

# **Modeling the Effect of Climatic and Human Impacts on Margin Sedimentation**

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## **LONG-TERM GOALS**

Coordinate the EuroSTRATAFORM modeling effort. Model the hydrological routing of water and sediment into the Northern Adriatic and the Gulf of Lions. Determine the impact of changes in climate, the impact of humans, and fluctuations in sea level, on the transfer of sediment from land to sea. Determine the dispersal mechanisms of this terrestrial flux of sediment, including the impact of hyperpycnal discharge from rivers, and the coastal trapping of sediment of deltaic distributary channels.

## **OBJECTIVES**

- Coordinate the EuroSTRATAFORM modeling efforts designed to formulate predictive and diagnostic models on how sedimentary processes contribute to the stratigraphic record.
- Determine the long-term and short-term climate changes, and the perturbations from human impacts, on the hydrological routing of water and sediment (e.g., floods, droughts) including the Po, selected rivers along the Apennines, and the Rhone River.
- Determine any connections between point-source and line-source sediment supply and sea level, and whether these connections control canyon morphology, failure frequency, and gravity flow dynamics. Determine if the formation and intensity of hyperpycnal flows generated at river mouths directly affects the position and formation of submarine canyons.
- Support the effort to understand how the dynamics of delta lobe switching frequency imparts a recognizable signature on margin architecture (e.g., through plume sedimentation).
- Support the effort to understand the dynamic response of a continental margin to large-amplitude sea-level changes, beginning with those of the last glacial cycle.
- Support the effort to develop coherent techniques for upscaling individual processes/events into long-term stratigraphic-architecture and seascape-evolution models.

# Report Documentation Page

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## APPROACH

1. Through regular meetings and electronic communication, develop a NA-EU community of modelers who together develop and/or employ a suite of numerical tools to model events affecting strata formation that are otherwise difficult to observe. The cumulative impact of these high-energy events can be predicted through numerical experiments, within the context of other relevant marine processes (e.g., earthquakes, tsunamis, storms, seasonal discharge). Have the EuroSTRATAFORM modeling group work closely with scientists collecting field observation, for insight and validation.
2. Combine single-component models into a larger numerical framework, including the conversion of *2D-SedFlux* into *3D-SedFlux*. Encourage code sharing among participants of EuroSTRATAFORM.
3. Locate and analyze the discharge records for key rivers in our Mediterranean study areas. Collect appropriate climate and geomorphic data for input to HydroTrend, and generate synthetic discharge data and sediment loads, across historical and geological periods. Make HydroTrend results (water and sediment discharge) available to other EuroSTRATAFORM participants. Predict flood probability distributions, and simulate conditions favorable to the development of hyperpycnal flows.
4. Determine if the Apennines Rivers are able to generate hyperpycnal flows. Model the interaction between long-shore currents and an evolving hyperpycnal or hypopycnal plume.
5. Construct a numerical model to handle both autocyclic and allocyclic processes. Test the model against the switching frequencies of well-studied deltas. Add the delta-switching model to the 3DSedFlux model and model the offshore sedimentation patterns given *HydroTrend* synthetic discharge data. Compare model results with field data from the Gulf of Lions and the Adriatic.
6. Investigate the employment of two scaling techniques:
  - (i) coherency-modified probabilistic frequency distributions (e.g. for river discharge), and
  - (ii) application of statistical properties of Laplace-generated deposits within a compute-and-drift scheme. Scale between laboratory experiments and continental margin observations, employing *SedFlux*.

## WORK COMPLETED

1. Convened, hosted, participated, or organized workshops to ensure the success of EuroSTRATAFORM by:
  - (i) integrating models across time and space,
  - (ii) coordinating laboratory modeling efforts with numerical modeling efforts,
  - (iii) coordinating proposed modeling and field efforts, and
  - (iv) linking efforts with European EC projects: EURODELTA, PROMESS, and EU-EuroSTRATAFORM. The last FY accomplished:

- a. a special issue of *Oceanography* (Syvitski et al., 2004),
- b. a special issue of *Marine Geology* (Trincardi and Syvitski, 2005),
- c. an all-hands *AGU session* ("Strata Formation on European Continental Margins", Dec. 12-17, 2004, San Francisco).

2. Refined the *HydroTrend* model to handle the flux of sediment from glacial rivers so that melt-water contributions could be modeled and the erosion-activity of the ice fields. Applied the revised model to estimate the flux of sediment discharge from the Po, Tet and Rhone rivers over a 18,000 period (Kettner and Syvitski, in press).

