Η ΕΠΙΔΡΑΣΗ ΤΩΝ ΑΝΘΡΩΠΙΝΩΝ ΕΠΕΜΒΑΣΕΩΝ ΣΤΗ ΜΟΡΦΟΛΟΓΙΑ ΚΑΙ ΤΗ ΔΙΑΧΕΙΡΙΣΗ ΤΗΣ ΚΟΙΤΗΣ ΤΟΥ ΠΟΤΑΜΟΥ ΣΤΡΥΜΟΝΑ ΤΗΣ ΒΟΡΕΙΑΣ ΕΛΛΑΔΑΣ

Στύλλας Μ., Βουβαλίδης Κ.
Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης, Τμήμα Γεωλογίας,
Τομέας Φυσικής και Περιβαλλοντικής Γεωγραφίας, 54124 Θεσσαλονίκη

Περίληψη

Στην παρούσα εργασία εξετάστηκαν οι μεταβολές στην μορφολογία, που οφείλονται σε ανθρώπινες παρεμβάσεις, σε τρία τμήματα της κοίτης του ποταμού Στρυμόνα με σκοπό να προσδιοριστούν η εξέλιξη της μορφής της καθώς και οι συνθήκες ροής και ιζηματομεταφοράς. Η ανθρώπινη επέμβαση στην κοίτη του Στρυμόνα ξεκίνησε την δεκαετία του 1930 με μια σειρά υδραυλικών έργων (κατασκευή φράγματος και τεχνητής κοίτης με αναχώματα, αποστράγγισης των πλημμυρικών πεδίων, αμμοληψιών). Αμέσως μετά την ολοκλήρωση των έργων διαβρωτικά φαινόμενα στον πυθμένα της κοίτης κατάντη του φράγματος της Κερκίνης δημιούργησαν συνθήκες έντονης στερεομεταφοράς. Η απόθεση των διαβρωθέντων υλικών έγινε μέσα στην κοίτη, στο χαμηλό τμήμα της λεκάνης με τις μικρότερες κλήσεις, μειώνοντας την διατομή της κατά 60,5%. Στην εργασία αυτή μελετήθηκαν οι μεταβολές της μορφολογίας και οι σχετικές διακυμάνσεις της πορείας μέγιστου βάθους της κοίτης σε έναν αριθμό θέσεων κατά μήκος του ποταμού. Τα αποτελέσματα έδειξαν τη σημασία του ποταμού Αγγίτη και του χειμάρρου Καστρόλακκου στην ιζηματογένεση και εξέλιξη της κοίτης. Επίσης προσδιόρισαν τις συνθήκες ροής κάτω από τις οποίες έχουμε τη βέλτιστη ιζηματομεταφορά. Μια τέτοια γνώση είναι απαραίτητη στη διαχείριση των παροχών του ποταμού Στρυμόνα κατάντη του φράγματος της Κερκίνης, γιατί διατηρώντας συγκεκριμένες παροχές για μεγάλα χρονικά διαστήματα μπορούμε να επιτύχουμε διάβρωση και μεταφορά των υλικών, συντηρώντας έτσι την καλύτερη δυνατή διατομή της κοίτης. Με τον τρόπο αυτό μπορεί να διατηρηθεί η παροχετευτική ικανότητα της κοίτης σε υψηλά επίπεδα, βοηθώντας στην αντιπλημμυρική προστασία της λεκάνης.

