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A LUCIFS Strategy: Modelling the Sediment Budgets of Fluvial Systems.

Introduction

Cumulative Global Change is occurring through the removal of forests, conversion of marginal land to cultivation, and intensification of cultivation. Systemic Global Change, in the form of changes in climate and atmospheric chemistry, is likely to alter land use patterns during the next century. All of these changes will affect rivers and their catchments, altering the fluxes of water, sediment, nutrients, carbon and pollutants. The effects of past changes of land use and climate are still being felt in many catchments, and are difficult to understand without an historical perspective. Future changes, when superimposed on changes triggered in the past, will produce complex responses, which may be difficult to anticipate.

There is therefore a clear need for a better understanding, and a better theory, of the response of fluvial systems to land use and climate change, in order to anticipate and perhaps predict future changes, and to understand current dynamics. Although most of the relevant scientific research has been conducted in small catchments, most interest in future responses relates to large catchments. The time period over which a large catchment responds to land use or climate change is much longer than that for a small catchment; much longer than most instrumental time series.

The PAGES-LUCIFS (Past Global Changes - Land Use and Climate Impacts on Fluvial Systems component of the IGBP, the International Geosphere and Biosphere Program) Project aims to assemble a library of fluvial system responses from around the world, using case studies selected to represent both a wide range of land use and catchment types, and areas where land use has evolved slowly over millennia and where industrial agriculture has been transplanted to non-agricultural landscapes during the last few centuries. Models capable of application to this library of responses are being developed to provide the tools for anticipation and/or prediction of future change.

Although the impacts of Global Change on fluvial systems are important in themselves, change to these systems will also affect the coastal zone by increasing material fluxes to the coasts in some cases and decreasing fluxes in others. Changes in the carbon and nutrient fluxes of rivers will also impact on global biogeochemical cycles, particularly in terms of carbon and nutrient sequestration within the fluvial system and the coastal zone. Rivers play an important role as a link between the major global biogeochemical systems, but, more than that, they are crucially important to human well being and for aquatic organisms. The importance of fluvial systems, as phenomena that are affected by Global Change and in turn affect Global Change, is clear, along with their wide-ranging societal and ecological significance.

LUCIFS Aim and Scientific Questions

The main aim of the LUCIFS programme is to understand the changes in water and particulate fluxes through fluvial systems and their associated budgets, over the period of agriculture. These changes and budgets are to be investigated at global, regional and local scales, and over both long and short time scales. There are five questions, which are central to LUCIFS investigations. These are:

1. How have fluvial systems responded to past changes in climate and/or land use?
2. What are the key factors that have controlled water and particulate fluxes (as sediment, P, C and other) in different regions?
3. In each region, does the response and sensitivity of the system to these key factors vary spatially and temporally?
4. In each region, how do long-term processes affect the present day responses of fluvial systems?
5. What feedback exists between variations in water/particulate fluxes and global environmental change?

By answering these questions within a global conceptual framework, a global view can be obtained. The LUCIFS project involves temporal scanning of a complex spatial phenomenon - the fluvial system, which is controlled both by natural and socio-economic processes. However, information concerning the fluvial system and about key controlling factors can only be partial at any temporal scale. The level of information varies both spatially and across the different components of the fluvial system and between different regions. One of the main approaches to filling information gaps involves modelling of spatial phenomena and temporal processes.

A definition of the fluvial system

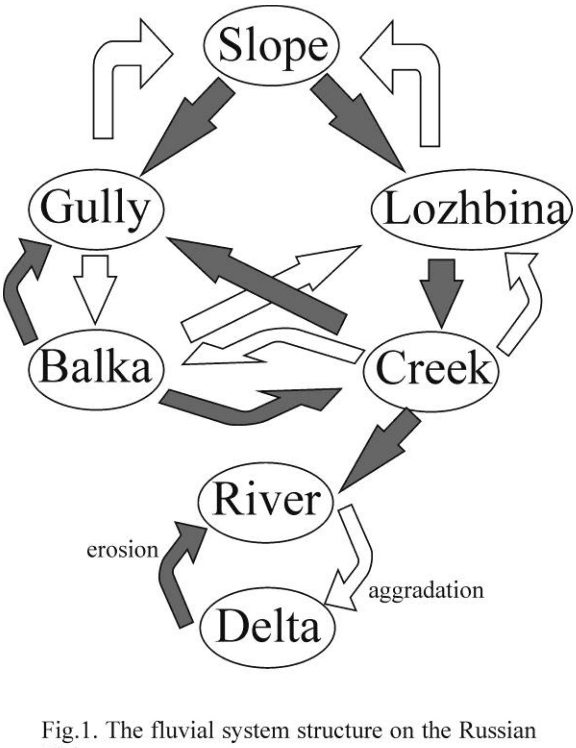

Fig.1. The fluvial system structure on the Russian Plain.

The fluvial system can be defined (in the broadest sense) as the complex of connected channels (including ephemeral flows on hillslopes) and reservoirs on the surface of the globe, associated with water flow and the erosion, transport and deposition of sediment and other particulate matter. According to the different types of flow (permanent or ephemeral), the geomorphological history and the types of erosion and sedimentation processes operating, the system can be characterised by different elements. For example, on the Russian Plain the most common morphological elements of the fluvial system (Fig. 1) are: 1) the slopes and rills; 2) elongated gentle troughs on the slopes (lozhbina); 3) active smaller gullies and their fans; 4) aggraded larger gullies or stream channels (balka); 5) active stream channels; 6) rivers and floodplains; 7) river deltas.