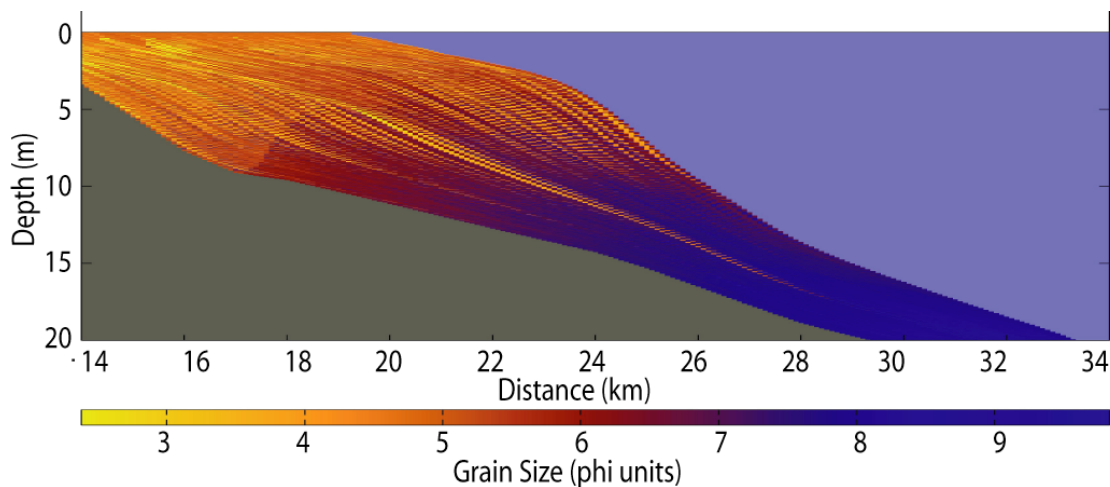
3. Completed an assessment of the discharge of Apennine Rivers and their potential for hyperpycnal flows, though both analysis of historical data and numerical modeling (Syvitski and Kettner in press). Although highly regulated, the Pescara River produced a potential hyperpycnal event in January 1970, producing a discharge-weighted sediment concentration  $>57 \text{ kg/m}^3$  over 72 hours days. The analysis provides direct evidence that hyperpycnal events are possible even by regulated Apennine Rivers.

4. Completed a study using a 2-D depth-integrated finite volume model for the simulation of a spreading hyperpycnal plume and its interaction with alongshore currents (Khan et al., 2005). Simulations indicate that an alongshore current has great impact on the development of undulating bed forms generated from sequential flow events.

5. Completed a survey of 3-D numerical models of delta evolution and highlighted the advances to 3D-SedFlux (Overeem et al., in press), a modular numerical model that is able to simulate the discharge of water and sediment into the coastal ocean from multiple rivers having multiple distributary channels.

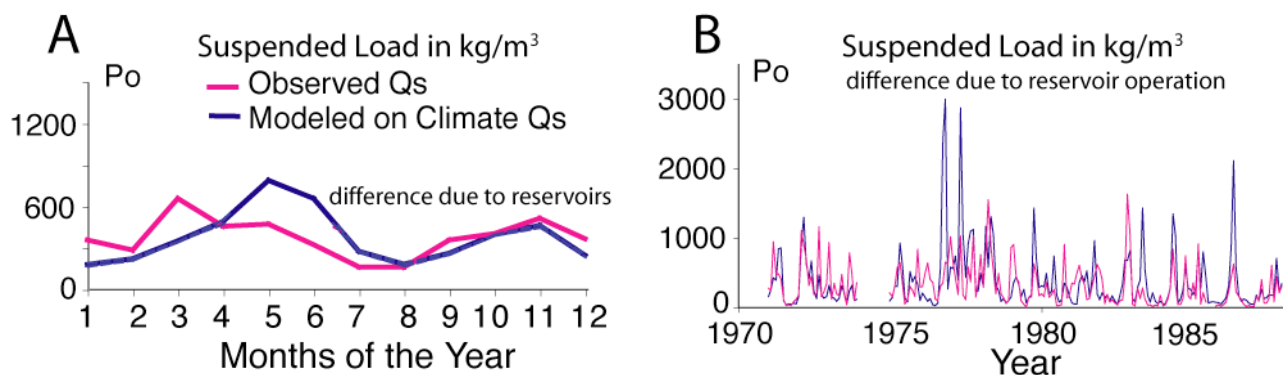
6. Contributed to the survey of numerical models being developed and employed in the EuroSTRATAFORM project (Pratson et al., 2004).