CHANNEL ADJUSTMENTS AND MANAGEMENT IMPLICATIONS FOLLOWING HUMAN IMPACTS IN STRIMONAS RIVER, NORTHERN GREECE

Styllas M., Vouvalidis K.
Aristotle University of Thessaloniki, School of Geology,
Department of Physical & Environmental Geography, 54124 Thessaloniki

Abstract

Channel changes responding to human disturbances are examined along three reaches of Strimonas River in Northern Greece, to define channel evolution pattern, and current flow and sediment transport regimes. Major human impacts that took place during the 1930's include a series of hydraulic works (dam construction, drainage of the floodplains, construction of artificial channel, sand mining and construction of levees and weirs). Degradation of the streambed occurred below Kerkini Reservoir right after the termination of the works and the available material was transported further downstream where the minimal slopes resulted in excessive sediment accumulation and significant reduction, up to 60.5% of the cross-sectional area. Analyses of channel shape factor and relative thalweg variations are examined for a number of locations along the course of the river. The results suggest the significance of the tributaries of Aggitis River and Kastrolakos torrent in channel sedimentation and evolution and define flow conditions under which sediment transport is most efficient. Since Strimonas River flow is mainly regulated from the Kerkini reservoir outflow, preserving certain discharge values for extended periods of time can lead to natural erosion of river sediments and decrease the chances for major floods, which are hazardous for the agricultural fields of Serres Valley. The study outlines the initial and final (present) channel morphology and suggests the need for more detailed surveys in order to provide a better understanding of how several types of human disturbances affect channel morphology and sediment transport.

Λέξεις κλειδιά: ποτάμια κοίτη, διάβρωση, ιζηματομεταφορά, Στρυμόνας, Σέρρες

Key words: river channel, erosion, sediment transport, Srimonas, Serres

1. Introduction

Natural rivers are characterized by a number of changes resulting from natural and human changes. River channels respond to such changes by adjusting the channel morphology, channel slope, channel forms, sediment load and other hydraulic characteristics (Schumm et al. 1984). Throughout Greece most of the large rivers have experienced numerous human modifications since the onset of the 20th century and only few reaches of those still remain in natural condition. Human disturbances include land use changes, drainage of wetlands, canalization, construction of dams as well as sand and gravel mining. The temporal extent of channel adjustments following those disturbances varies from short periods of days to decades depending on the magnitude and the type of the disturbance (Simon, 1997), with river channels reaching equilibrium when several of the extremal hypotheses, summarized in Huang and Nanson, 2000 are met. These adjustments are generally much larger than the ones responding to explicitly natural changes even though in some cases natural phenomena like climatic oscillations, extreme floods and wildfires have an important role in channel instability.

Channel modifications following human disturbances have a great range of environmental and socioeconomic effects, as sediment accumulation, undermining of structures, loss of habitat diversity, flooding of agricultural areas and indicate the need for better understanding in order to predict future channel evolution. River and floodplain management, as well as water resource strategies should take into account channel adjustments to avoid disastrous effects from future human activities.

In this paper our goal is to: (a) define the changes of the channel's geometry from 1930 to present; (b) define the longitudinal trends of channel adjustments; and (c) establish the current patterns of sediment transport regime under various flow scenarios in order to provide general guidelines for proper river and floodplain management.

2. General setting

Strimonas River basin belongs to three different countries has a total area of 17.150 km2, 63% of which is within Bulgaria and F.Y.R.O.M. and 37% is in Greece (Vouvalidis, 1998). Along the Greek part there are many tributaries that enter the river along its course to Strimonikos Gulf the most important being Aggitis River, with annual flow and high sediment transport potential during high stages of discharge. The Greek part of Strimonas River runs through Serres Valley, a fertile valley created by the old flood deposits of the river, whereas today most of the surrounding area is depended mostly on agriculture.

The geology of the drainage basin consists of marbles, metamorphic, and igneous rocks of the Rhodope Belt, on top of which lie tertiary and quaternary and flood deposits. Active tectonic faults bound the east and west margins of Serres Valley.

The climate of the study area is characterized as "temperate" with relatively wet winters and dry summers. Average annual precipitation ranges from 500mm to 600mm in the lowlands and from 700-950mm in areas with higher elevations. River discharge is mainly regulated from Kerkini Reservoir and has an average daily value of 126m3/sec, 20m3/sec of which are lost to irrigation especially during the summer months, while peak discharge for a 20-year event can reach a value of 1000m3/sec (Psilovikos et al., 1994).

