International scientific conference

DELTAS: GENESIS, DYNAMICS, MODELLING AND SUSTAINABLE DEVELOPMENT

Istomino, Republic of Buryatia, Russian Federation
July 21-25, 2014

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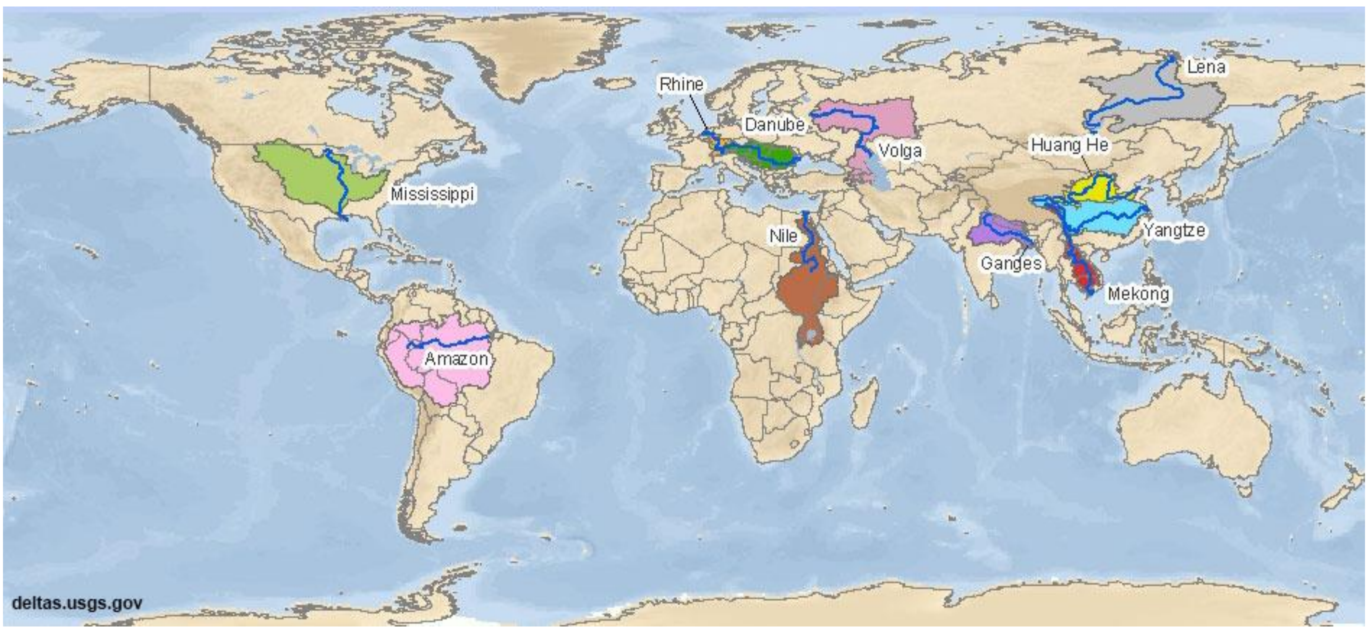

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The Conference allowed scientists and experts to get acquainted with the latest world achievements in the field of hydrology, geomorphology and biogeochemistry of river delta systems.

The participants of the conference are the world's leading schools on river deltaic systems. The participants presented papers on theoretical and experimental developments in the field of delta formation processes, river morphology, engineering design, biogeochemistry, ecology and limnology. The works on mathematical modeling in deltaic systems were well represented too.

The conference was partly financed by the project «Organization and holding of the International scientific conference «Deltas: genesis, dynamics, modelling and sustainable development» of Russian Foundation for Basic Research, Project No. 14-05-20089.

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PREFACE

Seas and oceans, lakes and swamps, yards and underground hydrosphere, glaciers and snow cover are traditionally allocated among all the aquatic elements of the geographical environment. Sea coasts relief is considered as individual geomorphic structures. Deltas of large river systems are mentioned in their compound.

However, when considering their morphology and origin, we see that river deltas are special morphosystems which are formed under the conditions of the positive balance of sediment drift, sea coast peculiarities and a neotectonic regime. That is why such major rivers as the Amazon, the Yenisey, the Ob, the Amur and the Congo do not have classic deltas. Moreover, the estuarial endings of such rivers can be represented by narrow sea bays or estuaries.

From our point of view, the classic blade deltas are very special element of the earth's surface at the interface of land and sea, which have two fundamentally new properties, such as barrier and contact capabilities. It is here where fresh river water and salty ocean water mass interact.

Favorable conditions are created in delta shoals for vegetation and plankton, which is the first link in the food chain of many aquatic organisms. If biologists argue that life has originated in a «pool», then you can most likely say that that «pool» was in a river delta.

It is not by chance, that the main hydrocarbon deposits are located on the sea shelf, where in the historical past paleodeltas of irremeable rivers were forming. They are the Gulf of Mexico and the Caspian Sea, the Yellow River delta and the Middle East, the North of West Siberia and Sakhalin.

Many natural areas of preferential protection, which are located in river deltas, are included in the list of sites of the Ramsar convention, which protects habitats and flight of migratory birds. The feeding grounds and spawning stock of valuable anadromous fish species are located here.

Modern studies indicate the possibility of obtaining energy in the contact zone of fresh river water and the salty waters of the seas.

The Selenga River delta occupies an absolutely unique position among all the other river deltas, as it is the world's only classic blade delta, which has been formed at the confluence of the Selenga River into the ultra fresh Lake Baikal. It is a unique natural formation, which had been developing during the process of a long-lasting interaction of the system «Lake Baikal – the Selenga River». A part of the Baikal Reserve is situated here, and it is included in the list of the Ramsar Convention sites, moreover, natural remedies of oil and gas are identified here too. Proval Bay is situated in its northern part, it was formed in 1860 as a result of the strongest ten-point earthquake. An active transformation of aquatic and semi-aquatic plants and animals in the Selenga Delta occurred after the raising of Lake Baikal up to 1 meter due to the construction of the Irkutsk hydroelectric station on the Angara River in 1957.

It is in the Selenga River delta, where the river water is filtrated from the suspended and dissolved sediments if there are changes in the rate of water flow, temperature and chemical composition. For more than 20 million years of existence of Ust-Selenga depression more than 8 km of sediments have accumulated here, and they are predominantly of alluvial composition.

Thus we can argue that the Selenga River belongs to the most ancient river systems of the Earth, in comparison with lots of other water streams of the North Asia, which occurred during the post glacial time.

An ecosystem of the Selenga River Delta is not only a natural barrier for the river sediment drift, but also an indicator of the state of Lake Baikal ecosystem. And the whole biota of Lake Baikal depends on the well-being of the vegetative and animal world of the Selenga River Delta.

Total amount of all those facts allows to define the importance of researchers' challenges and a range of issues of the Conference. That is why the drafters of this collected works attempted to mark out actual problems and to set out further research activities, to draw attention of interdisciplinary sciences to the integration of different scientific approaches to the study of river deltas.

International Conference «Deltas: genesis, dynamics, modeling and Sustainable Development» was held in the international ecological and educational center «Istomino» of the Baikal Institute of Nature Management SB RAS (Istomino, Republic of Buryatia) 21-25 of July, 2014.

About 60 scientists from the world's leading schools on river delta systems attended the conference. The participants presented reports on theoretical and experimental developments in the field of delta formation processes, river morphology, engineering design, biogeochemistry, ecology and limnology. The works on mathematical modeling in deltaic systems were well represented too.

Director of the Baikal Institute of Nature Management SB RAS Endon Zh. Garmaev

TECTONIC, BASE LEVEL AND CLIMATE CONTROLS ON DELTA MORPHOLOGY AND STRATIGRAPHY

RIVER DELTAS AS A UNIQUE SOURCE OF INFORMATION ON GEOLOGICAL AND ECOLOGICAL PROCESSES IN THE CONTACT ZONE OF SEA AND LAND

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In the diversity of geographical features and relief elements a special place belongs to river deltas that occupy boundary position between land and sea. As a rule, they are large alluvial-lacustrine plains at the mouths of major river systems which were formed during a geologically long process of river alluvium terrigenous sedimentation (The Selenga river Delta…, 2008).

The first human civilizations emerged and developed in warm climates of the subtropics in the major river deltas of the Nile, the Tigris, the Euphrates, the Indus, the Ganges, the Red, the Irrawaddy, the Yangtze and other rivers, where, in addition to rich food resources, river trade routes ended and merchants sea voyages started from. Under the hot sun the sea salt which was urgent for the preservation of food was evaporating.

However, the volatility of the hydrological regime of the rivers in combination with complex geological history of deltafication did not reveal many interesting pages in the history of the formation of the first nations who lived on the border of land and sea.

Currently, a lot of river delta ecosystems are protected areas, where, in accordance with the Ramsar Convention many "Red Book" species of flora and fauna, especially migratory birds, are under special attention. Rich biodiversity of semi-aquatic fauna, river and sea mammals, fish and other organisms attracts tourists and scientists, but a high degree of waterlogging of the territory reduces the availability of delta research.

Meanwhile, in geography there is still no satisfactory classification and description of the morphology of river deltas, which are equally marked with signs of terrigenous and marine relief-factors. In the first approximation, it can be argued that deltas are formed by the accumulation and discharge of river alluvium that is handed down by water currents in the estuary.

This raises an important question: "Why are the classic Deltas absent in such rivers as the Amazon, the Yenisei, the Ob, the Amur and other equally large river systems that endure into the sea not a smaller amount of sediment?"

It can be concluded that the volume of river sediments in the form of tractional dissolved and suspended solids is not decisive in the formation of delta complexes. Of course, in some cases, river alluvium can go to great depths if there is steep continental slope and no shelf. However, in most cases, the formation of large river deltas is affected by mode of recent tectonic movements.

The Case study of the shoreline of Lake Baikal, Lake Hubsugul, coast of the island of Taiwan, Sakhalin Island, New Zealand, Madagascar, the Kamchatka Peninsula and other large linear morphostructures, which are elongated in the submeridional direction, can make sure that the convex seaward landforms and deltaic formation are usually formed in the zones of neotectonic uplift and vice versa bays and fjord-shaped landforms and estuaries are formed along the zones of subsidence. The volume of river alluvium does not have time to fill estuarine deepening and therefore does not affect Relief formation in the contact area of land and sea (Tulokhonov, 2008).

From this point of view, the Selenga River delta has a special place among other river deltas. First of all, it should be noted that this is the world's only freshwater delta, which was formed in the estuary and the freshwater basin of Lake Baikal in the center of the Eurasian continent. As you know all the other more or less large deltas were formed at the outlet of the rivers in the salty seas and oceans. In addition, the Selenga River delta can be attributed to the ancient river counterparts encountered in the middle of the Cenozoic. This is evidenced by almost nine kilometers long layer of alluvial material that has been accumulating in the Ust-Selenga Basin for almost thirty million years of sedimentation.

The fact that tectonic movements actively occur in modern times is proved by numerous earthquakes in the Baikal rift zone. One of them in 1861 was of 10 points and led to lowering of the northern part of the delta and the formation of the Gulf failure area of about 200 square kilometers. According to drilling data, cultural layer with the remains of human activity continues to sink and is currently at a rate of 3-5 cm per year. At different depths in the recent sediments there can be found traces of the use of chemical fertilizers, radioactive elements after nuclear explosions at the Semipalatinsk and the Tarim field test sites, which allows to determine precise time of sedimentation.

It should be noted that in the Selenga River Delta and adjacent coast of Lake Baikal there were findings of bitumen and show of oil and gas. Therefore, in the middle of the last century there were drilled exploratory wells of a depth down to 3 kilometers, which revealed a layer of sand and clay deposits with signs of hydrocarbons. In the vicinity of the delta Gas springs and gas hydrates submarine outputs (gas in the solid state) were detected. Tectonic activity is expressed by the presence of hot springs near the shore, and the relics of permafrost are preserved in marshes.

Thus, it can be argued that a unique sedimentary material has been accumulated in the Selenga river delta sediments, and a continuous geological and paleoclimatic history of the second half of the Cenozoic in the center of the Asian continent is fixed in the material.

Slowing of the rate of the river’s flow in the delta, the precipitation of suspended sediment, dissolved material and nutrient accumulation play a special role in the evolution of the delta ecosystem of Lake Baikal. A powerful geochemical barrier is formed on the area of over 100 square kilometers in the Selenga Delta. The barrier accumulates transit water flow in the deltaic sediments, including alien toxicants and other contaminants. Ultimately, the delta serves as a natural filter that purifies the Selenga waters, which amount is a half of the total river runoff flowing into Lake Baikal.

It should be noted that at present time Lake Baikal is an artificial body of water, the level of which is determined by the activity of the Angara cascade hydropower plants. After the construction of the Irkutsk hydroelectric station in 1957, the level of Lake Baikal raised up for more than 1 m. During the operation of hydropower plants its level varied in the range of more than 1 m.

If the base level of erosion lowers, there occurs an incision of river tributaries of a lake, drainage of wetlands and shallow lakes. When the level of lake water rises, lake water props up river water. It results in a rise of groundwater, flooding of low floodplain, increased erosion of the coastline. For more than half of a century after the construction of the dam of the Irkutsk hydropower plant, the reformation of a new coastline has completed and coastal sand bars became the basic mechanical barrier to the migration of sediment into the lake. During the periods of low water, they form in front of the delta a chain of low islands bearing the local name Yarki. It is here where the small river alluvium is accumulated.

Groundwater and marshes of the delta contain a considerable amount of iron compounds, which are a good sorbent for a number of metals. Oxygen barriers are formed for many outputs of groundwater (gley or sulfide). Gley conditions usually occur in the decomposition of organic matter without oxygen. Local acidic micro-barriers are formed on the rotting timber, which is deposited by silica.

Acid and recovery barriers can be formed on the ground of gas and petroleum products outlets, which are a breeding ground for sulfate-reducing bacteria. Humic acids are widespread in swamp soils, and form complexes with various metal ions under certain conditions. Geochemical anomalies cause the formation of many clay minerals, primarily kaolinite and montmorillonite, as well as peat.

Vegetation of the delta plays a special role in the formation of geochemical barriers. Every year, a large part of the delta is covered with reeds, which create huge reserves of organic matter, which turns into peat deposits when the reeds are dying-off. Such phyto-barriers serve as a natural sorbent that extracts significant amounts of nutrients from the river waters. In total, these geochemical and mechanical barriers, combined with the presence of other micro and macro nutrients, filtering Baikal water, are the main factor of the unique ecosystem of the lake and its ultra-fresh hydrochemical composition.

Fundamentally new element of the research on Lake Baikal ecosystem and especially its delta is the study of lake ice cover, which is formed in a stable state with a thickness exceeding 1 m in the period from January to March. In addition to the physical properties of the ultra fresh heavy water, the researcher is interested in the physical properties that represent its reflection on the seismotectonic progress of geological substrate. According to preliminary data, jointing of ice and its movements closely linked with the micro-movements of the earth's crust and can be useful in the prediction of earthquakes.

Habitats of Baikal seals (nerpas), that make holes in the ice to breathe and relax, refer to large cracks of ice cover. An account of the number of Baikal seals on foot is not effective, because of the low visibility. Therefore, it is advisable to use unmanned aerial vehicles or trikes with high-resolution cameras.

According to the satellite imagery in recent years on the ice of Lake Baikal there are various dark circles with a diameter of several kilometers. According to some reports, their origin may be related to the release of large amounts of gases arising from the destruction of submarine gas hydrates. And that is only one part of the scientific issues and assumptions arising in the study of Lake Baikal as an open natural science laboratory.

Considering this article, first of all as an invitation to participate in collaborative research across the spectrum of natural history studies, the author would like to acknowledge the organizational issues associated with conducting field studies and scientific conferences.

In pursuing these aims, The Baikal Institute of Nature Management has all the necessary laboratory facilities – International environmental-educational center "Istomino", which is located directly on the shore of Lake Baikal near the Selenga Delta. The center has all the necessary equipment and transport for the study of the aquatic environment and biota, including boats, hang-glider and motor vehicles. There are comfortable hotel-type rooms, sauna, telephone, satellite television, dining room, which operate all year-round for work and leisure.

A priori, we argue that new discoveries in the study of the nature of Lake Baikal as a World Heritage Site are inevitable. However, this requires joint efforts of the international scientific community.

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PUNCTUATED LATE QUATERNARY DELTA EVOLUTION IN THE NORTHWESTERN GULF OF MEXICO BASIN: RESPONSE TO EPISODIC SEA-LEVEL FALL AND VARIABLE SEDIMENT SUPPLY

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The northwestern Gulf of Mexico basin receives sediment from several rivers that have a wide range of drainage-basin size, relief, and lithology, as well as river discharge and sediment yields (Fig. 1). The variable discharge also reflects the steep climate gradient of the region, mainly precipitation. An extensive grid of high-resolution seismic data, hundreds of sediment cores and borings and a robust chronostratigraphic framework were used to examine the evolution of late Quaternary deltas of the northwestern Gulf of Mexico throughout the last (~120 ka to Present) eustatic cycle (Fig. 2).

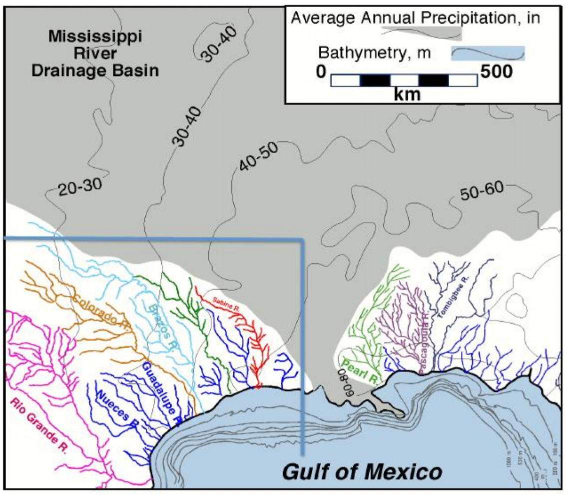

Fig. 1. Map showing drainage basins of rivers that drain into the northern Gulf of Mexico. The area is characterized by a significant difference in precipitation from east to west across the area as shown by average precipitation gradients. The blue box is the study area

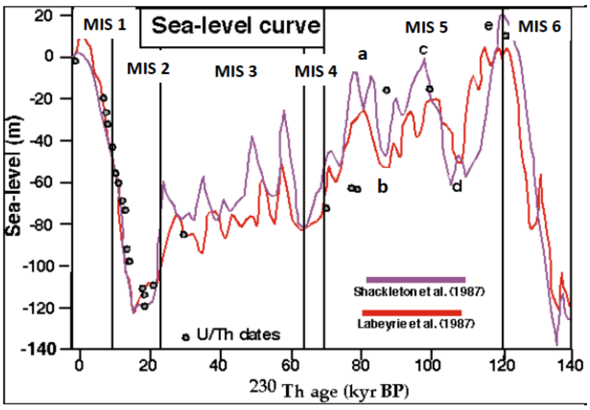

Fig. 2. Sea-level curve, derived from oxygen isotope records, used for this study. Also shown are the marine oxygen isotope stages (MIS 6-MIS1)

During the overall fall in sea level (MIS 5 through MIS 3, Fig. 2) the ancestral western Louisiana, Brazos, Colorado and Rio Grande rivers constructed large fluvial-dominated deltas on the shelf (Anderson et al., 2004) (Fig. 3). Detailed sequence stratigraphic analysis revealed that the growth of these deltas was punctuated and was regulated by the episodic nature of the overall sea-level fall between ~120 ka and 20 ka (Fig. 2) and by increasing sediment supply throughout the overall fall in sea level. The deltas experienced phases of seaward progradation across the inner self during MIS 5e, 5c and 5a (Fig. 2). These episodes of basinward growth were interrupted by back-stepping during episodes of sea-level rise (MIS 5b and 5d; Fig. 2). Sediment delivery to these deltas increased during the overall fall due to erosion and recycling of sediment on the inner shelf, where subsidence is minimal, to the more rapidly subsiding outer shelf. The sediment flux from the Brazos River increased 3-fold and the flux of the Colorado River increased 6-fold by the late stages of sea-level fall through the lowstand. Increased sediment supply during the falling stage was also the result of purging of incised valleys, which in the case of the Brazos River contributed ~ 30 km^3 of sediment to the evolving delta.

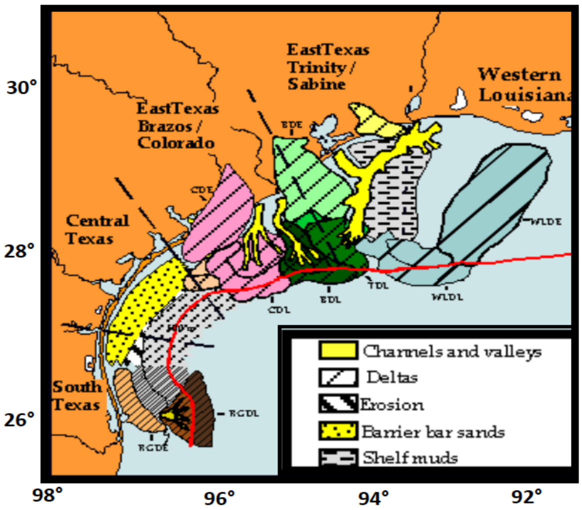

Fig. 3. Paleogeographic map showing major falling stage depositional systems of the study area (modified from Anderson et al., 2004). Blue=Western Louisiana Delta, Green=Brazos Delta, Pink=Colorado Delta and Brown=Rio Grande Delta.

During the MIS 2 lowstand (~22-17 ka), the Western Louisiana Delta was abandoned as its fluvial feeder was captured by the Mississippi River. The Brazos River abandoned its MIS 3 shelf margin delta to merge with the Trinity/Sabine rivers and together these rivers nourished a lowstand delta and slope fan complex. The Colorado River and Rio Grande rivers behaved more as point sources of sediment to thick lowstand delta-fan complexes. There were two widespread episodes of increased riverine sediment flux and delta growth during the MIS 1 transgression (Fig. 2), between ~ 11.5-9.5 ka and 9.5-7.0 ka. These episodes of delta growth occurred during reversals from warm dry to cool/wet climate conditions (Anderson et al., 2004; Van Heijst et al., 2001).

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INFLUENCE OF SEDIMENT COHESION ON LONG TIME SCALE DELTAIC MORPHODYNAMICS

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Introduction

Movement of the shoreline in deltaic environments is influenced by sea level rise and subsidence rates in addition to input sediment flux to a system. A rich body of work documents how variations in these parameters influence the movement of shorelines and the stacking of sedimentary deposits (Blum and Tornqvist, 2000; Muto, 2001; Sun et al., 2002; Van Wagoner, 1995). While variations in these three parameters determine the long term average location of a shoreline, morphodynamics can drive high magnitude deviations from the long term mean.

While a range of field, experimental, and numerical studies document autogenic processes and their stratigraphic products, we still have only a cursory understanding of the influence of allogenic forcings (both steady and unsteady in time) on the internal dynamics of sedimentary systems. Studies that do examine how autogenic processes change as a function of allogenic forcings primarily focus on dynamics that occur over micro (<10^1 years) to meso (10^1–10^4 yrs) time scales (following Sheets et al. (2002)). For example, studies by Bryant et al. (1995) and Powell et al. (2012) have improved our understanding of avulsion dynamics as a function of basin aggradation rate and water and sediment discharge rates. Recent studies that couple experimental and field work, though, suggest that autogenic processes also influence stratigraphic architecture at the macroscale (>10^4 years) (Hajek et al., 2010; Straub et al., 2009; Wang et al., 2011). While these studies provide convincing evidence for the existence of macroscale stratigraphic products resulting from autogenic processes, few studies have examined how these autogenic products vary as a function of basin boundary conditions. Here we use experiments on fluvial systems experiencing relative subsidence to examine how macroscale autogenic dynamics vary as a function of basin input sediment cohesion. Further, we investigate the role of autogenics in setting mean properties of a delta, focusing here on sediment retention rate.

Experimental Setting

We use physical experiments to explore the role of sediment cohesion on the magnitude and time scales of autogenic processes in deltaic settings. We explore results from three experimental stages where the cohesion of sediment entering an experimental basin varied, while all other parameters were held constant. Conditions for all experimental stages included a base level rise rate balanced against an input sediment supply such that the long-term average delta area remained approximately constant. Properties of the sediment delivered to the basin was modeled on the sediment mixture developed by ExxonMobil to study the influence of sediment cohesion on meso-scale autogenic processes (Hoyal and Sheets, 2009). Hoyal and Sheets (2009) found that a key to forming strong channelization at the laboratory scale is enhanced sediment cohesion provided through an artificial polymer. This enhanced sediment cohesion appears to mimic cohesive effects of vegetation and de-watered clays at field scale. Our three experimental stages included 0 g, 40 g, and 80 g of NewDrill polymer per 120 lbs batches of sediment for our non-cohesive, weakly cohesive, and strongly cohesive experiments, respectively.

Experimental Results

Time series of terrestrial delta top area, A_{TDT}, for the three experiments are presented in Fig. 1. We observe an increase in variability of A_{TDT} as we increase the amount of cohesion in the input sediment mixture. In the strongly cohesive experiment, high sediment cohesion enhanced a characteristic autogenic cycle of channel formation, elongation and abandonment. This cycle drove shoreline transgressions that reduced delta-top area by up to 45% of the long term average. Deposition of fine grained material dispersed into the marine realm during transgressions produced flooding surfaces in the resulting stratigraphy that could be confused with surfaces produced by increases in sea-level rise or subsidence rates (Fig. 2).

We compared our time series of measured experimental A_{TDT} with a simple mass conservation numerical model for delta growth. This model incorporates knowledge of input sediment volume per unit of time, sea level rise rate, average delta top and delta forset slopes, deposit porosity, and basin geometry to calculate the radius from the basin infeed location to the shoreline, where the topset and forset meet. This radius can then be used calculate a predicted A_{TDT}. Importantly, the model assumes 100% sediment retention on the composite delta form (topset + forset). Initial model results strongly over predicted experimental observations. We investigated the importance of sediment retention on our predictions of A_{TDT} by simply varying the amount of sediment input into the models. When reducing our model sediment input, analogous to decreasing the sediment retention of a delta through net bypass of sediment through the delta top and forset, the quality of the fit between model and data increased. Implementation of a root mean squares reduction technique resulted in estimates for sediment retention equal to 73%, 66%, and 58% for the non-cohesive, weakly cohesive, and strongly cohesive stages, respectively (Fig. 1).

We investigate the correlation between sediment retention and channel mobility, as a function of cohesion, in our experiments by measuring a channel time scale, T_{ch}. T_{ch} represents the average amount of time it take for flow to visit 95% of the locations on a delta top. As such, T_{ch} is inversely related to channel mobility. We find that as cohesion in our system increases, we observe increase in T_{ch} (Fig. 3a). Our measured T_{ch} are also inversely related to our measured sediment retention rates.

Discussion

Our experiments demonstrate an increase in the spatial and temporal scales of autogenic processes as a function of sediment cohesion. Importantly, an increase in sediment cohesion in our experiments was linked to an increase in autogenic shoreline migrations which produced parasequence architecture that could be incorrectly interpreted as the product of changing environmental condition.

Second, the observed decrease in sediment retention with increasing sediment cohesion as implications for theory related to the influence of vegetation on delta evolution. One way to enhance cohesion of deltaic systems is to increase the quantify of vegetation with roots that bind sediment grains and enhance the critical shear stress necessary for erosion. Vegetation has often been discussed as a way to increase sediment retention on deltas by reducing the speed of sediment laden overbanking flows, thus promoting deposition (Cahoon et al., 2011). Our experiments do not include vegetation and therefore do not incorporate the process discussed above. However, our experiments do indicate that a reduction of channel mobility, which enhances the time scale of autogenic processes, can aid the development of long lived channels. These channels can be capable of efficiently transporting fine grained sediment over the delta top where it can be transported in suspension past the delta forset and be deposited as pro-delta material. The relative importance of these two processes for bulk sediment retention rates remains unclear and will require future work to resolve.

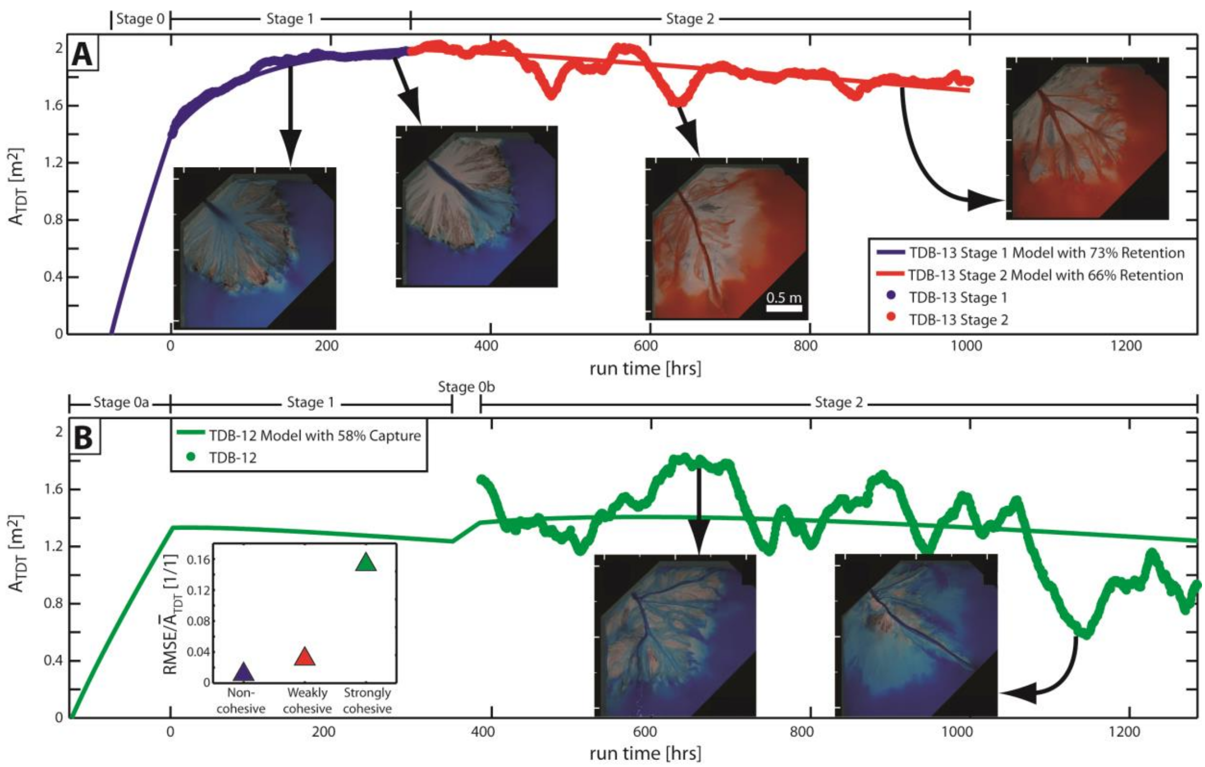

Fig. 1: Time series of terrestrial delta top area measurements for the three experimental stages performed, including images of delta form at various points in time of each experiment. Solid lines represent best-fit model time series of evolution of delta top area with associated sediment retention values in figure legends. Insert plot shows normalized root-mean square error between data and model for each stage.

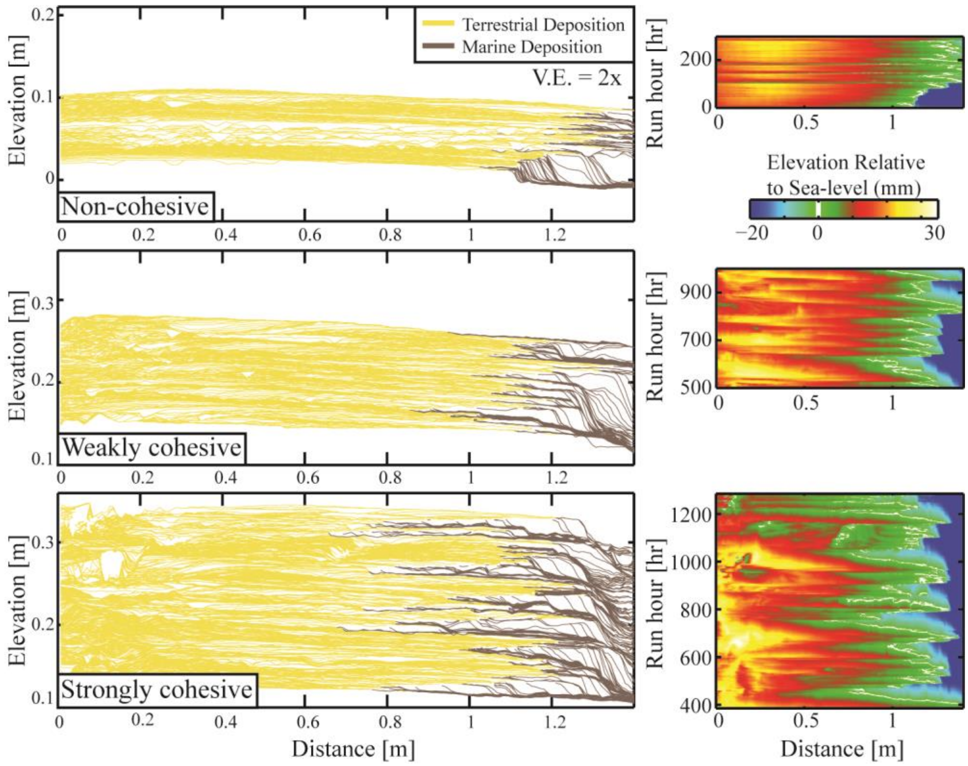

Fig. 2: (Left panels) Synthetic stratigraphy of dip transects along basin mid-point for each experiment. Each line represents a measurement of topography, taken once per hour, that are clipped to account for sediment removed during erosional events. Synthetic time lines colored by environment of deposition. (Right panels) Time Space matrixes of elevation relative to sea level for dip transects along basin mid-point for each experiment.

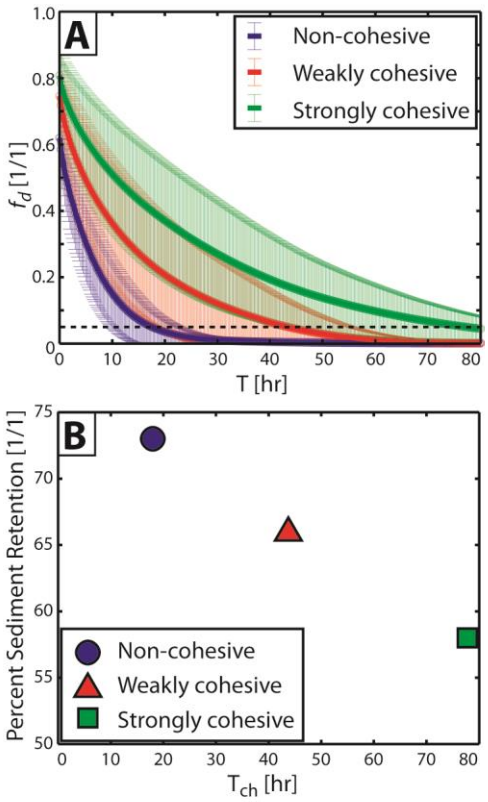

Fig. 3: (A) Data defining the reduction in remaining dry fraction on the fluvial surface as a function of time, used to estimate T_{ch} for the three experimental stages in the study. Thick dashed lines represent a fraction dry, f_d, of 5%. (B) Data defining sedimentation retention rate as a function of channel time scale for the experimental stages in this study.

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A SPATIAL PECULIARITY OF GRADED ALLUVIAL CHANNELS IN DELTAIC SETTINGS

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A segment of river which conveys sediment without net deposition and net erosion is referred to as "graded" with respect to that segment. A correct understanding of grade is fundamental in the morphodynamics and geology of river deltas, because grade is an incarnation of the critical condition that discriminates between aggradational and degradational regimes in river systems, and also because the study of alluvial grade is nothing else but an exploration of intrinsic river responses to base level forcing.

Recent renewal of debates as to the grade concept brings a whole new understanding that in an alluvial-deltaic system growing under a moving-boundary condition, (1) the feeder alluvial river can become graded only during base level fall, (2) time patterns of the base level fall to allow the river to be graded depend on basin configuration, and (3) alluvial rivers can be graded both allogenically and autogenically. This set of notions, referred to as the "autostratigraphic view of grade" (Muto et al., 2007), has been derived largely from 1D geometrical modeling and corroborative 1D flume experiments. There still remain a few of critical questions unsolved, such like how a graded river behaves in a 2D spatial setting, what planometric geometry and channel patterns could be intrinsic to a graded river, and what stratigraphic signs could be left by a graded river in geological records. The present tank experiments, conducted under both fixed-boundary and moving-boundary conditions, bring a clarification of diagnostic spatial peculiarities of the graded alluvial system in a deltaic setting.

In the "fixed-boundary" series of experimental runs, a submerged overfall with a significantly large drop was set at a particular basinward distance from the initial shoreline. When the prograding delta was still apart from the overfall, a delta steadily expanded both landward and basinward, with the alluvial topset invariably aggrading (i.e. remaining nongraded). While the delta was growing, distributary channels incessantly changed their positions and frequently avulsed, thereby developing an isotropic shoreline configuration as a whole. But soon after the delta toe had reached the overfall, the channels evolved to a single large channel, or a valley, that was stabilized in the axial portion of the delta plain (Fig. 1). At the same time, the upstream end of the feeder alluvial river (ABT: alluvial-basement transition) moved slightly downstream and then came to a sustained halt, which is a sign of the attainment of alluvial grade. The grade attained due to the presence of downstream-fixed boundary is here referred to as "forced grade".

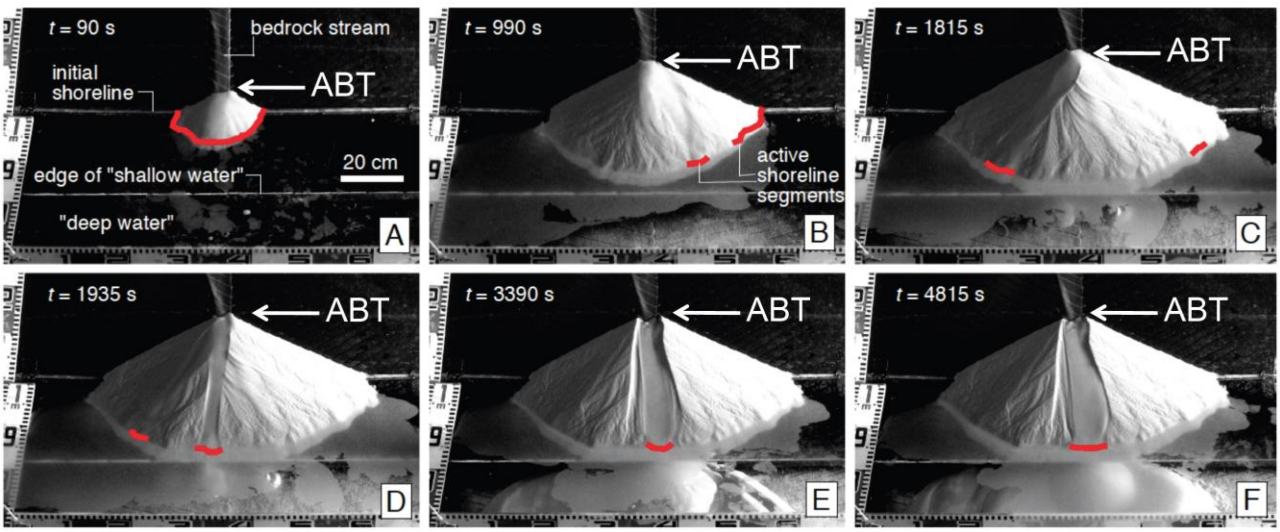

Fig. 1. Sequential photo images of an experimental run of the "fixed-boundary" series. Note that soon after the delta toe reached the submerged overfall, distributary channels evolved to a single large channel that was stabilized in the axitial part of the delta plain. Red lines indicate active shoreline segments. ABT = alluvial basement transition

In the "moving-boundary" series, a delta was built with constant base level fall to produce "autogenic grade". Significant channel incision such as observed in the fixed-boundary series did not take place. Instead, an active deltaic lobe progressively protruded basinward in linear trend, without lateral shifting/avulsing of the feeder alluvial channel(s). During the basinward extension of the lobe, ABT remained stationary, reflecting that the alluvial system sustained grade or quasi-grade.

The results of the two experimental series, combined with a previous experiment conducted with differential water depth (Muto et al., 2011) and a geometrical model that explains the effect of basin water depth on distributary channel behavior, suggest that in a graded alluvial-deltaic system, (1) lateral shifting and avulsing of active distributary channels are suppressed regardless of whether or not the downstream boundary of the deltaic system is fixed, (2) in a delta having a fixed downstream boundary, a graded alluvial channel is stabilized in the axial part of the delta plain, whereby the outside of the channel is abandoned as terraced surfaces, and (3) under a moving boundary condition the graded river simply extends basinward as a linearly elongated channel-lobe system, without forming distinct terraces.

Sea level conditions matter with the attainment of alluvial grade in natural systems. During stillstand sea level, graded alluvial rivers would most likely be found within a stabilized large channel, or a valley, that was incised to the axial part of a fan delta adjacent to very deep water (i.e. a downstream-fixed setting). During a falling stage of sea level, graded alluvial rivers could be realized in outer to marginal areas of a deltaic continental shelf which evolved through multiple cycles of sea level rise and fall. During a rising stage of sea level, alluvial rivers would have no chance to attain grade.

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INVESTIGATION OF RELATIONSHIPS BETWEEN GEOSTRUCTURAL CONDITIONS AND MORPHOGENETIC TYPES OF RIVER MOUTH SYSTEMS

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Abstract: Analysis of geological and geomorphologic structure and settings of the large rivers deltas of Siberia and the Caspian Sea basin provides a reliable basis to establish a considerable influence of specifics of structural and tectonic composition of seacoast on morphogenetic types of river mouth systems that are formed along it.

V.V. Dokuchaev (1878) and G. Kredner (1878) were first to note the importance of relationships between the river delta morphology and structure on one side and type and direction of vertical tectonic movements of the coastal zone on the other side. V.V. Dokuchaev, while developing his thoughts on principals of the river longitudinal profile evolution theory and associated processes of mouthward increase of stream length, first proposed the more rational and potentially promising idea that vertical movements can make river mouth processes more complex. Those idea were further developed in works by V.G. Rihter (1960, 1965), who associated delta formation, morphology and evolution trends with interactions between intensity and direction of modern tectonic movements and river sediment yield. He proposed to distinguish the two main types of river deltas – on uplifting and subsiding coasts.

It was later found out (Korotaev, 1991; Korotaev, 2012) that formation of different types of mouth systems on morphologically uniform shelf (for example, the Russian Arctic) by large rivers with close values of annual discharge and sediment yield (Lena and Enisey, Olenek and Yana, Kolyma and Indigirka Rivers) can most likely be explained by differences in structural conditions as well as differences of neotectonic movements. Essentially it means that there exists a geological control on major morphogenetic types of large river mouth systems. For example, the rivers located in zones of long-term and relatively constant subsidence (such as northern part of the Western Syberian Plain, Lower Amur Depression, Dnieper-Don Depression) where channel water surface gradient in lower reaches is low (0.015-0.055‰) have mouths represented by long estuaries which had maximum lengths (up to 200-1000 km) during the highest postglacial transgression period (Kolyma, Enisey, Ob and Pechora estuaries). Under present geomorphic conditions such sections of coasts are characterized by well-developed river valleys with prominent terrace sequence and ingression gulfs in mouth reaches continued by submerged valleys cut into the shelf surface down to the 100-200 m depths.

Completely different is the morphology of river mouths situated in zones of recent folding where coasts are affected by strongly differentiated tectonic movements and channel water surface gradient in lower reaches of rivers can vary within a range of 0.15-0.9‰. Marine transgressions during the Late Pleistocene had limited spatial extent in such areas. Inland depth of gulfs did not exceed 100 km. In certain cases narrow valley sections formed where rivers cut through the coastal ridges directly transform into wide mouth openings along the open coastline (Lena and Olenek Rivers).

These two main structurally and tectonically controlled types of the river-sea transition zone described above also correspond to the distinctive morphogenetic types of river mouth systems. Estuaries, firths and rias-type coasts are typical for the first type (subsiding coasts), while expansion deltas along the open coasts or infill deltas along the coasts with lagoons. Probably the most striking example of the tectonic impact on delta-forming processes is the Holocene evolution of the Lena River delta. Graben-shaped depressions within the Primorskaya Lowland territory are occupied by mouth gulf infill systems along the Olenekskaya and Bykovskaya deltaic arms. Local uplift zones coincide with expansion deltaic systems of the Tumatskaya, Trofimovskaya and Sardahskaya deltaic arms alluvial fans (Estuarine-deltaic systems…, 2007).

Another illustrative example of structural and tectonic control on the morphology and development of deltas is provided by the large rivers flowing into the Caspian Sea. Those rivers have gone through a long period of evolution following the numerous sea level oscillations of different magnitude and frequency (Rychagov, 1977). Lower reaches of those rivers are presently characterized by presence of different morphogenetic types of delta systems – from the ingression gulf infill deltas (the Kura River) to the open sea coast expansion deltas (the Terek, Volga and Ural Rivers). Morphological differences of these rivers deltas cannot be explained solely by various hydrological regimes or gradients of underwater coastal slope. For instance both the Volga and Ural River deltas are formed on very shallow and gradual coastal slope (with gradient less than 0.0002‰), while annual suspended sediment yields of the two rivers is significantly different, 8.6 and 2.7 million tons respectively (for the 1978-1993 period). However, morphogenetic type of the deltaic systems is the same for both rivers – expansion delta formed along the open coast (Mouths of the

Caspian…, 2013).

The Kura and Terek Rivers flow into the sea at the open coast sections with the same underwater slope gradient. Both rivers are characterized by relatively close suspended sediment yield – 17.12 and 15.1 million tons respectively (for the 1966-1981 period). However, morfogenetic types of the mouth systems they form are different. The Kura River forms the ingression gulf infill delta, while the Terek River – the expansion delta on the open coast.

Below we will consider in more details the formation of river mouth systems of large rivers flowing into the Caspian Sea, as the most investigated.

It is known that structural and tectonic properties of the Caspian Sea are determined by a presence of several large tectonic-morphological structures (Kuznetsov, 1970; Leontiev, 1977). The entire northern coast and adjacent part of the north Caspian Sea shallow zone are located within the physiogeographic province of the Prikaspiyskaya Lowland, which territory coincides with the geological structure of the Prikaspiyskaya syneclise. Those are associated with south-eastern margin of the Eastern European platform. The syneclise depression is infilled by Paleozoic and Meso-Cenosoic sedimentary complexes. Specific features of the Paleozoic sedimentary complex are very distinctive dislocations associated with evaporite (salt) deposits of the Kungurian stage of the Permian period – intrusion of the salt diapirs into the overlying strata as a result of their pressure on the relatively plastic evaporite layer and resulting formation of the so-called salt domes. The later represent the geomorphic manifestation of the salt tectonic structures as positive landforms. Such landforms exert significant influence on the specific features of the Ural River delta system, which can be classified as the so-called incised delta.

Deep geological structure of the southern part of the Prikaspiyskaya Lowland where the Volga river delta and its shallow submerged distal part (so-called foredelta) are situated is significantly different from its other parts. Its main feature is a presence of the buried latitudinal folded structure formed during the Hercynian (Variscan) orogeny named the Karpinskiy Ridge. The latter consists of the several parallel latitudinally elongated zones of uplift and subsidence. There are four relatively uplifted zones distinguished under the Volga river delta and foredelta: Krasnoyarskaya, Astrakhanskaya, Novogeorgievskaya, Promyslovo-Rakushechnaya.