7. Added a nearshore-to-shelf sediment-transport module to *SedFlux* that modifies the seafloor through a surface-gravity wave field and bottom currents, and their interaction with a multi-grain-sized sea-bottom. Waves transmitted towards the shore have their shape modified using the dispersion relation for surface gravity waves. An advection-diffusion approach allows for grain-size dependency on sediment transport. Erosion below an equilibrium profile in the breaker zone is tied to alongshore transport in the shore-parallel direction. The newly modified *SedFlux* was then used to simulate the seafloor in the Adriatic region and examine the acoustic-reflectivity response to river flood events (Fig. 1: Pratson et al., in review).



**Figure 1.** 2000 yr SedFlux simulation of the build out of the Adriatic clinoform. Displayed is grain size (in phi units where  $<4$  is sand, and  $>8$  is clay) distributed both in distance (km) from the Pescara coastline (Italy) and in depth (m). Shown are the layers within the clinoform, some of which truncate other layers, with variable sediment size reflecting sediment sources and ocean storms.

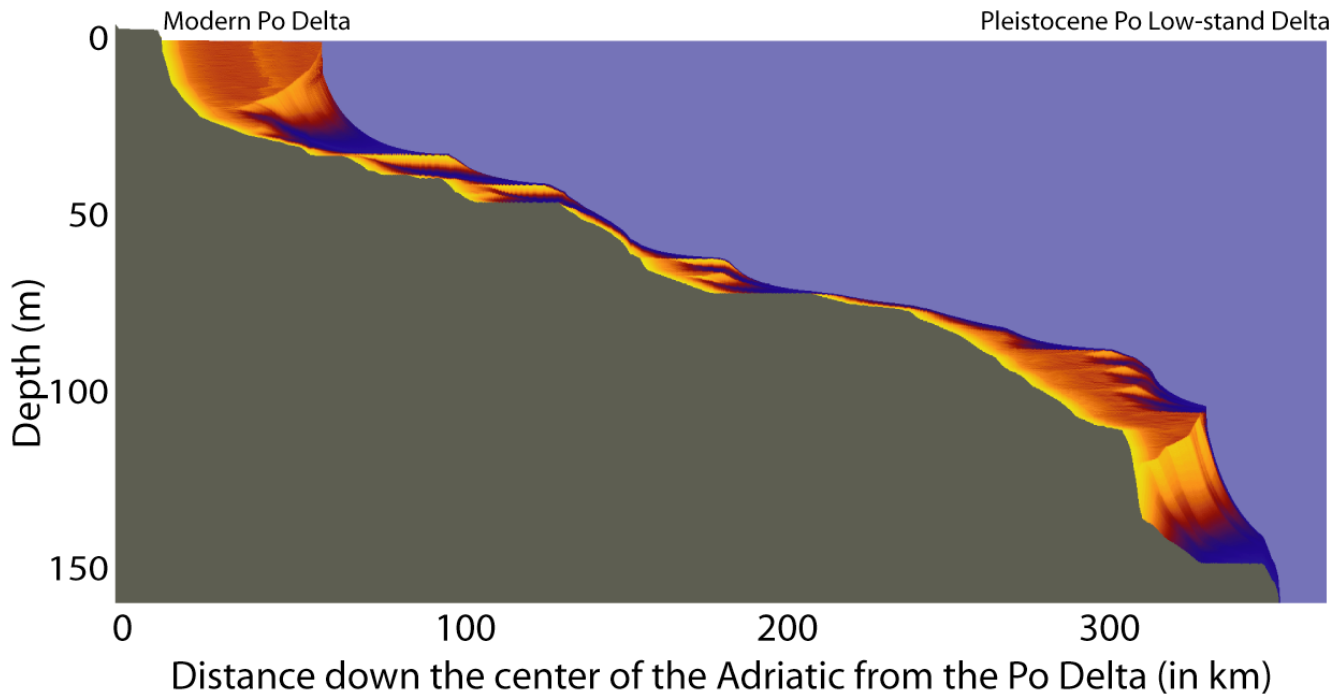
8. Analyzed the flux of water and sediment from the Po River to determine the influence of runoff from a small part of the drainage basin not impacted by reservoir operations and thus important in controlling the delivery of sediment to the Adriatic (Syvitski et al., in press-a; Syvitski et al., 2005: Fig. 2).



