THE POTENTIAL INFLUENCE OF SMALL DAMS ON BASIN SEDIMENT DYNAMICS AND COASTAL EROSION IN CONNECTICUT

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ABSTRACT: *To date, little work has attempted to link dam sedimentation with the growing problem of coastal erosion, particularly with respect to small dams on comparatively small rivers. This paper reviews past work linking coastal erosion to river sediment regimes and evaluates potential linkages between small reservoir sedimentation and coastal erosion processes in Connecticut through a case study analysis of five dams. Though Connecticut's coastline is not eroding as rapidly as in some others regions, coastal erosion problems in the state have been identified. By developing a methodology to estimate sediment storage behind small dams, we provide a mechanism by which to quantitatively evaluate the potential contribution of river sediment entrapment to coastal erosion in Connecticut. Results indicate that the ~ 4,000 dams in Connecticut are storing a substantial amount of sediment and potentially significantly contributing to coastal erosion.*

Keywords**:** *Coastal erosion, River sediment, Fluvial-coastal sediment transport*

INTRODUCTION

Coastal erosion is a widespread problem affecting the environmental integrity and economic viability of coastal systems globally. In the United States, coastlines are receding at an average rate of more than 30 cm/yr (Friedman et al., 2002) with the majority of beaches experiencing erosion (Chen, 1998). Along the East Coast of the United States, the rate of coastal erosion averages 60-90 cm/yr. However, these rates vary significantly over even short distances due to local controlling variables such as geology, coastline configuration, local patterns of wave energy, and human modifications to the coastline. It is estimated that by the year 2060, approximately one quarter of homes within 500 feet of the coastline (excluding those located in most urban centers) will fall victim to the effects of coastal erosion. The resulting loss of property is estimated to cost approximately 30 billion dollars. It is widely acknowledged that coastal erosion has made our coastal ecosystems and communities much more susceptible to damage from storm events (Friedman et al., 2002)

To date, little work has attempted to link dam sedimentation with the growing problem of coastal erosion, particularly with respect to small dams (1-20 meters high) on comparatively small rivers (4^{th} order and smaller). Most studies of this process have focused on large rivers obstructed by large dams (such as the Anwar Dam on the Nile River). One exception is a modeling study of California's smaller coastal drainages which estimated that over 500 dams are potentially reducing sand and gravel transport to the coast by 25% (Willis and Griggs, 2003). For coastal management to be successful in areas of coastline supplied with sediment by comparatively smaller rivers, it is critical to understand how much sediment is not making it to the coastline. The purpose of this paper is to review past work linking coastal erosion to river sediment regimes and to evaluate potential linkages between reservoir sedimentation and coastal erosion processes in Connecticut through a case study analysis of several dam sites in the state. While Connecticut's coastline is not eroding as rapidly as in some others regions (Bernd-Cohen and Gordon, 1999), the abundance of small dams in the state warrants an investigation of possible interruptions of sediment transport to the coastline.

Linking Coastal Erosion to River Sediment Regimes

The uninterrupted supply of sediment to coastal environments via fluvial transport functions as a process of constant sediment replenishment to the coastal regime. Fluvial sediment is delivered to the coast and then transported by coastal sediment processes to marshes, beaches, dunes, and other coastal depositional features. The primary coastal sediment transport mechanism is the longshore current. Waves rarely hit the beach and the coastal regime directly head on, and the angle of wave approach sets up a pressure gradient which results in a current parallel to the coastline that drives transport of sediment, referred to as longshore transport (Stanley, 1989). This longshore transport moves fluvial-supplied sediment away from the mouth of a river and along the coastline in the prevailing direction of the longshore current. Interruption or alteration of this river-sea sediment delivery by dams results in a change in character and/or reduction in sediment supply to the longshore transport stream, leading to alterations in the sedimentology of coastal environments and/or coastal erosion.

