European Water 57: 261-266, 2017.

Methodological framework to estimate the coastal sediment supply of the island beaches

I. Kontogeorgos, O. Tzoraki*, N. Moutafis, Th. Hasiotis and A. Velegrakis
Department of Marine Science, University of the Aegean, University hill, 81100 Mytilene, Greece
* *e-mail: rania.tzoraki@aegean.gr*

Abstract: A new framework is developed to guide the assessment of the sediments deposition from the upland/upstream areas to island beaches. The study of the coastal sediment supply of insular river basins involves the collection and analysis of meteorological and geomorphological data, the assessment of climatic trends and the use of erosion models to estimate the sediment 'output' of various management scenarios including the effect of Climate Change on the erosion processes. Important step in this procedure is the selection of the appropriate tools considering also data availability. In case of beaches that are fed with sediment by an upstream river, a combination of a semi-distributed hydrologic and a hydraulic model is suggested. This framework was applied in Eresos coastal basin (Lesvos, Greece) with a drainage basin of about 57 km^2, 26 km^2 of which are drained through Halandra stream to the Eresos reservoir (total capacity 2.76 Mm^3). Only 17% of the produced sediment is reaching the marine environment, since 73% of the produced sediment is retained in the riverbed and Eresos reservoir. The findings of the current study show that the application of the developed framework and the combination of various modelling tools may decrease uncertainty due to limited or the absence of monitoring.

Key words: erosion, beaches, SWAT, HEC-RAS, sediment

1. INTRODUCTION

Beaches are critical components of the coastal system as they provide a buffer against marine flooding to backshore coastal ecosystems and assets (Neumann et al., 2015) and, at the same time, have high earning potential. Tourism, an economic sector that contributes an estimated 5 % of the Global Gross Product and about 6 – 7 % of the global employment (Hall et al., 2013) has been increasingly associated with beach recreational activities according to the 'Sun-Sea-Sand-3S' tourism model (Phillips and Jones, 2006). Aegean archipelago islands are important 3S tourism destinations, and at the same time face increasing erosion which is projected to intensify in the future to sea level rise with devastating impacts (Monioudi et al., 2017). However, sea level rise is not the only ('natural') challenge to the island beaches: beach erosion is driven also by decreasing terrestrial sediment supply (Velegrakis et al., 2008).

Fragmentation of insular watersheds, the intermittent flow character of most island rivers as well as the lack of monitoring form significant challenges in the estimation of the terrestrial sediment supply. This short contribution presents results from a study aiming to develop a methodological framework to estimate the coastal sediment supply of island beaches in the Aegean Archipelago, focusing on ungauged and/or poorly gauged watersheds. The methodological framework was applied to estimate the coastal sediment supply of Eresos beach, Lesvos, Greece.

2. METHODOLOGY

2.1 Methodological framework

A complete, integrated approach on the management of beach sediment budgets involves combination of marine and terrestrial modelling of coastal sediment transport, morphological analysis for the assessment of erosion trends, and the design/implementation of a management plan to address impacts using multi-criteria analysis for different scenarios, and the subsequent monitoring and revision of the management plan (Figure 1). The methodological framework attempts to use the processes involved in sediment transport as guidelines in estimations of the sediment budgets of the Aegean island beaches.