**Figure 2.** The monthly sediment flux of Po River comparing observed values with a simulation modeled on discharge driven by climate (rainfall, snowmelt) and basin properties. A) Comparison of monthly load values averaged over 20-years. B) Time series of monthly load values (1971-1990). In both cases the differences are from the impact of reservoir operations within the Po drainage basin.

9. The coupled hydrologic model *HydroTrend* and stratigraphic model *SedFlux* was used to investigate deposits deposited during the rising sea level, in the north Adriatic Sea area, over the last 21,000 years. Naval interests include developing an ability to invert for major below-seafloor

reflections using a forward model, as a constraint to subsurface acoustic propagation and reverberation. A series of one-step forward, two-steps back (pseudo-inverse modeling), were conducted to take into account areas of progradation and aggradation of the seafloor, and sea-level fluctuations. The subsurface architecture of the Po delta was successfully reconstructed despite the lack of three-dimensional features in the model (Kubo et al., in review).



**Figure 3.** A 360 km long SedFlux simulation of the seabed deposits formed over the last 18,000 years and found along the center of the Adriatic stretching out from the modern Po Delta. Shown is the layering and grain size (see Fig 1 for the color key) distributed within the deposits. The modern delta formed at 0 m over the last 6000 y is contrasted with the Pleistocene delta that formed at 120 m during the late Pleistocene.

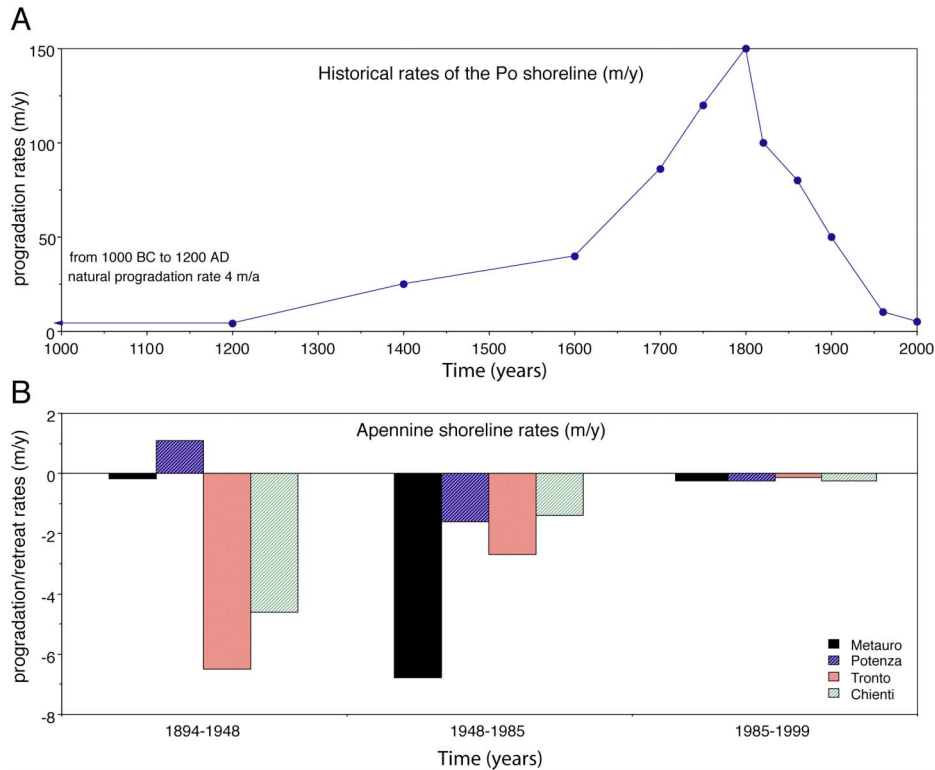
## RESULTS

The long-term experiment shows that sea level fluctuation is the largest control on the fluxes of the Po since the last glacial maximum (Table 1). Sea-level rise controls the 2.6-fold decrease in drainage area of the Po River, which proportionally affects the absolute discharge and sediment flux. Temperature and precipitation are of importance only as they impact the melt or growth of the Alpine Icecap. The release of melt-water from the ablating Alpine Ice-cap adds substantial water and sediment to the coastal ocean system. We found that in strong glacier ablation year 90% of the total discharge could be attributed to glacial melting in the summer months. Sediment transport increased up to 45 times in such an extreme glacier ablation year. The temperature and precipitation are the main forcers of daily variations, and determine the occurrence of peak events. The modern sediment load to the northern Adriatic is 43 Mt/y where the northern Alpine Rivers contributes 8 Mt/y, the Po River 13Mt/y and the Apennine Rivers contribute 22 Mt/y. Sediment flux to the Adriatic was highest in the 1800's and manifested as rapid progradation of the Po River delta (150 m/y: Fig. 4). With the proliferation of

reservoirs on land, that act to filter the sediment load to the ocean, shoreline progradation has substantively decreased since 1800. The Po coastline presently progrades at 10 m/y, and the Apennine coastline has largely retreated during the 20<sup>th</sup> century (Fig. 4).