The process of longshore current sediment starvation has been noted downshore (in the direction of longshore transport) of many major river deltas (e.g. Stanley, 1989; Ciavola et al., 1999; Panin, 2002). Near the Nile delta, coastal depositional areas were noted to have a much higher percentage of local sediments rather than deltaic sediments – a problem that has been linked to the construction of two dams in the Aswan region (Stanley, 1989; Stanley, 1996). It is believed that when the large High Aswan Dam on the Nile River was closed longshore current was deprived of the sediment supply from the Nile and, due to the increase in expendable energy, it eroded the local coastal sediment rather than depositing deltaic sediments (Stanley, 1989). Panin et al. (2002) have linked the completion of a large dam, Iron Gates Dam, to the inactivity of the Danube delta in the Black Sea, by documenting a 30-40% decrease in sediment supply from the Danube River following the completion of the Iron Gates Dam (Panin, 2002). On the Yangtze River in China, where new engineered structures are being constructed, the dams are expected to have a similar effect on the downstream deltaic coastal system (Chen, 1998). Along the USA's Texas Gulf Coast, researchers also attribute the loss of fluvial-deltaic environments to upland reservoirs (White, 2002). While it has been identified that these upland reservoirs most likely are the cause of reduced wetland sedimentation rates in the coastal environment (White, 2002), work completed by Phillips et al. (Phillips, 2001) on the Trinity River in Texas contradicts these conclusions. This suggests that the unique physical characteristics of the downstream reach of this particular river continue to provide historical rates of sediment export to the sea, indicating that the upstream and downstream reaches of the dam were essentially decoupled prior to dam construction, minimizing the effects of dam construction on river sediment delivery to the coast.

Numerous researchers have noted the importance of sediment supply in replenishing coastal environments to keep pace with natural factors such as sea level rise and subsidence (e.g. Stanley, 1996; Chen, 1998; Adam, 2002; Davidson-Arnott, 2002; Hughes, 2004). Research related to sedimentation in salt marsh environments has shown marshes will only grow and keep up with sea level rise and other natural processes as long as the sediment supply is available (Adam, 2002; Davidson-Arnott, 2002). If the sediment supply is reduced, marsh erosion will occur (Adam, 2002; Davidson-Arnott, 2002). Other studies have attributed this salt marsh loss to sediment starvation due to watershed modifications that resulted in reduced fluvial sediment delivery to the coastal regime (Adam, 2002). The importance of an available sediment supply has also been addressed in research pertaining to coastal dune environments, as it is noted that without adequate supply of sediment this system will not keep up with erosion processes and will therefore result in the lack of creation of this environment and over time will contribute to the erosion of dunes (Nordstrom, 2002). The idea of interrupted sand-transport and altered sediment budgets for many coastal regimes by human intervention is also addressed in the context of deltaic environments (Brown, 2002; Panin, 2002; Stanley, 1989).

The problem of sea level rise has garnered considerable attention as a driving agent of coastal erosion. While the threat posed by sea level rise is very real, even if accelerated by human-mediated climate change, it will take centuries to millennia for this process to produce considerable coastal erosion. In contrast, coastal erosion can occur on decadal scales in response to alterations in the volume of sediment supplied by rivers to the coast – a process that can happen quite quickly after closure of sediment-trapping river impoundments (Heinz Center, 2002). While it is widely acknowledged that natural processes such as changes in relative sea level, subsidence of coastal environments, and changes in ocean currents and energy regimes are contributing to coastal erosion, it is also widely accepted that some of these processes are being accelerated by human impacts on the coastal sediment regime (Kennish, 2002; Stanley, 1996). One of the most direct ways that humans affect coastal sediment regimes is by entrapping sediments behind dams in river systems.