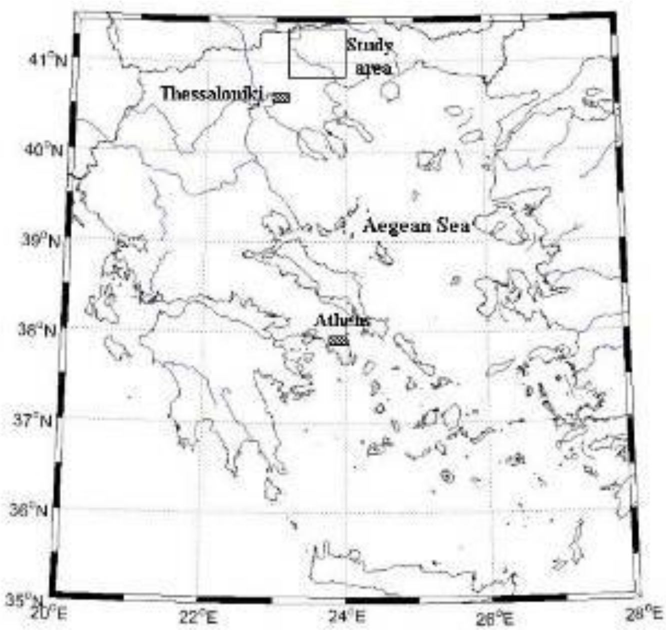

Figure 1. General setting of the study area.

3. Human impacts in Strimonas river

Since the 1930's Strimonas River has been subjected to a number of human impacts, the most pronounced of which include the construction of Kerkini reservoir and the construction of an artificial channel. The main purpose of those works was to drain the old Achinos Lake, which imposed a great danger for disease and flooding in the surrounding area and to increase the channel's conveyance so that boats could enter the river up to the village of Penthelinos, 32 km upstream from the river mouth. During the time span from 1930 to today minor hydraulic works have also been contemplated and include the construction of numerous pumping stations for irrigation, construction of weirs along the river course while a sand mining operation has been established in the confluence of Strimonas with Aggitis River.

The present paper examines the part of the river that is of greatest importance to the sedimentation and thus to the frequent flooding of Serres Valley. For this reason the river channel is divided in three major sections.

The first section (Section A) is the stretch from the confluence of Strimonas with Aggitis river to the beginning of Amphipoli narrows (60 – 70km, distance is measured downstream from Kerkini reservoir at 0.0 km). This section is characterized by minimum slopes in the order of 0.1 – 0.3 o/oo, so that when discharge is not exceeding certain threshold values sediment accumulation is occurring. Section B includes the Amphipoli narrows where the river meanders with the channel becoming narrower and deeper (70-74km), while the third section begins at the end of Amphipoli narrows all the way to Strimonikos gulf (74-80km) (Figure 2).

The artificial channel had been excavated at an initial datum of -2.5 m for the section A and at datum of -4.5 m for the two other sections, while the channel width for the three sections was at 90, 65 and 115 meters respectively.

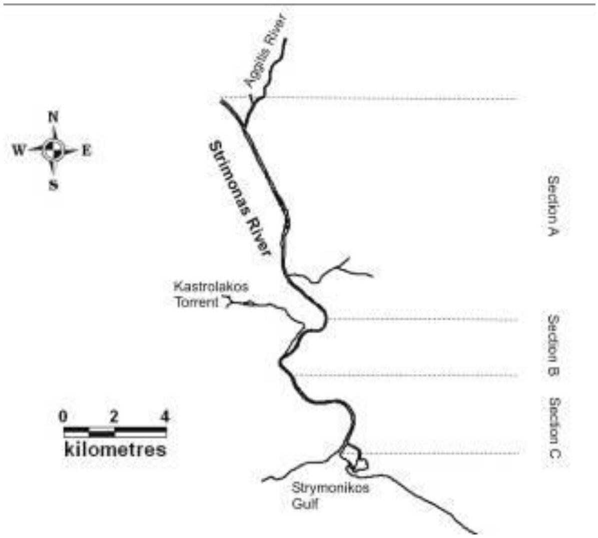

Figure 2. Strimonas channel morphology and the three sections used for this study

The fact that sections B and C were excavated below the Mean Sea Level (MSL) resulted in a new base level which in turn caused upstream erosion, different flow regimes and potentially backwater effects.

