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Journal of Hydrology 320 (2006) 501–517
Journal of Hydrology
www.elsevier.com/locate/jhydrol

A water-budget approach to restoring a sedge fen affected by diking and ditching

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Received 10 May 2005; revised 23 May 2005

Abstract

A vast, ground-water-supported sedge fen in the Upper Peninsula of Michigan, USA was ditched in the early 1900 s in a failed attempt to promote agriculture. Dikes were later constructed to impound seasonal sheet surface flows for waterfowl management. The US Fish and Wildlife Service, which now manages the wetland as part of Seney National Wildlife Refuge, sought to redirect water flows from impounded C-3 Pool to reduce erosion in downstream Walsh Ditch, reduce ground-water losses into the ditch, and restore sheet flows of surface water to the peatland. A water budget was developed for C-3 Pool, which serves as the central receiving and distribution body for water in the affected wetland. Surface-water inflows and outflows were measured in associated ditches and natural creeks, ground-water flows were estimated using a network of wells and piezometers, and precipitation and evaporation/evapotranspiration components were estimated using local meteorological data. Water budgets for the 1999 springtime peak flow period and the 1999 water year were used to estimate required releases of water from C-3 Pool via outlets other than Walsh Ditch and to guide other restoration activities. Refuge managers subsequently used these results to guide restoration efforts, including construction of earthen dams in Walsh Ditch upslope from the pool to stop surface flow, installation of new water-control structures to redirect surface water to sheet flow and natural creek channels, planning seasonal releases from C-3 Pool to avoid erosion in natural channels, stopping flow in downslope Walsh Ditch to reduce erosion, and using constructed earthen dams and natural beaver dams to flood the ditch channel below C-3 Pool. Interactions between ground water and surface water are critical for maintaining ecosystem processes in many wetlands, and management actions directed at restoring either ground- or surface-water flow patterns often affect both of these components of the water budget. This approach could thus prove useful in guiding restoration efforts in many hydrologically altered and managed wetlands worldwide.
Published by Elsevier B.V.

Keywords: Ground-water/surface-water interactions; Water budget; Wetland restoration; Seney National Wildlife Refuge

1. Introduction

The largest wetland drainage project in the history of the State of Michigan, USA was initiated in 1912 when ditching began on lands that are now part of Seney National Wildlife Refuge (Fig. 1). Ditches

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0022-1694/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jhydrol.2005.07.026

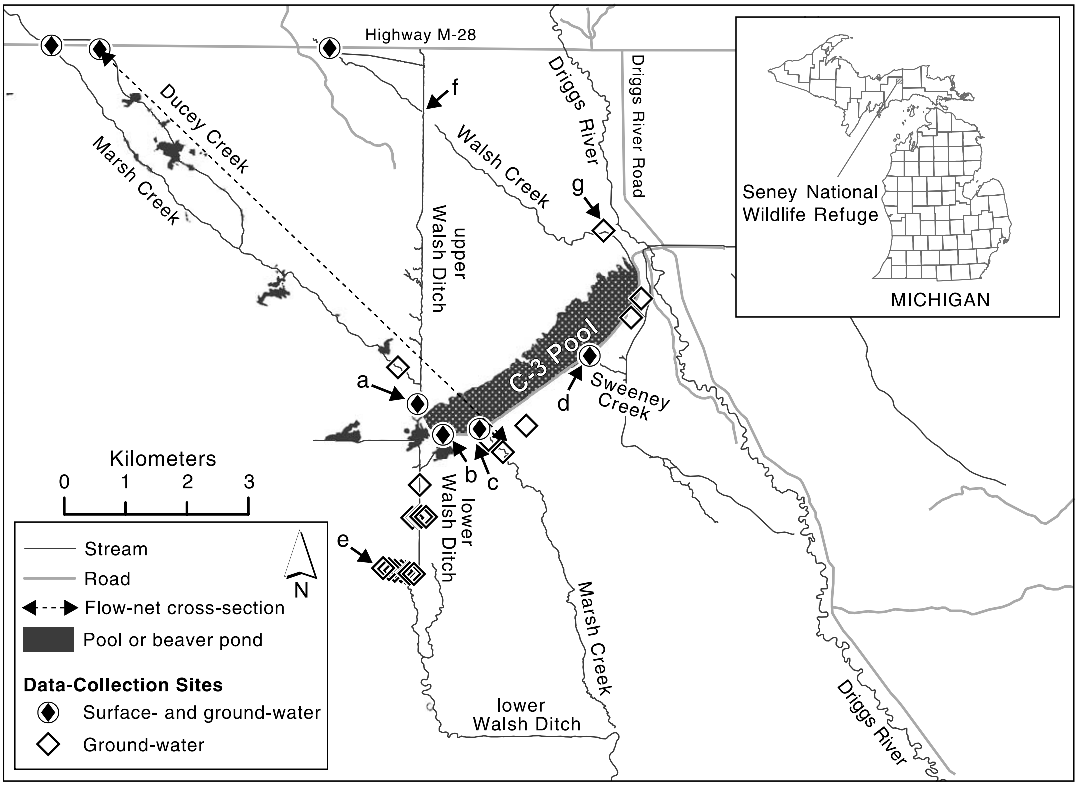

Fig. 1. Map of the C-3 Pool and Walsh Ditch study site in Seney National Wildlife Refuge showing water features and data-collection sites. Letter designations represent locations referenced in the text. The entire drainage system flows generally from northwest to southeast. Lower Walsh Ditch enters the Manistique River 20 km to the south.

totaling more than 30 km in length were dug across an undeveloped sedge fen approximately 20,000 ha in area in an attempt to convert the land to agricultural use. The agriculture venture failed, the drainage system was abandoned, and the land eventually was included in the refuge in 1935, much of it now designated wilderness. In the early 1940 s, numerous earthen dikes were constructed perpendicular to the natural springtime sheet flow of water across the wetland to create potential wildlife habitat.

The largest impoundment is C-3 Pool, which intersects the main ditch system in the wetland (Walsh Ditch). Walsh Ditch and C-3 Pool greatly altered natural hydrology in the wetland and resulted in other environmental impacts. Walsh Ditch intercepted the flow of Walsh and Marsh Creeks, incised the ground-water table, and directed the flow of water to the Manistique River to the south. Peak flows during spring runoff caused extensive erosion in Walsh Ditch and adjacent wetlands below the pool and sent large volumes of sand to the Manistique River, increasing its bed load and adversely affecting fish habitat (M. Tansy, pers. comm.). Lowering of the water table in the wetland allowed oxidation and subsidence of wetland peat, fostered an extensive peat fire, and altered vegetation and wildlife habitat in the hydrologically affected part of the wetland. C-3 Pool created habitat for some wildlife species, but the impoundment interrupted springtime sheet flow and converted peatland to open water.

US Fish and Wildlife Service managers at Seney National Wildlife Refuge proposed to restore habitat in the affected wetlands and reduce deposition of sand into the Manistique River by blocking Walsh Ditch downslope from C-3 Pool and diverting water to the original Marsh Creek channel and to sheet flow across the wetland. This proposed action had many potential ramifications. Improper distribution of diverted water could cause erosion in Marsh Creek and damage wetlands or downstream property; improper treatment of the abandoned ditch could result in failure to restore natural ground-water flows; wetland vegetation would likely change in some areas as a result of new hydrologic alterations; and water chemistry in wetlands could change as a result of changes in water supply. The presence of beaver throughout the refuge could also affect both hydrology and vegetation.