Most coastal erosion research has focused on a few geographic regions, such as Louisiana, that are demonstrating very rapid rates of coastal erosion. In these high-erosion locales, studies have investigated delta erosion, wetland loss, changes in salt marsh habitat, dune reduction, and changes in sandy shore environments (Adam, 2002; Bourman, 2000; Chen, 1998; Davidson-Arnott, 2002; Hughes, 2004; Kennish, 2002; Nordstrom, 2002; Stanley, 1996; White, 2002). Little attention has been focused on regions with lower, less dramatic, rates of coastal erosion. Furthermore, although many researchers have identified the importance of large-river (> order 5) sediment supply to coastal sediment regimes, there seems to be a limited amount of research linking impoundment structures on smaller (< order 5) river systems with coastal erosion (Chen, 1998; Panin, 2002; Stanley, 1989; Stanley, 1996; White, 2002).

STUDY AREA AND METHODOLOGY

Connecticut is drained by three major river systems (the Housatonic, the Connecticut, and the Thames) in addition to several smaller coastal watersheds (Figure 1). The Connecticut River is the state's largest river, with its source located just over the Canadian border and draining a significant portion of Massachusetts, Vermont and New Hampshire prior to entering Connecticut. Small dams (ranging in size from less than 1 m to over 20 m in height) are numerous in all Connecticut drainages. For example, the Willimantic River system, which drains approximately 580 km^2 contains at least 47 small dams (Figure 2). While some are still in active use to produce energy or to maintain recreational or water supply reservoirs, many are the cultural relics of Connecticut's rich history of water-powered industry extending from the late 1700's to the 1980's. Many are in ill repair and are the subject of dam removal initiatives.

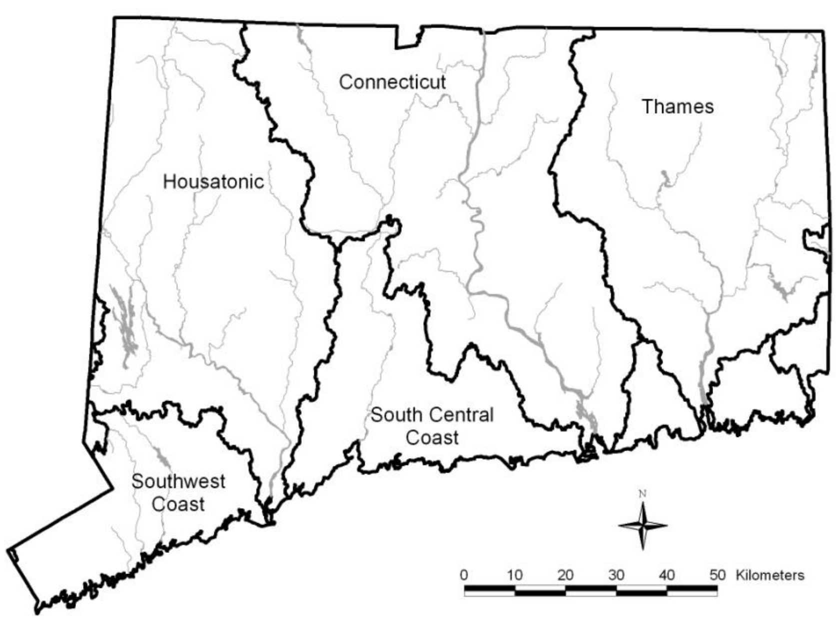

Figure 1. Map illustrating major drainage basins of Connecticut.

Table 1. Dam Age Characteristics at Study Sites

Dam	Year of Dam Construction	Age of Dam (years)	Watershed Area above Dam (km^2)
Willimantic River Dam	1860	145	288
Schoolhouse Brook Dam	1974	31	2
US Pomperaug Dam	1840	165	165
DS Pomperaug Dam	1900	105	205
Blackberry River Dam	1750	255	116

Rough estimates of the volume of sediment trapped behind dams were generated for five dams in Connecticut: the Eagleville Reservoir on the Willimantic River in Mansfield, Bicentennial Pond Dam on Schoolhouse Brook in Mansfield, Blackberry Dam on the Blackberry River in East Canaan, and two dams located on the Pomperaug River in the towns of Southbury and Woodbury. There are two different types of dams represented in this sample, spill-over and underflow dams. Four of the five dams (Eagleville dam, the two Pomperaug River dams, and the Blackberry river dam) are spill-over dams, meaning that water flows over the lip of the dam, which is made of durable material such as masonry or concrete. However, the dam on Schoolhouse Brook is an underflow dam, meaning that water flows under the earthen dam through an outflow pipe and an emergency flood spillway is present to the side of the earthen dam. The dams also vary in age and impoundment area (Table 1).

