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Modeling the Impacts of Suspended Sediment Concentration and Current Velocity on Submersed Vegetation in an Illinois River Pool, USA

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PURPOSE: This technical note uses a modeling approach to examine the impacts of suspended sediment concentrations and current velocity on the persistence of submersed macrophytes in a shallow aquatic system. Studies were conducted on Peoria Lake, Illinois, spanning historical times when a meadow-forming species (*Vallisneria americana*) successively thrived and disappeared, and current times when the return of submersed canopy-forming (*Potamogeton pectinatus*) and meadow-forming species is anticipated. Canopy-forming plants concentrate their shoot biomass at the water surface, and meadow-formers just above the hydrosoil. In turbid conditions canopy-forming plants are expected to colonize earlier and persist longer than meadow-forming plants. Hydrodynamic, sediment transport, and aquatic plant viability models have been used to evaluate the key environmental conditions in which submersed aquatic vegetation would persist. Simulation results of the various models formed the basis for mapping historical, current, and potential (future) habitat suitability for submersed vegetation under various model scenarios. Several model results illustrated situations in which plant persistence was better at deeper sites than at shallow sites. The latter is contrary to common opinion where biomass production of submersed plants is thought to decrease with increasing water depth and increase with increasing light availability. Thus, simulations generated new insights in habitat quality for submersed vegetation. Information obtained from this study may be used to modify river management practices, and to implement operational scenarios aimed at maintaining/optimizing aquatic vegetation habitat.

INTRODUCTION: Many submersed aquatic macrophyte communities in freshwater and marine environments have experienced dramatic losses during the past three to five decades. Most commonly, declines are attributed to changes in the underwater light climate due to anthropogenic influences (Spence 1976, Kenworthy and Haunert 1991). Less frequently these declines are attributed to factors such as extremely high water levels (Spink and Rogers 1996), high current velocity (Chambers et al. 1991), droughts, or diseases that are unrelated to light. However, once the plants are lost from a given locale, increased sediment resuspension may place significant constraints on plant regrowth at that site. Thus, rehabilitation of these water bodies to promote macrophyte growth requires insights into the factors contributing to the turbidity within the water column and, possibly, other factors preventing recolonization.

This study explores environmental physical conditions in which two submersed plant species common in the Upper Mississippi River System (UMRS), one meadow-forming, *Vallisneria americana*, and one canopy-forming, *Potamogeton pectinatus*, would persist in Peoria Lake, IL (Korschgen and Green 1988, Spink and Rogers 1996). To this end, models on hydrodynamics, sediment transport, and submersed plant growth were used to simulate (a) historical conditions in which, respectively, mass colonization and disappearance by *V. americana* occurred, (b) current conditions in which submersed plants are lacking, and (c) current conditions altered by creating a 10-km-long dike along the eastern descending line of the navigation channel to reduce suspended sediment concentrations through resuspension in the southeastern part of Upper Peoria Lake (Figure 1).