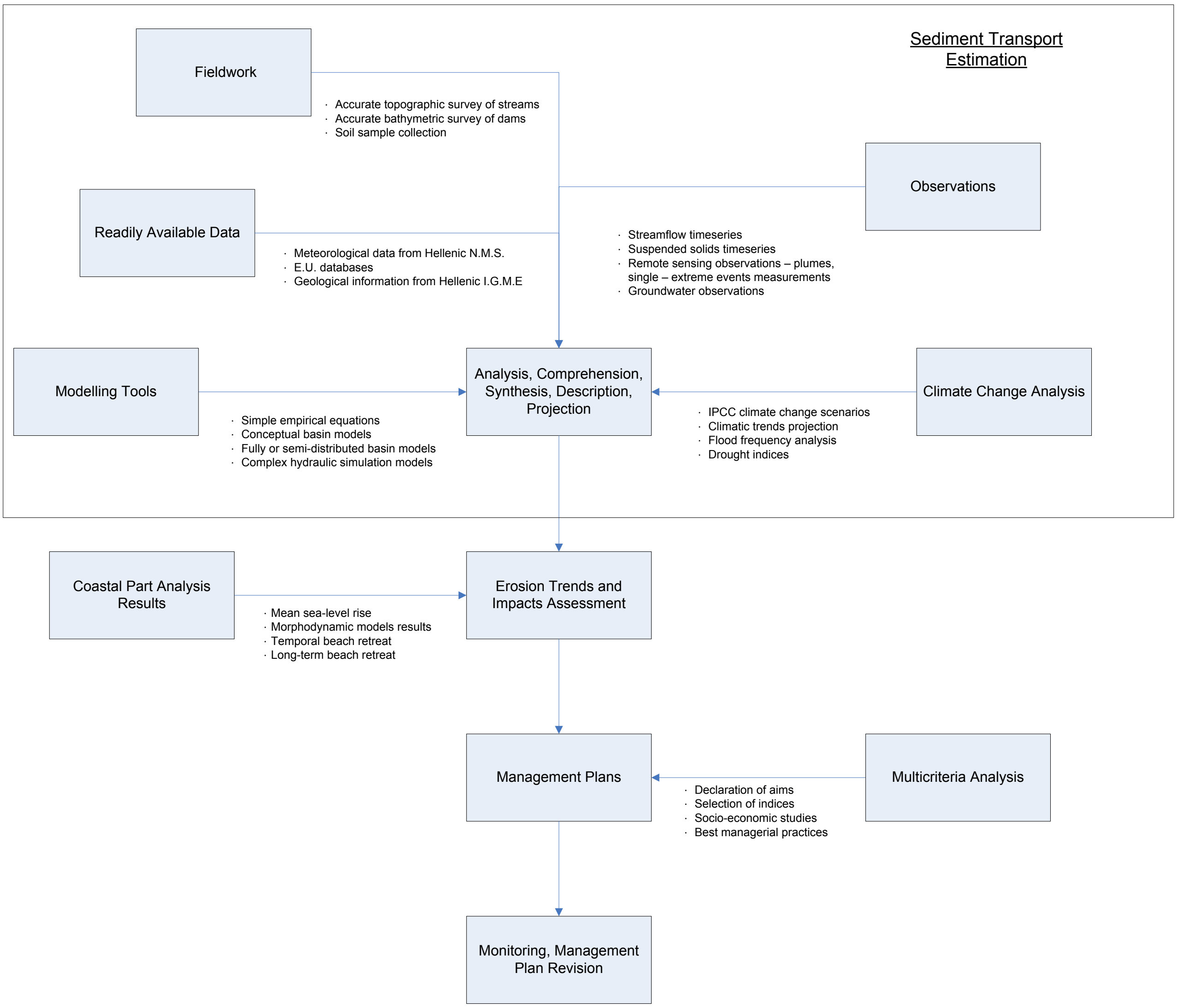

Figure 1. Conceptual framework for the estimation of the coastal sediment supply, beach erosion and management plan implementation.

The study of the inland (terrestrial) sediment transport involves data collection, selection of appropriate modelling tools and/or their combination and projection of future trends, as necessary constituents of the analysis, synthesis, description and future projection of inland erosion rates and sediment transport.

The first step includes the collection of available spatial, meteorological, hydrological and sediment data, and additional fieldwork to evaluate the information and fill gaps. Meteorological data are available from the Hellenic National Meteorological Service (N.M.S.), while other meteorological station operators (e.g. Universities), collect also data. Spatial information (satellite data, digital elevation models, soil maps, land-use and land-cover maps) is mainly available through EU inventories (http://www.copernicus.eu/, http://www.eea.europa.eu/data-and-maps/data/eu-dem, http://esdac.jrc.ec.europa.eu/, http://land.copernicus.eu/pan-european/corine-land-cover/clc-2012) as well as national inventories (i.e. maps published by the Institute of Mineral and Geological Exploration (IGME) and Geographical Army Service). Additional fieldwork may be carried out, such as topographic surveys of the basin and riverbed, collection of soil samples and recording of streamflow and suspended sediment. Installation of automatic level loggers is suggested to measure water level at high frequency and collection of monthly discharge measurements to construct the rating curves for each station; however, the torrential character of many streams exposes monitoring personnel and instrumentation to high risks. In the case of a reservoir present in the basin, this forms a highly recommended monitoring site.