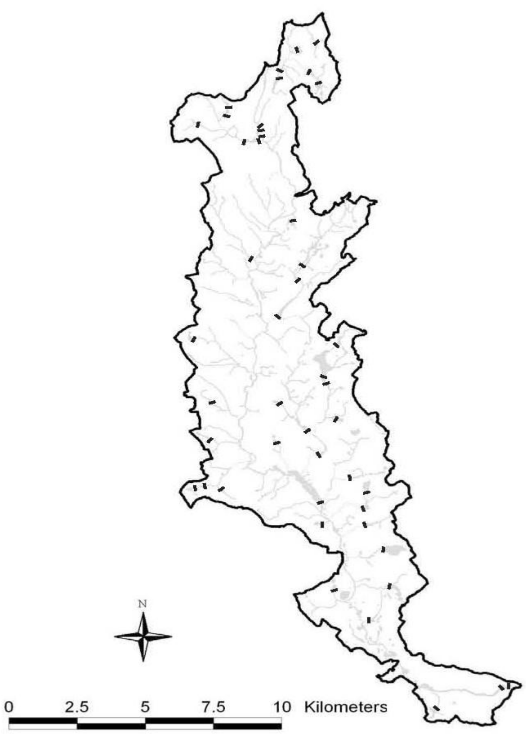

Figure 2. The Willimantic River drainage basin. Locations of dams are indicated by black rectangles.

Estimates of Dam Sedimentation

To estimate the sediment volume stored behind the study dams, the pre- and post-dam longitudinal profiles of the impoundment areas were compared (Figure 3). First, the modern longitudinal profiles were constructed by taking water depth measurements using a survey rod from a canoe beginning near the dam and working through the impoundment centerline to its upstream limit. Locations of depth measurements were recorded using GPS and later downloaded into an ArcGIS system to georeference the depth measurement points. The number of depth measurements taken at each of the reservoirs was dependent upon the size and shape of the reservoir impoundment area.

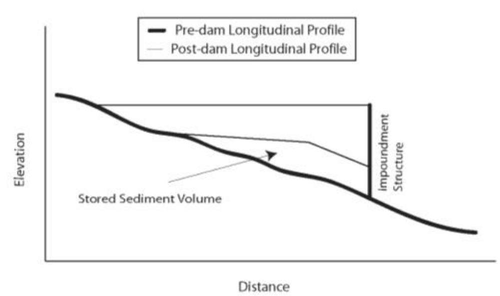

Figure 3. Conceptual diagram depicting longitudinal profile of pre and post impoundment conditions and volume of stored sediment.

Geo-rectified ortho-quad aerial photographs of each study impoundment were brought into an ArcGIS system. The impoundment boundaries, centerline of entering and exiting river channels, and dam structures were digitized as separate themes. The georeferenced depth measurement points were then integrated into this GIS, showing the exact locations of depth measurements in each reservoir. Each impoundment area was then split into lateral polygons over which the point sediment depths could be generalized.

The pre-dam longitudinal profiles were estimated by linearly connecting elevations at the head of the impoundment and base of the dam taken from USGS topographical maps (Figure 4). Measurements of water depth were then used along with the estimated pre-dam longitudinal profiles to calculate estimates of sediment storage. To estimate total impoundment sedimentation volumes, the sediment depth measured in each polygon were multiplied by the average channel width measured for that polygon. Volumes were then added and the total divided in half to produce an estimate of total impoundment sedimentation. This procedure produces a conservative estimate that is likely to underestimate the total sediment stored in the impoundments (Figure 5). Yearly sedimentation rates were calculated by dividing the total sedimentation volume estimates by the age of the impoundment.

