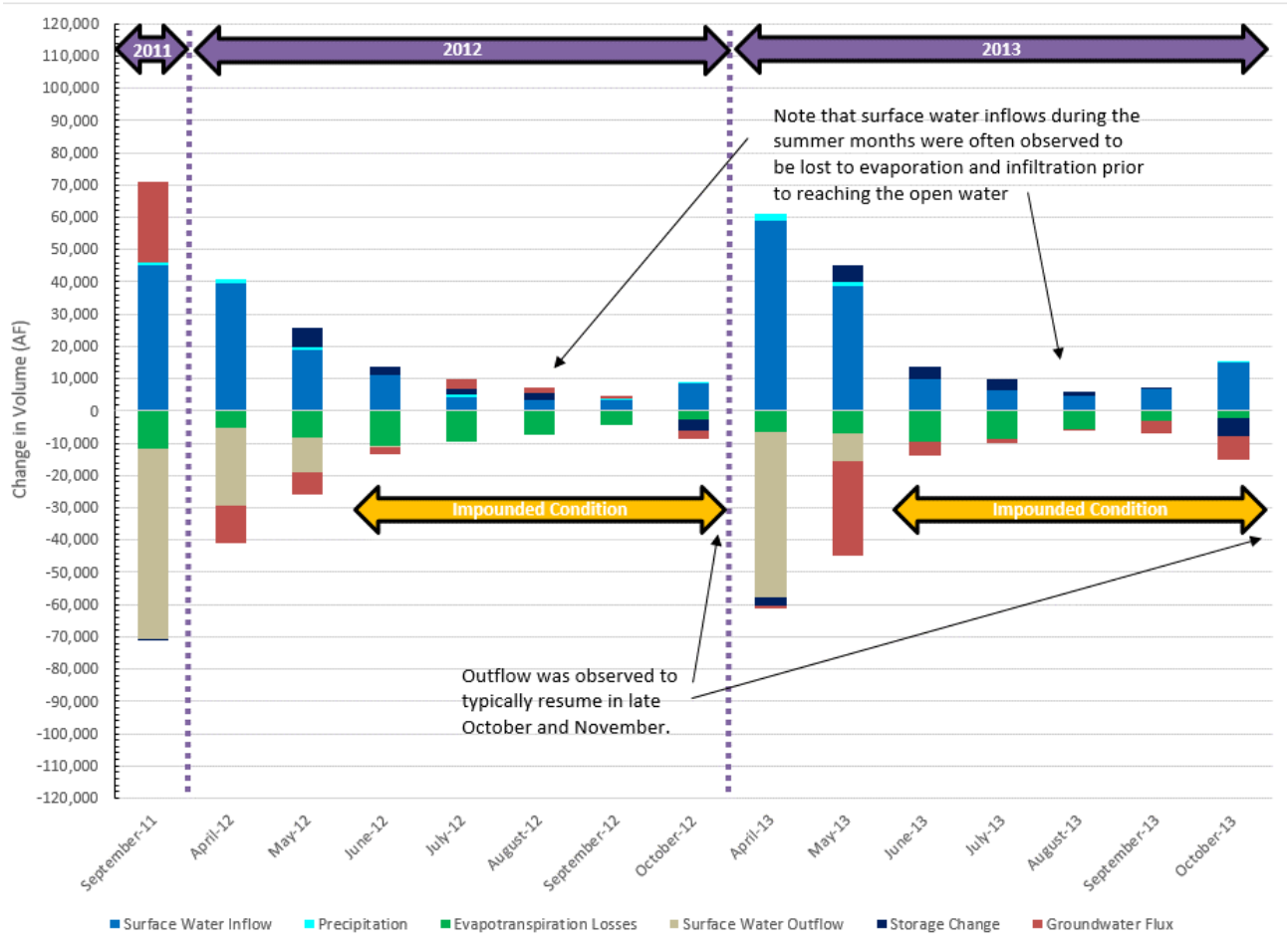


Figure 12. Estimated Monthly Water Mass Balance for Willard Spur, 2011–2013

3.4 Observations

A number of observations can be made from the computed water mass balance for Willard Spur (see Figure 12):