Tersko-Sulakskaya Lowland coincides with the Tersko-Caspian foredeep tectonic structure. It is infilled by thick Quaternary sediment body in excess of 500 m. This depression is bounded by the eastern slope of the Stavropol Upland and the northern slope of the Caucasus frontal ranges. Under the Caspian Sea it continues as the Derbent depression of the middle part of the sea bottom. This tectonic structure, especially its eastern part, is characterized by the stable and long-term subsidence tendency at a rate up to 2 mm year^{-1}.

The Kura and Arax Rivers mouth system is spatially associated with the Kura-Arax tectonic depression which represents the eastern closure of the larger Kura intermontane depression stretched between the ridges of the Large Caucasus, Small Caucasus and Talysh. The depression was formed in early Paleogene inheriting the location of the central microplate with platform regime of tectonic movements. At present it is represented by the secondary megasynclinorium formed during the last stage of the geosynclinal period of the Caucasus development. That was a stage of formation of large folding-blocky uplifts and associated foredeeps and intermontane depressions. Main structural elements of the Kura depression are the Verhne-Kurinskiy, Sredne-Kurinskiy and Nizhne-Kurinskiy synclinoriums. All three have for a pronounced period been an area of subsidence and intensive sedimentation (Mamedov, 1967; Shirinov, 1973; Shirinov, 1975). Total thickness of only the Quaternary deposits within the depression is 1000-1100 m.

The described differences in structural and tectonic composition of the of the Volga, Ural, Terek and Kura Rivers mouth systems combined with the Caspian Sea level fluctuations gave rise to the presently observed morphological features of these rivers deltas. For example, the first phase of the Volga River expansion delta formation is dated to the Ulluchaysk stage of the Novocaspian transgression while its present appearance was shaped after the Derbent regression (about 1000 years ago) when the sea level laid below the –25 m (elevation Baltic system). During that period the sea waters did not get outside the so-called "mounds zone" of the delta (territory where the most prominent relics of the so-called Baer mounds are observed). During the lower seal level periods the Volga River reached the sea not as a single large channel, but through a number of comparatively smaller deltaic arms such as Buzan, Bolda, Bahtemir, Kizan. These arms were adjusting to system of depressions between Baer mounds. Their separate alluvial fans formed expansion delta segments outside the "mounds zone": firstly the Late Holocene (floodplain-channel subtype), later the modern (so-called ***kultuk*** subtype, ***kultuk*** being the local term for gulfs on the delta outer edge separating the deltaic arms mouths). As a result of such history, the total area of the Volga River delta reaches about 12000 km^2 (without the marginal lakes), including the youngest distal zone of 6400 km^2 (Rychagov, 2009; Rychagov, 2010).

In the lower reaches of the Ural River (downstream from the Uralsk City) there is a system of relic deltas coincident with various distinct stages of the Caspian Sea level (Foteeva, 1963; Leontiev, 1965). Unlike the larger and deeper Volga River valley, relatively shallower valley of the Ural was not filled by large ingression gulfs. Small and thin alluvial fans with fan-shaped systems of deltaic arms incised into the marine sediments formed at the partly submerged zones of the river mouth. All such relic deltas of the Ural River can be classified as ***sculpted*** or ***incised*** deltas. On one hand it was associated with lower annual discharge (about 8-10 km^3) and suspended sediment yield (3.1-2.7 million t), on the other – with exceptional shallowness of the adjacent sea and with widespread active salt domes which were flown around by the anabranching deltaic arms. The present delta of the Ural River has been developed during as short period as about 200 years and is therefore very small in size (area about 500 km^2).

The Terek-Sulak deltaic plain is situated within the Terek foredeep which is in turn a northwestern part of the large Terek-Caspian depression. Within the deltaic plain territory, the foredeep is characterized by wide and flat bottom sharply bound by northern and western slopes. From the south the Terek foredeep is separated by relatively low and wide uplifted zone from the narrow and deep mountain range front trough. The latter runs along the margin of frontal folds of the Large Caucasus Range. In fact, northern slope of the depression is at the same time the southern margin of the Terek-Sulak deltaic plain. Main structural elements describe above were initially formed before the Akchagyl epoch, but continued to develop later. From the Late Neogene until the Early Khvalyn there was a large sea bay with varying size within the present Terek River mouth area. That territory has experienced long-term continuous subsidence (its present rate is about 2 mm $year^{-1}$), especially its eastern part. As a result, thickness of marine deposits of Baku, Khazar and Khvalyn ages together reaches 500 m and more at the Terek River mouth.

The Terek and Sulak Rivers deltaic deposits infilled the formerly large bay. As a result of that the Early-Late Khvalyn deltaic plain was formed. Its formation at present still continues only at several locations. Those include filling of the Agrahan bay, continuing growth of the Terek River beak-shaped expansion delta at the Kargalinskiy arm mouth and beginning of the new beak-shaped expansion delta of the Sulak River at the seaside of the Agrahan Peninsula. The oldest deltaic plain surfaces have experienced significant modifications as a result of aeolian and solonchak-deflation processes activities. At present there is a serious human impact represented by melioration activities. It has been established (Rychagov, 1958; Rychagov, 1960) that the Terek-Sulak deltaic system with total area about 10000 km^2 was formed mainly during the Late Khvalyn sea regression. The younger (Novocaspian, modern) later formed deltas at several locations were either overlain or attached to the older delta surface.

Additional specifics of the Terek-Sulak deltaic plain is in the fact that the continuing tectonic subsidence of the area is compensated by deposition of huge volumes of sediment transported by Terek, Sulak and their smaller tributaries. The resulting channel aggradation makes it relatively elevated by 2-3 m above the surrounding delta surfaces. This in turn is the main reason of periodical channel levee breaks, dramatic channel shifts, inundation of lowland areas between leveed channels and burying of the Upper Khvalyn delta deposits by superimposed modern alluvial sediments. Main result of such a combination of processes is a formation of the so-called ***superimposed swampy-festooned local deltas.*** At least seven cycles of formation of different generations of such local superimposed or attached deltas of the Terek River have been reconstructed for the last 500 years. Their locations were primarily determined by irregularities of the underlying Quaternary deposits surface, which, in turn, was controlled by deep tectonic structure of the Terek-Sulak deltaic plain. Local delta generations formed during such cycles are Kuru-Terek, Ak-Terek, Kuru-Chubutly, Sula-Chubutly, Sredniy Terek, Noviy Terek, Stariy Terek, Borozdinskaya Prorva, Talovka, Kargalinskiy Proryv. Modern expansion subdeltas of the Terek and Sulak Rivers situated on the open coast have areas of 10 km^2 and 50 km^2 respectively.

Geomorphic system of the Kura River mouth is tectonically coincident with the Kura depression. In the past, during the Quaternary transgressions of the Caspian Sea, the depression periodically transformed into the sea bay. However such bays occupied only the central part of the depression. Bay heads reached the Mingechaur Gorge. Succession of the Kura River deltaic plain development has been reconstructed in details by V.V. Egorov (Egorov, 1955). Spatial locations of the five main relic delta generations have been established in addition to the modern one. These deltas form most of the Kura-Arax Lowland territory. One of the oldest delta formations (represented by the expansion palaeodelta) is located on the right side of the Kura River valley upstream of the Arax River mouth (on a boundary between the Karabahskaya and Milskaya steppes). Modern channel of the Kura River bypasses that surface from the north. The channel is bent towards the central part of the Shirvanskaya steppe, where the next (second) palaeodelta surface is situated. After that delta was abandoned, the Kura River channel shifted to the south and the third palaeodelta generation was formed expanding towards the present Muganskaya steppe. Margin of the third palaeodelta generation is represented by a prominent concavity that separates its surface from a flat lowland plain to the north from the former Ah-Chala Lake. Later the Kura River channel flowed around that palaeodelta from the northern side while changing its general direction from latitudinal to the southward. As a result of that channel shift, the fourth generation palaeodelta was formed upstream from the Salyany City. The fifth generation palaeodelta of the Kura River can be traced within the Salyanskaya steppe territory where the river flowed during into the former Caspian Sea gulf named Kyzylagadzh. Total area of the Late Novocaspian age part of the Kura-Arax deltaic system is about 9000 km^2.

Spatial arrangement of the Kura River palaeodeltas described above is largely related to the structural and tectonic settings of the Kura-Arax Lowland. Generally its evolution is integration of continuous subsidence of the depression bottom and the Caspian Sea level fluctuations. Since the Early- to Middle Quaternary subsidence movements changed into uplift along the northern and southwestern marginal belts of the depression. Such differential change of the tectonic movement tendency was unavoidably accompanied by folding and faulting. Those resulted in formation of gradual but prominent anticline rolling hills and uplands within the Naftalanskaya Plain territory. Another series of young anticline ridges (Mishovdag, Kyurovdag, Babazanan) accompanied with mud volcano mounds (Kalmas, Kyursangya, Byandovan, Durovdag, etc.) complicate the generally plain background of the Kura-Arax Lowland northeastern part (South-Eastern Shirvan). Surface of the lowland is composed of predominantly coarse-grained alluvial deposits of Upper Pliocene to Quaternary ages in its western part and along the margins changing into Upper Quaternary to Holocene age marine sands and clays in its eastern part. The Kura River channel present location almost coincides with the modern tectonic axis of the Kura depression. However, its ancient axis was located further northward under present Adjiondgura piedmonts where the highest thickness of the Pliocene-Quaternary deposits is observed. Southward shift of the depression axis was related to the regional uplift of the Large Caucasus meganticlinorium. That also caused the Kura River palaeochannel shift in the same southward direction as indicated by a presence of coarse-grained alluvial deposits and a vast belt of presently waterlogged depressions stretched parallel to the modern river channel. At the same time, the marine regression occurred and inclined piedmont alluvial plains expanded as a result of growth of series of alluvial fans.

The Kura River modern delta began to form after the river again changed its direction from southward to latitudinal and cut through the ancient coastal shell bar. It is represented by the expansion subdelta on the open coast and has a present area of about 190 km^2.

Despite the striking examples provided above, it is generally evident that for development of the contemporary hydrographic network for the majority of river mouth systems neotectonic movements play only secondary role. That can be explained by incomparability of rates of channel deformations and tectonic movements.

Results of the palaeogeomorphic investigations of deltaic plains of large rivers of Northern Siberia and the Caspian Sea basin prove that the main morphogenetic types of deltas (infill and expansion) largely coincide with general basics of the global geomorphic concept of the river mouth systems evolution developed for the oceanic coasts and marginal sea coasts of the World Ocean.

It can be generally concluded that structural and tectonic conditions control spatial patterns and formation of specific morphogenetic types (infill or expansion) of deltaic systems, while the sea level and river flow (discharge and sediment yield) fluctuations determine cyclisity of delta development, intensity of delta formation processes and the modern pattern of hydrographic network of deltaic systems.

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MORPHOMETRIC RELIEF ANALYSIS OF THE SELENGA RIVER DELTA ON THE BASIS OF THE DIGITAL ELEVATION MODEL SRTM

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Abstract: The morphometric relief analysis of the Selenga River delta on the basis of the digital elevation model SRTM is carried out. Maps of the major morphometric features (hypsometry, slopes and aspects) are created. This allowed to carry out the profound relief analysis of this territory.
Keywords*:* remote sensing, digital elevation model, automated classification, morphometric analysis

Delta of the Selenga River is a rare type of morphogenetic estuarine-deltaic geosystem on the coasts of World Ocean and inland waters – delta extension in the open seashore. The physical basis of the formation process is the deposition of river sediments due to reduced flow velocity of the river flow at the inflow to the receiving reservoir. Processes of the delta formation have different temporal and spatial scales from the secular to the short-term. Millions of years ago, the delta of the Selenga River was much higher in the river valley. Cape Oblom of the Ulan Burgasy mountain range and the Khamar-Daban mountain range are on the one line of the mountain system of the eastern coast of Lake Baikal. It is clearly seen that the Selenga River broke through the line and started to promote its bed deep into the waters of the lake due to the sand brought in from its numerous tributaries. Today, the delta of the Selenga River is quite large land, arc-shaped curved beyond the shoreline Oblom – Boyarskiy. The width of the shelf is from 50 to 70 km, and the length from north to south is about 100 km (Estuarine-deltaic systems…, 2007).

Externally the mouth of the Selenga River is a vast meadow plain; the top of it is active used under arable land, and at the bottom, in the delta, meadow and marsh plain is often flooded with an increase in the level of the lake Baikal and shared by numerous channels, oxbows and lakes. Below Krasnoyarsk channel hundreds of large and small islands appear.

One of the most important tasks in the studying the landscape structure of the river valleys is the analysis of key morphometric parameters of valley geosystems. The application of the capabilities of GIS and DEM allows to deep and refine this analysis significantly. Digital models created by regular network of the initial points are the most effective for the computer aided modeling of the relief images (Moore et al., 1991). In recent years DEM SRTM (Shuttle Radar Topography Mission) which is the basis for large-scale morphometric mapping becomes widespread. SRTM is the unique raster DEM in the coverage of the earth's surface (captured 85% of the territory of the globe). Shooting was made from board of the Space Shuttle Endeavour on the basis of radar interferometry (comparison of the images of the separated by 80 m radio-radar sensors SIR-C and X-SAR) for 11 days in February 2000 (Farr et al., 2007).

DEM file was downloaded from FTP-server of NASA. Each such file covers geoid square with sides of 1 degree and is a matrix size of 1201 × 1201 from a double-byte values. Last 1201-th column and the 1201-th row of the matrix form overlap with the adjacent squares. Each element of the matrix – cell of geo-bound raster – corresponds to the elevation point of the lattice site in increments of 3 arc seconds (1/1200 of a degree) in longitude and latitude. On a cylindrical conformal Mercator projection this lattice is rectangular, each file corresponds to a rectangle with size 1 degree to 1 degree, for the Baikal region it is 57 × 92 m in longitude and latitude respectively. Matrix points are counted from west to east and from north to south; the rows correspond to the parallels, columns to the meridians (Rodríguez et al., 2005).

SRTM radar mapping is designed to build a sufficiently accurate DEM. Initially, the mission of SRTM had the following objectives in the accuracy: a linear absolute error in height is less than 16 m, a linear relative error in height – less than 10 m, a circular absolute error in the plan – less than 20 m, a circular relative error in plan – less than 15 m, a relative error in height for a data of X-band SRTM – less than 6 m. Values for the Eurasian continent turned significantly better in practice: the absolute error in the plan – 8.8 m, the absolute error in height – 6.2 m, the relative error in height – 8.7 m, the error in height for the data of X-band – 2.6 m (all errors in the 90% confidence interval) (Rodríguez et al., 2005; Farr et al., 2007; Karwel at al., 2008).

Own research on the assessment the vertical accuracy of the model SRTM was conducted by comparing with the elevation points of four sheets of digital topographic map M 1: 100 000, covering the area of the delta of the Selenga River (N-48-129, N-48-130, N-48-141, N-48-142). Sheets of the scanned topographic maps were geo-referenced in the software product OziExplorer to carry out the high-altitude analysis. The height of the points, corresponding to the elevation points found on the map, were captured from the downloaded altitude matrix (Table 1).

Found that the standard error on the height of SRTM model is 7.9 m (comparable with the results from (Rodríguez et al., 2005; Farr et al., 2007; Karwel at al., 2008). On the basis of the obtained value of the standard error, we can conclude that the digital model SRTM on its accuracy in the altitude corresponds to map scale and it is quite acceptable for a sub-regional spatial analysis of a relief.

In the research we used software package ENVI 4.8, which includes a large set of functions for processing of remote sensing data and their integration with GIS, it allows to describe the relief in the form of a regular DEM of the earth's surface. The initial radar image was edited, i.e. minor errors related to the disparity of elevation points of the map and model were identified and subsequently removed.

Table 1

Elevations points obtained by the map M 1: 100 000 and DEM SRTM
(the fragment of the final table, sheet N-48-142)

Geographic coordinates		Elevation points, m		Difference, m	Note
Latitude	Longitude	Map	SRTM		
52°18′59,5″	106°47′35,5″	456.5	455	1.5	Between the villages Dubinino and Oymur
52°05′44,0″	106°30′34,5″	471.5	470	1.5	Near the village Bolshoe Kolesovo
52°06′24,2″	106°41′02,1″	465.8	463	2.8	Right of the village Romanovo
52°07′24,8″	106°44′33,1″	464.1	463	1.1	Above the village Shergino
52°09′00,2″	106°36′38,3″	470.3	465	5.3	Below the village Kabansk
52°04′13,6″	106°42′56,8″	468.3	466	2.3	Left of the village Phophonovo
52°01′22,7″	106°30′40,8″	471.8	467	4.8	Left of the village Zakaltus

In the original DEM borders of the delta of the Selenga River were outlined and exploration area was determined. For the beginning of the delta we selected the bridge in the village Treskovo because the separation of the main channel of the river to numerous channels begins in this place. The boundaries of the delta were obtained in the form of a vector closed polygon, which served as a mask for the determination of the exploration area. For objective obtaining of the boundaries we used tool "Topographic Features", which is designed for the classification of the initial image to detect some forms of relief: peaks, ridges, passes (canyons), planes, channels, caves (pits). When using this tool, each pixel of DEM refers to some type of terrain. As a result, the boundaries of the delta are delineated by the altitude limit equal to 489 m, because above this value the altitude sharply increased (reach tens of meters). The square of the obtained polygon is 873.9 km^2.

In modern conditions, an important quality of the data of remote sensing of the Earth is the capability to produce three-dimensional geospatial information, advent of digital maps and plans, increasing the speed of the computer technology bring new ways to represent the terrain. The works on the topographical modeling of three-dimensional image were carried out. There is a perspective view of the delta on Fig. 1.

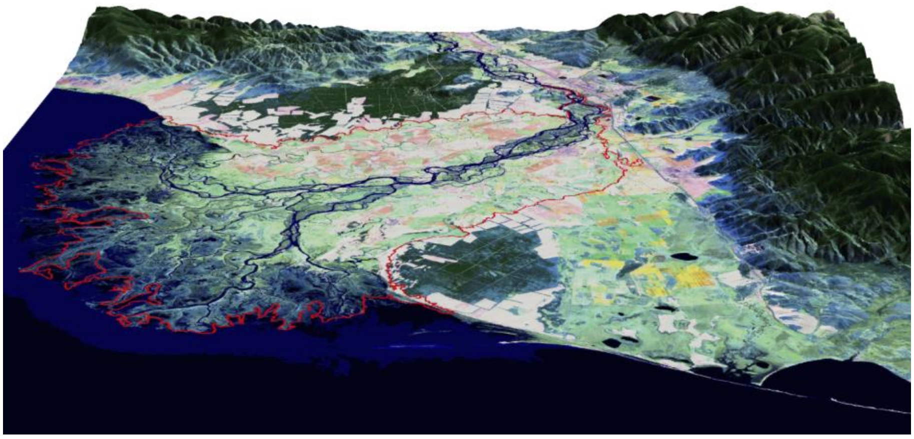

Fig. 1. Three-dimensional representation of the part of the image Landsat (picture rotated to 90 degrees counter-clockwise).
Thick red line shows the boundary of delta of the Selenga River

In contrast to the two-dimensional map, three-dimensional terrain models allow to clearly see and visually assess the shape and "plastics" of the relief and borders of geomorphological units. For greater clarity, the three-dimensional terrain model is draped by space image. 3D-model with the superimposed texture is more informative, because in addition to the information about the relief terrain features are presented on the model in details. The orthotransformed satellite imagery – a fragment of a multispectral image was used as a texture to drape three-dimensional model (Landsat-5 satellite, spectroradiometer TM, shooting date – September 8, 2010) in the form of RGB-composite in intentionally false combination of channels 7:5:3 (almost complete absorption of radiation by water in the mid-infrared band allows very clearly highlight the coastline and emphasize the water objects on the image). Partial difference in outlines of vector layer of delta front with coastlines on space image is connected to the fact that the digital elevation model obtained in February 2000, but the image of Landsat – in September, 2010.

For the first time a series of large-scale maps of key terrain indicators was built on the basis of satellite DEM for the delta of the Selenga River: hypsometric map (Fig. 2), maps of the slope degree and exposure, it allowed conduct in-depth morphometric relief analysis. For this purpose, the classification of radar images for heights, angles and orientation of the slopes was made by tools of topographic modeling that is laid in ENVI software. Areal characteristics of the delta were obtained on the above morphometric relief indicators (Table 2).

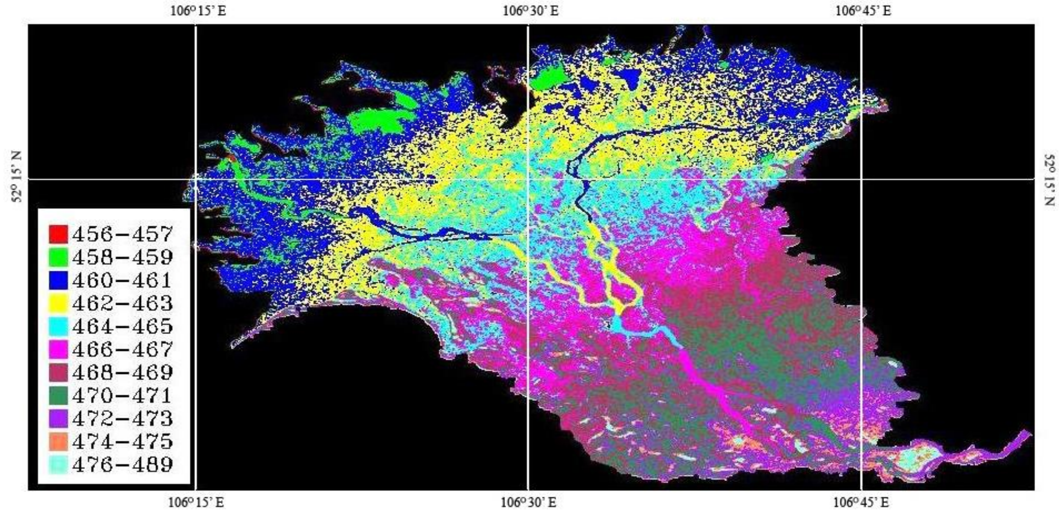

Fig. 2. Classified image on the height steps (in meters)

Table 2

Classification of surface of the delta of the Selenga River on the heights and angles of slopes

Heights, m	Square, km^2	Square, %	Angles of slope, angular degrees	Square, km^2	Square, %
456-457	5,5	0,6	0,0-1,25	650,9	74,5
458-459	37,9	4,3	1,25-2,50	172,5	19,7
460-461	162,1	18,6	2,50-3,75	34,0	3,9
462-463	166,4	19,0	3,75-5,00	9,8	1,1
464-465	109,6	12,6	5,00-6,25	3,9	0,4
466-467	92,7	10,6	6,25-7,50	1,7	0,2
468-469	109,4	12,5	7,50-8,75	0,7	0,1
470-471	103,6	11,9	8,75-10,0	0,3	0,1
472-473	56,0	6,4	**Total:**	**873,9**	**100,0**
474-475	20,6	2,4			
476-489	10,1	1,2			
Total:	**873,9**	**100,0**			

As a result of the classification it is established that the terrains with altitudes 460-471 m occupy the largest area. Created map of the slope angles shows the slope degree of large landforms and extended elements (the slopes of the river valleys, shelves, etc). Surfaces and slopes with different gradient are clearly seen on the map. The general inclination of the surfaces in the delta reaches 5°, and strongly dissected landforms with slopes of mostly 10-45° predominate on the territory of surrounding mountains.

Consequently, the digital elevation model and morphometric characteristics obtained by remote sensing methods let us make the detailed analysis of the relief of the delta of the Selenga River.

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RESULTS OF COMPREHENSIVE STUDIES OF THE SELENGA RIVER DELTA FORMATION (2003-2014)

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Abstract: The results suggest a general trend the runoff redistribution from the main channel Selenga to Lobanovsky sector of the Delta. The strong erosion occurs in the top of Delta and in the mouths. The central part of the Delta mainly in the channels of Selenginsky sector is dominated by the accumulation of erosion processes, which leads to a shallowing of the channels. Source alluvium is mostly products of, coastal erosion transported from the top of the Delta. In the peripheral part the growth of the Delta due to biogenic factor, combined with the accumulation of fine-grained sediments.

Keywords: delta, main channel, sector of the Delta, the accumulation, the erosion process

Studies of the delta of the Selenga River historically associated with the development of Siberia. One of the earliest surviving sources is "Drawing the Siberian land" I.P. Godunov (1667). Later produced descriptions delta. Selenga (S.U. Remezov, 1701; A.P. Bogoslovsky et al., 1893). One of the most comprehensive, reliable and relevant geographic and cartographic products useful for cartographic analysis is currently Atlas F.K. Drizhenko (1908).

In Soviet times, the lower reaches of the downstream territory of Selenga river investigated in the framework of the geological survey and individual scientific papers (Korytny et al., 2012; Lopatin et al., 2004; Zorin et al., 1956; Bogoyavlenskiy, 1979; Geological map…, 1965; Dynamics…, 1976). In matters of the age of the delta there is no consensus, but, nevertheless, the age is estimated at least 78-500 thousand years (Lopatin et al., 2004; Zorin et al., 1956; Bogoyavlenskiy, 1979; Geological map…, 1965).

Our research covers the surface of the modern delta, delta, including bars and limited curve of II Late Pleistocene terraces. Key events in shaping the image of the delta occurred in several stages: Earthquake in 1862, the construction of the Irkutsk hydroelectric station (1958) and the current stage of delta forming.

In recent years, the study area has expanded to Proval Bay and other shallow sors, which are separate pools of rainwater ducts delta. Experimental studies on the interaction of the Selenga River and Lake Baikal include:

1. Installation and hydrometric observations on hydrological monitoring stations (currently there are 13) and longitudinal profiling in the main channels to evaluate the flow distribution of the substance in the body of the delta.
2. Observations of coastal and fluvial erosion in key areas.
3. Description of the coastal outcrops of deltaic facies and definition of stages of accumulation of alluvium in the delta cone.
4. Grain size survey in the beds of the main channels and in the Proval Bay.
5. Complex hydromorphological work in the Proval Bay, including bathymetric survey, obtaining the surface sediment, sediment drilling, installation of sediment traps, geomorphological survey the coast.

The modern image of Selenga river delta form the hydro-meteorological conditions and over-regulated level of Lake Baikal, tectonic movements, the underlying rocks and economic activity.

Hydrological and geomorphological approach allowed doing zoning the natural features of the delta. the main hidromorpho-structural elements were defined: location of the external borders (coastline) and bars, position of the channel network and lakes of the subaerial part of the delta.

Hydromorphological parameters change in time is not even in different parts of the delta. This observation suggests the uniqueness of the processes of its formation and divide the delta into three sectors: Lobanovsky, Sredneustevsky and Selenginsky (Korytny et al., 2012). Individuality of each sector is manifested mainly in high level water periods and most humidity years, when there is global redistribution of water flow across sectors. Consequences of such events in the delta are reflected in the formation of new channels, migration of the channels, as well as changing the elevation in interarm spaces (Fig. 1).

Lobanovsky sector includes the area of relief formation channels of the same name. Sector boundary extends Bounding delta mainland coast near of Dubinino village to the mouth of channels average change. This sector has historically continued extension of the delta, the growth rate of 30-40 m/year from the boundaries of the natural position of the shoreline to the modern (2009). Manifested heredity waterfront development, as expressed in the planned straightening shape that corresponds to the position of the seismogenic alleged reset. Lobanovsky sector is confined to the area of seismotectonic subsidence from the earthquake's epicenter (Seismogeology…, 1981). The length of the coastline has been changing with the overall grow up. Limiting factor in the development of the shoreline on Lobanovsky sector can be considered modern faults. Area of the sector increased from 127 to 148 km^2, there is a slight increment of the area lakes. Lobanovsky sector since 2009 is under activation, resulting in the extension of the channel, increasing the angle of the river bed, and in the mouth area is marked infeed channel (Ilicheva et al., 2014). Over the entire period of observation channel average and new change, the flow Saharkova, became shallow, changed their configuration; merged with the flow channels Lobanovsky Dologan previously had their own importance in the distribution of flows in the sector.

The outer boundary Sredneustevsky sector is from the mouth of channels average of change to the mouth of channels Galutay (on the right bank). In tectonically sector refers to the negative morphostructure sharply differentiated neotectonic crystalline basement, with a capacity of Cenozoic sediments up to 6 thousand meters (Seismogeology…, 1981). Area of the sector is reduced from 228 to 186 km^2 with an increase in the length of the coastline. Reduction of the area is due to flooding of the delta front and education intra-deltaic lakes, which increased from 18 to 26 km^2. Bounding around the delta is dominated by the negative bias planned shoreline with a maximum of 6.5 km. Sector that was previously regarded as an area of dynamic equilibrium (Bogoyavlenskiy, 1979), but the results of our study revealed a negative trend hypsometric marks in the surface of the peripheral portion of the sector, probably due to the instability of the seismotectonic setting. Sector is characterized by the maximum amplitude of the oscillation of the absolute levels at the bifurcation, which has a high terrace remnant (460-458 m above mean sea level) and minimum marks in the mouths of canals and flooded areas. In Sredneustevsky sector channels length decreases, the slope is almost stable, and in the mouth area is dominated by accumulation, leading to siltation themselves channel and the newly formed estuaries.

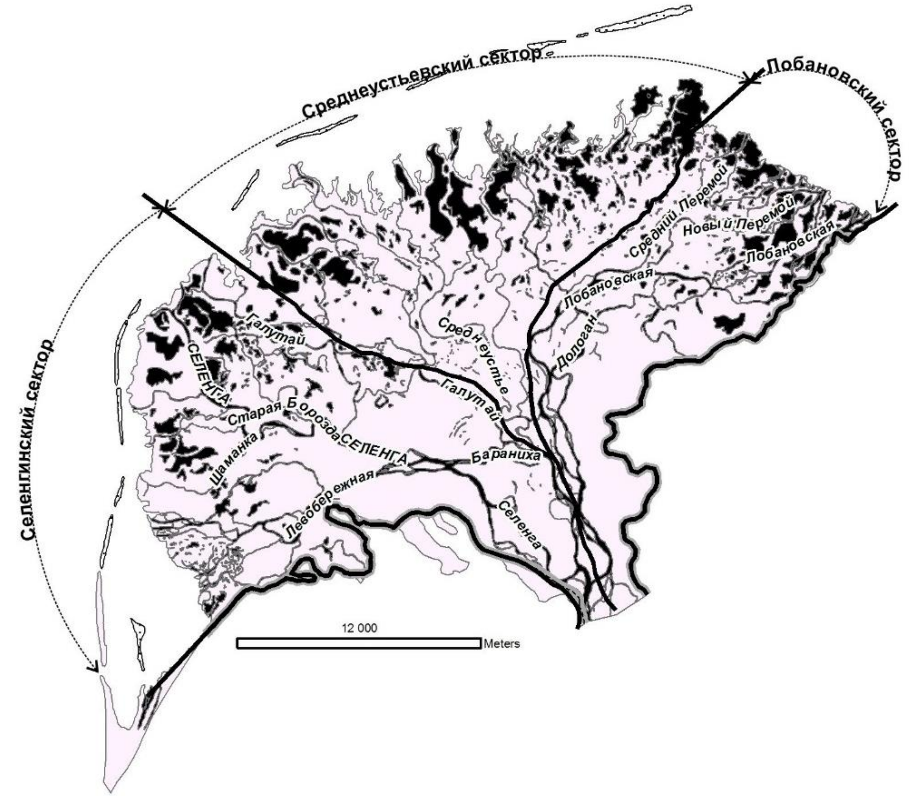

Fig. 1. Zoning of the Selenga river delta

Selenga sector occupies a plot of the delta formed by the accumulation of sediments, submitted Selenga river-bed network and limited coastline of the mainland coast in an area. Istomino to the mouth of channel Galutay. Sector is characterized by positive dynamics of the shoreline is almost all over. The maximum displacement of the shoreline is observed in the area between the rivers flow and the mainstream of the Left Bank (Kharauz), where the growth of the delta was 2 km in 100 years. The average speed of the growing is up to 10-20 m/year. By extending the shoreline sector increased its area from 207 km^2 in 1898 to 224 km^2 according to modern data. Coastline length is reduced by filling the rugged areas sediments. In sector there was a significant change in the hydrographic network: the redistribution of runoff, the emergence of new lakes and increase their total area. The dynamics of the channel network is expressed by a decrease in transit the mainstream interception drain in the newly formed channel Levobereznaya and the shoaling of the shipping channels Kharauz, has lost its meaning and plot ducts, now called Staraya Borozda (Old Furrow).

Rate analysis of coastal erosion, sediment runoff, we have created models of various hypsometric time slices allowed us to identify areas of erosion and accumulation, and to assess the stability of the surface of the sub aerial delta. In general, the time slice 1956 the average height of the surface of the delta was 457 meters above sea level. By 1986 year, the absolute elevation increased by 0.6 m, and, by 1998, an increase of 0.8 meters. It is also important to note that by 1986, the surface of the delta increased uniformly throughout the area, and by 1998 the increase marks confined to the central parts Sredneustevsky and Lobanovsky sectors. Maximum level rises after filling Baikal Irkutsk reservoir observed until 1972 year (Dynamics…, 1976). This long period has made a significant contribution to the reformation of the shores of Lake Baikal and the restructuring of the river network in the Selenga River delta As a result of long standing high levels of Lake Baikal and the high level of the water table in the delta of the Selenga River was flooding of large areas of the sub aerial part of the delta According to the latest data in this period the level reached in some periods of absolute marks 459-460 m above sea level, which corresponds to the complete flooding of the delta until the main node of bifurcation near the Maloe Kolesovo village.

Annual sediment load measurements have shown that the amount of sediment entering into the top of the delta average is 8.5 km^3, of which 3 km^3 accumulated in the central part of the delta downstream, transported 5.5 km^3, of which shall be made part of the sor to 1.5 km^3.

The calculations of sediment load during the period and the amounts of material obtained by comparing the absolute elevations of the surface of the delta by hypsometric models for various time slices in the past, we have similar values of the accumulation of alluvium: 5.5 and 5.1 km^3 per year, respectively. Modern alluvium accumulation occurs in the central part of the delta. The main volumes were created in the period from 1986 to 1998 years. By 1998, the surface of sub aerial delta has gained the greatest compartmentalization.

One of the geological evidence of the events that created the modern look of the delta, can serve as the thickness of the modern alluvium overlying soil horizon formed 1 m thick alluvium. We refer to the time of the flooding of the delta waters of Lake Baikal during the construction of hydroelectric power station and filling of reservoir. The horizon with palaeosoils commonly found in the central part of the delta. The spore-pollen analysis and dating of samples from the outcrop is carried out. Marked modern spectra throughout the section. The base section is dated by the bones of horse 420 ± 190 years.

The modern development of the delta is accompanied by a change in the parameters of the channel network, redistribution flow – both water and sediment runoff. Mobility of the channel network is most pronounced during the period of high water, and is characteristic of the high-water flow, bank erosion is largely fixed in the channels Lobanovsky sector. Significant restructuring of the channel network occurred in Selenginsky sector mostly due to Levoberezhnaya channel and flooding the southern part of the delta. Most intensively eroded banks of the Head of the delta (more than 70 m in the last 10 years) and channel Lobanovsky and Dologan (more than 3 m/year).

Delta network runoff is undergoing change every moment according to the observations in the flood in 2012 the rate of erosion of the left bank in the top of the delta was a meter or more per day. Such intensity was the same during the flood season of 2013. Left bank of the head delta were eroded about 10 meters during one month.

Products bank erosion entering the water flow, depending on the hydraulic size, can be transported over a distance of 50-500 m and form a new accumulative forms in the beds and banks of streams. Thus, the position of the channel of the river is not constant even for a short time period. The results of processing materials grain size survey a map gof the distribution channel alluvium was created. The regularity of their distribution from the main nod of bifurcation of the delta down to the mouth. In these areas, reduced size of river bed material from gravelly and sandy sediments to the silt and organic mud. Organic mud sedimentation in the peripheral part depends on the production of biomass.

Based on years of longitudinal profiling identifies the main trends of erosion and accumulation processes in the channels. Channels at the mouths erode previously accumulated material. Alluvium accumulation observed in the mainstream and channel Galutay. The fluvial erosion is dominated in other direction of river flows.

Accumulation in Harauz is permanent, in connection with which annually dredging for navigation. The deleted material can be used in the national economy.

We investigated the dynamics of the delta lakes their appearance and existence, due to channel processes, water content in the river level fluctuation of Lake Baikal and the modern tectonic processes. When uniform meteorological conditions general trend of increasing the number and area of lakes by 1998 is uneven in different sectors of the delta. Particularly flooding of peripheral part in Sredneustevsky sector, which is probably due to the lowering of the site of the delta.

The results show a general trend of flow redistribution from Selenginsky to Lobanovsky sector. There is a strong erosion in the head of delta and in mouths. The central part of the delta is mainly in the channel of the Selenga sector is dominated by the accumulation under erosion processes, which leads to a shallowing of the channel. Source channel alluvium are mainly products of bank erosion, carried from the top of the delta. In the peripheral part of the growth of the body of the delta due to biogenic factor, combined with the accumulation of fine-grained sediments.

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CURRENT STATE OF THE COAST AND DEPRESSION PROVAL BAY

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Abstract: Water depression of Proval Bay has tectonic genesis and originated in 1861-1862. This paper presents comparison of sailing directions edited since 1897-2001 years and bathymetric survey data 2011-2013 years. Obtained data show decreasing of water surface area up to 20%, displacement of beach ridges and shoreline about 1.5 km, rise of bottom elevation up to 1m. According to the dating of coastal sediments, thicknesses of modern lake sediments and sediment traps estimated average sedimentation rate, accounting on average 0.8 cm per year. The main sources of sediment are water from Lobanovskaya channel, coastal erosion and longshore sediment transport. The sedimentation rate shows Proval Bay reaches the state of modern shallow «sores» in 200 years, if we exclude the factor of new catastrophic earthquakes.
Keywords: delta, channel, sediments, deposits, bathymetric, coastal erosion, underwater bars

Proval Bay is unique in its origin. Failing phenomenon known in the coastal zone of Lake Baikal, however, so large-scale immersion of the surface was not observed. The Proval Bay in a large number of scientific and applied research (Sailing Directions…, 1898; Atlas of Lake Baikal, 1902; Atlas of Lake Baikal, 1959; Zorin, 1956; Ladokhin, 1960; Tulokhonov et al., 2006; Rogozin, 1993; Dynamics…, 1976; Bogoyavlenskiy, 1979; Baikal course…, 2009). In recent years, the work was resumed in the Proval Bay and, basically, confirmed the findings of precursors (Tulokhonov et al., 2006). As a result of the geological survey were identified fault lines, and the expected structural deformation, expressed lineaments. One such alleged nodes strains isolated in the peripheral part of the Selenga River delta, at the mouth of the channel Lobanovsky (Seismogeology…, 1981). The most modern and thorough view to failure events in the study region is represented by G.F. Ufimtsev (Ufimtsev, 2004) stating that the failure of the bay is difficult tectonic formation, which includes the horst-graben structures that led to immersion of the surface.

Our studies are carried out in the bay, and in the coastal zone. In the bay area, a detailed bathymetric survey made the selection of the surface sediment samples were obtained sediment cores obtained data on sediment traps. In the coastal zone undertaken leveling the terrain with the release of geomorphologic sites and processes described in the coastal sections.

To be able to compare and analyze data bathymetric surveys (1897, 1956, 2001 and own data echo sounding) reduced to a single coordinate system, linked to the level of Lake Baikal at the time of the shooting and brought to the Baltic system, translated into meters depth. Also evaluated the change of marks on the bottom of the three profiles. A comparison of the absolute position of the bottom marks with sailing directions 1908 and 2001. On average, the level of the bottom of the rose over the entire area of the Proval Bay of 1-1.5 m, maximizing marks confined to the mouth Lobanovsky channel and in the vicinity of Cape Oblom.

Significantly reduced the area of the Proval Bay by 20% and is now estimated at 164 km^2. Underwater bars, bordering the waters, moved a distance of about 2 km inland of the Bay coastline in the Bay Delta popped more than 1.5 km. Changed and the coastline of the Bay due to abrasion and accumulation activity waves and improve as a result of the Baikal Irkutsk hydroelectric station.

When comparing the bathymetric data revealed the amplitude of the provisions of underwater landforms. Spit and bars are moved to a distance of 300 m, depending on seasonal and annual changes in the level of Lake Baikal, and their movement inland Bay is directly related to the rise of the level.

Repeated level fluctuation is reflected in the structure of the section of beach ridges. In terms of beach ridge near Dulan village marked peat layer, the visible output of more than 1 m, covered with sand up to 1 m. Absolute elevation of the roof of the peat layer is 40 cm higher than the surface of modern swampy river valley Dulan is located in the coastal bar. The age of these deposits belong to the late Holocene and evaluated according to laboratory SPSU 200 ± 40 years (radiocarbon age). Thus, the detected horizon of peat deposits is a contemporary preexisting Tsagan steppe. According to drilling in the (2012) under the 1.0-1.2 m layer of silt opened compacted peat, presumably of the same age.

Heterogeneity of sediment deposition on the bottom of the Proval Bay (Fig. 1) shows the different types of sedimentation. Silks and fine-grained sediments are formed by the flow of delta channels and deposited in the waters area. Assorted grits and silts are confined to the central part of the bay and spread up to Cape Oblom and subsea trees. In the coastal mainland of coarse-grained sediments deposited from sand to pebbles inequigranular. The thickness of sediments in the column is 1.3 m, which corresponds to the results of the comparison data bathymetry. Main material supply water masses channel Lobanovsky because, according to the period of the experimental observations, the average volume of sediment is 0.2-1.7 million tons/year in the period of open water.

According to the sediment traps in summer 2012 sedimentation rate was 0.02-0.04 cm per day, in the summer of 2013 – 0.002-0.003 cm per day in winter turbidity of river water in the mouth of Lobanovsky channel and the Proval Bay negligible. The experimental data are fully correlated with the results of calculations of the rate of sedimentation in sediment cores. Depositional mechanism is complicated by the unrest and currents throughout the water column of the reservoir, as well as permanent displays of seismotectonic that causes precipitation seal.

The material presented a prerequisite to a discussion of possible future states of the Gulf of failure. Proval Bay will reach state of current shallow sors after 200 years in the case of modern sedimentation rates and in the absence of catastrophic earthquakes.

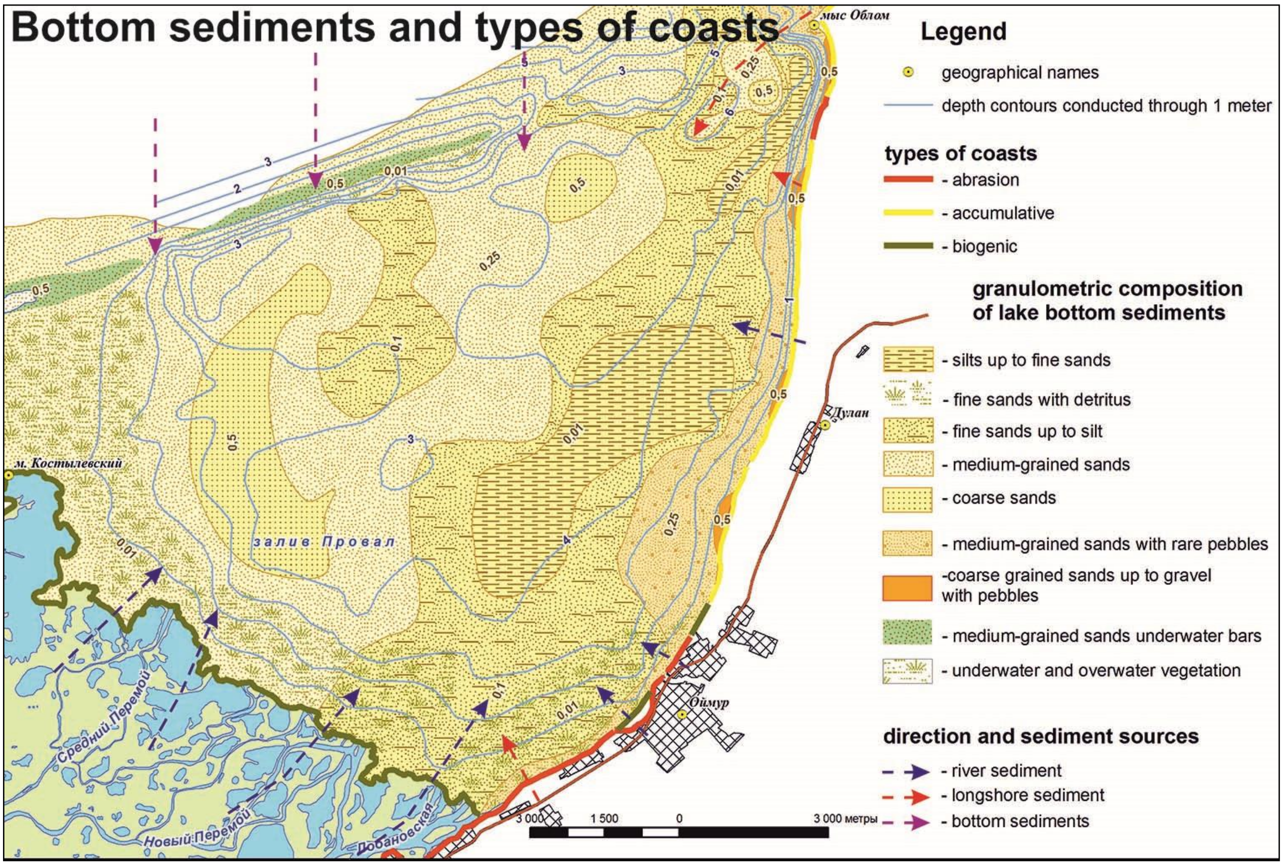

Fig. 1. Proval Bay sediments and types of coasts

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NATURAL INDICATORS OF MODERN SEISMOTECTONIC PROCESSES IN SELENGA RIVER DELTA

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Abstract: An analysis of the hydrological and geomorphological data obtained during the last 50 years discovers the natural indicators of tectonic manifestations in the Selenga river delta. Considered the position and configuration of the coastline, the dynamics of intra-deltaic lakes, changes of longitudinal profiles in the main channels. The complex of factors shows common tendency to lowering in the single parts of the Delta. Geodynamic polygons scheduled for instrumental observations.
Keywords: intra-deltaic lakes, tectonic indicators, prolong profiling, Selenga river Delta, river bed.

Selenga River Delta is the most seismic active region with intense recent movements in Baikal. Basement of the Delta deflection represented with lenticular crustal blocks, elongated in the north-east direction, which is formed by the branches of a powerful deep structure Chersky fault. One branch goes along the Selenga delta and it is accompanied by numerous seismotectonic forms of basement topography (tranches, dips, shafts), the second goes into depression and limits from the south and south-east the deltaic deflection. This area is especially dangerous in Baikal, which is most clearly evident destructive effects of earthquakes, the strength of which can be up here nine points with a local increase of up to eleven. Earthquake recurrence in the Selenga Delta is very high. Over the last century there have been many earthquakes: 1862 – X points; 1871 – IX points; 1902 – VIII points; 1903 – VIII points; 1912 – series of earthquake activity to VII points; in 1935 and 1936 – VII points; 1959 – IX points; 1959 1960's four seven-point; 1963 – VII points; 1964 – VI points; January 1967 – two VII of score. According to the geological map identifies several sources, as a result of one of them originated Proval Bay.

During hydrological and geomorphological survey in the Selenga river delta we have identified some natural indicators seismotectonic implications: forms of shoreline, fracture of the longitudinal profile in the channels and a decrease marks of the river bed, and finally, the dynamics of intra-deltaic lakes during artificial control of lake Baikal.

With the new level mode the position and the configuration of shoreline of the delta in its various parts depend on specific factors. Shoreline of Lobanovsky sector has heredity development of waterfront, as expressed like planned straightening shape that corresponds to the position of the seismogenic alleged fault. Lobanovsky sector is confined to the area of seismotectonic subsidence from the earthquake epicenters. The length of the shoreline hasn't any changes, but permanently growth. Limiting factor of the development of the shoreline in Lobanovsky sector is modern faults. The negative bias of shoreline with a maximum of 6.5 km is dominated in Sredneustevsky sector (Fig.1).

