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PRACTICAL RESULTS OF A WATER BUDGET ESTIMATION FOR A CONSTRUCTED WETLAND

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Abstract: An experimental water treatment plant was established to verify the effectiveness of constructed wetlands to improve water quality in the Venice Lagoon watershed. The wetland comprised three different subsystems, ranging from a riparian swamp to a marsh ecosystem. As a first step, monitoring was conducted over three years to evaluate the efficacy and efficiency of the system. Here, we report an analysis of the water budget resulting from routinely collected hydraulic and meteorological data. We used independent estimates of the water-budget terms, rather than budgetary residual estimation, because we wanted to estimate the water-budget error. Surface-water inflow, surface-water outflow, and direct precipitation were measured. Daily potential evapotranspiration values were estimated using the FAO Penman Monteith equation; runoff was estimated using the USDA Soil Conservation Service curve number model; indirect precipitation that flows toward the wetland via subsurface flow was estimated from the soils field capacity; and seepage was estimated using Darcy's law. The objectives of the research were to establish the best way to develop a water budget useful for application and design purposes, to determine the term that most influences the water-budget error, and to perform a sensitivity analysis on the parameters affecting this term. Surface flow dominated the wetland system, precipitation and evapotranspiration contributed about 10% to the water budget, and changes in water storage and the seepage flow contributed less than 5% to the water budget. The seepage flow term had the highest uncertainty, and the frequency of ground-water level measurements had the greatest impact on the water-budget error (ranging from 10.0%–28.6%). Therefore, in a free-water surface wetland with a shallow ground-water system, the main effort in field measurement should be to ensure a measurement frequency of less than five days.

Key Words: seepage, sensitivity analysis, surface wetland, water budget

INTRODUCTION

Wetlands are effective for the treatment of polluted water sources (e.g., Kadlec and Knight 1996, Frankenbach and Meyer 1999, Kovacic et al. 2000, Larson et al. 2000, Mallin et al. 2002). The Venice Lagoon in Italy is a delicate environment that is threatened by water pollution and is at risk of eutrophication. To address these problems, the Venice Region has established a master plan for nutrient load abatement (Regione Veneto 2000), which includes the use of wetlands as one of several tools for nonpoint-source pollution control. An experimental water treatment plant in the form of a constructed wetland was established to verify the efficacy and efficiency of semi-natural wetlands to improve water quality, given the wastewater characteristics and pedo-climatic conditions of this brackish-water area.

Several studies have highlighted the importance of understanding the hydrology of wetland systems in evaluating wetland functions and processes (Mitsch and Gosselink 2000, Kincanon and McAnally 2004, ITRC 2005, Zhang and Mitsch 2005). Nevertheless, water-budget calculations are affected by difficulties in measuring water inflows, outflows, and changes in storage, and by the relatively large errors associated with many of the budget components (Hunt et al. 1996). Ground-water inputs are generally considered the most difficult to quantify because they usually cannot be measured directly (Choi and Harvey 2000). Aquifer heterogeneity complicates flow patterns, and seasonal variation in hydraulic gradients may necessitate long-term studies (Hunt et al. 1996, Cole and Brooks 2000, Zhang and Mitsch 2005).

Because of these difficulties, there have been few comprehensive studies of wetland hydrology and hydrochemistry (Eser and Rosen 1999, Koreny et al. 1999). Net ground-water fluxes are commonly ignored or estimated as a residual term in the water budget. Independent estimates of wetland ground-water inflows are generally made using Darcy's law (Hunt et al. 1996, Raisin et al. 1999, Larson et al. 2000). The water budget for a wetland can be calculated using several methods involving the use of models that attempt to simulate all or the majority of the terms of the water budgets (Bidlake and Boetcher 1996, Arnold et al. 2001, ITRC 2003, ITRC 2005). Unfortunately, there is still a great deal of uncertainty over hydrologic budgets (Drexler et al. 1999, Arnold et al. 2001).

Here, we describe an integrated approach to develop a comprehensive water budget for a constructed wetland using field (meteorological, geopedology) and design (wetland volume, inflow-outflow) data that are generally available or monitored. We used the experimental constructed wetland "Canale Novissimo" in Venice, Italy. Our objectives were 1) to establish the best way to improve a water budget useful for application and design purposes, 2) to determine the term that most influences the water-budget error, and 3) to perform a sensitivity analysis of the parameters that affect this term.

MATERIALS AND METHODS

Study Area

An experimental free-water surface (FWS) wetland (Canale Novissimo, Ramo Abbandonato) was constructed in the Venice Lagoon watershed near Chioggia, Venice, Italy, in 2002. The wetland was created in a reclaimed lowland delta, currently below sea level, using an abandoned channel parallel to the Brenta River (Figure 1). There were no differences in hydraulic head across the wetland; therefore, pumps were used to circulate surface water through the wetland. The main hydraulic factors (water levels, volumes, and detention time) were controlled using the S7 SIMATIC SIEMENS 300 software. A sensor registered the input-output flow and the corresponding water level with a frequency of 10 Hz and recorded these data on a data logger. This software regulated pumping rates to maintain the desired surface-water levels within the wetland system. An integrated remote control allowed the acquisition of data and modification of software settings. Water volumes calculated from hydraulic head measurements were used to change pumping rates and alter residence times within detention ponds. The water entering the system came from a reclaimed agricultural channel that drained a 135-ha sub-basin (80% cropland, 20% urban and industrial land use).