1. The water balance supports the observation previously discussed, that inflows during the months of October–May fill Willard Spur and overflow into Bear River Bay. As spring flows dissipate in June, a decline in outflow to the point where there is no outflow is observed, and Willard Spur becomes an impoundment. There is a significant reduction in the surface area and water storage within Willard Spur during summer months until surface water inflows increase again in the fall.
2. Willard Spur appears to have already been "full" in April 2012 and April 2013, as indicated by the lack of change in storage over each month. This indicates that winter and early spring flows had already maintained a "full" storage volume, and the late spring runoff peak was largely flowing through Willard Spur and into Bear River Bay.
3. The open water of Willard Spur appears to contribute to the groundwater aquifer during the spring runoff period but then be fed by groundwater contributions during the summer months. Given that the surface water inflow volumes shown during these summer months were observed to evaporate and infiltrate across the mudflats prior to reaching the open water, this connection to the groundwater appears to be critical in maintaining the open water impoundment during the summer. The groundwater contribution appears to have been more significant in 2012 than in the following dry year of 2013.
4. Willard Spur appears to contribute to the groundwater aquifer again as fall surface water inflows increase. As discussed in CH2M (2014a; Appendix A), a comparison of water levels monitored by UDWQ at water level station WS-6 and estimated total inflows to Willard Spur indicates that outflows to Bear River Bay stopped at surface water inflow rates of approximately 200 cfs (Figure 13). Outflows to Bear River Bay resumed when inflow rates were at approximately 400 cfs. The water balance (September and October) appears to confirm that the disparity between these two flow rates is likely a function of evaporation, infiltration, and a lag resulting from the rising hydrograph first filling the available storage volume, including the groundwater storage volume, and then proceeding to outflow into Bear River Bay.
5. Surface water inflow volumes were less in 2012 than in 2013, yet Willard Spur maintained an open water area in 2012 while completely drying up in 2013. Additionally, the water mass balance indicates that more water was "lost" to groundwater in fall 2013 than in fall 2012. This occurred while surface water inflows were increasing and before surface water flowed out and into Bear River Bay in late October or early November. Both factors appear to indicate that groundwater levels may have dropped year to year from 2011 through 2013.
6. Evapotranspiration losses were greater in 2012 than in 2013, largely due to more open water surface area. If evapotranspiration losses during the summer had been greater than those shown, such as from the mudflats surrounding the open water, then groundwater contributions to the open water would also have been greater.