**Table 1. Simulated characteristics of four time periods, each based on 50 y daily simulations.**

Period	Modern	Younger Dryas	Bølling	Würm LGM
(Ky before present)	0	12.3	14.7	19.6
Drainage area (km <sup>2</sup> )	74,500	107,300	194,400	194,500
Average discharge (m <sup>3</sup> /s)		1500	1655	3663 3003
Peak discharge (m <sup>3</sup> /s)		10,800	6,418	14,686 9,887
Glacier discharge (%)		0	1	11.6 8.2
Suspended load (MT/y)		16.4	24.1	61.3 100.3
Peak Susp. load (MT/y)		38.9	34.7	124.2 156.8
Bedload (MT/y)	0.4	0.5	1.1	0.9
Sediment yield (T/km <sup>2</sup> /y)		207	226	317 519



**Figure 4: Historical shoreline progradation rates (m/y) along the Italian Adriatic coast (Syvitski and Kettner, in press). A) Po progradation rates showing that the rates achieved their highest levels circa 1800 with modern rates similar to ambient or natural rates measured before the 12<sup>th</sup> century. B) Apennine shoreline progradation as measured near the rivers mouths of the Metauro, Potenza, Tronto and Chienti rivers. Only the Potenza showed coastline progradation between 1894 and 1948. The Apennine shoreline, between 1985 and 1999, has change little, stabilized by urbanization.**

The same trends can be seen in Table 2, where the prehuman sediment load is larger than observed today with the impact of reservoir construction, except for Ocean islands including Indonesia where modern sediment flux is much higher.

**Table 2. The main continental landmasses including islands, defined in terms of area, discharge, runoff, sediment yield, prehuman sediment load, modern sediment load, and sediment load retained in reservoirs (after Syvitski et al., 2005).**

Landmass	Area Mkm <sup>2</sup>	Discharge km <sup>3</sup> /yr	Runoff Q/A)	Yield Qs/A	Prehuman Qs MT/yr	Modern Qs MT/yr	Qs Change %	Reservoir Retention
Africa	20	3,800	190	66	1,310	800	38.9	33%
Asia	31	9,810	316	176	5,450	4,740	13.0	40%
Australasia	4	610	153	105	420	390	7.1	10%
Europe	10	2,680	268	92	920	680	26.1	16%
Indonesia	3	4,260	1,420	300	900	1,630	-81.1	1%
North America	21	5,820	277	112	2,350	1,910	18.7	17%
Oceans	0.01	20	2,000	400	4	8	-100.0	0%
South America	17	11,540	679	158	2,680	2,450	8.6	17%
<b>Global</b>	<b>106</b>	<b>38,540</b>	<b>364</b>	<b>132</b>	<b>14,030</b>	<b>12,610</b>	<b>10.1</b>	<b>26%</b>

## IMPACT/APPLICATIONS

New numerical tools predict the general nature of seafloor morphology and the developing sediment stratigraphy, and allow for realistic characterization of the littoral zone. Tools ingest environmental data they provide seafloor information of continental margins at the global level. By being able to model river systems under natural conditions and under anthropogenic influence, INSTAAR models provide a powerful tools to investigate both paleo, glaciated conditions and engineered conditions.

## TRANSITIONS

ExxonMobil is using versions of *HydroTrend* and *SedFlux2D* and *3D* in their industrial applications. The International Geosphere Biosphere Program uses the models to examine the global water system through its core projects (GWSP and LOICZ).