Because so little was known about the ramifications of the proposed actions, studies were conducted in association with the restoration project to provide guidance to refuge managers and to provide pre-restoration data for use in evaluating ecological and environmental changes that occur during and following restoration. The studies evaluated current ecological conditions related to presence of the ditch and pool (Kowalski and Wilcox, 2003) and assessed hydrologic conditions in the wetland (Sweat, 2001). The objectives of this paper are to describe the use of the hydrologic data to evaluate potential reallocation of inputs and outputs during high flow periods and to guide restoration of both surface- and ground-water hydrology in the affected C-3 Pool/Walsh Ditch area. Hydrologically altered and managed wetlands are common in wildlife refuges worldwide; thus, this approach may have broad applications for restoration efforts.

2. Site description

Seney National Wildlife Refuge is located in the east-central and southeastern Upper Peninsula hydrologic provinces of Michigan (Rheaume, 1991) about mid-way between lakes Superior and Michigan (Fig. 1). Terrain slopes S75°E at 1.1–1.3 m/km (Heinselman, 1965). Surface deposits, primarily of glacial origin, are well-sorted sand, 0–60 m thick, overlying Ordovician sandstone, limestone, and dolomite. Two-thirds of the refuge is mantled by peat deposits, which range in thickness from a few centimeters to more than 2 m. Peatland vegetation consists of broad expanses of sedge fen mixed with shrub- and tree-dominated areas, as well as outcrops of underlying sand that result in a scattering of islands with upland vegetation across the wetland. Long-term average precipitation is 80.4 cm/yr, and long-term average temperature is 5.1 °C (National Climatic Data Center, 2000). However, precipitation was below average and temperature above average during the study period. Water in the peatland is mineralized and representative of water chemistry of a highly alkaline fen (Malmer, 1986). During the low flow season, surface-water specific conductance generally falls within the range of 175–275 μS/cm, pH in the range of 6.8–7.7 units, and alkalinity in the range of 115–150 mg/L as $CaCO_3$. Ground-water specific conductance generally falls within the range of 215–400 μS/cm, pH in the range of 6.5–7.1 units, and alkalinity in the range of 140–180 mg/L as $CaCO_3$ (Kowalski, 2000).

As built, south-flowing Walsh Ditch captured the flow of Walsh creek and redirected it from the Driggs River to Marsh Creek and, ultimately, to the Manistique River. It also rerouted the flow of Marsh Creek after its confluence with Ducey Creek (Fig. 1). The ditch flowed south 11.2 km from state highway M-28, turned east for 3.2 km, and then flowed another 20.9 km south to the Manistique River, not all of which was through wetland (Fig. 1). The ditch later became the major source of water for C-3 Pool. The portion of the ditch from 2.2 to 3.7 km south of C-3 Pool is no longer functional due to collapsing peat and sand, and water now flows in adjacent channels eroded through the peat. The 6.3-km-long C-3 Pool dike crosses the wetland from southwest to northeast and creates a pool approximately 269 ha in area that varies in size with season (Fig 1). The watershed for C-3 Pool comprises approximately 5520 ha. During winter, snow and ice accumulate in the watershed, to be released as surface water in the spring. Maximum flows into C-3 Pool typically occur during spring rainstorms via sheet flow from northwest to southeast and through upper Walsh Ditch after its confluence with Walsh and Marsh Creeks (Fig. 1). Surface water then accumulates behind the C-3 Pool dike and must be released. A control structure in the C-3 Pool dike regulates the level of C-3 Pool and discharge to lower Walsh Ditch. A smaller control structure in the dike regulates discharge to Sweeney Creek, which augments flow to a series of smaller pools further to the south. In 1997, a culvert was installed in the dike to allow future discharge into the historical Marsh Creek channel, which had been segmented by dike construction (Fig. 1). Past management practices allowed some discharge to Sweeney Creek, but most excess water was discharged to lower Walsh Ditch, resulting in erosion of peat and underlying sand and formation of a gully as wide as 50 m and as deep as 6 m. The water table in peatland adjacent to the downstream Walsh Ditch gully subsequently declined, the peat surface subsided, and a lightning-strike peat fire that persisted for three months occurred in 1976 (Anderson, 1982; M. Tansy, pers. comm.).

3. Methods

Addressing two general management concerns, reallocation of outflows from C-3 Pool in the spring and hydrologic restoration of the study area, required slightly different approaches. A water budget for C-3 Pool that encompassed the high flow season and focused on surface water could address reallocation of outflows. However, information on other hydrologic inputs and outputs, an annual water budget, and further information about ground-water flows were necessary to address overall hydrologic restoration. Many of the same data could be used in meeting both objectives. Despite the uncertainty that is inherent in most water-budget calculations, the dominance of surface-water flows to C-3 Pool likely overshadowed the errors sufficiently to allow management decisions to be made.

3.1. Precipitation

Daily precipitation data were obtained from the National Climatic Data Center (2000) for the former Seney National Wildlife Refuge station located 17 km southeast of C-3 Pool, which was in operation until 2002. Data were summed over the 1999 water year (October 1, 1998 to September 30, 1999) and over the spring runoff period (January 15 to June 30). To determine precipitation input to C-3 Pool alone, those sums were then multiplied by the 269 ha area of the pool.

3.2. Surface water

To quantify surface-water inflow to C-3 Pool, a staff gage was established in September 1998 in upper Walsh Ditch at the most downstream point possible before it enters backwater from the pool (a: Fig. 1), the ditch cross-section was profiled, and nine discrete discharge measurements and staff gage readings at various flow regimes were made over 22 months, with qualitative ratings noted for each discharge measurement. However, the surface-water record for determining annual surface-water input was not continuous; therefore, a time-slice method was used to replace missing data. Measured instantaneous discharges were first converted to estimated 24 h discharges. For each daily discharge, a time interval was determined in which start and end dates were bounded by points midway to previous and subsequent collection dates, respectively. The number of days in the time interval was multiplied by the corresponding daily discharge value, and those products were then summed over the water year and the spring runoff period to determine total surface-water input. This upper Walsh Ditch data-collection site accounts for nearly all of the upstream watershed west of Walsh creek. No data-collection point was established for surface-water input from the C-3 Pool watershed east of Walsh Ditch because flows were not detected in the remnant of Walsh Creek downstream from where it was cut off by Walsh Ditch (Fig. 1). Therefore, precipitation input for that part of the watershed, determined as described above, was reduced by losses expected from evapotranspiration from that part of the watershed and used as surface-water input to C-3 Pool. The area is bounded to the north and east by the Driggs River basin and has no other surface-water inputs (Fig. 1). Ground water may also have discharged to this area prior to restoration actions, but data were not sufficient to quantify it.

Evapotranspiration loss for the area described above was calculated using the Mather equation (Mather, 1978). Studies have shown that estimates of evapotranspiration by this equation compare reasonably well with methods using energy budget calculations in wetlands of similar latitudes when only temperature data are available (Winter et al., 1995; Rosenberry et al., 2004). Daily temperature data for the Seney National Wildlife Refuge weather station were obtained from the National Climatic Data Center (2000). The evapotranspiration calculations were summed over the two study periods. These sums were then multiplied by the upslope area not accounted for by surface-water data to obtain volume of water lost to evapotranspiration.

Outflow from C-3 Pool was measured at the Walsh Ditch (b) and Sweeney Creek (d) control-structure outlets of C-3 Pool (Fig. 1) by making 10 and 20 wading discharge measurements, respectively, using either a Pygmy or Price AA vertical-axis current meter. Discharge was also measured in Marsh Creek (c) downstream from the dike, although no flow was detected routinely. In July 1999, water was discharged for 2 days from the Marsh Creek control structure in the C-3 Pool dike at a rate of 0.88 $m^3 s^{-1}$ to evaluate the ability of the remnant channel to contain the maximum capacity discharge of the control structure culvert.