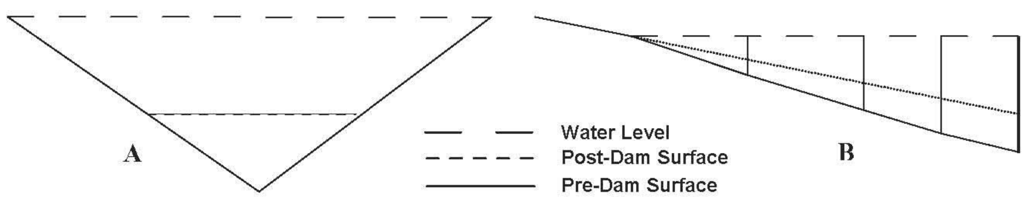

Figure 4. Cross-section (A) and longitudinal (B) conceptual view of an impoundment, illustrating difference in pre and post impoundment longitudinal profile.

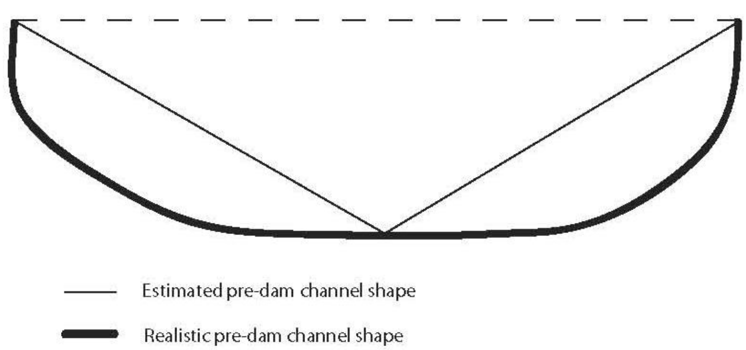

Figure 5. Illustration of estimated pre-dam channel shape versus a more realistic pre-dam channel shape.

RESULTS

Field checked depth measurements from the water-line of the reservoir to the sediment layer for the study reservoirs are presented in Figure 6. Reservoir sedimentation measurements produce total sedimentation volume estimates of 865,568 m^3 in the Willimantic Impoundment, 48,090 m^3 in the Schoolhouse Brook Impoundment, 18,234 m^3 in the Upstream Pomperaug Impoundment 765 m^3 in the Downstream Pomperaug Impoundment and 1,553 m^3 in the Blackberry River Impoundment (Table 2). The total sediment volume estimate in all five impoundments is