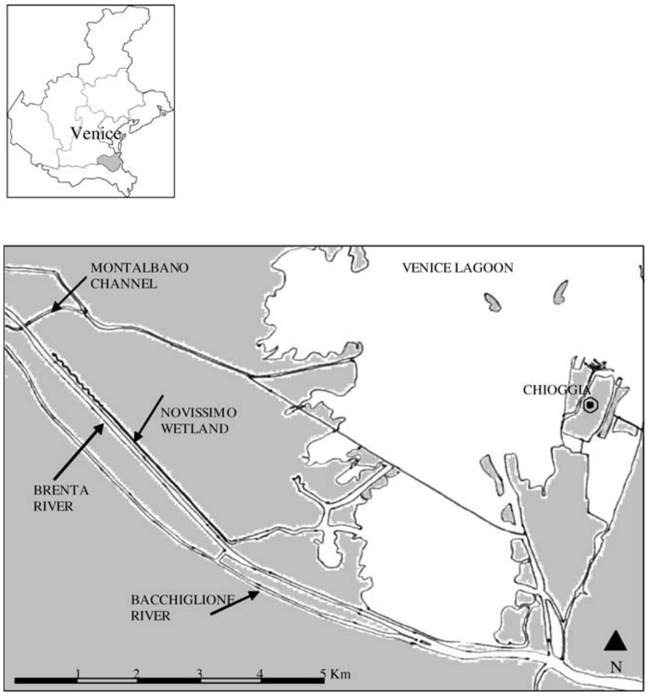

Figure 1. Location of the Canale Novissimo wetland.

The wetland was 50 m wide and 4,140 m long, with a mean depth of 80 cm, and was divided into three subsystems that differed in morphology and vegetation. The first subsystem (1,480 m) was a riparian swamp ecosystem dominated by hydrophytic trees and shrubs; meanders were reconstructed to allow soil flooding and to maximize the contact volume between the water and the root zone. The second subsystem (1,040 m) was a wet riparian ecosystem. The channel was linear, and trees and shrubs comprised one-third of the area of emergent plants, whereas the remaining area was covered by marsh vegetation. Finally, the third subsystem (1,620 m) was a marsh ecosystem, with shrubs and trees playing an ancillary role (slope protection, habitat). Vegetation for the restoration of the three ecosystems was chosen in agreement with the phytosociological classification of the transitional zone between the mainland and the Venice lagoon. This area contained Mediterranean and xerophilous species comprising a hydrophytic forest typical of shallow ground-water areas (Ferrari 1984). From this ecological arrangement, we selected the following species to accelerate the evolution of the riparian forest: maple (*Acer campestre* L.), ash (*Fraxinus oxyphilla* M. Bieb., *F. excelsior* L.), alder (*Alnus glutinosa* [L.] Gaertn.), and oak (*Quercus robur* L., *Q. peduncolata* Ehrh.). Shrub vegetation included willow (*Salix* spp.), dogwood (*Cornus sanguinea* L.), viburnum (*Viburnum opulus* L.), and buckthorn (*Frangula alnus* Mill.). The marsh vegetation was recreated by adding seed to the existing topsoil, which was dominated by common reed (*Phragmites australis* [Cav.] Trin. ex Steud.), and sago pondweed (*Potamogeton pectinatus* L.). Construction of the first and part of the second ecosystems required extensive modification of the original conditions, which was achieved by adding agricultural soil to the previous channel banks.

A regional 1.5-m soil survey profile by the Regional Agency for Environmental Protection (ARPAV 2004) classified the soils of this area as fine to silty mixed, calcareous, mesic, cumulic Humaquepts, with high organic carbon content, low permeability (10^{-5}–10^{-6} cm s^{-1}), and neutral pH. The carbonate content of these soils varied between 43 and 264 g kg^{-1}. During wetland construction, we sampled the first 20 cm of soil, and during piezometer installation, we performed a stratigraphic analysis of the first 5 m below the soil surface (five probes for each ecosystem). Our results agreed with the regional classification: the organic carbon content changed from about 8% organic matter in the first subsystem to about 2% in the third. Peat layers occurred at variable depths. The sand content increased from 50% in the first subsystem to 90% in the third. In the first subsystem and part of the second, an alloctone sandy-loam/silty loam soil (2% organic matter) was used to redesign the wetland berms. However, modeling of the berms involved only the surface soil layer; the deep soil structure was not modified.

Experimental Design

The organization of the pump and water level control system and the design measures for wetland morphology allowed us to control the main hydraulic parameters. The inlet and outlet pumps released the required amount of water in or out, and data loggers at the inlet and outlet pumps provided continuous records of water levels, inflows, and outflows. Until April 2004, a staff gauge was installed in each subsystem of the wetland and in the Brenta River to measure the actual water levels on sampling days (Figure 2).