To quantify changes in surface-water flow related to ground-water discharge, staff gages were established and wading discharge measurements at high and low flow were initiated in September 1998 upstream from C-3 Pool where Walsh, Ducey, and Marsh creeks cross state highway M-28 (Fig. 1) for comparison with surface-water flows at the Walsh Ditch site immediately upslope from C-3 Pool (a). Several small culverts between these creeks drain roadside ditches and then flow under a railroad grade into the C-3 Pool watershed. Flow through the culverts is sporadic and was quantified when possible by measurements made with a bucket and stopwatch or wading discharge measurements.

3.3. Ground water

Water-table wells and/or piezometers were installed at all surface-water sampling sites to allow comparisons of the direction and magnitude of ground- and surface-water movements around C-3 Pool. Site accessibility and presence of the proper conditions for surface-water discharge measurements dictated the location of sampling sites. Water was typically beneath but near the surface at all well and piezometer sites. Wells were constructed by hand-augering through the peat into underlying sand. PVC pipe (7.62 cm diameter) was then assembled with a 20 cm screened section straddling the water table as measured when the hole was augered. Holes were back-filled with bentonite clay from the bottom of the hole to the bottom of the screen. Coarse, angular sand was placed in the annulus to the top of the screened interval and bentonite clay placed above the sand to land surface. Several piezometers were also installed below the water table at the peat–sand interface in a similar manner, except that the screened interval was only 10 cm long. Ground-water levels were measured approximately monthly, except during winter when access was not possible, and also whenever surface-water discharge measurements were made at adjacent sites. Head differences between surface- and ground-water levels were calculated and then multiplied by the hydraulic conductivity (10^{-2} m s^{-1}) over a 1 m^2 unit area to obtain instantaneous and 24 h ground-water discharge values. Where both an instream piezometer and a bank water-table well (<10 m from the stream) were installed, the mean ground-water level was used in the head calculation.

A simple ground-water flow net was conceptualized using differences in hydraulic head between ground-water levels and surface-water levels at sampling sites that paralleled the regional direction of flow. Ground water was assumed to be discharging to the watershed at sites where ground-water levels exceeded surface-water levels, and ground water was assumed to be recharging at sites where ground-water levels were lower than surface-water levels. The reach or area represented by each site was extrapolated to be between the midpoints of the distance to adjacent sites. Ground-water discharge or recharge was calculated using a 1 m^2 grid and an average hydraulic conductivity of 10^{-2} $m^3 s^{-1}$, as most wells and all piezometers were finished in sand (Freeze and Cherry, 1979, p. 29; Fetter, 2001, p. 85). Hydraulic head was calculated using the difference between ground- and surface-water levels at each site (Appendix A). Heads were extrapolated along the boundary represented by each data site and between upstream and downstream boundaries.

Temporary water-table wells screened their entire length were also installed and measured in July 1999 to identify changes in the elevation of the water table caused by the eroded Walsh Ditch gully downstream from C-3 Pool. The original ditch crossed an upland island 2.2 km south of C-3 Pool, but collapsing peat and sand eventually blocked the ditch and forced water to spread to the east and west of the island, eroding new braided channels. A transect of wells was placed at a location where the peat was very desiccated to the west of the gully that passed around the western side of the island (e: Fig. 1). The transect extended 400 m west of the gully and 100 m toward the island to the east. The distance between wells was shorter at closer proximity to the gully. Land-surface elevations were surveyed and depths to the water table and underlying peat–sand interface measured.

3.4. Evaporation

The little emergent vegetation that exists in C-3 Pool is sparse and not likely to result in substantial loss of water through transpiration. Therefore, evaporation outputs were calculated, rather than losses by evapotranspiration. Monthly pan evaporation data were acquired from the National Climatic Data Center (2000) for the Cornell 5 SE weather station located in Delta County, approximately 100 km southwest from the refuge. Those data were summed over the 1999 water year and spring runoff period. Lake evaporation was calculated for C-3 Pool by multiplying the sums by a pan coefficient of 0.80 (Farnsworth et al., 1982), which yielded a value similar to the May–October evaporation average for a shallow lake or free water surface (FWS) given by Farnsworth et al. (1982). To calculate annual volume loss due to evaporation, this value was then applied over the 269 ha open water area of C-3 Pool. Because May 1999 data were not available at the Cornell station, evaporation during the spring runoff period could not be calculated using the same methods as annual evaporation. Instead, the method for calculating monthly FWS evaporation from regional averages given by Farnsworth and Thompson (1982) was used. Using this evaporation value as actual lake evaporation may produce inaccuracies associated with lack of data on heat inflow/outflow and storage on a seasonal scale (Farnsworth et al., 1982).

3.5. Error analysis

Possible sources of error in construction of seasonal and annual water budgets include the following: hydraulic conductivity rates selected, using a lumped value for the sands and overlying peat, extrapolation of data from a point in time to seasonal and annual values, methods of measurement, and methods selected to estimate evaporation and evapotranspiration. No field tests were made to assess the hydraulic properties of the materials in which wells and piezometers were completed; rather, generally accepted values were used for hydraulic parameters that can span as much as five orders of magnitude. These estimates, however, only represent about 2% or less of the budget presented. Reducing ground-water hydraulic conductivity by 10^{-1} reduces the total budget by only about 2% or less. Further reductions of hydraulic conductivity would have lesser effects on the budget.

Greater error likely lies in the extrapolation of single surface-water discharge measurements to represent seasonal and annual discharges. Using representative hydrographs from continuous record stations located near the study area, instantaneous discharges were converted to daily discharges and also used to make estimates of seasonal and annual discharges. Measurement error ranged from more than 2% (a ‘good’ measurement; 31 measurements made) to more than 8% (a ‘poor’ measurement; six measurements made); 71 measurements of more than zero flow were made and rated. Extrapolated estimates based on these measurements could over- or under-represent actual discharges by as much as 50% or more.

4. Results

4.1. Precipitation

Precipitation during the 1999 water year totaled 65.2 cm, a third of which fell during the spring runoff period. Over the 269 ha area of C-3 Pool, the water volume provided by precipitation accounted for 3.6% of the total inputs during the 1999 water year and 1.6% over the spring runoff period (Table 1).

4.2. Surface water

Surface-water flow was highly seasonal, with 91.3% of the inputs to C-3 Pool occurring between January 15 and June 30 and most of that flow in early April. The greatest flow measured in Walsh Ditch upslope from C-3 Pool was 8.6 $m^3 s^{-1}$ on 6 April 1999, and lowest flow measured was 0.21 $m^3 s^{-1}$ on 24 August 1999 (Table 2). Discharge into C-3 Pool from Walsh Ditch provided 91.6% of the total inputs to the pool during the 1999 water year and 95.2% during spring runoff (Table 1). Eighty-one percent of the precipitation that fell directly on the portion of the C-3 Pool watershed not captured by Walsh Ditch was lost to evapotranspiration over the 1999 water year, and 74% was lost during the spring runoff period. However, precipitation reduced by evapotranspiration on this area still provided 2.2% of the total inputs to the annual water budget and 1.3% of the input during spring runoff (Table 1).

Table 1
Water input and output data for C-3 Pool at Seney National Wildlife Refuge

Water source or discharge	Discharge (m^3)		Percent of total	
	1999 water year	1999 spring runoff	1999 water year	1999 spring runoff
INPUTS				
Total surface water	46,200,000	40,100,000	93.8	96.5
Walsh Ditch upstream from C-3 Pool	*45,100,000*	*39,600,000*	*91.6*	*95.2*
Watershed precipitation–evapotranspiration	*1,070,000*	*547,000*	*2.2*	*1.3*
Ground water	1,310,000	782,000	2.6	1.9
Precipitation into C-3 Pool	1,750,000	661,000	3.6	1.6
Total	49,260,000	41,543,000	100	100
OUTPUTS				
Total surface water	61,800,000	56,400,000	86.7	91.9
Marsh Creek at C-3 outlet	*7,420,000*	*0.0*	*10.4*	*0.0*
Sweeney Creek at C-3 outlet	*22,900,000*	*22,000,000*	*32.1*	*35.8*
Walsh Ditch at C-3 outlet	*31,500,000*	*34,400,000*	*44.2*	*56.1*
Ground water	8,380,000	4,540,000	11.8	7.4
Evaporation from C-3 Pool	1,080,000	438,000	1.5	0.7
Total	71,260,000	61,378,000	100	100
Flux (total outputs − total inputs)	22,000,000	19,835,000		

Lines in italics are subcomponents of total surface water.

