The Influence of Climate on the Flux of Sediment to the Coastal Ocean

James P. M. Syvitski
Environmental Computation and Imaging Facility, INSTAAR, University of Colorado,
1560 30th Street, Boulder, CO, 80309-0450, U.S.A.
syvitski@colorado.edu

***Abstract*-A global approach involving data assimilation schemes allows for the prediction of the flux of water and sediment into the coastal ocean, at the dynamic level (daily). The result is either a real-time, or a hindcast or a forecast of coastal hydrology, optimized to estimate sediment loads of rivers. The approach links a compendium of global and regional web-based databases into a GIS system. Because of the explicit link between climate and hydrology, climate is seen to control the flux of sediment. Relational and spatial methods (i.e. RiverTools®, HYDRO1k, ArcInfo®) facilitate the process of data acquisition useful to sediment discharge models (i.e. HydroTrend). HydroTrend incorporates drainage basin properties (river networks, hypsometry, relief, and lakes) through high-resolution digital elevation models, along with other biophysical parameters (e.g. basin-average temperature, precipitation, canopy, soil depth, hydraulic conductivity, ice fields). Considering that <4% of world-rivers are monitored for their sediment loads, the approach provides a unique means to predict the sediment flux across an entire coastline at a high-resolution temporal scale. Model comparison to long-term observations from the Lanyang River, Taiwan, shows the model can capture average conditions and inter- and intra-annual variability of water discharge, sediment concentration and loads. Application of the schema to the Adriatic coast of Italy shows how the Apennine Rivers are strongly influenced by rare floods, capable of generating hyperpycnal flows.**

I. INTRODUCTION

Since the mid 1980's many countries have reduced the number of gauging stations located on rivers, particularly stations having both the discharge of water and sediment monitored [1, 2]. Yet there remains a continuing need to determine the flux of sediment to the coastal ocean for the assessment of coastal erosion, harbor dredging activities, aging of estuaries, and flux and dispersal of pollutants [3]. Even when present, gauging stations are located far inland of river mouths, so as to avoid the impact of tidal pumping, or for reasons of convenience [3].

Perhaps the largest impact to coastal stability is from human modification to the regional flux of sediment to the coastal zone [4]. Changes in upstream hydrology can modify the timing and intensity of floods, and therefore the effective discharge available for sediment transport. Over 75% of the world's rivers have seen stream flow modification through the reservoir construction, and/or water withdrawal for agriculture, industry and municipalities. Climate shifts have further varied the contributions from meltwater (snow, ice), altered the intensity of rain, changed drainage basin water-storage capacity, and altered precipitation and evaporation rates [4].

Some rivers that once had continuous flow now run dry every year due to these impacts. Some rivers can no longer provide the necessary energy to disperse sediment up and down the coastal zone, and thereby replenish beaches with new sediment [4]. Other rivers that were once dominated by suspended load have become bedload-rivers through the trapping efficiency of upstream reservoirs [4]. Other rivers can no longer sweep the fine-grained organic matter and mud out from their estuarine system [4].

This paper reports on a data assimilation scheme and accompanying model to provide a first order approximation of the flux of water and sediment discharged to the coastal ocean from ungauged rivers. The schema and model are briefly described. The models sensitivity to changing climate is explicitly discussed. A few examples show application to the model, addressing issues of climate and human perturbation.

II. METHODOLOGY

To calculate the flux of sediment discharged to the coastal ocean, two parameters need to be assessed: (1) the time-dependent nature of surface water runoff, and (2) the relationship between sediment and water discharge. Precipitation and temperature are the driving forces for most hydrologic simulation models. Both forces are variable in space as well as in time and spatial variation that can strongly affect runoff. Processes that are too complex or poorly understood are often modeled by statistical characteristics. Quantity models convert precipitation and snow or ice melt into runoff and may also perform flow routing, e.g. *HEC-ACE, IRIS-Cornell, TOPMODEL-USGS, HydroTrend-CU, WATFLOOD-WSC*, and *MIKE 11-ACE*. Water-quality models often begin with calibration and verification data e.g. *BASINS-EPA, QUAL2E-EPA, WQRRS-ACE,* and *WEPP-DOA*.