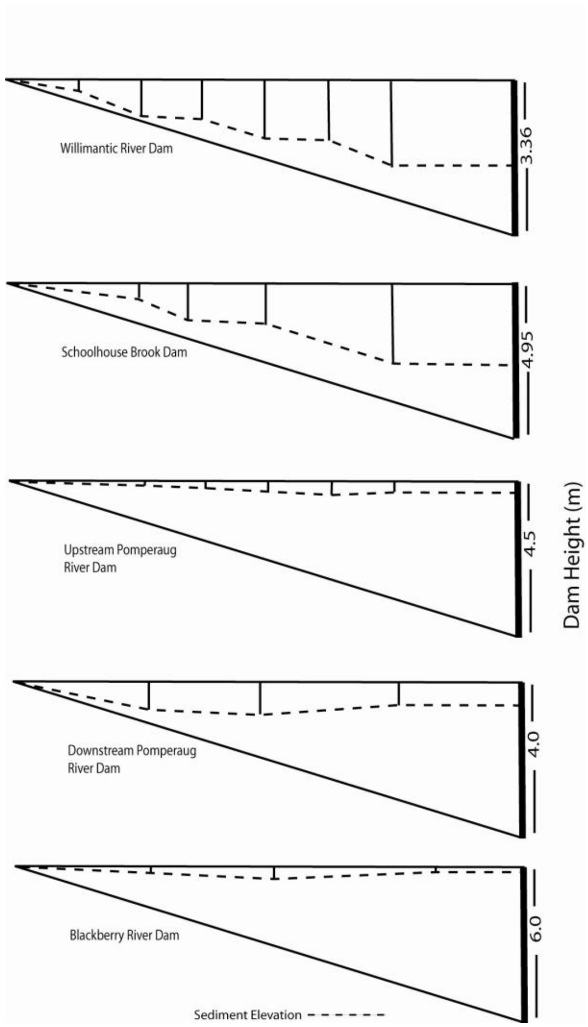

Figure 6. Field measurements of water depth and comparisons of pre- and post-dam longitudinal profiles at the five study dams.

Table 2. Sedimentation Estimates at Study Dam Sites

Dam	Total Sedimentation Volume (m^3)	Sedimentation Rate (m^3/yr)
Willimantic River Dam	865,568	5,969
Schoolhouse Brook Dam	48,090	1,551
US Pomperaug Dam	18,234	110
DS Pomperaug Dam	766	7.3
Blackberry River Dam	1,554	6.1

934,211 m^3. The Willimantic impoundment has the highest sedimentation rate per year (5,969 m^3 yr^{-1}), followed by the Schoolhouse Brook impoundment (1,551 m^3 yr^{-1}) the Upstream Pomperaug impoundment (110 m^3 yr^{-1}), the Downstream Pomperaug impoundment (7.29 m^3 yr^{-1}), and the Blackberry impoundment (6.1 m^3/yr). The total yearly sedimentation rate of all five impoundments is 7,664 m^3 yr^{-1}. Impoundment age, watershed area, dam height, and sedimentation rates show no significant correlation with sedimentation rates.

DISCUSSION

The results of this study demonstrate that, when contrasted with estimates of coastal erosion sediment volumes, a substantial amount of sediment can be stored behind small dams. However, yearly sedimentation rates for the Eagleville Dam (5,969 m^3yr^{-1}) and for Bicentennial Pond Dam (1,551 m^3 yr^{-1}) are much greater than sedimentation rates for the three other dams. The comparatively large sedimentation rate to watershed area ratio for Bicentennial Pond is likely the result of the land use history in the contributing watershed since dam construction that would produce larger than normal hillslope sediment yields. Based on field measurements and visual observations, the Eagleville Dam and the Schoolhouse Brook Dam are the two impoundments that are much less "full" of sediment than the other impoundments, which may be the cause of their higher sedimentation rates. The sedimentation in these impoundments in located primarily in the upstream end of the reservoir, while in the other impoundments sedimentation is visible right up to the dam face. The Blackberry River Dam and the Downstream Pomperaug Dams were the two impoundments that appeared to be most filled with sediment and are also the two impoundments with the lowest sedimentation rates, a situation likely reflective of the older ages and likely lack of maintenance of these dams. Although these structures are still considered small dams and are generally considered to be insignificant in terms of sediment transport disruption, these results indicate that "unfilled" small dams function like larger dams and remove large quantities of sediment from through-transport in river systems. Results from the near "full" dams seem to indicate that these structures are no longer acting as sediment traps in the way they once were, and that sediment most likely moves over the tops of these structures during transport events. So, while small dams can present a considerable obstacle to sediment transport continuity, once they fill to capacity, there is a negligible impact on the downstream transport of sediment to the coastline.