Table 2
Surface-water input discharge measurements for the 1999 water year near Seney National Wildlife Refuge, Michigan

Date	Ducey Creek at M-28		Marsh Creek at M-28		Walsh c at M-28		Upper Walsh Ditch upstream from C-3 Pool	
	Instantaneous discharge ($m^3 s^{-1}$)	Estimated daily discharge ($m^3 day^{-1}$)	Instantaneous discharge ($m^3 s^{-1}$)	Estimated daily discharge ($m^3 day^{-1}$)	Instantaneous discharge ($m^3 s^{-1}$)	Estimated daily discharge ($m^3 day^{-1}$)	Instantaneous discharge ($m^3 s^{-1}$)	Estimated daily discharge ($m^3 day^{-1}$)
10/1/1998	0	0	–	–	–	–	0.22	19,000
10/2/1998	–	–	<0.01	80	0.09	8000	–	–
10/27/1998	–	–	–	–	–	–	0.32	28,000
10/28/1998	–	–	0	0	0.17	15,000	–	–
12/9/1998	0.23	20,000	0.07	6000	0.38	33,000	0.80	69,000
12/10/1998	–	–	–	–	–	–	–	–
3/17/1999	–	–	0	0	–	–	–	–
4/5/1999	2.61	225,000	0.52	45,000	5.58	482,000	–	–
4/6/1999	–	–	–	–	–	–	8.61	744,000
4/13/1999	1.17	101,000	0.31	27,000	1.87	162,000	4.16	360,000
4/28/1999	0.15	13,000	0.08	7000	0.38	33,000	–	–
4/29/1999	–	–	–	–	–	–	0.92	79,000
6/2/1999	0.29	25,000	0.02	2000	0.54	47,000	–	–
6/4/1999	–	–	–	–	–	–	0.92	80,000
6/28/1999	0	0	–	–	–	–	0.23	20,000
6/30/1999	–	–	0	0	0.08	7000	–	–
8/24/1999	–	–	–	–	–	–	0.21	19,000
9/20/1999	–	–	–	–	0.05	4000	0	0

Instantaneous discharges were measured directly and converted to 24-hour estimates.

Release of water from C-3 Pool was managed and also peaked on 6 April 1999 at 8.5 $m^3 s^{-1}$ through the Walsh Ditch control structure (Table 3). The structure was closed in late June, reducing flow to about 0.0008 $m^3 s^{-1}$ through the summer. Despite the closure, the majority of flow from C-3 Pool was directed into Walsh Ditch through this structure and represented 44.2 and 56.1%, respectively, of the total annual and springtime outputs from C-3 Pool (Table 1). Sweeney Creek received 32.1% of the annual output and 35.8% of springtime output from the pool (Table 1). These managed flows also peaked on 6 April 1999 at 5.5 $m^3 s^{-1}$ and were reduced through the summer.

Marsh Creek was generally not used for release of surface water during the study period. However, on 6 and 7 July 1999, a two-day test discharge was made from C-3 Pool to lower Marsh Creek. Maximum measured discharge was 0.88 $m^3 s^{-1}$, which was near the design maximum for the control structure (M. Tansy, pers. comm., 1999). A discharge of 0.88 $m^3 s^{-1}$ was again measured on 28 March 2000 after routine use of Marsh Creek had been established as a viable method to release water from C-3 Pool (Table 3). Combined discharge measured in upstream sites on Marsh and Ducey creeks for the same date was 2.5 $m^3 s^{-1}$. Analysis of the Marsh Creek channel below C-3 Pool indicated that it was capable of carrying almost four times more water than the control structure in the dike was capable of releasing. Before construction of the dike, this channel carried the combined flows of Marsh and Ducey creeks, which during this study had a maximum discharge of 3.1 $m^3 s^{-1}$. The historical channel has been maintained by ground-water discharge and beaver activity, and it is identifiable throughout its length below C-3 Pool to the Manistique River.

Table 3
Surface-water output discharge measurements for the 1999 water year near Seney National Wildlife Refuge, Michigan

Date	Marsh Creek at outlet of C-3 Pool		Sweeney Creek at outlet of C-3 Pool		Lower Walsh Ditch at outlet of C-3 Pool	
	Instantaneous discharge ($m^3 s^{-1}$)	Estimated daily discharge ($m^3 day^{-1}$)	Instantaneous discharge ($m^3 s^{-1}$)	Estimated daily discharge ($m^3 day^{-1}$)	Instantaneous discharge ($m^3 s^{-1}$)	Estimated daily discharge ($m^3 day^{-1}$)
10/1/1998	0	0	0.22	19,000	–	–
10/2/1998	0	0	–	–	<0.01	100
10/27/1998	0	0	0.01	800	–	–
10/28/1998	0	0	–	–	–	–
12/9/1998	0	0	0.76	65,000	–	–
12/10/1998	0	0	–	–	<0.01	200
3/17/1999	0	0	–	–	–	–
4/5/1999	0	0	–	–	–	–
4/6/1999	0	0	5.52	477,000	8.50	74,100
4/13/1999	0	0	–	–	–	–
4/14/1999	0	0	1.54	133,000	2.78	240,000
4/20/1999	–	–	–	–	1.42	122,000
4/28/1999	–	–	0.78	67,000	–	–
4/29/1999	–	–	–	–	0.35	31,000
6/2/1999	–	–	–	–	0.28	24,000
6/3/1999	–	–	–	–	0.29	25,000
6/4/1999	–	–	0.42	36,000	–	–
6/30/1999	–	–	–	–	<0.01	50
7/6/1999	3.01	25,700	–	–	–	–
8/24/1999	0.08	700	0.04	3000	<0.01	90
9/9/1999	0	0	–	–	–	–
9/16/1999	0	0	–	–	–	–
9/20/1999	0	0	0.02	2000	<0.01	70
9/29/1999	0	0	–	–	–	–

Instantaneous discharges were measured directly and converted to 24-hour estimates.

4.3. Ground water

Ground-water levels varied seasonally and generally corresponded to changes in surface-water levels. Ground-water levels were generally slightly above the screened interval, except in a few instances when they were within the screened interval. Water levels were generally highest in spring and lowest in late summer and early fall (Appendix A). Ground-water levels, generally, mimicked surface-water levels, with only a slight lag, indicating a close hydraulic relation between the surface water and ground water.