While any of these hydrological models can be used to determine the time dependence of water discharge, we highlight the use of *HydroTrend* [5] and its associated data assimilation scheme. The first step is to define the hydrological boundaries of the river basin(s) using *HYDRO1k*, a 1km global Digital Elevation Model (DEM) database: http://edcwww.cr.usgs.gov/landdaac/gtopo30/hydro/index.html.

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HYDRO1k defines the hydrological boundaries and topology of each hydrological basin, useful to locate the World Meteorological Organization climate stations through query of *DODS* (Distributed Oceanographic Data System) servers (ftp://ftp.unidata.ucar.edu/pub/dods/ps-docs/guide.pdf). Pertinent information about specific basins is then extracted through *ArcInfo* (ESRI) and transferred into *RiverTools* (RSI), where input parameters such as hypsometric curve, basin length, area, slope, and relief are calculated. *RiverTools* creates *shapefiles* with numerous attributes for every link in the river network, which are brought back into *ArcInfo* for advanced queries. *IDL* (Interactive Data Language) serves as a translator between the drainage basin data and the information needed by *DODS* to query the NCDC-NCEP climate sites: www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.html.

Extraneous databases needed for the hydrological modeling include (1) CCM3 dataset of Equilibrium Line Altitudes from glaciers world-wide; and (2) IGBP-DIS global soil 5x5 arc-minute dataset on water holding capacity, field capacity, soil depth, slope, % content of various particle sizes and bulk density (see http://www.daac.ornl.gov/SOILS/IsricGrids.html) to generate groundwater parameters. Together these climate and terrain data are merged within ArcInfo to supply ASCII input files for *HydroTrend* that subsequently simulates the daily flux of water for any river, whether gauged or not. *HydroTrend* ingests either climate observations (precipitation, temperature) or statistical estimates of climate from modeled climate or historical databases.

Once the time-dependent nature of surface water runoff is determined, sediment flux can be calculated. *HydroTrend* v.2, employs relationships to predict a river's sediment load for any given discharge. [1, 6, 7]:

$$Qs_{i-temp} = \psi_i (Q_i / \overline{Q})^{C_i} \quad (1)$$

where $Qs_{i\text{-}temp}$ is the initial estimate of daily sediment discharge (kg/s), ψ_i is the inter-daily variability or deviations from the sediment rating curve, Q_i is the daily discharge at the river mouth (m^3/s), $\overline{Q}$ is the long term average of Q, and C is a normal random variable, otherwise known as the rating coefficient, and defines the slope of the rating curve. If

$$\Delta = \left[\frac{(\Sigma Qs_{i-temp})}{N}\right] / \overline{Qs} \quad (2)$$

where N is the number of days, and $\overline{Qs}$ is the long term average of sediment load (see below). Then

$$Qs_i = \frac{Qs_{i-temp}}{\Delta} \quad (3)$$

where Qs_i is the final estimate of the daily sediment load (kg/s). The following relationships define the terms in (1):

$$E(\psi) = 1 \quad (4)$$

$$\sigma(\psi) = 0.763\left(0.99995^{\overline{Q}}\right) \quad (5)$$

$$E(C) = 1.4 - 0.025\overline{T} + 0.00013R + 0.145\ln\left(\overline{Qs}\right) \quad (6)$$

$$\sigma(C) = 0.17 + 0.0000183\overline{Q} \quad (7)$$

where $\overline{Qs}$ is the long-term sediment load (kg/s); R is maximum relief (m); and $\overline{T}$ is mean surface temperature across the entire drainage basin (°C). The variance of the conditional distribution F(ψ) captures both measurement error and flood dynamics. Large rivers smooth out small perturbations in factors such as time-varying sediment and water sources, and have relatively small $\sigma(\psi)$. Small rivers are inherently noisy in terms of their discharge signal, with larger values of $\sigma(\psi)$. The conditional distribution of the rating coefficient C varies between years. The variance of the conditional distribution F(C) is dependent on mean discharge (mean runoff times basin area). Smaller rivers have more characteristic (singular) values of C. Rivers with large discharge have greater values of $\sigma(C)$, depending on the importance of their various tributaries to the overall discharge within a given year.