All these elements are interconnected and can be transformed from one to the other in space and time due to erosion or deposition. Rapid erosion and sedimentation under conditions of variable climate and sparse vegetation (often human-induced) cause rill and ephemeral gully formation on slopes, which may be transformed into active bank and slope gullies and, in favourable conditions, into large gullies and stream channels. In this situation, small rivers transport high sediment loads and can be aggraded. They often become buffering areas for sediment deposition between the slopes and large river channels. With a mild climate and good vegetation cover, erosion on slopes is very slow, and gentle elongated troughs are formed not only by surface erosion, but also by seepage water and by slow mass movement. In such situations, streams and small rivers are fed by clean water and can erode their channels.

The main methods of modelling the spatial properties of the fluvial system involve topographic and geomorphological mapping, recently aided by the construction of Digital Terrain Models. These DTMs can be used to show the whole complex of connected elements comprising the fluvial system, the elements of the system, or the morphological parameters of these elements and their statistical characteristics. Such maps allow the linear and non-linear interpolation and extrapolation of the spatial features on the basis of spatial relationships. For example, interpolation of the map of gully density between key sites on the Russian Plain was based on relationships with the density of the network of streams and small rivers and the percentage of arable land (Kosov et al., 1989).

The response of the fluvial system to long-term changes in climate and land use: a qualitative approach

The fluvial system is controlled by the well-known factors influencing erosion-deposition processes, namely: 1) precipitation (rainfall and snowmelt); 2) relief; 3) vegetation cover; 4) soil texture and erodibility. This control is complicated, and often one parameter is related to several factors. At the qualitative level an increase in precipitation or relief generally increases the activity of erosion processes, whereas their decrease reduces erosion and promotes deposition. An increase in vegetation cover and soil strength decreases erosion intensity, and vice verse . As the elements of the fluvial system are connected, the same combination of controlling factors may cause sequentially altered processes of erosion and deposition through the system. These factors can be influenced by climate change or by human impact. The sign and intensity of process reactions to the same changes in controlling factors can be different in different parts of the fluvial system. For example, in the upper Don River basin the fluvial system was highly eroded in the cold Late Glacial time, when precipitation was twice as high as present , surface flow was reinforced by the low permeability of permafrost, and vegetation cover was sparse. This was a period characterised by intensive sheet and rill erosion on bare slopes, formation of long and deep gullies, and incision in the small and medium-sized river valleys. The eroded matter was mainly transported along the large rivers and accumulated in the river deltas (Fig. 2a). At the beginning of the Holocene, the incidence of permafrost was reduced over this region and soil permeability increased dramatically. This resulted in a sharp decrease in surface flow, aggradation in the valleys of the small and medium-sized rivers, and intensive deposition in the large gullies. During the Holocene thermal optimum, dense forest-steppe vegetation covered the territory and the surface flow became relatively low due to infiltration and increased evotranspiration. These changes caused the general stabilisation of the whole fluvial system (Fig. 2b). During the period of intensive agriculture (the last 400 years) the forests were cut and 60-70% of the territory was ploughed. Intensive slope and gully erosion occurred and sediment concentrations in the surface runoff increased rapidly within the upstream parts of the fluvial system. Deposition occurred in the large gullies and small river channels and on the floodplains, and suspended sediment concentrations decreased downstream (Fig. 2c).