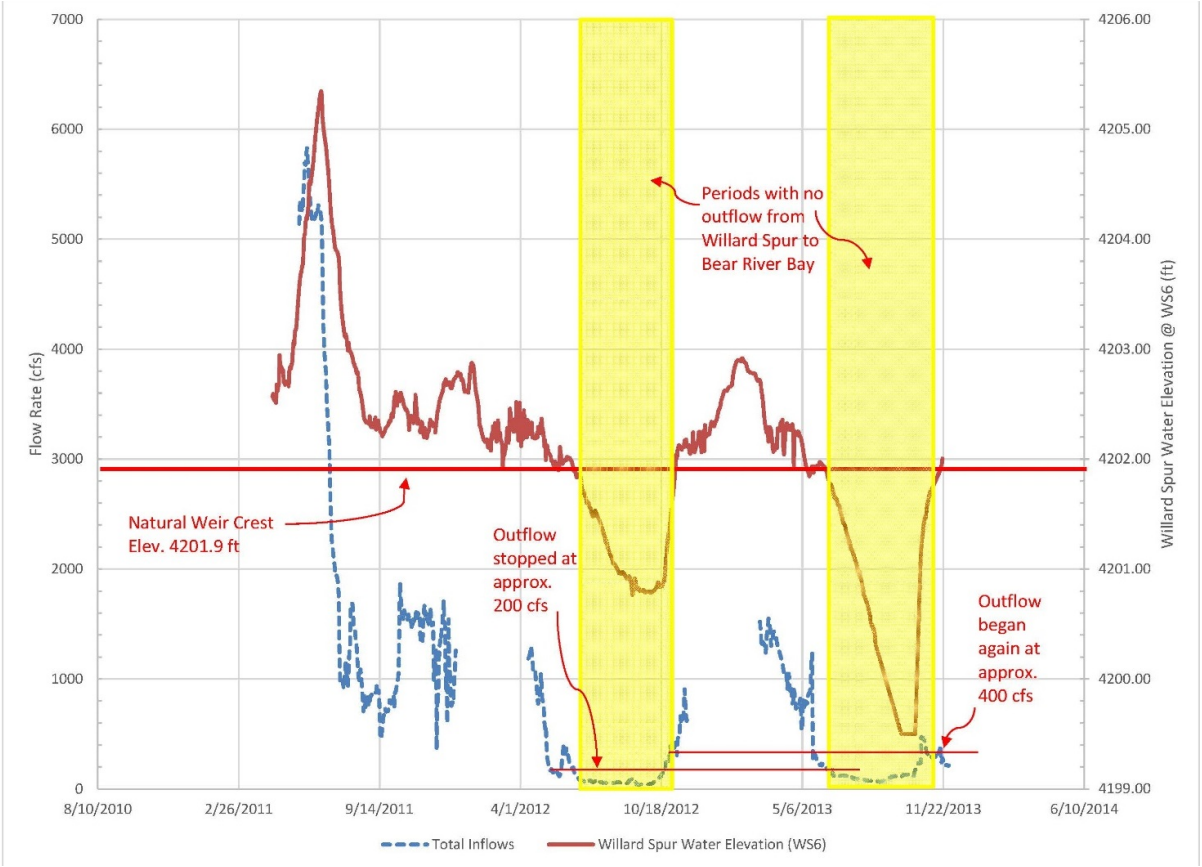


Figure 13. Occurrence of Outflow from Willard Spur vs. Water Elevation and Estimated Total Inflow Rates, 2011–2013

Conclusions

UDWQ invested significant resources to understand Willard Spur's hydrology, how it supports its ecosystem, and the role the Plant's effluent plays in these dynamics. The results provide insight into the mechanisms that support the complex ecosystem of Willard Spur and represent a foundation upon which decisions can be made regarding the potential impacts of the Plant and how Willard Spur can be protected into the future. This section summarizes the most pertinent observations made as part of this study.

4.1.1 Comprehensive and Integrated Hydrologic Monitoring Was Essential to Meeting Objectives

Very little information was available at the outset of the project to describe and understand the dynamics of Willard Spur's hydrology. Careful integration of inflow measurements, water surface elevation monitoring, and outflow measurements over the period of 3 years was essential to understanding how water is received, stored, and conveyed by Willard Spur to GSL. This led to a better understanding of Willard Spur's surface water inflow sources, interactions with groundwater, how surface water outflow is controlled, and perhaps how and why Willard Spur's chemistry and vegetation, fish, avian, and macroinvertebrate communities are so dynamic.

4.1.2 Surface Water Inflows from Three Basins

The Bear River Basin, on the northern boundary of Willard Spur, typically contributed the vast majority of surface water inflows to Willard Spur. All of these flows were managed by the USFWS as they were conveyed through the BRMBR. Surface water inflows from the Weber River Basin, on the southern boundary, although substantially less in volume, were similarly managed by the UDWR as they were conveyed through the HCWMA. HCWMA was an important and consistent source of water during critical, dry summer months observed in 2012 and 2013. The East Side Basin had several different sources. The Willard Bay Reservoir was a significant source of inflow only during the flooding conditions experienced in 2011. The Plant contributed a consistent but negligible volume of water—less than 1.5 percent of the total inflow (at "end-of-pipe") during the driest months observed. The quantity of these surface water inflows that then flow across the mudflats and actually reach the open water during critical summer months became an important question, especially in light of determining the impact of the Plant's effluent (CH2M, 2014b–d; Appendixes B–D).