If a river has been monitored across several decades, in terms of its sediment flux $\overline{Qs}$, this observational value should be used in (1). However very large observational uncertainties in $\overline{Qs}$ are common, resulting from loads estimated from too few samples and collected over too few years that do not capture high-energy events, measurement techniques, and human impacts [8]. Observational uncertainties in $\overline{Qs}$ may range from a factor of two for estimates for well-monitored rivers [6], to an-order-of-magnitude for poorly monitored rivers [8]. In 1977 the Eel River transported a sediment load of 0.6 kg/s, in 1965 reached 4838 kg/s. Even large rivers with reduced inter-annual variability, like the Mississippi, have order of magnitude ranges (1963: 2916 kg/s vs. 1951: 16524 kg/s). El Nino/Southern Oscillation–induced climate changes recur on a multidecadal time scale. Sediment loads measured in any one of these periods provide very different mean load estimates, with the wet period contributing sediment flux about five times greater than the dry period [9].

Where the long-term average of Qs is poorly defined through observations, [8] provide for two alternate methods for its estimate:

$$\overline{Q_s} = \alpha_3 A^{\alpha_4} R^{\alpha_5} e^{k\overline{T}} \quad (8)$$

or

$$\overline{Q_s} = \alpha_6 \overline{Q}^{\alpha_7} R^{\alpha_8} e^{k\overline{T}} \quad (9)$$

where units are previously defined and α's are coefficients defining major climate zones (Table 1). While the impact of basin size and relief as controlling factors on a river's sediment load is long accepted [10], [8] provides evidence that temperature plays an important (albeit secondary) role. Basin-wide temperature influences the rate of chemical breakdown of the rocks and thus soil formation. Basin temperature also defines the polar feedbacks (frozen soils, summer snow and ice melt dominated discharge, frozen river beds, frontal rainfall), temperate feedbacks (spring snow melt, freeze-thaw cycles, mixture of frontal and convective rainfall), and tropical feedbacks (convective rainfall, monsoons and typhoons, soil formation, tropical canopy, high lapse rates). Temperature also controls the pathway of precipitation, from storage as ice and snow in the polar and alpine regions, to impacts on evaporation, groundwater and other precipitation-to-discharge dynamics. Delayed runoff, from snow or ice-melt, is the main control on the discharge dynamics of many temperate rivers, even for large rivers like the Mississippi.

Basin-average temperature is dependent on geographical location (latitude, longitude and altitude):

$$T(x,\theta,H) = T_{0m}(x,\theta) - [L(x)H] \quad (10)$$

where H is the elevation (km), x is the latitude (degrees), L is the estimated lapse rate [see 8 for details] (°C/km), T_{0m} (°C) is temperature at the river mouth, and θ is longitude.