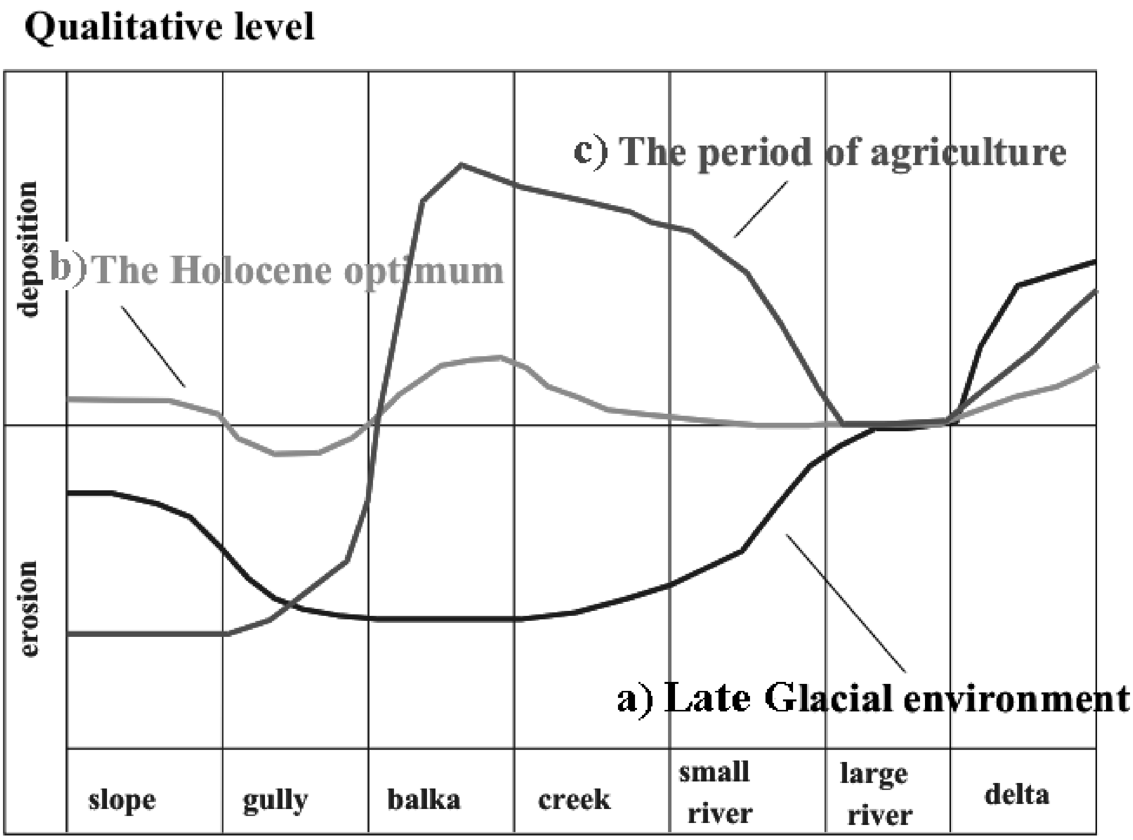

Fig.2. Qualitative estimate of erosion and deposition rate change along the fluvial system of the upper Don River during a) the Late Glacial; b) the Holocene optimum; c) the period of intensive agriculture.

The response of the fluvial system response to long-term changes in climate and land use: a quantitative approach

The sediment budget for the water flow can be described by the equation of mass conservation, which can be written in the simplified form:

$$\frac{\partial Q_s}{\partial X} = q_{sl} + M_0 W + M_b d - C\frac{d}{D} V_f W \qquad (1)$$

Here $Q_s = QC$ represents the volumetric sediment discharge ($m^3 s^{-1}$); Q = water discharge ($m^3 s^{-1}$); X = longitudinal co-ordinate (m); C = mean volumetric sediment concentration; q_{sl}= specific (for a unit of the length) sediment discharge of the lateral input from the river basin ($m^2 s^{-1}$); M_0 = upward sediment flux from the river bed ($m\ s^{-1}$); M_b = sediment flux from the channel banks ($m\ s^{-1}$); W = flow width (m); d = flow depth (m); V_f = sediment particle fall velocity in turbulent flow ($m\ s^{-1}$); D = the bed load particle size.

The fall velocity V_f in turbulent flow with a mean velocity U is less than Stokes's fall velocity V_{st} in steady or laminar flow due to turbulent flow oscillations. Therefore, as a first approximation, the modified formula of Hwang (1983) can be used to estimate V_f.

$$V_f = \frac{V_{st}}{1 + \frac{0.5U}{(9.0V_{st})^2}} \qquad (2)$$

In the case of very fine particles and high turbulence, V_f can be close to 0.

The left side of the equation of mass conservation (Equation 1) defines the sediment budget for the channel reach. The right hand side of the equation defines the sediment fluxes: the first term

is the lateral flux from hillslopes in the basin, the second is the upward flux from the river bed, the third is the sediment flux from the banks, and the fourth is the downward flux to the river bed.
A 1D equation of mass conservation is universal for a fluvial system, which is defined as a 2D net of 1D flowlines. This approach can be used at most scales, ranging from the small rills on a slope to large river basins. For some special cases (sedimentation on floodplains, in reservoirs and in lakes), a 2D mass conservation equation is coupled with 2D and 3D fluid dynamics modelling.

Equation (1) is a first order ordinary differential equation, and the solution of this equation depends on the form of the terms, which describe the sediment fluxes. When $M_0 = kU\frac{U^2}{U_{cr}^2}$ and $M_b = k_b \frac{W}{d} M_0$ (cf. Sidorchuk, 1999), Equation (1) can be written in the nondimensional form:

$$\frac{d}{Q}\frac{\partial}{\partial}\frac{Q_s}{X} = k_1 \frac{U^2}{U_{cr}^2} + \frac{q_{sl}d}{Q} - \frac{d}{D}C\frac{V_f}{U} \qquad (3)$$

Here U_{cr} is the critical velocity for erosion initiation and k_1 is an empirical coefficient. Equation (3) indicates that a nondimensional sediment budget is controlled by three factors : 1) the relative sediment input from the river basin; 2) the ratio between the flow velocity and its critical value (a measure of flow erosivity); and 3) the ratio of the fall velocity for the sediment particles to a flow velocity. When the right hand side of Equation 3 is positive, sediment concentration increases along the stream and the segment of the fluvial system is eroded . When the right hand side of Equation 3 is negative the system is depositional , and when it is zero the fluvial system is in equilibrium . The solution of Equation (3) shows the change in sediment concentration along the stream:

$$C_i = C_{i-1}\exp\left(-\frac{V_f}{UD}(X_i - X_{i-1})\right) + \frac{UD}{V_f}\left(\frac{k_1}{d}\frac{U^2}{U_{cr}^2} + \frac{q_{sl}}{Q}\right)\left[1 - \exp\left(-\frac{V_f}{UD}(X_i - X_{i-1})\right)\right] \qquad (4)$$

The term "$\frac{V_f}{UD}$" controls deposition within the channel section. Deposition increases with the particle size of the suspended sediment, and decreases as flow velocity and turbulence increase. Part of the increase in sediment load within the reach can be accounted for by erosion of the channel bed and bank $\left(\frac{k_1}{d}\frac{U^2}{U_{cr}^2}\right)$ and by sediment delivered directly to the channel from the surrounding river basin $\left(\frac{q_{sl}}{Q}\right)$. Substantial deposition leads to the decreasing influence of the first term in Equation (4) on the suspended sediment load and an increase of the effect of the second term. The second term in Equation (4) mainly reflects the local sources of the sediment load.
Thus the sediment budget regime of a fluvial system can be classified in the 'phase space' of three key non-dimensional numbers viz. $\frac{k_1}{d}\frac{U^2}{U_{cr}^2}$, $\frac{V_f}{UD}$ and $\frac{q_{sl}}{Q}$. Several cases can be identified :

1. The flow velocity is much greater than the critical velocity for particle detachment. In this case the upward particle flux is significant. Fall velocity V_f is also high and intensive exchange of sediment between the channel and the flow will occur in the fluvial system. The erosion and deposition processes change along the channel. Deposition increases because of the lateral flux of sediment from the catchment. This is the most complicated regime of the fluvial system, and Equation (3) in its general form must be used for modelling.