Along highway M-28 (Fig. 1), median ground-water discharge to the watershed was 9.0×10^{-7} $m^3\,s^{-1}$ for

Table 4
Ground-water input discharge measurements for the 1999 water year near Seney National Wildlife Refuge, Michigan

Date	Ducey Creek at M-28		Marsh Creek at M-28		Walsh creek at M-28		Upper Walsh Ditch upstream from C-3 Pool		C-3 Pool at Walsh Ditch Control behind dam	
	Instantaneous discharge ($m^3\,s^{-1}$)	Estimated daily discharge ($m^3\,day^{-1}$)	Instantaneous discharge ($m^3\,s^{-1}$)	Estimated daily discharge ($m^3\,day^{-1}$)	Instantaneous discharge ($m^3\,s^{-1}$)	Estimated daily discharge ($m^3\,day^{-1}$)	Instantaneous discharge ($m^3\,s^{-1}$)	Estimated daily discharge ($m^3\,day^{-1}$)	Instantaneous discharge ($m^3\,s^{-1}$)	Estimated daily discharge ($m^3\,day^{-1}$)
10/1/1998	–	–	–	–	–	–	–	–	0.06	200
10/27/1998	–	–	–	–	–	–	−2.42	−9670	–	–
10/28/1998	−0.13	−260	0.46	1100	−0.18	−1800	–	–	–	–
11/2/1998	0.16	320	0.89	2100	–	–	–	–	–	–
11/3/1998	–	–	–	–	−0.26	−2700	−2.24	−8940	–	–
12/9/1998	1.15	2300	0.25	580	0.40	4200	−2.70	−10,800	–	–
12/10/1998	–	–	–	–	–	–	–	–	–	–
3/17/1999	0.11	220	–	–	0.07	700	–	–	–	–
4/5/1999	−2.11	−4220	−0.93	−2200	0.28	2900	–	–	–	–
4/6/1999	–	–	–	–	–	–	−3.60	−14,300	–	–
4/8/1999	0.5	1000	−0.28	−650	0.64	6600	–	–	–	–
4/13/1999	0.46	910	−0.27	−620	0.67	7000	−3.70	−14,800	–	–
4/14/1999	–	–	–	–	–	–	–	–	−0.99	−4000
4/20/1999	0.45	890	−0.06	−100	0.53	5500	−3.39	−13,600	−0.89	−3600
4/28/1999	0.42	830	0.04	80	0.45	4600	–	–	–	–
4/29/1999	–	–	–	–	–	–	−3.09	−12,400	−0.93	−3700
6/2/1999	0.42	830	0.97	2300	−2.92	−30,400	–	–	−0.92	−3700
6/4/1999	−0.84	−1700	−0.08	−200	−1.13	−11,700	−4.2	−16,800	−2.00	−8000
6/10/1999	−0.91	−1800	−0.19	−450	−0.88	−9100	−4.05	−16,200	−2.14	−8560
6/16/1999	−0.81	−1600	−0.21	−490	−1.20	−12,500	−4.05	−16,200	−2.13	−8520
6/23/1999	−0.72	−1400	−0.01	−10	−1.28	−13,300	−4.15	−16,600	−2.01	−8040
6/28/1999	0.45	900	0.38	890	0.04	400	−2.99	−11,900	–	–
6/30/1999	–	–	–	–	−0.38	−3900	–	–	–	–
7/26/1999	0.19	380	0.65	1500	−0.22	−2200	−3.17	−12,700	−1.21	−4840
8/7/1999	−0.04	−80	0.37	870	−0.63	−6600	−3.04	−12,100	−1.02	−4080
8/15/1999	0.19	370	0.78	1800	−0.23	−2300	−1.54	−6140	−3.55	−14,200
8/20/1999	0.28	550	0.57	1300	−0.43	−4400	−3.31	−13,200	−1.02	−4080
8/24/1999	0.27	540	0.91	2100	–	–	−3.05	−12,200	−1.02	−4080
9/3/1999	0.12	240	0.38	890	−0.37	−3900	−3.18	−12,700	−1.03	−4120
9/9/1999	0.04	70	0.33	780	−0.46	−4700	−3.42	−13,700	−1.11	−4440
9/16/1999	0.04	80	0.24	550	−0.41	−4300	−3.05	−12,200	−1.10	−4440
9/20/1999	0.28	550	0.49	1100	−0.11	−1100	−2.90	−11,600	−1.54	−6160
9/29/1999	0.09	200	0.16	360	−0.40	−4100	−2.67	−10,700	−1.13	−4520

Instantaneous discharge values are the product of surface- and ground-water head differentials and hydraulic conductivity over a one-square-meter unit area and were converted to 24-hour estimates across respective boundary lengths for each site. Negative values indicate ground-water recharge.

Table 5
Ground-water output discharge measurements for the 1999 water year near Seney National Wildlife Refuge, Michigan

Date	Marsh Creek at outlet of C-3 Pool		Sweeney Creek at outlet of C-3 Pool		C-3 Pool at Walsh Ditch Control below dam	
	Ground-water discharge (10^{-5} m^3 s^{-1})	Estimated daily discharge (m^3 day^{-1})	Ground-water discharge (10^{-5} m^3 s^{-1})	Estimated daily discharge (m^3 day^{-1})	Ground-water discharge (10^{-5} m^3 s^{-1})	Estimated daily discharge (m^3 day^{-1})
10/1/1998	–	–	–	–	13.2	18,400
10/27/1998	1.03	1070	1.07	1860	–	–
12/9/1998	1.96	2040	0.32	560	–	–
4/6/1999	2.92	3050	0.43	750	–	–
4/14/1999	3.02	3150	0.20	350	19.3	26,800
4/20/1999	2.75	2870	0.19	330	18.9	26,200
4/28/1999	–	–	0.33	570	–	–
4/29/1999	2.56	2670	–	–	18.6	25,900
6/2/1999	–	–	–	–	19.7	27,300
6/4/1999	1.93	2010	−0.87	−1500	20.5	28,500
6/10/1999	3.03	3160	−0.90	−1600	19.8	27,500
6/16/1999	1.84	1920	−0.88	−1500	19.6	27,200
6/23/1999	0.94	980	−0.79	−1400	19.7	27,400
6/28/1999	2.90	3020	–	–	–	–
7/26/1999	1.50	1560	−0.01	−20	16.1	22,400
8/7/1999	0.99	1000	1.62	2820	13.2	18,300
8/15/1999	0.94	980	0.01	20	13.0	18,000
8/20/1999	0.34	360	−0.07	−100	13.4	18,600
8/24/1999	0.81	840	0.03	50	13.3	18,500
9/3/1999	0.20	210	0.02	40	12.7	17,700
9/9/1999	1.25	1300	−0.14	−240	12.8	17,800
9/16/1999	1.51	1580	<0.01	0	13.0	18,100
9/20/1999	–	–	0.07	100	13.2	18,300
9/21/1999	1.59	1660	–	–	–	–
9/29/1999	0.37	390	0.01	20	12.7	17,700

Instantaneous discharge values are the product of surface- and ground-water head differentials and hydraulic conductivity over a one-square-meter unit area and were converted to 24-hour estimates across respective boundary lengths for each site. Negative values indicate ground-water recharge.

water year 1999, compared to median surface-water discharge during the same period of 0.16 m^3 s^{-1} (Table 4). At C-3 Pool, median ground-water discharge was 1.3×10^{-4} m^3 s^{-1} for water year 1999, compared to median surface-water discharge during the same period of 0.28 m^3 s^{-1} (Table 5). Although ground-water discharge increased by four orders of magnitude between the upper bound of the study area and C-3 Pool, it was a relatively insignificant 2.6% of the total annual input to the pool and 1.9% of the springtime input (Table 1).

Throughout the study area, the water table and potentiometric surfaces ranged from just below to just above land surface (Appendix A). In April, during the period of greatest surface-water flows, ground water discharged across most of the study area upslope from C-3 Pool (Table 4; Fig. 2). This regional discharge, plus seepage under and through the dike that is likely deflected by an impervious cutoff in the dike, created water-table and potentiometric surfaces along the back and face of the dike that were elevated with respect to the land and water surfaces (Table 5; Fig. 2). In September, when surface-water flows were lowest, discharge was of lesser magnitude and recharge sometimes occurred near highway M-28. September water levels in C-3 Pool were about 0.4 m lower than in April, and loss of head differential, coupled with less regional flow, caused the discharge zone on the downslope side of the dike to move further from the dike.