TABLE 1: REGRESSION COEFFICIENTS ON $\overline{Q_s} = \alpha_3 A^{\alpha_4} R^{\alpha_5} e^{k\bar{T}}$ AND $\overline{Q_s} = \alpha_6 \overline{Q}^{\alpha_7} R^{\alpha_8} e^{k\bar{T}}$

Global Sector	α_3	α_4	α_5	α_6	α_7	α_8	k
Polar T<0°C	2 10^{-5}	0.50	1.50	1.3 10^{-4}	0.55	1.5	0.1
Temp. N Lat>30°N T>0°C	6.1 10^{-5}	0.55	1.12	1.1 10^{-3}	0.53	1.1	0.07
Tropics N Lat 0 to 30°N	0.31	0.40	0.66	2.0	0.45	0.57	-0.1
Tropics S Lat 0 to 30°S	0.57	0.50	0.37	162	0.65	-0.05	-0.1
Temp. S Lat>30°S T>0°C	1.3 10^{-3}	0.43	0.96	?	?	?	0

T is basin-average temperature (°C), A is drainage basin area (km^2), R is the maximum relief from sea level to the mountain-top (m), Qs is long term sediment load (kg/s), Q is average discharge (m^3/s)

Globally, soil erosion is accelerating (e.g. deforestation, mining, some agriculture practices), while at the same time sediment flux to the coastal zone is globally decelerating (e.g. water diversion schemes, reservoirs). Reference [12] estimate that approximately 30% of the global sediment flux is trapped behind large reservoirs. Equations (8, 9) provide an estimate of the long-term steady state flux of sediment before the impacts of humans, and in addition coefficients α_3 and α_6 need to be adjusted for unique but natural conditions. Equations such as the Brune and Brown formulae for Trapping Efficiency of reservoirs [see 8] can be used to modify these coefficients. Unfortunately the influences on sediment flux of other human impacts (agriculture, urbanization, deforestation) are not so easily calculated. The natural versus anthropogenic fluxes may favor by a factor of 3 or 4, and in rare cases much more. Similarly the faulted terrain often produces higher sediment yields than comparable non-faulted terrain [9]. Where known, or can be estimated, then corrections to the coefficients α_3 and α_6 of (8, 9) should be employed.

III. HOW CLIMATE INFLUENCES SEDIMENT FLUX

Climate influences on the sediment load variability of rivers comes from two key factors:

1) Flood wave dynamics, as proxied by the ratio of $Q_i/\overline{Q}$, and
2) Sediment transport efficiency, as proxied by the rating coefficient C.

A. Flood Wave Dynamics

The world's climatic zones in part control the $Q_i/\overline{Q}$ ratio. The **polar zones** have limited and low intensity rainfall in the summer with river discharge largely derived from meltwater (snow and ice fields) during a very short runoff season. Where large rivers globally have modulated river flow (i.e. low $Q_i/\overline{Q}$ ratio), the short melt season and low lapse rates allow large polar rivers to have comparatively high $Q_i/\overline{Q}$ ratios. Compared to other climate zones, polar regions have low inter and intra annual variability in precipitation and this limits their ability to generate, for example tropical scale floods.

The **temperate zones** have moderate rainfall levels and moderate levels of inter and intra annual variability. By receiving discharge from springtime snowmelt, summer convective rainfall, and fall time frontal rainfall, rivers may generate relatively high $Q_i/\overline{Q}$ ratios. The **tropical zones** receive little to no meltwater, but rather intense rainfall, providing high inter and intra annual variability in precipitation and high $Q_i/\overline{Q}$ ratios. The tropical zones are impacted by monsoon convective rainfall, and tropical storms (typhoons). Tropical rainfall is also very orographic, with intense rains falling on steep mountain slopes causing numerous landslides.

B. Sediment Transport Efficiency

The rating coefficient typically varies between 1 and 3 [1]. The larger the coefficient, the more reactive the river is to changes in the $Q_i/\overline{Q}$ ratio. Rivers with large values of C are typically large rivers, and or are mountainous. Polar rivers typically have large values of C compared to temperate or tropical rivers of similar size and relief, although polar rivers typically have lower $Q_i/\overline{Q}$ ratios. In contrast tropical rivers have relatively low values of C but higher $Q_i/\overline{Q}$ ratios.