The second step involves the selection of the appropriate models. Model selection is strongly depended on the problem at hand and the available data. Tools include simple empirical erosion models, simplified conceptual river basin models, advanced hydraulic models, fully and semi-distributed models and models for reservoir siltation. Simple empirical models consist of simple empirical equations, require less data, give estimates at monthly and annual scales, often have similar accuracy with complex river basin models, and are preferred for small runoff basins (runoff surface <10 km^2) which are homogeneous in terms of topographical relief, soil type and land use. Universal Soil Loss Equation (USLE) is a widely used empirical model to estimate soil loss caused by surficial run off in small scale, low gradient areas (Wischmeier and Smith, 1965) and has been used since in various environments (Fistikoglu and Harmancioglu, 2002; Pandey et al., 2007; Velegrakis et al., 2008).

Hydraulic river simulation models (i.e. HEC-RAS) require, in addition to the available meteorological data, detailed topographic data of the river bed and the riparian area and the sediment textural characteristics. Hydraulic models can provide reliable estimates of the sediment processes (erosion/deposition) along the main river corridor providing necessary information for decision making on restoration projects and constructions works. River basin models (i.e. SWAT, HSPF) also require spatial data, DEM, land-use and soil maps, and meteorological information; such information (in varied spatial resolution) can be abstracted from European Union databases. These models require discharge measurements at daily scale or lower and at least monthly suspended sediment measurements that often are not available for calibration and validation purposes. In case of an ungauged basin, model parameter values may be calibrated using information from a neighbouring, gauged basin with similar characteristics.

Hydraulic and hydrologic model results can be combined in an effective and integrated estimation of the hydrological and sediment transport processes. They also provide the option to run various scenarios in the estimation of flow and sedimentation trends, e.g. scenarios of future environmental conditions, land-use and water management practices. If a reservoir is present in the basin, then additional techniques could be employed, such as specialized isotope techniques that can track terrestrial sediments from soil sources to freshwater systems and assess reservoir sedimentation rates (Porto et al., 2014). This type of fieldwork demands special laboratory equipment, but is significant in the verification of model results in the absence of monitoring data in the catchment.

The third step concerns the study of climatic trends. At this stage, meteorological time series from global and regional models may be incorporated into calibrated hydrologic models for streamflow and sediment transport projections under different climatic scenarios. The results may be used for flash flood analysis and their impact on sediment transport. Flood frequency analysis, employs different kinds of methods such as the use of stochastic methods, Bayesian analysis and traditional statistical distributions such as the log – Pearson Type III, the Generalized Extreme Value (GEV) and Extreme Value Type EV1 (Gumbel).

These three steps are combined in the data analysis, the comprehension of the processes, the synthesis of the processed results, the description of the current state and future projection of hydrological processes, erosion rate and sediment transport for the estimation of the inland sediment transport in the downstream beach (Figure 1).

2.2 Study area

The study area is the drainage area of Eresos (Lesvos, Greece), located to the southwest (SW) of the island, 52 km away from the capital of the island, Mytilene (Figure 2). The drainage basin of Eressos is 57 km^2, 26 km^2 of which are drained through Halandra stream to the Pythari reservoir with a total capacity 2.76 Mm^3, located approximately 2.5 km east of Eresos village and about 5 km from Eresos beach. Parts of the river and its small estuary are susceptible to intense flood events. The downstream Eresos beach is characterised by significant erosion, part of which has been attributed to negative sedimentary balance (Velegrakis et al., 2008). This study is focused on the flood and sediment transport characteristics of the two main river branches, Karasaris and Halandra streams, both of which play an important role in the sediment supply of Eresos beach.

3. RESULTS – DISCUSSION

Hydraulic modelling (with the model HEC-RAS) showed that the Halandra stream generally experiences calm/river flow. However, rainfall events with short return period may lead to serious flood events at junctions where the flow passes from subcritical to critical. Sediment deposition is projected in a small plateau located downstream of the reservoir and in the small river estuary, which in the summer period is blocked by a sand beach barrier. It appears that the aforementioned plateau operates as a sediment trap during both low and high flows, whereas the sand barrier facilitates sediment entrapment in the estuary during low flows; in high river flows the sand barrier is breached and riverine sediment is flushed out, forming river plumes in the sea. These processes have been also validated by the long-term, video imaging of the beach.