The sediment stored in these five impoundments has been removed not only from the fluvial system but also from the coastal sediment transport system as well. It is possible to consider the potential impact of impoundment sediment storage on coastline erosion in Connecticut by comparing the storage estimates produced in this study with estimates of coastal erosion in the state. Though Connecticut's coastline is not eroding as rapidly as in some others regions, coastal erosion problems in the state have been identified (Bernd-Cohen and Gordon, 1999). If estimates of Connecticut coastal erosion rates are converted to volumes of sediment, the claims of coastal erosion amount to approximately 116,738 m^3yr^{-1} of erosion. The total sedimentation estimate produced by this study, based on only a five impoundment sample, is approximately 6.5 % of this total erosion estimate, a percentage substantially, though not surprisingly, lower than the 25% reported for uplifting coastal California watersheds (Willis and Griggs, 2003). If the sediment volumes stored behind the ~ 4,000 additional dams in Connecticut were added to the estimated volumes above, it is possible that this number would approximate the amount of sediment lost through coastal erosion. While the problem of coastal erosion in Connecticut, as elsewhere, is undoubtedly the result of many variables, these results suggest that impoundment sedimentation may have significantly contributed (in the case of "full" impoundments) and may indeed continue to contribute to (in the case of open impoundments) coastal erosion along the Connecticut coastline.

Implications for Management

Currently, the problem of coastal erosion is not addressed in a coordinated manner in the USA. Instead, responses vary and are often uncoordinated between by Federal, state, local governments and private land owners (Heinz Center, 2002). Local government entities develop zoning plans, building codes, and coastal management practices, all of which can vary from community to community along the same coastal system (Heinz Center, 2002). Even the passage of the 1972 Coastal Zone

Management Act did not extend coastal management practices to holistically consider river sediment input as a serious coastal issue applicable to any shoreline, regardless of rate of coastal erosion. As demonstrated here in the case of Connecticut, many coastal areas may be suffering from sediment entrapment far inland and "out of sight" of the coastal erosion problem.

Management responses to coastal erosion are driven by stakeholder interests and economic feasibility (Parsons and Powell, 2001). For example, beach nourishment has become a commonplace erosion management strategy in many coastal areas(e.g. Nordstrom et al., 2004). Sand is imported from inland areas or pumped onto the beach from offshore. While beach nourishment may replace the lost volume of beach sand, it is a temporary fix and does not in any way address the process of coastal erosion (Brown, 2002). In fact, beach nourishment has been shown to cause ecological problems because oftentimes the imported sand is significantly different than locally produced sediments in terms of grain size and mineral composition, leading to changed in local fauna (Peterson et al., 2000; Rakocinski et al., 1996). Little thought is given to natural sand delivery pathways that, if unobstructed by dams, would deliver sediments in a less costly and more ecologically appropriate manner than beach nourishment.

CONCLUSIONS

Based on the results from the five impoundments studied in this research, it seems very likely that the ~ 4,000 dams in Connecticut are significantly contributing to coastal erosion rates. It is clear that small dams are capable of storing a significant amount of sediment and removing it from the transport pathway to the coast. Dams that are "full" of sediment do little to continue disruption of sediment transport continuity to the coast, but "unfilled" dams act like larger dams and seem to trap much larger volumes of sediment. Sediment storage assessments are needed of more, diverse sizes and types of impoundments to develop predictive relationships between dam characteristics and sediment storage volumes and to accurately quantify the total volume of sediment stored behind small dams in Connecticut. Detailed patterns and rates of coastal erosion have not been quantified for many coastal regions of the United States. To better understand the linkages between fluvial sediment transport interruption and coastal erosion, more detailed knowledge is required of the magnitudes and rates of both of these processes. Despite the lack of available detailed information, this paper has demonstrated that small dams may be significant sediment trapping devices and are likely influences rates of coastal erosion.

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REFERENCES

Adam, P., 2002. Saltmarshes in a time of change. Environmental Conservation, 29(1): 39-61.

Bernd-Cohen, T. and Gordon, M., 1999. State Coastal Program Effectiveness in Protecting Natural Beaches, Dunes, Bluffs, and Rocky Shores. *Coastal Management*, 27(2-3): 187-217.