CHARACTERISTIC	YEARS				
	1898	1956	1986	1998	2007
Lobanovsky sector (north)					
Area, km^2	127,1	141,6	149,2	148,2	147,9
Area of intra-deltaic lakes, km^2		5,2	3,6	11,2	8,3
Shoreline length, km	12,71	21,24	13,41	27,53	17,78
Sredneustievsky sector (middle)					
Area, km^2	228,4	237,4	222,2	170,4	168,2
Area of intra-deltaic lakes, km^2		18,3	21,9	29,9	26,2
Shoreline length, km	56,75	62,24	74,79	88,84	102,16
Selenginsky sector (south)					
Area, km^2	207,4	225,7	230,8	216,6	223,9
Area of intra-deltaic lakes, km^2		6,2	4,1	16,1	15,8
Shoreline length, km	50,24	43,43	44,51	73,3	40,49
Delta area					
Area, km^2	562,9	604,7	602,2	535,2	558
Area of intra-deltaic lakes, km^2		29,7	29,6	57,2	50,3
Shoreline length, km	119,7	126,92	132,72	189,67	160,12

Fig. 1. Hydromorphological characteristics of delta sectors

According to a multi-year longitudinal profiling of the main channels and comparison, we observe a decrease marks in the some river beds, cutting through certain parts of the delta cone. Collected data of longitudinal profiling in different seasons allow us to determine the main trends of erosion and accumulation processes. The most significant areas are the peripheral parts of channels in Sredneustevsky sector (Kolpinnaya and Sredneustie). The average bed slope of the sector is 0.2-0.13 ‰. Bed slope decreases sharply to 0.03 ‰ five kilometers from the mouth. These changes are appeared in the last 10 years, in addition the absolute level of the river beds dropped down to the 10-30 cm (Fig. 2).

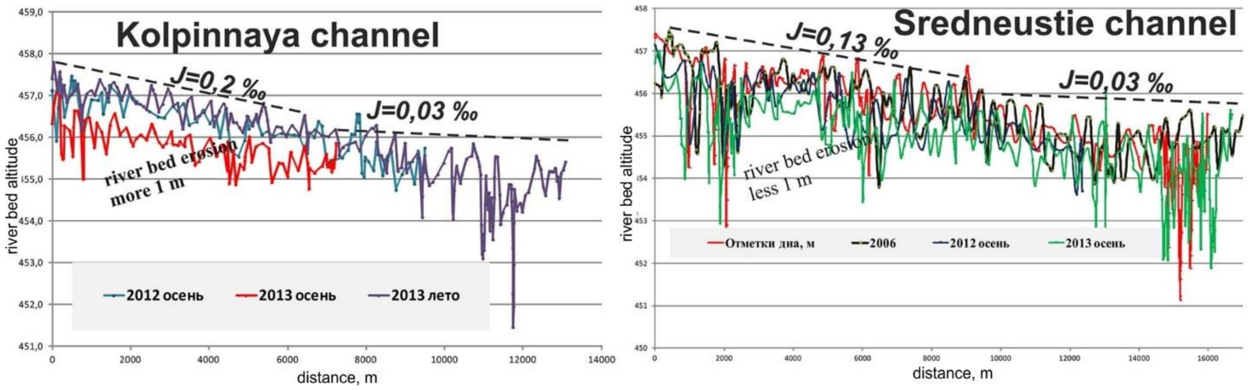
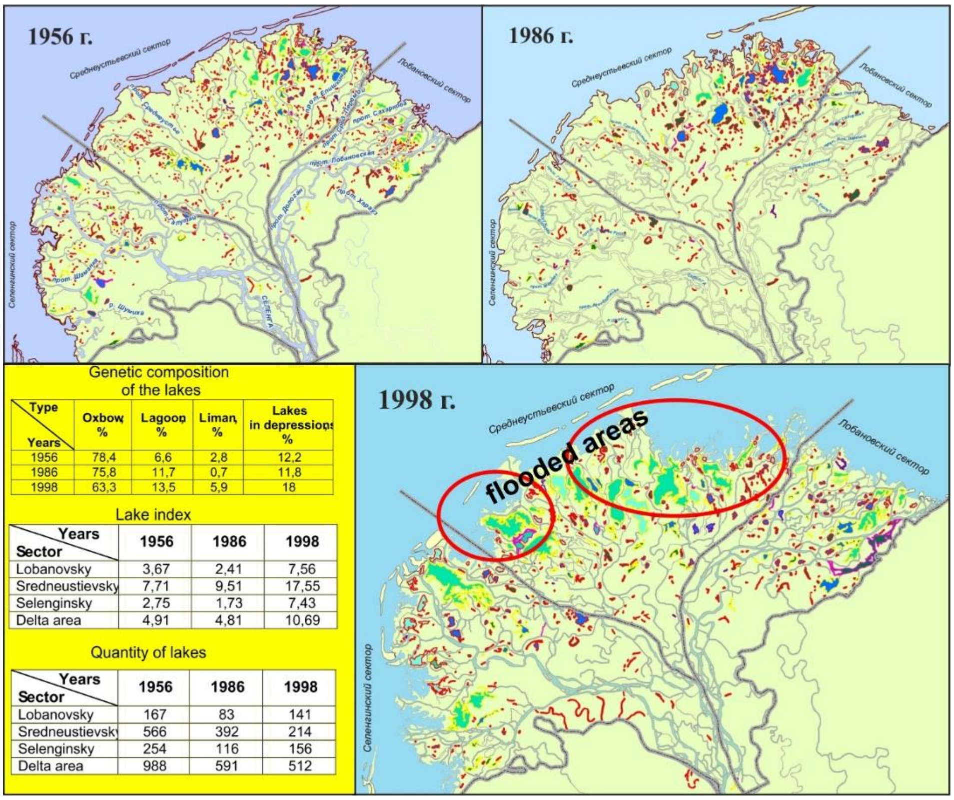


Fig. 2. Prolong profiles and river bed slope

Studies of altitude of the delta surface by the topographic maps edited since 1956 show a general decrease it up to 0.5-1 m in Sredneustevsky sector. The area of the sector is reduced during this period due to increasing intra-deltaic lakes area and negative dynamics of the shoreline. Area of coastal lakes increases up to 30-40% during last 50 years. Lakes occur when flooding mouths of pre-existing channels (Fig. 3).



Genetic composition of the lakes

Type / Years	Oxbow %	Lagoon %	Liman %	Lakes in depressions %
1956	78,4	6,6	2,8	12,2
1986	75,8	11,7	0,7	11,8
1998	63,3	13,5	5,9	18

Lake index

Sector / Years	1956	1986	1998
Lobanovsky	3,67	2,41	7,56
Sredneustievsky	7,71	9,51	17,55
Selenginsky	2,75	1,73	7,43
Delta area	4,91	4,81	10,69

Quantity of lakes

Sector / Years	1956	1986	1998
Lobanovsky	167	83	141
Sredneustievsky	566	392	214
Selenginsky	254	116	156
Delta area	988	591	512

Fig. 3. Dynamics of intra-deltaic lakes and delta shoreline

The obtained results allow considering the lowering of some parts of the delta due to compaction of sediments, and are an indicator of tectonic movements. Accuracy of the results is low and allows only determining sites for further seismotectonic measurements at the geodynamic polygons.

CONTROLS OF VEGETATION, AND SEDIMENT SUPPLY AND GRAINSIZE, ON DELTA DYNAMICS

SELENGA RIVER DELTA: LANDSCAPE, HYDROLOGICAL AND GEOMORPHOLOGICAL ANALYSIS

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Abstract: The paper discusses the features of relationships of landscape, hydrological and geomorphological processes in the Selenga river delta. The factors of water regime influence on the vegetation structure of the territory and the formation of the modern aspect of the delta are revealed.
Keywords: water catchments, landscape, water return, the formation of runoff, morphological characteristics.

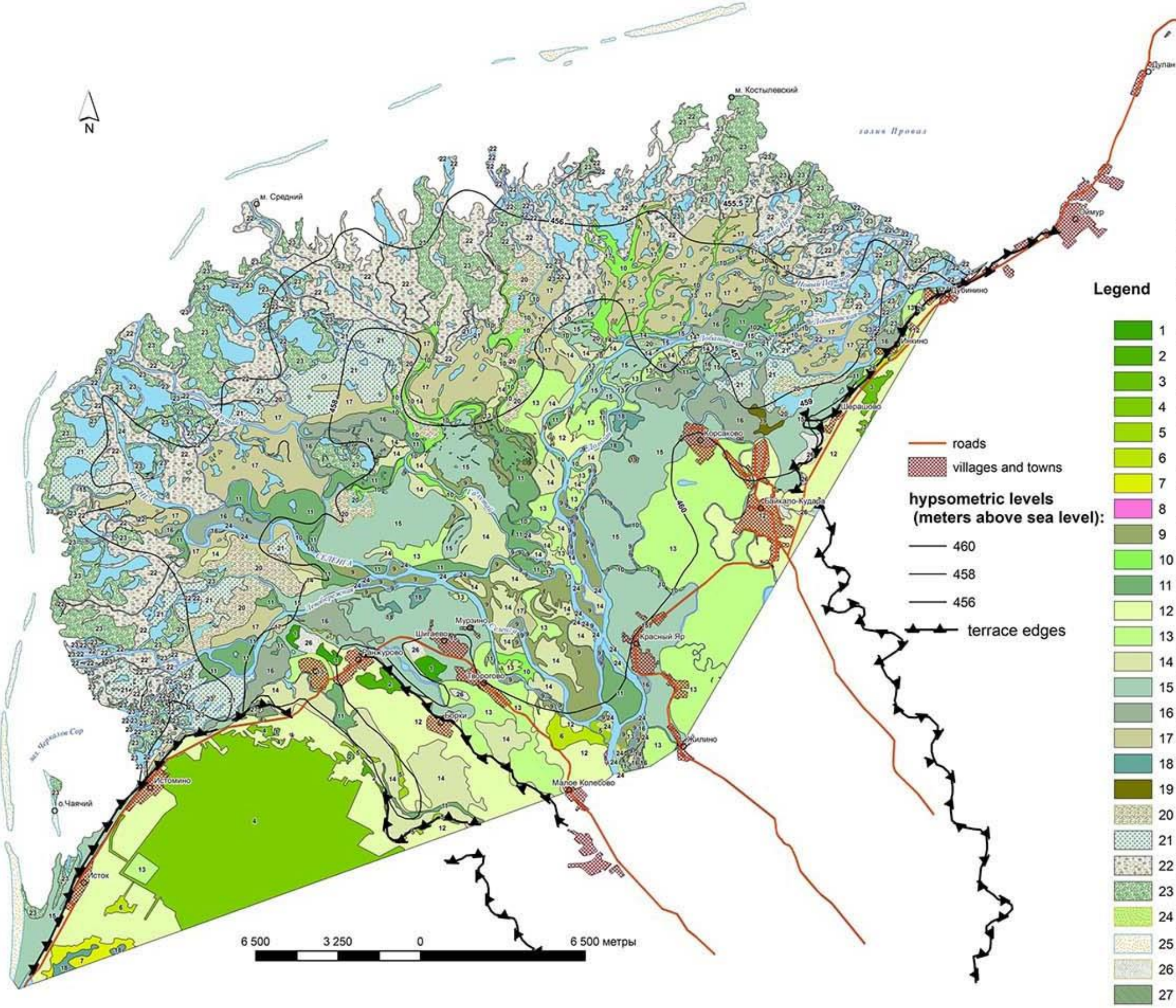
The Selenga river delta has a well developed river network, the formation of which began in the Jurassic period and is currently in progress. Several large distributaries, namely, the Main channel (Kharauz), Levoberezhnaya, Galutai, Sredneustie, Kolpinnaya, Lobanovskaya, and Dologan, are combined with many small distributaries, dead channels, lakes and bogs. Elevations in the delta region range from 455.5 to 460 m. The maximum altitude difference of 3.5 m is confined to the terraces, which are located at the head of the delta and along the sides of the delta deflection. The Selenga delta is an active tectonic area, which, along with the exogenous processes, leads to the development of geosystems of the territory.

Formation and transformation of landscapes of the delta are dependent on geomorphological and hydrological processes, the long-term study of which has revealed direct interrelations between the water regime and changes in landscapes. The delta surface is under the constant influence of fluvial, erosion and accumulation processes, which, in combination with different variations of flooding, waterlogging, etc., create conditions of reorganization of natural complexes. A comparative analysis of studies over 10 years shows significant changes in plane, altitude and structural characteristics of landscapes (Konovalova, 2010; Environmentally oriented…, 2002). We succeeded in distinguishing landscape-hydrological-geomorphological regions in accordance with modern transformations. The structure of vegetation and hypsometric location of landscapes (Atutova, 2013), and the stages of development of the channel network and morphological characteristics (Fig. 1) were selected as the main features for zoning.

The first region from the head of the delta corresponds to the most ancient geomorphological level with elevation marks above 460 m, and is represented by the surfaces of terraces (Fofanovskaya and Kudarinskaya) and their remnants, composed of alluvial deposits of Middle and Late Pleistocene. Here, on weakly-undulating surfaces, unique ancient steppes have survived (Vinogradov, 1997), and pine woods and small-leaved forests are present. In the process of formation of the modern aspect of the delta, this territory acts as a supplier of sediments, generated as a result of exogenous processes (weathering, areal water erosion) and direct erosion of steep river banks. Thus, modern landscapes of the delta are being formed below this level, limited by the edge of the second terrace above the floodplain, but under the direct influence of this territory. This region fulfils a serious environment-forming function, in terms of both landscape and hydrological processes. From the ecological standpoint, the nature of this region is very susceptible to anthropogenic impacts, however, hayfields, arable lands and cutover areas are almost ubiquitous.

On the lower (460-459 m) geomorphological level the most part of the delta area is presented by valley complexes of three main distributaries: Krasnoyarovskaya, Tvorogovskaya and Galutai. The area is characterized by the flow-through moisture regime, and water runoff here has predominantly an intra-riverbed character. Flooding and underflooding are rare, which contributes to free development of tree, shrub and grass communities. Forb-grass meadows in combination with shrubs mainly on alluvial well-drained soils are a relatively stable structure in relation to the hydrological processes and may be of interest for recreational development.

Downstream, in the range of altitudes of 458-456 m, intense runoff dissipation in the multi-channel network takes place. It is an area of water meadows and bogs with overmoistening and a contact of ground and surface waters. Water bodies are characterized by small surface slopes and backwater from Lake Baikal. Meadow-bog communities of this territory are of particular water protection and flow control value, especially with respect to saline ground waters and runoff, brought by the main river and saturated with pollutants.



Number in the legend	Geomorphological levels / Facies group	Surfaces of Middle to late Pleistocene fluvial terraces (over than 460 m)	Surface of Terraces above the Flood-plain (458 to 460 m)	Flood-plain (456 to 458 m)	Delta front and surfaces of spurs and rock ledges (455.5 to 456 m)	Footprint area (%)
Forest – 8.85%						
1	Pine forests	■				0,23
2	Pine forest with undergrowth	■				0,21
3	Pine forest with underbrush, mixed herbs	■				0,18
4	Pine forest with birch, brush and herbs	■				7,35
5	Pine forest and parvifoliate with brushwood	■	■			0,19
6	birch and aspen-birch(parvifoliate) with singular pines, mixed herbs	■	■			0,36
7	Parvifoliate forests	■				0,31
8	Apple (wild), briar and spiraea areas	■	■	■		0,01
Bushes – 8.4%						
9	Willow and bushes on isolated hills and watersheds between river arms		■	■		2,72
10	Osier bed in flood-plains		■			1,99
11	Bushes with moistured sedge and mixed herbs in topographic low		■			3,69
Grasslands – 50.22%						
12	Steppificated mixed herbs and gramined meadows	■	■			10,55
13	meadows with mixed herbs	■	■			9,26
14	mixed herbs with light underbrush	■	■			5,90
15	mixed herbs and gramineous meadows in combination with sedge and grass bogs		■			12,38
16	Sedge and rush haughlands		■	■		3,67
17	Sedge and reed meadow bogs			■		8,47
Meadow bogs -30.57%						
18	Grass bogs	■	■			0,36
19	muskeg swamp in topographic low		■	■		0,10
20	Hummocky plots on drained areas			■		2,71
21	Sedge and horsetail and grass wetlands			■		4,33
22	Rush and reed along mud Banks of creeks and soundings			■		14,45
23	Water vegetation in overgrown sors and soundings – hydrophytes and hydatophytes			■	■	8,62
Weakly defined in scale – 1.96%						
24	Vegetation of spurs, braid bars and wave built shores		■	■	■	0,18
25	Vegetation of underwater bars				■	1,28
26	Weakly sodded slopes rarely with pines high terraces and isolated hills	■				0,42
27	Forest plantation	■				0,07

Fig. 1. The distribution map of groups of facies in the Selenga river delta

The outermost peripheral zone of the delta and delta front, limited by underwater bars, is shallow waters with depths of 0.4-1 m. Here, along the outer edge of the delta and on the surface of lakes hydrophytes are ubiquitous, creating conditions for the delta growth due to the accumulation of river sediments and the die-off of biomass.

Of particular interest is the formation of vegetation on channel mesoforms, which are conventional forms. Vegetation of midstream sandbanks, bars and beaches is represented by willow shrub formations, the occurrence of which takes place within one growing season. Gradual expansion of such thickets leads to sodding and strengthening of bars, shoals and banks of watercourses, which prevents their further erosion and creates certain directions in the channel process and plane rearrangement of the river network. In our view, vegetation of channel forms is an indicator of certain hydromorphological processes and can serve as a starting point in determining periods of reformation (age) of the delta surface. The opportunity to study this process in the Selenga river delta is considered by us to be a promising direction of work.

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MAP CREATION SERVICE FOR MODELLING OF THE DELTAIC AREAS OF THE COAST OF LAKE BAIKAL

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Abstract: The report considers the mechanism of creating geo-information resources for interdisciplinary research of the deltaic areas. It discloses the working methods of vector data storage and suggests practical examples of automated and interactive work. The map service for investigation of the deltaic areas of the coast of Lake Baikal is represented in the report.
Keywords: coast of Lake Baikal, deltaic areas, geoinformation resources, GIS, map service

An important task of information support of an integrated research infrastructure is spatially distributed data and the introduction of modern information and communication technologies that enable efficient search and access to the distributed geographic information resources (GIR).

The need for a comprehensive study and evaluation of precise geometric deltaic geosystems is due to the important role of these areas of the earth as a natural biofilter and mechanical barriers to the migration of the products of human activities in Lake Baikal. Moreover, the largest deltaic areas are important in life of the local population and are a major source of natural resources. Under the conditions of informatization of the territorial activity, creation of geo-information resources of the deltaic geosystems and providing access to their repositories improve the efficiency of research of these areas and contribute to the unification of efforts of the international community to study Lake Baikal.

In order to optimize interdisciplinary research of the deltaic geosystems, specialists of BINM SB RAS developed and implemented in detail-oriented GIS, which is a software-controlled complex of recording and modeling of the dynamics of natural and socio-economic institutions and processes. The objects of study are the deltaic areas of the largest and economically important rivers flowing into Lake Baikal (21 deltaic areas). The main analytical functions of GIS are geometric and overlay operations, the selection of objects on request, aggregation of data, construction of buffer zones and network analysis. GIS meets all systems open to complement any geodata methodologically simple and controllable, which implies the possibility of creating different types and the subject of maps and geographic information requests. The technological realization of GIS can reliably assess qualitative and quantitative changes in the deltaic landscape, identify and investigate the structure of spatial and temporal trends of their dynamics, capture the positive and negative aspects of the transformation of nature and formulate recommendations for the optimization of the territorial activities.

Implementation of GIS is carried out on three levels of scale. Regional level (1:1 000 000) reveals the external socio-economic and natural communication of the deltaic areas in the aggregate peer geosystems (climate, air transport, etc.). Local level (1:200 000–1:500 000) provides the mapping system of nature management and landscape types, and describes physical-geographical and socio-economic conditions of the deltaic region as a single natural-economic complex. Object level (1:50 000–1:100 000) shows the relationship between the economic infrastructure and natural geosystems and provides an estimate of the territory within the tract, and allows to monitor specific natural and socio-economic facilities.

When organizing interdisciplinary research of geosystems and nature management, the most popular include the basic spatial data – digital and raster topographic maps, plans, satellite imagery. Geographic information resources based on these materials are metric model of physiographic condition of the territory and are legitimate electronic documents. Mapping the shore of the lake created 21 electronic topographic maps (ETM) of the deltaic areas on a scale of 1: 100 000, in accordance with GOST R 52293-2004. Each ETM has been formed in the draft format *mxd* Arc GIS environment, representing a set of vector layers (*shp*-files), and attribute tables (*dbf*-table). In addition, to each ETM binding scene RSD Landsat is performed.

For aggregation of thematic information was created repository vector data storage. Each vault is formed from the combination of thematic layers on natural and socio-economic conditions of the area and is an integrated vector coverage and a relational database. For each attribute of the coating *avl*-legend is designed, which allows instant visualization of geodata. The modeling technique of vector data is a set of sequential operations of the software environment, which involves the formation of a plurality of map representations, which vary only elements of the content and methods of cartographic representation of objects, but the integrity and topological connectivity datasets is saved and does not depend on their combination. Application of this approach provides a topological data integrity and ease of use of any reconversion, both in interactive and automatic mode, according to the algorithm (Fig. 1).

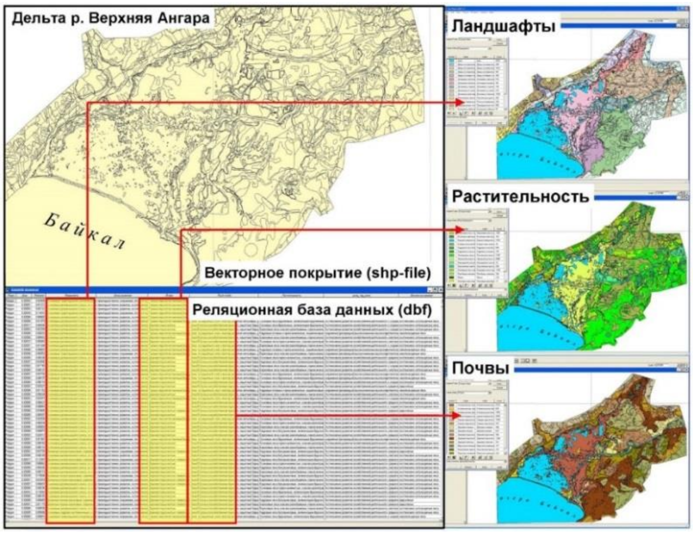

Fig. 1. An example of an automated work with the vector storage

Such controlled mapping optimizes solution of the traditional problems associated with the choice of the mathematical framework and maps montage, allows to change projections quickly, free scaling, providing new visual means and algorithms of automatic generalization, as for drafting and design of the maps, preparation for publication are implemented on a single workstation. An important mechanism for modeling is interactive work with the GIS through geo-information requests generated by the user and corresponding to the specified substantial and topological criteria. For example, on the basis of interpretation of the satellite imagery Landsat was established maximum flood zone on the river Selenga and the corresponding vector layer was put into storage. When prompted «Estimate agricultural damage Kabansky area from flooding on the river Selenga», the first step is to select the layers to simulate (farmland and flood zone). Then the topological relationship between these layers is set and an automated metric evaluation of the formed polygons is performed. This creates a new layer, which records spatial and quantitative status of the simulated phenomena (in this case, the flooded farmland) (Fig. 2).

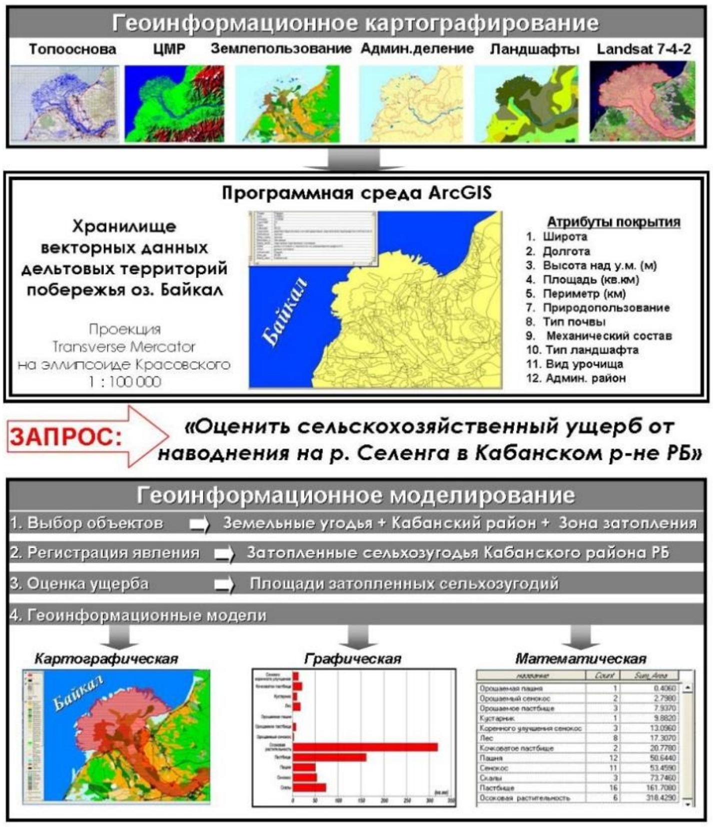

Fig. 2 An example of an interactive work with the vector storage

Access to the materials of the GIS of the deltaic areas of Lake Baikal coast is organized through the geo-portal ISDCT SB RAS www.geos.icc.ru, as well as by means of the cartographic Atlas «River deltas of Lake Baikal» (www.deltagis.info) (Fig. 3). This map service is an integral cartographic work, organized in the Internet as a collection of geo-information arrays describing the deltaic areas of the largest rivers of Lake Baikal. The thematic content of the Atlas is a collection of geo-information arrays description of the deltaic areas (21 arrays). Each geo-information array is structured on the headings:

– Mapping project of the scale 1:100 000;
– Vector layers (*shp*-files) and dbf-tables;
– Satellite scene Landsat (binding to the project);
– Electronic map scale 1:100 000;
– Three-dimensional terrain models based on the Landsat-scenes;
– Descriptions;
– Photos.

Fig. 3 Home page of the atlas

According to the spatial coverage atlas is a regional document because it covers a large area of the Baikal region. According to the content, the atlas is comprehensive because it contains maps of an interrelated phenomenon and captures differently-native options of the displayed territory (natural and socio-economic characteristics). For its intended purpose the atlas is of wide use and can be applied as for reference purposes, because it allows you to get a general and a comprehensive view of the state of the deltaic landscape, and can also serve as a metric tool for the scientific study of the dynamics of modern geographical environment and monitoring of the regional nature. According to the technological solution, the Atlas is a telecommunications-and-information system that publishes relevant and reliable information on the declared category, and is implemented in the content management system Bitrix 5.0 with an access to the standard HTTP-protocol and operates on a single database and a common information exchange standards. Access to the documents may be performed through the home page, through a column, or by searching.

This map service provides reliable service for users with geographic information resources, problem-oriented comprehensive assessment and monitoring of the physical-geographical and economic state of the deltaic areas. Metadata for the information resources description is consistent with international data circuits.

The developed technique of the GIS-atlas creating allowed to optimize the organization of similar technology telecommunication products, to determine the features of necessary technological support and software to identify and minimize the problem of information security and technological sustainability of the software and hardware complex, and network resources.

The creation of the telecommunication nodes and providing access to the geographic information resources provides the reliability and efficiency of interdisciplinary research and information sharing with the international community about the results of scientific research of Lake Baikal, and also contribute to the formation of regional infrastructure of scientific spatial data.

SELECTIVE METHODOLOGY OF BEDLOAD DISCHARGE CALCULATIONS IN RIVERS

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Introduction

The problem of bedload calculation is one of the most important and difficult issues in the theory of channel processes which so far have not found a satisfactory solution. To date several hundreds of formulae are created but in practice they produce results differing in tens, hundreds and more times. Hence today the calculation accuracy of 1.5-2 times is considered satisfactory.

The reasons of the poor statement of this problem are discussed in details in the paper of Z.D. Kopaliani and A.A. Kostyuchenko (Kopaliani, Kostyuchenko, 2004). To the main sources of low accuracy of bedload calculations can be attributed inconsistency of terminology (what exactly should be regarded as bedload and incipient motion), low accuracy and narrowness of field measurements, insufficient account of the forms of bedload transport and bed material composition, river size and so on.

To solve the problem of bedload calculation in rivers we use the selective methodology. It is founded on the fact that character of bedload transport in nature varies greatly depending on river size, its hydrological and hydraulic regimes, basin relief and bed material composition. Depending on hydrological conditions and current composition of the bed the bedload movement can occur in structural form (as dunes) as well as nonstructural form in the same river. Every case requires special consideration.

Within this approach we have divided bedload transport into the following types:

- bedload transport in plain rivers, almost always in the form of dunes ($\frac{H}{d} > 30$, $\frac{V}{V_0} < 2.5 \ldots 3$). Here H – flow depth, d – sediment diameter, V, V_0 – flow velocity and particles entrainment velocity;
- bedload transport in mountain-piedmont rivers:
  - in structural (dune) form:
    - with bed material composition close to uniform ($\frac{d_{90}}{d_{10}} \leq 4$): $\frac{H}{d_{90}} > 15 \ldots 17$, $\frac{V}{V_0} < 4 \ldots 6$
    - with heterogeneous sediments – $\frac{H}{d} > 30$, $\frac{V}{V_0} < 4 \ldots 6$.
  - in non-structural form: $\frac{H}{d} < 30$.

For each type of bedload transport were selected reliable from our point of view data sets and performed comparison of the collected formulae separately for each type of sediments motion.

In this article dune transport mode of sediments in plain rivers and nonstructural transport in mountain rivers are considered.

Plain rivers

Bedload transport in plain rivers has some peculiarities:

- bedload movement in steady flow occurs mainly in the form of dunes;
- particle size distribution is relatively uniform so it is appropriate to use weighted average diameter d.

Dunes are the microforms of river channel. They represent low-inertia sand formations on the flow bottom. Dunes are comparable with flow depth and determine bottom roughness, hydraulic resistance to flow, vertical fluctuations of the bottom and bedload. They are generated by macro scale turbulent eddies, the length of which regardless of the flow size and flow regime varies from 2 to 10 flow depths and averages $6{,}5H$. That's why the length of dune is average $6.5H$. Dunes have the greatest stability in comparison with other dune forms of smaller scale – ripples, which exist in narrow range of hydraulic conditions in the initiation stage of sediment motion.

The bed load per unit channel width in dunes motion is calculated by the formula:

$$q_s = \alpha h_d C_d \tag{1}$$

where q_s – bed load per unit channel width in bulk volume units,
α – a coefficient of the form of the dune on average amounting 0.6,
h_d – the height of the dune,
C_d – the velocity of sand dunes motion.

Thus in dune form of sediment motion having reliable formulae for sand dunes height h_d and dunes motion velocity C_d we can calculate bedload discharge.

Under this type of bedload transport the set of data collected by the Channel Processes Department of the State Hydrological Institute (SHI) served the basis for formulae comparison. It was formed during many years expeditions to large, small and middle-sized plain rivers of the USSR. The data set consists of 200 measurements. All the data were obtained by unified method of repeated longitudinal eco-sounding of river channel with fixation of geometrical and dynamical characteristics of steady profile dunes with steady hydraulic characteristics of the flow. The data of sand dunes height and velocity measurements are not averaged characteristics at the site of eco-sounding but data of specific dunes of steady profile geometrical (height, length) and dynamical (velocity of motion) characteristics of which during the measurements stay constant. Hydraulic and morphometric characteristics of the data are presented in the Table 1.

Table 1

Range of the hydraulic characteristics of flow and sand dunes in the field studies of the SHI

Characteristics	Range of variation			
	Large rivers (105 measurements)		Small and middle-size rivers (95 measurements)	
	min	max	min	max
Depth of flow H, m	2.90	13.7	0.20	5.40
Velocity of flow V, m/s	0.72	2.10	0.45	1.76
Grain size of sediments d, mm	0.30	2.90	0.26	7.50
Height of sand dunes h_d, m	0.31	1.75	0.0145	1.00
Length of sand dunes l_d, m	15.0	120	0.79	21.0
Propagation velocity of sand dunes C_d, m/day	0.96	55.0	12.0	146
Froude number $Fr = \frac{V}{\sqrt{gH}}$	0.09	0.19	0.13	0.50
Velocity of flow in initial motion of particles V_0, m/s	0.55	0.96	0.37	0.87
H/d	3897	38571	144	8269
h_d/H	0.07	0.20	0.07	0.54
h_d/d	328	4861	10,1	3704
l_d/H	1.43	8.33	0.89	11.1
V/V_0	1.25	2.78	1.16	3.18
C_d/V	0.00001	0.00035	0.00012	0.00291

50 formulae were analyzed: 18 – for sand dunes height, 32 – for velocity of sand dunes. 15 formulae for velocity of sand dunes are inapplicable in practice because the authors didn't comment all the variables. Formulae were compared by calculation of the relative error ($\Delta = \frac{|h_{d_{calc}} - h_{d_{meas}}|}{h_{d_{meas}}} 100\%$, the same for velocity of sand dunes). As a result of comparison 6 formulae for sand dunes height and 7 formulae for sand dunes velocity were selected.

Comparison of bed load formulae were done for two situations: when data for height of sand dunes are available and when they are absent. The first version assumes multiplying the dune form coefficient 0,6 by measured value of sand dunes height and calculated value of sand dunes velocity. The second one assumes that both values (height and velocity) are calculated.

Basing on the analyses the following recommendations were developed.

Bedload for **large plain rivers** when *sand dunes height data are available* should be calculated by the following formulae (error 42-51%) (Samokhvalova, 2012):

- Dou Guo-Zhen (1960): $C_d = 0.26 \frac{d}{H} (V - V_0) \frac{V^2}{{V_0}^2}$;
- O.M. Kondap, R.J. Garde (1973): $C_d = 0.021 V Fr^3$;
- Z.D. Kopaliani (1989): $C_d = 0.009 V \left(\frac{V}{V_0}\right)^2 \left(\frac{h_d}{d}\right)^{-0.8}$;

- B.F. Snishchenko, Z.D. Kopaliani (1978): $C_d = 0.019VFr^3$.

Bedload for **small and middle-sized plain rivers** when *sand dunes height data are available* should be calculated by the following formulae (error 42-50%):

- O.M. Kondap, R.J. Garde (1973): $C_d = 0.021VFr^3$;
- Z.D. Kopaliani (1989): $C_d = 0.009V\left(\frac{V}{V_0}\right)^2\left(\frac{h_d}{d}\right)^{-0.8}$;
- B.F. Snishchenko, Z.D. Kopaliani (1978): $C_d = 0.019VFr^3$;
- T. Tsubaki, T. Kawasumi, T. Yasutomi (1953) (Samokhvalova, 2012): $C_d = 7.03\frac{I\sqrt{gd}}{\sqrt{\frac{\gamma_T-\gamma}{\gamma}}}$.

Bedload for **large plain rivers** when *sand dunes height data are absent* should be calculated by the following formulae (error 43-50%):

- Combination formula for sand dunes velocity by Z.D. Kopaliani (1989): $C_d = 0.009V\left(\frac{V}{V_0}\right)^2\left(\frac{h_d}{d}\right)^{-0.8}$ – with formulae for sand dunes height by:
  - Z.D. Kopaliani (1989) (Samokhvalova, 2012): $h_d = 0.39d\left(\frac{V}{V_0}\right)^{2.5}Fr^{-3.75}$;
  - Z.D. Kopaliani and A.A. Kostyuchenko (2004) (Samokhvalova, 2012): $h_d = 0.13H$;
  - O.A. Samokhvalova (2011) (Samokhvalova, 2012): $h_d = 0.11H$;
  - B.F. Snishchenko (1980) (Samokhvalova, 2012): $h_d = 0.25H$ when $H \leq 1$ м, $h_d = 0.2 + 0.1H$ when $H > 1$ m;
  - B.F. Snishchenko, Z.D. Kopaliani (1989) (Samokhvalova, 2012): $h_d = 2.1\frac{d}{Fr^{4.1}}\left(\frac{V-V_0}{V_0}\right)^{1.4}$.
- Combination formula for sand dunes velocity by B.F. Snishchenko, Z.D. Kopaliani (1978): $C_d = 0.019VFr^3$ – with formula for sand dunes height by Z.D. Kopaliani (1989): $h_d = 0.39d\left(\frac{V}{V_0}\right)^{2.5}Fr^{-3.75}$.

Bedload for **small and middle-sized plain rivers** when *sand dunes height data are absent* should be calculated by the following formulae (error 49-50%):

- Combination formula for sand dunes velocity by Z.D. Kopaliani (1989): $C_d = 0.009V\left(\frac{V}{V_0}\right)^2\left(\frac{h_d}{d}\right)^{-0.8}$ – with formulae for sand dunes height by:
  - Z.D. Kopaliani and A.A. Kostyuchenko (2004): $h_d = 0.13H$;
  - O.A. Samokhvalova (2011): $h_d = 0.11H$;
  - B.F. Snishchenko (1980): $h_d = 0.25H$ when $H \leq 1$ m, $h_d = 0.2 + 0.1H$ when $H > 1$ m.
- Combination formula for sand dunes velocity by B.F. Snishchenko, Z.D. Kopaliani (1978): $C_d = 0.019VFr^3$ – with formula for sand dunes height by B.F. Snishchenko (1980): $h_d = 0{,}25H$ when $H \leq 1$ м, $h_d = 0.2 + 0.1H$ when $H > 1$ m.

Mountain rivers

Bedload transport in mountain rivers has its own peculiarities:

- bedload transport occurs only in periods of high water (flood, floods) and not throughout a year as in plain rivers;
- grain size distribution of mountain rivers is heterogeneous therefore different fractions of sediments don't start motion at the same time;
- bedload in mountain river in mean water period is extremely low and can't be measured during the floods (flow velocities reach 8 m/s, floods are difficult to predict and often occur at night);
- the most reliable method of bedload assessment in mountain rivers today is its physical modeling especially because mountain stream can be reproduced in laboratory with compliance of its geometric, kinematic and dynamic similarity and without distortion of granular roughness. Also laboratory allows to reproduce flood wave and measure granulometric composition and bedload on every step of the flood.

In this work we assessed accuracy of 84 formulae not taking in account the form of bedload transport.

The source material was composed of the data of two experiments carried out on purpose of comparing formulae in the Channel Laboratory of the SHI. Two sites of the river Mzymta (Black Sea coast of the North Caucasus) were taken as prototypes. The calculations were carried out for natural conditions in the scale of 1:55. Both experiments modeled flood rises. In the first experiment granulometric composition was heterogeneous ($\frac{d_{90}}{d_{10}} = 29$), in the second – uniform ($\frac{d_{90}}{d_{10}} = 2$). The conditions of the second experiment belong to the case after pavement breakdown when smaller particles have already been washed out by the previous weaker flood. In Table 2 the range of hydraulic characteristics of the experiments are presented. On Fig. 1 the integral curves of particle size distributions of both experiments and the parameters of granulometric composition are presented.

Table 2

The range of the hydraulic characteristics of the flow and bedload in laboratory modeling of nonstructural transport of bedload

Characteristics	Range of variation			
	First experiment (7 flood stages)		Second experiment (6 flood stages)	
	I stage	VII stage	I stage	VI stage
Depth of flow H, m	0.66	2.64	0.83	2.48
Velocity of flow V, m/s	1.49	5.20	2.38	5.55
Froude number $Fr = \frac{V}{\sqrt{gH}}$	0.58	1.02	0.84	1.13
Water discharge Q, m^3/s	11.2	157.0	22.4	157.0
Water discharge per unit channel width q, m^3/s/m	0.97	13.60	1.94	13.60
Volumetric bedload discharge Q_s, m^3/s	0.0001	0.4178	0.0021	0.3945
Volumetric bedload discharge per unit channel width q_s, m^3/s/m	0.000012	0.036176	0.000180	0.034153
Mass bedload discharge Q_s, kg/s	0.36	1107.27	2.60	603.53
Mass bedload discharge per unit channel width q_s, kg/s/m	0.03	95.87	0.22	52.25
Volume concentration $\frac{Q_s}{Q}$, m^3/m^3	0.0000	0.0041	0.0001	0.0025
Mass concentration $\frac{Q_s}{Q}$, kg/m^3	0.03	7.05	0.12	3.84
Bulk density of sediment ρ_s, kg/m^3	1438	1700	1250	1530

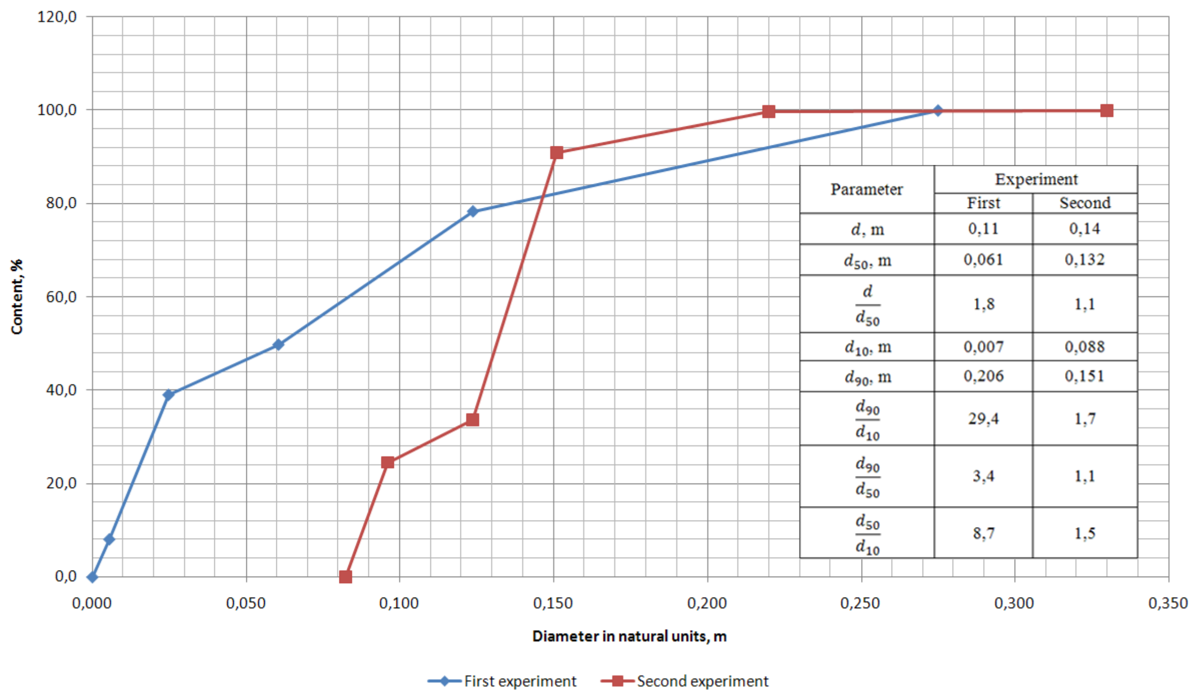

Fig. 1. Integral curves of particle size distributions of the first and second experiments with the parameters of granulometric composition

Formulae not taking in account the form of bedload transport by structure used in this study can be divided into several groups:

1. Incipient motion approach. Options of the criterion are follows:
   - critical flow velocity $q_s = f(V_0)$ – 18 formulae,
   - critical water discharge $q_s = f(q_0)$ – 7 formulae,
   - critical non-dimensional shear stress at the bottom of the flow $q_{\text{т}} = f(\theta_0)$ – 34 formulae,
   - critical energy slope $q_s = f(I_0)$ – 1 formula.
2. Probabilistic approach $q_s = f(P)$ – 4 formulae.
3. Equal mobility approach – 1 formula.
4. Regression approach $q_{\text{т}} = f(x,\ y,\ \dots)$ – 19 formulae.

Distinctions of our approach to the bedload formulae intercomparison in contrast to the previous works are as follows:

- Particular values of calculation accuracy were compared for every stage of the floods characterized specific granulometric composition and specific degree of sediment involvement in movement.
- The calculations were done for two variants of granulometric composition accounting bedload composition on every flood stage and the bed material composition.
- Special attention is paid to granulometric composition accounting methods used by different authors and critical values of non-dimensional shear stress. All the formulae used non-dimensional criterion of Shields and non-dimensional Einstein function were analyzed in several variants. As a characteristic of granulometric composition we took weighted average diameter d and median value d_{50} as well as other value if it was proposed by the author (for example d_{35} by Einstein). It turned out that in the situation of heterogeneous composition the difference between θ calculated by d and d_{50} can amount 2 times and more hence it is overestimated or underestimated 2 times. Critical values of non-dimensional shear stress were used as follows: θ_0 – by author (if he/she proposed his/hers), 0.06 – by Shields and 0.03 – by Kopaliani. The calculations showed that critical value of non-dimensional shear stress θ_0 proposed by Shields for our situation of mountain river is overstated.

5928 calculations of bedload were performed. Accuracy of the formulae was estimated using the following criterion: $\Delta = \frac{q_{s_{calc}}}{q_{s_{meas}}}$. The interval of permissible accuracy we took as the range of $0.5 \leq \Delta \leq 2$ i.e. two times over- or underestimation. The formula was recognized satisfactory if it gave aforesaid result in not less than for 5 of 7 stages of the first experiment and for 4 of 6 stages of the second experiment.

The calculations showed that only 8 formulae (< 10%) gave satisfactory results in both experiments: L.G. Gvelesiani's (1946) (Shamov, 1952), I.I. Levi's (1957) (Grishanin, 1969), G.I. Shamov's (1952) (Shamov, 1952), A.D. Abrahams' and P. Gao (2006) (Talukdar et al., 2012), J. Fredsoe's and R. Deigaard (1992) (Talukdar et al., 2012), J.S. Ribberink's (1998) (Ribberink, 1998), C.B. Brown's (1950) (Brown, 1950) and G. Parker's (1979) (Talukdar et al., 2012). And only three first of them didn't demand to change the characteristic of the granulometric composition (from d to d_{50} or vice versa). The formulae by Brown and Parker gave good results only for sediment composition.

Bedload calculation in nonstructural form of transport in mountain rivers in the given range of hydraulic and granulometric characteristics is recommended by the formulae:

Author and formula	Notation
L.G. Gvelesiani (1946) $q_s = 12.95 \frac{dV_0}{\left(\lg\frac{12d_{max}+d}{d}\right)^2} \left(\frac{V^3}{{V_0}^3} - 1\right)\left(\frac{V}{V_0} - 1\right)$ kg/s/m $V_0 = 3.4 \frac{\lg\left(\frac{8,8H}{d}\right)}{\lg\left(\frac{12d_{max}+d}{d}\right)} \sqrt{d}$ m/s	Formula gives good results for 5 of 7 stages of the first experiment and for 4 of 6 stages of the second experiment with both types of granulometric composition. So we can recommend to use this formula with granulometric composition of sediment.
I.I. Levi (1957) $q_s = 0.00076 \left(\frac{V}{\sqrt{gd_{50}}}\right)^3 d_{50}(V - V_0)\left(\frac{d_{90}}{H}\right)^{0.25}$ m^3/s/m For hydraulically rough flow ($Re_d > 25$, $d_{50} > 1\dots1{,}5$ mm): $V_0 = \left(\frac{d_{50}}{d_{90}}\right)^{0.1} \frac{C}{\sqrt{g}} V_{*0}$ м/c $V_{*0} = 0.16\sqrt{\left(\frac{\rho_{\text{т}}}{\rho} - 1\right) gd_{50}}$ m/s	Formula gives good results for 5 of 7 stages of the first experiment and for 4 of 6 stages of the second experiment with both types of sediment granulometric composition. It allows to recommend to use this formula with granulometric composition of sediment. Heterogeneity correction for critical flow velocity $\left(\frac{d_{50}}{d_{90}}\right)^{0,1}$ doesn't give significant improvement of the result so it is possible to calculate with or without this coefficient.
G.I. Shamov (1952) – critical flow velocity with correction for	Formula gives good results for 5 of 7 stages of the first

heterogeneity of sediment by Lazarev and Chernyshov (Lazarev, Chernyshov, 1974): $q_s = \alpha \sqrt[3]{d_{max}}^2 \left(\frac{V}{V_0}\right)^3 (V - V_0) \left(\frac{d}{H}\right)^{0.25}$ kg/s/m $V_0 = 3.83 \left(\frac{d_{50}}{d_{90}}\right)^{0.2} d^{\frac{1}{3}} H^{\frac{1}{6}}$ m/s	experiment and for 5 of 6 stages but only for granulometric composition of sediment.