2. Exchange of sediment between the channel and the flow is intensive, but upward and lateral fluxes are equal to the downward flux. This is the case of channel bed dynamic equilibrium, which is common for medium and large rivers. In small rivers, this equilibrium is often disturbed by accelerated erosion of the catchment, which results in a high lateral flux and causes aggradation in small river channels. In Equation (3) the term on the left-hand side can be omitted:

$$\frac{q_{sl}d}{Q}+k_1\frac{U^2}{U_{cr}^2}-\frac{d}{D}C\frac{V_f}{U}=0 \qquad (3.2)$$

$$C=\left(\frac{q_{sl}d}{Q}+k_1\frac{U^2}{U_{cr}^2}\right)\Bigg/\left(\frac{d}{D}\frac{V_f}{U}\right) \qquad (4.2)$$

3. The flow velocity is much greater than the critical velocity for particle detachment, and the upward particle flux is significant. Flow turbulence is high and the fall velocity V_f is low. Deposition is limited and erosion is intensive. Such a regime is common for active rills, for the initial stages of gully erosion and for channel erosion in cohesive sediments. In Equation (3) the last term on the right-hand side can be omitted:

$$\frac{d}{Q}\frac{\partial}{\partial}\frac{Q_s}{X}=k_1\frac{U^2}{U_{cr}^2}+\frac{q_{sl}d}{Q} \qquad (3.3)$$

$$C_i=C_{i-1}+\left(\frac{q_{sl}}{Q}+\frac{k_1}{d}\frac{U^2}{U_{cr}^2}\right)\Delta X \qquad (4.3)$$

4. Flow velocity is less than the critical velocity for particle detachment, and the upward particle flux is limited. At the same time catchment erosion delivers only fine particles in the lateral flux and the flow turbulence is sufficiently intense to reduce the fall velocity V_f . This is the case of channel static equilibrium, with limited (zero) erosion and deposition. All terms in Equation (3) are equal to zero:

$$\frac{k_1}{d}\frac{U^2}{U_{cr}^2}=0,\ \frac{V_f}{UD}=0 \qquad (3.4)$$

$$C_i=C_{i-1} \qquad (4.4)$$

5. The same as in (4), but with a significant lateral flux of sediment from the catchment and/or upper reaches of the channel, and aggradation of channels This is common for reservoirs, floodplains, and river deltas. In Equation (3) the first term on the right-hand side is omitted:

$$\frac{1}{Q}\frac{\partial}{\partial}\frac{Q_s}{X}=\frac{q_{sl}}{Q}-\frac{1}{D}C\frac{V_f}{U} \qquad (3.5)$$

$$C_i=C_{i-1}\exp\left(-\frac{V_f}{UD}(X_i-X_{i-1})\right)+\frac{q_{sl}}{Q}\frac{UD}{V_f}\left[1-\exp\left(-\frac{V_f}{UD}(X_i-X_{i-1})\right)\right] \qquad (4.5)$$

The LUCIFS modelling strategy

Three main options for modelling the sediment budget of a fluvial system can be identified viz.

1. Process-based modelling of the whole basin. Equations (3-3.5) are applied to all types of erosion and deposition processes in the basin. The spatial limits are set by DTM resolution. This approach requires large quantities of initial data, involves many model parameters, and is generally used only for small catchments.

2. Combination of simple statistical models (e.g. USLE, RUSLE and similar) for estimating slope erosion and empirical data on gully erosion, with process-based modelling in the river network. Equations of the (3-3.5) type are applied only to permanent streams. The main limitation of this approach is the estimation of the empirical delivery ratio which needs to be applied to the sediment load that is transported from the slopes and gullies to the rivers. The data requirements for the calculations can generally be met and the approach can be used for long-term modelling of fluvial systems of different sizes.

3. Combination of simple statistical models for estimating erosion rates with empirical information on erosion, transport and deposition in the river net. The main limitation of this approach is the need to estimate the empirical sediment delivery ratio for all catchments within the basin. This approach is best suited to coarse modelling.

Modelling of small catchments

Use of the GULTEM model (Sidorchuk & Sidorchuk, 1998) to model gully erosion and thermoerosion provides an example of the first of the approaches listed above. This model describes the first stage of rapid gully development. During snowmelt and/or rainfall events, flowing water erodes a rectangular channel in the topsoil or in the gully bottom. Shallow landslides quickly transform the gully cross - section to a trapezoidal form during the period between water flow events. GULTEM was applied to the net of flowlines established using a topographic DEM. The soil texture was estimated for each horizon (including the surface horizon with vegetation cover) with a different composition. Runoff due to snowmelt and rainfall was calculated from meteorological information using a physically-based hydrological model.

DEMs were used to provide information on elevations, flowline directions and gradients, and catchment areas. The original interactive procedure was extended to incorporate the filling or linking of closed depressions associated with errors in the interpolation of the initial relief. One of eight possible directions of flow with maximum gradient was used for flow path estimation. The ability to set the preferred direction was used to estimate the influence of small features such as roads or the pattern of ploughing. The catchment area of any point was calculated as the sum of the pixel areas of all flowlines linked to the point above it. Elevations of the soil surface were estimated from DEMs for each soil with a similar texture, and the main soil characteristics were determined from direct field observations.

