Irrigation Water Storage Cost Reduced by Stream Level Control

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ABSTRACT

Irrigation water costs are becoming of greater concern as groundwater supplies decrease and irrigation demands increase. This paper compares water storage costs for a stream water level control system (SWLC), which provides underground storage, with storage costs for impoundments and excavated ponds. A Fabridam, an automatic, water-inflatable dam was used to control the stream water level for a distance of more than 3 000 m (9800 ft) upstream. Underground storage volume was calculated from data collected during the driest year (1983) of a four-year study. A least-squares regression line through measured water volume values was determined and extrapolated to the lowest expected stream elevation. From this relationship, it was estimated that a water volume of 900 000 m^3 (730 acre-ft) could be pumped frm the creek for irrigation with the Fabridam in place. This storage volume was used to determine the size, number and cost of impoundments and excavated ponds required to provide equivalent storage. Annual costs of irrigation water storages are \$0.039, \$0.051, and \$0.121 per m^3 (\$48, \$63 and \$149/acre-ft), respectively, for SWLC, impoundments and excavated ponds. The lower-cost SWLC method could be used on an estimated 5 million hectares (12.4 million ac) of land in the southeastern Coastal Plain.

INTRODUCTION

Cost of water supplies for irrigation is becoming of greater concern as groundwater supplies decrease and irrigation demands increase. In some areas of the United States, groundwater levels are declining 2 to 3 m/yr (7 to 10 ft/yr) (U.S. Water Resources Council, 1978). In North Carolina, groundwater levels have dropped because withdrawals from aquifers have exceeded recharge (Padgett, 1984). Piezometric levels in the Yorktown, Castle Hayne and Cretaceous Aquifers have dropped 3, 24 and 30 m (10, 79, and 98 ft), respectively, since 1965; and in South Carolina, piezometric levels in the Black Creek and Middendorf Aquifers have dropped 9 m (30 ft) since 1965 (U.S. Geological Survey, 1985). The overall water budget in North Carolina (Padgett, 1984) showed that 70% of rainfall is lost to evapotranspiration and 24% is lost to direct runoff. This leaves 6% of rainfall available for use by industry (3%), by agriculture (2.5%) and for domestic purposes (0.5%). Thus, current water resources in the southeastern United States may soon be fully allocated and additional supplies for agriculture may not be available. Yet, average daily stream flows to the Atlantic Ocean and Gulf of Mexico are estimated to be about 4.2 billion m^3 (3.4 million acre-ft) (U.S. Water Resources Council, 1978). Despite this loss to runoff, about 5 million hectares (12 million acres) of sandy loam and organic soils in the Atlantic Coastal Plain must be drained because of seasonally high water tables (Wenberg and Gerald, 1982). Also, approximately 15 to 25 million ha (37 to 62 million acres) of farmland in the humid region of the United States are artificially drained, yet average crop yields for some years may be decreased from 15 to 30% because of deficient soil-water conditions. Lack of good water management is the single greatest barrier to producing sustained profitable yields in these areas.

The volume of irrigation water that can be obtained from the water now lost to runoff and stream flow into the ocean can be increased by three methods: (1) storage of runoff and drainage in the soil profile and in shallow aquifers [2 to 8 m (7 to 26 ft) below the surface] by controlling the stream water level (Doty et al., 1987),