Bourman, R.P., Murray-Wallace, C.V., Belperio, A.P., Harvey, N., 2000. Rapid coastal geomorphic change in the River Murray Estuary of Australia. *Marine Geology*, 170: 141-168.

Brown, A.C., McLaughlan, 2002. Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. *Environmental Conservation*, 29(1): 62-77.

Chen, X., Zong, Y., 1998. Coastal erosion along the Changjiang deltaic shoreline, China: history and prospective. *Estuarine, Coastal and Shelf Science*, 46: 733-742.

Ciavola, P., Mantovani, F., Simeoni, U. and Tessari, U., 1999. Relation between river dynamics and coastal changes in Albania: an assessment integrating satellite imagery with historical data. International *Journal of Remote Sensing*, 20(3): 561-584.

Davidson-Arnott, R.G.D., van Proosdij, D., Ollerhead, J., Schostak, L., 2002. Hydrodynamics and sedimentation in salt marshes: examples from a macrotidal marshe, Bay of Fundy. *Geomorphology*, 48: 209-231.

Friedman, R.M., Dunn, S.V. and Merrell, W.J., 2002. Summary of the Heinz Center Report on Coastal Erosion and the National Flood Insurance Program. *Journal of Coastal Research*, 18(3): 568-575.

Heinz Center, 2002. Evaluation of Erosion Hazards.

Hughes, R.G., Paramor, O.A.L., 2004. On the loss of saltmarshes in south-east England and methods for their restoratoio0-448n. *Journal of Applied Ecology*, 41: 4.

Kennish, M.J., 2002. Environmental threates and environmental future of estuaries. *Environmental Conservation*, 29: 78-107.

Nordstrom, K.F., Jackson, N.L. and Pranzini, E., 2004. Beach sediment alteration by natural processes and human actions: Elba Island, Italy. *Annals of the Association of American Geographers*, 94(4): 794-806.

Nordstrom, K.F., Jackson, N.L., Bruno, M.S., de Butts, H.A., 2002. Municipal initiatives for managing dunes in coastal residential areas: a case study of Avalon, New Jersey, USA. *Geomorphology*, 47: 137-152.

Panin, N., Jipa, D., 2002. Danube River Sediment Input and its Interaction with the North-western Black Sea. *Estuarine, Coastal and Shelf Science*, 54: 551-562.

Parsons, G.R. and Powell, M., 2001. Measuring the Cost of Beach Retreat. *Coastal Management*, 29(2): 91-103.

Peterson, C.H., Hickerson, D.H.M. and Johnson, G.G., 2000. Short term consequences of nourishment and bulldozing on the dominant large invertebrates of a sandy beach. *Journal of Coastal Research*, 16: 368-378.

Phillips, J.D., 2001. Sedimentation in bottomland hardwoods downstream of an east Texas dam. *Environmental Geology*, 40: 860-868.

Rakocinski, C.F., Heard, R.W. and LeCroy, S.E., 1996. Reponses by macrobenthic assemblages to extensive beach restoration at Perdido Key, Florida, USA. *Journal of Coastal Research*, 12: 326-353.

Stanley, D.J., 1989. Sediment Transport on the Coast and Shelf Between the Nile Delta and Israeli Margin as Determined by Heavy Minerals. *Journal of Coastal Research*, 5(4): 813-828.

Stanley, D.J., 1996. Nile delta: extreme case of sediment entrapment on a delta plain and consequent coastal land loss. *Marine Geology*, 4: 189-195.

White, W.A., Morton, R.A., Holmes, C.W., 2002. A comparison of factors controlling sedimentation rates and wetland loss in fluvial-deltaic systems, Texas Gulf coast. *Geomorphology*, 44: 47-66.

Willis, C.M. and Griggs, G.B., 2003. Reductions in Fluvial Sediment Discharge by Coastal Dams in California and Implications for Beach Sustainability. *Journal of Geology*, 111: 167-182.