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SEDIMENT YIELD AND ITS CHANGE IN RIVER MOUTHS

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Abstract: The analysis of river runoff change limits in the mouth areas of the rivers is made. The main attention is paid to transformation of sediments yield. Theoretical differences of mineral particles transit and accumulation processes for mouth sites with domination of river and sea factors, and also for mouths of the rivers of different type are studied. Natural data on the Russian rivers with the characteristic of sediments yield transformation in deltas of the rivers and on mouths beach are generalized. Features of deposits accumulation influence and change of reception reservoir level on change of deposits volume in the Volga river mouth are considered. Regularities of sediments yield change at different stages of the Kargalinsky cycle of delta Terek evolution are studied.

Keywords: sediment yield, mouth processes, marginal effect, sediment balance

In zones of river and reception reservoir interaction special natural objects – mouths are formed. The mouth of the river occupies the region of its confluence to reception reservoir (ocean, sea, lake, reservoir). It has peculiar features of a morphological structure, a hydrological mode, evolution depending on landscape conditions of an arrangement of the river basin and the mouth, slope of a coastal zone, a wave-wind situation in this zone (Koleman, Wright, 1979; Mikhaylov, 1997). Considerably specified specifics depend on receipt in the mouth of the river of water discharge and sediments yield, transformation of these characteristics under influence the mouth processes, ratios of river factors contribution and factors of a reception reservoir in volume change of mouth deposits in deltas and on seashore. Their role can significantly change under the influence of economic activity. All these events occur against climatic instability of a river runoff, level of reception reservoirs, and also the directed tectonic movements, characteristic for evolution zones of mouth areas. Tectonic lowering or increase of land sites, regression and transgression of the seas and oceans, change of the general basis of an erosion are the most important reasons of radical transformation of conditions of evolution of mouths. In this work features of development of mouths under the influence of generally characteristics of a river runoff in the assumption of geological factors stability are considered.

Annually on a planet in limits of river mouths rivers arrives about 39500 км^3 volume of water (Water resources, 2008) and 15.7 billion t of river deposits (Dedkov, Mozzherin, 1984; Walling, Webb, 1987); 3.0-4.0 billion t of the dissolved and weighed chemical and organic substances (Losev, 1989; Walling, Webb, 1987). These estimates have nature of the first approach as monitoring of a river drain is imperfect. Many closing points of supervision are located rather far from tops the mouth areas. In unaccounted part of the river basin and directly in mouth area the additional drain of water and deposits yield (a zone of excess and sufficient moistening) or drain loss (a condition of arid climate) (Mikhaylov, 2004) are formed. The size of an additional drain depends on distance between a closing alignment and top of the delta, a value of the inflows falling below on a channel, the sizes of the delta and its geographical position. In the Arctic region of Russia the size of an additional water runoff reaches a maximum in the lower current of rivers Mezen, Pechora, Nadym, Pur, Taz, Khatanga, Anabar and Kolyma (about 15-37% of a drain in the lower point of hydrological monitoring). For other big rivers of the region it doesn't exceed 10%. Additional inflow of water to deltoid channels naturally increases at increase in the sizes of deltas. It is maximum for big river deltas and makes for Pechora (1.24 km^3/year), Ob (1.02), Yenisei (1.13) and Lena (5.28 km^3/year).

Along with increase in a drain of water also the sediment yield not linearly increases. From the closing alignments to deltas of the rivers the turbidity of water and discharges of the weighed deposits change owing to change of water discharge, and also a mass exchange between a transit stream of deposits and river deposits. Dependence between an annual discharge of weighed deposits R_0 and water Q_0 has the nonlinear increasing character: $R_0 = aQ_0$, where a is empirical parameter of a correlation ratio. For the rivers of the Arctic region of Russia the value of parameter changes from 0.005 to 0.176 (Alekseevsky, Magritsky, 2007).

In river mouths the drain of the weighed deposits and a turbidity of water test complex changes (Alekseevsky, 1998). Generally they cause reduction of quantity of deposits W_m (a share α_{m}) within estuarial area in comparison with their receipt to river border of the mouth W, i.e.

$$\alpha_{\text{mp}} = \frac{W_m}{W}\ . \qquad (1)$$

Processes of sediments yield transformation have specifics within mouth area of the river with prevalence of river and sea factors. In river part of the mouth change of sediments yield on its length

$\Delta W_{\text{p}} = W_2 - W_1$, (2)
where W_1 and W_2 – sediments yield on the top and lower borders of river part of the mouth. On its upper bound size $W_1 = W$.

The resultant of balance of deposits ΔW_{p} characterizes set influence of mouth processes on transformation of sediments yield on length of river part of simple and (or) estuarian type of the mouth according to the equation

$$\Delta W_{\text{p}} = (W + W_{tr} + W_b + W_{bot}) - (W + W_{acf} + W_{acbot}) \pm W_{eol}. \quad (3)$$

In the equation (3) the following designations are accepted: W_{tr} − inflow of deposits from a reservoir lower than river border of the mouth; W_b and W_{bot} − increase in sediment yield due to washout of coast and a bottom of deltoid water channels (estuary); W_{acf} and W_{acbot} respectively accumulation of part of river deposits on a surface of the deltoid plain (on the flooded parts of estuarian coast); $\pm W_{eol}$ inflow (+) or removal (−) mineral particles by air streams. After reductions and the simplifications connected with an assessment of the importance of separate mechanisms of sediments yield transformation within river part of the mouth, we receive

$$\Delta W_{\text{p}} = (W_b + W_{bot}) - (W_{acf} + W_{acbot}). \quad (4)$$

From this it is follows that the directed change of sediments yield in river part of simple or estuarian type of the mouth is absent, if $\Delta W_{\text{p}} > 0$ and ($W_b + W_{bot} > W_{acf} + W_{acbot}$). It isn't expressed and at transit of river deposits on length of unbranched and dynamically stable course (from the point of view of a mass exchange between a stream and riverbed) to an estuary, i.e. at $\Delta W_{\text{p}} = 0$. The marginal effect of sediment yield change (the directed accumulation) arises only under a condition $W_b + W_{bot} << W_{acf} + W_{acbot}$ ($\Delta W_{\text{p}} < 0$). For this case value

$$\alpha_{\text{mp}} = \frac{W_m}{W} = \frac{\Delta W_{\text{p}}}{W} \approx \frac{W_{acf} + W_{acbot}}{W}. \quad (5)$$

In case of deltoid and estuarian-deltoid type of mouths processes of sediment yield transformation, considered above, essentially don't change. Under the influence of consecutive bifurcation of the course change of a drain of deposits happens not on length of one course, and on their some set ($j = P$, $P1$, PN), which crosses the conditional line connecting knots of consecutive bifurcation of deltoid water channels $U = i$ ($i = 0, 1, 2, 3,\ldots M$). Therefore the equation (2) takes a form

$$\sum_{i=1}^{M}\sum_{j=1}^{P} W_{i,j} - \sum_{i=0}^{M-1}\sum_{j=1}^{PN} W_{i,j} = \sum_{i=1}^{M-1} \Delta W_{\text{p}i} \geq 0. \quad (6)$$

Therefore, value

$$\alpha_{\text{mp}} = \frac{\sum_{i=1}^{M-1} \Delta W_{\text{p},i}}{W} \approx \frac{\sum_{i=1}^{M-1} (W_{acf,i} + W_{acbot,i})}{W}. \quad (7)$$

According to this equation resultant change of sediment yield in river part the mouth areas depends on erosive and accumulative processes on all their space.

In the river mouth with prevalence of sea factors

$$\Delta W_{uw} = W_2 - W_1 = W_2 - \alpha_{\text{mp}} W \quad (8)$$

or

$$\Delta W_{uw} == (W_b + W_{bot}) - (W_{acf} + W_{acbot}) \pm W_m, \quad (9)$$

where $\pm W_m$ – receipt (+) mineral particles in sea part from structure of an alongshore stream of deposits or their removal (−) out of limits of sea part of the mouth (involvement in alongshore movement). From this it follows that at $(W_b + W_{bot} \pm W_m) \to 0$ coefficient of sediment yield transformation in sea part of the mouth

$$\alpha_{mm} = \frac{W_2 - \alpha_{\text{mp}} W}{\alpha_{\text{mp}} W} = \frac{W_2}{\alpha_{\text{mp}} W} - 1 = \alpha \frac{W_2}{W} - 1, \quad (10)$$

where $\alpha = \alpha_{mp}^{-1}$, a W и W_2 – a sediment yield on the upper bound of river and on the lower bound of sea part of the mouth. Change of sediment yield within this part of the mouth it is expressed to those less value of

α_{mp} the bigger value is $\alpha W_2 W^{-1}$. At $W_2 \geq \alpha_{mp} W$ the effect of accumulation of deposits in sea part and in general in the mouth of the river isn't expressed.

Synthesis of data on the studied mouths of the rivers shows that change of sediment yield in their limits is expressed in different degree (Table 1). On mouth beach of Pechora it is arrives to 60, and in gulf of Ob – 54% of sediment yield in delta top. The annual coefficient of carrying out of the weighed deposits α_m makes of Ob gulf already 0.7, and their accumulation in mouth area – 99.3%. In mouth area of Yenisey these figures are respectively equal to 7 and 93%, and in the Pyasina River mouth – 20 and 80%. For mouths of rivers Khatanga, Anabar, Olenyok and Yana value of $\alpha_{тр}$ is equal 2.9; 2.9; 9.4 and 10.5% (Modern…, 2005). For Volga river the percent of detention of deposits in river part of the mouth is equal 80% of a drain of the weighed deposits in delta top.

Long-term and century variability of a drain of river deposits of the main reason for change of volume of estuarial deposits W_0 at active (due to accumulation of deposits) evolutions of the mouth. In case of considerable fluctuations of level of reception reservoirs the increase or reduction of volume of deposits can appear a consequence of passive change of the area occupied with the mouth of the river. For example, volume the afterkhvalyn (Q_{IV}) deposits within the delta continuously increased in the delta of Volga under the influence of both mechanisms of its change (Alekseevsky, Aybulatov, 2011). From 1817 for 1978 the volume of deposits increased in river part of the mouth twice. The maximum rates of increase in this volume were characteristic for 1817-1868 and 1920-1978. After 1978 value W_0 decreased owing to sea level rise. The equation of communication $W_0 = \Psi(T)$ has an appearance

$$W_0 = r_1 + r_2 T, \quad (11)$$

where r_1 = 103 billion t; r_2 = 0.633 billion ton/year. Value r_1 characterizes the volume of the deltoid deposits created till 1817.

Table 1

The report of data on extent of sediment yield transformation in mouths of Russian rivers and the adjacent countries

River	Coefficient of deposits detention in river part of the mouth, %	Coefficient of carrying out of deposits on an near-shore zone, %	Coefficient of carrying out of deposits to the sea, %	Source of data
Pechora	40	60	18ю3	Modern…, 2005
Mezen	–	–	14	Modern …, 2005
North Dvina	–	–	24.2	Modern …, 2005
Onega	–	–	8.2	Modern …, 2005
Ob	46	54	0.7	Modern …, 2005
Enisey	–	–	7.0	Modern …, 2005
Piasina	–	–	20	Modern …, 2005
Lena	–	–	13.3	Modern …, 2005
Hatanga	–	–	2.9	Modern …, 2005
Anabar	–	–	2.9	Modern …, 2005
Olenek	–	–	9.4	Modern …, 2005
Yana	–	–	10.5	Modern …, 2005
Terek	10	90	58	Authors
Volga	80	–	–	Alekseevsky N.I., Sinenko L.G., 1998
Kura	–	–	15	Azimov et al., 1986
Sulak	–	–	22	Azimov et al., 1986
Samur	–	–	30	Azimov et al., 1986

At average intensity of formation of deltoid deposits of Volga of 640 million tons/year (1817-1998) by 2010 within the delta about 117 billion t of deposits was collected. From them 45 billion t (sediment yield modified on coefficient of transformation of sediment yield of $\alpha_{mp} = 0.2$) have river genesis. It means that delta evolution in essential degree is defined by the passive mechanism of change of its volume. At fall of a sea level dH/dt = 0.05 m/year the role of this factor provides 71%, and at dH/dt = 0.15 m/year − 93% of total size of promotion of sea region of the delta. At small intensity of the Caspian Sea level fall (dH/dt < 0.035 m/year) prevails active promotion of the delta.

Distribution of deposits thickness is a peculiar sign of activity of this or that area of the delta concerning promotion of sea region of the delta. Thus there is a certain communication between the sizes of water channels in the delta of Volga and the thickness of deposits in a zone of their existence. The size of water channels is implicitly connected with the volume of deposits which is formed in the direction of their pro-deleting. Regions of a bedding of the most thick afterkhvalyn deposits correspond to an arrangement of the least water-discharge channels. The main directions of a drain and the most water-discharge channels in the delta of Volga are displaced to the West and the East from areas with the maximum capacities of deposits where hydraulic conditions of interface of the Volga waters with waters of the reception basin are more favorable.

Transformation of sediment yield in deltas of the rivers with a big sediment yield depends on a stage of their evolution (Alekseevsky, 1998). For lake-marshy stage of a long-term cycle of their development practically all river deposits accumulate in depressions of the deltoid plain and in courses of deltoid water currents as the value W_2 (2) is almost equal in the equation to zero and $\Delta W_p \approx -W_1$. On lake-marshy stage of evolution of the imposed delta of the Terek River (Kargalinsky break) the resultant of balance ΔW_p even is more than W_1 ($\Delta W_p = 1.034 \cdot W_1$), as passed into structure of deltoid deposits even products of destruction of a bottom and coast in the main bed of the river. In process of "registration" of the bed of the river at later stages of formation of the delta the size of coefficient of sediment yield transformation in river part of the mouth gradually decreased at the expense of increase in transit of river deposits in sea part of the mouth of the river. In the last 12 years in the delta only 10% of sediment yield in delta top accumulate. In sea part of the mouth accumulation of river deposits changed from 0 (1914-1939) to 32.1% (1995-2008). It reached a maximum (52.2%) in 1963. 1977 at a stage of formation of the low-quantity channels modern delta of Terek.

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VEGETATION CONTROLS ON DELTA TIDE-FLAT STABILITY

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The Fraser Delta, located in Southwestern British Columbia, Canada, is a macrotidal-dominated delta formed over the past 10,000 years following deglaciation of the region. The modern delta avulsion node sits approximately 10 km upstream of the delta front. Avulsions have built tidal flats that are now at risk of erosion because of changes in sediment supply to the delta. The historic sediment load of the Fraser river is ~17 Mt/a, of which ~3.2 Mt/a was transported as bed material into the distributary channels (McLean et al., 1999), forming the base of the modern delta. Dredging of the Main Channel for navigation purposes has reduced bed material supply to the delta front to ~1.3 Mt/a. Channel control measures have focused bed material transport into a submarine channel, bypassing the tide flats. The modern delta is buffered from widespread erosion by subaqueous eelgrass (*Zostera marina*) and biofilm on the intertidal zone.

Within this context, we have been examining the impacts of these biological factors on sediment transport to better quantify how it might influence the larger scale morphodynamics of the delta. Limited field observations of erosion thresholds in the intertidal zone suggest biofilm renders sediment immobile under the current hydrodynamic conditions.

We also used a simple laboratory experiment to explore how simulated eelgrass patches impact flow and sediment transport. We examined the response of a fine sand bed to two play densities. The lower density was below the threshold for significant flow modifications and the higer density is above. At both densities, a scour hole formed at the upstream end of the plant patch due to increased stem turbulence. At low density, the downstream bed was flat downstream (with fixed ripples). At high density, a sand deposit formed increasing slope through patch, which increased the sediment transport capacity, passing the incoming load through the plat patch (Fig. 1). By partitioning total shear stress between the plants, small-scale bedforms and the sand grains, we found that the shear stress available for sediment transport is 6-14% of the total shear stress, depending on the plant density. This reduces the sediment transport capacity through a plant patch and the morphodynamic response is an increase of the bed slope to accommodate the upstream sediment supply (Le Bouteiller and Venditti, 2014).

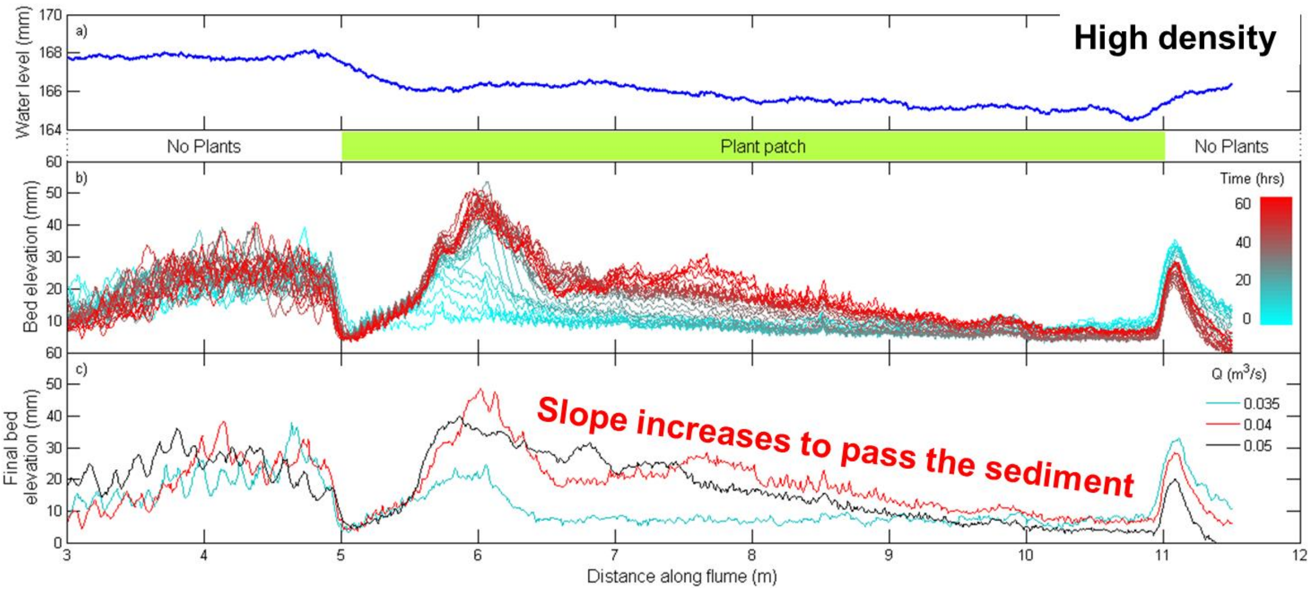

Fig. 1: Evolution of bed surface at the high plant density in the experiments of Le Bouteiller and Venditti (2014): (a) Water surface and (b) bed surface evolution from blue to red lines over 60 h and (c) final bed morphology for 3 discharges examined.

We also found that a plant patch induces a scour zone as flow enters the plants, followed by a depositional zone downstream. The downstream length of the scour zone scales as

$$Lo \approx \frac{3}{C_p a} + 6.9 h_p ,$$

where C_p is the plant drag coefficient (~1), a is the frontal area of the plants and h_p is the deflected plant height. Vegetation is commonly thought to produce a depositional environment, but our experiments suggest that there is a morphodynamic length scale (L_o) over which a plant patch may actually cause erosion. This suggests that plant patches smaller than L_o are likely to be unstable and patches larger than L_o are likely to induce deposition within and behind the patch, creating conditions favorable to colonization and expansion of the vegetation patch (Le Bouteiller and Venditti, 2014).

Our experiments suggest that the stability of the Fraser Delta against erosion, under the reduced sediment supply regime, may be dependent on the persistence of the biofilm and eelgrass meadows.

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RECENT DISCOVERIES ABOUT THREE DIFFERENT DELTAIC SYSTEMS: AMAZON, MEKONG, AND ELWHA

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Recent studies of fine-grained sediments provide novel insights to deltaic processes, and three examples are described below. The common theme is the recognition that the transfer of sediment from source to sink can deviate from general expectations for deltaic processes.

Tributaries that reduce fluvial discharge

The Amazon tidal river (no salinity) extends roughly 800 kilometers upstream of the river mouth. Previous studies suggest that as much as one third of the fine sediment measured at the upstream limit of tides does not reach the ocean, and is likely trapped along the tidal river (Nittrouer et al., 1995). Many different depositional environments are active along this reach. Amazon sediment is transported into the drowned tributary confluences (rías) of the Xingu and Tapajós Rivers by density-driven underflows. In the Tapajós Ría, sediment from the Amazon River has built a 25-km long birdfoot delta, suggesting these tributaries are net sinks of sediment, rather than sources. This is confirmed through measurements of accumulation rates in the tributaries (Fig. 1; Fricke et al., 2013).

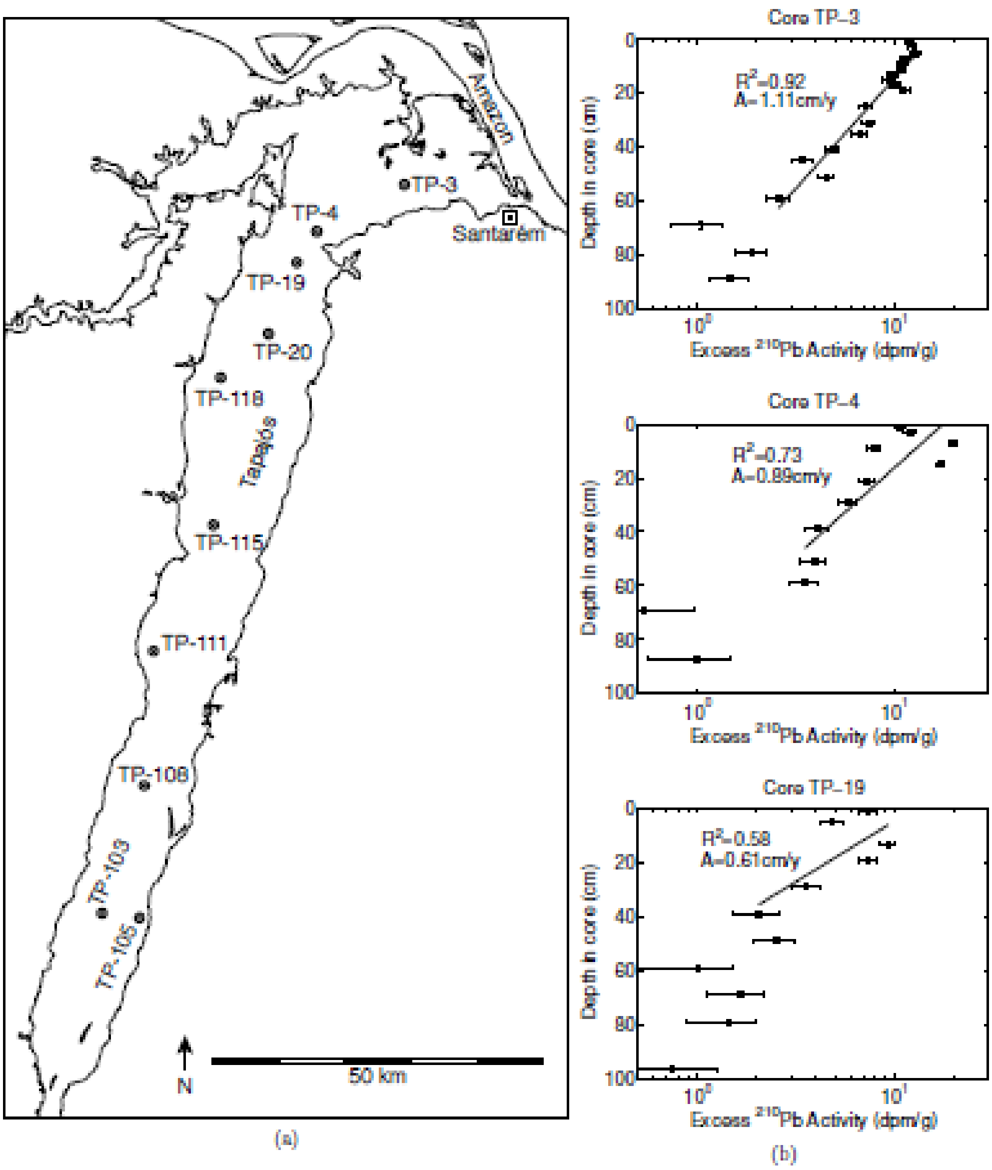

Fig. 1: a) Chart of the Tapajós tributary mouth, showing locations of 10 kasten cores; b) Three profiles of ^{210}Pb activity from cores TP-3, -4, -19 near confluence with the Amazon River, indicating the sediment accumulation rate.

Distributaries that are seasonal sources of fluvial sediment and traps of shelf sediment

Processes impacting fine-grained sediments were investigated under conditions of high and low seasonal discharge in the primary Mekong distributary, Song Hau (Nowacki et al., submitted). In the region between fluvial and estuarine conditions, tidal flow reversed throughout the water column during both low and high flow. Salinity was spatially variable over seasons: during low flow, salinity >10 PSU was observed 30 km upstream during maximum flood; at the same location during high flow, salinity was <0.5 PSU at all times. Conditions were partially stratified during low flow. When present, stratification was in the form of a salt wedge during high flow. During both seasons and at all locations, distinct, preferential pathways of water and sediment were present through the tidal cycles. The integrated effect during high flow was sediment export from the river, and during low flow was sediment import from the adjacent continental shelf (Fig. 2).

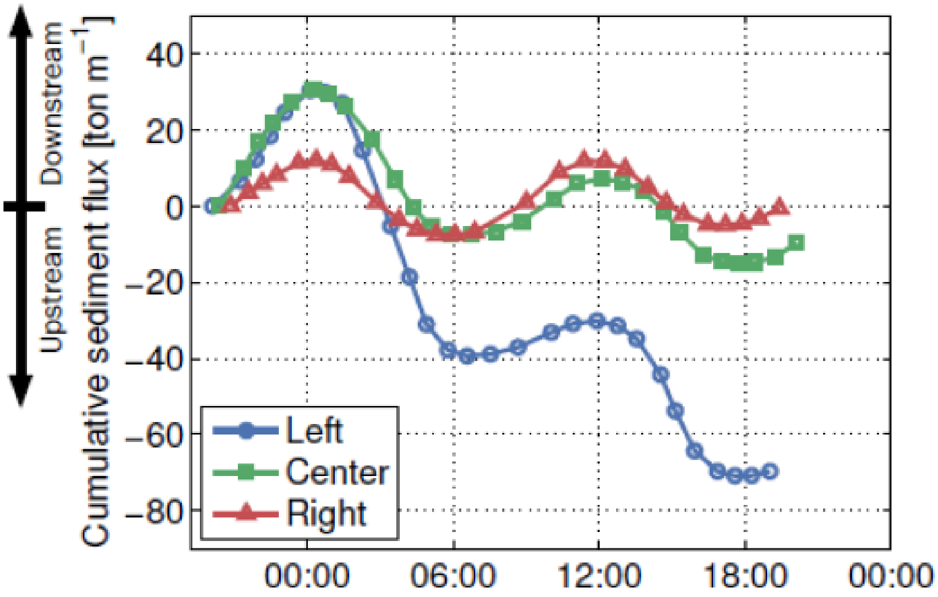

Fig. 2. Tidal time series for observations of sediment flux integrated throughout the water column at three cross-channel locations (center, and ~20% of distance from left left and right banks). These were collected during April 2013 (seasonal low flow of the river), and the left side (thalweg) demonstrates net upstream flux of sediment.

The difficulty of starting a subaqueous deltaic deposit

During the two years since dam removal from the Elwha River, fine-grained sediment pulses have generated new seabed deposits adjacent to the river mouth (Fig. 3).

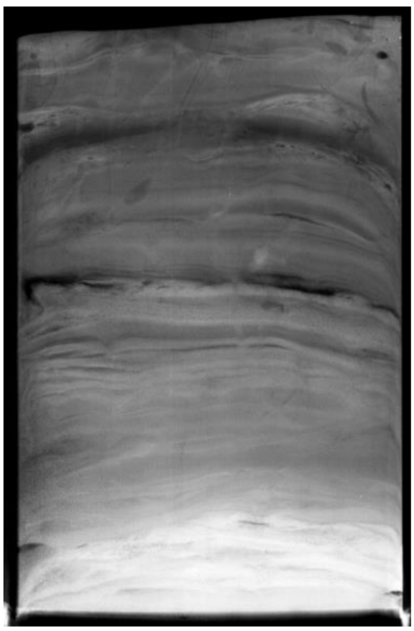

Fig. 3. X-radiograph (negative; dimensions ~22 cm x 12 cm) of recent sedimentary deposit in shallow (~15 m depth) subaqueous environment at mouth of Elwha delta. This is a result of dam removal started in Sep 2011

These thin deposits (<50 cm thick) have formed in water depths of <35 m on the surface of a relict, coarse-grained, post-glacial subaqueous delta, but only in isolated regions where large-scale coastal eddies produce weak currents (Eidam et al., submitted). The remainder (~75%) of the relict, subaqueous delta continues to host a gravelly lag layer, swept clear of fine-grained sediments by strong (up to 100 cm/s) tidal currents. Ephemeral deposition may occur on tidal time scales, but generally, fine-grained sediment appears to bypass these energetic areas.

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CHANNEL MIGRATION RATES AND AVULSIONS

MODELS OF RIVER MOUTH DEPOSITS

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The mouths of deltaic distributary channels and rivers are often the locations where sediments accumulate and new land forms. At these locations sediment deposition can occur as progradation of natural levees and channel elongation, or as deposition and vertical aggradation of a central mouth bar. Irrespectively of their shape and evolution, these landforms are of paramount importance within the coastal landscape. Mouth bars and levees form the bulk of the subaerial portion of deltas and therefore are critical for coastal communities and the diverse fauna and flora that inhabit them. Highly productive oil and gas reservoirs are often found in these deposits. Numerical models have allowed scientists to test the validity of theoretical results and simplified analytical approaches for river mouth hydrodynamics. Among these the coupled hydrodynamic-sediment transport model Delft3D (Lesser et al., 2004) is becoming an increasingly common tool in morphodynamic studies, due to its robustness, extensive documentation, and ease of use. Most of the numerical results presented here were obtained with Delft3D simulations.

Recent experiments showed than jet instability, characterized by large scale meanders, increases the sediment eddy diffusivity, i.e. the tendency to transfer sediment to the side of the jet and hence to build lateral deposits (Rowland et al., 2010). Mariotti et al. suggested that such enhancement is caused by the peculiar dynamic of the sediments that are trapped in the large scale eddies, which act as a conveyor belt (Mariotti et al., 2013). If the settling time scale, i.e. the time needed for the sediment to reach the bed, is comparable to the meandering time scale, i.e. the time needed for a mender to complete a half revolution, sediments settle at the farthest distance from the centerline (Mariotti et al., 2013). If the settling time scale is significantly greater than the meandering time scale, sediments move back and forth within the eddy, effectively reducing the eddy diffusivity (Rowland et al., 2010; Mariotti et al., 2013). Mariotti et al. pointed out that if the settling time scale is much shorter than the meandering time scale, sediment cannot exploit the eddy conveyor belt, and they will tend to deposit close to the centerline (Mariotti et al., 2013).

Therefore in shallow river mouths the main mechanism responsible for levee formation is jet instability and the formation of large scale meanders, which is mostly controlled by bottom friction (Canestrelli et al., 2014).

Nardin and Fagherazzi showed that waves and the direction from which they approach a river mouth play an important role in the distribution of sediments and related deposits (Nardin and Fagherazzi, 2012). Wave angles with respect to the coast between 30° and 45° are the least favorable to bar formation, producing instead a deflected river mouth.

Four possible distinct morphologies stem from the combination of wave angle and the relative strength of waves with respect to the river flow (Fig. 1, Nardin and Fagherazzi, 2012).

For weak wave conditions the bar forms at the center, producing a bifurcation of the flow similar to the case without waves. When moderate waves propagate ashore at an angle, the bar forms on the opposite side of the wave direction (side bar case, Fig. 1), still triggering a bifurcation of the flow and the formation of two channels. Strong waves with a small angle deflect the river mouth, leading to a jet that flows parallel to the shoreline. In this case large quantities of sediments are deposited between the jet and the shoreline, producing a swash bar that extends along the coast. A fourth case occurs when strong waves reach the mouth perpendicular to the shoreline, destabilizing the jet. The jet starts oscillating, spreading sediments on a vast area without forming a distinct bar.

Tides affect the hydrodynamic of the jet exiting the river mouth and also have important consequences from a morphodynamic point of view. Depending on the relative strength of river inertia with respect to tidal energy, different hydrodynamic processes dominate the sediment deposits with consequent development of distinct morphologies. Leonardi et al. analyzed the effect of micro- and meso-tidal conditions at rivers mouths for two end member configurations, i.e., a fluvial dominated case in which the river discharge is constant and the tidal discharge is zero, and a tidal dominated case in which the river discharge is small compared to the oscillating tidal discharge (Leonardi et al., 2013).

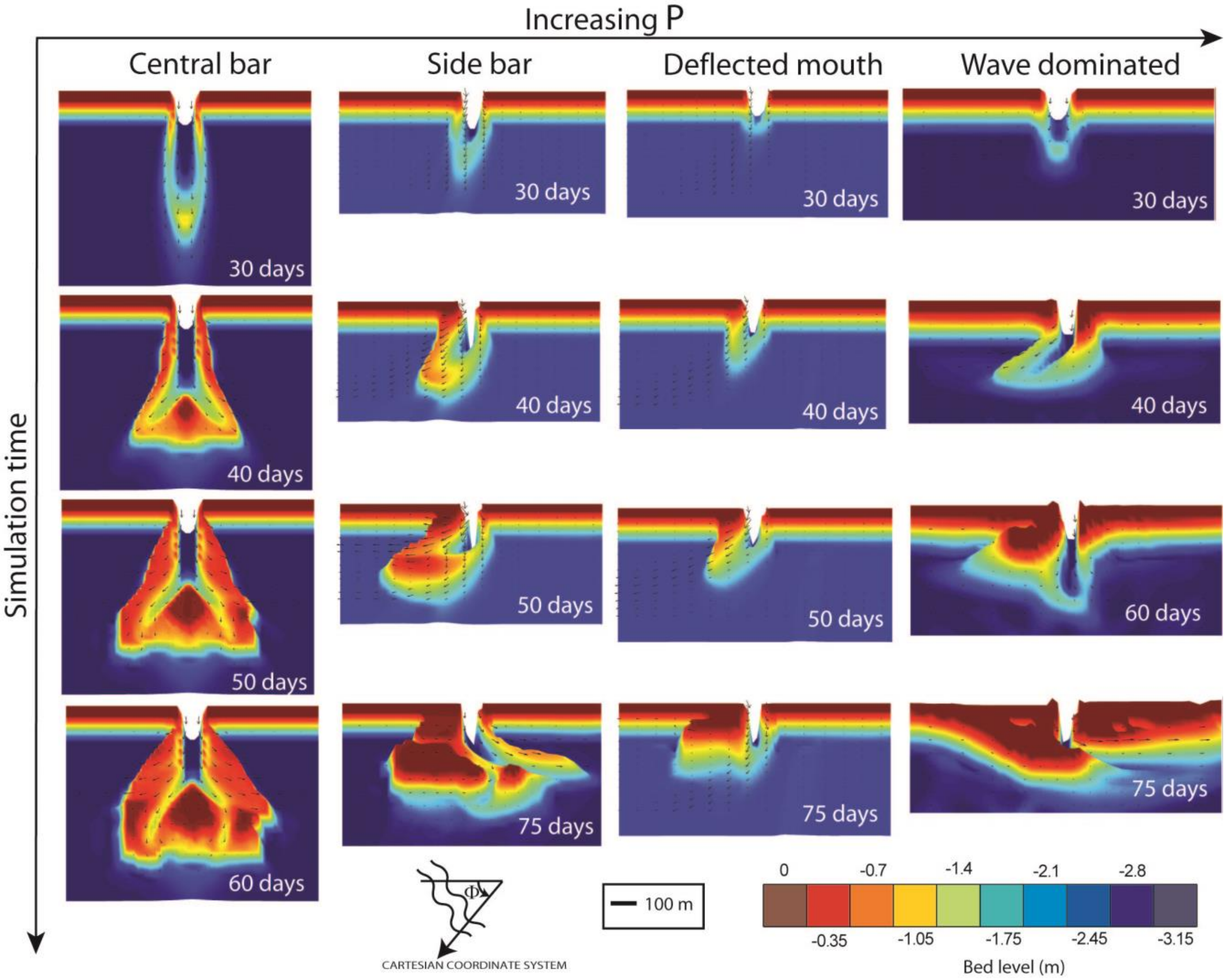

Fig. 1. Snapshots from 4 model runs showing the evolution of the river mouth under different wave climates. Each series consists of four images of a subaqueous mouth bar evolving for 6075 days. *P* is the ratio of the wave shear stress and the current shear stress at the river mouth

From a morphological point of view, mouth bars in the fluvial dominated case with tides result in a classical triangular shape. These mouth bars are wider and shallower with respect to the case without tides and also show a faster initial growing rate due to the tidal residual currents within the channel.

The tidally-induced higher spreading rate also promotes bar widening. This is because at low tide even an incipient mouth bar becomes an obstacle to the flow and, as a consequence, strong currents establish at the two sides of the bar that promote lateral spreading of sediments. After an initial period, bar widening starts prevailing upon accretion.

The tidal dominated case presents hydrodynamic features similar to tidal inlets, with a large tidal prism and strong flow reversal. From a morphological point of view, the final mouth bar display features that are intermediate between tidal inlets and river dominated mouth bars. An ebb dominated central channel, typical of tidal inlets, forms together with two lateral channels (Leonardi et al., 2013). Contrary to tidal inlets, the lateral channels are ebb dominated due to the effect of the riverine discharge (Leonardi et al., 2013).

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CONNECTING BATHYMETRY, THE FLOW FIELD, AND BATHYMETRIC EVOLUTION ON THE WAX LAKE DELTA, COASTAL LOUISIANA, USA

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Fluid flow on river deltas transitions from being focused in discrete, self-formed channels to being more evenly distributed on the sub-aqueous delta front. This flow pattern dictates sediment transport and therefore the growth patterns of river deltas, but has rarely been measured on a field-scale delta. We quantify flow patterns, bathymetry (Fig. 1) and bathymetric evolution for the subaqueous delta front immediately downstream of two distributary channels on the Wax Lake Delta, an ~80 km^2 delta actively prograding into Atchafalaya Bay in coastal Louisiana.

Repeat surveys of the delta front reveal two important and distinct channel behaviors; a phase where channels volume is conserved during river flood and a phase of channel extension during a period of low river flow (Shaw and Mohrig, 2014). The flood of 2011 produced no systematic channel extension and the total volume for the channels in the survey area decreased by 1.2×10^3 m^3 as channel volume increased in two channels and reduced in the remaining two. During the 8 month period of low flow preceding the 2011 flood, each of the four surveyed channels extended basinward distances between 150 and 500 m and channel beds incised up to 0.80 m or 160% of their previous depths. Increased channel length and incision produced an increase in total channel volume of 2.3×10^5 m^3, with individual channel contributions ranging from 15-35%. We posit that bifurcations are most likely to occur during times of low discharge when bay-driven processes combine with river flow to rework flood-deposited sand allowing multiple distributary channels to extend and incise on the delta front.

The flow direction field is measured using streaklines of organic detritus traceable in aerial photography collected during high discharge (4800 m^3 s^{-1}) in November 2009 (Fig. 1; Shaw, 2013). Distributary channels extend 2-6 km beyond the shoreline where channel banks fall below sea level, and have adverse bedslopes in this reach. Horizontal flow divergence is concentrated within 0.5-1.5 km (2-4 channel widths) of the subaqueous channel margins, and persists just 0.4 km (1.6 channel widths) beyond channel tips. This pattern of horizontal flow spreading over the final reaches of the extant channel network differs from existing models of turbulent, jet-flow pattern postulated for the Wax Lake Delta, where all spreading occurs beyond the channel terminus.

Importantly, flow spreading from neighboring channels appears to constrict the space available for spreading from each distributary channel. Evidence of the interaction between neighboring channels is found in "interdistributary troughs;" channel forms that are ~1 m deep and ~200 m wide and (contrary to distributary channels) grow wider and deeper in the basinward direction. These troughs lie directly beneath the boundary separating fluid flow from each of the neighboring distributary channels. Lateral transects across interdistributary bays show that the flow distance from a channel margin to reach a transect increases non-linearly in the interdistributary troughs. If sediment flux decreases with distance from a channel boundary, then the interdistributary troughs would form simply because of the spreading patterns outside of the channel network on the Wax Lake Delta.

Classic models of channel mouth morphodynamics that are based upon the turbulent spreading of fluid from a discrete channel mouth do not apply at the Wax Lake Delta. We recommend that new models take into account (1) channel extension during low flows, (2) lack of channel extension or discrete mouth bar deposition during high flows, and (3) the strong lateral spreading of flow in the subaqueous reach to resolve channel growth in prograding delta systems.

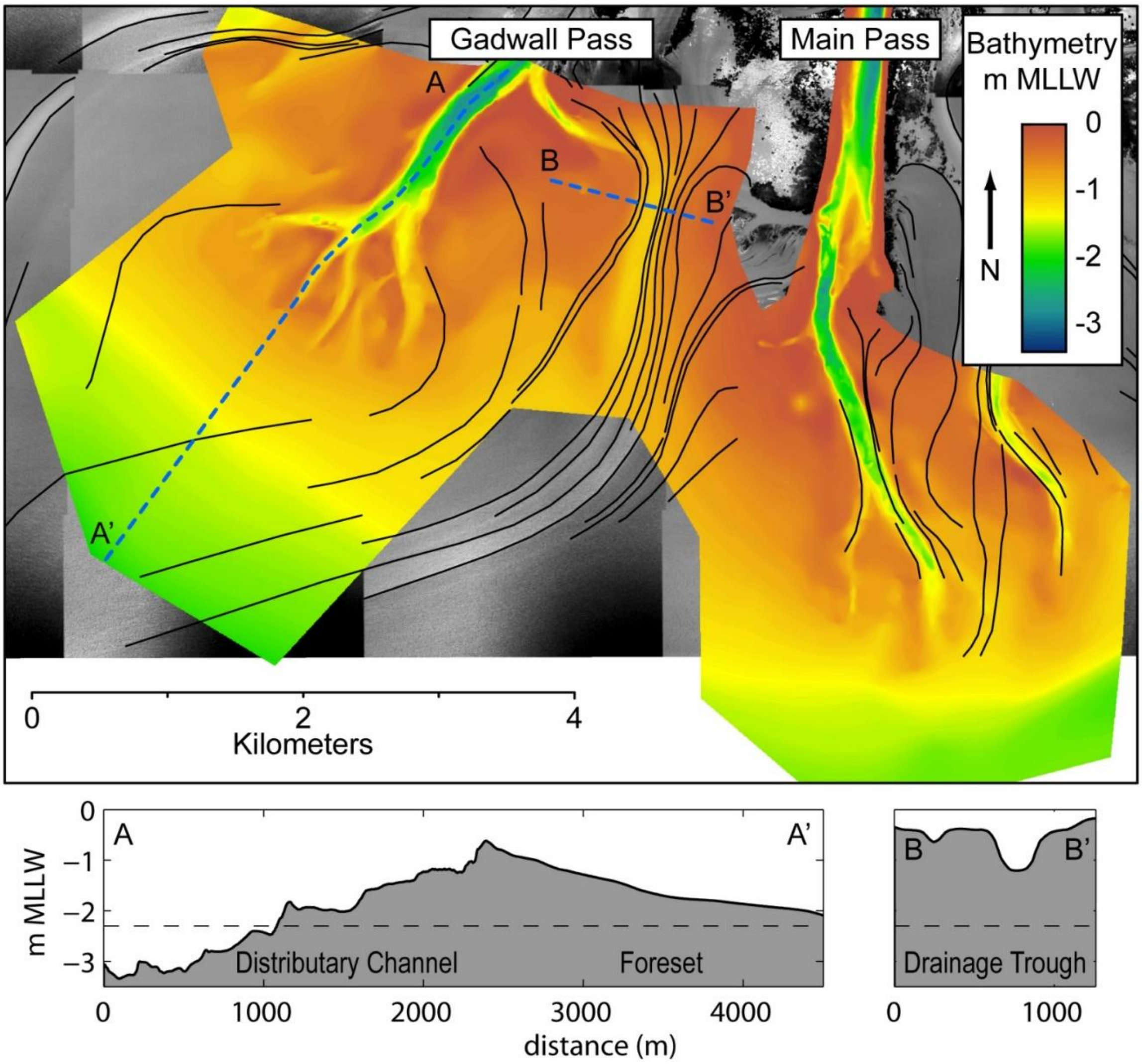

Fig. 1. Bathymetric map of two sub-aqueous distributary channels on the Wax Lake Delta. Bathymetry was collected in June 2010. Transect A-A' shows the adverse bed-slope of a distributary channel over its final reach. Transect B-B' shows the morphology of an interdistributary trough. The black lines are streaklines collected from aerial imagery collected in November, 2009.

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STRUCTURE OF DELTOID CHANNELS NETWORK AND FEATURE OF ITS FORMALIZATION

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Abstract: Theoretical and methodical approaches to an assessment of substance streams transformation in mouths of the rivers are considered. For deltoid type of mouths methods of channels network structure formalization, based on ideas of elements of this network, knots of branches merge and channels bifurcation are offered. Ratios between characteristics of deltoid water channels structure, and also from characteristics of river runoff are received. Application of rivers orders concept (conditional orders of deltoid water channels) for an assessment of river deltas similarity (or systems of water channels within certain deltas) under the terms of water runoff dispersal from delta top to its sea edge is proved. Examples of use of the developed technology in relation to problems of studying of river runoff transformation processes in deltas of the Russian rivers are given.

Keywords: structure of deltoid water channels, geometry of deltas, conditional orders of deltoid water channels

At a confluence of the rivers to reception reservoirs there are complex processes of river water masses transformation into the water mass of the seas, lakes and reservoirs. Most brightly they are expressed in mouths of the rivers where there is an essential change of hydrological characteristics of a water stream. Set of the phenomena of a condition of river waters transformation in limits of mouth areas of the rivers is considered as the physical content of the concept "marginal filter" (Lisitsyn, 1994). In geological time scales this effect causes formation of various types of river mouths (simple, estuarine, estuarine-deltoid and deltoid) (Mikhaylov, 1997). In mouths of deltoid type under the influence of marginal effect zones with various conditions of accumulation and transit of the weighed substance, formation of areal and lateral zones of deposits of sand, a dust, silt and clay accumulation are formed. Their configuration within mouths of the rivers predetermines an arrangement of sandy sedimentary bodies of potential collectors of gas and oil (Coleman, Wright, 1971; Rainwater, 1964).