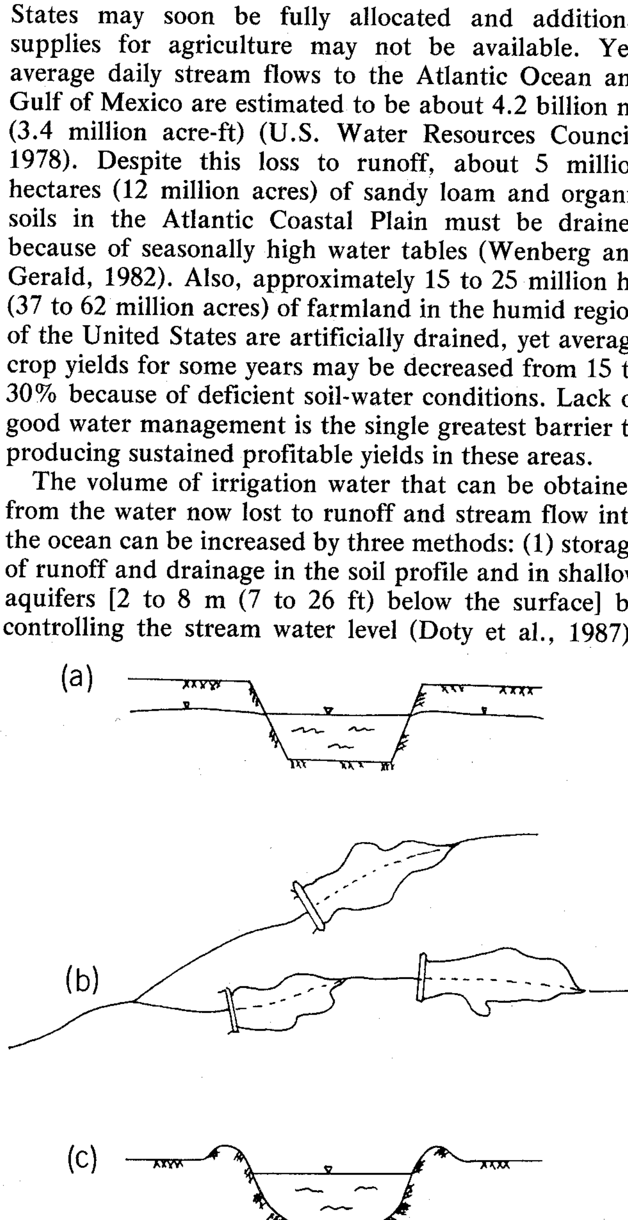

Fig. 1—Schematic diagrams of three water storage methods: (a) stream water level control (SWLC), (b) impoundments along streams, and (c) excavated ponds.

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(2) impoundments can be built along stream channels for surface storage of rainfall and runoff, and (3) ponds can be excavated into the landscape to store rainfall and runoff. Schematic diagrams of these three methods are shown in Fig. 1.

The objective of this article is to compare irrigation-water storage costs using stream water level control (SWLC), which provides underground storage, with costs for surface storage of water in impoundments and excavated ponds.

METHODS AND MATERIALS

The stream water level control (SWLC) study was located on a 3.5-km (2.2-mile) section of Mitchell Creek in Edgecombe and Pitt Counties, North Carolina (Fig. 2) (Doty et al., 1984a,b, 1986, 1987). The area, approximately 800 ha (2,000 acres) in size, was flat to gently rolling with no more than 1.5 m (5 ft) difference in elevation. Soils (Altavista, Augusta, Cape Fear, Conetoe, Portsmouth, Roanoke, State, Tarboro, and Wahee series) were mapped by the Soil Conservation Service in greater detail than for a standard soil survey. These soils are poorly-to somewhat-excessively drained and were formed in sandy fluvial and marine sediments. They are underlain by a coarse sandy aquifer extending from approximately 2 to 8 m (7 to 26 ft) deep with a layer of blue, impermeable clay below the coarse sand.

Stream water level control was accomplished by installing a rubber-coated nylon water-inflatable fabric dam, Fabridam[3], across Mitchell Creek (Doty et al., 1984a). This provided water storage in the stream channel, in connecting ditches, in the soil profile, and in the shallow aquifer (Doty et al., 1987). Other types of structures could be used in SWLC systems but were not considered in this study.

The volume of water pumped from Mitchell Creek for irrigation was measured by flow meters installed on each irrigation system. The area irrigated was determined by the area covered by each system. The water volume pumped during the driest year of the study (1983) was