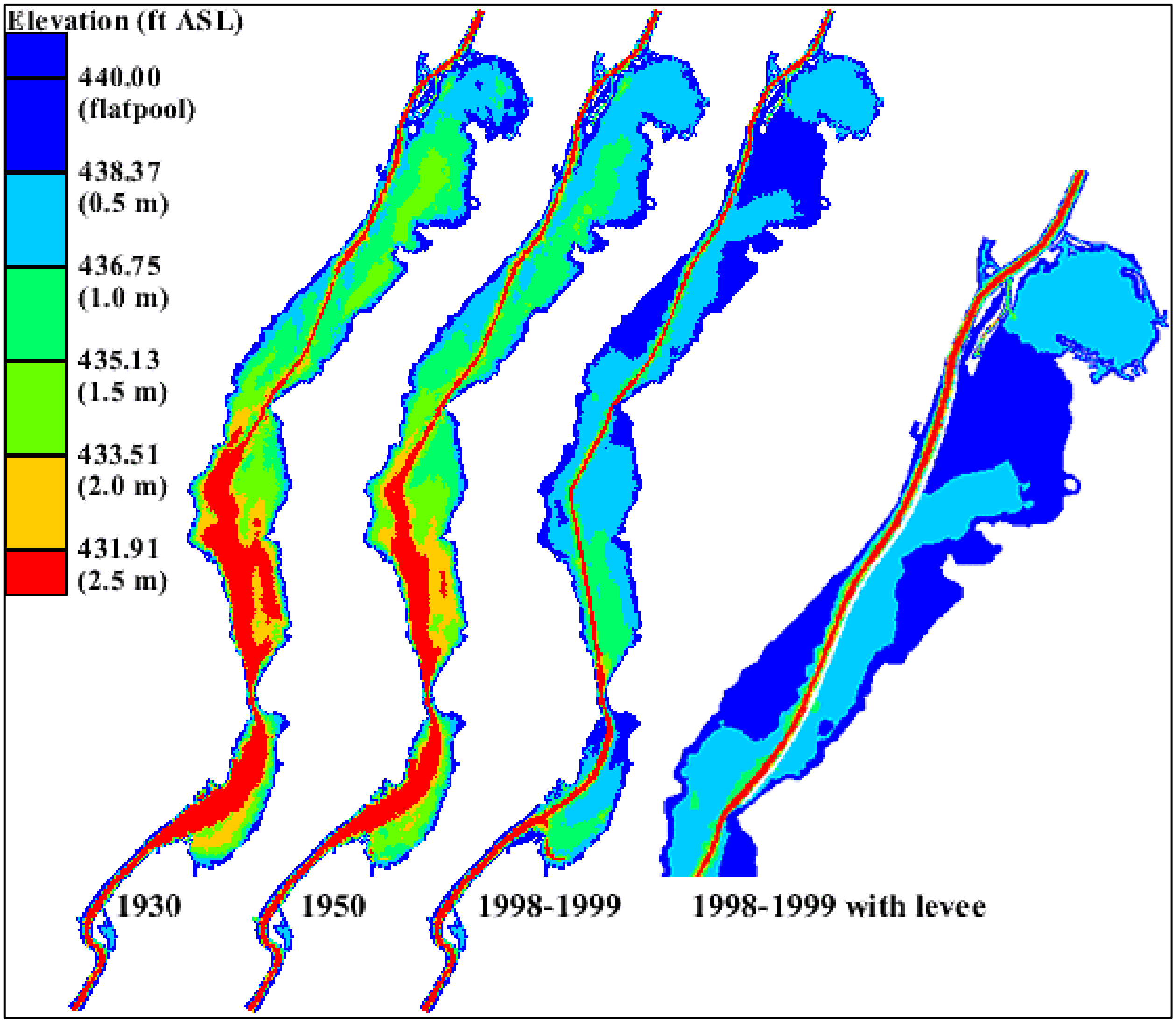

Figure 1. Bathymetry of Peoria Lake, IL, before dam construction (1930), during the years for which the simulations of aquatic macrophyte growth were performed, and for the hypothetical situation in which a levee along the north-south axis of the lake would be constructed in Upper Peoria Lake (ASL - above sea level)

STUDY SITE: Peoria Lake is a large, shallow impoundment of the Illinois River, in Illinois, USA. The lake was created by the construction of Peoria Dam in 1938 (Figure 2). This event raised the water level in Douglas Lake, the northern part of Upper Peoria Lake, by about 0.6 m and flooded the original emergent bulrush vegetation. *V. americana* colonized upper Peoria Lake in 1946, reached its peak in 1949, and disappeared in 1954 (Bellrose 1941; Mills et al. 1966). Other submersed macrophytes colonized also, but did not reach a dense cover. No aquatic vegetation records for Lower Peoria Lake exist. The two main reasons under consideration for the disappearance of submersed vegetation from the bottomland lakes of the Illinois Valley are: (1) altered water levels - mainly of local importance, and (2) an increase in turbidity, the latter being more widespread and deemed most significant (Bellrose et al. 1979).