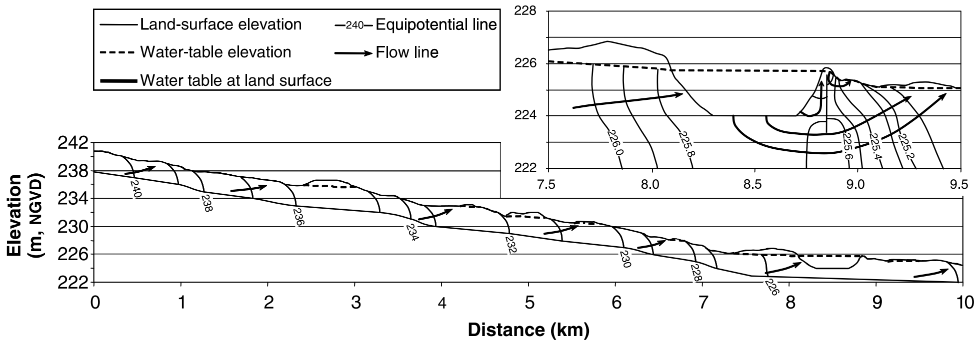

Fig. 2. Cross-sectional diagram showing conceptual patterns of lines of equal hydraulic head and direction of ground-water flow in April 1999. The water table could not be measured physically across much of the area and was assumed to follow the land surface within 0.1 m. Vertical exaggeration is 80× (125× for inset).

The transect of temporary water-table wells that crossed the Walsh Ditch gully south of C-3 Pool (e: Fig. 1) identified a peat layer approximately 1.4 m in thickness (Fig. 3). The water table was in peat at 0.8–0.9 m below the surface from the 300 to 400 m points along the transect west of the gully. At 250 m west, the water table dropped into underlying sand and remained in sand as it gradually sloped to the gully. Depth of the water table then varied from approximately 1.4 to 1.8 m below the surface. The water table to the east of the gully was in sand at approximately 2 m below the surface except for the 10 m closest to the gully (Fig. 3).

4.4. Evaporation

The free water surface evaporation estimate for the region amounted to 40.17 cm over the 1999 water year and 16.30 cm during May and June, the only spring runoff months for which evaporation data were available. The latter is likely an underestimate if the ice cover of C-3 Pool melted prior to May 1. Over the open-water area of C-3 Pool, 41% of evaporation from the 1999 water year occurred during the spring runoff period, amounting to less than 1% of the total seasonal water budget (Table 1). Evaporation accounts for less than 2% of the total output annually (Table 1).

4.5. Water budgets for C-3 Pool

Precipitation, evaporation, surface- and ground-water input and output comprised the water budget for C-3 Pool. Surface-water flow comprised the major component of the water balance during both study periods and was the driving force to the system (Fig. 4). Ground-water input contributed slightly more volume than was lost to evaporation annually (Fig. 4a) and during the spring (Fig. 4(b)). Ground-water output

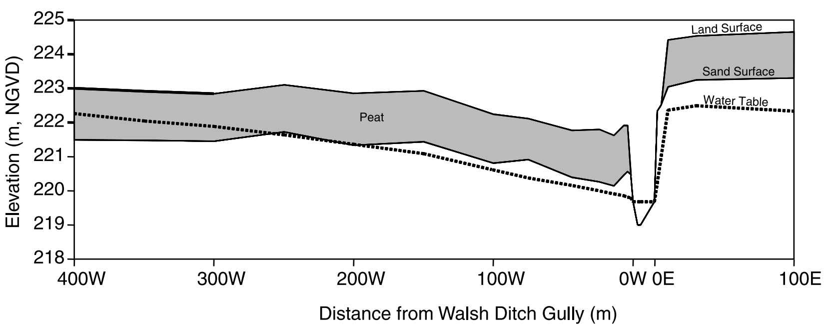

Fig. 3. Cross-section of the Walsh Ditch gully in July 1999 showing the upland island to the east and the water-table slope from peat into underlying sand when approaching the gully from the west. Vertical exaggeration is 25×.

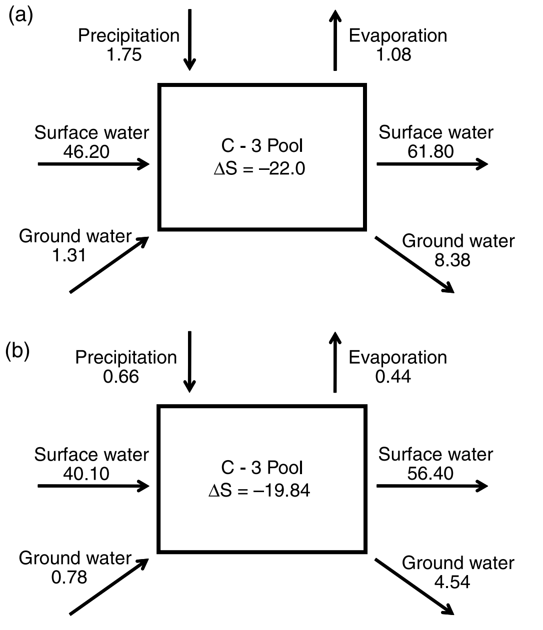

Fig. 4. Water-balance diagrams for C-3 Pool over the 1999 water year (a) and the spring runoff period from 15 January to 30 June 1999 (b). Units are millions of cubic meters.

from C-3 Pool, driven by the head created by the pool, was greater than ground-water input in both study periods (Fig. 4). Over both the 1999 water year and the spring runoff period, the storage of C-3 Pool decreased (Fig. 4), indicating that more water was released from control structures on the dike than arrived as input to the pool. However, a net negative change in storage was not unexpected for this system because water levels are purposefully managed to meet wildlife habitat objectives.

5. Discussion

5.1. Hydrologic restoration

Despite their uncertainty, the two water budgets for C-3 Pool, along with accompanying hydrologic and ecological data provided refuge managers with information about seasonal surface-flow volumes and annual hydrologic functions that allowed them to begin restoration actions to address their concerns. Refuge managers wanted to change the distribution of water from C-3 Pool in the spring to reduce erosion in lower Walsh Ditch and also reduce the effects of Walsh Ditch on surface- and ground-water flow, both upslope and downslope from C-3 Pool. Elimination of C-3 Pool and the habitat functions that it provides to the refuge was not considered.

In October 2002, water flow in the portion of Walsh Ditch upslope from C-3 Pool was halted by construction of the first of nine earthen dams across the ditch; six of the dams were reinforced with metal sheet piling. These dams effectively reduced localized removal of surface water and restored water levels in the ditch to those of the surrounding water table. The furthest upstream dam (f: Fig. 1) also directed the flow of water from Walsh Ditch to the old Walsh Creek channel. During spring runoff, water overflowed the creek channel and restored sheet flow of surface water across the area upslope from C-3 Pool. Standing water remained in the wetland even in the summer when there is generally little flow in the creek, and ground-water discharge was readily observed at some locations in the area (M. Tansy, pers. comm.). Thus, closure of the ditch seemingly allowed ground-water discharge to restore the water table, and a restoration goal was met. In addition, a water-control structure was placed in Walsh Creek near the east end of C-3 Pool (g: Fig. 1) to allow water to be diverted to its natural outlet—the Driggs River; the flow can also be directed to C-3 Pool if it is needed for management purposes.