IV. APPLICATION EXAMPLES

A. Lanyang River, Taiwan

In a blind test, the *HydroTrend* model schema was applied to the Lanyang River, Taiwan, using only web-available data [13]. No parameters were tuned to make the simulations agree with the observations. Observations on the Lanyang River were not used to generate the coefficients used in the development of the original sediment transport model [6]. This is important if ungauged basins are to be modeled.

HydroTrend was provided 6 years of climate data and generated 50 years of synthetic climate data (e.g. daily precipitation and temperature) conserving the same inter- and intra-annual variability seen in the ground observations. From the synthetic climate data, 50 years of daily discharge was generated. *HydroTrend* produced-hydrographs showed little difference compared to the observations and were within the observational errors (Table 2). *HydroTrend* was also able to predict the long-term suspended load estimate (within 1.3 % of 45 yr observations), including the annual peak loads and suspended sediment concentrations (Table 2). The Lanyang River is seen to be very responsive to high-energy precipitation events and both the simulated values and observations on sediment load span 8 orders of magnitude, across 4 orders of magnitude in water discharge. When *HydroTrend* employed sequential climate input, predictions were similar, if not better, than the values generated from statistical realizations of climate (Table 2).

TABLE 2: COMPARISON OF OBSERVATION (MEAN ± STANDARD DEVIATION) AND MODEL PREDICTIONS FOR THE LANYANG RIVER, NORTHERN TAIWAN [13].

	Observations	**HydroTrend** Statistical Climate	Sequential Climate	**Observations**
Annual Q km^3/yr	1.96±0.66*	2.09±0.76	1.68±0.53	1.56±0.20*
Annual Q-peak m^3/s	1245±638*	1387±754	1257±447	1249±523*
Annual Qs kg/s	232±528*	235±170	240±2280	190±200*
Annual Cs kg/m^3	1.6 ± 5.5#	0.43±2.1	0.40±2.0	0.7±2.4#
Annual Cs-peak kg/m^3	13.5 ± 20#	25.6±22	20.6±10	18.2±10.7#
Years	1951-1994	50 yrs	1978-1990	1978-1990

Q is discharge, Qs is suspended sediment load, Cs is suspended sediment concentration. * Observation values based on annual rating curve determined from a few samples (≈27 samples per year) distributed across the hydrograph. # Observation values based only on averaged instantaneous samples in each year (≈27 samples per year)

This successful application of HydroTrend to the Lanyang River, demonstrates the value of linking global data sets to data ingestion schemes attached to hydrological models, so as to simulate the temporal variability in the discharge of sediment to continental margins. This is important since the magnitude of sediment transport to the coastal zone is unavailable for most rivers, because: 1) measurements have never been made, 2) measurements are no longer made, and 3) measurements are not publicly available.

The Lanyang River, used for this field-model comparison, reflects a suite of rivers that drain steep sided, tectonically active basins. These basins include, among others, the west coasts of North and South America, the Apennines, New Zealand, and Japan [14]. Their high sediment yields have generated recent interest to the Geoscience community for their ability to generate hyperpycnal discharge [15]. Hyperpycnal flows have strong impact on the coast. Where the bedload and coarser suspended sediment load would otherwise be trapped within the coastal zone, hyperpycnal flows can move this sediment across the shelf and to the deep ocean.

To generate a hyperpycnal event, a river needs to carry high suspended-sediment concentrations and allow the otherwise freshwater of a river overcome the ambient ocean density [15]. The Lanyang River often carries sediment concentrations during flood conditions that are capable of generating hyperpycnal flows [13]. The return interval of hyperpycnal events, based on both observed and modeled concentrations, is approximately every 2nd year. Hurricanes (typhoons) are the most common environmental event to create the conditions for hyperpycnal flows. Fully 50% of the Lanyang River's load can escape the coast under transport of hyperpycnal flows.