In September 2002, a total of 24 piezometers (numbered from 01 to 24) were installed along two transects in each subsystem, perpendicular to the berm (Figure 2). The piezometers were 3.81-cm diameter PVC tubes, 1.95–4.4 m in length, with slots beginning 1.5 m from the piezometer top. Each piezometer had a quartz sand pre-filter and was wrapped in a nonwoven sheath. In October 2005, we installed an additional 12 piezometers (numbered from 25 to 36), with two for each transect. The new piezometers were 5.08-cm diameter PVC tubes, 5 m in length, with slots beginning 2 m below the piezometer head. Bentonite was used to seal the annular space from the top of the gravel pack to the soil surface to prevent the vertical movement of water along the piezometer casing.

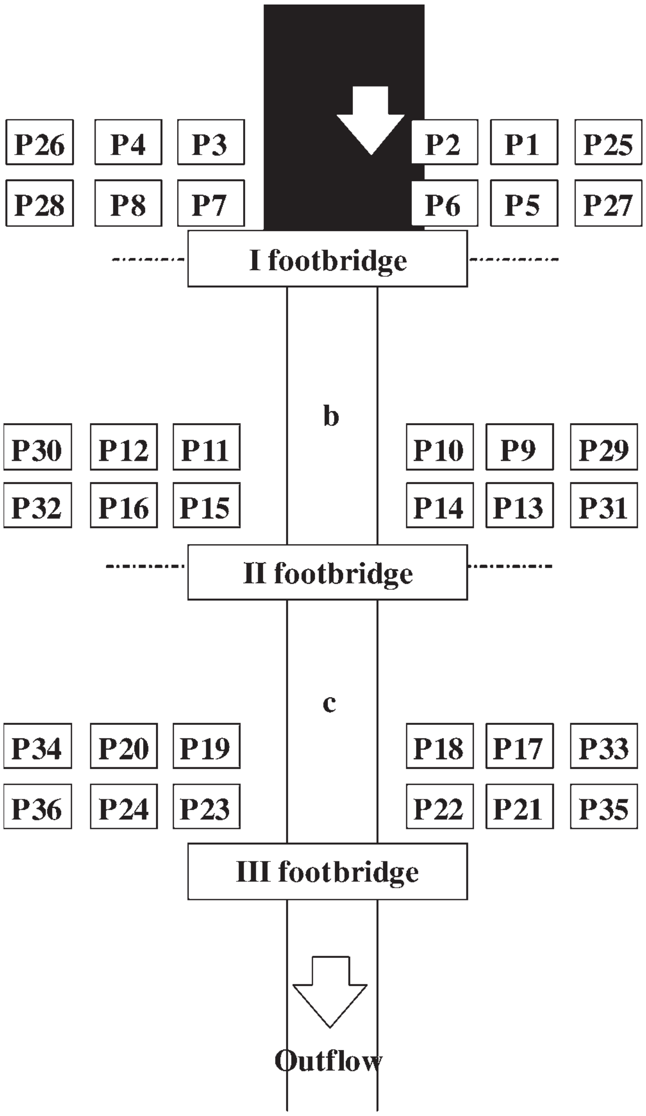

Figure 2. Schematic diagram of the location of piezometers (P) in the three subsystems (not to scale): a) first subsystem, b) second subsystem; c) third subsystem. We measured the wetland water level at each footbridge and at the inlet and outlet point.

At the beginning of the study, we measured the hydraulic head of the piezometers every 18 days; after October 2005, they were measured every five days. The hydraulic conductivity was measured in the field using a pumping method for each of the 36 piezometers (Lefranc method; Beretta 1992).

The research began in October 2002. The initial period from October 2002 to March 2004 was

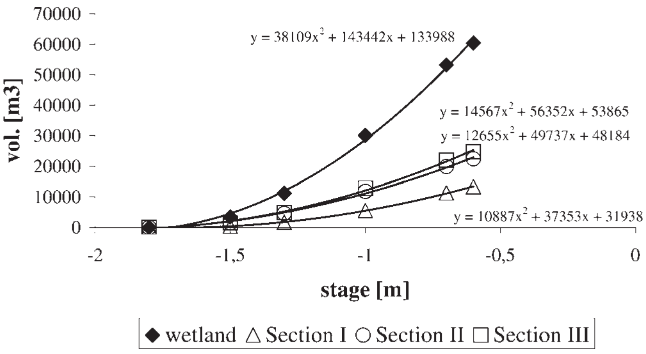

Figure 3. Water-level storage curves for the whole wetland and each of the three subsystems.

affected by hydraulic disturbance because of vandalism. Here, we considered only data collected in the period from April 2004 to June 2006, which was characterized by steady and controlled experimental conditions. The pump systems did not work from October 2005 to January 2006 because of vandalism.

Daily air temperature, wind velocity, solar radiation, relative humidity, and precipitation were recorded by a meteorological station of the Regional Agency for Environmental Protection, located in Codevigo, about 4 km northwest of the Novissimo wetland.

Wetland Volume

The water volume inside the wetland was estimated using water level–storage curves (Figure 3), derived from the topographical relief and a calibration during the first year of study (Larson et al. 2000, Goulet et al. 2001). For each study period, we calculated the average area of the wetland from the average volume and depth.