The main meteorological and hydrological processes taken into account in modelling surface runoff were:

- Precipitation amount, in form of snow or rainfall.
- The thermal dynamics of the snow, the thawing of the snow and the meltwater output.
- Interception of water by crops and natural vegetation.
- Water storage in micro-depressions.
- Infiltration

The runoff was represented using a kinematic wave approach coupled with the Manning formula, applied to the network of flowlines. The width and depth of flow was calculated using empirical regime formulae. The main formula used to describe gully erosion was of the (3.3) - (4.3) type, where erosion is the main process and the eroded material is completely removed from the system. GULTEM was used to model gully development on the Yamal Peninsula, in the presence of deep permafrost, snowmelt and rainfall. One such gully, for which both initial and actual longitudinal profiles were available, is situated on the right bank of the Se-Yakha River in the central part of the peninsula (Sidorchuk, 1996). Before 1986 there was a shallow linear depression with a dense vegetation cover and ephemeral flow. In 1986 an exploitation camp was built at the top of the basin. Surface disturbance and increased meltwater flow led to intensive gully erosion. A gully 840 m long (measured along the thalweg) developed. In 1991 and 1995 the longitudinal profile of the gully was investigated. The initial profile was available from a large-scale map. The depths of runoff associated with snowmelt and rainfall were calculated using available meteorological data. The coefficients in Equation (3.3) were calibrated using observations for the 1986 - 1995 period.

The results of the calculations (Fig. 3) are mainly controlled by the soil texture (aggregate size and cohesion), vegetation cover density (a function of land use) and water discharge (a function of the climate).

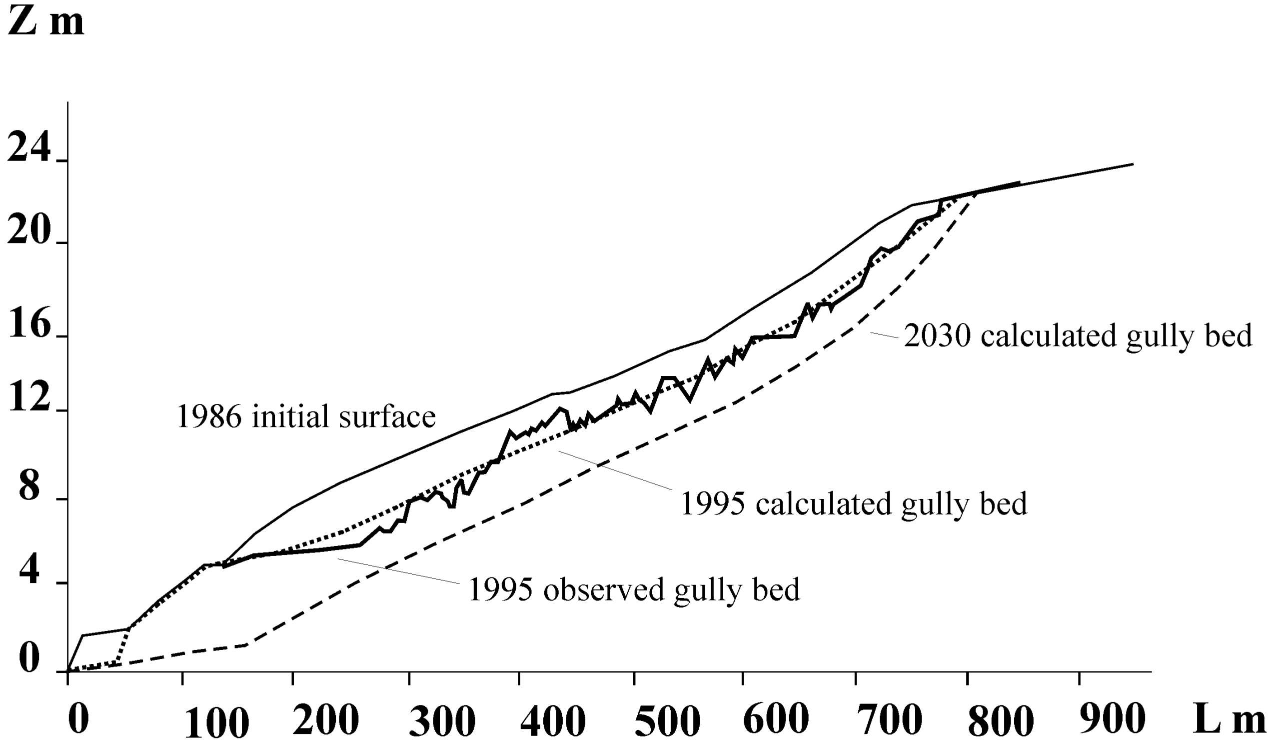

Fig.3. Calculated gully dynamics on the Yamal Peninsula (Northern West Siberia).

Modelling medium -sized basins

The reconstruction of sediment budgets in medium -sized fluvial systems can be based on the second approach: i.e. the combination of integrated (lumped) estimates of the sediment supply to the river network from the slopes, rills, gullies and other ephemeral channels with accurate evaluation of the sediment budget in the distributed permanent river network. The basin must be divided into subcatchments; each connected to a segment of a stream or small river. The volume of erosion from the slopes, rills and gullies must be calculated for each subcatchment for a given period of time. The Sediment Delivery Ratio (SDR) must be estimated for each slope-rill-gully complex. The volume of erosion combined with the value of SDR gives the value for the lateral flux in Equation (3) for each stream or river segment. Other terms in Equations (3) and (4) are calculated based on regional data on channel and floodplain processes. The solution of (4) gives the change in sediment discharge along the river network over a given period of time.