B. Apennine Rivers of Italy

Recent research on the formation of strata on continental shelves has highlighted the role of hyperpycnal flows generated from rivers [16, 17, 18]. The flows are rare but carry much sediment, and therefore contribute significantly to the stratigraphic record. However there continues to be scientific disagreement on their influence [18, 19]. In an effort to discern the likelihood and contribution of hyperpycnal flows to the transfer of sediment to the Western Adriatic margin, *HydroTrend* was applied to five Apennine Rivers (Table 3). Modern climate from *DODS* was ingested, and 100yr were simulated. For each river, two scenarios were analyzed (Table 3): (1) natural, pre-anthropogenic, conditions, and (2) the river basins populated with small reservoirs.

TABLE 3. MODELED NUMBER OF DAYS OF HYPERPYCNAL DISCHARGE OCCURRING IN A 100-YR PERIOD UNDER NATURAL CONDITIONS AND WITH HINTERLAND RESERVOIRS, FOR FIVE APENNINE RIVERS, ITALY.

River Name	Area km^2	Relief m	Dams	By duration of flow >24h	>18h	>12h	>6h
Metauro	1400	1050	No	2	2	5	28
			Yes	0	0	2	28
Potenza	770	1573	No	2	5	14	81
			Yes	1	3	14	61
Chienti	1300	1625	No	2	5	12	54
			Yes	0	1	6	50
Tronto	1200	2460	No	4	7	17	64
			Yes	0	1	7	60
Pescara	3100	2910	No	2	4	9	39
			Yes	0	0	1	27

Using buoyancy considerations alone, a hyperpycnal flow requires around 40 kg/m^3 of sediment concentration to overcome the density contrast between freshwater and ocean water [15]. This value may be as much as five times smaller to initiate hyperpycnal flow if convective settling dynamics are developed [17]. Under natural conditions, the Apennine Rivers are likely to develop hyperpycnal discharges (Table 3): a few (i.e. 25yr to 50yr return interval floods) will last for greater than 24 hours, but many more events are likely to occur for shorter duration (reoccurrence interval of 2 to 4 yr). While *HydroTrend* has a daily time step, we use the logic of [20] to convert the daily-averaged concentrations to quarterly values (Table 3). When reservoirs are included in the simulation of the otherwise natural river basins, then the number of hyperpycnal events that could last greater than 12 h is greatly reduced.

Based on these model results, hyperpycnal flows may account for 20 to 40 % of the total sediment flux from these Apennine Rivers. The five-modeled rivers (Table 3) transport on average between 0.4 and 1.3 MT/yr. However a single hyperpycnal event, while relatively rare, can transport between 0.3 and 4 MT in one day.

V. Conclusions

A new data ingestion approach coupled to a hydrological model *HydroTrend* allows for the relatively routine approximation of water and sediment discharge from coastal rivers. *HydroTrend* is able to process both sequential climate data and statistical approximations of climate. While not a water quality model that includes many anthropogenic influences, *HydroTrend* is capable of assessing the impact of reservoirs through sediment impoundment and flood wave modulation. Both of these processes work to limit the flux of sediment to the coastal zone. When applied in a blind test to a Taiwanese River, *HydroTrend* is able to capture both average and flood conditions of water and sediment discharge. When applied to Apennine Rivers flowing into the Adriatic, the model was able to simulate the intensity and reoccurrence of hyperpycnal events.

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References

[1] J.P.M. Syvitski, M.D. Morehead, D. Bahr, and T. Mulder, “Estimating fluvial sediment transport: The Rating Parameters,” *Water Resource Res.*, vol. 36, pp. 2747-2760, 2000.

[2] J.P.M. Syvitski, “Supply and flux of sediment along hydrological pathways: Research for the 21st Century”, *Global & Planetary Change,* in press.

[3] J.P.M. Syvitski, and M.D. Morehead, “Estimating river-sediment discharge to the ocean: application to the Eel Margin, northern California”, *Marine Geol.*, vol. 154, pp. 13-28, 1999.