Water Budget

The following equation describes the wetland water budget (Figure 4):

$$\mathrm{Qi} - \mathrm{Qo} + \mathrm{Qs} + \mathrm{Qp} + \mathrm{Qc} + \mathrm{Qd} - \mathrm{Qet} + \mathrm{Qe} = \frac{\mathrm{dV}}{\mathrm{dt}} \qquad (1)$$

where:

Qi = Surface-water inflow (measured) $[\mathrm{m}^3\ \mathrm{s}^{-1}]$
Qo = Surface-water outflow (measured) $[\mathrm{m}^3\ \mathrm{s}^{-1}]$
Qs = Seepage (calculated) $[\mathrm{m}^3\ \mathrm{s}^{-1}]$
Qp = Direct precipitation inflow (calculated) $[\mathrm{mm\ d}^{-1}]$
Qc = Runoff (calculated) $[\mathrm{m}^3\ \mathrm{s}^{-1}]$

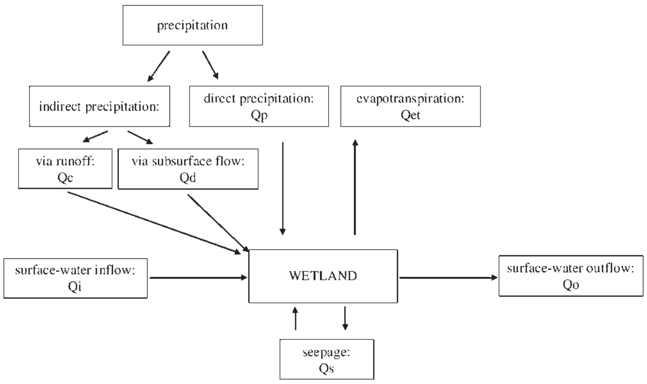

Figure 4. Components of the water budget and associated terminology.

Qd = Indirect precipitation via subsurface flow (calculated) $[\mathrm{m}^3\ \mathrm{s}^{-1}]$
Qet = Evapotranspiration (calculated) $[\mathrm{m}^3\ \mathrm{s}^{-1}]$
Qe = Flow needed to close the budget $[\mathrm{m}^3\ \mathrm{s}^{-1}]$
t = Time (measured) [s]
h = Water level (measured) [m]
V = Volume (calculated) $[\mathrm{m}^3]$

We calculated the water budget using daily values for all parameters except seepage, and then averaged each component over the analyzed time periods. For April 2004 to September 2005, we calculated the water budget using data from the first 24 piezometers measured every 18 days, whereas for October 2005 to June 2006, we used data from 36 piezometers measured every five days.

Surface-Water Inflow and Outflow (Qi, Qo). The inlet and outlet pumps released the required amount of water in or out, and data loggers at the inlet and outlet pumps provided records of water levels, inflows, and outflows every 10 seconds.

Precipitation (Qp, Qc, Qd). During meteorological events, the wetland area between the two berms received a certain amount of precipitation P $[\mathrm{mm\ d}^{-1}]$, measured by the meteorological station of Codevigo. Part of this precipitation volume fell directly on the flooded area A $[\mathrm{m}^2]$, calculated from the wetland volume V and the mean depth h [m]: $A = V/h$, and was assumed to be the direct precipitation flow $Qp = P{*}A$ $[\mathrm{m}^3\ \mathrm{s}^{-1}]$ (Kadlec and Knight 1996). The remaining volume, i.e., indirect precipitation, fell on the vegetated area, which was assumed to be the runoff area of the catchment.

We assumed that only precipitation greater than 20 mm day^{-1} would generate runoff (Qc) (Verchot et al. 1997, Clausen et al. 2000, Fierer and Gabet 2002, Fiener and Auerswald 2003, Kleinman et al.

2004, Turner et al. 2004). We then used the USDA Soil Conservation Service curve number model to estimate the runoff generation from daily precipitation values, and decreased these results by 90% to account for the effect of vegetation (Udawatta et al. 2002). This estimate was based on research performed in similar soil, yearly average precipitation, and vegetation conditions (Fiener and Auerswald 2003).

The amount of indirect precipitation that does not reach a wetland via runoff infiltrates the soil, but when the specific field capacity of the soil is exceeded, this water flows toward the wetland via subsurface flow. To estimate the indirect precipitation via subsurface flow (Qd), we evaluated the field capacity for each ecosystem from the results of previous soil analyses and the hydraulic conductivity test.

Evapotranspiration (Qet). Daily potential evapotranspiration values were estimated using the FAO Penman Monteith equation (Allen et al. 1998). This method provides good estimates when evapotranspiration from the wetland is limited primarily by meteorological factors (Bidlake et al. 1996, Jacobs et al. 2002, Xu and Singh 2002), and when compared to the eddy covariance and Bowen ratio methods (Bidlake et al. 1996).

Seepage (Qs). The amount of water moving across the berms was estimated using Darcy's law (Larson et al. 2000):

$$\mathrm{Qs} = \mathrm{Kc} * \mathrm{i} * \mathrm{As} \tag{2}$$

where Qs = seepage, volumetric flow rate ($m^3\ s^{-1}$); Kc = hydraulic conductivity ($m\ s^{-1}$); i = hydraulic gradient (dimensionless); and As = cross-sectional area (m^2).