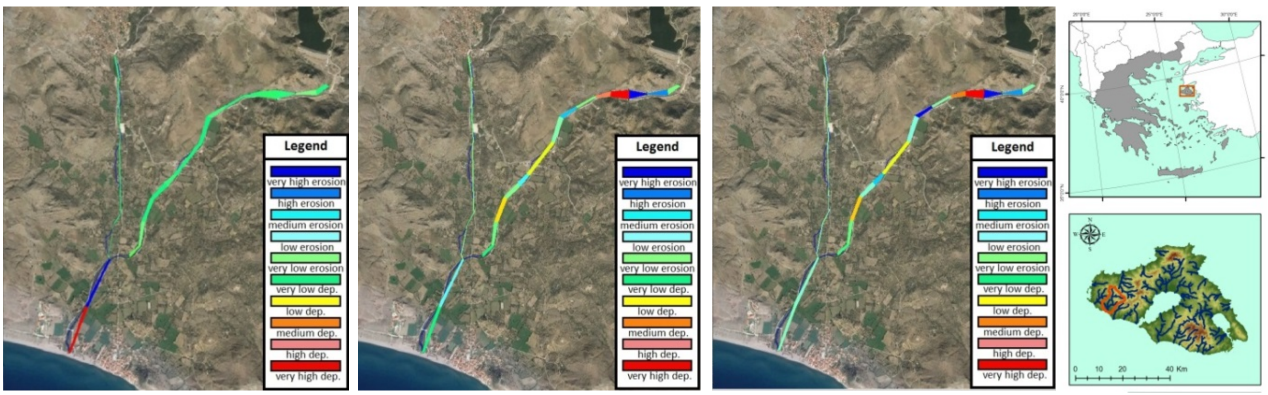

Figure 2. Riverbed change for peak discharges with return period 2, 100, 1000 yr, scale from blue to red shows relevant erosion and deposition. Modified by: Image © 2016, CNES / Astrium; Data SIO, NOAA, U.S. Navy, NGA, GEBCO; © 2016, Google

Hydrology, erosion and sediment transport was modelled on a daily time-step for the period 2009/09/01 - 2016/08/31 (Figure), as well as three-year warm-up period for two scenarios, with reservoir and without reservoir operation. SWAT hydrological calibration was transferred from a neighbouring calibrated basin and irrigational demands (affecting the reservoir water storage) were calibrated using the water level records of the reservoir for the periods 2014/05/07 – 2014/10/10 and 2015/12/05 – 2016/06/19 (Figure); it should be noted that the recorded reservoir water height, at full capacity, differs for each period, due to the water level logger forced relocation at different altitude. Personal communication with the reservoir operators suggests that the irrigation demand ranges from 0.7 to 1.2 Mm^3 of water during the summer season, SWAT tends to underestimate the irrigation needs from 0.6 to 0.7 Mm^3.

SWAT estimates an erosion rate of 8 t/ha – yr that generates 45 kt/yr of sediment, out of which only 17 % reaches the beach. The sediment generated by the reservoir drainage area was predicted 5.7 kt/yr by the SWAT model, whereas the reservoir siltation rate was estimated around 14.5 kt/yr. However, the modelled erosion rate appears to be underestimated when compared with the siltation rate of the reservoir estimated from the comparison of sequential detailed bathymetric surveys with historical topographic information. Finally, the comparison of the two scenarios outputs (with and without reservoir) shows that the reservoir retains only a fraction of the sediment generated in the basin with high sediment volumes retained in the small plateau downstream of the reservoir and in the NATURA area of the river delta.

It should be noted that the above simulation results involve uncertainties, since they have not been compared with suspended sediment observations and only the hydrological part of the model has been calibrated. Nevertheless, they can provide an estimation of the erosion and deposition processes within the basin, as well as an estimate of the percentage of sediment that eventually reaches the beach. HEC-RAS results indicate two sediment traps along the riverbed downstream of the reservoir, supporting the results of the SWAT hydrological analysis. Combination of HEC-RAS with river plume imagery and precipitation records also allowed an initial estimate of the threshold over which the stream ceases to function as a sediment trap and releases sediment to the sea.