[4] J.P.M. Syvitski, N. Harvey, E. Wollanski, W.C. Burnett, G.M.E. Perillo, and V. Gornitz, “Dynamics of the Coastal Zone,” in *LOICZ: Coastal Change and the Anthropocene*. C. Crossland, Ed. Springer, in press

[5] J.P.M. Syvitski, M.D. Morehead, and M. Nicholson, “*HydroTrend*: A climate-driven hydrologic-transport model for predicting discharge and sediment to lakes or oceans”, *Computers and Geoscience*, vol. 24 (1), pp. 51-68, 1998.

[6] M.D. Morehead, J.P.M. Syvitski, E.W.H. Hutton, and S.D. Peckham, Modeling the inter-annual and intra-annual variability in the flux of sediment in ungauged river basins. *Global and Planetary Change*, in press.

[7] J.P.M. Syvitski, “Sediment Transport Variability in Arctic Rivers: Implications for a Warmer Future,” *Polar Research*, vol. 21 (2), pp. 323-330, 2002.

[8] J.P.M. Syvitski, S.D. Peckham, R.D. Hilberman, and T. Mulder, “Predicting the terrestrial flux of sediment to the global ocean: A planetary perspective,” *Marine Geology*, in press.

[9] D.L. Inman, and S.A. Jenkins, “Climate change and the episodicity of sediment flux of small California rivers,” *J. of Geology,* vol. 107, pp. 251-270, 1999.

[10] J.D. Milliman, and J.P.M. Syvitski, “Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers,” *J. of Geology* vol. 100, pp. 525-544, 1992.

[11] C.J. Vörösmarty, L.D. Hinzman, B.J. Peterson, D.H. Bromwich, L.C. Hamilton, J. Morrison, V.E. Romanovsky, M. Sturm, and R.S. Webb, *The hydrological cycle and its role in Arctic and global environmental change: A rationale and strategy for synthesis study*. Fairbanks: Arctic Research Consortium of the U.S. 2001.

[12] C.J. Vorosmarty, M. Meybeck, B. Fekete, K, Sharma, “The potential impact of neo-Castorization on sediment transport by the global network of rivers,” in *Human Impact on Erosion and Sedimentation*, IAHS Publ. No. 245 pp. 261-273, 1997.

[13] J.P.M. Syvitski, A. Kettner, S.D. Peckham, and S.-J. Kao, Predicting the Flux of Sediment to the Coastal Zone:Application to the Lanyang watershed, northern Taiwan, unpublished.

[14] J.D. Milliman, and J.P.M. Syvitski, “Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers,” *J. of Geology*, vol. 100, pp. 525-544, 1992.

[15] T. Mulder, and J.P.M. Syvitski, “Turbidity currents generated at river mouths during exceptional discharge to the world oceans,” *J. of Geology*, vol. 103, pp. 285-298, 1995.

[16] J. Imran, and J.P.M. Syvitski, “Impact of extreme river events on the coastal ocean,” *Oceanography,* vol. 13(3), pp. 85-92, 2000.

[17] J.D. Parsons, J. Bush, and J.P.M. Syvitski, “Hyperpycnal plume formation with small sediment concentrations,” *Sedimentology*, vol., 48, pp. 465-478, 2001.

[18] H.J. Lee, J.P.M. Syvitski, G. Parker, D. Orange, J. Locat, E.W.H. Hutton, and J. Imran, “Distinguishing sediment waves from slope failure deposits: Field examples, including the ‘Humboldt slide’, and modeling results,” *Marine Geology*, vol. 192, pp. 79-104, 2002.

[19] A. Correggiari, F. Trincardi, L. Langone, and M. Roveri, “Styles of failure in late Holocene highstand prodelta wedges on the Adriatic shelf,” J. Sediment. Res. 71, 218-236, 2001.

[20] J.A. Warrick, and J.D. Milliman, “Hyperpycnal sediment discharge from semi-arid Southern California rivers – Implications for coastal sediment budgets,” Geology, in press.