4. Channel geometry adjustments

Huang and Nanson (2000) suggest that both maximum sediment transport capacity and minimum stream power conditions are responsible for adjustments in channel geometry following a disturbance. Soon after the termination of the works, degradation of the streambed began to occur in the upstream reaches of Section A where channel slopes were greater. Upstream migration of knickpoints is likely to have occurred but there are no available data to support this. The eroded material was being transported in Section A resulting in maximum sediment transport capacity along this reach.

In addition, during the same time the river's discharge has been mainly regulated from the outflow of Kerkini reservoir (minimum stream power condition) and the inflow from Aggitis River, so that both of the above mentioned conditions have been met leading the river's channel towards equilibrium. Between these end-member type conditions we assume a steady and uniform flow nearly at bankfull stage for the most time, except of periods of extreme discharge (1954, 1994 and 2002 flood events) when flooding of Serres valley occurred.

A number of cross-section profiles have been obtained from different studies and the comparison between initial and present conditions suggests a reduction in cross-sectional area up to 93.3% (Figure 3). More interesting is the way that these adjustments have taken place and are discussed below.

In order to obtain more insight about the longitudinal changes of channel's geometry the values of two shape parameters have been estimated. These include the bankfull width to depth ratio (ω) and a non-dimensional parameter describing the elevation of the thalweg relative to mean channel grade line ζ = E/Zbankfull , where E is the deviation of the actual thalweg elevation from the expected one (Western et al. 1997). Cross-sectional data used for the analyses were obtained from the PhD study of Vouvalidis (1998) for sections B and C and from another survey (Vouvalidis et al., 2001) for section A.

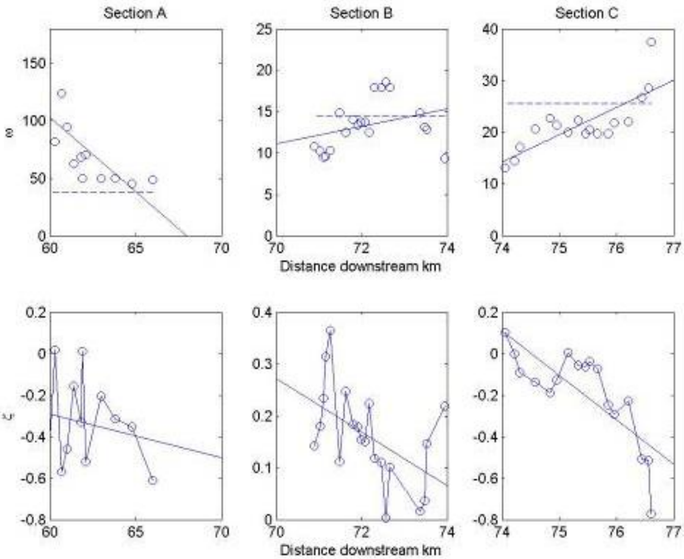

Figure 3. Downstream variations in ω and ζ. Distance downstream increases from Kerkini reservoir (distance 0 km) to the river mouth. Dotted lines represent the conditions of the artificial Strimonas channel constructed in the 1930's.

The locations of the measured cross-sections were randomly chosen and were positively tested to be drawn from normal populations so that no bias was evident. The downstream changes of the channel shape parameters for the three reaches are shown in Figure 3.