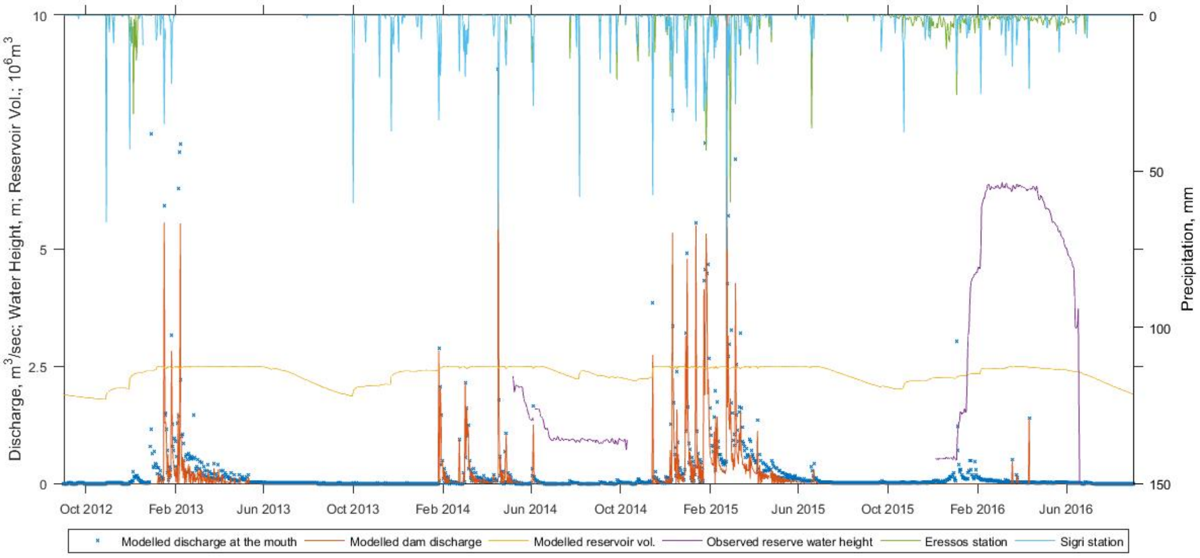

Figure 3. Modelled discharge results at the mouth of the river and the dam vs precipitation, and comparison of modelled reservoir storage vs observed water reservoir water height (water height corresponds to different altitude for each period due to instrument relocation)

4. CONCLUSIONS

The terrestrial sediment supply module of a methodological framework proposed to assess the coastal sediment supply, beach erosion and management of island beaches has been tested in Eresos basin (Lesvos). The results show that the combination of different tools can increase our knowledge on the sediment dynamics of the coastal basin and provide assessments of the terrestrial sediment supply to downstream beaches. HEC-RAS incorporating detailed riverbed topographical data has revealed two additional sediment deposition sites along the riverbed downstream of the reservoir, the river estuary that operates as a sediment trap in low-flows and a small plateau downstream of the reservoir that can trap sediment also during high river flows. SWAT also managed to adequately model the Eresos basin hydrology, although the lack of flow and sediment observations may affect the accuracy of its results. Finally, a series of steps proposed in the framework were utilized to overcome the absence of monitoring information and reduce uncertainty. However, it appears that systematic monitoring of river systems should be employed to reduce uncertainty in estimation of floods and the terrestrial sediment supply to coastal areas.

AKNOWLEDGEMENTS

The current work has been supported by the EraBeach Project (http://erabeach.aegean.gr/), cofunded by the EEA GRANTS (2009-2014) and the Public Investments Programme (PIP) of the Hellenic Republic.

REFERENCES

Ballabio, C., Panagos, P., Monatanarella, L., 2016. Mapping topsoil physical properties at European scale using the LUCAS database. Geoderma 261, 110–123. doi:10.1016/j.geoderma.2015.07.006

Bouraoui, F., Benabdallah, S., Jrad, A., Bidoglio, G., 2005. Application of the SWAT model on the Medjerda river basin (Tunisia). Physics and Chemistry of the Earth 30, 497–507. doi:10.1016/j.pce.2005.07.004

Brunner, G.W., 2016. HEC-RAS River Analysis System, Hydraulic Reference Manual, Version 5.0 (No. 69). U. S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA.