4.1.3 Typical Seasonal Cycle Is Key to Willard Spur's Present Condition

The seasonal hydrologic cycle that Willard Spur typically experiences every year, accentuated by extreme events such as those observed in 2011, contribute to the resiliency of Willard Spur and its nutrient-cycling processes. The typical seasonal cycle is as follows:

- A small peak in surface water inflows in February–March as snow in the surrounding foothills melts.
- A larger peak during spring runoff in April–June as snowmelt from the upper watershed reaches Willard Spur
- A sharp reduction in surface water inflow in May–September as snowmelt ends and upstream water demands reach their peak, typically resulting in an impounded condition (no outflow) during these summer months
- An increase in and sustained surface water inflow pattern in October–January as upstream water demands decrease significantly

Uniquely and perhaps most importantly is that this annual pattern includes an impounded condition during the summer months followed by continuous, higher flushing flows during fall–spring. The impounded condition creates the limiting, critical conditions for nutrient cycling during the summer and the potential for nutrients and organics to accumulate over time and exacerbate nutrient responses (UDWQ 2015a). By contrast, the higher flushing flows during fall–spring appear to remove any nutrients and organics that may have accumulated during the annual impounded period and reduce the likelihood of these nutrients becoming a long-term nuisance. These patterns had been observed from satellite imagery, but their importance became evident through the detailed monitoring conducted by UDWQ (UDWQ 2015b).

4.1.4 Natural Weir Is Central to Conditions in Willard Spur

Willard Spur has historically functioned as either a saltwater- or a freshwater-dominated ecosystem, though it has been a freshwater-dominated ecosystem since approximately 2001 (see Figure 10). Existing mudflats form a natural weir near the western boundary of Willard Spur and appear to be a key factor that controls when GSL waters can spill into Willard Spur and how they mix within Willard Spur. Similarly, this same natural weir also serves as a control for surface water outflows and helps create the impounded condition observed in 2012 and 2013 (CH2M, 2014e; Appendix E).

4.1.5 Groundwater Interactions Are More Significant Than Initially Thought

A review of the literature had indicated at the outset of the project that the groundwater flux was likely zero or could be fully accounted for by measuring surface water outflows. Field observations midway through the project (2012) indicated that significant quantities of surface water inflows were evaporating and infiltrating into the mudflats before reaching the open water of Willard Spur. This was critical in that much of the Plant's effluent did not reach the open water during the critical, dry summer months when the open water of Willard Spur was impounded. Groundwater levels were found to be an important factor in preserving the open water surface area; thus, open water areas are likely not solely dependent upon surface water inflows at low water levels. Further, the mass balance appears to indicate that the shallow groundwater aquifer may need to be recharged before surface water flows out into Bear River Bay in the fall. All of these observations reinforce the importance of groundwater interactions to the hydrology of Willard Spur.

4.1.6 Impounded Condition Appears to Be the Critical Condition

As surface water inflows diminish and an impounded condition occurs within Willard Spur, many important changes begin to take place within the ecosystem. The open water of Willard Spur continues to recede, becoming warmer and more saline with time (UDWQ 2015b). Surface water inflows no longer reach the open water but largely infiltrate into the mudflats depending upon the open water and groundwater level. Groundwater interactions become critical toward maintaining the open water and determining if Willard Spur will dry up completely. Any addition of new surface water inflow (for example, effluent from the Plant) has the opportunity to influence conditions within this largely closed open-water system. Anything that is added to the impounded ecosystem likely stays within the ecosystem until surface water inflows increase in the fall and water again flushes through Willard Spur.