For smaller time scales the marginal effect influences type of development of deltas (promotion, degradation), redistribution of streams of substance in space of the mouth areas, increase or reduction of deposits volume in different sectors of mouth area of the rivers, processes of accumulative or erosive processes activization in certain areas of river deltas. The orientation and intensity of these processes depends on characteristics of a river water runoff, hydrological conditions and morphological features of a coastal zone of a reception reservoir. The ratio of these factors defines type of the mouth of the river. In the mouth areas of deltoid type this ratio influences complexity of structure of water channel network of deltas: one-hose, small and multihose structure (Mikhaylov, 1997). Depending on complexity of a structure of water currents network there is a nature of seasonal and long-term transformation of substance streams arriving in mouths of the rivers. In a certain degree the arrangement of deltoid water channel systems marks borders of zones with systematic accumulation of a terrigenous material of different fractional structure in historical time scales. However lack of methodical means for an assessment of expressiveness of marginal effect depending on characteristics of a structure of deltoid branchings interferes with detection of regularities of transformation of a river runoff within deltas, to determination of similarity and distinctions of this process in a different environment.

In this work the method of deltoid water channel structure formalization which allows comparing deltas of the different rivers and system of water channels of one delta under the terms of dispersal of water runoff and sediments yield is offered.

The method is based on use of the main feature of channels network of low-hose and multihose deltas. It consists in consecutive bifurcation of the course on more and more small elements (Fig. 1). Consecutive division of the main channel of the river into channel systems of smaller size causes existence in channels network of the delta of Ka elements forming generally knots of channels division and connection.

Density of deltoid water channels is inverse function of the delta area. The more is area of deltas, the less is density of channel network. Though the number of deltoid water channels also increases with increase in the area, but it increases more slowly in comparison with increase in the area of the deltoid plain. With other things being equal the number of water channels in network of tideless deltas depends on the water runoff, turbidity of water, a ratio of sediment yield of suspended materials and ripple-wake suspension (Alekseevsky, Aybulatov, 2003). The less is turbidity and more share of ripple-wake suspension in transport of river deposits, the multihose deltas are more often formed (Fig. 2).

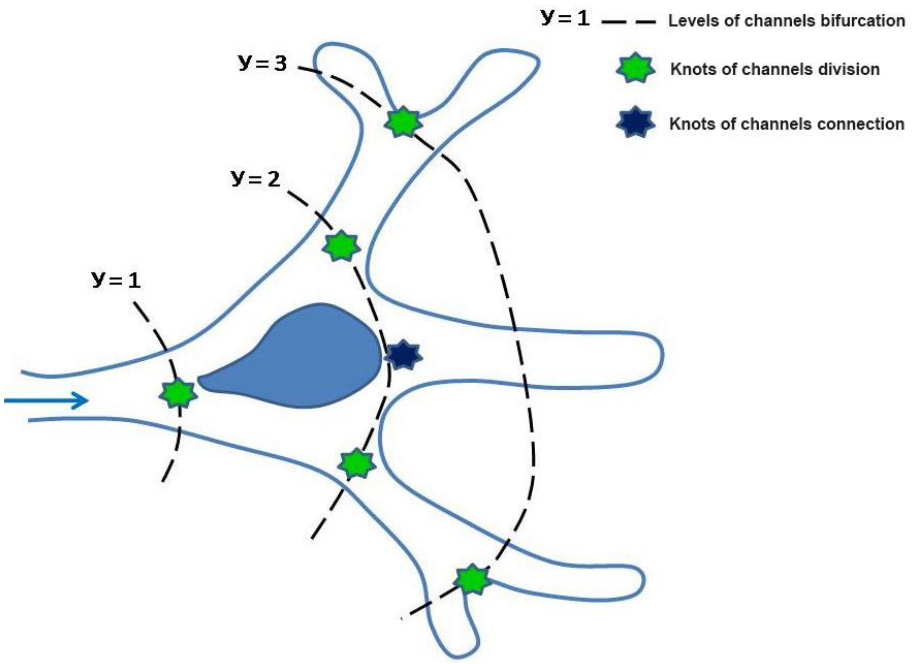

Fig. 1. Characteristic structure of water channels in the multihose delta

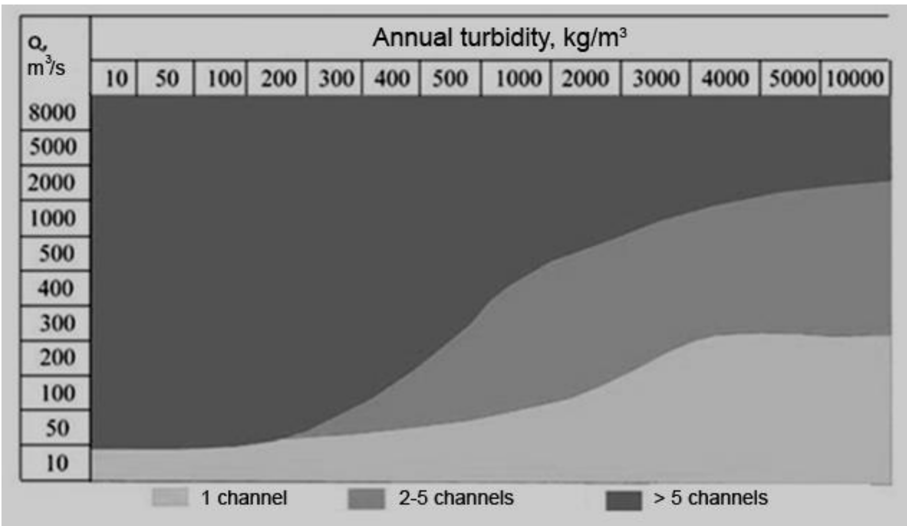

Fig. 2. Ratio of water channel network structure complexity in not tidal deltas of the rivers of Russia, annual water discharge Q and a water turbidity

In the delta Volga the expense of the main channels having their own systems of water channels has the main impact on the size Ka. At increase in annual water discharge *Qoj* the size of *Ka* also linearly increases in headland of these channels, i.e.

$K_{aj} = 0.06Q_{oj} + 11.2.$ (1)

The analysis of structure of water channels in deltas of the Russian rivers showed that the size *Ka* changes in the wide range of values. Exclusively seldom it reaches or exceeds the size *Ka* =50. For 28 studied deltas the size K_a = 20-30. Number of elements of the channel network *Ka* = 11-19 (88.6% of deltas of the Russian rivers). For 23 deltas it is less than 10. For many mouths of the Arctic region of Russia low-hose deltas aren't formed at all. In mouths of the rivers flowing into the Lake Baikal, there is parity between many and low-hose deltas.

Each knot of bifurcation is formed by not less than three elements of channel network. In nature the channel can share and on bigger number of streams, however the option of its structure of the knot, including larger channel and two streams of the smaller size which have appeared owing to bifurcation of channel is most probable. The structure of water channels in knot of their merge is similar. Two or bigger number of streams form removing element of water currents merge knot. Characteristic feature of channel network of deltas is domination of channels division knots number K_b in comparison with number of knots of connection of deltoid streams K_k.

The number of the water channels presented in structure of delta network, defines possibility of existence in the delta of bigger or smaller number of river channel division knots. From the hydrographic scheme of knot of bifurcation of stream follows that:

$K_b = (K_a - 1)/2$. (2)

From a ratio (2) follows that the size $K_b \leq 0.5\ K_a$. In nature its theoretical size can significantly differ from the actual value. In the Volga delta the actual size K_b for different systems of water channels Volga changes from 30 to 250, and its corresponding theoretical values from 23 to 210. Available differences are connected with small bed slope in the river delta. The number of of the main river channel bifurcation knots or its main streams depends on their water discharge (according to Q_0 and Q_{oj}).

$K_{bj} = 0.0264\ Q_{0j}$. (3)

In the Lena delta the actual number of bifurcation knots (231) is much less than its theoretical value (356). Probably, it is connected with a large number of merge knots (K_k =121) or permafrost existence.

For the majority of deltas of Russia the number of merge knots doesn't exceed 4. Only for 8% of the studied rivers $K_k > 4$. In the Lena delta, for example, there are about 230 knots of bifurcation and 120 knots of merge. Thus in Trofimovskaya's system channels relation Kb/Kk = 2.1, and in Bykovskaya's system – 3.2.

Consecutive bifurcation of the main channel on streams and in systems of arising water flows happens at consecutive increasing distance from top of the delta (Fig. 1). If tops of knots consecutive (U = I, II, III, …, T) on each of the main directions of runoff dispersal to connect course divisions by lines, they will characterize zones of consecutive bifurcation of channel network of the delta U. The more is size of U, the longitudinal dispersal of water runoff in space of the deltoid plain is more strongly expressed. Dispersal power (longitudinal transformation) of river drain is connected with total number of division knots K_b in the river delta (or within private system of water channels). Dependence between these variables has theoretical character:

$U = \log_2(K_b + 1)$. (4)

Existence of 3-4 levels of bifurcation is the most characteristic feature of the Russian rivers. Bigger or smaller number of these levels is rather rare event for evolution of channel systems in deltas of Russia rivers. Local conditions have strong impact on size of U (slope of the seaside plain, permafrost existence, powerful and frequent surge waves, etc.). In the Volga delta size of U for systems of the main channels changes from 8 to 13 (on the equation (4) they fluctuate respectively ranging from 5 to 8 that is caused by exclusively small slope of Caspian Depression. The more is an average long-term consumption of water in a source of sleeves of Qoj, the more is size U (R^2 = 0,804).

$Uj = 1.48 \ln Q_{0j} - 0.246$. (5)

Similar on structure dependence of division levels number on an average annual water discharge in sources of the main channels is characteristic and for the Lena delta. Channel bifurcation in the Lena delta is shown on 5-12 levels. The maximum dispersal of runoff is characteristic for Trofimovsky system of water channels (number of levels of bifurcation equally 12), minimum for Olenekskaya – 5 (Alexeevsky et al, 2014).

Information on structural features of channel systems in deltas isn't enough for comparison of deltoid water channels. For this purpose it is necessary to have data on their absolute or relative sizes. In a hydrology for this purpose the complex of characteristics is usually used: water basin area, length, annual water discharge, river order. However for comparison of the sizes of deltoid channels the most part of these characteristics isn't applicable. For comparison of deltoid water channels it is possible to use their water runoff. Two (and bigger number) deltoid water channels can be considered similar by the quantity if their water runoff Q_{0j} is identical. In this regard deltoid waterways don't differ from the rivers with a treelike channel network which often compare in value of annual water discharge Q_0. For a concrete natural zone it depends on the area of river basin F and an order of the rivers N_{sh}, i.e.

$Q_{0j} = a_j \exp(b_j N_{sh})$, (6)

where N_{sh} – an order of the river to A. Shaydegger (Alekseevsky et al., 2013). In this equation b_j parameter value practically a constant (changes in the range from 0.67 to 0.73). Regional conditions of runoff formation in a bigger measure it is considered by parameter $a = 0.005 \div 0.12$. The equation (6) allows to solve and the return problem: on a known consumption of water to establish the settlement size of its order N_{shu}. In particular, thus it is possible to define an order of a deltoid channel. As it is established not according to characteristics of channel network, and depending on water discharge, such orders are called conditional (Alekseevsky, Aybulatov et al., 2014; Alekseevsky, Chalov, 2009). The conditional order of a deltoid channels N_{shu} numeric is equal to a river N_{sh} order if their annual water discharge Q_0 is equal.

It allows to receive the quantitative characteristic of the size of each channel in network of the delta, to consider a role of each element of a network in longitudinal and cross dispersal of a drain within the deltoid plain. Existence of the deltoid water channels given about conditional orders creates basic prerequisites for the analysis of processes of transformation of water runoff from top to the sea region of the delta. Use of this information allows to establish similarity of deltoid branchings of the different rivers (and (or) different systems of deltoid water channels of the same river) under the terms of drain dispersal in space of mouth area. For this purpose it is necessary to make the difference analysis between river order in top of the delta $N_{sh} = N_{sh}$, max and the minimum conditional order of a deltoid channel $N_{shu} = N_{shu,\ min}$. The channel of such size arises at consecutive division of the main channel of the river (channel of one of the deltoid streams having own network of water channels) on the lesser elements:

$$\Delta N_{sh} = N_{sh} - N_{sh,min}. \quad (7)$$

As the size ΔN_{sh} depends on the size of the channel forming the delta or system of streams in the delta, it is normalized on $N_{sh,\ max}$, i.e.

$$\Delta N_{sh1} = \Delta N_{sh} / N_{sh,max}. \quad (8)$$

From the analysis of the equation (8) follows that the size of branchings similarity criterion under the terms of longitudinal dispersal of water runoff can change in the range of $0 \le \Delta N_{shu} \le 1$. Data processing on channel branchings of the Russian rivers allows to qualify as a first approximation intensity of transformation of water drain (to establish similarity of processes of bifurcation) at drain dispersal on systems consistently decreasing elements of a network. To weak, moderate, strong and extremely big intensity of bifurcation of the course there correspond values $\Delta N_{sh1} \le 0.26$; 0.26-0.45; 0.46-0.65 and $\Delta N_{sh1} >$ 0.65 (Alekseevsky, Chalov, 2009). Nature of dispersal of water runoff (channel bifurcation) in deltoid branchings can be considered similar if for them the condition ΔN_{sh1} = const is satisfied.

Taking into account this technology features of water runoff transformation in Volga, Danube, Lena, Urals deltas are studied. For the delta of Selenga it is established that reduction of water turbidity from delta top to its lake margin reaches 2-3 time. During the flood periods this process amplifies, and in low - weakens. Existence of these and other data on conditions of dispersal of river drain creates a methodical basis for research of hydrological functions of deltoid branchings. Functions of branchings are understood as natural change of hydraulic and morphometric characteristics of a stream and the channel, a condition of river water mass, volume of river deposits, heat contents and water temperatures, an ecological condition of water channels and a water management situation under the influence of channel bifurcation. Research of these functions is a way to studying of water runoff components transformation regularities in the mouth areas of the rivers, large-scale effects of material streams change in their limits.

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INTRODUCTION TO A DEPOSITIONAL WEB DELTAIC MODEL

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We propose a so-called depositional web delta model to understand how deltas fill space in a receiving basin over time. The model integrates a channel network with a depositional length term, L_D, which extends perpendicular to each channel. The channel network is implicit, so the physical structure or pattern of links and nodes is undefined. Instead, we only count the quantity of channels that exist at any radial distance, *r*, away from the delta apex. L_D is a function of local channel width, so as channels bifurcate and narrow near the basin, L_D also decreases. This characterizes a pattern of smaller inter-channel islands forming further away from the delta apex. Fig. 1 illustrates the proposed delta model organization. Currently, this model assumes axial symmetry in which bifurcations distribute water and sediment evenly at all points. The Depositional Web model relates the channel network with inter-channel deposition to understand how vacant space is filled.

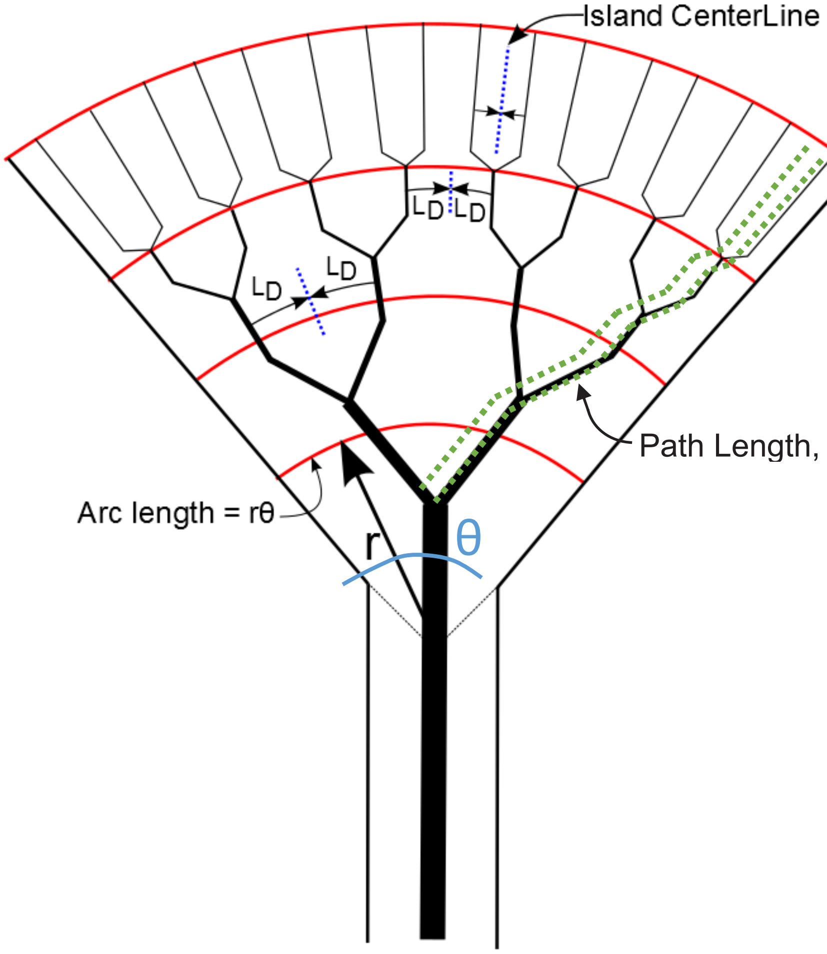

Fig. 1. Diagram of the depositional web model. The channel network and spatial bifurcation rate are symmetric, i.e. all channels a distance r from the delta apex have identical discharge*, channel depth, channel width, slope,* and channel bed elevation. The thickness of each line can represent the cascade for both *discharge and width* with distance away from the delta apex; this model carries the assumption that the input *discharge* is split evenly between bifurcate channels. The deposition length, L_D, is a function of local channel width, so it decreases as channel *width* decreases down-delta. This diagram is the simplest solution to this model, as the angle of delta span is held constant in *r*.

Recent work by Li et al. (2014) develops an empirical formulation for the dimensionless formative Shields number, τ^*_{form} , which is dependent on mean bed slope and Van Rijn's (1984) dimensionless grain size. Previous models (e.g., Kostic and Parker, 2003; Parker et al., 2008; Kim et al., 2009) have used a constant value for τ^*_{form} presented by Parker et al., 1998 and Dade and Friend, 1998; this term allows channel width to change, but results tend to predict over-deepening and over-narrowing of channels near the basin

(Czapiga et al., 2013; Li et al., 2014). The Li et al. closure improves on these results and application to a *1-D* Delta model shows values that are more realistic for the Fly River Delta (Czapiga et al., 2013). We extend this closure into our Depositional Web model for prediction of channel width.

The channel network is developed through a spatial bifurcation rate, which is still under construction at this time. Current methods attempt to relate the bifurcation rate to local channel width or local backwater length. Active delta width at any radial distance, r, from the apex is the sum of the number of channels, channel widths, and depositional lengths of those channels.

The model is quasi-steady and based on the *1-D* shallow water equations for hydraulics and a modified distributed Exner equation for elevation change and progradation rate. The hydraulics are computed along the channel path length, r_p, and elevations are computed along radial length, r (Fig. 1). Elevations are split into channel, floodplain, and average elevations. The traditional Exner equation is computed with an average delta elevation and the channel and floodplain elevations are found via a geometric average weighted by channel and floodplain widths, respectively. Progradation is computed with a shock condition as done previously by Swenson et al., 2000, Kostic and Parker, 2003, etc. During each time step, the model computes hydraulics, channel network, average, channel bed, and floodplain elevations and a progradation distance, then steps forward in time.

The model is a work in progress, but an analytical solution using the normal flow assumption has shown promise that a more sophisticated version with a backwater implementation will be successful. This model will develop a methodology that explains how deltas select their channel networks and fill space while prograding into a basin.

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STUDYING OF DYNAMICS OF THE SELENGA RIVER DELTA BY MEANS OF GEOINFORMATION TECHNOLOGIES

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Abstract: The purpose of this work is studying of dynamics of the delta of Selenga from 1983 for 2001 by means of geoinformation technologies. As the software for geoinformation method of studying of the Selenga river delta the full-function program ArcGIS 10.1 complex and the program for vectorization of raster images of EasyTrace 8.3 were used. The card of dynamics of the Selenga River and the card of change of the area of lakes during the specified period were as a result constructed. The analysis of cards and made calculations showed a considerable decrease of the area of the delta and increase in the area of lakes for considered time.
Keywords: Selenga river delta, digital elevation model, changes

Computer simulation provides great opportunities in the examination of river deltas, by which it is possible to predict the changes caused by a complex and multifactor hydrological and geomorphological processes that form the delta, as well as anthropogenic interference with their natural flow.

The aim of this work is to study the dynamics of the Selenga delta for the period from 1983 to 2001 using geographic information technologies.

Selenga – is the largest river flowing into Lake Baikal in the south-east. At the confluence of the river forms a vast lake mouth area related to a group of delta. Selenga River Delta – a unique natural formation formed during long-term interaction between the system "Lake Baikal – the Selenga River." It juts out into the waters of the lake as a semicircle being confined to the south-west Gulf CherkalovSor, from the north-east – the Proval bay. Topside area of the delta of Selenga river is 550 km^2, with delta front – about 1120 km^2 (Ilicheva et al., 2014).

The initial data for the constructions of the project were topographic maps from 1983 and from 2001 the scale of 1: 100000. As the software for geo-information method of studying the delta of Selenga river were used a full-featured software package ArcGIS 10.1 (ESRI Inc.), modules ArcGIS 3D Analyst and Spatial Analyst and software for vectorization of raster images (vectorizer) EasyTrace 8.3 (Easy Trace Group). Digital elevation model (DEM) of the delta of Selenga river was created in ArcGIS 10.1 (ESRI Inc.) using 3D Analyst module using Delaunay triangulation. As the initial data wereused digitized, topographic based horizontals. As additional data, polygonal and linear features of the hydrographic network were used, which contributed in the calculation of the DEM as a clear line of inflection of the relief (the edges of the triangles), and polygons lakes with known water's edge – a flat surface replacement of one height. As the result, triangulated irregular network (TIN) and based on it – the hypsometric map were built.

Map of dynamics of Selenga river for 1983-2001 years (Fig. 1) was created in ArcMap by applying to the hypsometric map from 1983 layers of the hydrographic network and the border of the delta data from 2001.

Also, a map of the delta area changes by sector was created (Fig. 2), which were added to the layer boundaries sectors identified in three main areas of the effluent: Lobanovsky, Sredneustevsky, Selenginsky (Information…, 2013), as well as changes in the area of the delta layer.

Calculation of changes in the area of the delta was conducted by allocating ranges of growth or decline in the additional layer and statistics functions in the table of contents of this layer.

The calculation showed that in the period under review there was a growth area of the delta only Selenga sector by 2.32 km^2, Lobanovsky sector changes are small and are all about decrease (0.5 km^2), and in Sredneustevsky sector area decreased by 43.4 km^2.

Map of changes in lakes area (Fig. 3) in the period under review was constructed by overlapping the hypsometric map layers of lake area in 1983 and 2001, using the statistics tool their area and increase in water surface area of 25.9 km^2 were discovered.

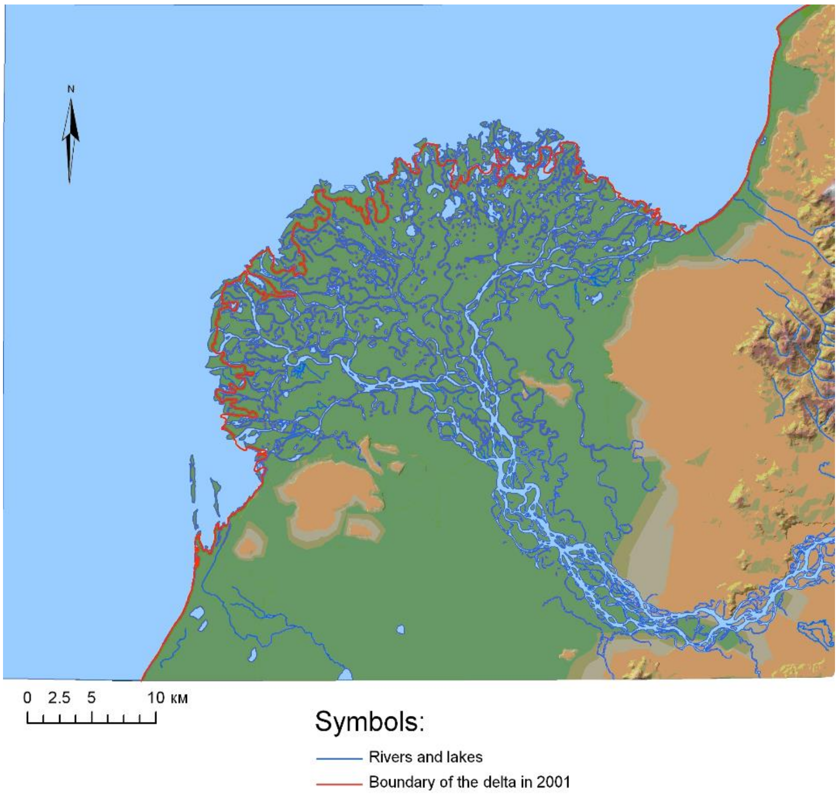

Fig. 1. Map of dynamics of Selenga river for 1983-2001 years

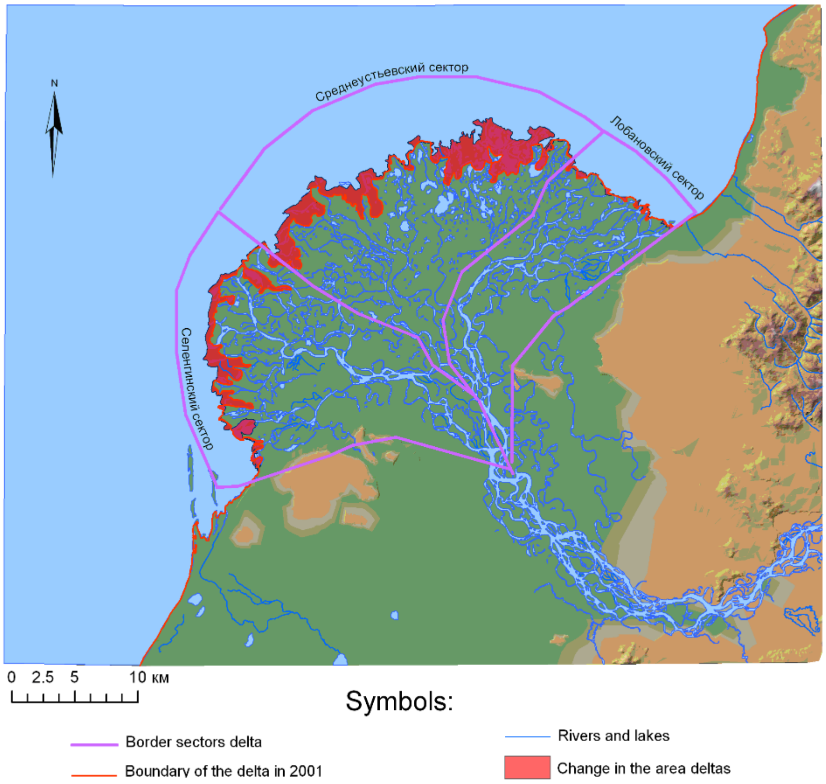

Fig. 2. Map of the delta area changes by sector for 1983-2001 years

An analysis of the constructed maps and produced on their basis calculations revealed that between 1983 and 2001 there was a significant reduction in the area of the delta of the Selenga River and the increase in the water surface of lakes on its territory. Most of these changes account for Sredneustevsky sector, due to a small fraction of the water flow and sediment in its ducts. Selenginsky and Lobanovsky sector, including large sleeves and having a relatively higher level of sedimentation, sustained over the period and experienced less significant changes. Also overregulation of the Lake Baikal after his recovery has led to flooding and groundwater backwater area of the delta, that, as one of the factors that led to the increase in the area of lakes and reduce the surface part of the delta of the Selenga River (Ivanov et al., 2007).

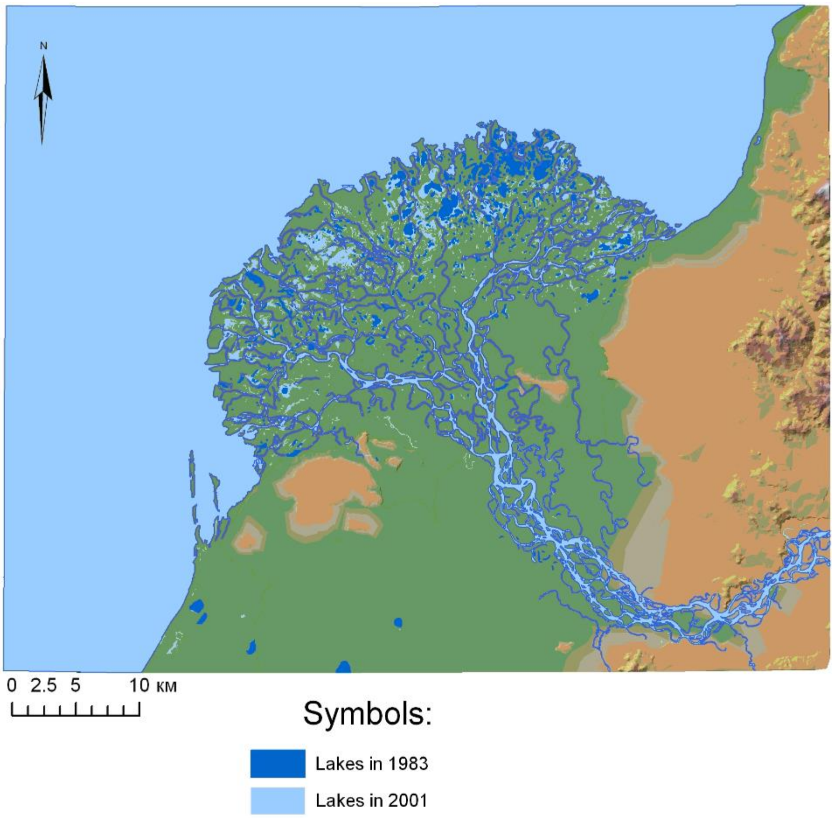

Fig. 3. Map of changes in lakes area for 1983-2001 years

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FRESH VERSUS SALT-WATER DELTAS

THE EFFECT OF WAVES ON THE SHAPE OF DELTAS

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River deltas are dynamic and complex depositional landforms, shaped by fluvial processes often in conjunction or competition with marine influences. This presentation addressed the effect of waves on delta evolution, with a particular emphasis on plan-view delta shape. Building upon concepts of shoreline development set forth by Zenkovich half a century ago (1959, 1967), recent numerical modeling research with the Coastline Evolution Model (CEM) has emphasized the importance of wave approach angle upon alongshore sediment transport and resulting shoreline form (Ashton and Murray, 2006). Numerical modeling is able to capture many self-organizing shoreline features arising from the presence of a maximum in alongshore sediment transport when waves approach from large oblique angles to the coast (Ashton and Murray, 2006; Ashton et al., 2009), developing a deeper process understanding of features previously identified by Zenkovich (1959, 1967).

With application to deltas, CEM model results suggest that if sediment is able to freely bypass a river channel, the spread in wave approach angles can have a first-order control on delta plain widths and river progradation rates (Fig. 1). This planform asymmetry can include the development of discrete breaks in shoreline orientation and the appearance of self-organized features arising from shoreline instability along the downdrift delta flank, such as spits and migrating shoreline sand waves—features observed on natural deltas. Somewhat surprisingly, waves approaching preferentially from one direction tend to increase sediment deposition updrift of the river. This 'morphodynamic groin effect' occurs when the delta's planform aspect ratio is sufficiently large such that the orientation of the shoreline on the downdrift flank is rotated past the angle of maximum alongshore sediment transport, resulting in preferential redirection of fluvial sediment updrift of the river mouth, which has implications for computing mass balances on growing deltas (Mikhailova, 1995).

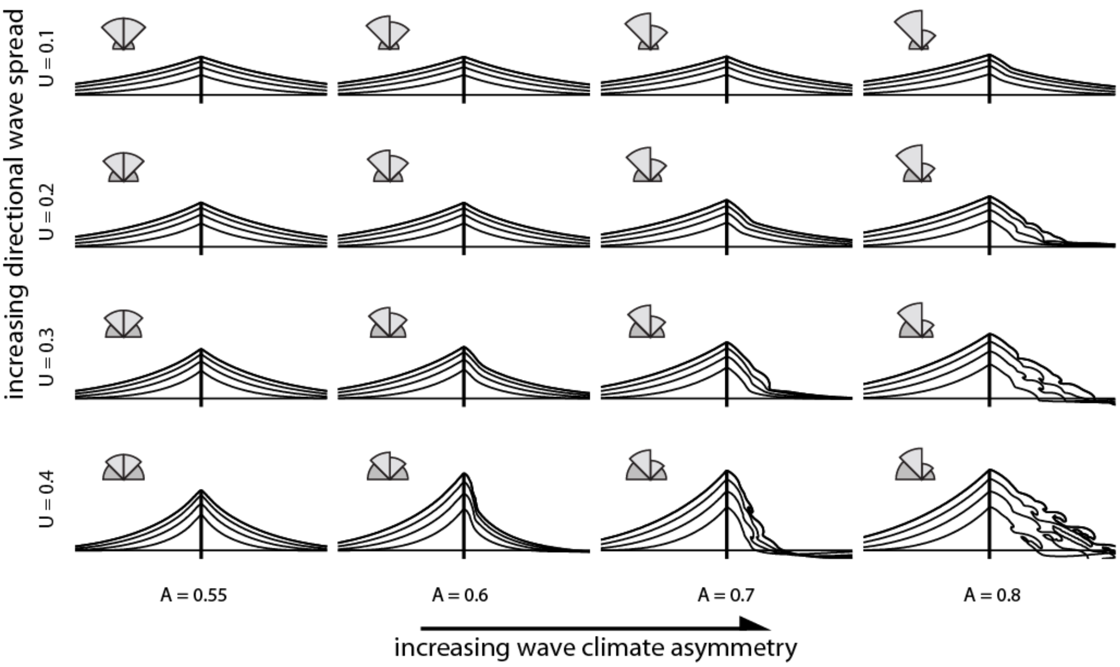

Fig. 1. Modeled planform delta geometries for different wave approach angle climate. Note that fluvial input and wave height is the same for all cases. From Ashton and Giosan (2011)

Cuspate deltas with sharply protruding coastlines are approaching the limit of wave influence, and an increase of sediment supply could transition to a river-dominated morphology. We hypothesize that wave dominance requires that the magnitude of the fluvial influx of shoreface-compatible sediment to the nearshore region be less than the capacity of waves to move sediment alongshore away from the river mouth. Defining a fluvial dominance ratio of river sediment input versus the potential maximum sustained alongshore sediment transport away from the delta mouth allows a quantitative assessment of this sediment transport balance. We find for natural examples that shoreline deflection increases as this fluvial dominance ratio does, and that this river dominance ratio generally predicts the observed transition from wave-to-fluvial dominance. Sharply protruding wave-dominated deltas are the most sensitive to changes in environmental forcings, and may be able to transition in morphology for moderate changes in sediment influx. This approach can help predict the potential morphology of artificial deltas created by engineered sediment diversions.

A cessation of fluvial sediment delivery, either from dam construction or a river avulsion, can result in different modes of delta reworking, ranging from shoreline diffusion to the generation of alongshore-extending spits (Fig. 2) (Nienhuis et al., 2013). Results are compared to examples of wave-influenced deltas found worldwide, including those of the Nile, Ebro, and Rhone rivers. Our results provide quantitative insight into the potential evolution of active delta environments in light of future extreme reduction of fluvial sediment input. Overall, this research emphasizes the often overlooked influence of marine processes, namely waves, on delta morphology and evolution.

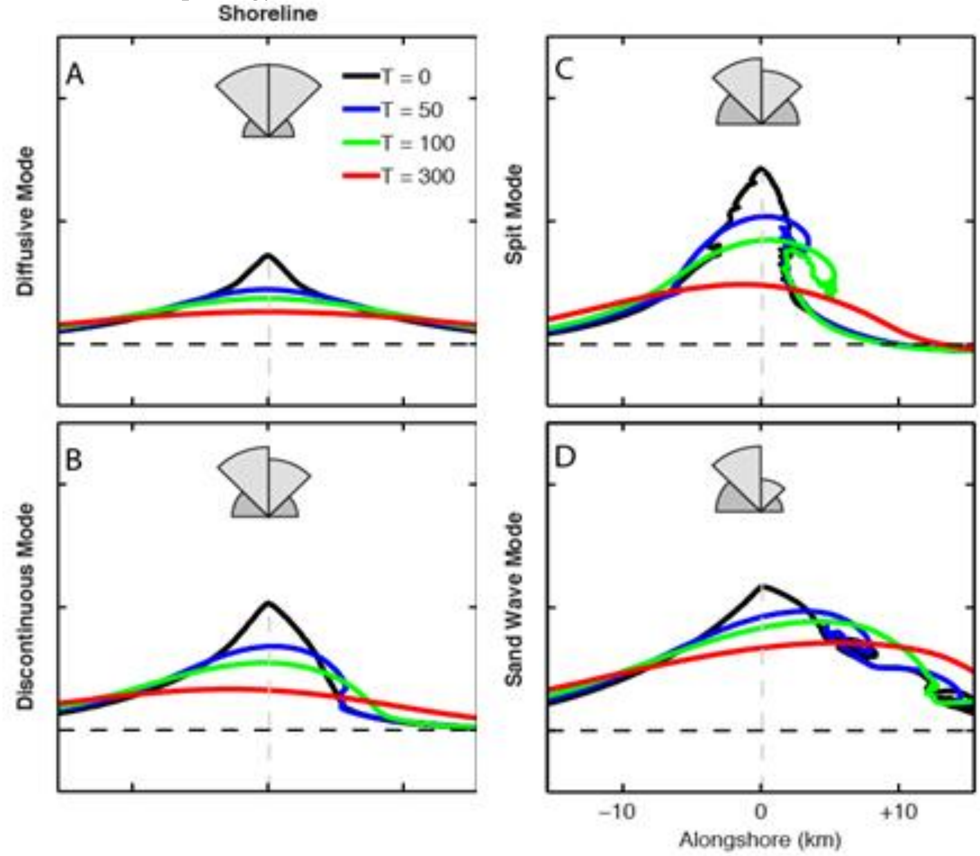

Fig. 2. Model simulation results showing modes of reworking of deltas after reduction of sediment input, including A) smooth diffusive shoreline, B) discontinuous shoreline, C) growing spit, and D) shoreline sandwaves. After Nienhuis et al. (2013)

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BACKWATER ZONE FLUCTUATIONS IN FRESHWATER RESERVOIR DELTAS

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Typical marine deltas exhibit morphodynamic processes at a range of scales up to the sizes of backwater zones. They generally experience very consistent base level conditions over the timescales of formation of a single delta lobe. The most obvious exceptions are periods of sea level fluctuation due to changes in continental ice sheets. Deltas constructed in lakes behind dammed rivers give a stark contrast to this. Impounded rivers flow into bodies of water that typically provide a much wider range of base level conditions than their marine counterparts. This is the result of complex combinations of hydrologic cycles and management of river basins. In these lakes, base level can exhibit large fluctuations at sub-annual scales, and backwater zones must migrate as base level changes. This affects sediment transport conditions throughout a delta and has substantial implications for the relative importance of the record of autogenic and allogenic processes in a delta's stratigraphy.

I hypothesize that a fundamental controlling parameter is the ratio of a characteristic change in base level, $\Delta\sigma$, to a characteristic depth, H, of a river channel at the end of a normal flow reach (Fig. 1). A characteristic base level change is defined here as a vertical scale of base level change over the period of deposition of a single delta lobe. Naturally, avulsion is influenced by base level change and therefore the avulsion timescale itself is not in this definition. The controlling ratio very closely approximates the length that an avulsion node would migrate during base level change, L, relative to the length of a backwater zone itself, L_B. When channels are much deeper than a characteristic base level change, backwater zones are relatively immobile and compensational stacking should be the dominant process of delta-scale stratigraphy. When channel depths are small relative to fluctuations in base level, backwater zones move distances larger than the backwater zone itself. As a result of these latter conditions, a delta is likely to produce stratigraphy that is substantially modulated by base level changes including a long-lived channel with potential cut-fill episodes.

These conditions are evident in freshwater deltas of impounded rivers throughout the world. Although their lakes are an obvious place to look for this control on depositional architecture, the signature of base level fluctuations are hypothesized to be recorded wherever they are large relative to channel depths.

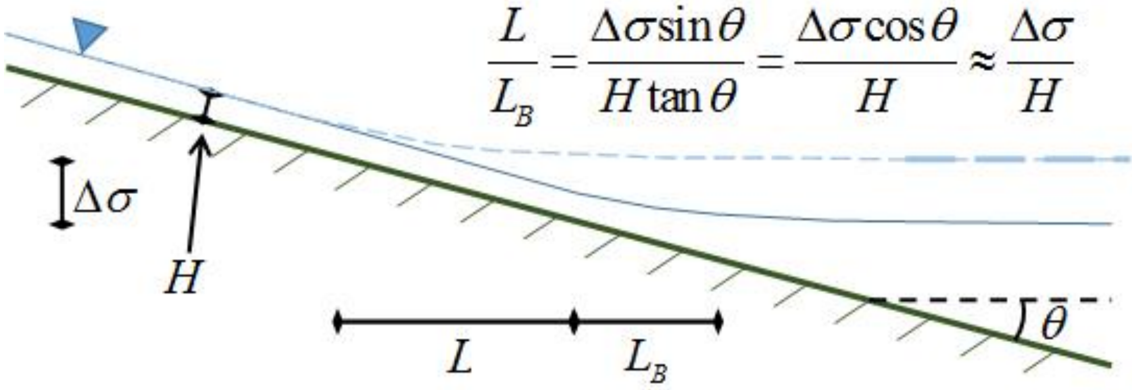

Fig. 1. Definition sketch for backwater zone migration

HYRAULIC GEOMETRY OF TIDALLY INFLUENCED RIVER DELTAS

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Interpreting the geometry of river deltas in terms of physical processes is highly challenging. Looking at the planform of a river delta influenced by tides, distributary channels can often readily be distinguished from tidal channels, which show a more rapid width convergence and a higher sinuosity. The delta planform encrypts detailed information about tidal dynamics and the division of river discharge over distributary channels. The concept of downstream hydraulic geometry (HG) can be used to decipher this information, adding diurnal and semidiurnal tidal velocity amplitudes to the existing set of parameters in HG relations such as channel velocity, width and depth. Results from the Mahakam Delta (Indonesia) show a break in scaling behaviour along an arc that splits the area between the delta apex and the coastline in two parts (Sassi et al., 2011). The tidal influence on flow in the channels is reflected by the systematic variation of the exponents in the power law HG relations. The channel geometry of the river-dominated part of the distributary network scales with bifurcation order, similar to what has previously been found in river deltas. In the tide-dominated part of the delta, distributary channels resemble funnel shaped estuarine channels, where discharge distribution functions are influenced by river-tide interactions.

The tidal motion in deltas cannot be viewed separately from the river discharge. Continuous time-series of river discharge from acoustics-based measurement methods (Hoitink et al., 2009; Sassi et al., 2011a; Hidayat et al., 2012) showed that the tidal averaged discharge can increase while the tidal averaged water level decreases, and vice versa. This was explained from theoretical analyses, quantifying all terms in the Saint Venant Equations based on field data (Buschman, 2009; Sassi et al, 2014). A river discharge superimposed on the tidal motion creates a tidal-mean water level setup related to friction, which can reach beyond the point of tidal extinction. In deltas, this water level setup may vary between different distributaries, which we term differential water level setup (Sassi et al., 2011b). Differential water level setup directly impacts the distribution of river discharge and sediment over the downstream distributaries. Tides further impact the division of water and sediment at junctions by generating Stokes fluxes, which occur when the vertical tide is not in counter phase with tidal velocity (Buschman et al., 2010). In a single channel estuary, the Stokes flux is typically compensated for by a residual return flow generated by the water level setup, but in tidal channel networks the Stokes flux entering the network in one distributary may leave the system via another channel. The complexity of the division of water and sediment over downstream branches further increases in near-coastal areas, where salinity stratification impacts the water motion. The associated gravitational circulation promotes near-surface flows to become seaward, and steers near-bottom flow landward. Again, there are large differences in the degree in which this occurs between the major distributaries. This results in highly dynamic flow processes at junctions, where channels subject to different regimes meet (Buschman et al., 2013). The generalised implication of the mechanisms described above on delta morphology is that tides act to let the distribution of sediment over distributaries become more uniform, stabilizing channel morphology. Locally, and especially near junctions, the tides enhance morphological complexity as a result of the asymmetry between ebb and flood currents.

Ongoing efforts are focussed on the Kapuas Delta (Indonesia), the Pearl Delta (China), and the Rhine-Meuse Delta (the Netherlands). The Kapuas Delta is a nearly pristine system, featuring a planform that resembles an Escher image. The Pearl Delta and the Rhine-Meuse Delta are heavily engineered causing disruption of the natural HG, which bears consequences for extreme water levels (Vellinga et al., 2014), salinity intrusion (Zhang et al., 2012) and residual sediment transport patterns (Zhang et al., 2013).

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QUANTIFYING CHANNEL DYNAMICS IN NUMERICALLY SIMULATED DELTA STRATIGRAPHY

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Introduction

The most widely used classification of river delta morphologies (Galloway, 1975) holds that the surface characteristics of a delta, including the distribution of depositional environments and shoreline shape, can be predicted by the relative strengths of the fluvial and marine processes that influence the delta. Though almost 40 years old, the Galloway ternary diagram of wave, river, and tide dominated deltas is still widely referred to in textbooks and in literature, and has commonly been used as a starting point to develop models that describe the distribution of facies and morphological features in coastal deltaic systems (e.g. Dalrymple et al., 1992; Roberts, 1997; Bhattacharya and Giosan, 2003). More recent workers have pointed out the perils of relying too heavily on so simple a classification system (Edmonds and Slingerland, 2009; Romans and Graham, 2013), but as a basic conceptual model of delta morphologies the Galloway diagram seems secure.

What is often forgotten, though, is that Galloway's article was originally written to present both a morphological and a stratigraphic model. And while the morphological Galloway diagram has obtained wide acceptance as a way of describing the relationship between morphological processes and the distribution of depositional environments over a single delta "event" (such as the progradation of one delta lobe) there is no similar classification scheme that addresses the ways that deltas, under various forcing conditions, are preserved over deeper timescales that include many such events. Sequences of depositional events act to set the architecture of entire sedimentary basins, so it is important to gain an understanding of how coastal and fluvial processes affect the preservation of deltaic stratigraphy over basin-filling timescales.

The goal of this project is to use measurements of autogenic behavior in channelized depositional systems to examine the formation of stratigraphy in river deltas deposited across a range of forcing conditions. To do this, we use Delft3D to numerically simulate the development of thick packages of deltaic stratigraphy (>10 channel depths thick) under the influence of a range of river, tide, and flood-dominated conditions.

Delft3D is a feature-rich hydrodynamic modeling suite that is commonly used to simulate water and sediment transport in coastal and deltaic settings (Lesser et al., 2004). We use Delft3D to simulate the development of stratigraphy over much longer timescales than the software is designed for in order to integrate information about depositional environment and the local physical conditions into the simulated stratigraphy. In effect, this approach drags information about sediment transport processes into long term stratigraphic simulations in a way that is not possible with models that are developed specifically to simulate long timescales.

The primary measure of autogenic behavior that we will use in the proposed study is the Compensation Index, as described in Straub et al.(2009), which has been observed to vary systematically in field scale systems, and in experimental deltas deposited under a range of river dominated conditions (Straub et al., 2009; Straub and Wang, 2013). This work will extend that range into deltas with significant tide, and flood influence.

Research Questions and Hypotheses

The primary goal of this work is to examine the ways in which environmental signals relating to marine processes are transferred into the stratigraphic record. Previous studies (Straub and Esposito, 2013; Straub and Wang, 2013] have used physical laboratory experiments to examine the effects of variable sediment and water inputs on the compensation index and completeness, but common natural processes such as tides and floods have not been explored. As a starting point for this study, we reason that tides act to make the interface between the river and the receiving basin more energetic and chaotic. Since stratigraphic completeness depends on sediment being deposited and then left in place, we hypothesize that simulations with waves and tides will result in lower completeness values. Conversely, we see that tides can act to stabilize channels, resulting in lowered compensation indices. We also see floods as a mechanism to stabilize channels, and expect deltas with significant flood influence to display lower compensation indices than their less flood prone counterparts.