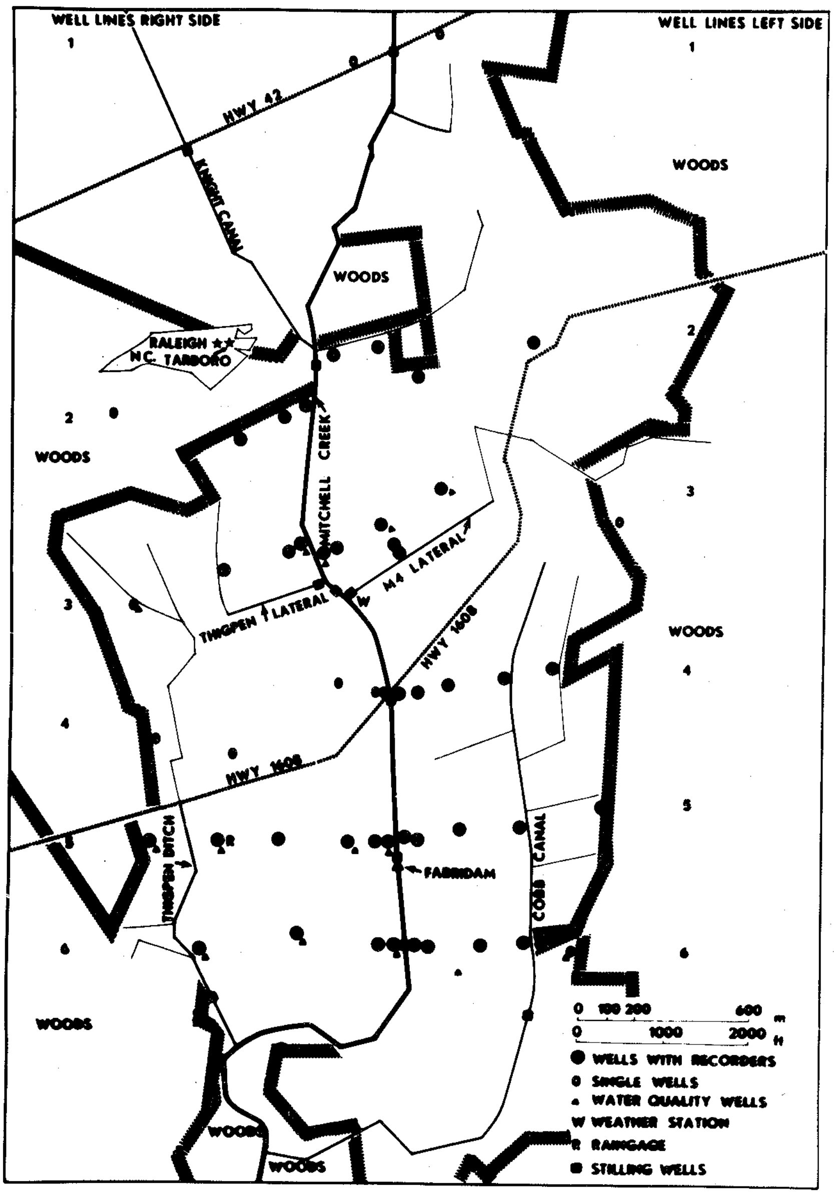

Fig. 2—Map of Mitchell Creek Watershed showing stream channel system and observation well locations.

used to project the water storage potential for SWLC. An empirical relationship was developed between volume of water pumped and the water elevation in Mitchell Creek at the structure. During an extended drought in 1983, little or no water flowed over the structure for a period of 64 days (Doty et al., 1986). The water volume pumped during this period was accumulated by time intervals and plotted as a function of stream water elevation at the end of the interval. The maximum water storage was determined by extrapolating the regression line generated from these points to the lowest stream water elevation from which water could be pumped (Fabridam base).

The initial cost of the Fabridam and its maintenance cost over the four-year period of study were used to determine the cost of water storage by SWLC. The costs of surface water storage by impoundment along streams and by excavated ponds were calculated using costs for comparable construction in Edgecombe County provided by the Soil Conservation Service (SCS).

RESULTS AND DISCUSSION

The SWLC system installed in 1982 provided (1) higher field water table levels for direct use by crops (subirrigation), and (2) an underground water supply for surface irrigation. Water was stored in the soil profile adjacent to the stream and flowed underground through the coarse sand to Mitchell Creek where it was pumped into irrigation systems (Doty et al., 1984a,b, 1986, 1987). Various estimates of water volume stored by the SWLC system have been made. Doty et al. (1986) estimated the water volume at about 4 000 000 m^3 (3200 acre-ft). Water stored in the soil profile (excluding storage in the channel itself) was estimated at about 570,000 m^3 (460 acre-ft) from flow into the stream (Badr, 1983; Doty et al., 1987).