4.1.7 Plant's Effluent Does Reach the Open Water, but Under Certain Conditions

The Plant's effluent was observed to reach the open water of Willard Spur typically when open water levels were high and the effluent was then more easily diluted, dispersed, and exported to Bear River Bay. It was less likely to reach the open water of Willard Spur when open water levels were low and the effluent could not be diluted, dispersed, and exported as easily. This was a function of where the effluent was discharged and that the effluent had a propensity to evaporate and infiltrate as the water flowed through wetland areas. Effluent discharged to the Willard Bay Outlet Channel was more likely to reach the open water of Willard Spur when water levels were low than if discharged to wetlands simply

because the channel is deep and remains connected to the open water for most dry conditions (CH2M, 2014c; Appendix C). This is considered to be the critical condition in terms of potential impacts from the Plant.

Figure 14 represents the results of a simulated water balance for the Plant's effluent expressed as a percentage of the Plant's effluent that reaches the open water of Willard Spur for a wet year (2011). The private wetland/pasture was within the open water of Willard Spur for most of 2011. The slight losses observed from the Willard Bay Outlet Channel are entirely from evaporation of the channel's water surface. Figure 15 presents results from a similar analysis for a dry year (2013). The primary difference in a dry year is that water levels in Willard Spur are considerably lower than those in a wet year. Thus, there is a greater water surface area in the private wetland/pasture where evaporation and infiltration present significant losses. Similar losses, although not as significant, are observed from the Willard Bay Outlet Channel. These estimates illustrate how the evapotranspiration and infiltration could reduce effluent contributions to the open water of Willard Spur.