A secondary goal of this project is to demonstrate how to use a model like Delft3D, which is designed to investigate short term (days to months) coastal processes, to simulate the development of delta stratigraphy over basin filling time scales. Hajek and Wolinsky (2012) suggest a method of "bootstrapping" models so that results from a short timescale model are used as input to longer timescale simulations, essentially piggybacking a long term model on top of the results from a short term one. Here we take a different approach; we demonstrate how a short term model can be simplified in order to simulate a system over long timescales. The models we use are simple enough to generate a data set that addresses the timescales that are observable in reduced complexity models, but with the firm physical foundation of a high quality hydrodynamic solver. This approach allows the researcher to investigate more fully the causes of and dynamic response to autogenic behavior.

Modeling Methods

Here we present simulations of three deltas. Our River case simulates a river whose discharge is absolutely constant in time, discharging into a basin with no tide or wave energy. The Tide case tests the influence of a downstream tidal signal, while the Flood case tests the influence of an upstream fluctuation in sediment and water discharge. Each delta discharges into an identically sized basin (see Fig. 1), with identical inputs of sediment and water. In each case the water level at the downstream boundary is steadily raised in order to create enough accommodation to keep the delta's shoreline is approximately constant.

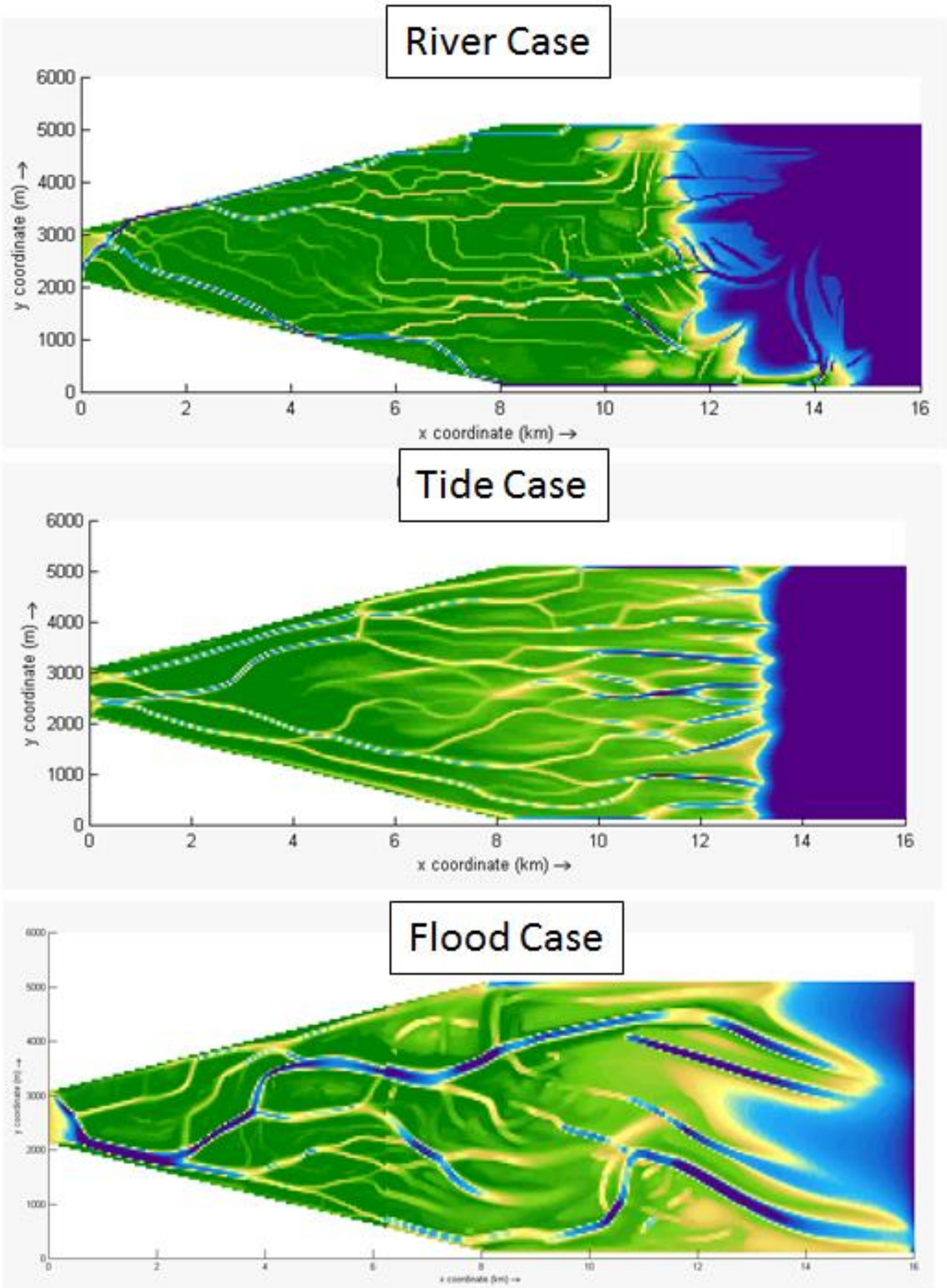

Fig. 2. Plan view of the River (top), Tide (middle), and Flood (bottom) deltas. The basin geometry is identical in each case, consisting of a 16 km long basin that flares outward in the first 8 km

All numerical modeling parameters are the same across all deltas. The only change is the treatment of the upstream and downstream boundaries.

Results

The River delta generates narrow, anastomosing channels in a network that reorganizes through abrupt avulsions. By contrast, the channels of the Tide delta are wider, and move across the delta top by laterally eroding their banks. The shoreline of the Tide dominated delta is significantly more ordered than that of the River only case, and there are no evident interdistributary bays. The Flood influenced delta is the most distinctive case, and typically has only one large trunk channel in operation at a time.

Completeness and Compensation Index

The downstream trend in compensation index for the three simulated deltas is shown in Fig. 2b. For the River and Tide deltas, the compensation index drops from approximately 0.4 on the delta top to 0.1 in the offshore environment, indicating that the depositional trends in the marine environment are more persistent with time. This result is consistent with data from physical models of delta stratigraphy (Wang et al., 2011). The outlier in these simulations is the Floods model, which has an extremely high compensation index upstream, but then drops to extremely low values by the distal edge of the delta top, indicating that a rapid change in the style of preservation occurs over a relatively short distance.

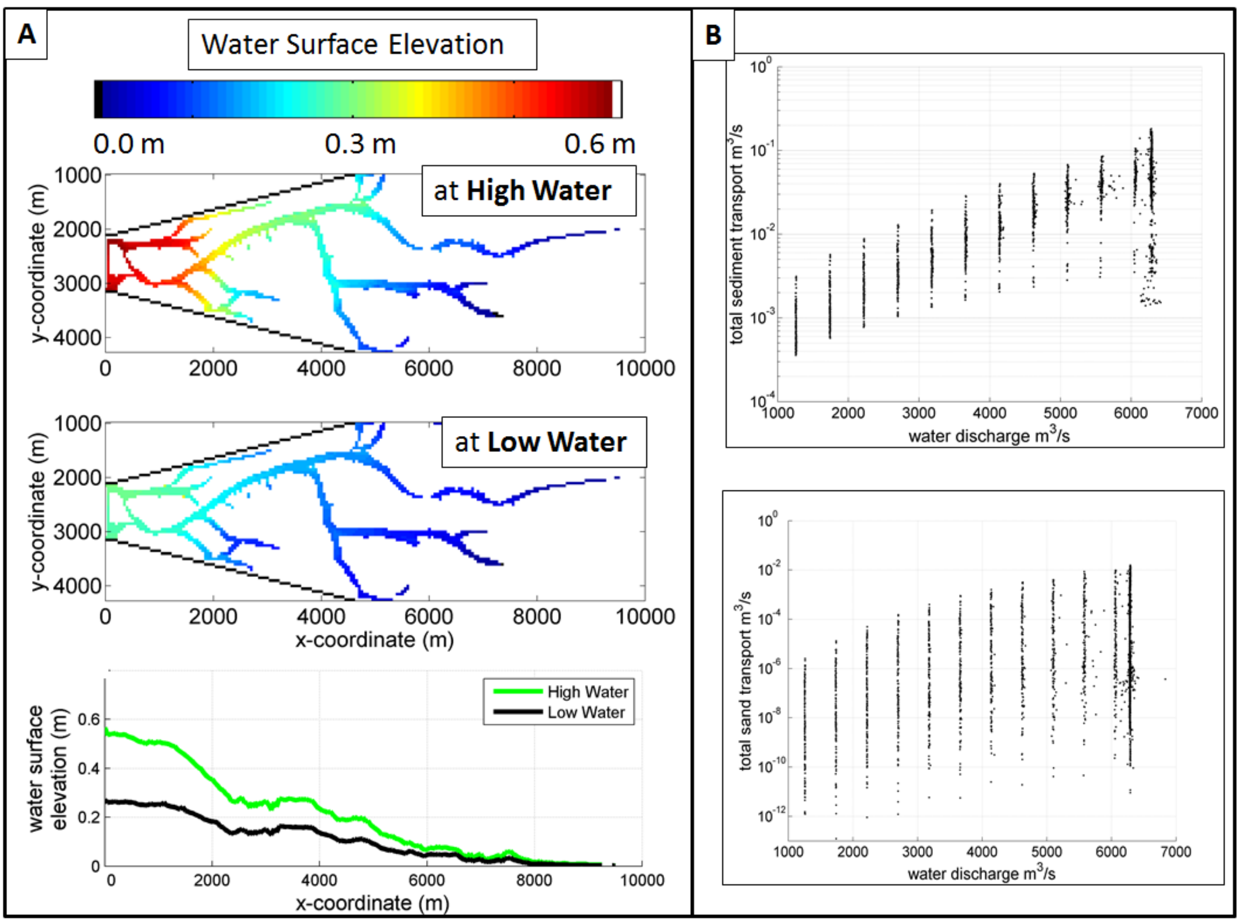

Fig. 3: A) The two top panels show the water surface elevation during a flood and then during the subsequent low water event. The bottom panel compares the slopes of the two conditions. As has been seen in field scale coastal rivers, the upper reaches of the channel respond much more dramatically to discharge variations than the lower reaches, resulting in a divergence in sediment transport rates. B) Sediment discharge as a function of water discharge, showing that a five-fold increase in water discharge results in a change in sediment discharge of several orders of magnitude. Note that the vertical axes are in log scale

Sediment Transport in Floods

We examine the Floods model, armed with recent theory developed for studies on the effects of gradually varied flow on sediment transport in the backwater reaches of coastal rivers. Fig. 2a shows the water surface elevation in the channels. Consistent with models of backwater in coastal rivers (Nittrouer et al., 2011; Lamb et al., 2012), the water surface fluctuates with discharge in the upper reaches but is nearly fixed at the coast. As is the case in natural systems, the resulting change for the in-channel energy gradient leads to significant changes in the sediment transport rates, with the total sediment transport varying several orders of magnitude for a flood whose discharge is only 5 times that of the low water.

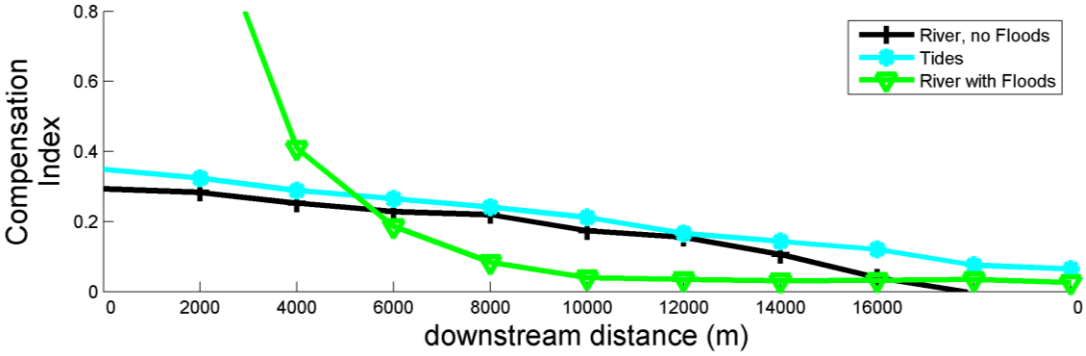

Fig. 4. Downstream trend in Compensation Index

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ANTHROPOGENIC INTERACTIONS, ECOLOGY AND DELTA SUSTAINABILITY

BUILDING LAND IN A DELTA FROM RIVER-SEDIMENT DIVERSIONS: CONSTRAINTS, POTENTIAL, AND EXAMPLES IN THE MISSISSIPPI RIVER DELTA

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Introduction

The natural building of land in a coastal river delta is controlled by interacting rates of sediment supply from a river and organic production (source terms), and the combined effects of sediment retention in the receiving basin, eustatic sea level rise, and local subsidence (sink terms). Temporal and spatial patterns in these interacting controls may be complex. Sediment supply is influenced by river stage and local hydrodynamics. Sediment retention is controlled by sediment type, waves, currents, morphology, and vegetation in the receiving basin. For design and construction of manmade river-sediment diversions to build land, further constraints include a range of human needs.

In river deltas around the world, anthropogenic alteration of both source and sink controls is driving land loss and submergence at accelerating rates. This poses an immediate threat to the 500-1,000 million residents, many in megacities, that live on deltaic coasts. Compounding the problem, most river deltaic coasts are also important regions for agricultural production, fisheries, hydrocarbon production, and shipment of commercial goods. The Mississippi River Delta is a large laboratory in which we can study the negative anthropogenic effects of river engineering, and also our engineering attempts to reverse damaging anthropogenic land loss.

The primary objective of this study is to evaluate these controls, particularly the effects of sediment properties, waves, currents, and basin morphology, in the context of recent studies in the Mississippi River Delta: the West Bay Diversion in the Birdsfoot Delta (Andrus and Bentley, 2007; Andrus et al., 2014) and Caernarvon Diversion/Lake Lery, in the Breton Sound Estuary (Lo et al., 2014).

Caernarvon Diversion and Lake Lery Receiving Basin

Lake Lery is a coastal receiving basin for the Caernarvon Diversion from the Mississippi River (Fig. 1). Lo et al. (2014) studied the related processes of sediment consolidation and resuspension in a coastal basin and how these processes influence retention of fine sediment delivered by a river diversion. Sediment samples were collected from Lake Lery.

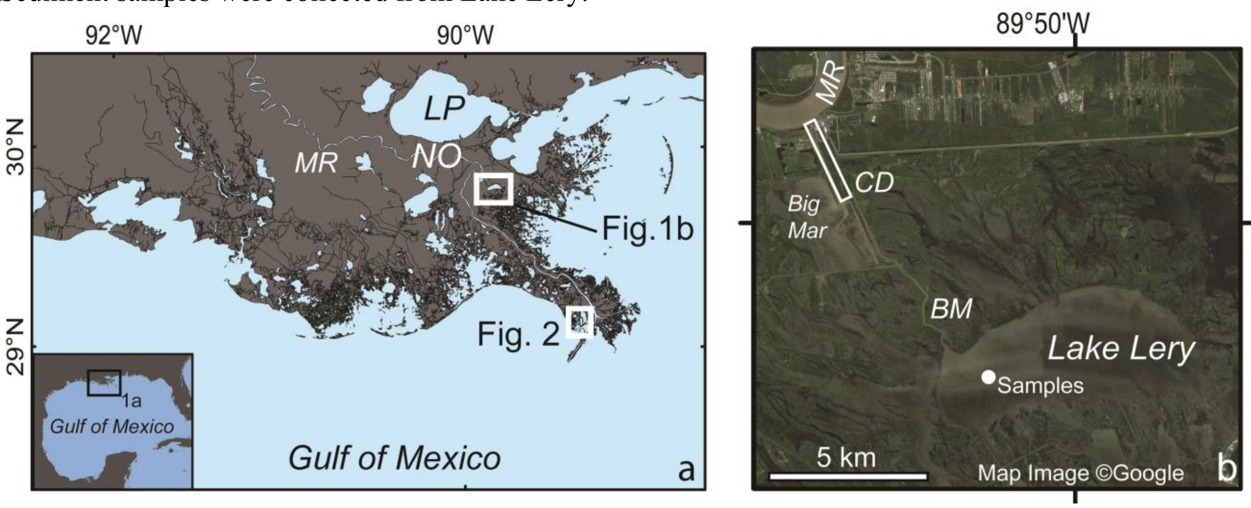

Fig. 1. (A) location of Lake Lery and West Bay study areas in the Mississippi Delta, showing the Mississippi River (MR), New Orleans (NO), and Lake Pontchartrain (LP) for reference. (B) Detail of Lake Lery sampling locations, showing the Mississippi River, Caernarvon Diversion conveyance channel (CD), and Bayou Mandeville (BM) for reference

Consolidation was tested for six initial sediment concentrations (14.0-105 kg·m^{-3}) in a settling column over 15-day periods. Mud erodibility was tested at seven shear stress regimes (0.01-0.60 Pa) using a dual-core Gust erosion microcosm system, on cores containing suspensions that consolidated for 1, 2, and 4 weeks. Consolidation rates were found to be inversely and exponentially related to initial suspension concentration, over concentrations ranging from fluid mud (10-200 kg·m^{-3}) to hydraulic dredge effluent. Consolidation is best predicted by a function consisting of two exponential terms and one asymptotic constant, describing rates of rapid initial and slower subsequent settling. Coupled resuspension and consolidation tests (concentrations of 20-21 kg·m^{-3}) show that shear stresses generating the highest turbidity peaks increase from ≤0.30 Pa after 2 weeks of consolidation to ≥0.45 Pa after 4 weeks (Fig. 2), and this strengthening cannot be attributed solely to increasing sediment concentration over time. Comparison of measured erosion shear stresses to bed shear stresses typical of coastal lakes and bays suggest that this degree of strengthening, if given time to occur, could increase the overall retention of fine sediments deposited on lake and bay floors.

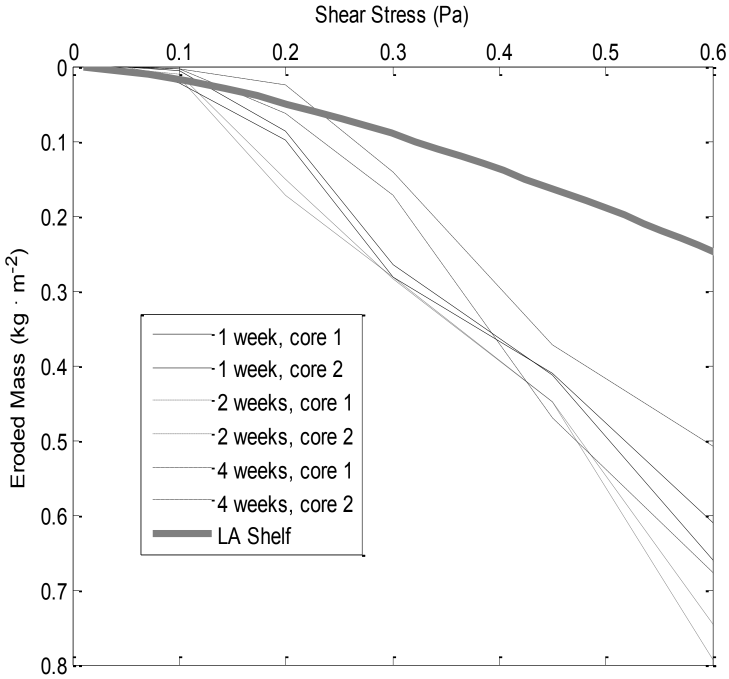

Fig. 2. Time-series of cumulative sediment erosion in Gust Erosion Microcosms. Note the decrease in sediment mass erosion from the week one and two tests to the week four test, indicating an increase in erosion shear stress of >0.1 Pa, sufficient to resist erosion by locally generated waves. After Lo et al., 2014

West Bay Diversion

The West Bay Diversion was opened in 2004 on the east bank of the Mississippi River near Head of Passes, as the first moderate to large river-sediment diversion in the lower Mississippi River designed to build land. Andrus and Bentley (2007) and Andrus et al. (2012) studied sediment delivery to and retention in the receiving basin, which is a relatively open, wave-swept coastal bay (Fig. 3), compared to Lake Lery (see Fig. 1). Andrus and Bentley (2007) determined that, as of 2007, the ratio of sediment delivered to sediment accumulating (retention rate) was ~0.25, indicating that ~75% of sediment delivered by the diversion was escaping to the coastal ocean, and not contributing to land-building. Despite this, by 2011, land was emergent, and a new subdelta lobe was building (Kolker et al., 2012). Some of the sediment accumulation was attributed to the effects of two dredge-spoil islands placed in the central part of West Bay, which may have reduced local wave resuspension.

To evaluate the possible effects of waves on sediment retention, Andrus et al. (2012) developed a wave model for West Bay using STWAVE comparing waves pre- and post-island construction, and evaluated it for a set of characteristic wind fields for the region. Fig. 3 shows the difference in wave height produced by the addition of the dredge spoil islands. The intermediate to maximum decrease in wave height of 10-20 cm (for very small waves in shallow water) yields reduction in bed shear stresses comparable to the shear-stress reduction suggested by Lo et al. (2014) that would be required to reduce local sediment resuspension. These results collectively suggest that design of diversion receiving basins to minimize wave fetch and reduce wave height is an effective approach to increasing sediment retention in river-sediment diversions designed for coastal restoration.

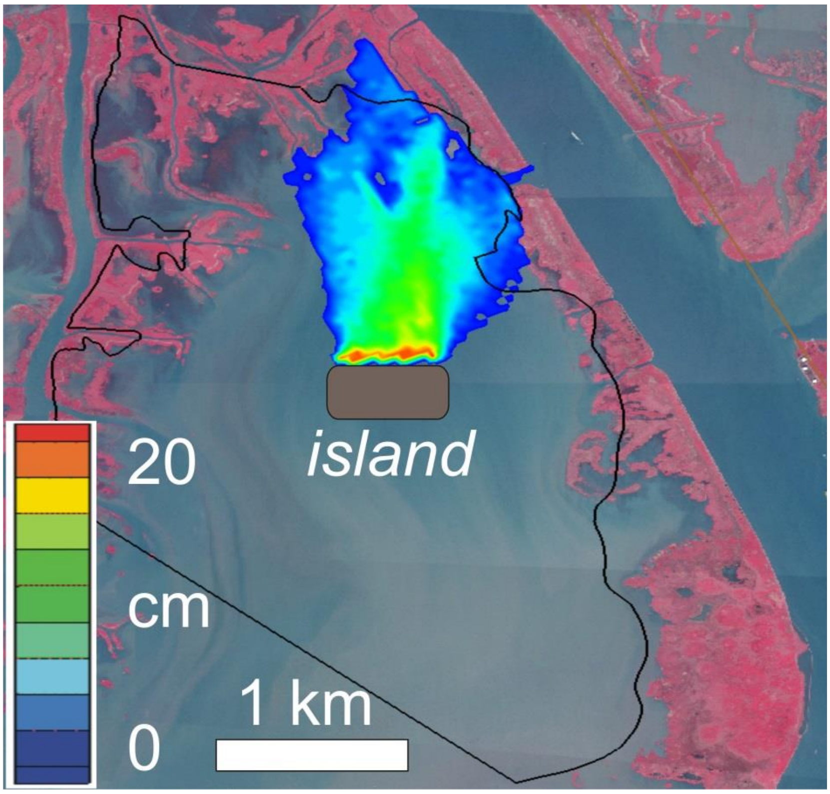

Fig. 3. False-color satellite image of West Bay, with schematic of dredge-spoil island location, and plot of wave-height reduction produced by island construction. Bar scale of wave-height change in cm

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THE DEVELOPMENT OF A DELTA OBSERVATORY TO TEST HYPOTHESES ON THE BIOGEOCHEMISTRY OF COASTAL DELTAIC FLOODPLAINS

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Coastal Louisiana, like all river-dominated deltaic earth surfaces, is a highly dynamic environment (Paola et al., 2011). This succession of lobe formation follows the well-established cyclic nature of delta development. Briefly, after a distributary captures the river, there is a period of rapid subaerial growth (regressive phase) of newly emerged landforms followed by relative stability. These soils are dominated by mineral sediment, and much like the classic Walker and Syers (1976) model of soil development, are rich in phosphorus and poor in nitrogen content. Developmentally young systems tend to exhibit nitrogen limited plant growth and support symbiotic nitrogen fixation. As soils develop, they generally show a marked decrease in phosphorus coupled to an increase in nitrogen. Coinciding with increased nitrogen availability are increased rates of nitrogen mineralization, nitrification, and nitrous oxide production. With time, the increase in nitrogen shifts plant growth to phosphorus limitation. Whereas the Walker and Syers (1976) conceptual model has been extensively applied to describe long-term patterns of soil development, nutrient availability, and plant succession in terrestrial ecosystems, no work to date applies their model to short-term evolution of biogeochemical processes during delta formation.

The biogeochemical model associated with deltaic wetland succession is important to understanding how these wetlands reduce nitrogen loading to coastal and offshore environments. Today, the Mississippi River delta is losing extensive areas of wetland because the delta is cut off from the sediment supply of the river. To stimulate wetland development and mitigate further loss, large-scale restoration efforts have been proposed to divert freshwater and sediment from the Mississippi River back into coastal bay environments (Louisiana Coastal Master Plan, 2012). These freshwater diversion projects are designed to reduce salinity and increase sediment delivery to the receiving basin by mimicking the historical overbank flooding of the Mississippi River (Twilley and Rivera-Monroy, 2009; Paola et al., 2011). There is a particular interest in the capacity of deltaic wetlands to remove the reactive nitrogen introduced by these diversions via the process of denitrification. Ultimately, the ability of emerging wetlands to reduce the nitrate load in the Mississippi River depends on the development of biogeochemical cycles as sediment deposition from diversions forms primary substrates (Henry and Twilley, 2013).

Located within the Atchafalaya basin of the Mississippi River delta plain, the Wax Lake delta (WLD) provides an ideal ecosystem for the application of Walker and Syers (1976) biogeochemical model of primary substrate formation. The Atchafalaya River begins at the convergence of the Mississippi and the Red Rivers and flows approximately 275 km through the wooded lowland and cypress-tupelo swamps of the Atchafalaya basin before reaching the Gulf of Mexico. At the convergence, the Old River Control Structure stabilizes the Atchafalaya River at 30% of the combined flows of the Mississippi and Red Rivers (mean annual discharge 6,371 $m^3 \cdot s^{-1}$). In 1942, the Wax Lake outlet was constructed to provide flood relief for the lower Atchafalaya. Thirty percent of flow from the Atchafalaya River is diverted through the outlet, approximately 10% of the Mississippi River discharge.

We developed a network of self-activating sensors in coastal marshes of Wax Lake Delta (WLD), LA using a wireless telemetry system, to study the behavior of sediment and nutrients as water filters over an emerging deltaic lobe (Fig. 1). This system of sensors monitors delta behavior during major events (storms, river floods) and complement an intensive survey program to measure ecosystem properties and relate them to high-resolution topography, bathymetry, and flow fields. These data are incorporated into high-resolution, quantitative models incorporating hydrodynamics, biogeochemistry, ecology, and stratigraphy to predict river delta dynamics over engineering to geologic time-scales, and to address questions of system dynamics, resiliency, and sustainability.

The real time water quality monitoring program in the upper (1.75 km length) section of Mike Island (MI) complements the real-time data collection of self-activating sensors installed in permanent platforms in coastal marshes of WLD. The information collected during this intensive monitoring program will be used to calibrate and validate a biogeochemical model developed for MI and to test accuracy of model predictions with field conditions. Thus, this information is critical to understand the functional role of coastal wetlands in sequestering carbon and nutrients and could have tremendous implications as to how aquatic and estuarine ecosystems have the potential to mitigate increased loads of nutrients to ameliorate water quality conditions in coastal Louisiana.

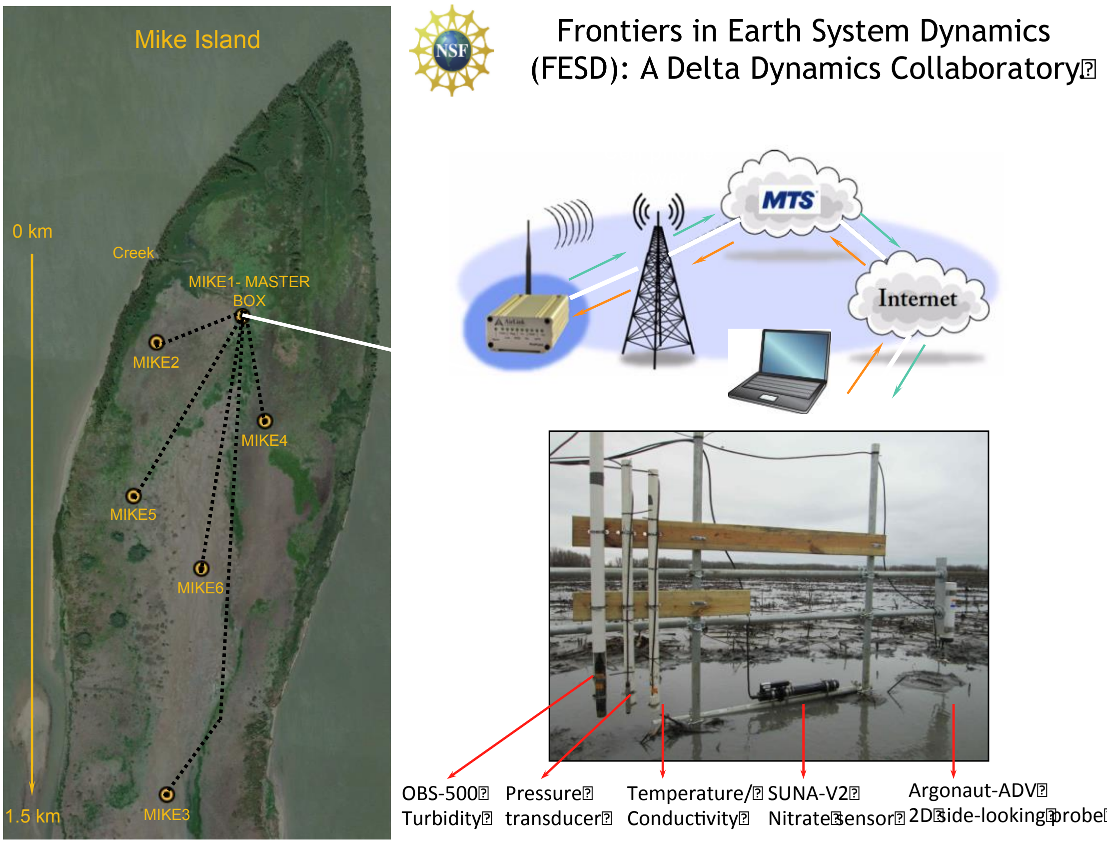

Fig. 1. Map of the six platforms positioned in upstream and downstream locations along Mike Island in Wax Lake Delta

A network of self-activating sensors was installed in six permanent platforms in MI during January and February 2014. These instrument platforms are located within the 30 stations grid survey to capture the observed upstream-downstream gradient in flow paths (west, central, and east side of the island) within MI. Each platform is equipped with sensors that measure water depth (pressure transducer sensor, Campbell Scientific), temperature and conductivity (Campbell Scientific), turbidity (OBS-500, Campbell Scientific), surface water nitrate concentrations (SUNA V2, chemical-free sensor, Satlantic), and water velocity and direction (Argonaut-ADV, Sontek). Data from all sensors are recorded at one-hour interval and stored in a CR-1000 Datalogger (Campbell Scientific) in each platform. Data from all platforms are then transferred to an LSU computer server using a wireless telemetry system equipped with PicoStation 2HP radios (Ubiquity Networks) and a Sierra Wireless Airlink PinPoint X modem. This network system uses a cellular provider (telephony system) as an ISP (Internet Service Provider) for real-time communication. This cellular network system (Code Division Multiple Access – CDMA) is a radio network technology used by many cellular providers across the globe (Figure 1). Power for all sensors and electronic devices is provided by a Lightway 235 watts module solar panel and two Power Patrol batteries (model SLA1185, 12 volts, InterState) that are installed in each platform. Finally, LoggerNet is used as the computer interface software to monitor real-time data collection and storage in the LSU server.

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EPISODIC OVERBANK DEPOSITION AS A DOMINANT MECHANISM OF MISSISSIPPI DELTA AGGRADATION – IMPLICATIONS FOR COASTAL RESTORATION BY RIVER DIVERSIONS

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The long-standing, traditional view that fluviodeltaic aggradation largely occurs as a persistent and gradual process associated with frequent overbank flooding has been challenged by both field and experimental investigations. However, to date no studies exist that quantify overbank deposition in such environments over centennial to millennial timescales, mostly due to the difficulty to develop age models for clastic strata with sufficient resolution. Here we address this problem based on 38 optically stimulated luminescence (OSL) ages from the late Holocene Mississippi Delta. We focus on the upstream reach of Bayou Lafourche (Fig. 1), a precursor of the modern Mississippi River that was active from ~1500 to 600 years ago. We demonstrate that fluviodeltaic aggradation by means of crevasse splays – the dominant mode of overbank deposition in this area – is highly episodic in nature (Fig. 2). In contrast, evidence for gradual overbank deposition is rare. The pattern of OSL age clustering at different localities highlights the strongly autogenic nature of sedimentation. As a consequence, the fluviodeltaic stratigraphic record at any given locality consists of a patch work of discrete sediment bodies, rather than a smooth and continuous record. Century-scale aggradation rates are consistently ~1 to 4 cm/yr, further reflecting the episodic nature of aggradation.

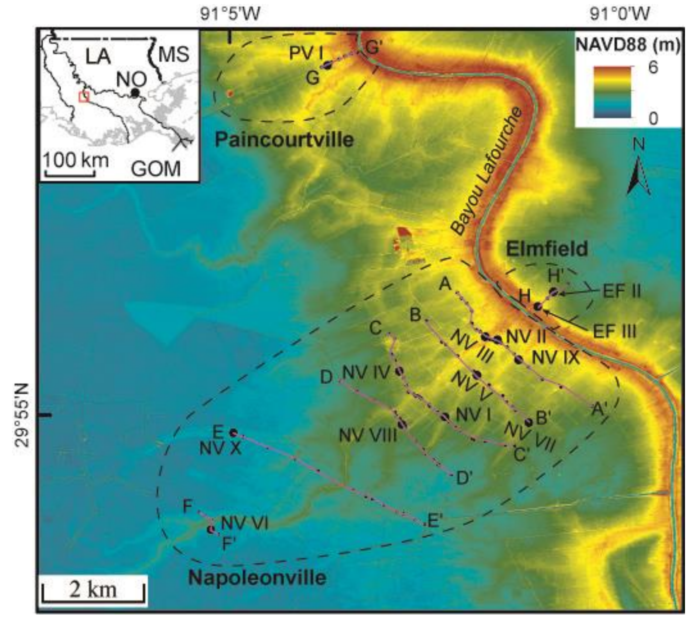

Fig. 1. Digital elevation model (DEM) of the three study areas. The DEM is derived from LiDAR data (provided by the Louisiana State University CADGIS Research Laboratory, Baton Rouge, Louisiana, 2010, accessible at http://atlas.lsu.edu/lidar/); elevations are with reference to the North American Vertical Datum of 1988 (NAVD 88). The three study areas (names in bold) are outlined by the dashed lines. Small and large black dots mark core sites and OSL dated core sites, respectively (NV, Napoleonville; PV, Paincourtville; EF, Elmfield). Purple lines mark cross sections. Inset map shows the location of the study areas with a red rectangle. LA: Louisiana; MS: Mississippi; NO: New Orleans; GOM: Gulf of Mexico

We proceed to examine crevasse-splay evolution as a potential model for coastal restoration by means of river diversions. While the crevasse splay that is the main focus of our study is similar in scale to the widely studied Wax Lake Delta (WLD), it is distinctly different in terms of its grain-size composition, consisting predominantly of silt and only ~5% sand (the WLD contains as much as ~70% sand). We infer that inland crevasse splays are extremely efficient at trapping overbank sediment, with a retention rate for this particular case conservatively estimated at >60%. We attribute this to the fact that this crevasse splay formed in a swamp, where vegetation-induced roughness enhanced the settling of the fine grain-size fractions. In contrast, the WLD is exposed to waves, tides, and currents and hence the majority of the fine fraction is carried farter offshore, resulting in a retention rate of only 20 to 30%. The high crevasse splay retention rate is consistent with the high aggradation rates and suggests that river diversions in settings that are still vegetated are likely to be the most efficient in building new land.

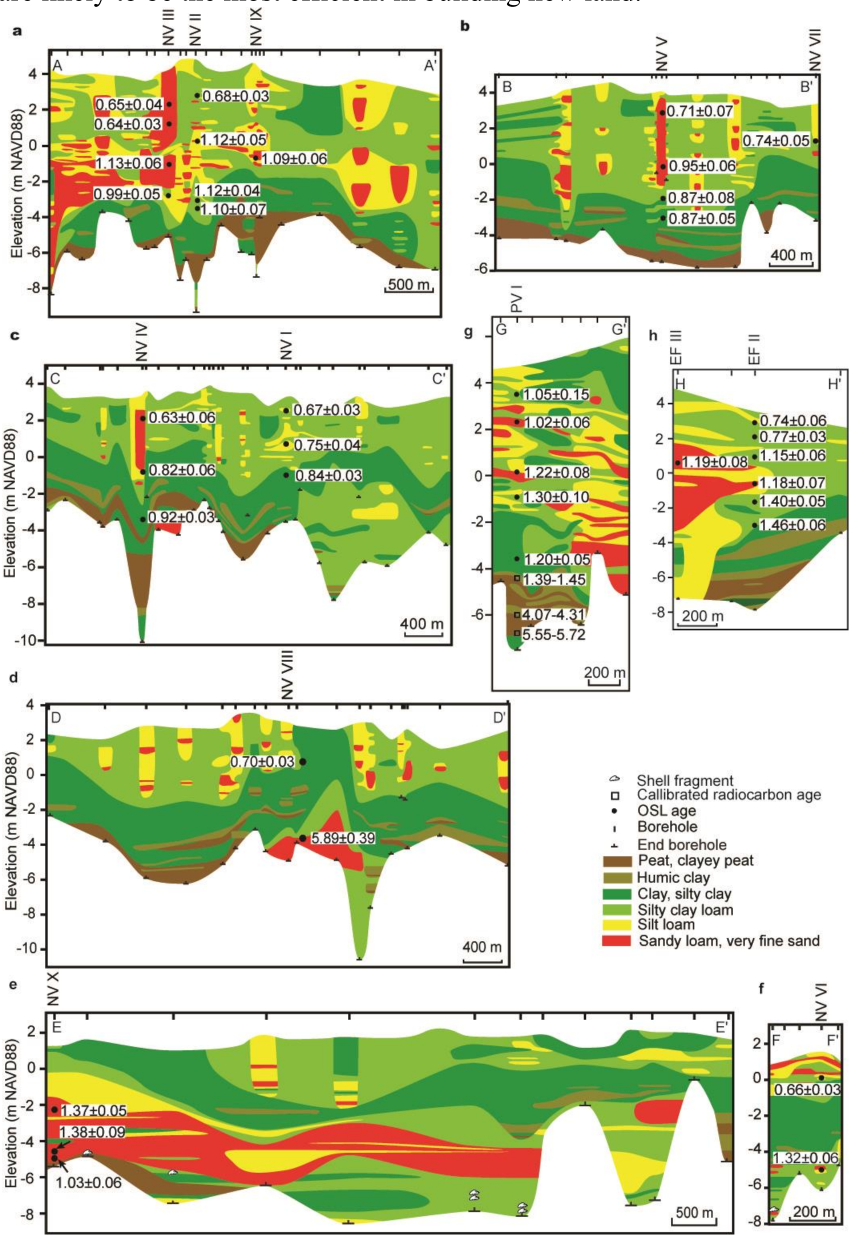

Fig. 2. Cross sections and OSL data in the Napoleonville (**a-f**), Paincourtville (**g**), and Elmfield (**h**) areas. Sediment textures follow the US Department of Agriculture texture classification. All ages are in ka with respect to AD 2010

MODELING THE MORPHODYNAMIC RESPONSE OF THE LOWERMOST MISSISSIPPI RIVER, LOUISIANA, USA, TO ENGINEERED LAND-BUILDING DIVERSIONS

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The lowermost Mississippi River, Louisiana, USA, is defined herein as the approximately 500 km long reach of the Mississippi River hydrodynamically influenced by the Gulf of Mexico (Nittrouer et al., 2012). An approximately 230 km long bedrock reach bounded by an alluvial-bedrock and a bedrock-alluvial transition characterizes this river segment (Nittrouer et al., 2011).

Since the first decades of the last century, land loss and shoreline retreat has been observed and measured in the Mississippi River delta, with land loss rates ranging between 8 and 120 km^2/yr (Craig, 1979; Penland et al., 1990). Engineered land-building diversions are one of the delta restoration projects proposed to mitigate land loss in the Mississippi River Delta in the 2012 Louisiana Coastal Master Plan. A land-building diversion project consists of a hard-engineered diversion structure that captures a significant amount of flow and bed material (sand) from the main channel and diverts them into an engineered distributary channel. The distributary channel conveys the diverted water and sand into a drowned area, where a delta lobe forms and grows under quasi-natural conditions (Paola et al., 2011).

Previous research efforts demonstrated that 1) land-building diversions are a sustainable strategy to build deltaic land on the Louisiana coast (Kim et al., 2009), and 2) the supply of bed material to the Mississippi River delta is steady and it will likely remain constant in the near future, i.e. 2-5 centuries (Nittrouer and Viparelli, 2014). However, none of these studies investigated the morphodynamic response of the lowermost 500 km of the Mississippi River to a land-building diversion project and its effects on navigation and flood control.

We have thus implemented a one-dimensional mathematical formulation that is able to reproduce the morphodynamics of both the alluvial and bedrock reaches of the lowermost Mississippi River channel. Governing equations of the model are the shallow water equations of mass and momentum balance for the flow, and the Exner equation of continuity of channel bed material, i.e. sand, in mixed bedrock-alluvial rivers (Zhang et al., 2014). Suspended sand load and flow resistances are computed with the Wright and Parker (2004 a and b) formulation for large, low-slope sand bed rivers, and the bedload transport rate is estimated with the Ashida and Michiue (1972) relation.

The model is applied to predict the spatial and temporal evolution of the lowermost Mississippi River in response to two hypothetical land-building diversion projects. Model initial and boundary conditions are determined from the available datasets (Viparelli et al., 2014 and references therein). The application is done in three steps. The model is first zeroed to reproduce an undisturbed condition of mobile bed equilibrium characterized by stable alluvial-bedrock and bedrock-alluvial transitions. In the zeroing phase all the flow and the bed material contributed to the Mississippi River delta are routed through the Mississippi River main channel, i.e. it is assumed that the distributary channels can be neglected.

The second step is the simulation of the present flow conditions. In this phase, the distributary channel of the Mississippi River, the Atchafalaya River, and the flow regime regulated by the US Army Corp of Engineers are accounted for in terms of a controlled partition of flow and bed material. In particular, we assume that since 1940 at river kilometer 500 – i.e. 500 km upstream of the Mississippi River outlet in the Gulf of Mexico (Head of Passes), 1/3 of the flow and the bed material load are diverted to the Atchafalaya River, and 2/3 are routed through the Mississippi River main channel. The initial condition for the second modeling step is the equilibrium longitudinal profile obtained at the end of the zeroing phase. The model results after 70 years of controlled flow regime, i.e. in 2010, are presented in Fig. 1 in terms of longitudinal profile of channel bed elevation.

In Fig. 1 the grey dots represent the elevation of the channel thalweg, and the orange dots are the 40^{th} percentile of the distribution of channel bed elevations in a given cross section, eta 40, which is appropriate for morphodynamics calculations (Nittrouer et al., 2012). The green dots are the 90^{th} percentile of channel bed elevation, eta 90, i.e. an approximation for the elevation of the artificial levees. The orange line is the modeled channel bed profile, which falls within the 2010 field data representing, showing that the model reasonably reproduces the long-term evolution of the Mississippi River channel.

The continuous and dashed grey lines in Fig. 1 respectively represent the bedrock elevation, and the minimum channel bed elevation for complete alluviation, which is set equal to the sum of the bedrock elevation and the minimum thickness of alluvial cover, L_{ac}. If the elevation of the predicted channel bed profile is higher than the minimum channel bed elevation for complete alluviation, the reach is fully alluvial. If the predicted channel bed elevation is lower than the minimum channel bed elevation for complete alluviation, exposed bedrock should be expected. Alluvial-bedrock and bedrock-alluvial transitions are located where the modeled channel bed profile intersects the line representing the minimum channel bed elevation for complete alluviation (blue dots in Fig. 1). The model predicts the transitions at river kilometers 232 and 36. Keeping in mind that on the lowermost Mississippi River the transitions are at river kilometers 230 and 40 (Nittrouer, 2013), this result shows that the model reasonably accounts for the alluvial morphodynamics in the bedrock reach.

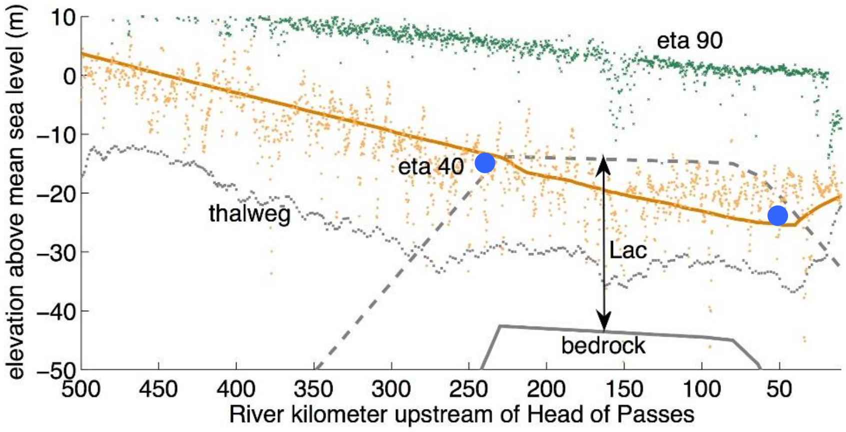

Fig. 1. Comparison between numerical channel bed elevation – orange line – and field data representing the thalweg (grey dots), the 40th and the 90th percentile of the distribution of channel bed elevations in a given cross section – eta 40 and eta 90 (orange and green dots). The continuous grey line represents the elevation of the bedrock, and the dashed grey line is the minimum channel bed elevation for complete alluviation, equal to the sum of the bedrock elevation and the minimum thickness of alluvial cover, L_{ac}. The blue dots represent the alluvial-bedrock and the bedrock-alluvial transition

The prediction of the response of the lowermost Mississippi River to land-building diversion projects is the third step of our model application. Under the assumption that 20% of the flow and of the bed material are diverted at a diversion site, we consider two scenarios, 1) a land-building diversion project at river kilometer 100, and 2) a land-building diversion project at river kilometer 200. Model results are presented in Fig. 2 in terms of elevation difference between the predicted Mississippi River channel bed 150 years into the future in the case of a diversion project, and in the absence of land-building diversion. The red line in Fig. 2 refers to the scenario with the diversion structure located at river kilometer 200, and the blue line represent the results for the diversion structure at river kilometer 100.