Cook, A., Merwade, V., 2009. Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping. Journal of Hydrology 377, 131–142. doi:10.1016/j.jhydrol.2009.08.015

Fistikoglu, O., Harmancioglu, N.B., 2002. Integration of GIS with USLE in assessment of soil erosion. Water Resources Management 16, 447–467. doi:10.1023/A:1022282125760

Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G., 2007. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. Transactions of the American Society of Agricultural and Biological Engineers 50, 1211–1250. doi:10.13031/2013.23637

Glavan, M., White, S., Holman, I.P., 2011. Evaluation of river water quality simulations at a daily time step–Experience with SWAT in the Axe Catchment, UK. CLEAN–Soil, Air, Water 39, 43–54. doi:10.1002/clen.200900298

Hall, C.M., Scott, D., Gössling, S., 2013. The Primacy of Climate Change for Sustainable International Tourism. Sustainable Development 21, 112–121. doi:10.1002/sd.1562

Maingi, J.K., Marsh, S.E., 2002. Quantifying hydrologic impacts following dam construction along the Tana River, Kenya. Journal of Arid Environments 50, 53–79. doi:10.1006/jare.2000.0860

Monioudi, I.N., Velegrakis, A.F., Chatzipavlis, A.E., Rigos, A., Karambas, T., Vousdoukas, M.I., Hasiotis, T., Koukourouvli, N., Peduzzi, P., Manoutsoglou, E., et al., 2017. Assessment of island beach erosion due to sea level rise: the case of the Aegean archipelago (Eastern Mediterranean). Natural Hazards and Earth System Sciences 17, 449–466. doi:10.5194/nhess-17-449-2017

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009 (No. 406). Texas Water Resources Institute, College Station, Texas.

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding-A Global Assessment. PloS one 10, e0118571. doi:10.1371/journal.pone.0118571

Panagos, P., 2006. The European soil database. GEO: connexion 5, 32–33.

Pandey, A., Chowdary, V.M., Mal, B.C., 2007. Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing. Water Resources Management 21, 729–746. doi:10.1007/s11269-006-9061-z

Phillips, M.R., Jones, A.L., 2006. Erosion and tourism infrastructure in the coastal zone: Problems, consequences and management. Tourism Management 27, 517–524. doi:10.1016/j.tourman.2005.10.019

Porto, P., Walling, D.E., Alewell, C., Callegari, G., Mabit, L., Mallimo, N., Meusburger, K., Zehringer, M., 2014. Use of a 137Cs re-sampling technique to investigate temporal changes in soil erosion and sediment mobilisation for a small forested catchment in southern Italy. Journal of Environmental Radioactivity 138, 137–148. doi:10.1016/j.jenvrad.2014.08.007

Tóth, B., Weynants, M., Nemes, A., Makó, A., Bilas, G., Tóth, G., 2015. New generation of hydraulic pedotransfer functions for Europe. European Journal of Soil Science 66, 226–238. doi:10.1111/ejss.12192

Velegrakis, A., Vousdoukas, M., Andreadis, O., Adamakis, G., Pasakalidou, E., Meligonitis, R., Kokolatos, G., 2008. Influence of dams on downstream beaches: Eressos, Lesbos, Eastern Mediterranean. Marine Georesources and Geotechnology 26, 350–371. doi:10.1080/10641190802425598

Velegrakis, A.F., Trygonis, V., Vousdoukas, M.I., Ghionis, G., Chatzipavlis, A., Andreadis, O., Psarros, F., Hasiotis, T., 2015. Automated 2D shoreline detection from coastal video imagery: an example from the island of Crete. In: Hadjimitsis G. et al. (Eds.) Proceedings of the 3rd International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2015) doi:10.1117/12.2192687

Williams, J.R., 1995. Computer Models of Watershed Hydrology. In: Singh, V.P. (Ed.), Water Resources Publications, Highlands Ranch, CO, pp. 909–1000.

Wischmeier, W.H., Smith, D.D., 1965. Predicting Rainfall - Erosion Losses from Cropland East of the Rocky Mountains, Guide for Selection of Practices for Soil and Water Conservation (No. 282). U.S. Deparment of Agriculture, Agricultural Research Service, Washington, DC.