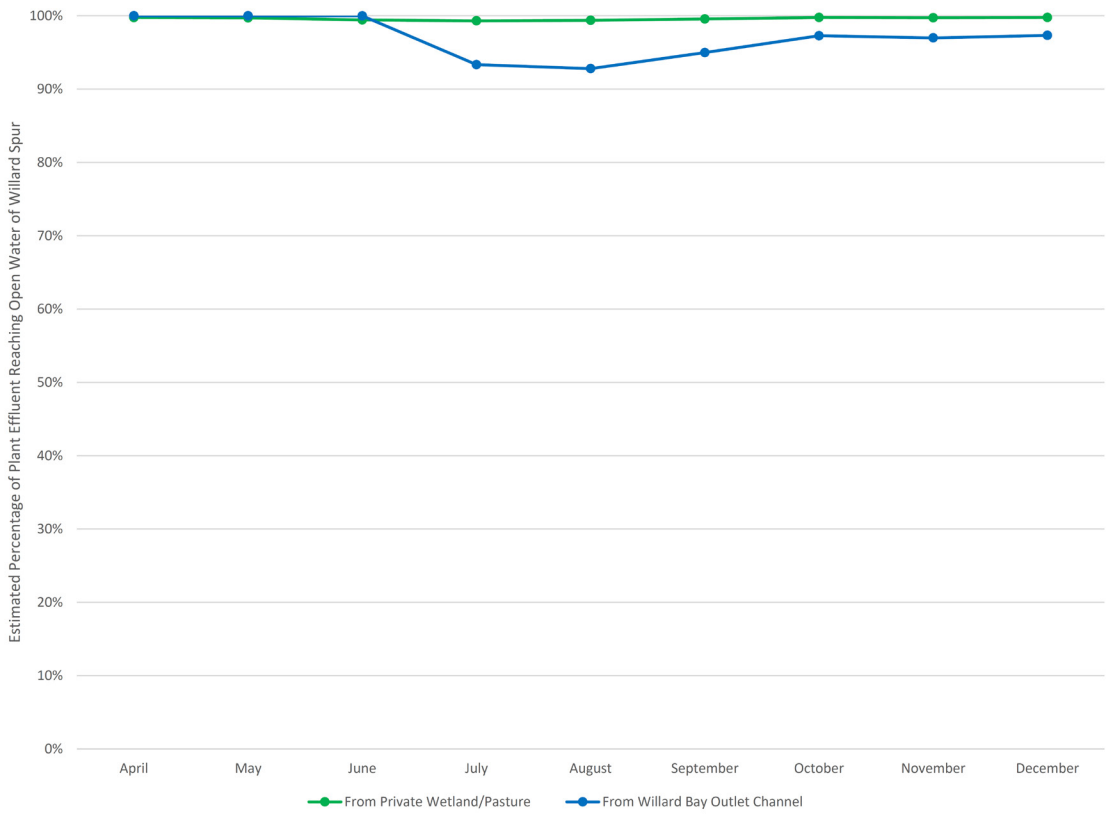


Figure 14. Simulated Percentage of Plant Effluent Reaching the Open Water of Willard Spur for a Wet Year (2011)

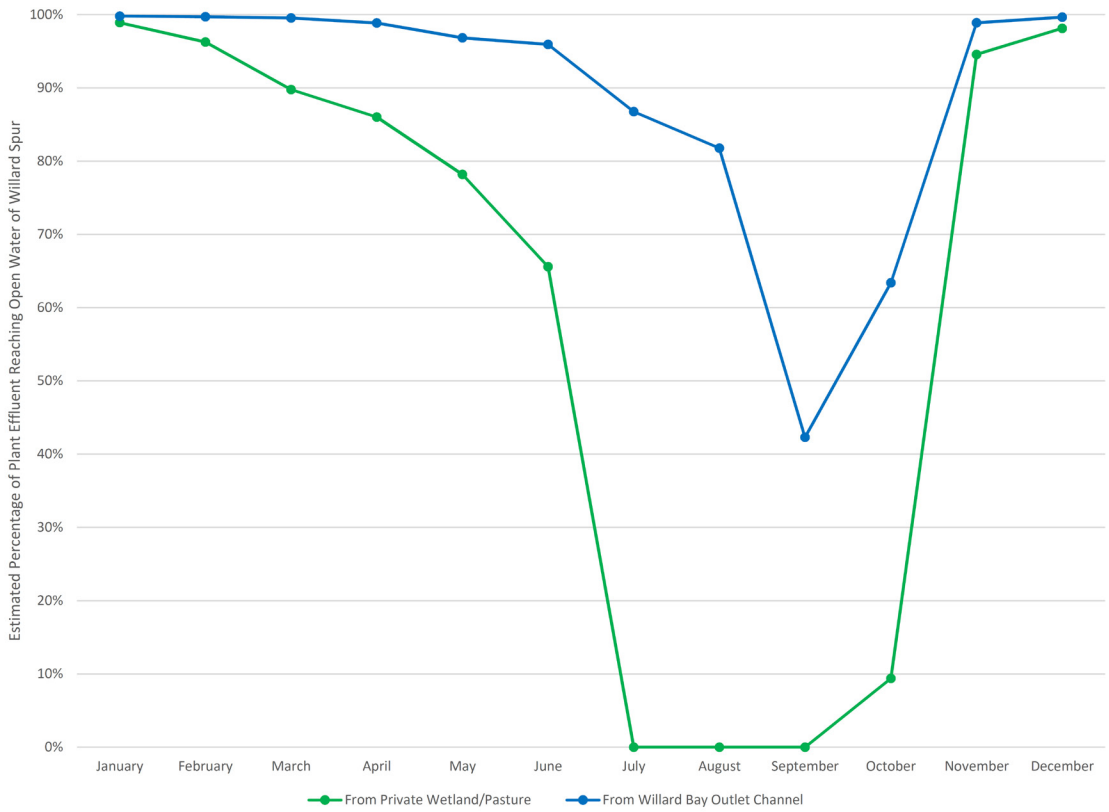


Figure 15. Simulated Percentage of Plant Effluent Reaching the Open Water of Willard Spur for a Dry Year (2013)

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