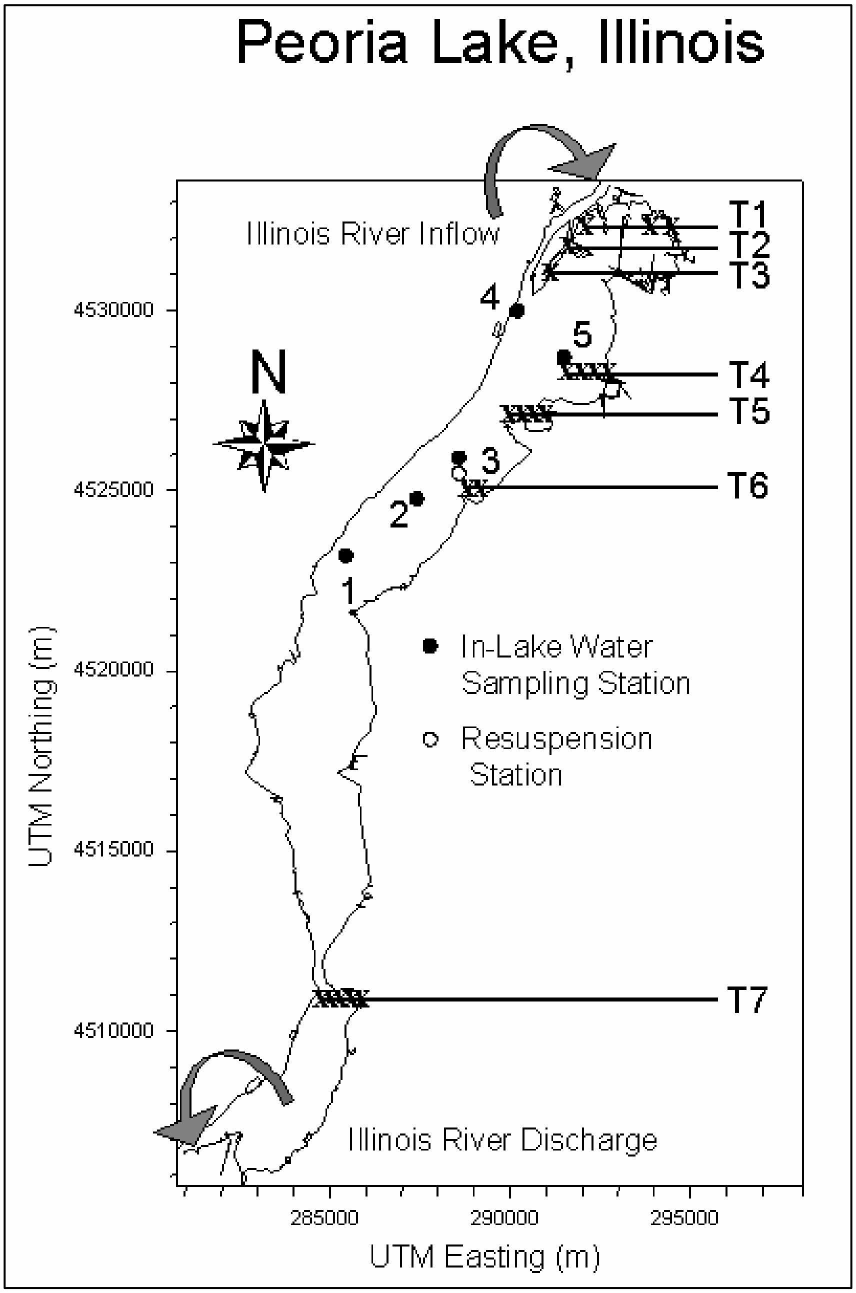

Figure 2. Map of Peoria Lake, IL, showing transects (T1-T7) for which simulations of aquatic macrophyte growth were performed

Detailed descriptions do not exist of the habitats where submersed vegetation thrived in the past and are currently lacking. However, historical records indicate that total suspended solids (TSS) concentrations increased by a factor of 2 between 1938 and 1976 and subsequently remained at the same high levels (at station Baker Bridge close to Peoria Dam; Table 1). Although the water transparency at the point of inflow would allow submersed plant persistence (light extinction coefficient of 1.91 m^{-1} in 1999), far higher values occurred at the wind-exposed sites in Upper Peoria Lake, which were formerly occupied by submersed vegetation (James et al. 2002). Estimates of sedimentation indicate that the in-lake sedimentation rate was initially 1.58 cm yr^{-1} from 1930-65, increased to 2.43 cm yr^{-1} from 1965-1976, and is currently (1976-99) leveling off to 1.1 cm yr^{-1} (C.A. Beckert).[1] Nitrate, ammonium, and total-phosphate levels increased strongly up to 1972, and subsequently decreased at a rapid rate to stabilize at far lower levels in 1994 (Table 1).

Table 1
Properties of Peoria Lake, IL

Property	Value	Date	Reference
Area (ha)	5,279	1998-99	C.A. Beckert[1]
Residence time (d)	1.89	1998-99	W.F. James[2]
Discharge Illinois River at Marseilles[a] ($m^3\ s^{-1}$)	272,760	1939-81	Demissie and Bhowmik (1986)
Mean depth (m)	1.0	1998-99	C.A. Beckert[1]
Flow-weighted mean total suspended solids at point of inflow (mg L^{-1})	75	2000	W.F. James[2]
Mean extinction coefficient (m^{-1})	1.91	2000	James et al. 2002
pH	7.9-8.5	1946-94	USEPA, STORET; ISWS, unpubl.
Mean total alkalinity (mg L^{-1})	179.2	1994	USEPA, STORET
Mean nitrate (mg L^{-1})	3.50	1994	USEPA, STORET
Mean ammonium (mg L^{-1})	0.25	1994	USEPA, STORET
Mean ortho-phosphate (mg L^{-1})	0.39	1994	USEPA, STORET

[a] Marseilles is located approximately 20 km northwest of the point of inflow of Peoria.
[1] Personal communication. (2000). C.A. Beckert, U.S. Army Engineer District, Rock Island, IL.
[2] Personal communication. (2002). William F. James, Manager, Eau Galle Aquatic Ecology Laboratory, Spring Valley, WI.

HYDRODYNAMIC AND SEDIMENT TRANSPORT MODELS USED: TABS-MD (Thomas and MacAnally 1991) is a suite of generalized numerical models and utility codes developed at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. TABS-MD models are designed to study multidimensional hydrodynamics in rivers, reservoirs, bays, and estuaries. These models can be used to study (planned) impacts on flows, sedimentation, constituent transport, and salinity. In the current study, two of the numerical models from TABS-MD were used (RMA2 and SED2D). Characteristics and application possibilities of these models for ecological resource management are discussed by Copeland et al. (2001) and Teeter et al. (2001).

RMA2 is a two-dimensional, depth-averaged, finite-element hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for subcritical free-surface flow in two-dimensional flow fields. RMA2 uses a finite-element solution technique to solve the Reynolds form of the Navier-Stokes equations for turbulent flows. The effect of

[1] Personal communication. (2000). C.A. Beckert, U.S. Army Engineer District, Rock Island, IL.

friction is accounted for with the Manning's or Chezy equation. Dynamic eddy viscosity coefficients are used to characterize turbulence diffusion characteristics. Both steady- and unsteady-state (dynamic) problems can be analyzed. Input to RMA2 includes bed elevations, hydraulic roughness, downstream water-surface elevation, water discharge at the upstream boundary, dynamic eddy viscosity (turbulent exchange coefficients), and water temperature. With this input, the computer program calculates water-surface elevations and depth-averaged velocity magnitudes and directions throughout the model grid. The number of computation points is defined by the level of detail in the numerical grid that describes the model reach. In this study, RMA2 was used to calculate ambient water-surface elevations and velocities at a number of points or nodes for use in the aquatic plant growth models.