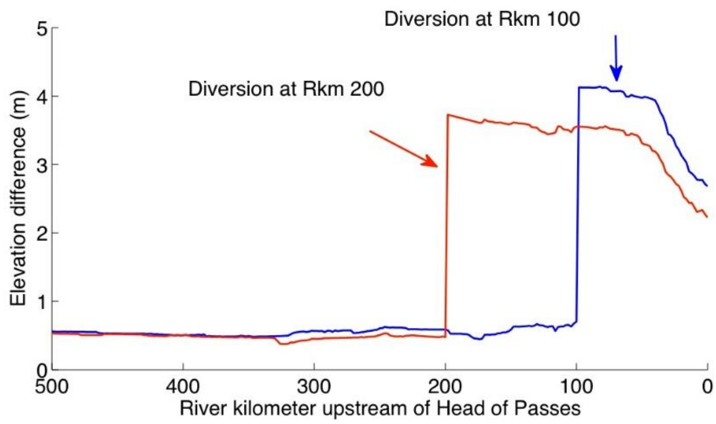

Fig. 2. Elevation difference between the predicted channel bed elevations of the lowermost Mississippi River 150 years into the future in the case of a diversion project and in the absence of land-building diversion

Our results clearly show that a land-building diversion project will result in negligible channel bed aggradation upstream of the diversion sites. Channel bed aggradation of the order of approximately 3.5 m is predicted downstream of the diversion sites. Noting that in the lowermost Mississippi River 3.5 m of channel bed aggradation is of the same order of magnitude of the bedforms at low flow (Nittrouer et al., 2008), and it is on the order of 1/10 of the average channel depth, we conclude that engineered land-building diversions are sustainable delta restoration projects for the Mississippi River Delta, and they will not likely represent a significant hazard for navigation and flood control.

Finally the land-building potential, i.e. the amount of sand diverted at each diversion site in the 150 years of simulation, is represented in Fig. 3. The red line refers to the scenario with the land-building project at river kilometer 200, and the blue line is for the scenario with the land-building diversion structure at river kilometer 100. Fig. 3 shows that for the considered diversion scenarios the land-building potential is higher when the diversion site is located at river kilometer 200, and approximately 4 Mt/yr of sand can be diverted from the Mississippi River main channel.

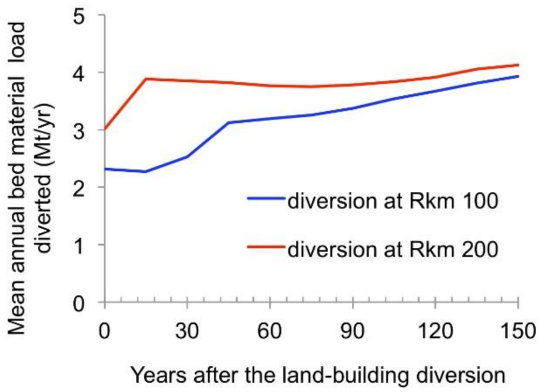

Fig. 3. Land building potential for the modeled diversion scenarios

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CHANNEL-ISLAND HYDROLOGICAL CONNECTIVITY IN A RIVER DELTA

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Land loss and increased nitrogen loading are among the factors altering the eco-geomorphic equilibrium of coastal systems. As a result, sustainable practices in the management of river, coastal, and wetland areas have emerged in recent years. River diversions, for example, have been implemented or planned in hopes of mitigating land loss throughout the coast of Louisiana. Denitrification in coastal wetlands has the potential of limiting the risks of hypoxia and related ecological issues by reducing the nutrient export to receiving waters.

Delta islands are a fundamental part of the delta network; island characteristics carry the signature of delta forming processes and vegetation (Passalacqua et al., 2013) and play an important role in ecological processes, such as denitrification, which are influenced by the hydraulic residence time. Island inundation is controlled by the hydrological connectivity of the channels and islands and basinal forces. Temporal dynamics of inundation and how external and internal forces modulate channel-island connectivity are key questions in addressing the hydrologic and ecologic roles of delta islands.

In this study we perform a network scale analysis of flow partitioning at Wax Lake Delta (WLD) in coastal Louisiana. Based on ADCP data collected along two main channels in WLD (Gadwall Pass, Main Pass, Fig. 1), we deduce that channel discharge is not conserved within the channel network, resulting in significant loss of the incoming flow to the islands (46-77% of the incoming discharge), and thus suggesting hydrological connectivity between the distributary channels and the islands (Fig. 2). Hydrological connectivity increases with decreasing distance from the shoreline as vegetated subaerial levees become partially vegetated and subaqueous.

We address the dynamics of water within islands with field hydraulic tracer studies over a range of tidal conditions and analyze the effect of forces such as tides and wind on water level fluctuations. The results show that dye is present in the system for the whole duration of the experiment, suggesting potential hydraulic resident time HRT of about four days (estimate of minimum HRT) (Fig. 3). Our results also point at the importance of wind, able to cause water level set-up (wind from the South) and water level draw-down (wind from the North) on the order of decimeters. Wind thus plays an important role in the hydrodynamics of WLD and should be included in numerical modeling.

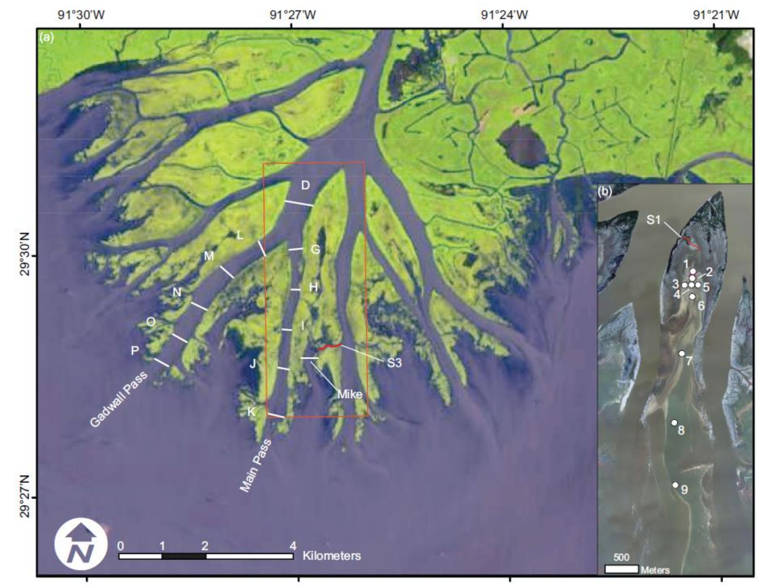

Fig. 1. Map of the field measurements at Wax Lake Delta. (a) Locations of ADCP transects traversed in Main and Gadwall Passes (06/16/2014 – 06/29/2014) and on Mike Island (07/23/2012 – 07/24/2012). The extent of the S3 channel has been mapped with a red line. Image specifications: LANDSAT 8 image from 06/19/2014 at 30 m resolution obtained from the USGS Global Visualization Viewer (available online at http://glovis.usgs.gov/) (b) Sensor locations for the dye tracer study performed on Mike Island from 02/07/2014 through 02/11/2014. The pink hexagon between sites 1 and 2 marks the location of the dye release point. Site S1 is the location of a secondary channel measured on 07/22/2012 and the extent of the channel is mapped with a red line. The image is aerial photography from 2009 with 0.30 m resolution. Figure reproduced from Hiatt and Passalacqua, in review

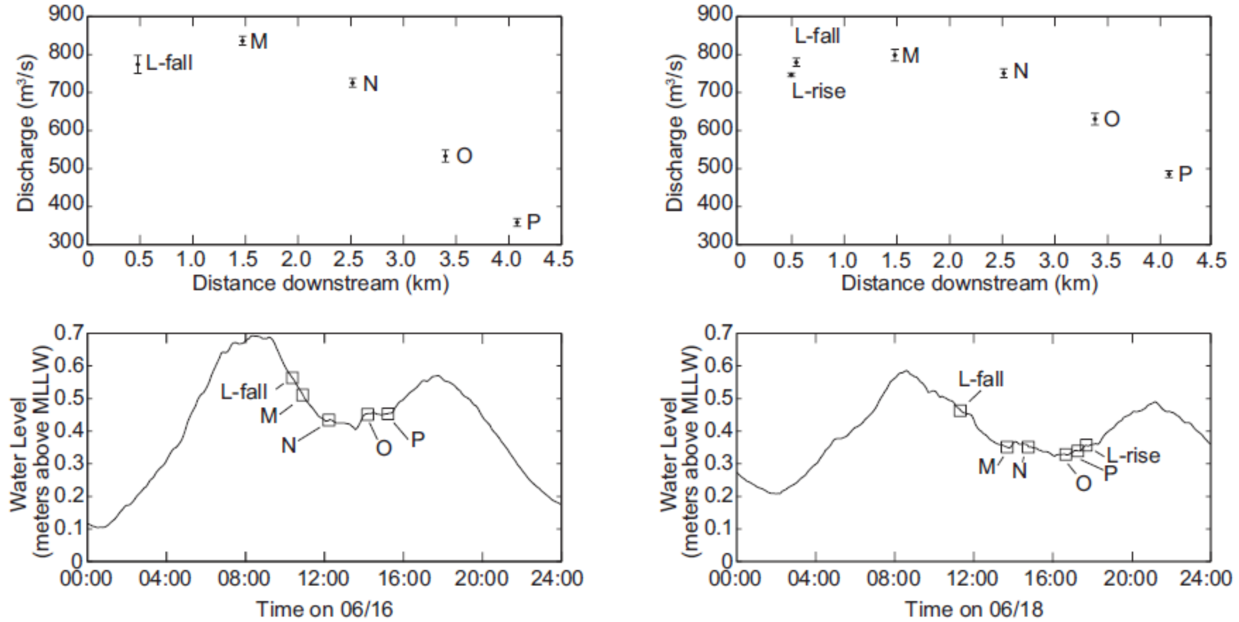

Fig. 2. Discharge summary for Gadwall Pass. The top panels show the average discharge at each transect with the standard deviation of the measurements. The lower panels show the measured water levels at the Lawma-Amerada Pass station (NOAA #8764227). Figure reproduced from Hiatt and Passalacqua, in review

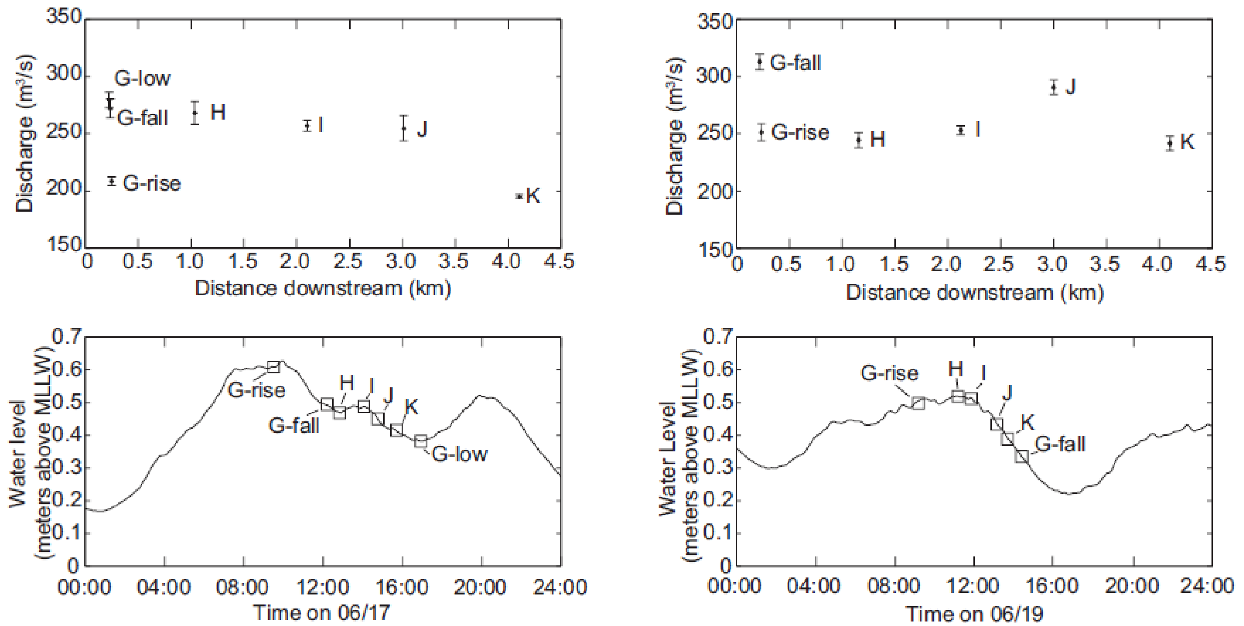

Fig. 3. Discharge summary for Main Pass. The top panels show the average discharge at each transect with the standard deviation of the measurements. The lower panels show the measured water levels at the Lawma-Amerada Pass station (NOAA #8764227). Figure reproduced from Hiatt and Passalacqua, in review

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TEMPORAL VARIATION OF HYDRAULIC GEOMETRY AT THE INLET OF THE ESTUARY OF THE YELLOW RIVER

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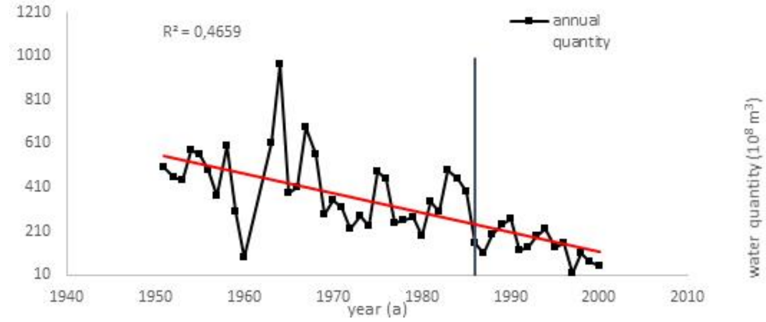
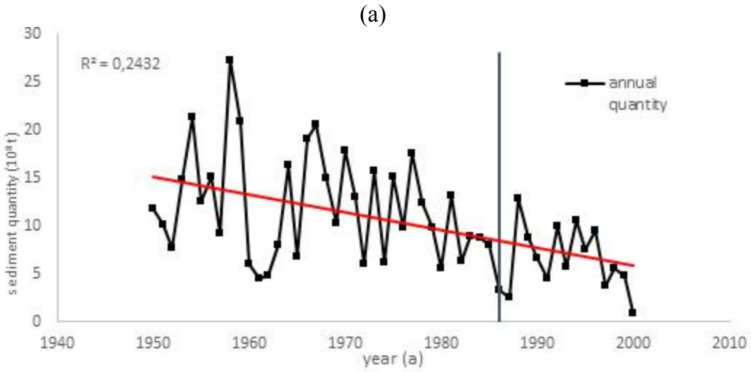
Channel morphology of fluvial rivers is determined by inputting water and sediment conditions and base eroding levels in estuaries. Therefore, as an outlet hydrology station of the Yellow River, Lijin has exhibited temporal variations of hydraulic geometry impacted by the environmental change. Analyzing the inputting water and sediment conditions upstream, the river length in the delta downstream, and the adjustments of transverse and longitudinal sections of Lijin Station, it shows that:

(1) In the past 50 years, the inputting water and sediment conditions agree well with the adjustments of transverse sections (variations of bankfull width and bankfull depth), and show an obvious mutation point with dam constructions (Fig. 1 and Fig. 2). We simulate the relations with a log-linear equation.

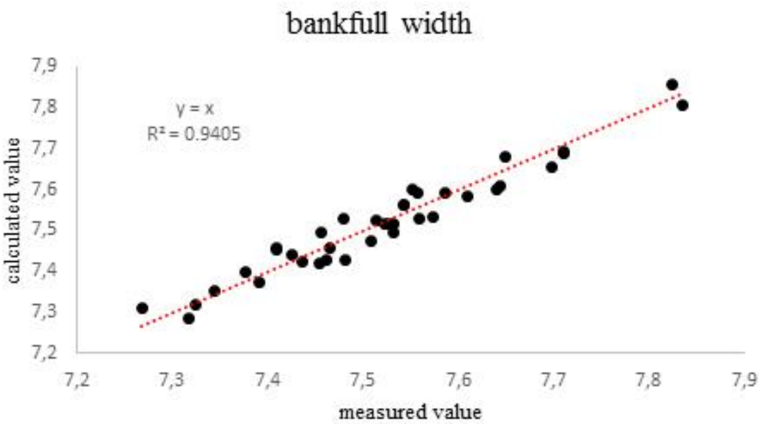


(a)



(b)

Fig. 1. The decreasing trends of incoming water and sediment conditions of Lijin Stations (a: water conditions; b: sediment conditions)



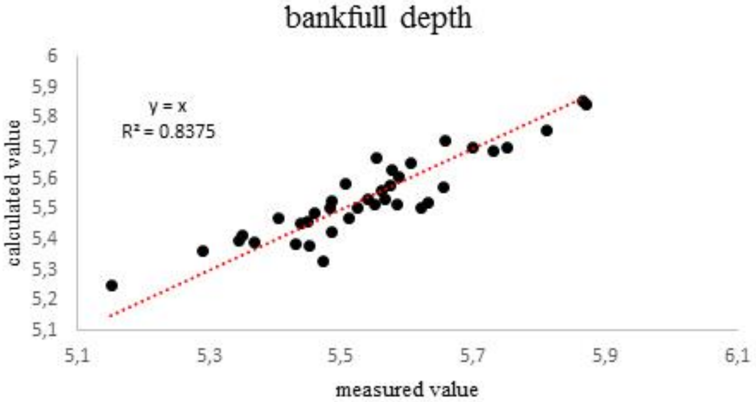


Fig. 2. The relations between bankfull geometry (width and depth) and incoming water and sediment conditions at Lijin Station

(2) On the other hand, the adjustments of longitudinal sections (including riverbed elevation, water level for the same discharge of 3000 m^3/s) show continual increasing trends, which is obviously impacted by the base eroding levels in estuaries. Using the river length in the delta as a variable, a feedback log-linear relationship with the adjustments of longitudinal sections is also made and the correlated result is acceptable. It implies that the increasing trends of the river length in the delta, is the key impact factor of the adjustments of longitudinal sections (Fig. 3).

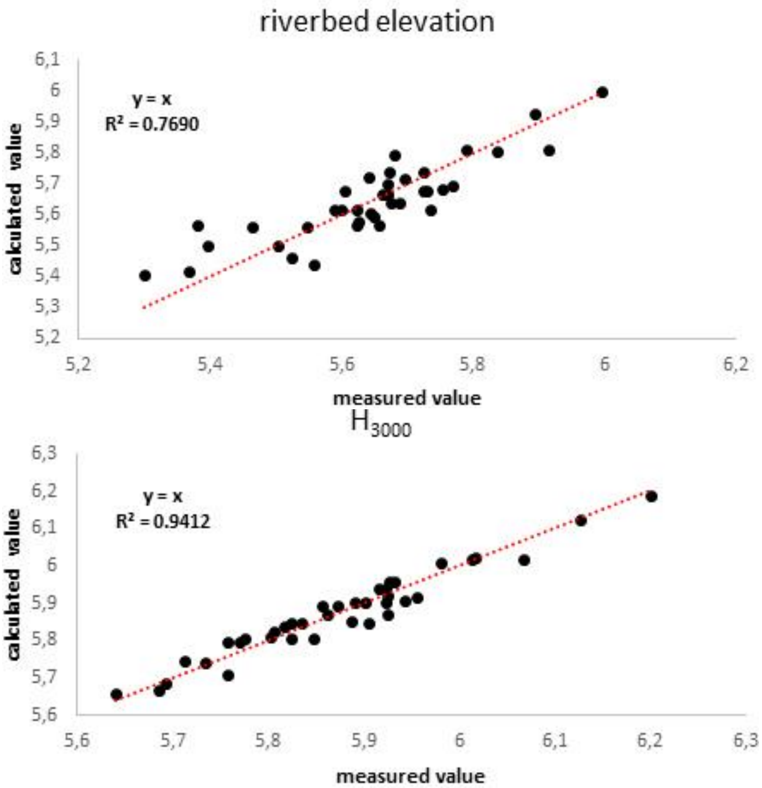


Fig. 3. The relations between the adjustments of longitudinal sections (including riverbed elevation, water level for the same discharge of 3000 m^3/s) and the river length in the delta below Lijin Station

HIGH-PRECISION GEOMONITORING USING MICRO AERIAL VEHICLES

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Abstract: This paper demonstrates the potential of employment of small Unmanned Aircraft Systems (mUAS) for environmental research applications and the research of natural waterway systems in particular. Specifically, we describe the recent advances in the field of navigation technologies, and methodologies for high-precision determination of position and orientation of micro aerial vehicles (MAVs), which weight does not exceed 5 kg. Although the MAV systems feature high flexibility and capability of flying into areas that are inhospitable or inaccessible to humans, the lack of precision in positioning and attitude estimation on-board decreases the gained value of the captured imagery. This limits their mode of operation to indirect georeferencing. We present a development of MAVs which can overcome such limitations due to the incorporation of a surveying grade GNSS receiver and an in-house developed Redundant Inertial Measurement Unit (R-IMU). In particular, we focus on physical integration, synchronization and quality evaluation of navigation components. After calibrating the data acquisition system, we present preliminary results from a real mapping flight.
Keywords: remote sensing, photogrammetry, geomonitoring, direct georeferencing, resource managements, unmanned aircraft

Introduction

Low-cost and low-weight unmanned aerial vehicle (UAV) systems with imaging capability have enjoyed a rapid development over the past years and are increasingly deployed as carriers for mapping purposes. They present a well-established tool for local-area remote sensing in the fields of agriculture, forestry, mining and hydrology as well as in the scientific research (Remondino et al. 2011). Although these systems allow a new way of data collection in the field of geomatics, they inherit an old, i.e. indirect, approach to sensor/image orientation. Indeed, most of the commercially available micro aerial vehicles (MAVs) carry consumer-market non-metric cameras and single-frequency GPS receivers without precise carrier phase observations providing position accuracy at level of several metres in optimal conditions. That is indeed insufficient for large scale mapping projects and cadastral surveying for which accuracy at a 2-5 centimetre-level is needed. Furthermore the quality of the employed inertial sensor, often part of a low-cost autopilot unit, is not sufficient for accurate attitude determination. Hence, missions with the need of accurate mapping require image acquisition in a block-structure with large forward and side overlaps, the existence of possibly many ground-control points (GCPs) as well as contrast in the surface texture. Although single-strip operations are theoretically possible, the requirement on the number and distribution of GCPs makes them impractical. Overall, the need of ground operations limits the mapping productivity of MAVs.

Georeferencing of MAVs

The task of georeferencing is the determination of the exterior orientation parameters of a sensor at the time of recording and the restitution of the scene from the image data. The EO parameters may either be deduced indirectly from known ground control points, mechanically (historical method – stereocomparator) or by measuring them directly by navigation sensors – GNSS/INS (Skaloud and Legat, 2008). The determination of EO parameters is a fundamental condition for the use of any kind of imagery in a photogrammetric way. With direct or integrated sensor orientation the requirement for ground control points, tie point matching and aerial triangulation is significantly reduced (Reese and Heipke, 2006). The most expensive part of the mapping project is the need of GCPs – the field measurement and the manual identification of these points in the images.

Nowadays, the most common processing of MAV imagery is done indirectly under joint use of known GCPs and their corresponding image coordinates. For a block of images a sufficient forward and side overlap is essential (usually min. 60% and 30%). Neighboured images are connected using advanced digital matching methods with hundreds of tie-points. The EO parameters for each image in the image block can be estimated within a least-square adjustment known as bundle block adjustment (BBA). This approach is called aerial triangulation (AT) or automatic aerial triangulation (AAT). The huge redundancy in measurement of tie-points allows to add additional unknown parameters, for instance the internal orientation parameters, which are very often unstable in time (e.g. an influence of vibrations) due to the usage of non-metric cameras. The observed exterior parameters are very inaccurate and enter only during the image pre-selection and/or serve as an initial approximation in the bundle adjustment to ensure convergence. The problem occurs when sufficient distribution of the GCPs is not feasible, when flying in a single-strip or over homogeneous terrain. The ability of resolving the EO parameters indirectly is therefore limited in such scenarios (e.g. dense vegetation, coastal areas etc.).

Direct Georeferencing

Direct georeferencing (DG) or also called direct sensor orientation (DiSO) provides the ability to directly relate the data collected by a remote sensing system to the Earth, by accurately measuring the geographic position and orientation of the sensor without the use of traditional ground-based measurements (Mostafa et al., 2001). By merging the GNSS and inertial navigation technologies, accurate position and orientation of the airborne imaging sensor, with respect to the Earth, can be determined directly. The GNSS procures an absolute position and velocity, whereas INS provides also attitude estimation. Besides that, such combination enhances the performance of both, the GNSS ensures the long-term absolute stability while INS is able to eliminate short GNSS outages (e.g. cycle slips) and corrects the absolute position between two GNSS epochs. In order to be able to benefit from both systems, an advanced synthetic through Extended Kalman filter/smoother has to be carried out. The parameters estimated by GNSS/INS system are called external orientation parameters. To georeference frame-based imagery, the parameters of interior orientation have to be also known, i.e. coordinates of the principal point x_0, y_0, the camera constant c and the geometric distortion characteristics of the lens. These parameters must be stable enough during each mission and their consistency has to be checked regularly. In many cases, the INS/GNSS is the enabling technology behind various imaging sensors such as LIDAR, SAR (Synthetic Aperture Radar), and IfSAR (Interferometric SAR), providing the georeferencing component to the data. While for scanning sensors the use of DG is compulsory, frame digital cameras can also directly benefit from this technique of sensor orientation.

The MAV systems

We present two in-house developed MAV platforms, a multi-rotor helicopter and a fixed wing plane. Both feature a high payload capacity and flying stability and they allow performing different mapping tasks. The custom design of both systems allows mounting the necessary devices needed to perform modern photogrammetry. The vertical take-off and landing (VTOL) MAV is equipped with eight brushless motors to enhance the payload capacity and to increase the redundancy in case of engine failure (Fig. 1).

Fig. 1. Octocopter MAV

The UAV accommodates appropriate sensors and an autopilot to perform stabilized and autonomous flights. The system is powered by high capacity lithium polymer (LiPo) batteries. Depending on the application and especially on the payload (1 kg – 1.5 kg), the flight times vary from 10 to 15 minutes. The system with all the equipment and additional sensors weighs 4.8 kg. The on-board control segment is an embedded micro-PC with an Atom processor connected to the Arduino autopilot. In its current configuration the PC governs the process of data acquisition and sets up the Autopilot. All the sensors are mounted on servo-powered gyro-stabilized holder that keeps the equipment in level (or in selected inclination) during the flight. At the same time it dampens the vibrations from the engines (Fig. 2).

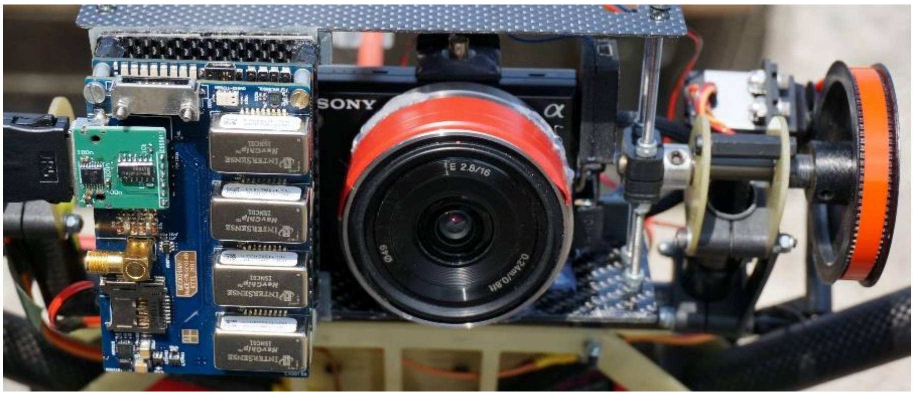

Fig. 2. Sensor mount for direct georeferencing

The second developed system is a fixed wing plane (Fig. 3). The wingspan is 1.6 m and take-off weight varies between 1.5-2.5 kg. With a payload of 600 g, the autonomy is approximately 40 minutes. Both platforms are equipped with advanced sensors comprising of a surveying grade L1/L2 GNSS receiver, R-IMU and a Sony Nex 5 digital camera. The quality of this mirror-less camera is comparable with a SLR camera despite being considerably smaller (only 111×59×38 mm) and lighter (210 g without lens). These properties make it highly suitable for MAV platforms. The camera is equipped with a 16 mm fixed Sony lens, which has a reasonable optical quality given its size and weight.

Fig. 3. Fixed-wing MAV

Case study

To evaluate the previously described development and to actually validate the existing integration of all system components, several field tests were carried out. Each test was performed for a specific task including tests on image quality, target recognition, camera calibration and synchronization of all components. However, this study is focused mainly on the quality of direct positioning (Rehak et al., 2014).

An experiment of digital orthophoto map production has been carried out in a rural area close to Lausanne, Switzerland. The area of interest has approximately 1.5 square kilometres. A set of 27 check points was surveyed and was used for final accuracy evaluation. The flight was done autonomously and resulted in a set of 540 images. Thanks to an accurate synchronization of camera-GNSS receiver and R-IMU, each image could be paired with an exact position and attitude.

After image processing, the image measurements were subsequently fed into a bundle adjustment (Lichti & Champan, 1997) together with the measured camera positions. The latter were obtained by interpolating between the 10 Hz GNSS solutions of carrier-phase differential results obtained by a professional software package. Self-developed Matlab scripts were used to carry out the assignment of images to the events exported from the receiver. The Table 1 depicts the most important results. During the BBA, no GCPs were used.

Table 1

Summary of the achieved georeferencing accuracy

	X (m)	Y (m)	Z (m)
Mean estimated accuracy of GNSS positions	0.015	0.015	0.025
RMS on the Check points	0.038	0.035	0.057

Conclusions

This research aimed at proposing and investigating a novel approach in data acquisition with MAV. We presented two custom made MAV systems dedicated to photogrammetry. The outcomes from the bundle adjustment confirmed the correctness of the preceding development in terms of camera/GNSS integration. The most challenging part of the sensor integration and synchronization on the relative small and low cost UAV systems was accomplished. The employed realization isolates the measuring devices from vibrations and provides stable spatial offsets between them. A small case study was performed to verify the quality of synchronization and the accuracy of camera position control. The latter is at 2-6 cm level which corresponds to the kinematic accuracy of a carrier-phase differential GNSS. The method of integrated sensor orientation allows performing mapping with cm-level accuracy without the need of ground control points. Future investigation will study the attainable attitude accuracy of the redundant MEMS IMU on-board the MAV.

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GEOCHEMICAL SITUATION AND PEDOGENESIS OF THE SELENGA RIVER DELTA REGION

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Abstract: The genesis and evolution of soil of the Selenga delta river have been investigated, classification status of soils is defined, the soil map of the scale of 1: 100,000 is composed, the soil-geochemical zoning has been performed, soil geochemical barriers are identified. It is shown that along the Selenga river downstream in the modern period the heavy metals migrate. Accumulation of the heavy metals in the combined barriers namely, mechanical and sorbative, evaporative, alkaline and sorbative. At these barriers concentration of Zn in the flooded soils of the Selenga Delta exceeds of standard levels defined by the Maximal permissible concentration for soil. Also, exceeding of Cu, Zn, and Pb in the submontane trough in the vicinity of the delta has been revealed.
Keywords: Selenga delta river, genesis of soil, alluvial soils, lake-river benches, tectonic depression, peat bog, soil map, soil cover, elementary landscapes, soil-geochemical barriers, heavy metals

Lake Baikal and adjacent territories are World Heritage sites by UNESCO. It contains 20% of the world's total unfrozen freshwater reserve. The main inflow of Lake Baikal is the river Selenga. Delta of Selenga river accumulates various substances, including heavy metals coming from the river and groundwater. It defines actuality of soil-geochemical studies. The relief of the territory is flat, is complicated by several lakes and river floodplain terraces. The absolute height of this area vary from 455 to 530 m above sea level. The climate of the region – is extremely continental, mean value of rainfall – 200-400 mm per year, mean value temperature – July 14-18 °C; February – 22 °C.

The purpose of the work:

To establish the particularities of the soil formation in delta river Selenga (Eastern Baikal region), its role of soil formation processes in lateral migration of substances associated with the activity of Selenga river.

Specific character of the Selenga delta's soil genesis and evolution are determined by Baikal rift, the nature of alluvium accumulation, the continental climate, the freshwatering of Lake Baikal and its water-level changeability. The deep water of the lake and tectonic activity prevent from delta area extension, stipulate the creation of the sorsandkultucs and make more active the changes of the Selenga direction and its channels, erosion of longstanding ground-levels and forming new ones.

This led to the formation of delta run in the former Bay Lake and the in shape similar a fan delta advances in the deep part. Simultaneously with the rise of the delta above the lake waters began hydromorphic soil formation and further development of the soil in accordance with the evolution of morphological structure. In modern times, this process can be traced to a transect from the peripheral part of the delta extension to the base of the delta.

Alluvial soils

In this series the mainly reduction conditions of the pedogenesis and subacidic and nearly nonacid medium reaction in the periphery area of the delta change into oxidizing conditions and nearly nonacid and alkalescency one of the base and central floodplain.

On the top floodplain there is a change of the pedogenesis regime again into subacidic and nearly nonacid, and the oxidation-reduction conditions become more variable. According to this there are 3 stages of development floodplain-delta soils:

I – the stage of periodical flood by freshet and lake's water, marked by the formation of the alluvial meadow moor humi-gleyic fluvisols (according to the world report base (WRB): Humi-GleyicFluvisols) (Krasilnikov, 1999) and histic soils fluvisols (WRB: Histicfluvisols) on the depressions and alluvial sod saturated soils (WRB: EutricFluvisols) on the river-bed swell formation.

II – the stage of mainly ground water moistening of the paddle-shaped part of the delta and central floodplain. This stage is characterized by the formation of the alluvial meadow saturated (WRB: Molli-GleyicFluvisols) and carbonate (WRB: Calcari-GleyicFluvisols), rarely alkali soils. In the depressions there is the formation of the alluvial moor soils and meadow moor histic soils.

III – the stage is characterized by the transition of soils into automorphic conditions and the formation of postalluvial meadow soils (WRB: MollicGleysols) and alluvial meadow saturated soils.

Comparing the pedogenesis of the river deltas in Russia and in the former Soviet republics (Egorov, 1959; Kovda, 1973; Dobrovolsky; 1975; Deneva, 2003) with the pedogenesis on the contemporary floodplain-delta sediments of the Selenga, the latter is conditioned by the specific character of the geochemical situation, determined by the bicarbonate-calcium fresh river and ultra fresh Baikal water composite.

Relatively weak paludification's formation of the alluvial moor and meadow moor soils in the periphery and prebenches delta area, conditioned by stagnant overmoistening with long-term and frost penetration freezing influence, shows some similarity between the Selenga river and the Northern seas deltas' soils. The weak and sporadical salinity development, connected with the activization of evaporation process during arid period at the high islands of paddle-shaped part of delta and central floodplain, shows some similarity with the Southern deltas seas.

The uniqueness of the Selenga river delta soils is that there the soils are prevailing with nearly nonacid medium reaction, developing in the direction of the formation meadow postalluvial soils.

Postallyuvial stage of development characterized soil of terraces.

The soils of lake-river terrace (lake-river benches)

The lake-river benches on the delta region were formed in the result of the Selenga functioning and ingressions of the lakewater during tectonic movements of the Siberian platform in the period from the middle neopleistocene to holocene.

Lake-river benches are the former islands and knolls, left after the retreat of the waters outside the influence of channel processes. Lake-river benches partially blurred water and redeposited by air currents.

The soils, that form catena on the slightly slopes, are structured in the taiga landscapes of lake-river benches of the Selenga delta area in South-Eastern Pribaikalie. In the upper catena's level sod Al-Fe-humus soils are formed under the poorgrass pine forests; as well as mollic grey forest soils (Tsybzhitov, 2000) are formed in the middle levels of the slopes, covered with grassy pine-birch forests; and the dark-grey forest gleyic soils – on the low levels of the bench slope, structured by loamy sediments under the grassy birch forests.

Geochemical characteristics of the elementary landscapes (EL), which show acid-alkaline and oxidation-reduction conditions, influence on the formation of the bench soils. The oxidation-reduction conditions clearly define soil variety. The upper benches' levels, covered with sod Al-Fe-humus soils, are characterized by total moisture seep and constant oxidative conditions, with the help of which the type of subacidic EL – H-Ca are formed. On the slightly bench slopes with mollic grey forest soils (a regional term, so that is why the classification is absent) in the humid conditions the short-term overmoistening, marked by not numerous short, but extent enough Fe-Mn nodules in the middle horizons of cross-section can be observed. Moisture is spent to evaporation and its absorption, not provoking eluvial-illuvial processes. I-In these conditions subacidic and nearly nonacid EL*H-Ca* and *(H)-Ca*types are formed. The low benches level, covered with grey forest gleyic carbonate soils, is influenced by groundwater moistening, that provides the supply of the alkaline-earth elements, and marks nearly nonacid EL - *H-Ca.* For this type the formation of amorphous ferriferous nodules forming is typical, which prove the oxidation-reduction conditions' rippling without long-term redundant overmoistening and dehydration.

The geochemical characteristics determine the direction and intensity of the pedogenesis. In the formation of the mollic forest soils' profile the great role belongs to the configuration of the inert litter and slow humus accumulation to humification. The makeup of humus is humate-fulvating. It is also characterized by the absence of the deep layer transformation, by the existence of alfehumus migration in the form of the accumulation of amorphous forms of ferric compounds in the middle level of the profile. The activity of the processes of the substances' vertical migration in the research sod Al–Fe–humus soils is not intense.

The researches' results of sod Al-Fe-humus soils diagnose the metamorphism process and poor marked separate ferric accumulation in the middle level of the profile, which is largely presented with high-crystal form. The makeup of humus is fulvate-humating with the prevalence of the brown humic acid. The bulk chemical composition is homogeneous in the profile. The visible reinforcing with sesquioxides of metamorphic horizons is not noted.

The dark-grey forest soils, located in the low catena's level, are characterized by the biogenic humus accumulation, mainly with lime humates, clearly expressed metamorphism of profile's solid part, hydrogenic and biogenic calcareousization of the whole profile, coagulating and cryogenic aggregation of horizons.

The soil of tectonic depression

In the foothills of the Khamar-Daban range, in the zone of tectonic depression, peat bog has been formed. Delivery of water from a high ridge and low plain reliefis of the formation of marsh soils are cause. In the eastern part and in the transbaikalian part of back bog Rheic Histisols (Eutric-Histic Gleysols) are formed. In the middle part Eutric-Histic Gleysols have a thickness of 5 or 7 m.

The soils of eastern and central parts of bog are formed on loam, that characterized by high zonality, high level of peat decomposing, close to nonacid medium reaction. In the Transbaikalia part soils are formed on floating sands, the level of peat decomposing is low, medium reaction is subacidic.

In the north-eastern part the peat bog is drained by the net of irrigation canal and is used for hayfields. While being drained. Rheic Histosols/Eutric-Histic Gleysols were transformed into Mollic Gleysols, Anthri-Rheic Histosols.

Mollic Gleysols soils are characterized by close to nonacid and subacidic medium reaction. Anthri-Rheic Histosols are carbonated and has nonacid and acidic medium reaction. Soils are base-saturated. Peat pereentage of ash is high, but lower than in undrained soils.

The map of soil and geochemical situation

The research let us make a soil map, 1:100,000 scale. In the Selenga delta allocated 13 soils types, 20 subtypes and 24 genera, which are shown on the soil map. On the base of the soil map the map of geochemical landscapes, showing acid-base and redox conditions, was make. In soils of different landscapes subtypes there was the determination of the abundance of heavy metals, easily migrated with rivers: Cu, Pb, Zn, Co, Ni, Cr (Gordeev, Lisitsyn, 1978).

The research showed that along the Selenga river there is the migration of heavy metals and its accumulation on the united barriers: mechanical and sorption, evaporation, alkalic and sorption (Perelman, Kasimov, 1999). In the elementary landscapes and deltas the increasing of TLV for soils is noticed on the barriers for Zn, and in tectonic depression – for Cu, Zn and really for Pb.

For the making geochemical zoning the elements of soil cover structure, in accordance with subtypes of elementary landscapes, are singled out at different levels of categorization of soil – type, subtype and genus.

All these let us distinguish united geochemical barriers, where the heavy metal are actively accumulated: 1) mechanical and sorptional; 2) evaporational, alkalic and sorptional.

In the elementary landscapes of the floodplain and delta the excess of TLV for soils are noticed in these barriers for Zn, and in tectonic depression – for Cu, Zn and rarely for Pb.

Conclusions:

1. The unique climatic conditions in delta Selenga resulted formation of soils of different genesis: in the delta – alluvial, on the tectonic depression – marsh and on the terraces – the forest, which revealed profile formation processes.

2. Soil genesis and evolution of the Selenga delta different from the soils of coastal marine deltas, due to fresh water of lake, soil texture and low alkaline pH, to the alluvium. Characterized by a low pronounced tendency to salinity.

3. In the Selenga delta allocated 13 soils types, 20 subtypes and 24 genera, which are shown on the soil map.

4. The soils are realized water conservation functions, involving the alluvium and dissolved substances in soil formation and accumulating them on the soil-geochemical barriers.

5. On the soil-geochemical barriers identified varying degrees of accumulation and dispersion of heavy metals. As a rule, the dispersion of heavy metals is characteristic of sandy soils of terraces, the accumulation for the soil of loamy composition or peat. The accumulation of Zn in the soils riverbed and islands, and in the tectonic depression – Cu, Zn and Pb are revealed.

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HYDROLOGICAL AND GEOCHEMICAL PARTICULARITIES OF CURRENT DEVELOPMENT OF THE LENA RIVER DELTA

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Dissolved and solid material runoff to the Arctic Ocean increase on the base on hydrological regime and erosion of permafrost landscapes changes due to climate change. One of the main elements of Arctic circulation is the Lena River with a big delta. There are riverine, lacustrine, swamped as well as permafrost active layer hydrological and geochemical systems in the delta. Current state of system and its development have inherited particularities.

Current river discharge, water distribution through delta channels, suspended matter formation / accumulation in the central delta, local factor (ice complex thaw) of water and dissolved elements runoff formation are presented in the report. Hydrochemical changes under anthropogenic impact are presented also.

According to lacustrine cores geochemical analyses and biogenic elements in water of the delta lakes and channels a high self-cleaning ability has been carried out for the delta hydrosystems. On the base of field measurements and long-term Roshydromet data an interaction between water discharge/regime and dissolved organic carbon concentration has been noticed for the Lena River and will be presented in the report.

THE SPATIAL-TEMPORAL DISTRIBUTION OF SUSPENDED SEDIMENTS IN THE SELENGA RIVER DELTA

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Abstract: The results of field data runoff of suspended sediment are presented. Obtained materials are the basis for the prediction of the formation of the channel network and the cone of the delta.
Keywords: sediment, delta, erosion, accumulation processes

The Selenga River Delta is the largest inland delta of the planet. The sediment load is the main factor in the formation and development of the Selenga river delta. Sediments are the result of processes occurring within the catchment area of the river bed (Alekseevsky, 1998). Differences in the duration of these processes, as well as their nature and terms of engagement of the underlying soils and surface water are expressed in the spatial and temporal distribution of sediment load (Rzhanitsyn, 1985).

The process of sedimentation on the delta, as well as the process of formation and change ducts occur constantly and continuously, so lately on hydrological and geomorphologic study of deltaic processes has received increased attention (Alekseevsky, 1998).

Sediment load is formed by the products of physical weathering, wash from the slopes of the catchment basin, and also due to erosion products streambeds, constituting the river system.

Sediment load is caused by physical and geographical features of the watershed: the nature of the climate and vegetation cover, soil properties, soil resist mechanical and chemical resistance of water flow, size and chemical composition of the groundwater supply, transport capacity of surface runoff (Lopatin, 1952). 50-70% river sediments is usually delayed on the surface waters of the river delta. In some cases, this value is around 90-95% (Mikhailov, 1996).

The sediment load increases in summer due to heavy rainfall and severe erosion and it decreases in autumn. Variability of sediment transport along the length of the channel is determined by seasonal variations and the increase in the volume of deposits in the low flow channel and a decrease in the flood.

If we consider the amount of suspended sediment on the sleeves of the Selenga delta, then there is an uneven distribution. Since the delta of the Selenga has a large area (605 km^2), and the average length along has 20-25 km, then on different parts of the delta is possible to increase and decrease in the amount of suspended sediment. On this basis, it can be assumed that in different parts of the delta can go simultaneously processes of water erosion and accumulation.

The map was compiled on the basis of field data of the Selenga river delta (Fig. 1), which shows that in the marginal sectors observed coastal erosion and intensity of suspended sediment is highest, while in the central part of the delta and accumulation of sediment suspended sediment less than throughout the delta.

Summarizing, we can say that the relevance of the study of sediment load is not in doubt, as suspended sediment have a tremendous impact on the formation and evolution of river deltas.

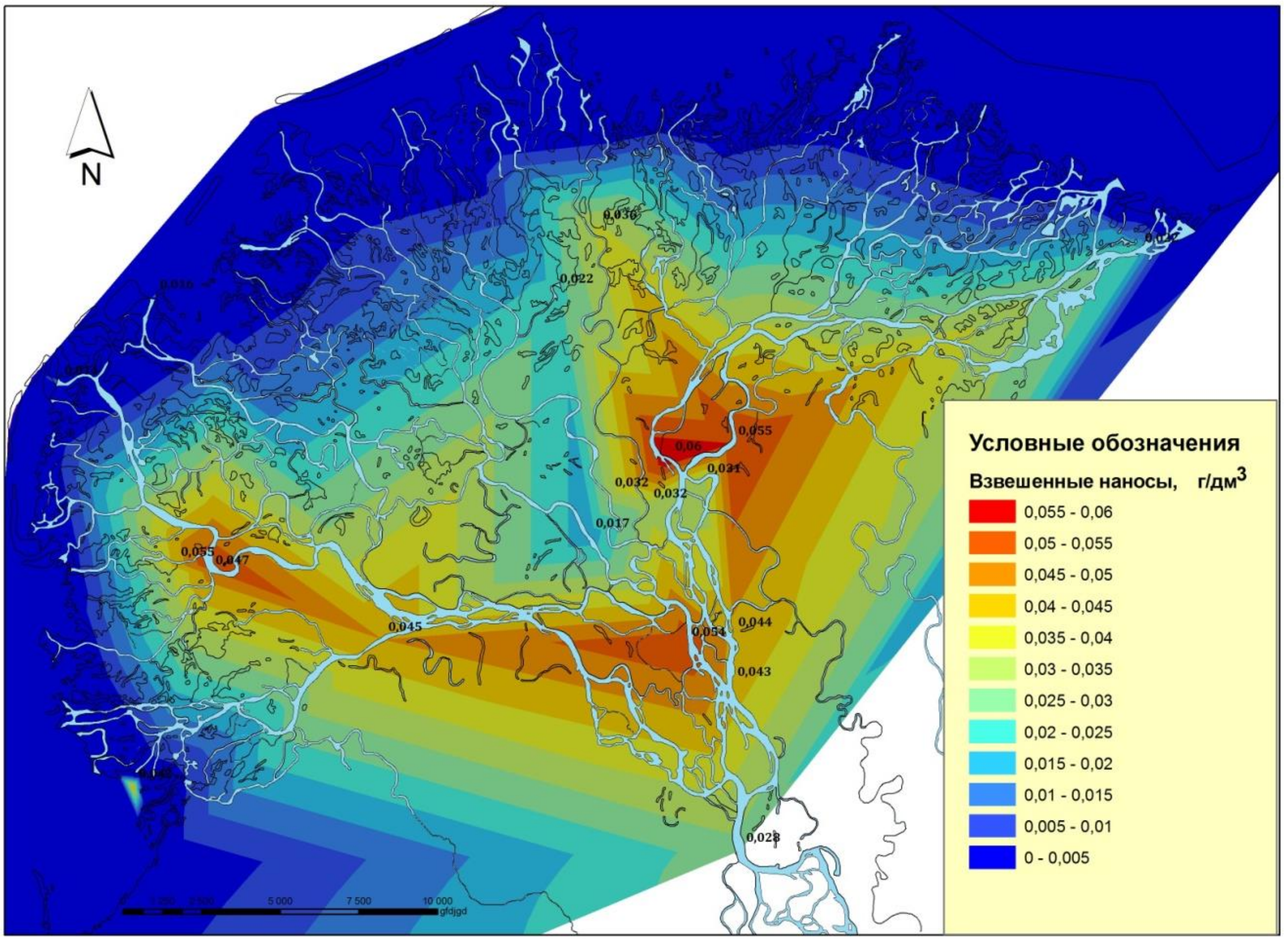

Fig. 1. The erosion-accumulation map of the Selenga river delta

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COMPARATIVE CHARACTERISTICS OF THE SELENGA AND HUANG HE RIVER DELTAS

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River deltas are a special geomorphological and landscape structure of the continental land. Unlike all the other elements they are formed only at the border of systems "river – sea" in the conditions of positive regime of river alluvium. According to the hydrophysics and geomorphology laws, all the major rivers are formed at the mouths of the delta, the dimensions of which are comparable with the volume of the removal of alluvium.