A case study of the Zusha River basin

The basin of River Zusha (a tributary of the upper Oka River) is located in the Central Russian Upland, with altitudes in the range 140-280 m above mean sea level. The fluvial system here consists of slopes; rills; lozhbinas; gullies and fans; balkas; streams; and small and medium size rivers with floodplains. Erosion takes place on the upper parts of the slopes, and sedimentation occurs on their lower parts, with a predominance of erosion overall. The gullies are primarily characterised by erosion. The balka and stream valleys are the main areas of sediment deposition. Sedimentation also

occurs on the river floodplains. A complicated process of sediment exchange between the bed and the flow takes place in the small and medium rivers. The contemporary rate of sheet and rill erosion for agricultural land was calculated by Belotserkovskiy et al. (1991) using two main Soil Loss models, which were verified for Russian Plain conditions viz. the State Hydrological Institute Model (SHI - Model) for estimating erosion during spring snowmelt and the Universal Soil Loss Equation for the period with rainfall. The estimated rate of soil loss varies from 3.0 to 10.0 t ha^{-1} $year^{-1}$ within the basin. The volume of gully erosion (i.e. the volume of gullies more than 50 m long) during the period of intensive agriculture was calculated by Kosov et al. (1989), who reported a mean value of 640 t ha^{-1}. The structure of the main channel network (tributaries more than 10 km long) and the main morphometric and hydrological parameters used in the calculations were derived from Hydrological Survey data.
The regional version of equation (4) is (Sidorchuk, 1996a):

$$C=\left(C_o-\frac{2.8Q_oS}{q_w(Y+1)}-\frac{C_w}{Y}-\frac{0.0025\sqrt{Q_oS}}{q_w(Y+0.5)}\right)*\left(\frac{Q_o}{Q}\right)^Y+\frac{2.8Q\ S}{q_w(Y+1)}+\frac{C_w}{Y}+\frac{0.0025\sqrt{QS}}{q_w(Y+0.5)}$$

Here Q_0 and C_o are the water discharge and volumetric sediment concentration in the channel flow at the beginning of the reach, S is the water surface slope, q_w is the lateral specific (for a unit of the channel length) water discharge in m^2 s^{-1}, C_w is the volumetric sediment concentration in the lateral flow. $Y=\left(q_w+V_f*W\right)/q_w$

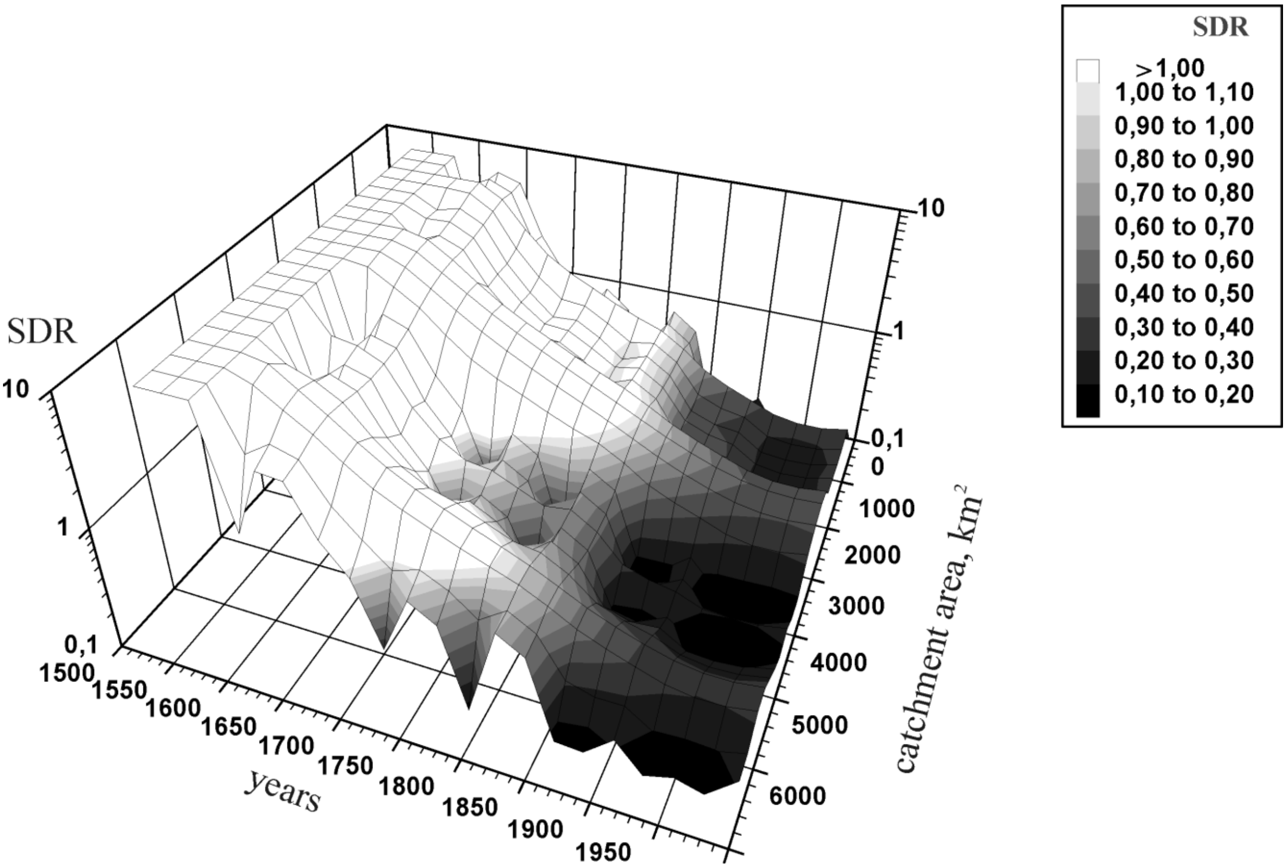

Fig.4. Sediment Delivery Ratio change through time and in space for the Zusha River basin.