SED2D is a two-dimensional, depth-averaged, finite-element sedimentation numerical model. It uses the same numerical grid as RMA2. The depths and velocities calculated by RMA2 are used as input to SED2D, whereupon SED2D calculates changes in sediment concentration and bed elevation in space and time using the convection-diffusion equation with bed source-sink terms. The SED2D code was enhanced to calculate sediment transport using the Garcia-Parker equation (Garcia and Parker 1991) when it was utilized for Upper Mississippi River studies. In the sediment transport calculations for sand, a single representative grain size is used. Silt and clay erosion is calculated using Partheniades' (1965) equation. Silt and clay deposition is calculated using Krone's (1962) equation. As with RMA2, both steady- and unsteady-state (dynamic) problems can be analyzed using SED2D. The sediment diameter and fall velocity in SED2D are represented by one characteristic value; thus, this value may represent sediment entrainment, transport, and deposition, where depth and velocity changes are abrupt or highly variable. The model does not account for sediment moving as bed load. SED2D is not explicitly coupled with hydrodynamic calculations, and, thus, changes in bed elevation during the simulation period must not be significant. These limitations were acceptable for the purpose of the current study, which was to evaluate general sedimentation process responses for conditions during years and scenarios of interest for the persistence of submersed aquatic vegetation. With proper input, SED2D calculated:

- Bed shear stress.
- Depth-averaged sediment concentration.
- Changes in bed elevation.
- Advective and diffusive transport of suspended sediment at points or nodes throughout the model grid.

To include the effects of wind-wave action on TSS, the SED2D model was modified to allow for time-variable atmospheric forcing, combined with currents, in the calculation of shear stresses. Other SED2D model enhancements included:

- Addition of an exponent to the excess shear stress term of the erosion equation.
- A modified depositional probability distribution with shear stress.
- An improved method of handling bed layering. The atmospheric drag coefficient was made a function of water depth, as well as of wind speed, as described by Teeter et al. (2001).

MODEL GEOMETRY: A prototype numerical computational grid was developed for Peoria Lake representative of the period 1998-99. GIS data were provided by the U.S. Army Engineer District, Rock Island, in Champaign, IL. Delineation of the model boundaries was facilitated by using aerial photographs from 1993. Elevations were based on a hydrographic survey conducted in 1998-99. The grid consisted of 5,885 elements and 14,045 nodes. Nodal coordinates were referenced to the Illinois state plane coordinate system, West zone, NAD 1983. Bathymetry was referenced to the NVGD 1929 datum. The upstream boundary for the lake model was set at river mile 182, at Chilicothe. For this boundary, data collected at a station further upstream were used (Station Henry (River Mile 196)). The downstream boundary was set at Station Peoria Dam (River Mile 157.7). An alternative scenario for the same period was created by modifying the existing conditions by creating a 10-km-long dike along the eastern descending line of the navigation channel representing a plan condition intended to reduce suspended sediment concentrations in the southeastern part of Upper Peoria Lake.

To simulate submersed vegetation persistence for other years of interest, i.e. 1946 and 1954, the prototype grid was coupled to the bathymetric data from the hydrographic survey of 1950 performed by the U.S. Army Engineer District, Rock Island.

CALIBRATION OF HYDRODYNAMIC AND SEDIMENT TRANSPORT MODELS: Water surface elevations and velocities calculated by RMA2 were used as inputs to SED2D. A water temperature of 15 ºC was assigned.

The specified hydrodynamic boundary conditions were:

- Discharge at the upstream boundary.
- Water surface elevation at the downstream boundary.

For the period 1996-2000, two prototype sediment-inflow datasets were available for numerical model adjustment of SED2D.

- One dataset collected by the U.S. Geological Survey provided biweekly data on flow and TSS concentrations at the points of in- and outflow for the period April-November 1996.
- One spatial dataset collected by ERDC-EL (James et al. 2002) provided total suspended solids (TSS) concentrations for several consecutive days in September 2000 near the point of discharge.

These datasets were combined to develop the correlation required to convert discharge into TSS concentration at the point of inflow. Additional input included:

- The diameter or fall velocity of the characteristic grain size.
- Sediment concentration of the characteristic grain size at the upstream boundary.
- Initial concentration throughout the flow field.
- Erosion and deposition characteristics of the characteristic grain size.
- Density of the bed layers.
- Sediment diffusion coefficients.
- Water temperature.

Wind measurements at Peoria Lake covered about 75 percent of the model simulation period (James et al. 2002). These wind values were adjusted to the standard measurement height of

10 m required for the model input. Wind measurements from Peoria Airport, adjusted from overland to overwater values, were used for the remainder of the simulation period.

The sediment model was validated using the bimonthly TSS measurements collected at six stations in Peoria Lake. An optical backscatter gauge at one of these stations provided hourly readings over most of the simulation period, which enabled a comparison of model results with short-term resuspension events (after conversion of backscatter to TSS; James et al. 2002).