## RELATED PROJECTS

ONR Geoclutter: Predicting the Distribution and Properties of Buried Submarine Topography on Continental Shelves. ([http://instaar.colorado.edu/deltaforce/projects/geo\\_clutter.html](http://instaar.colorado.edu/deltaforce/projects/geo_clutter.html))

ONR Seabed Uncertainty: Seabed Variability and its Influence on Acoustic Prediction Uncertainty. (<http://instaar.colorado.edu/deltaforce/projects/dri.html>)

## PUBLICATIONS

Kettner, A.J., and Syvitski, J.P.M., 2005. Predicting Discharge and Sediment Flux of the Po River, Italy since the Late Glacial Maximum. IAS, Special Issue. [in press, refereed]

Khan S.M., Imran, Bradford, J.S., and Syvitski, J.P.M. 2005, Numerical modeling of hyperpycnal plume. Marine Geology. [in press, refereed]

Kubo, Y., Syvitski, J.P.M., Hutton, E.W.H., Paola, C. 2005, Advance and application of the stratigraphic simulation model 2D-*SedFlux*: From tank experiment to geological scale simulation. Sedimentary Geology 178: 187-195. [published, refereed]

Overeem, I., Syvitski, J.P.M., and Hutton, E.W.H., in press, Three-dimensional numerical modeling of deltas. SEPM Special Publication 83, Deltas. [in press, refereed]

Parsons, J. Friedrichs, C., Garcia, M., Imran, J., Mohrig, D., Parker, G., Pratson, L., Puig, P., Syvitski, J.P.M., Traykovski, P. in review. Sediment gravity flows: Initiation, transport and deposition. In: Nittrouer, C., Austin, J., Field, M., Steckler, M., Syvitski, J.P.M., Wiberg, P., (Eds.) Continental-Margin Sedimentation: Transport To Sequence. Blackwell Publ. [in press, refereed]

Pratson, L., Swenson, J., Kettner, A., Fedele, J., Postma, G., Niedoroda, A., Friedrichs, C., Syvitski, J.P.M., Paola, C., Steckler, J., Hutton, E., Reed, C., and Das, H., 2004, Modeling continental shelf formation in the Adriatic Sea and elsewhere. Oceanography, 17(4): 118-131. [published, refereed]

Pratson, L.F., Hutton, E.W.H., A.J. Kettner, and J.P.M. Syvitski, in review, The Impact of floods and storms on the acoustic reflectivity of the inner continental shelf: A modeling assessment. Continental Shelf Research. [submitted, refereed]

Syvitski, J.P.M. 2004. River Plume. In: A.S. Goudie (Ed.) Encyclopedia of Geomorphology, pp. 866-867 (volume 2). London: Routledge. [published, refereed]

Syvitski, J.P.M., and Kettner, A.J., in press. On the Flux of Water and Sediment into the Northern Adriatic. Continental Shelf Research. [in press, refereed]

Syvitski, J.P.M., Kettner, A.J., Correggiari, A., and Nelson, B.W., 2005. Distributary Channels and their Impact on Sediment Dispersal. Marine Geology, [in press, refereed]

Syvitski, J.P.M., Weaver, P.P.E., Berné, S., Nittrouer, C.A., Trincardi, F., Canals, M., (Eds.) 2004, Strata Formation on European Margins: A Tribute to EU-NA Cooperation on Marine Geology. Oceanography 17(4): 165 pp. [published, refereed]

Syvitski, J.P.M., Kettner, A., Peckham, S.D. and Kao, S.-J., 2005a. Predicting the Flux of Sediment to the Coastal Zone: Application to the Lanyang watershed, northern Taiwan Hydrological Processes. Journal of Coastal Research 21: 580-587. [published, refereed]

Syvitski, J.P.M., Vörösmarty C, Kettner A.J., Green, P. 2005b, Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science, 308: 376-380. [published, refereed]

Syvitski, J.P.M., Harvey, N., Wollanski, E., Burnett, W.C., Perillo, G.M.E., and Gornitz, V. 2005c. Dynamics of the Coastal Zone. In: C. J. Crossland, H.H. Kremer, H.J. Lindeboom, J.I. Marshall Crossland, M.D.A. Le Tissier (Eds.) Global Fluxes in the Anthropocene. Springer, Berlin, pp. 39-94. [published, refereed]

Syvitski, J.P.M., Wiberg, P., Lee, H., Geyer, R., Imran, J., Morehead, M.D., Parker, G., Garcia, M., Steckler, M., Pratson, L., Hutton, E.W.H., in press. Prediction of margin stratigraphy. In: Nittrouer, C., Austin, J., Field, M., Steckler, M., Syvitski, J.P.M., Wiberg, P., (Eds.) Continental-Margin Sedimentation: Transport To Sequence. Blackwell Publ. [in press, refereed]

Trincardi, F., and Syvitski, J.P.M., (Eds.) 2005, ComDelta: Comparing Mediterranean, Black Sea and other Prodelta Environments. Marine Geology [in press, refereed].