Sediment delivery ratios and sediment yield variations for the Zusha River catchment were calculated through the time and across space (Fig. 4) for different levels of human impact. During the 16th century, under natural conditions with a very low level of slope and gully erosion, the SDR was greater than 1.0 for the entire basin. Channel erosion dominated. The sediment yield was equal to the transport capacity of the river channel, and it exceeded the input of sediment from the slopes and from gullies. As human impact at the beginning of 17th century increased and 14 % of the river basin was tilled, the SDR became less than 1.0 for the main part of the basin, because the transport capacity of the river flow (highest for the last 500 years due to maximum precipitation) remained smaller than the input of the sediment from the slopes and from the gullies. However, this input was not very great, and the rate of sedimentation in the upper reaches of the channel was also not very high. About 20-50% of the eroded sediment was transported out of the system. During the 1930's when 71% of the river basin was tilled, the value of SDR was less than 0.2 for the whole basin. Only 10% of eroded sediments was delivered to the outlet of the system. Erosion from the slopes dominated sediment yields in the upper part of the channel network and in the gullies, and was mainly controlled by land use: i.e. change in the area of arable land through time. The sediment yield in the lower river reaches was dominated by the transport capacity of the river flow, which was primarily a function of the climate (water discharge).

Modelling of large basins

The sediment budgets of large fluvial systems can be reconstructed using the third method, namely the Sediment Delivery Ratio approach. The large basin must be subdivided into a system of subbasins. The following values must be calculated for each subbasin for a given period of time:

- The volume of erosion from the slopes, rills and gullies.
- The Sediment Delivery Ratio defined as the ratio of the sediment transport from the subbasin outlet to the total erosion on the basin slopes by rills and gullies.

This gives:

- The sediment yield from each sub-basin outlet.
- The volume of sediment deposition within the sub-basin i.e. the difference between total erosion and the sediment yield at the sub-basin outlet.
- The depth of deposition in the river network.

When applied to the whole basin, this procedure gives the distribution of eroded sediment within the basin, the deposition depth in the network of streams and rivers, and the sediment flux at the outlet of the large basin.

Case study: the Khoper River basin

Erosion on the slopes was calculated by Belotserkovskiy *et al*. (1983) using the same two soil loss models as employed in the Zusha River study outlined above; i.e. the SHI model for spring snowmelt and the USLE for rainfall. The principle of superposition of erosion factors was used for mapping of the erosion rate. Each factor in the USLE or SHI-model was mapped separately. The erosivity factor R was calculated for all meteorological stations in the Khoper River basin using rainfall intensity measurements. A regional relationship between erosivity R and mean annual rainfall depth was established and erosivity was estimated for the stations where only rainfall depth measurements were available. On the basis of these data, the R factor was mapped using isolines. The soil factor K was calculated directly from the USLE nomograph for all categories of soil texture, structure, permeability and organic matter content for soils, shown on a 1:1,000,000 soil map of the USSR. The vegetation cover factor C was calculated from long-term crop rotation statistics, available for the smallest administrative districts. The seasonal changes in vegetation cover were taken into account. The same spatial resolution was used for the management factor P, which was estimated from regional statistics on land management. The most complicated approach was that used for the calculation of the relief factor LS. The national DEM was not available at the time of calculations, so the Khoper River basin was subdivided into several morphologically similar units, based on a geomorphological typology, using large-scale topographic maps. Measurements of relief characteristics were performed separately for cultivated and uncultivated land at 300-600 points, to obtain the distribution of the LS factor within the unit and its mean value. Superposition of information on soil type and the morphological units provided the main features of the soil erosion map of the Don River basin (Fig. 5), which includes the Khoper River basin.

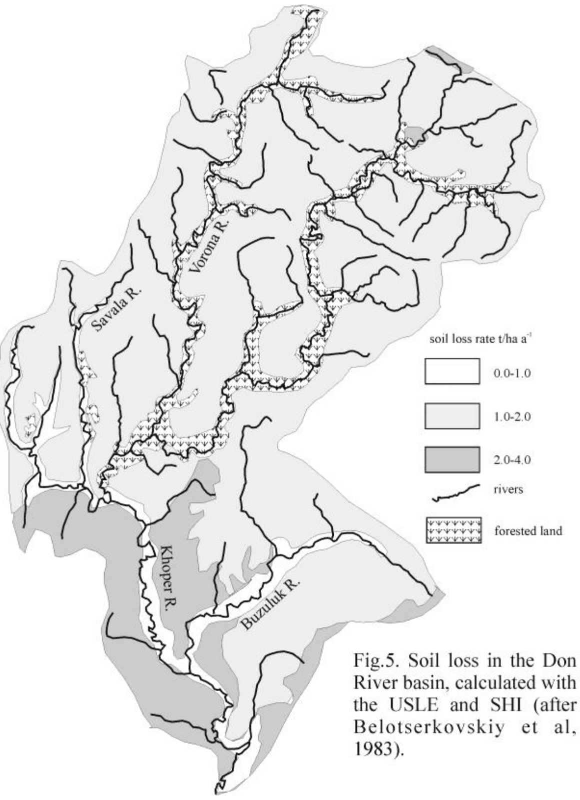

Fig.5. Soil loss in the Don River basin, calculated with the USLE and SHI (after Belotserkovskiy et al, 1983).