AQUATIC PLANT GROWTH MODELS USED: Two aquatic plant growth models, pertaining to meadow-forming *Vallisneria americana* (VALLA, Best and Boyd 2001) and canopy-forming *Potamogeton pectinatus* (POTAM, Best and Boyd 2003), respectively, were used for the current study. Both models incorporate insights into the processes affecting the dynamics of a typical submersed plant community in relatively shallow, hard, water (0.2-6 m depth; DIC concentration >0.8 mmol; pH ranging from 7.6-9.4) under ample supply of nitrogen and phosphorus in a pest-, disease-, and competitor-free environment, under the prevailing weather conditions. In these models, growth starts from the subterranean tubers alone. Successively, plant biomass peaks once a year, usually in July, flowering sets in, and intensive downward transport of soluble carbohydrates occurs, which is used for the formation of tubers within the sediment. The models were equipped with a relative function that decreases photosynthesis linearly with increasing current velocity between 0.10 and 0.94 m s^{-1}, becoming zero at a current velocity of 0.94 m s^{-1} (as measured in *P. pectinatus* by Chambers et al. (1991)). These models require as inputs:

- Daily data of irradiance and air temperature.
- Water level.
- Light extinction within the water column.
- Current velocity.

The models calculate the biomass of plants and vegetative propagules (tubers). Application possibilities of these models are discussed by Best et al. (2001) and Best et al. (2004).

MODEL RUNS: RMA2 and SED2D were run in succession for those periods of the year that are important for plant growth, i.e. from 1 April to 30 September, using 1-hr time-steps, and for those years that were considered important for the submersed plant species studied, including:

- 1946, the year in which colonization of Upper Peoria Lake by *V. americana* occurred.
- 1954, the year in which *V. americana* disappeared from Peoria Lake.
- 2000-base, being representative of current environmental conditions.
- 2000-levee, as 2000-base, except for a hypothetical 10-km-long dike created along the eastern descending line of the navigation channel in Upper Peoria Lake.

The boundary input data for all runs of the hydrodynamic model were obtained from the U.S. Geological Survey Website. Because wind data prior to the end of the 1960's were lacking, it was assumed that wind speed and direction were the same during all years.

The following TSS data for the runs of the sediment transport model were used for the point of inflow:

- For 2000-base and 2000-levee, James' et al. (2002) data.

- For 1946 and 1954, the models were run in steady state with various TSS input data until a TSS concentration close to that interpolated from historical data (collected at Peoria Dam) was found; the TSS input value that matched the historical data best was then used for the simulations of that year.

From the hydrodynamic model run results, daily median values on water depth and current velocity were calculated. From the sediment transport model results, the daily median TSS concentrations were computed. The light extinction coefficients (E) were calculated from the TSS concentrations using the following regression equation pertaining to Peoria Lake (James et al. 2002): $\ln(E) = (0.585 (\ln TSS))-0.614$.

The aquatic plant growth models were run using the daily median values of water depth, current velocity, and light extinction coefficient as inputs. These models were run for depth classes along transects at locations likely to support plant growth (i.e. where submersed plants used to grow in the past; Figure 2, Table 2). Because no irradiance data pertaining to Peoria were available for the period before 1970, 10-year average data on irradiance and air temperature over the period 1986-95 were used as inputs for the plant growth models.

Table 2
Transects in Peoria Lake for Which Simulations of Aquatic Macrophyte Growth Were Performed

Transect	Perpendicular to Lake Shore	Computational Grid Node Number				
		Water Depth (m below flat pool)[1]				
		0.5	1.0	1.5	2.0	2.5
Upper Peoria Lake						
Transect 1	Eastern	12251	12245	11275		
Transect 2	Western	13874				
Transect 3	Western		13587			
Transect 4	Eastern	10573	10245	10046	9834	
Transect 5	Eastern	9917	9783	9795	9719	
Transect 6	Eastern	9171	9173			
Lower Peoria Lake						
Transect 7	Eastern	4954	4866	4779	4626	4353

[1] Flat pool in 1946.

RESULTS AND DISCUSSION: As a measure of the persistence of both submersed plant populations studied, the finished number of tuber classes was selected. This selection was made since tubers are the perennating organs believed to be more important as plant propagules than seeds in *V. americana* and *P. pectinatus*. Simulation results indicated that in historical times (1946-54) *V. americana* populations could persist only at a 0.5-m rooting depth at transects 1, 2, 5, and 6 of Upper Peoria Lake, and at transect 7 in Lower Peoria Lake when starting from the default values for tuber size and tuber number (0.09 g DW $tuber^{-1}$, 5.5 tubers $plant^{-1}$; Table 3). Transect 6 would have supported most plant growth (Figure 3), followed by transects 2 and 5. In a few cases, considerable plant biomass was simulated (range 10-23 g DW m^{-2}), but no tuber class was finished (eight cases) because plant biomass reached its maximum too late in the season to allow for tuber production.

Table 3
Simulated Tuber Class Number of *V. americana* and *P. pectinatus* for Seven Transects and Four Scenarios