A new water-control structure was installed in the C-3 Pool dike at Marsh Creek (c: Fig. 1) that is capable of handling 3.11 $m^3 s^{-1}$ (the channel can handle at least 3.13 $m^3 s^{-1}$ without undue erosion per testing, see above). The water-management plan under development runs water through this structure at full capacity, and it now handles the majority of springtime outflow from C-3 Pool. The resulting flows to Marsh Creek also leave the channel, spread across the wetland, and restore sheet flow of surface water below C-3 Pool in the spring, per restoration goals (M. Tansy, pers. comm.). As determined by this study, the average springtime discharge from C-3 Pool is 3.91 $m^3 s^{-1}$, so Sweeney Creek would have to take the remaining 0.80 $m^3 s^{-1}$. Sweeney Creek carried as much as 5.52 $m^3 s^{-1}$ in 1999 (Table 2) and averaged 1.52 $m^3 s^{-1}$ in the spring. However, if a maximum release of 14.0 $m^3 s^{-1}$ is required during peak flow, such as occurred on 6 April 1999, both Marsh and Sweeney creeks could greatly exceed capacity and risk erosion, so managers have made use of the control structure in Walsh Creek (g: Fig. 1) to divert flows from the creek to the Driggs River. This action not only reduces the required flows on Marsh and Sweeney creeks but also restores natural springtime flows to the Driggs River and addresses an unforeseen restoration goal. Refuge managers will also try to plan storage capacity in C-3 Pool and release enough water through Marsh Creek early in the spring runoff period to avoid filling the pool too early in the year. Continued upstream measurement of flow should assist in this effort.

The water-management plan under development sends no water from C-3 Pool to lower Walsh Ditch. However, beaver dams are now being established on lower Walsh Ditch, seemingly supported by ground-water discharges. Beaver occasionally constructed dams in the ditch in past years, but the extreme water flows in the spring always washed them out. In portions of lower Walsh Ditch where deep gullying has not occurred, beaver dams may raise the water level in the ditch sufficiently to eliminate unnatural excessive ground-water discharge and lowering of the water table that was observed in the adjacent wetland, thus helping to meet the ground-water restoration objective. However, there may not be sufficient water supply or food supply in all portions of the ditch to support contiguous beaver ponds along the entire channel, which would be a requirement for fully restoring ground-water hydrology. Therefore, plans are being made to install earthen dams across the ditch channel every 400 m to raise the level of surface water and the adjacent water table, which would also allow sheet flows to pass over the ditch system (M. Tansy, pers. comm.). Such an approach, using metal sheet piling, proved successful in Big Meadows, a ditched sedge fen in Rocky Mountain National Park in Colorado, USA (Cooper et al., 1998) with many characteristics similar to those in Seney National Wildlife Refuge. If access problems prevent construction of some of the earthen dams at Seney, beaver management (letting beavers do the work) may become critical in meeting restoration goals. However, it is unlikely that dams of any type can be constructed that will raise the water level completely in the heavily eroded gully area. It is also unlikely that dried peat will rehydrate and regain its original hydraulic properties (Okruszko, 1995).

5.2. Interaction of ground water and surface water

The interactions of ground water and surface water have received increased attention in recent years (e.g., Winter and Rosenberry, 1995; Winter et al., 1998). Surface-water conditions often determine the direction and rate of localized ground-water flow, and ground-water supply often determines the state of surface-water conditions, including water chemistry. These relationships are especially important in fens, where ground-water discharges are a major source of peatland water (e.g., Wilcox et al., 1986; Shedlock et al., 1993). Drainage of surface water from peatlands via ditches has been shown to lower ground-water levels near the ditches (Boelter, 1972; Lieffers and Rothwell, 1987; Bradof, 1992; Hillman, 1997; Cooper et al., 1998), although the dewatering effect may be minimal or very localized (Braekke, 1983; Stewart and Lance, 1983; 1991; Coulson et al., 1990; Fisher et al., 1996). Factors that determine the effectiveness of ditches in peatlands include hydraulic conductivity of the peat (Boelter, 1972), accompanying contributions of precipitation (Stewart and Lance, 1991; Cooper et al., 1998), speed at which storm runoff is removed (Robinson, 1985; Stewart and Lance, 1991), depth and spacing of ditches (Braekke, 1983; Hillman, 1992; 1997), and state of repair of the ditches (van Strien et al., 1991; Fisher et al., 1996). Impacts of hydrologic alterations caused by ditches include changes in peatland vegetation (Wilcox et al., 1984; Lieffers and Rothwell, 1987; Stewart and Lance, 1991; Bradof, 1992; Mountford and Chapman, 1993; Fisher et al., 1996; Cooper et al., 1998) and fauna (Stewart and Lance, 1983; Coulson et al., 1990), subsidence of peat (Bradof, 1992; Hillman, 1992; 1997; Prevost et al., 1997), and changes in the physical character of peat (Okruszko, 1995). In addition, surface impoundments adjacent to peatlands have been shown to alter downslope vegetation by supplying a greater source of water through ground-water seepage, even during dry periods of the year (Wilcox et al., 1984). Sedges and grasses go dormant during dry periods, and when those dry periods are eliminated, they lose their competitive advantage over larger, fleshier plants with greater water requirements, such as cattails.

The peatlands surrounding C-3 Pool in Seney National Wildlife Refuge demonstrate some of the above-mentioned interactions between ground water and surface water. Cattails now grow on the immediate downslope side of the C-3 Pool dike that receives seepage from the pool and remains wetter than normal during the summer (Kowalski and Wilcox, 2003). Upslope from C-3 Pool, ground water discharges in much of the area during the period of greatest surface-water flows in the spring (Fig. 2), which suggests that surface water is recharging ground water at some location upslope from the modeled study area during the high water period. Later during the low flow season, that upslope recharge is lessened. Although discharge in the area upslope from C-3 Pool then decreases, ground water still boils through the sand in sections of now-dammed-off upper Walsh Ditch and forced the installation of metal sheet piling in six of the nine dams to prevent erosion of the dams and to maintain surface-water flows (M. Tansy, pers. comm.). Some parts of the area upslope from C-3 Pool may become recharge zones in the low flow season, although recharge is likely minimal. The drop in surface-water level in C-3 Pool from high flow to low flow seasons, coupled with less regional discharge, likely affects ground-water discharge below C-3 Pool. Further downslope, expedited removal of surface water along the gullied portion of lower Walsh Ditch also affects ground water in adjacent peatlands (Fig. 3) and has resulted in peat subsidence and changes in vegetation and the physical character of the peat. Finally, surface-water chemistry is strongly influenced by mineralized ground water, particularly in the low flow season, as evidenced by specific conductance in the creeks and ditches ranging from 175 to 275 μS/cm and alkalinity ranging from 115 to 150 mg/L as $CaCO_3$.

Interactions between ground water and surface water are critical for maintaining ecosystem processes in this wetland, and they had to be considered when making management decisions. Restoration actions required reconstruction of an environment in which ground water could again discharge naturally to the peat, both upslope and downslope from C-3 Pool, and thus provide the hydrologic support expected in a fen. Unnatural ground-water discharge to surface water in Walsh Ditch had to be stopped to create that environment, and redistribution of surface-water outflows from C-3 Pool was necessary to stop the erosion in lower Walsh Ditch that promoted unnatural ground-water discharge. The actions required to restore ground-water functions also served to restore natural sheet flows of surface water to the peatland by stopping diversion of springtime runoff to the ditch, returning surface-water flows to natural creek channels, and raising the water table upslope from C-3 Pool to allow ground water to discharge to the land surface. Whether lower surface-water levels in C-3 Pool in the summer will reduce ground-water discharges below the pool sufficiently to limit growth of invading cattails remains to be seen.

As described by this study, when both surface water and ground water are important components of wetland hydrology, a water-budget approach can prove useful in planning restoration efforts. This is especially applicable in managed wetland systems, where complexes of dikes, ditches, and pools are used to alter surface-water conditions. Worldwide, at both federal and regional levels, managers control water levels in wetlands to manipulate vegetation changes and produce food and habitat for wildlife, especially migratory waterfowl (Smith et al., 1989; Payne, 1992). These actions can result in long-term degradation of natural conditions and can also affect wetlands outside the managed area. As a result, wetland restoration may be required, with a primary focus on hydrologic restoration (Galatowitsch and van der Valk, 1994; Hey and Philippi, 1999; Wilcox and Whillans, 1999). However, most refuges lack current and historic hydrologic data, especially for ground water, sufficient to support these efforts, and fiscal budgets are often insufficient to generate detailed new hydrologic data. In such cases, as shown by this study, a relatively low-cost effort to develop a water budget for the wetland restoration site may prove very useful to managers in the planning, implementation, and continued management stages.