To calculate the amount of water exchanged via seepage, we considered three or four gradients (i.e., using 24 or 36 piezometers, respectively) on each berm: from the outside water level (Brenta River or fields) to the outer piezometer; between the central piezometers; and between the inner piezometer and the wetland. For each gradient, we calculated the amount of seepage using Darcy's law, and then the budget of the resulting seepage for the two berms. We averaged the resulting water budgets for the two piezometer transects in each ecosystem to account for soil heterogeneity.

The seepage area (As) was determined using the length of the berm for each ecosystem, i.e., 1,610 m for the first, 1,040 m for the second, and 1,620 m for the third, and the depth of the soil profile to the impermeable layer (Larson et al. 2000). We estimated the impermeable layer depth using stratigraphy and soil analyses, which showed a clay layer beginning 1.8–4.0 m below the soil level; the upper layers were permeable silt and/or sand. In the first ecosystem, the impermeable layer on the left berm began at 4.0 m below the soil surface, whereas that on the right berm began at 3.2 m below the soil surface. In the second and third ecosystems, the depth of the impermeable layer was similar on the left and right berms, at 1.8 m and 1.9 m below the soil surface, respectively.

Sensitivity Analysis

We performed a sensitivity analysis for data from October 2005 to June 2006 to determine which water-budget estimated term had the greatest effect on water-budget error. We did not test the influence of the terms that were directly measured in field (surface-water inflow and outflow every 10 seconds, precipitations every 30 minutes). The objectives of the research were to establish the best way to develop a water budget useful for application and design purposes, using routinely collected data; therefore, we only performed sensitivity analysis on the estimated terms that were easily determined with a low-cost or optimized monitoring design (e.g., runoff, subsurface rain flow, seepage). For parameters such as hydraulic conductivity, it is costly to reduce uncertainty; thus, such parameters were not included in the sensitivity analysis.

We left all water-budget terms unchanged, except runoff and indirect precipitation subsurface flow. We varied the runoff via the vegetation effect because it had a large effect on the amount of runoff; for example, a 10% increase in the vegetation effect caused a 100% increase in runoff. We varied the field capacity because it was estimated from soil analyses of highly heterogeneous soil. We tested the four possible combinations of maximum (26%) and minimum (13%) field capacity with maximum (90%) and minimum (10%) runoff reduction due to the vegetation effect.

We then tested the effect of the seepage term on the water-budget error by changing only the seepage estimate. We obtained eight seepage estimates based on four piezometer conditions, i.e., 24 piezometers measured every 18 days or every five days and 36 piezometers measured every 18 days or every five days, by two Brenta River stage conditions, i.e., fixed river stage (mean value from April 2004 to June 2006), and measured river stage. The combination of 36 piezometers measured every five days by measured Brenta River stage corresponded to the seepage estimate actually used to calculate the wetland water budget.

Table 1. Hydraulic conductivity measures in the three wetland subsystems. P: piezometers; K: hydraulic conductivity; N/A: not acquired.

	P	K [cm s^{-1}]	P	K [cm s^{-1}]	P	K [cm s^{-1}]
	First subsystem		Second subsystem		Third subsystem	
Left berm	P1	1.99×10^{-04}	P9	2.20×10^{-04}	P17	7.63×10^{-05}
	P2	7.67×10^{-05}	P10	8.28×10^{-05}	P18	1.73×10^{-03}
	P5	2.65×10^{-05}	P13	3.01×10^{-04}	P21	1.96×10^{-05}
	P6	1.76×10^{-03}	P14	2.29×10^{-04}	P22	N/A
	P25	3.74×10^{-05}	P29	4.43×10^{-05}	P33	2.53×10^{-05}
	P27	1.96×10^{-05}	P31	2.69×10^{-05}	P35	7.32×10^{-05}
Right berm	P3	1.05×10^{-04}	P11	1.40×10^{-03}	P19	1.04×10^{-03}
	P4	5.04×10^{-05}	P12	5.40×10^{-04}	P20	1.81×10^{-03}
	P7	2.53×10^{-03}	P15	4.05×10^{-03}	P23	2.61×10^{-03}
	P8	7.38×10^{-03}	P16	1.45×10^{-03}	P24	8.02×10^{-05}
	P26	4.85×10^{-05}	P30	8.78×10^{-05}	P34	1.63×10^{-04}
	P28	1.66×10^{-05}	P32	2.75×10^{-05}	P36	N/A

Water-Budget Error

To compare the results obtained from the sensitivity analyses, we estimated the water-budget error as:

$$\text{Error} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{ei} \times t_i)^2}}{V_m} \qquad (3)$$

where: Qe = flow needed to close the budget ($m^3\ s^{-1}$); Vm = mean wetland volume (m^3); n = number of data points; and t = time (s).