Variations of the width to depth ratio (ω) are 10 times higher for section A compared with sections B and C (Fig. 3a) and display different trends as well. Simon (1992) documented ω mean values of about 5.4 for fine-bed cohesive bank channel and 128 for a coarse-bed channel with non-cohesive banks, while in our case ω values range between 9.3 and 145.7. Increased ω values imply that channel adjustment is dominated by widening the opposite being true for decreasing ω values. Channel widening has been found to cause steeper slopes and some temporary bed erosion downstream of the widening point (Hunzinger, 1999). High ω values in the beginning of section A suggest the existence a wide and shallow channel, a result of periodic deposition of material transported by Aggitis River. Excessive sediment accumulation from Aggitis River has also caused bank erosion at the upstream parts of section A. On the other hand, decreasing ω values in the downstream part of section A imply that the channel becomes narrower and deeper towards Amphipoli narrows. Accordingly, sections B and C are dominated by a variable pattern of both narrowing and widening, with the general trend characterized by increasing ω values. In contrast with section A, ω values of sections B and C are close enough to their initial values, showing little change in channel shape.

The longitudinal distribution of the thalweg elevation ζ displays a variable pattern, as well as negative values (Fig. 3b). Section B appears to be dominated by relative bottom deposition or no change at all, while there is less variability in bed morphology towards the river mouth. This decrease is partly related in lower discharge values, since along downstream sections river water is being lost to irrigation. Negative ζ values suggest the existence of pools which are very important during periods of low flow. Pools are controlling factors for backwater effects, entrapment of saline waters and sediment transport processes.

The net changes of ω, bankfull channel depth and cross sectional area for the past 70 years are summarized in Table 3. Even though the mean values of the above mentioned parameters were used, the comparison between the hydraulic geometry properties with present day is indicative of the general trends since the onset of the human changes. The comparison between the three studied reaches suggests that section B is exhibiting the least change in both the width to depth ratio ω and the bankfull depth, and can efficiently transport the delivered sediment from upstream. Section A appears to have been subjected to significant geometric changes dominated by an increase in width to depth ratio by an order of 2. Section C also displays remarkable changes in channel geometry, characterized by bottom deposition and negative ζ values. This section presents the greatest reduction in cross-sectional area leading to the conclusion that existing flows cannot efficiently transport sediment to the river mouth.

The increase in ω values along section A accompanied by reduction in the mean bankfull depth suggests that channel widening has been taking place. The main mechanism responsible for this is sediment input from Aggitis River and upstream reaches at irregular time scales, which results in decrease of channel depth and bank erosion.

Table 1. Changes in cross-sectional hydraulic properties during the past 70 years along Strimonas River

Sect	μ_ω	Initial ω	Percent change	$\mu Depth_{bankfull}$ (m)	Initial $Depth_{bankfull}$ (m)	Percent change	μ_A (m^2)	Initial A (m^2)	Percent change
A	74.18	36	51.4 %	1.17	2.5	53.2%	-	225	-
B	13.39	14.44	-7.2 %	4.1	4.5	8.88%	168.94	292.5	42.2%
C	21.66	25.55	-15.2	3.46	4.5	23.1%	204	517.5	60.5%

These outbursts of water and sediment cause morphological changes in the downstream reaches with the system trying to reach new equilibrium following such events. However, continuity of mass requires that sections A, B and C are linked in terms of passage of waves of water and sediment so that these morphological changes are characterized by bank erosion at section A, followed by transport of sediments through section B and sediment deposition along section C during high stages of discharge.

The downstream trends in decreased bed channel variability together with increased ω values result in smoother flows, which can potentially result in efficient sediment transport under certain flow conditions. However, considerable quantities of sediment have been deposited along sections A, B and C, resulting in reduction of cross-sectional area and an important question is addressed here that postulates the problem of whether existing discharges are able of adjusting the channel's shape after such abrupt changes.

5. Sediment transport regime related with channel evolution.

The amount of sediment that has caused changes in channel geometry for the studied reaches comes mainly, from Aggitis River, from side torrents and from upstream channel erosion. The most significant amount of the side sediment input comes from Kastrolakos torrent. Since there are no available data on sediment transport rates, numerical simulations have been employed to provide better understanding of the way that the system has functioned since the termination of human impacts. Discharge is considered to be constant and at bankfull stage except from periods of flooding.