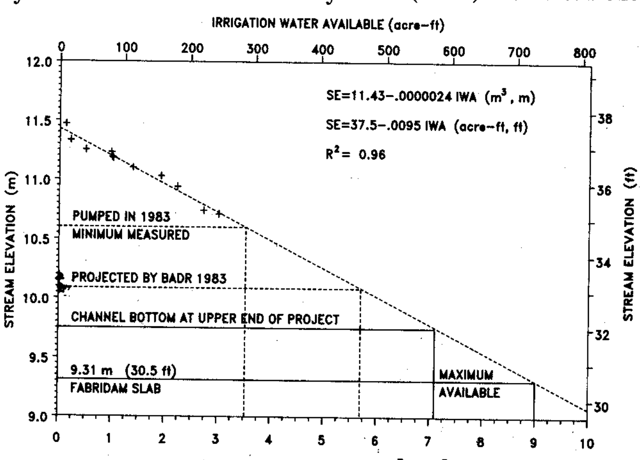

Fig. 3—Projected irrigation water storage for stream water level control (SWLC) system on Mitchell Creek for various stream water elevations.

The relationship between water volume pumped from the stream and stream water elevations obtained in this study is shown in Fig. 3. This regression line was extrapolated to the lowest stream water elevation from which water can be pumped (9.31 m or 30.5 ft above mean sea level (MSL), the elevation of the structure base). Using this rationale, the maximum volume of water that can be pumped from Mitchell Creek is 900 000 m^3 (730 ac-ft). The bottom elevation of the stream at a distance of 3 000 m (9800 ft) upstream from the structure, the upper reach of the project, is 9.75 m (32 ft) above MSL. For a stream water level elevation of 9.75 m (32 ft), the projected storage is 700,000 m^3 (567 acre-ft). Therefore, the potential volume of water in the SWLC system available for irrigation via pumping ranges from 700 000 to 900 000 m^3 (567 to 730 ac-ft). Since the coarse, sandy aquifer was located between 2 and 8 m (7 and 26 ft) below the soil surface (below 10.5 m or 35 ft stream elevation), the projected line is reasonable. However, pumping the stream level down to an elevation of 9.31 m (30.5 ft) above MSL will reduce the subirrigation effects of SWLC, which are not considered in this report.

The cost of the Fabridam was $248,700, and over a four-year period, the average maintenance cost was $3,000/yr (Doty et al., 1987). Stream bank maintenance was not included in maintenance costs. A typical impoundment in Edgecombe County is approximately 4.3 m (14 ft) high, has a pool size of 7 ha (17 ac) and a pool depth of 3.4 m (11.1 ft), costs $21,000 to construct, and has a storage capacity of 88 000 m^3 (71 acre-ft). In order to provide a storage volume equal to the maximum potential value for the SWLC system, ten impoundments would be required at a construction cost of $210,000. This would also remove at least 69 ha (170 ac) of land from production of trees or crops. A major disadvantage of surface impoundments for providing water storage is that it is often difficult to find the required number of reservoir sites along the stream near the desired location. An alternative would be to use excavated ponds.

Excavated ponds in Edgecombe County range from 1.8 m to 3.0 m (6 to 10 ft) in depth. Assuming a depth of 2 m (6.6 ft), a land area of 45 ha (111 acres) would be needed to provide storage equivalent to that of the SWLC system and impoundments. This does not include the

TABLE 1. Total and annual water storage costs for three methods to store 900 000 m^3 (730 acre-ft) of water assuming a 25-year life and 12% interest rate

Method	Land Area reqd		Land Value	Const Cost	Total Cost	Annual Cost	Annual Main	Total Annual Cost	Annual Unit Cost without land		Annual Unit Cost with land	
	ha	acre	$	$	$	$	$	$	$/m³	$/ac-ft.	$/m³	$/ac-ft.
SWLC*	0	0	0	248,700	248,700	32,700	3,000	34,700	0.039	48.11	0.039	48.11
Impoundments	68.8	170	136,000	210,000	346,000	44,100	2,000	46,100	0.030	37.00	0.051	62.91
Excavated ponds	65.1	161	128,600	706,500	835,100	106,500	2,000	108,500	0.100	123.35	0.121	149.25

*SWLC = stream water level control.

area required for spoil disposal. If spoil is piled approximately 4 m (13 ft) high, an additional 20.2 ha (50 acres) of land would be required. The average cost for excavation in this area is \$0.785 per m³ (\$968 per acre-ft). Assuming that sites could be found and that water storage volume could be obtained on a 1:1 ratio for earth moved, it would cost \$706,500 to excavate the ponds.