Acknowledgements

We thank Mike Tansy, Seney National Wildlife Refuge, for great cooperation and assistance in planning, organizing, and conducting this study, as well as providing considerable background information regarding the history of the site. Assistance in conducting field work and data analyses was provided by Cynthia Rachol, Dan Wydra, John Knudsen, Derrick Hubbell, Matt Whipple, and Ryan McDonald. Constructive reviews of earlier drafts of the manuscript were provided by Tom Weaver, Brian Neff, and Jeff Wilcox. This article is Contribution 1317 of the USGS Great Lakes Science Center.

Appendix A

Altitude of surface water and ground water in bank water-table wells and instream piezometers for the 1999 water year near Seney National Wildlife Refuge, Michigan.

Date	Ducey Creek at M-28			Marsh Creek at M-28			Walsh Creek at M-28			Upper Walsh Ditch upstream from C-3 Pool			Marsh Creek at outlet of C-3 Pool		Sweeney Creek at outlet of C-3 Pool		C-3 Pool at Walsh Ditch Control		
	Surface water (m)	Bank water-table well (m)	Instream piezo-meter (m)	Surface water (m)	Bank water-table well (m)	Instream piezo-meter (m)	Surface water (m)	Bank water-table well (m)	Instream piezo-meter (m)	Surface water (m)	Bank water-table well (m)	Instream piezo-meter (m)	Surface water (m)	Instream piezo-meter (m)	Surface water (m)	Instream piezo-meter (m)	Surface-water level in pool (m)	Surface-water level at outlet (m)	Instream piezo-meter (m)
10/1/1998	–	–	–	–	–	–	–	–	–	–	–	–	–	224.670	–	223.192	225.116	223.800	225.122
10/27/1998	–	–	–	–	–	–	–	–	–	226.906	226.647	226.681	224.666	224.769	222.844	222.951	–	–	225.222
10/28/1998	240.484	240.452	240.490	240.952	241.016	240.979	234.755	234.734	234.741	–	–	–	–	–	–	–	–	–	–
11/2/1998	240.389	240.418	240.392	240.818	240.930	240.883	–	–	–	–	–	–	–	–	–	–	–	–	–
11/3/1998	–	–	–	–	–	–	234.682	234.638	234.675	226.879	226.638	226.673	–	–	–	–	–	–	–
12/9/1998	240.463	240.584	240.572	241.147	241.368	240.975	234.856	234.926	234.866	226.936	226.666	226.667	224.711	224.907	223.301	223.333	–	–	–
3/17/1999	240.567	–	240.578	241.131	–	–	234.837	–	234.844	–	–	–	–	–	–	–	–	–	–
4/5/1999	240.885	240.554	240.794	241.346	241.334	241.172	235.717	235.761	235.728	–	–	–	–	–	–	–	–	–	–
4/6/1999	–	–	–	–	–	–	–	–	–	227.231	226.875	226.874	224.746	225.038	223.978	224.021	225.844	223.421	–
4/8/1999	240.770	240.828	240.812	241.341	241.324	241.303	235.647	235.756	235.665	–	–	–	–	–	–	–	–	–	–
4/13/1999	240.670	240.726	240.705	241.278	241.260	241.243	235.170	235.276	235.198	227.095	226.756	226.695	–	–	–	–	–	–	–
4/14/1999	–	–	–	–	–	–	–	–	–	–	–	–	224.724	225.026	223.474	223.494	225.624	223.599	225.525
4/20/1999	240.595	240.654	240.625	241.183	241.189	241.165	234.947	235.026	234.973	226.983	226.675	226.613	224.721	224.996	223.187	223.206	225.669	223.694	225.580
4/28/1999	240.545	240.603	240.570	241.166	241.173	241.166	234.836	234.901	234.860	–	–	–	–	–	223.168	223.201	–	–	–
4/29/1999	–	–	–	–	–	–	–	–	–	226.925	226.647	226.585	224.722	224.978	–	–	225.668	223.715	225.575
6/2/1999	240.565	240.613	240.600	241.049	241.156	241.135	234.907	234.323	234.908	–	–	–	–	–	–	–	225.704	223.647	225.612
6/4/1999	240.665	240.587	240.575	241.128	241.122	241.119	234.967	234.851	234.858	227.061	226.679	226.603	224.846	225.039	223.259	223.172	225.794	223.544	225.594
6/10/1999	240.645	240.561	240.547	241.108	241.093	241.085	234.877	234.781	234.798	227.081	226.729	226.623	224.746	225.049	223.159	223.069	225.814	223.624	225.600
6/16/1999	240.605	240.531	240.518	241.118	241.094	241.100	234.847	234.730	234.725	227.031	226.659	226.593	224.856	225.040	223.139	223.051	225.844	223.674	225.631
6/23/1999	240.525	240.458	240.448	241.048	241.053	241.042	234.807	234.511	234.848	227.041	226.659	226.593	224.876	224.970	223.239	223.160	225.824	223.654	225.623
6/28/1999	240.416	240.482	240.440	241.000	241.053	241.023	234.698	234.713	234.690	226.933	226.664	226.605	224.736	225.026	–	–	–	–	225.590
6/30/1999	–	–	–	240.900	–	–	234.702	234.681	234.648	–	–	–	–	–	–	–	–	223.750	–
7/26/1999	240.345	240.367	240.361	240.908	240.976	240.970	234.687	234.660	234.671	226.951	226.665	226.604	224.836	224.986	223.339	223.338	225.474	223.744	225.353
8/7/1999	240.355	240.341	240.361	240.898	240.934	240.936	234.687	234.587	234.661	226.931	226.657	226.598	224.786	224.885	223.189	223.351	225.174	223.754	225.072
8/15/1999	240.385	240.401	240.406	240.938	241.018	241.013	234.727	234.701	234.708	226.811	226.667	226.648	224.806	224.900	223.279	223.280	225.464	223.814	225.109
8/20/1999	240.375	240.409	240.396	240.938	241.003	240.986	234.697	234.639	234.670	226.951	226.650	226.590	224.796	224.830	223.219	223.212	225.184	223.744	225.082
8/24/1999	240.379	240.437	240.375	240.918	241.030	240.987	–	–	–	226.931	226.659	226.593	224.801	224.882	223.191	223.194	225.182	223.749	225.080
9/3/1999	240.297	240.322	240.296	240.849	240.892	240.882	234.633	234.602	234.590	226.922	226.631	226.578	224.795	224.815	223.169	223.171	225.142	223.765	225.039
9/9/1999	240.297	240.300	240.301	240.838	240.871	240.871	234.645	234.600	234.599	226.961	226.647	226.591	224.725	224.850	223.330	223.316	225.146	223.753	225.035
9/16/1999	240.315	240.320	240.318	240.848	240.884	240.859	234.655	234.619	234.609	226.923	226.647	226.590	224.698	224.849	223.341	223.341	225.155	223.746	225.045
9/20/1999	240.325	240.355	240.350	240.858	240.923	240.890	234.675	234.691	234.638	226.926	226.669	226.603	–	–	223.364	223.371	225.214	223.744	225.060
9/21/1999	–	–	–	–	–	–	–	–	–	–	–	–	224.694	224.853	–	–	–	–	–
9/29/1999	240.337	240.352	240.340	240.860	240.851	240.900	234.682	234.650	234.635	226.941	226.660	226.689	224.834	224.871	223.334	223.335	225.132	223.746	225.019

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