RESULTS

Geo-pedological Analysis

The hydraulic conductivity tests for the 36 piezometers produced values that agreed with the soil classification and stratigraphy (Table 1); measured values ranged from 7.8×10^{-3} to 1.7×10^{-5} cm s^{-1}. We could not complete field measurements of hydraulic conductivity for piezometers 22 and 36 because of no well recharge during the test and instrument problems, respectively. We assumed that these piezometers had the same hydraulic conductivity values of the nearest piezometers (21 and 24, respectively) because the stratigraphy indicated that the slotted zones crossed similar layers. The analyses indicated that soils were not homogeneous within the wetland area, and field capacity ranged from 11%–26% in volume.

The first subsystem had loam soils with higher field capacity than those of the third subsystem, which were sandier, and the right berm (downstream direction) contained clay spots, whereas the left berm contained peat layers. Therefore, assuming a constant variation in conductivity along the system and weighting the value for the length of each ecosystem, we estimated a field capacity of 26% for the first ecosystem, 20% for the second ecosystem, and 13% for the third ecosystem. In general, the left berm soils in the first and second ecosystems reflected the characteristics of the alloctone soil used to construct the ecosystems, whereas the right berm soil characteristics were similar to those of the original sandy soils.

Stratigraphy and hydraulic conductivity tests indicated that the slotted zone of piezometer 28 (first ecosystem) occurred within a clay layer. From the stratigraphy and hydraulic conductivity of the bordering piezometers (7 and 8) we deduced that this area was characterized by a silt soil with occasional clay spots. Thus, piezometer 28 was considered unrepresentative of the seepage flow and was excluded from the analysis. On the left berm in the third ecosystem, the hydraulic conductivity was highly heterogeneous, probably because of the heterogeneous distribution of the sandy-loam soil with peat layers, as suggested by the piezometers probes.

Wetland Water Budget

The water-budget terms are listed in Table 2. Over April 2004 to September 2005, the mean incoming surface-water flow (Qi) was 37.09×10^{-3} $m^3\ s^{-1}$, and the mean outgoing surface-water flow (Qo) was 33.72×10^{-3} $m^3\ s^{-1}$. The total amount of precipitation was 1,213 mm; the lowest precipitation occurred in winter, at 62 mm, whereas about 200 mm of precipitation fell in each of the other seasons. Of the total precipitation flow (3.86 ×

Table 2. Results of the water budget [10^{-3} m^3 s^{-1}]. Qi: surface-water inflow; Qo: surface-water outflow; Qp: direct precipitation flow; Qc: runoff; Qd: indirect precipitation via subsurface flow; Qet: evapotranspiration; Qs: seepage; and DT: detention time. The standard errors are reported in brackets.

Period	DT (days)	Qi	Qo	Precipitation Flow			Qet	Qs
				Qp	Qc	Qd		
April 1, 2004 to September 30, 2005	12	37.09 (2.92)	33.72 (2.30)	1.04 (0.14)	0.12 (0.03)	2.70 (0.38)	4.63 (0.49)	1.32 (0.36)
October 1, 2005 to June 15, 2006*	11	29.17 (3.70)	31.31 (3.68)	0.58 (0.25)	0.08 (0.07)	2.04 (0.81)	3.19 (0.36)	1.61 (0.73)

*Some hydraulic disturbance occurred during this period, and the pump did not function for about three months.

10^{-3} m^3 s^{-1}), the direct precipitation inflow (Qp) was 1.04×10^{-3} m^3 s^{-1}, the runoff inflow (Qc) was 0.12×10^{-3} m^3 s^{-1}, and the indirect precipitation via subsurface flow (Qd) was 2.70×10^{3} m^3 s^{-1}. The evapotranspiration flow (Qet) was a little higher than the total precipitation flow, 4.63×10^{-3} m^3 s^{-1}. The mean seepage flow (Qs) was 1.32×10^{-3} m^3 s^{-1}, with a maximum outgoing flow of 2.43×10^{-3} m^3 s^{-1} and a maximum incoming flow of 6.18×10^{-3} m^3 s^{-1}. The main term was surface-water flow (Qi and Qo), the proportions of surface-water flow represented by the other terms were: Qp, 2.9%; Qc, 0.3%; Qd, 7.6%; Qet, 13.1%; and Qs, 3.7%.

Over October 2005 to June 2006, the surface-water inflow (Qi) and surface-water outflow (Qo) changed from zero in the period of hydraulic disturbance to a mean value of 30×10^{-3} m^3 s^{-1} in the period of pump activity. In this period, the wetland area and associated watershed received 628 mm of precipitation. Of the total precipitation, 68% occurred in autumn (October–December), 14% occurred in winter (January–March), and 18% occurred in spring (April–June). The direct precipitation inflow (Qp) was 0.58×10^{-3} m^3 s^{-1}, the runoff inflow (Qc) was 0.08×10^{-3} m^3 s^{-1}, and the indirect precipitation via subsurface flow (Qd) was 2.04×10^{-3} m^3 s^{-1}. The mean evapotranspiration in this period was 3.19×10^{-3} m^3 s^{-1}. Daily seepage volumes varied from a maximum outgoing flow of 4.13×10^{-3} m^3 s^{-1} to a maximum incoming flow of 20.6×10^{-3} m^3 s^{-1}, with a mean of 1.61×10^{-3} m^3 s^{-1}. The greater daily seepage flow was caused by a day of strong rain (about 100 mm). The main term was surface-water flow (Qi and Qo); the proportions of surface flow represented by the other terms were: Qp, 1.9%; Qc, 0.3%; Qd, 6.7%; Qet, 10.5%; and Qs, 5.3%. The water-budget error was 13.5%.