		Tuber class number (N m^{-2})									
		V. americana					*P. pectinatus*				
		Depth class (m)					Depth class (m)				
Transect	**Scenario**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**
Transect 1	1946	1	0	0	NA	NA	2	0	1	NA	NA
	1954	1	0	0			2	1	0		
	2000-b	0	0	0			0	0	0		
	2000-l	0	0	0			0	1	0		
Transect 2	1946	2	NA	NA	NA	NA	2	NA	NA	NA	NA
	1954	2					2				
	2000-b	0					2				
	2000-l	0					0				
Transect 3	1946	NA	0	NA	NA	NA	NA	1	NA	NA	NA
	1954		0					1			
	2000-b		0					2			
	2000-l		0					0			
Transect 4	1946	0	0	0	0	NA	1	0	0	0	NA
	1954	0	0	0	0		1	1	0	0	
	2000-b	0	0	0	0		0	0	0	0	
	2000-l	0	0	0	0		0	0	0	0	
Transect 5	1946	2	0	0	0	NA	2	1	0	0	NA
	1954	2	0	0	0		2	0	0	0	
	2000-b	0	0	0	0		2	1	0	0	
	2000-l	0	0	0	0		0	0	0	0	
Transect 6	1946	5	0	NA	NA	NA	6	1	NA	NA	NA
	1954	5	0				7	0			
	2000-b	0	0				1	0			
	2000-l	0	0				1	1			
Transect 7	1946	1	0	0	0	0	2	1	0	0	0
	1954	2	0	0	0	0	2	0	0	0	0
	2000-b	0	0	0	0	0	1	1	1	1	0
	2000-l	0	0	0	0	0	0	1	0	0	1

Notes: b = base; l = levee; NA = not applicable.

Simulation results indicated that under current environmental conditions, *V. americana* would not be able to persist (Table 3). The creation of a dike in Upper Peoria Lake would not ameliorate the environmental conditions to such an extent that persistence would occur (Table 3). Changing the combination tuber size/tuber number combination by increasing the tuber size up to 0.12 g tuber^{-1} would not change this outcome. Larger tubers up to 0.12 g tuber^{-1} have a better survival value in spring.

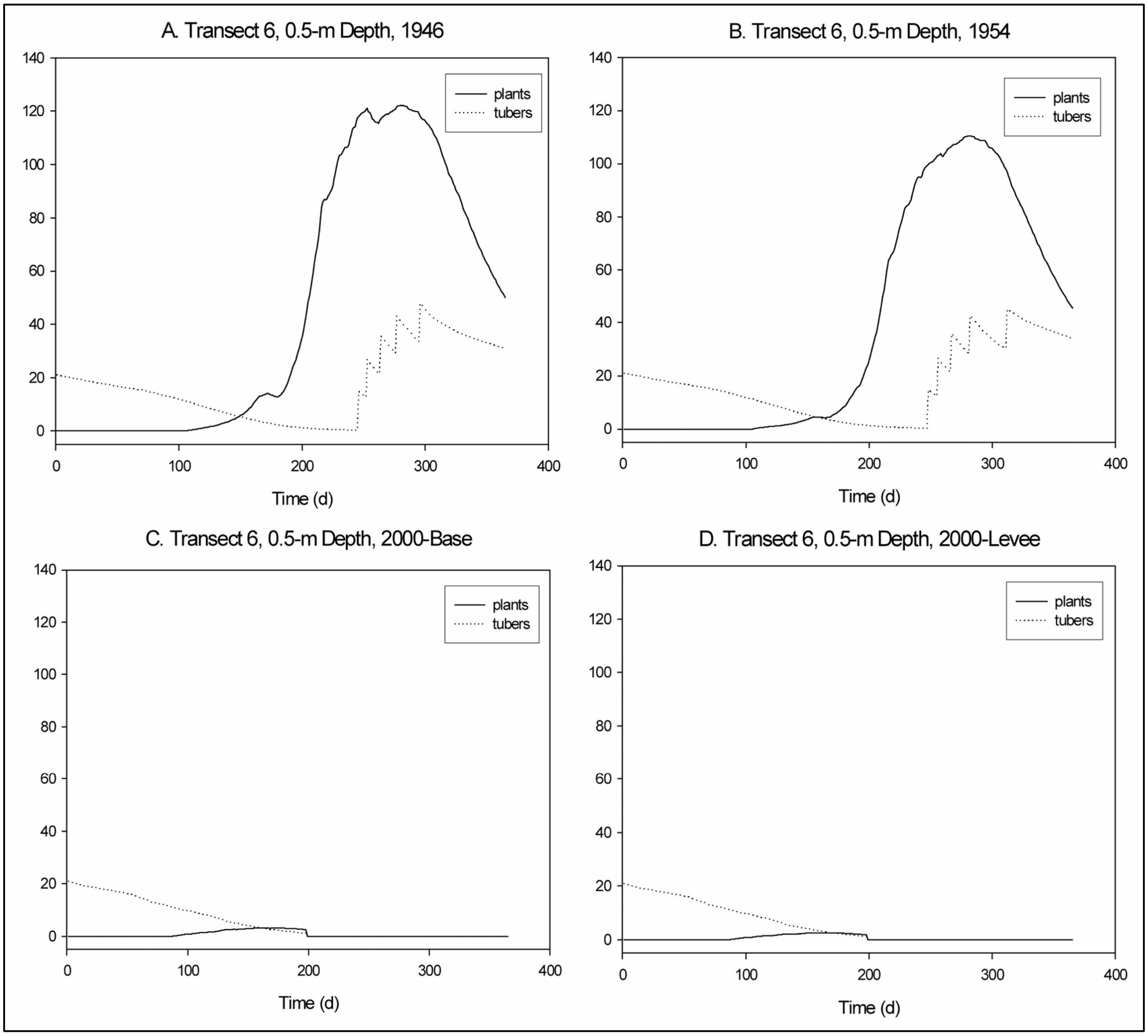

Figure 3. Simulated biomass of plants and tubers of *V. americana* in Transect 6 of Peoria Lake in different years and scenarios

No records exist on the occurrence of *P. pectinatus* in Peoria Lake. However, simulation results indicated that in historical times (1946-54) *P. pectinatus* populations would have had the capacity to persist at rooting depths from 0.5 to 1.0 m at all transects in Upper and Lower Peoria Lake when starting from a default tuber size and tuber number (0.083 g DW $tuber^{-1}$, 8 tubers $plant^{-1}$). Transect 6 could have supported most of the plant growth, followed by transects 1, 2, 5, and 7 (Table 3).