Annual, total and unit costs for facilities to store 900,000 m³ (730 acre-ft) of water for the three storage methods are shown in Table 1. A 25-year life and 12% interest rates were assumed. Storing water in impoundments is the cheapest of the three methods to construct. However, when the cost of land removed from production is added, costs for the SWLC system are 28% less than for impoundments and 70% less than for excavated ponds. These costs indicate that water storage using SWLC is the least expensive method even with the high cost of the prototype Fabridam, which is more expensive than a conventional structure.

Unit costs for two irrigation schemes that could be accomplished with a water supply of 900 000 m³ (730 ac-ft) are presented in Table 2. Using an annual irrigation need of 381 mm (15 in.) (SCS, 1967), 236 ha (583 acres) could be irrigated with 900 000 m³ (730 ac-ft) of water In 1983, the driest year of the study, a total water volume of 175 mm (6.9 in.) was applied to 514 ha (1270 acres). In both cases, SWLC provided a water supply at less cost than if water had been stored in either surface impoundments or exavated ponds.

Because estimates of water storage can vary, relationships between the annual storage costs and water storage volume were determined for the range of water storage volumes estimated by the three methods in this paper (Fig. 4). Water storage in excavated ponds is much more expensive than the other two methods for the entire range. SWLC provides water storage at less unit cost than impoundments for storage volumes above 650 000 m³ (527 acre-ft). This storage volume is less than that estimated for the condition when the water level in Mitchell Creek is pumped down to the bottom of the channel at the upper reach of the project (Fig. 3).

All three storage methods depend on rainfall to supply the water for storage. Water stored on the surface is subject to significant evaporation losses. In the southeastern United States, average daily evaporation from a water surface is estimated at 3-4 mm (0.12-0.16 in.) (Kohler et al., 1955). Evaporation losses are much less for the SWLC system because the water surface area is limited to the water stored in the channel and adjoining ditches, which is much less than that for the other two methods. Additionally, SWLC supplies water for subirrigation on additional land area that is not irrigated by surface systems, about 200 ha (495 acres) in this project (Doty et al., 1987). The main disadvantage of surface water storage is that sites for impoundments and excavated ponds are often not available at the desired location. The lower unit cost of the SWLC system and the scarcity of surface storage sites makes SWLC highly desirable in watersheds with characteristics similar to those of Mitchell Creek. Therefore, SWLC should be considered on all water resource projects for which it is suited.

TABLE 2. Costs to store 900 000 m³ (700 acre-ft.) of water for three storage methods and two irrigation schemes. Cost of land removed from production is included and a 25-year life and 12% interest rate is assumed

Storage method	Annual irrigation amount		Area irrigated		Annual cost	
	mm	in.	ha	acre	\$/ha	\$/acre
SWLC	381*	15 *	236	583	147	59
	175†	6.9†	514	1270	68	28
Impoundments	381	15	236	583	195	79
	175	6.9	514	1270	90	36
Excavated ponds	381	15	236	583	460	186
	175	6.9	514	1270	211	85

*Recommended by SCS (SCS, 1967).
†Water use measured in 1983.

SUMMARY AND CONCLUSIONS

The decrease in deep groundwater levels is causing concern for adequate irrigation water supplies at acceptable costs. Stream water level control (SWLC) is an effective means of conserving part of the 4.2 billion m³ (3.4 million acre-ft) of water per day flowing into the Atlantic Ocean and Gulf of Mexico.

With SWLC, it was estimated that 900,000 m³ (730 acre-ft) of water could be pumped from Mitchell Creek (and the shallow groundwater on either side of it) during the growing season. For this water volume, the cost of storage for the SWLC system was 28% less than for surface impoundments and 70% less than for excavated ponds. For storage volumes greater than 650,000 m³ (527 acre-ft), SWLC provided an irrigation water supply at less cost than with surface water impoundments.

The major disadvantages of surface water impoundments are higher costs and the availability of sufficient reservoir sites near the desired location. It is possible to establish SWLC in watersheds with relatively flat topography and soil properties that allow storage and adequate movement of water. It is estimated that SWLC is possible on about 5 million hectares (12.4 million acres) of land in the Atlantic Coastal Plain and 15 to 20 million hectares (37 to 62 million acres) in the humid region of the United States.