Sensitivity Analysis

Changes in the parameters of field capacity and runoff reduction in the calculation of subsurface rain flow and runoff did not significantly alter the water-budget error. The error varied by 1% at most, ranging from a minimum of 13.2% to a maximum of 14.5%.

Assuming that the Penman-Monteith equation yields a reliable estimation of potential evapotranspiration (see Materials and Methods), the largest variation in the water-budget error was related to the seepage estimates. Therefore, we analyzed which parameter most affected the seepage estimate. The resulting seepage amounts and relative water-budget errors are reported in Table 3; negative values indicate water leaving the wetland, whereas positive values indicate water entering the wetland. The

Table 3. Seepage and water-budget error for eight seepage estimates based on the monitoring combinations of 24 or 36 piezometers measured every 18 or five days and fixed (F) or measured (M) Brenta River stage.

Period		24 piezometers				36 piezometers			
		18 d		5 d		18 d		5 d	
		F	M	F	M	F	M	F	M
October 15, 2005 to January 15, 2006	Seepage [10^{-3} m^3 s^{-1}]	0.88	0.73	4.17	4.81	0.72	0.60	4.05	4.40
	Error %	19.1	21.8	16.7	17.2	17.7	19.7	16.7	17.0
January 16, 2006 to June 15, 2006	Seepage [10^{-3} m^3 s^{-1}]	0.55	0.65	0.54	0.66	0.32	0.39	0.24	0.23
	Error %	28.1	28.1	10.7	10.5	28.6	28.6	10.9	10.8
October 15, 2005 to June 15, 2006	Seepage [10^{-3} m^3 s^{-1}]	0.68	0.68	1.73	2.03	0.47	0.47	1.49	1.61
	Error %	25.0	25.9	13.3	13.5	25.0	25.6	13.4	13.5

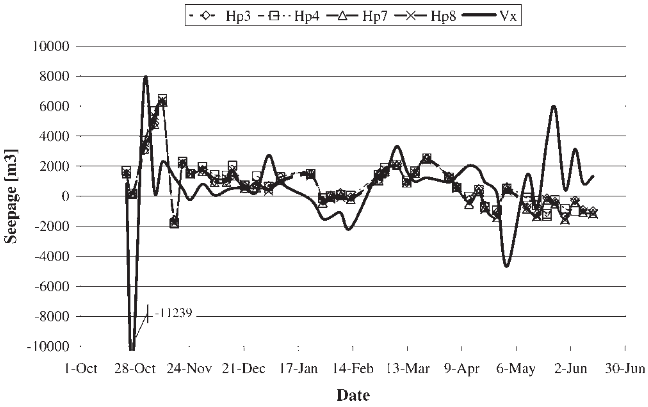

Figure 5. Seepage calculated using data measured every five days for 24 piezometers and fixed Brenta River stage (diamonds), 24 piezometers and measured Brenta River stage (squares), 36 piezometers and fixed Brenta River stage (triangles), and 36 piezometers and measured Brenta River stage (crosses). Vx = seepage estimated as a residual term in the water budget.

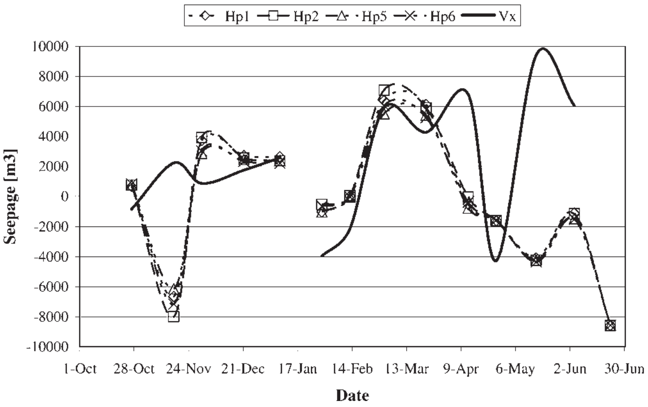

Figure 6. Seepage calculated using data measured every 18 days for 24 piezometers and fixed Brenta River stage (diamonds), 24 piezometers and measured Brenta River stage (squares), 36 piezometers and fixed Brenta River stage (triangles), and 36 piezometers and measured Brenta River stage (crosses). Vx = seepage estimated as a residual term in the water budget.

sensitivity analysis over the entire period from October 2005 to June 2006 showed that only the monitoring frequency significantly affected the seepage estimate. A smaller water-budget error was obtained for seepage calculated using data measured every five days (13%; Figure 5) than using data measured every 18 days (25%; Figure 6). During the active period (January to June 2006) the best seepage was calculated using data measured every five days (11% water-budget error). Neither the difference in the number of piezometers used (24 or 36) nor the level used for the Brenta River (fixed or measured) affected the water-budget error.