Simulation results indicated that under current environmental conditions, *P. pectinatus* would be able to persist at transects 2 (0.5 m), 5 (0.5-1.0 m), 6 (0.5 m), and 7 (0.5-2.0 m).

The creation of a dike in Upper Peoria Lake would have both positive and negative effects on *P. pectinatus* persistence. Positive effects were found in transects 1 and 6, where simulations show that one tuber class would be produced with a dike where none would be formed without a dike. Negative effects were found in transects 3 and 5, where simulations show that tubers would be formed without a dike but not with a dike. The latter negative effects were attributed to a combination of changes in water level and current velocity, since TSS levels did not change markedly. Figures 4 and 5 illustrate the situation where submersed plants would produce more tubers at deeper sites than at shallow sites. The latter effect is contrary to common opinion where biomass production of submersed plants is thought to decrease with increasing water depth and increase with increasing light availability.

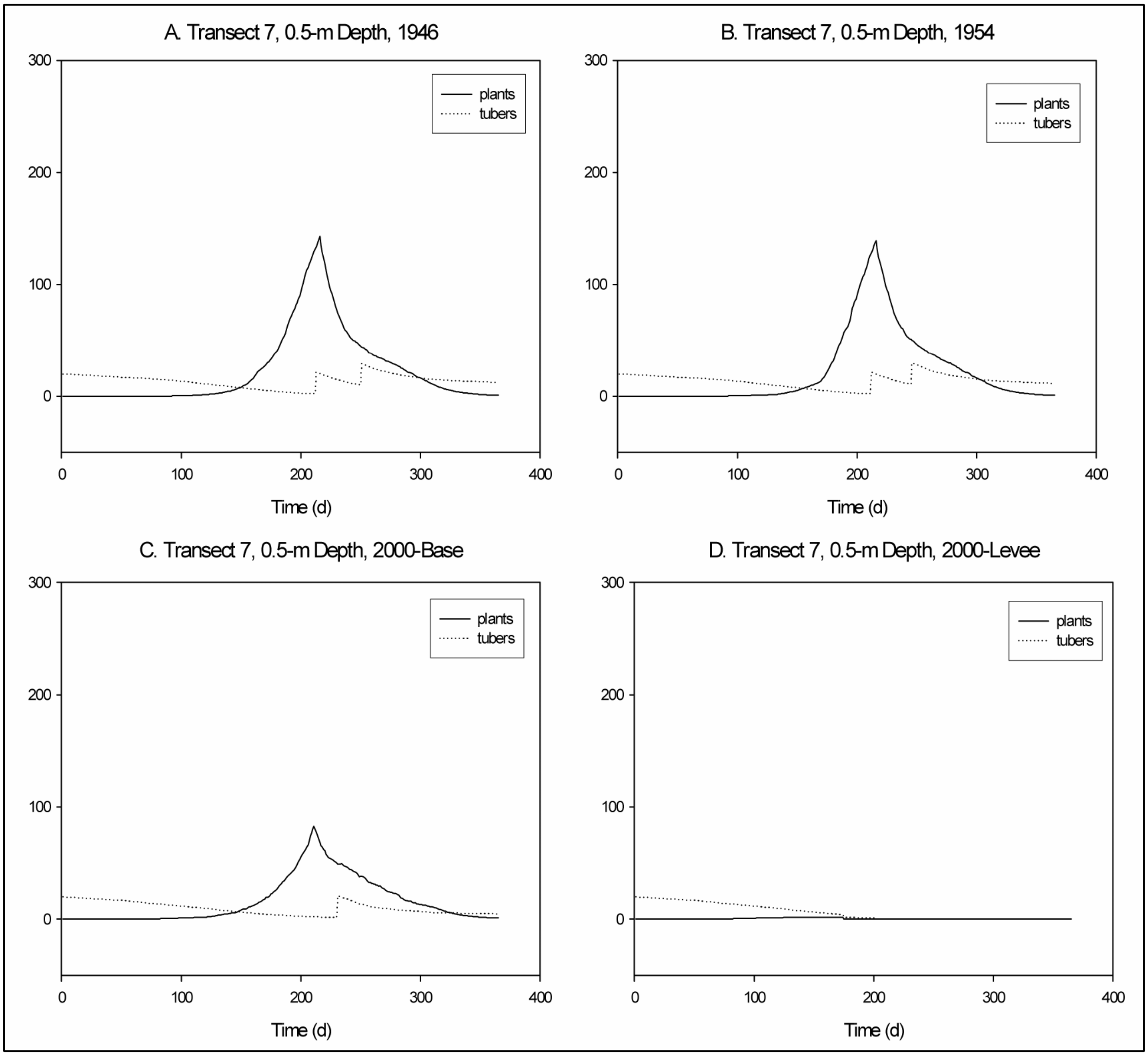

Figure 4. Simulated biomass of plants and tubers of *P. pectinatus* in Transect 7 of Peoria Lake in different years and scenarios