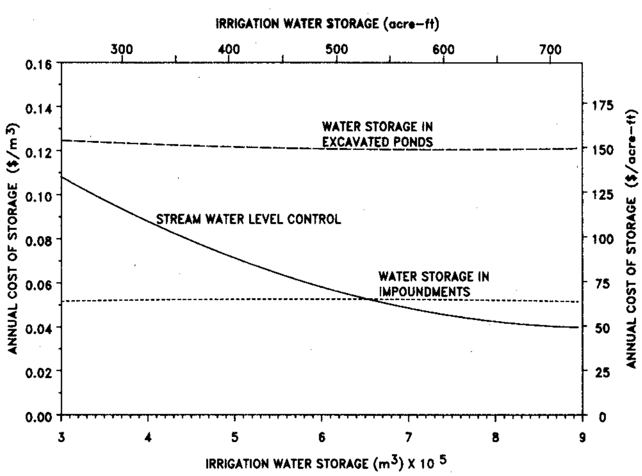

Fig. 4—Relationship between annual cost of storage and irrigation water storage for three water storage methods.

Engineering design criteria presented here and in Badr (1983), Doty et al. (1984a,b, 1986, 1987), Parsons (1987) and Parsons et al. (1987) should be used for future planning of water resource projects. Stream water level control should be considered for all past and future water resource projects, especially those with watershed characteristics similar to those of the Mitchell Creek Watershed. Properly designed and managed SWLC will provide water storage in the soil profile and in stream channels while providing adequate drainage and flood control during wet periods. Water for crop needs can be supplied by SWLC either directly to plant roots by capillary rise from a water table or through irrigation using water pumped from the stream.

References

1. Badr, A.W. 1983. Development and application of a simulation model for control drainage channels. Ph.D. thesis, Dept. of Biol. and Agric. Eng., North Carolina State University, Raleigh.
2. Doty, C.W., W.B. Thayer and R.G. Jessup. 1984a. Automated fabric dam aids water research project. Int'l Conf. on Geomembranes Proceedings. Denver, CO. Industrial Fabrics Association Int'l., St. Paul., MN.
3. Doty, C.W., J.E. Parsons, A. Nassehzadeh-Tabrizi, R.W. Skaggs and A.W. Badr. 1984b. Stream water levels affect field water tables and corn yields. *Transactions of the ASAE* 27(5):1300-1306.
4. Doty, C.W., R.M. Moore and T.L. Foutz. 1986. Performance of an inflatable dam during extreme events. *Applied Engineering in Agriculture* 2(2):108-113.
5. Doty, C.W., J.E. Parsons and R.W. Skaggs. 1987. Irrigation water supplied by stream water level control. *Transactions of the ASAE* 30(4):1065-1070.
6. Kohler, M.A., T.J. Nordenson and W.E. Fox. 1955. *Evaporation from pans and lakes.* U.S. Dept. of Commerce Res. Paper No. 38. Washington, D.C.
7. Padgett, L.B., ed. 1984. *Not one drop more.* Department of Agricultural Communications, P.O. Box 7603, North Carolina State University, Raleigh.
8. Parsons, J.E. 1987. Development and application of a three-dimensional water management model for drainage districts. Ph.D. thesis, Dept. of Biol. and Agric. Eng., North Carolina State University, Raleigh.
9. Parsons, J.E., R.W. Skaggs and C.W. Doty. 1987. Application of a three-dimensional water management model. *Transactions of the ASAE* 30(4):960-968.
10. Soil Conservation Service, USDA. 1967. *Irrigation water requirements.* Technical Release No. 21, Rev. 1980.
11. U.S. Geological Survey. 1985. *National water summary 1984.* Water Supply Paper 2275. Washington, D.C.: GPO.
12. U.S.Water Resources Council. 1978. *The nation's water resources 1975-2000, Volume I: Second Nat'l Water Assessment.* (December) Washington, DC: U.S. Water Resources Council.
13. Wenberg, R.D. and T.R. Gerald. 1982. Integrated subsurface drainage - Irrigation in the SE. *Specialty Conf. on Environmentally Sound Water and Soil Management, Proc.* (July) Am. Soc. Civil Engrs., Orlando, FL.