In order to evaluate the sedimentation regime that has resulted in present conditions we established a set of initial boundary conditions. These initial boundary conditions include relatively constant, uniform and steady flow ranging from 100 to 150 m3/sec and the initial dimensions of the man-made channel as described above. Since then the functioning of the artificial Strimonas channel is considered continuous and together with periodic inputs of sediment from the above mentioned sources has resulted in present day geometry.

The employment of DuBoys' sediment transport formula provides further insight about the way sediment discharge varies with the channel shape factor ω (Yang 1998). For constant values of channel slope S=0.28o/oo, sediment size d=1mm, water density ρ=1000kg/m3, and sediment density ρs=2650 kg/m3, we evaluated potential sediment transport rates that may have resulted in present day channel morphology. Figure 4 summarizes the results of this approach and provides a general view about how the studied reaches have evolved since their initial stage of construction.

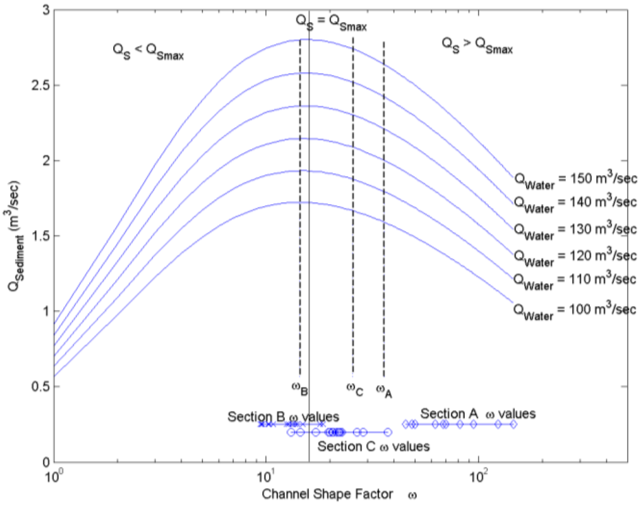

Figure 4. Sediment transport rates as a function of shape factor ω for different water discharge values and for (S=0.3/1000, d=1mm, ρ=1000 kg/m3 and ρs=2650 kg/m3). Also shown, the initial (ωA, ωB and ωC) and present day values of ω for the three sections plotted in their downstream directions from the left to the right.

For QS>QSmax (Fig. 4) the channel cannot efficiently transport the delivered sediment only by changing channel geometry and a change in either slope or discharge in inevitable, while for QS<QSmax channels can transport sediment by adjusting channel geometry alone (Huang and Nanson, 2000). As shown in Figure 4, ω values of section A and part of sections B and C fall within the right side of the condition QS=QSmax where ω values are higher. Most important is that for the discharge values used in our analyses the initial ω values of sections A and C are on the right hand side of the QS=QSmax condition. So, from the time of the construction of the artificial channel sections A and C were not capable of transporting sediment alone for discharges up to 150m3/sec. Also, present values of ωA have moved to the right of their initial values suggesting the each disturbance will force the system to become increasingly unstable. Section B and in part of section C channel ω values display some variability about their initial values and also oscillate between the QS=QSmax condition, suggesting that they can transport sediments efficiently especially in their

upstream locations. Bed degradation is concentrated in certain areas as a result of maximum shear stress. These areas are the transition points between sections A and B, and between sections B and C. The first being a constriction flow point, the later an expansion flow point.

The overall transport efficiency of sections B and C is better reflected on the downstream channel depth distribution. Figure 5 illustrates all the available channel depth data (1994, 2002 surveys). Downstream depth distribution suggests the existence of areas of greater depth and increased shear stress where sediment transport takes place. The 1994 survey shows minor changes in depth along section B and along the upstream part of section C, which comes in agreement with the results of our mathematical approach.