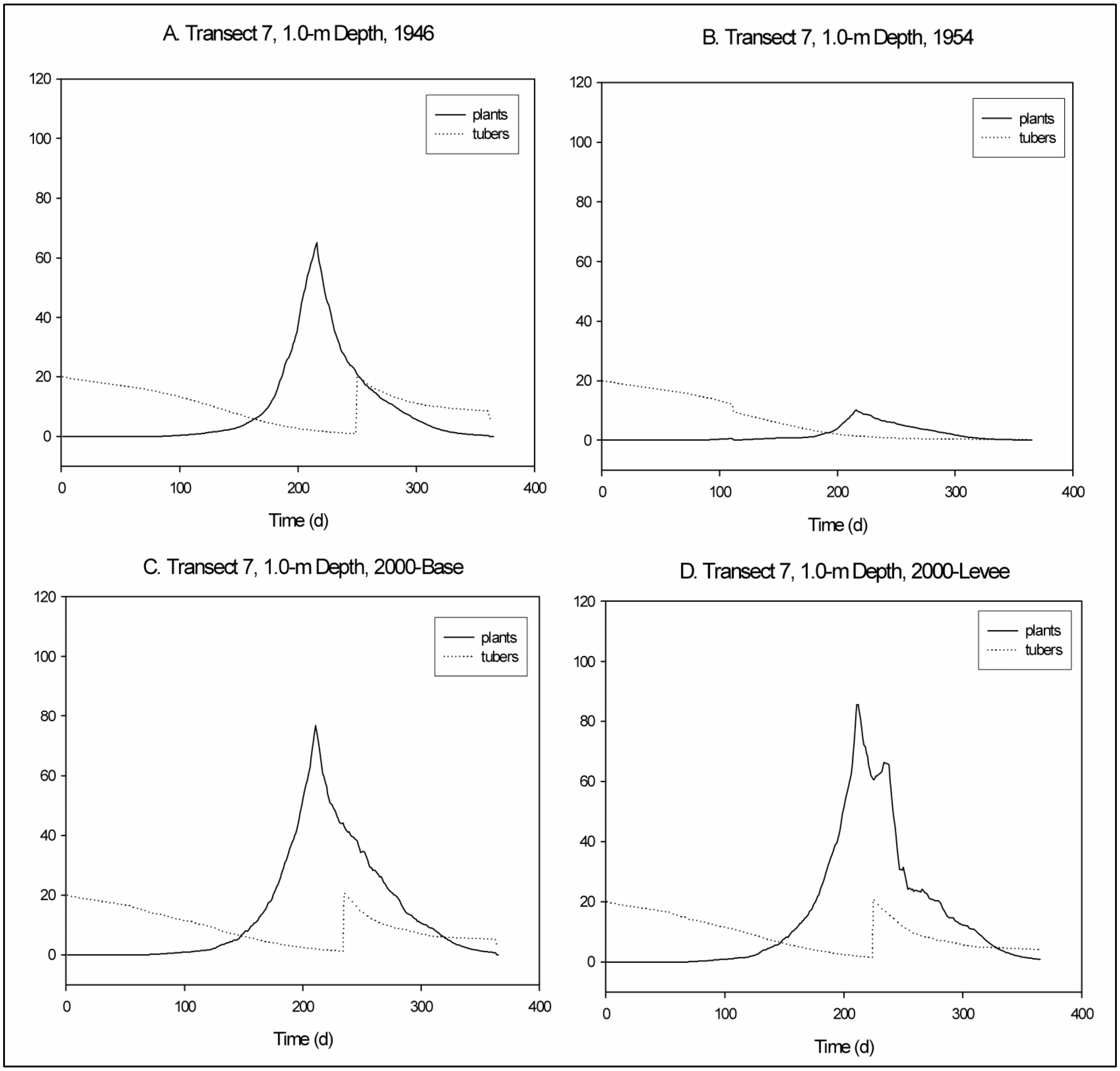

Figure 5. Simulated biomass of plants and tubers of *P. pectinatus* in Transect 7 of Peoria Lake in different years and scenarios

SUMMARY: Simulation results indicated that contemporary (2000) conditions of water depth, current velocity and turbidity, related to suspended sediment concentration in the water column, would allow the formation of a low amount of plant biomass, but prevent persistence of the meadow-forming *V. americana* because peak biomass is reached too late in the season. Simulation results also indicated that contemporary environmental conditions would allow the persistence of *P. pectinatus* at 8 out of 20 sites formerly inhabited by submersed vegetation. However, the construction of a hypothetical dike perpendicular to the predominant wind direction expected to minimize fetch and wave action from commercial navigation, would allow *P. pectinatus* to persist at only five sites. *P. pectinatus* is a canopy-forming species not formerly recorded in the lake, but likely to colonize. Several model results illustrated situations in which persistence was better at deeper sites than at shallow sites. The latter is contrary to common opinion where biomass production of submersed plants is thought to decrease with increasing water depth and increase with increasing light availability. Thus, simulations generated new insights in habitat quality for submersed vegetation. The results of model explorations such as those presented in this technical note can be used to modify existing river management practice, and to implement operational scenarios aimed at maintaining/optimizing aquatic vegetation habitat. An example of coupling models on hydrodynamics, sediment transport, and aquatic plant growth is presented by Black et al. (2003).

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