However, it is well known that the classic lobate deltas are formed at the small number of rivers. We can assume that deltas are formed at more ancient rivers, which carried out sufficient rainfall to the mouth of the river during the period of its existence. The last inland ice affected to the age of the river network in the northern hemisphere. However, the Ob, the Yenisei, the Lena Rivers are the same post-glacial age, but their estuarine closures have a different shape.

Meantime, the history of the origin of human civilization is inextricably connected with the river deltas of the Nile, the Tigris, the Euphrates, the Yangtze, the Yellow River, the Indus, the Ganges Rivers and other landscapes where there are vast fertile lands, fresh water and warm climate. In general, the same areas are connected to the largest marine transportation and logistics bases, which are the foundation of economic development of the world trade centers. Many specially protected sites of wetlands – the spots of migratory birds that included in the Ramsar Convention are located here.

Such combination of the small number of delta ecosystems and the favorable factors for their support creates unique objects for the systematic research. It should be mentioned that the collision of economic interests of society and the problems of environmental conservation often appears on these sections of the rivers and it can be solved on the concept of sustainable development.

Hydrological features of the formation of the largest river deltas are developed in detail in the scientific literature. This research examines the comparative characteristics of the Selenga River and the Yellow River delta systems, in particular, the problems of their natural and economic zoning.

The leading part in the economic development of any territory belongs to geographical location, landscape-forming factors and the presence of the resource potential. The objects selected by the author were formed in different latitudinal zones of the Asian continent. The delta of the Selenga River is the only one that was originated within the continent in the freshwater base level of deposition – Lake Baikal. Drilling data and geophysical studies show that the thickness of sedimentary alluvium in Ust-Selenginskaya draw-dawn reaches 8-9 km, which was accumulated here since the beginning of the Miocene. Therefore, we can affirm that, unlike the majority of the river systems that were formed after the melting of the last ice sheet, the Selenga River is one of the most ancient waterways of Northern Asia.

About a half of the annual river inflow into Lake Baikal is carried out through the delta of the Selenga River in the amount of about 30 km^3. The waters coming from whole river basin of the Selenga River, including from Mongolia, are being naturally filtered and purified. The distance between the ancient lake-river landforms reaches more than 100 km, and up to 50 km in depth. The main area of the delta is water-logged because of the construction of the Irkutsk hydroelectric dam and the rise of lake level up to 1.3 m. The Kabansky State Reserve is located in the center of the delta, and it is a part of the Lake Baikal State Nature Biosphere Reserve. There are species of valuable fish and beaver rats on the Selenga shallows. The nesting spots of migratory birds travelling further to the north are located here. Therefore, these landscapes are included in the list of wetlands included in the Ramsar List.

Unlike the Yellow River, which flows away from the mountain ranges on the Great Plains, the valley of the Selenga River crosses the system of the mountain ranges of the Khamar-Daban and therefore the process of sedimentation in the delta has been much faster in the background of a bigger neotectonic activity. Modern earthquakes occurring in the Baikal rift zone confirm this. It is known that one of the strongest seismic shocks in 1862 led to a lowering the northern part of the delta area of about 200 km^2 under the waters of Lake Baikal, the Proval Bay was formed in this place. In the recent geological past, such bays ("sor") appeared on the southern periphery of the delta of the Selenga River.

The relative antiquity of the deltaic deposits and its significant thickness determine the presence of oil and gas in Ust-Selenga Basin. The first investigators of the Baikal region found on the shores of Lake Baikal pieces of bitumen and oil film on the water surface. Drilling conducted in the late 50s, has reached the depth of 2950 m. However, there was not found any industrial oil or gas reserves. Then, because of the identification of hydrocarbon deposits in Western Siberia, the search was discontinued.

In the long term, the delta of the Selenga River is a specially protected natural area as a part of the World Natural Heritage Site – Lake Baikal, which is intended to preserve the flora and fauna of Lake Baikal, migratory birds, sport hunting and fishing with the limited economic use for the local population.

From a geological point of view the structure of the Selenga river delta reveals an obvious similarity with the structure of the delta of the Yellow River, where the second largest producer of oil-bearing region of China is located. The Oil is extracted here from the Tertiary deposits at the depths of more than three kilometers. Such a high power of the deltaic deposits is primarily determined by the fact that the Yellow River in the upstream water washes out the Loess Plateau. The Loess annually carried out by the Yellow River in large quantities composes its delta-alluvial plain area of about 260,000 km^2, which is launched in the Yellow Sea in the form of the Shandong Peninsula. There is no coincidence that in the translation from the Chinese language, it sounds like "Yellow River". The turbidity of the Yellow River in the mouth reaches up to 40 kg/m^3, the suspended sediments are carried far out to sea, and even at a considerable distance the river waters differ sharply from the sea. In general, the Yellow River annually makes 1.3 billion tons of the suspended sediment, ranking on this indicator the first place among the world's rivers. Sedimentation causes an increase of the delta of the Yellow River to 290 meters per year.

An intense deposition of sediment in the lower stream water increases the channel way, which is located at an altitude of 3 to 10 meters above the surrounding plains. The Yellow River and its tributaries are protected from flooding by the large-scale system of dams, the total length of which is about 5 thousand km. The breaks of Dam led to huge floods and displacement of the channel way. This used to lead to the death of many people and also gave the river the nickname "Grief of China." The maximum recorded channel way replacement of the Yellow River is about 800 km. After large displacements of the Yellow River channel ways merged to the river Haihe in the north, in the south - merged to the Yellow River and flowed into the Yellow Sea to the north, or in the south of the Shandong Peninsula. The last major movement of the channel occurred in 1938, when, during the war between China and Japan in the Yellow River had been blown up the dam and the river began to fall into the Yellow Sea to the south of the Shandong Peninsula. After repair of dams in 1947 the Yellow River once again started to fall into the Yellow Sea to the north of the peninsula.

Currently, a large amount of river sediment makes main channel meander intensively and causes catastrophic flooding after strong freshets. So today on a 300 km distance from Jinan to Dongying dams are built on both banks of the river, which stretch for miles stone blocks, designed for emergency situations when the dam is broken. Dam itself is an asphalt road with two-way traffic. Parking areas and the side branches are decorated with landscaped embankments.

It should be noted that the Shandong province has a population of over 90 million people and it is the second largest population in China. Therefore, bottomland is presented as fruit orchards and vegetable gardens with rare cattle population.

It is necessary to note that the significant part of the population lives in the bottomland of the Yellow River, which is located in the place at 2-3 m below its main channel. Probably, because of the frequent flooding, the valley in the lower reaches of the river is weakly populated by Chinese standards. Nevertheless, there are high cable 3-5 kilometer bridges, which cross the river every 70-90 km, and pontoon bridges. For the same reason the river below the Jinan city is not navigable.

Because of the accumulation of alluvium, the Yellow River delta is growing and new locations appear on these lands, for example, Dongying city, which officially was founded in 1983 and has a population of 2.4 million people.

Economically, the delta of the Yellow River is clearly divided into two zones. The nature reserve is located in the southern part, and its lower part is adjacent to the northern end of the delta. In general, delta of the Yellow River is the most holistic, comprehensive and young ecological system of wetlands. In recent years, area of swamped land in the delta of the Yellow River continues to increase. Thus, only in 2005, it increased by more than 1300 hectares, and the average due to the Yellow River the territory of Dongying city annually increases by 600 hectares. Now the large work is being done for the protection of wetlands, which helps to improve the ecology of the delta. Only the number of birds species has increased from 187 in the 1990-s to 283 at present on the protected area of the Yellow River delta. Every winter according to the experts more than 4 million birds fly. In recent years, four major projects for the protection of birds of the reserve are implemented. In particular, the restored number of wetland area of 10 hectares and measures were taken to improve the ecology of the delta of the river, the Center of Research and rescue birds.

The central territory and the most part of the northern territory of the delta is occupied by numerous oil wells. Coast protection structures were constructed and the Yellow River channel was artificially changed to increase the area for oil extraction. Satellite imagery and maps in 1976 shows that the runoff was carried out to the east and to the north of the delta. After the dam construction on the north creek the runoff sharply increased through the eastern creek where beakshaped microdelta was formed.

In addition to oil extraction, the local population collects various shellfish near the oil wells. The spots of natural evaporation of sea salt are located in different parts of the delta.

Thus, the lower reach of the Yellow River is the water-stressed region where the implementing the environmental projects and development of the industry and oil extraction can be possible. However, the main part of the delta is developed in the interests of the economic growth. Therefore, it is difficult to identify the dynamics of the natural processes.

The resulting natural-economic zoning of the reviewed deltas allows to select various scales of industrial transformation of wetland ecosystems. The most complete, in contrast to the Yellow River, the natural landscapes are preserved in the delta of the Selenga, which kept all the conditions for the existence of biota in accordance with the requirements of the Ramsar Convention. Such a comparative analysis of different types of transformation of nature and river deltas, located in different natural zones, creates the conditions for a more thorough study of the processes of delta as a unique natural sites, where there are favorable conditions for the realization of sustainable development.

ORGANIC MATTER IN SURFACE SEDIMENTS FROM THE SELENGA RIVER DELTA LAKES: A LIPID APPROACH

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Abstract: Lipid biomarkers distributions in surface sediments were determined using gas chromatography (GC) and GC-mass-spectrometry in order to investigate the lipid biomarkers signature in sediments of Selenga delta lakes and an attempt to evaluate the sources of organic matter (OM). More than 80 compounds were identified in lipid fraction of sediments. The major components of lipid fraction were saturated fatty acids (SFA, 46.04% – 65.17% of total lipids, TL), followed by monounsaturated normal and branch fatty acids (MUFA, 9.81% – 26.42%) and hydroxy acids (OH-FA, 8.08% – 17.35%). Also aldehydes, dicarboxylic acids (DCA), cyclic acids (CycFA) and sterols are found in surface sediments. Principal components analysis showed that organic matter in sediments of the lakes is mainly derived from terrestrial plants, bacteria and phytoplankton with the predominance of allochthonous sources of organic matter in July, and in spring and autumn - autochthonous sources (phytoplankton and bacteria).
Keywords: lipid biomarker, organic matter, Selenga river, sediment

The Selenga River is a one of major rivers in Asia, when it reaches the lake Baikal (the world's largest and deepest freshwater lake), forms a wide delta (S = 680 km²). It has to play the role of a natural filter carrying out the initial cleansing of industrial wastewaters that enter Baikal along the Selenga. Outwardly, the delta looks like a giant marshy water-meadow plain cut into islands by numerous channels, lakes and etc. These water bodies, which play a significant role in the biological production processes of the delta, not well investigated.

The interactions of water with bottom sediments play an important role in the ecological status of water bodies, which determines the need to study the biogeochemistry of sediments. In this direction, fatty acids and lipids widely used as biomarkers to provide valuable information regarding the origin, transport pathways and alteration and transformation processes of organic matter (OM) in environment (Wakeham et al., 1997; Hu et al., 2006; Yoshinaga at al., 2008; Holtvoeth at al., 2010). Furthermore lipid distribution in sediments allows to use their as proxies for paleoenvironmental, including paleoclimatic, reconstruction (Ishiwatari, 2005; Ishiwatari, 2006).

However the biogeochemistry of organic matter within this delta still remains poorly documented (Ishiwatari et al., 2005; Ishiwatari et al., 2006; Sorokovikova et al., 2001; Bashenkhaeva et al., 2006), yet no studies have been published concerning the biogeochemistry of biological markers in this estuarine system. This study investigates the lipid biomarkers signature in sediments of Selenga delta lakes and an attempt to elucidate their sources.

Materials and methods

Sediment samples were collected from May to September 2011 from four lakes near the main channel of Selenga – Harauz. These lakes vary in morphometric characteristics and in terms of water exchange with the river. Thus, the lake Zavernyaikha, remote from the mouth of 7 km, connected with the river in the spring and autumn period (Popovskaya et al., 2011). Tolstonozhikha lake is remote approximately of 1 km from Lake Baikal, and communicates with the main channel Harauz throughout the year. Lakes Berezovoe and Semenovskoe located on the same islands, practically non-flowing. Connecting them to the river is occurring during the high floods in delta (Sorokovikova at al., 2010). Sediment cores were taken from a boat using a gravity corer and consist mainly of sandy clays and diatom oozes. Samples were dried at room temperature and gomogenized by the quartering.

Lipids from sediments were extracted by the one-step extraction/methylation method (Osipov, 1993). At this stage, fatty acids and aldehydes of the complex lipids of microorganisms and other cells of the sample are released in the form of methyl esters and dimethylacetals. Then the hexane extract was treated with 20 mkl of N, O-bis (trimethyl silyl) trifluoroacetyl acetamide forming trimethylsilyl ethers of hydroxy acids and sterols. For the identification of the component composition the total ion scan mode was performed.

Results and discussion

In total, 81 compounds were identified in lipid fraction of sediments. The major components of lipid fraction (Table 1) were saturated fatty acids (SFA, 46.04% – 65.17% of total lipids, TL), followed by monounsaturated normal and branch fatty acids (MUFA, 9.81% - 26.42%) and hydroxy acids (OH-FA, 8.08% – 17.35%).

Also aldehydes, dicarboxylic acids (DCA), cyclic acids (CycFA) and sterols are found in surface sediments.

Saturated fatty acids

Straight-chain fatty acids are often the most abundant lipids found in marine sediments. Highest proportions of saturated fatty acids occur in the sediments taken in the summer/autumn, in particular in the Zavernyaikha and Tolstonozhikha sediments accounting for 68.27 and 63.53 % of total lipids, respectively. It's due to a high content of hexadecanoic acid, which along with octadecanoic acid is a biological marker of phytoplankton (Hu et al., 2006).

Within the short chain fatty acids (SCFA), C16 (15.13–34.02% of TLC), C18 (3.69 – 11.06%) and C14 (3.69 – 4.71%) SFA were most abundant, whereas C24 (2.92 – 8.11%), C22 (2.69 – 5.88%) and C26 (1.10 – 3.52%) had the high contributions among the long chain fatty acids (LCFA), showing a strong even over odd predominance. Long-chain fatty acids (carbon number more than 20) in marine sediments are typically associated with terrestrial inputs of organic matter from higher plants (Meyers, 1997). Contribution of vascular plants to bottom sediments was the highest in Semenovskoe Lake in July according to the higher level of terrestrial markers – LCFA.

Table 1

Relative amounts (as percentage of TL) of the lipid compounds and specific biomarkers/ratios in surface sediments of Selenga delta lakes

Lake	Zavernyaikha		Tolstonozhikha		Semenovskoe		Berezovoe
Date / Lipid components	May	Sept	May	July	May	July	May
SFA	58.16	68.27	59.98	63.53	52.41	59.80	50.96
ΣSCFAa	38.63	55.84	44.10	46.69	39.10	32.89	40.24
ΣLCFAb	19.54	12.43	15.89	16.84	13.31	26.91	10.71
ΣSCFA / ΣLCFA	1.98	4.49	2.78	2.77	2.94	1.22	3.76
CPIHc	27.06	9.35	15.87	15.95	9.94	59.54	6.29
branched SFA	7.62	3.63	11.60	8.86	9.14	6.42	8.17
MUFA	17.88	16.75	24.78	15.03	25.04	10.86	29.24
PUFA	1.42	1.69	0.03	1.70	5.17	1.32	1.79
DCA	0.06	1.17	0.21	1.31	d	–	–
Aldehides	2.54	1.34	1.96	4.69	2.74	3.33	4.96
Hydroxy-FA	8.99	4.66	6.60	6.00	7.57	9.17	4.09
Fatty alcohols	8.21	4.81	3.92	4.81	3.38	10.03	4.85
Cyc FA	–	–	–	0.74	0.55	0.33	0.18
Sterols	2.30	1.08	1.76	2.05	2.04	4.03	2.80

a Short chain (SCFA<C_{20});
b long chain (LCFA≥C_{20});
c CPI_H – the carbon preference index for even – over odd-numbered high-molecular weight SFAs (CPI_H = (ΣC_{22}–C_{30} +ΣC_{24}–C_{32})even/(2×ΣC_{23}–C_{31})odd (Matsudo and Koyama, 1977);
d not found.

The ratio ΣSCFAs/ΣLCFAs was applied to identify spatial and temporal variations in the contribution of marine vs. terrestrial sources for the saturated fatty acids.

Predominance SCFA over LCFA was observed for all sediments (Table 1), and demonstrates a greater contribution of marine than terrestrial OM to surface sediments, at that the highest ratio ΣSCFAs/ΣLCFAs is observed for sample Zavernyaikha'Sept, and the lowest value – Semenovskoe'July.

Further information can be gained from the carbon preference index (CPI), the ratio of even- over odd-numbered carboxylic compounds. This proxy is often used to assess the level of FA degradation based on the fact that unaltered biological material usually shows a strong even-over-odd predominance of its FAs whereas microbially altered material reveals higher amounts of odd-numbered FAs and, accordingly, lower CPI values (Holtvoeth et al., 2010). Matsudo and Koyama (1977) introduced a modification of the CPI for the application on FAs of high molecular weight (CPIH, range: C22–C32) using the equation CPIH = (ΣC22– C30 + ΣC24–C32)/2 × ΣC23–C31. Accordingly, the proportion of odd-numbered long-chain SFA (n-C23 to n-C31) is slightly increased only in the sample Berezovoe'May, resulting in the lowest observed

CPIH value of 6.29 (Table 1). The highest observed CPIH values of 27.06 and 59.54 in Zavernyaikha'May and Semenovskoe'July samples respectively are a result of high relative amounts of C22 and C24 FAs. The CPIH values of all other samples range from 9.35 to 15.95 and thus suggest a low level of FA degradation (Table 1).

Terminally branched (iso-, anteizo-) FAs were detected in relative high amounts in the surface spring samples of Tolstonozhikha and Semenovskoe lakes. They are known to be abundant across multitude of bacteria, but less significant in algae, fungi as well as in terrestrial plants (Kaneda, 1991; Gong and Hollander, 1997; Harvey and Macko, 1997; Dalsgaard et al., 2003).

Unsaturated fatty acids

In highest relative amounts are found C16:1 and C18:1 MUFAs. These compounds are abundant in phytoplankton, since diatoms are enriched in C16:1, mainly C16:1d9, while other microalgae (e.g. dinoflagellates and prymnesiophytes) are enriched in C18:1 (Volkman et al., 1989). Thus, the greatest relative contribution from diatoms to the OM is in the sediment from Berezovoe'May, as the highest relative amount of C16:1d9.

In all sediments samples (except september sample of Zavernyaikha lake), cis-vaccenic acid 18:1d11c was accompanied by 18:1d11t. This finding provides compelling evidence that bacterial cells can modify their membrane fluidity in response to stress (Keweloh and Heipieper, 1996; MacNaughton et al., 1999).

In lakes Zavernyikha and Berezovoe contribution of copepods to bottom sediments was significantly higher, than that in Tolstonozhikha and Semenovskoe lakes, according to the levels of FA marker of copepods, 20:1d11 and 22:1d13 (Brett et al., 2009).

PUFAs are very low in relative amounts and the algal-derived PUFAs (20:5n-3 and 22:6n-3) are absent (Zhukova and Aizdaicher, 1995; Volkman et al., 1998; Zimmerman and Canuel, 2001). Among PUFAs were identified only C16:2 and C18:2 acids, it is may be due to that unsaturated FAs are generally more susceptible to microbial degradation than saturated FAs (Haddad et al., 1992; Meyers and Ishiwatari, 1993). Low levels of PUFAs indicating that most of these labile fatty acids were effectively recycled during the whole settling and depositing process in Selenga river delta.

Hydroxy acids and fatty alcohols

Hydroxylated fatty acids have been found in all sediments, aliphatic long chain (C22-C26) α-monohydroxy fatty acids (2-hydroxy monocarboxylic acids) are more abundant. They are occurring in a wide range of organisms (i.e. in plants, animals and bacteria) and typically produced as intermediates in the α-oxidation of monocarboxylic fatty acids. In yeasts, α-hydroxy fatty acids are intermediates in fatty acid biosynthesis (Volkman, 2006).

At all sites, the alcohols with even number of carbon atom range from C 22 to C26 are identified, suggesting that the alcohol fraction is of terrestrial origin. Volkman et.al. (1999) found the C22-alcohol to dominate in eustigmatophytes, phototrophic marine and freshwater microalgae, while Jaffe et.al. (2001) observed large amounts of this compound in epiphytes.

Aldehides, cyclic and dicarboxylic acids

In the studied sediments were found simple linear, branched and mono-unsaturated aldehydes with a chain length of 14 to 22 carbon atoms. Aldehyde content is low and ranged from 1.28-4.53 %. In natural waters, carbonyl compounds, which include aldehydes, may appear from algae, as a result of biochemical and photochemical oxidation of alcohols and organic acids, decomposition of organic substances such as lignin. The source of these compounds is also may be terrestrial plants, which form the series of aliphatic aldehydes and furan derivatives. Much of the aldehydes and ketones enter into natural waters as a result of human activities (Vakulenko et al., 2006).

Also cyclopropane acids with 17 and 19 carbon atoms were identified, which are quite common in both gram-positive and gram-negative organisms.

Only short chain C8-C9 and long-chain C22 α, ω-dicarboxylic fatty acids are identified in sediments of Tolstonozhikha and Zavernyaikha lakes, predominantly in summer and autumn. Shorter-chain dicarboxylic fatty acids such as azelaic acid (C9) occur as natural constituents of some plants and as degradation products from oxidative scission of the double bonds in unsaturated fatty acids. Azelaic and other short-chain dicarboxylic acids have been found in marine sediments and in aerosols (Volkman, 2006.). C22 even-chain dicarboxylic fatty acid is often abundant in the plant biopolymer suberin (Kolattukudy, 1980).

Sterols

Sterol composition of the lake sediments sampled appeared to be dominated by ß sitosterol (ranged from 0.65% to 2.48% of total lipids). Campesterol, β-sitosterol and stigmasterol are common sterols in epicuticular waxes of vascular plants (Volkman, 2006; Laureillard and Saliot, 1993) but can also occur in diatoms and microalgae. Their use as biomarkers of terrigenous organic matter has been of concern since they have also been reported in several other organisms (Volkman, 2006).

Cholesterol is very common in living organisms and not very specific (Goosens, 1989). It is commonly abundant in natural coastal and marine sediments and seawater. Cholesterol may derive from zooplankton such as ostracods or zoobenthos such as gastropods (Thiel, 1997), however, it is also found in dinoflagellates, diatoms and some species of Prymnesiophycaean algae contain cholesterol as the major sterol (Volkman, 1986). Popovskaya et.al. (2011) have found the intensive development of phytoplankton in the lake Zavernyaikha in the ice period, where dinoflagellates have decisive role, and in the spring - diatoms are dominated.

Principal component analysis

Multivariate analysis (factor analysis) was employed to gain further insight into the relationships between samples (scores) and lipid markers (loadings) and to assist in determining the sources of organic matter. Previously, several authors have used multivariate analysis to help identify organic matter sources (Hu et al., 2006; Yoshinaga et al., 2008).

Principal component analysis (PCA) was performed using 7 samples and the following variables: individual biomarkers, including saturated and unsaturated fatty acids, fatty alcohols, cyclopropane fatty acids, α, ω-dicarboxylic fatty acids and individual sterols. Data were normalized via the log centered method prior to PCA analysis (Kvalheim and Karstang, 1987).

The two first components in the PCA analysis of biomarker lipid compounds (Fig. 1) explained a total of 63.5% of the data variance. The results of the Selenga delta lakes sediment factor analysis showed that there were three main factors that contributed to most of the variability. These factors consisted of an autochthonous source (i.e., phytoplankton, bacteria) and an allochthonous source (i.e., terrestrial plants).

These data show a clear clustering of samples and variables depending on the sources of organic matter, including marine phytoplankton, bacteria and terrestrial higher plants. According to their fatty acids "signature" PC1 shows (Fig. 1a) positive loadings of bacterial markers (branched fatty acids) whereas terrestrial derived compounds contributed positively on PC2 versus negative loadings of short-chain marine-derived fatty acids. The scores plot (Fig. 1b) shows a clear clustering of samples depending on the sources of organic matter. As you can see, terrestrial input in lakes Semenovskoe and Tolstonozhikha is more in July, whereas in spring and autumn autochthonous organic matter is predominance.

Conclusions

Our study presents a first inventory of lipid biomarkers present in sediments of Selenga delta's lakes. The composition/distribution of lipid biomarkers and principal component analyses of these data characterize the nature and distribution of organic matter, that clearly confirmed by principal components analysis.

Based on the results of the fatty acid and sterol biomarker studies, it can be seen that a combination of both lipid biomarkers are necessary to use in identifying sources of organic matter. It is very important to consider whole set of lipid biomarkers, all of their potential sources, and any additional information that is relevant to the sample and sample site when interpreting results of geochemical studies.

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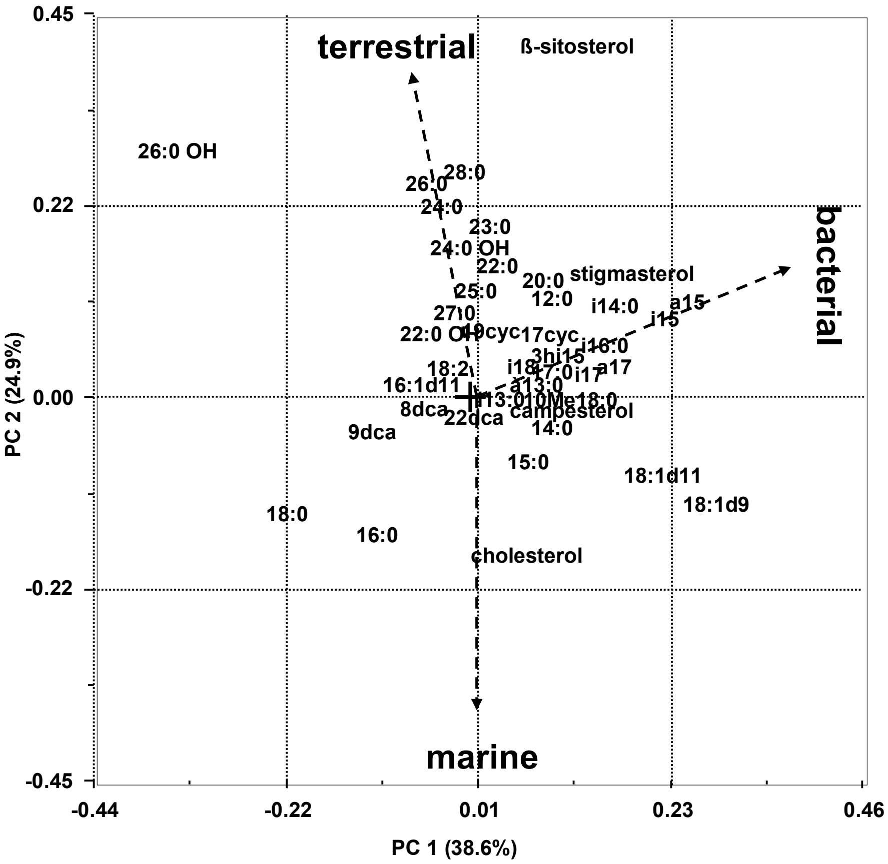
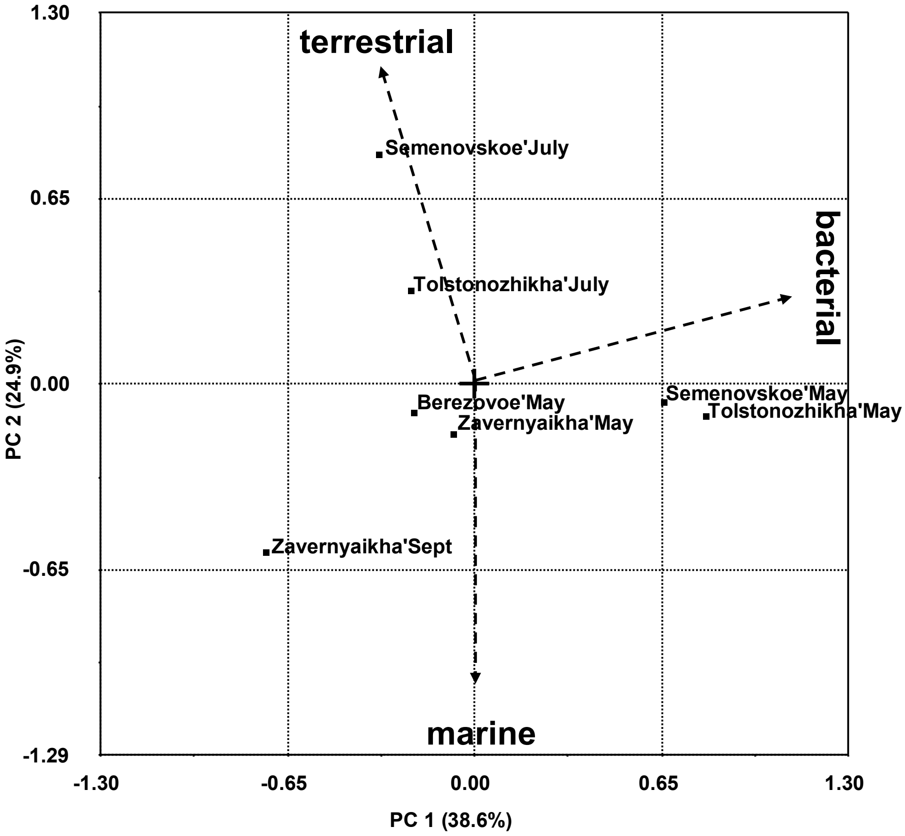


a)



b)

Fig. 1: a) the loadings on the first two principle components for biomarker fatty acids, alcohols and sterols; b) the scores of the first two principle components for each sampling site

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CHANGES IN THE CONCENTRATIONS OF HEAVY METALS IN WATER AND SEDIMENTS, DEPENDING ON HYDROLOGICAL CONDITIONS

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Abstract: Changes in terms of water content of river Selenga significant depend on the content of heavy metals water. Concentrations of heavy metals in surface water in the delta in 2011-2013 under conditions of high water content significantly decreased due to the dilution effect, iron and manganese content decreased by 5-10 times, copper decreased by 2-3 times, zinc decreased by 8-12 times in comparison ones in 2003.
Keywords: delta, heavy metals, sediment flow

Some of the objects in Central zone of Baikal nature territory, requiring the retention certainly applies River ecosystem. Selenga with a rich resource potential, use of which is, along with borderline status are defined the need to fulfill of environmental and predictive assessments of the state of aquatic and terrestrial ecosystems. This is primarily refers to the Selenga delta of the river, which is one of the largest freshwater deltas in the world. Despite the significant amount of scientific and applied research basin rivers of Lake Baikal, the Selenga River delta and remain key objects of study, as it is for the Selenga River is the main water stream contributed by volume of the lake, are seasonal migration paths of valuable commercial fish species.

Comprehensive investigation on the river Selenga and channels its delta since 2001 to the present day conducted by staff of the Baikal Institute of Nature Management, together with the staff of the Institute of Limnology [1-7]. According to the data of results a comprehensive study of perennial river delta Selenga obtained with 2001-2012 years noted that the change in hydrological conditions on the river Selenga largely determines the dynamics of the concentrations of chemical of components in the river and its delta ducts of. During the study period water content the river (2001-2010) Was lower (23.2-28.7 km 3) long-term average values (29 km3).

In 2011-2013 years. were continued monitoring observations over the content heavy metals (HM) in water and bottom sediments in the framework of the Global Environment Facility 00078317 RFQ/EMO/2012-009 (IWC-78317) "Integrated Natural Resource Management in the Baikal Basin transboundary ecosystem". Water sampling, as in previous years, was conducted on stations at the bottom stream of the Selenga delta and ducts of (Fig. 1) in which taken water samples for analysis of chemical components and measured water flow.

In the years 2011-2013 water samples were selected in the summer high water in comparison with previous years the river the water content of has been enhanced at the expense of abundant precipitation. This situation greatly had an impact on content of heavy metals in surface waters of the river Selenga. Concentrations of heavy metals in surface waters duct in the Delta 2011-2013 years. under conditions of increased water content significantly gone down due to dilution, the content of iron and manganese has decreased 5-10 fold (Fig. 2 and 3) copper in 2-3 (Fig. 4), zinc 8-12 times in comparison with 2003 (Fig. 5).

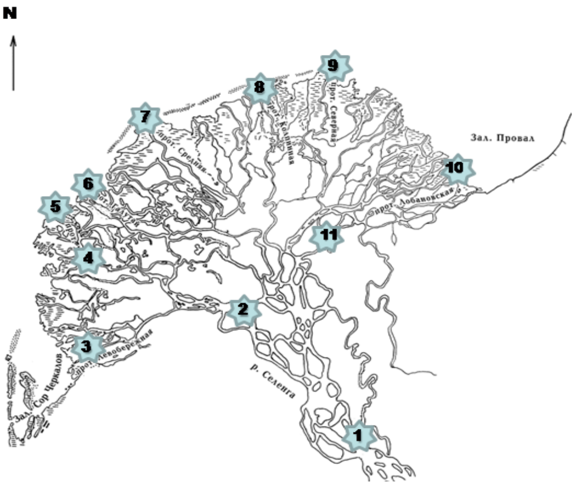

Fig. 1. Schematic map of sampling

The comparative analysis of the change contents of iron, manganese, copper, the main ducts of 2011-2013 shown that concentration of these metals did not undergo significant deviations, so the content of iron ranged in the range from 50 to 100 g/l (2013), from 63 to 88 g/l (2012), manganese from 4.8 to 40 g/l (2013), from 4 to 30 mg/l (2012), copper from 0.4 to 1.4 mg/l (2013), to 1.0 mg/l (2012).

In comparison with the 2003 The findings suggest that much reduced concentrations in 2011-2013. caused of increased water content in relation to 2003 (Fig. 2-4).

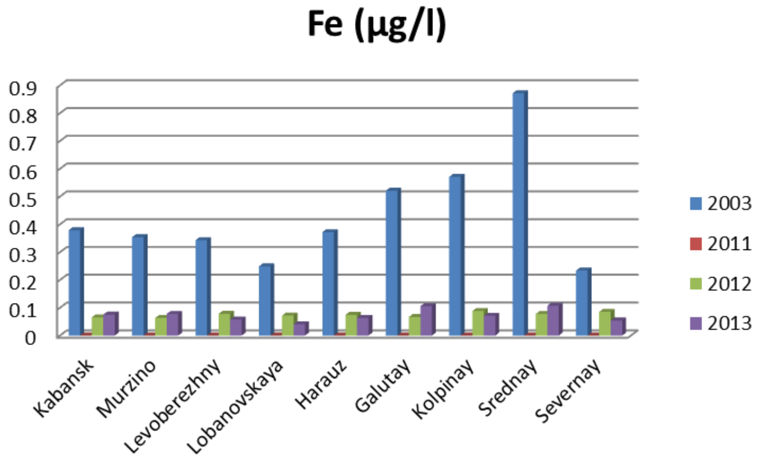

Fig. 2. The iron content of 2011-2013 in relation to the 2003

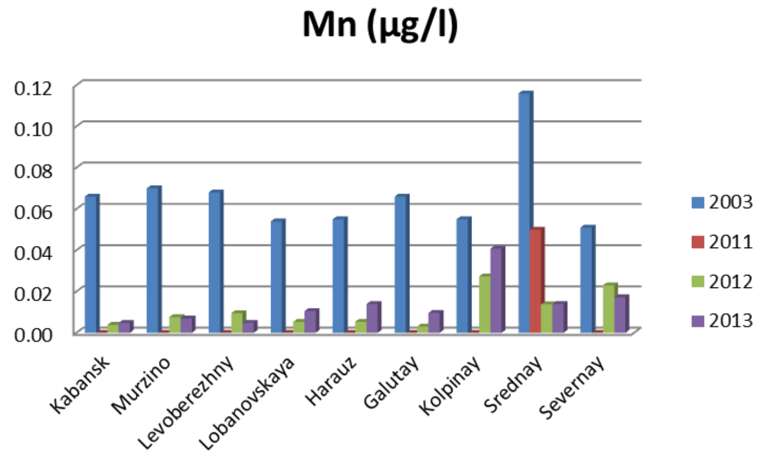

Fig. 3. The content of manganese 2011-2013 in relation to the 2003

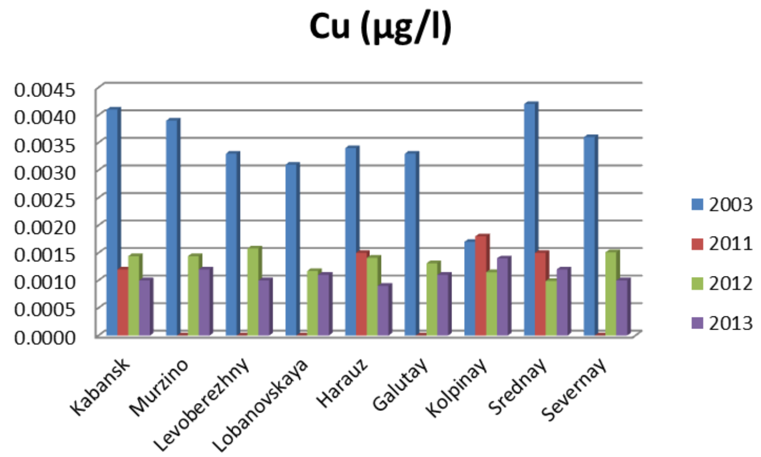

Fig. 4. The copper content of 2011-2013 in relation to the 2003

The zinc content in the surface water over a period observed with respect 2003 (Fig. 5), although it does not exceed the MPC values, nonetheless speaks of the local waters entering zinc waters of the river Selenga that requires further observation and research.

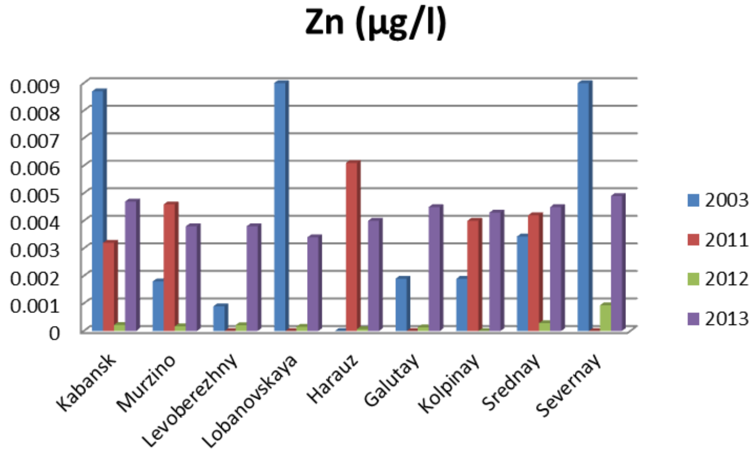

Fig. 5. The zinc content 2011-2013 in relation to the 2003

Thus the change in hydrological conditions has a significant impact on the content heavy metals in the water, so as a result high water content, heavy metal concentrations considerably gone down compared to 2003 when was registered the lowest water content of the river.

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Recommendations
of the International scientific conference
«DELTAS: GENESIS, DYNAMICS, MODELLING AND SUSTAINABLE DEVELOPMENT»

The International scientific conference «Deltas: genesis, dynamics, modeling and sustainable development» was held from 21th to 25th of July, 2014 at the International ecological-educational center «Istomino» in the Republic of Buryatia, Russian Federation. The organizers of the conference are Baikal Institute of Nature Management SB RAS (Ulan-Ude), Sochava Institute of Geography SB RAS (Irkutsk), Department of Geography of Lomonosov Moscow State University (Moscow), Rice University (Houston) and University of Illinois (Urbana-Champaign).

The conference brought together about 60 leading scholars, including the researchers from Rice University (Houston, USA), Woods Hole Oceanographic Institute (Massachusetts, USA), Louisiana State University (Baton Rouge, USA), University of Illinois (Urbana-Champaign, USA), Tulane University (New Orleans, USA), Boston University (Boston, USA), Tsinghua University (Beijing, China), Wageningen University (Wageningen, The Netherlands), University of Texas (Austin, USA), University of Wyoming (Laramie, USA), The Water Institute of the Gulf (Baton Rouge, USA), Nagasaki University (Nagasaki, Japan), University of Washington (Seattle, USA), Chevron Energy Technology Company (Houston, USA), Simon Fraser University (Burnaby, Canada), University of South Carolina (Columbia, USA), Ocean University (Qingdao, China), ExxonMobil Upstream Research Company (Houston, USA), Institute of Marine Sciences (Bologna, Italy), École Polytechnique Fédérale De Lausanne (Lausanne, Switzerland), Baikal Institute of Nature Management SB RAS (Ulan-Ude), Moscow State University (Moscow), Institute of Limnology SB RAS (Irkutsk), Institute of Geography SB RAS (Irkutsk), Institute of General and Experimental Biology SB RAS (Ulan-Ude), Arctic and Antarctic Research Institute (St. Peterburg), State institute of hydrology (St. Peterburg), Tomsk State university (Tomsk).

The participants of the conference emphasized the timeliness of the conference, recognizing the significant role of deltas in maintaining ecological equilibrium of water body ecosystems – receptacles of the flows of substance and energy, conduits of social and economic development.

The conference outlined the findings of research into the genesis, dynamics, modeling and sustainable development in the river deltas (Selenga, Volga, Huang He, Mississippi, Amazon, Rhine, Lena, Yenisei, Mekong, Yangtze etc).

The participants of the conference noted the importance of continuing research on the functioning of the world delta ecosystems, in particular, as they are impacted by the anthropogenic factors.

Recognizing the special significance of delta ecosystems as the indictors of ecological wellbeing of natural environment, the conference participants emphasized the problem of scientific research coordination in natural and economic sciences and decided to suggest the following:

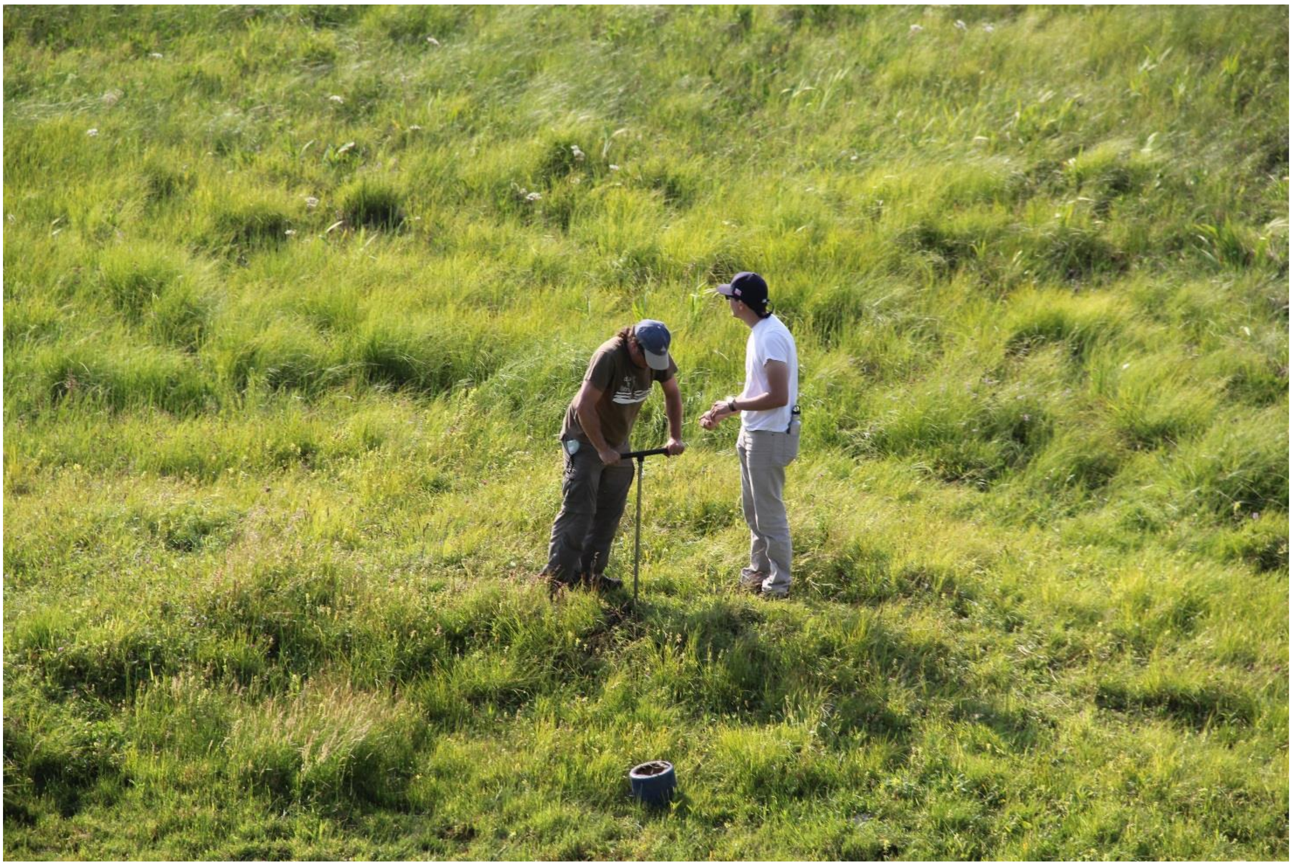
- To conceive and write a series of scientific papers for publishing in the top international peer-reviewed journals, registered by Web of Science and Scopus systems.
- To elaborate a joint complex program on the study of delta ecosystem functioning, their sustainability to anthropogenic factors and rational management of resources.
- To provide support to the proposal of the Sakha Repulic Government to set up a world heritage site in the Lena River delta.
- To publish information on this conference in Russian and foreign mass media outlets.

August 18, 2014
Istomino, Republic of Buryatia, Russia

Welcoming speech by Academician Arnold K. Tulokhonov

Tour around the Selenga river delta

Tour around the delta branches



Soil sampling with the soil tube

МЕЖДУНАРОДНАЯ НАУЧНАЯ ЭКСПЕДИЦИЯ
2013-2015
ЛЕМАН - БАЙКАЛ
ТРАНСЕВРАЗИЙСКИЙ ПЕРЕЛЕТ
Международный эколого-образовательный центр "ИСТОМИНО"
International eco-educational center "ISTOMINO"
WELCOME THE PARTICIPANTS OF THE INTERNATIONAL SCIENTIFIC CONFERENCE
DELTAS:
GENESIS, DYNAMICS,
AND SUSTAINABLE

CONTENTS

CHANNEL MIGRATION RATES AND AVULSIONS

FRESH VERSUS SALT-WATER DELTAS

ANTHROPOGENIC INTERACTIONS, ECOLOGY AND DELTA SUSTAINABILITY

НАУЧНОЕ ИЗДАНИЕ

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