During the hydraulic disturbance period (October 2005 to January 2006) the difference in the water-budget errors calculated using the various parameter values was smaller than in the other period. However, the smallest error (17%) was still obtained using data measured every five days. For data measured every 18 days, the error associated with the seepage estimate varied from 18% (36 piezometers, fixed Brenta River stage) to 22% (24 piezometers, measured Brenta River stage).

DISCUSSION

Our water budget was compared to other published wetland water budget (Table 4). Surface flow dominated the Canale Novissimo wetland system, and the surface-water inflow (Table 2) drove the wetland water budget, similar to other constructed wetlands. Precipitation, evapotranspiration, and seepage flow contributed about 10% to the budget, and changes in water storage contributed less than 5% (Koreny et al. 1999). Runoff and indirect precipitation that moved toward the wetland via subsurface flow contributed only a small amount to the variation in water-budget error, which was affected mainly by error due to the uncertainty of terms, such as seepage flow and evapotranspiration. From data literature (Bidlake et al. 1996, Jacobs et al. 2002, Xu and Singh 2002), we assumed that the estimation of potential evapotranspiration using the Penman-Monteith method could be excluded as a major source of error.

The seepage component of a water budget is often subject to large measurement errors (Nungesser and Chimney 2006). Hydraulic conductivity measurements depend on the scale of observation, resulting in a large coefficient of variation, and can vary over orders of magnitude, even in a relatively homogeneous aquifer (Hunt et al. 1996). One source of error in our estimates was the high heterogeneity in soil hydraulic conductivity, as shown by the soil analyses. One way to reduce this type of uncertainty is to perform a finer soil survey; however, this will significantly elevate costs.

Another source of error resulted from differences in the temporal resolution of estimates within the budget. Even if most variables were measured on a daily scale (e.g., water inflow, precipitation), the seepage estimates were based on piezometers level readings taken at time intervals of several days (i.e., five and 18 days). The sensitivity analysis for both the period of activity and the total period highlighted the importance of the measurement time scale. As expected, a smaller time interval for measurement resulted in a substantial improvement in the wetland

Table 4. Percent composition of other wetland water budgets. Qi: surface-water inflow; Qo: surface-water outflow; Qp: direct precipitation flow; Qc: runoff; Qd: subsurface rain flow; Qet: evapotranspiration; Qis: inflow from seepage; Qos: outflow from seepage; and ΔS: absolute relative change in storage (dV/Σinflow*100).

	% of Total Inflow			% of Total Outflow			
References	Qi	P (Qd + Qp + Qc)	Qis	Qo	Qet	Qos	ΔS
Novissimo (October 1, 2005 to June 15, 2006)	80	8	12	86	9	5	3
Moustafa 1999	82	9	9	69	7	24	
Choi and Harvey 2000	85	11	5	68	10	23	<1
Nungesser and Chimney 2006	85	11	5	68	10	23	<1
Raisin et al. 1999[a]	6	6	88	91	9		
Zhang and Mitsch 2005[a]	94	2		89	2	6	<1
	96	2		91	2	5	<1

[a] Seepage calculated as residual term.

water budget (Hunt et al. 1999, Gardner and Reeves 2002). In contrast, increasing the number of piezometers did not affect the result. The 12 additional piezometers were positioned beyond the previous piezometers and did not produce additional information regarding seepage flow. In addition, changing the precision of data for the neighboring river water stage (i.e., the Brenta River) did not affect the seepage estimate possibly because the difference between the mean river water stage and the wetland water stage was greater than the fluctuation in the river water stage.

During the active period, the water-budget error calculated using a measurement time interval of five days was approximately 10%, which is within the range of water-budget errors from other wetlands (Nungesser and Chimney 2006). Over the hydraulic disturbance period, the water-budget error was quite similar for all seepage estimates probably because the absence of surface flow changed the temporal range of ground-water fluctuations.

CONCLUSIONS

We investigated the hydrologic processes of a constructed wetland in the Venice Lagoon watershed. We examined direct and indirect precipitation estimates, evapotranspiration (from meteorological data), design data (inflow, outflow, wetland volume), and seepage (calculated using Darcy's law) necessary to obtain the best water-budget estimate. The water-budget calculation may be affected by large errors. Considering independent estimates of each of the water-budget terms may lead to the introduction of an error linked to the particular estimation method, but it is the only way to evaluate the error itself. Surface-water flow, water level, wetland volume and area, and meteorological data are generally easy to obtain for constructed wetlands and are considered constraints in the design budget; therefore, independent estimates of water-budget terms are preferred.

Generally, the highest uncertainty in the budget estimation was related to evapotranspiration and seepage estimates. We assumed that the Penman-Monteith equation provides a reliable estimate of potential evapotranspiration, thereby excluding it as a main source of error. However, over the next three years of the experiment, we will compare the Penman-Monteith results with direct measures collected using the eddy covariance method and perform a sensitivity analysis for this term in the water budget.

The seepage term is the most difficult to estimate. Our sensitivity analysis suggests that the measurement frequency is the driving variable underlying the uncertainty in the seepage estimate. A 10% smaller water-budget error was obtained by increasing the measurement frequency from 18 to five days. Therefore, in a fresh-water surface wetland with a shallow ground-water system, the main effort in field measurement should be to ensure a measurement frequency of less than five days.

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