During 1995 excessive rainfall and flooding occurred in the area so that all side torrents were activated. The most important of those that discharges into Strimonas channel is Kastrolakos torrent. During this flood event the torrent transported large quantities of coarse material into the channel causing in this way a natural disturbance. Post flooding discharges were not able to move the deposited sediments and downstream bed erosion took place. Given the flow conditions described above the Kastrolakos torrent case can be indicative of the way that Strimonas channel has been functioning.

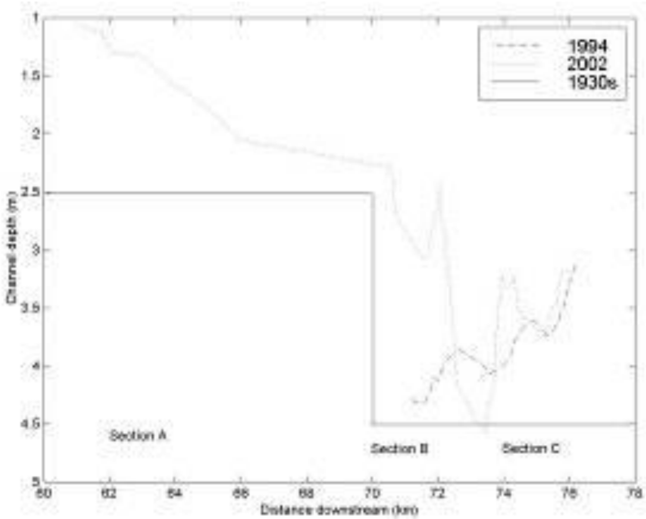

Figure 5. Downstream distribution of the 7km running mean of depth Strimonas River channel since the 1930's. Increased depths of the 2002 survey 72 km downstream correspond to the 1995 Kastrolakos flood deposits.

The scenario for Strimonas channel evolution given the boundary conditions established above suggests that following a disturbance such as excessive sediment load from Aggitis River there follows an expansion of flow at the beginning of section A, which causes channel widening and bed erosion further downstream resulting in increased depths and decreased channel width (decreasing ω values, Fig. 3a). The channel system begins to transport the excess of material downstream in order to reach a new equilibrium after certain time. Sediment is transported at section B and from there is efficiently transported towards section C. At the downstream part of section C sediment deposition begins to take place eventually as the channel becomes wider, shallower, water is lost to irrigation and a fresh with seawater interface exists. This results in the formation of an internal delta, which traps significant quantities of sediment.

6. General setting

The general view obtained for the previous analyses of channel evolution suggests that sections A and C are significant in trapping sediments, while section B exhibits an ability to efficiently remove sediments. To further investigate this we used Yang's criteria (Yang, 1998) for incipient motion to establish a threshold curve for sediment entrainment. Yang's criteria are based solely on the grain size properties and have been proved to provide relatively accurate estimates for sand fractions. Potential river discharge for given channel dimensions assuming rectangular channel has been calculated through the Manning's formula. Sediment grain-sizes range from gravel (d50=20mm) near the junction with Aggitis River to fine sand and silt (d50=0.1mm) in the shallow and sheltered parts of the channel.

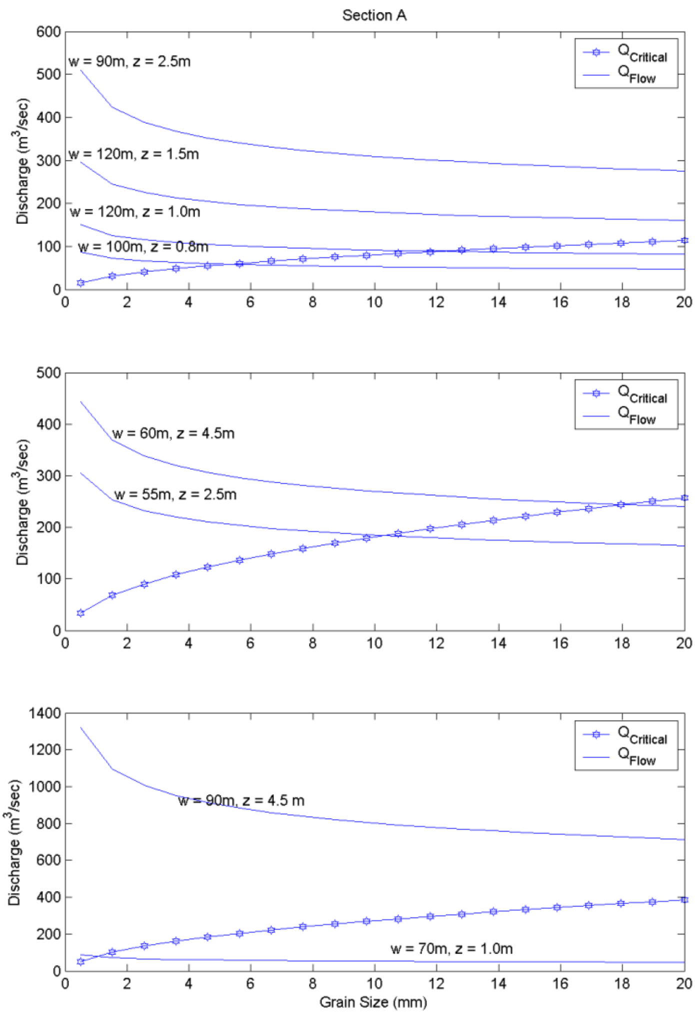

Figure 6. Threshold curve for sediment entrainment for the observed grain-sizes deposited for the three studied reaches. Solid lines represent discharge conditions for initial and reduced channel dimensions (w: channel width, z: channel depth).

The application of the incipient motion criteria suggests that section B is by far the most capable of removing material up to 1 cm in diameter, even for reduced cross-sectional area. Reduction in depth along section A caused by inputs of sediment results in removal of the finer parts only whereas coarser sand fractions cannot be immobilized given discharges lower that 150m3/sec. Section C is the weakest in terms of sediment transport. Even though it's initial dimensions were capable of funneling large amounts of water, controlled discharge from the reservoir has resulted in continuous sediment deposition with as only the mud fractions can be efficiently removed leading to a winnowing process.

7. Conclusions

The impacts resulting from a series of human constructions along the course of Strimonas River have been examined in terms of changes in channel geometry, shape and sediment transport potential, for three studied reaches (from 60 to 78km, downriver). Even though the artificial channel of the river was constructed on the basis of avoiding flooding and increasing the channels conveyance for transportation reasons, the opposite has occurred. For water discharges up to 150m3/sec, the initial channel of sections A and C could not efficiently transport sediments by adjusting form alone, but changes in slope or discharge are necessary. Section B is by far the most efficient part of the artificial channel in funneling sediments and has changed a little since the 1930's. Channel geometry analyses suggest that Section A has been experiencing channel widening near the confluence with Aggitis River due to episodic sediment input, which results in a wide and shallow channel. This in turn results in reduced sediment transport capacity near that point given steady discharges so that only some fractions of bed material can be removed leading to winnowing of fines. Section C has been subjected to significant changes, mainly reduction of depth. Average reduction of cross-sectional area along this stretch has reached a value of 60.5%. Along the downstream part of this section channel morphology and current flow regime have led to excessive deposition of material and the formation of a great number of pools (Figure 3b), which in turn results in entrapment of saline waters.

Discharges of water released from Kerkini reservoir are not adequate in preserving equilibrium conditions along the studied reaches. Especially during the summer months when evaporation and loss of water to irrigation are greatest bed erosion is minimal resulting continuous removal of fines and deposition along section C. Additional sampling and bottom surveying are appropriate in order to obtain better views of the channel morphology, and sediment size distributions before any management decisions should be made. From our analyses it comes that present day river morphology and discharge regimes are leading parts of sections A and C to anastomosis which can result in disastrous flooding during extreme flood events.

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