For each of these categories, the mean soil-loss and its distribution curve were estimated.

The erosion map was used to calculate the soil-loss from the slopes for all of the catchments where sediment yield was measured by the State Hydrological Survey for a period of more than 10 years. The SDR was calculated for each of these catchments within the Khoper River basin as the ratio of the volume of the measured sediment yield from the catchment to the calculated volume of erosion E in the catchment: SDR=T/E. These data provided a basis for establishing a regional relationship between the Sediment Delivery Ratio and river basin area (Fig. 6). This relationship was extended to the whole river network of the Khoper River basin. The volume of erosion, the SDR and, accordingly, the volume of sediment transported from the basin outlet and the volume of sediment deposited within each catchment, can be estimated for any subbasin for a given time period. Information on the length of all the permanent streams in this basin is available from the measurements of the State Hydrological Survey, and the floodplain width can be estimated from the regional relationship: $W = 14.8\sqrt{Q}$. This provides an estimate of the area of the floodplains associated with the permanent streams, and therefore the main areas of sediment deposition, and permits estimation of the depth of sedimentation on the floodplains for a given period of time (table 1).

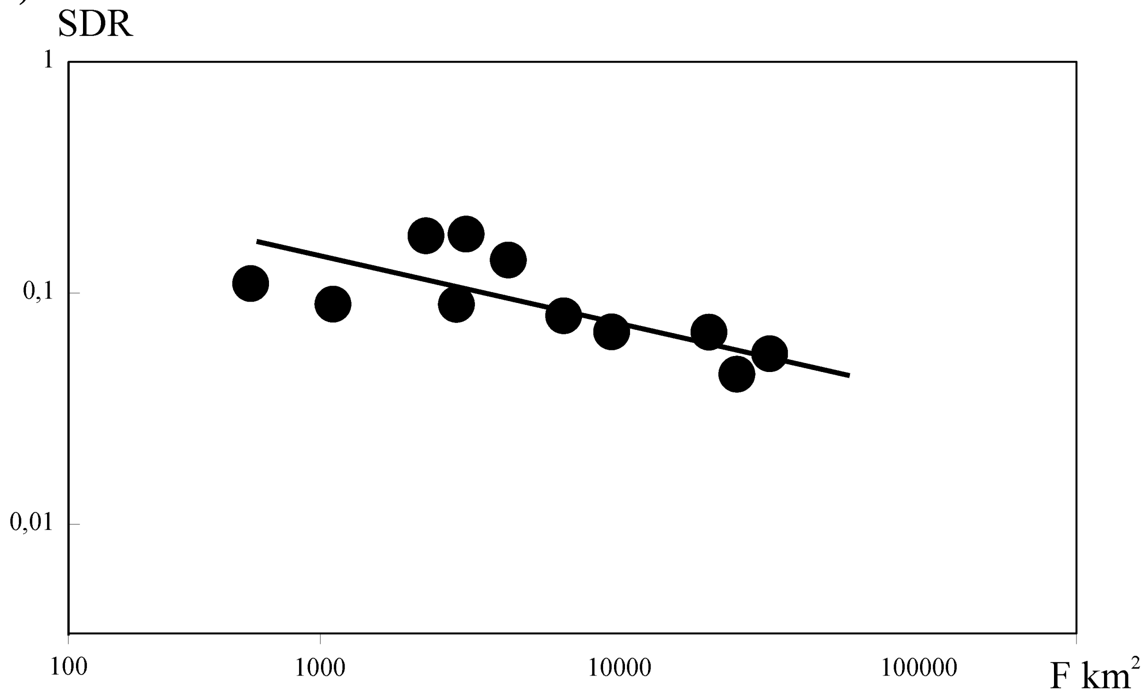

Fig.6. Sediment Delivery Ratio versus basin area for the Khoper River basin.

Table 1 River net structure and distribution of the annual sediment deposition in the Khoper River basin (up to Novokhopersk hydrological station)

River length, km	<10	10-25	26-50	51-100	101-200	201-500	501-1000
rivers number	735	131	35	16	3	1	1
Total length, km	2283	1961	1264	1141	414	454	656
Total area of the channel +floodplain, km^2	7.9	58.8	164.3	353.7	248.4	449.4	1377.6
Total deposition 10^6 t/a	2.25	0.35	0.17	0.14	0.1	0.14	0.03
Deposition thickness, mm/a	285	6.0	1.0	0.4	0.4	0.3	0.02

Conclusion

LUCIFS aims to develop an improved understanding of the variations in water and particulate fluxes through fluvial systems at various times since agriculture began on our planet. We wish to know how fluvial systems have responded to past changes in climate and/or land-use, what factors controlled fluxes of water and particulates (sediment, particulate nutrients and carbon), how sensitivity to these factors varies in space and time, and how present day changes are affected by long-term processes and trends. Finally, LUCIFS wishes to contribute to our understanding of the feedbacks to global environmental change from changes in fluvial systems. Such feedbacks occur principally through changes in the carbon cycle, modulated by sediments and nutrients delivered to the coastal zone by rivers.

Material budgets are central to all LUCIFS studies. The great variability of fluvial system types and of the level of investigation of their history, means that a single modelling framework cannot be identified. Different combinations of process-based sediment budget models, simpler statistical models and empirical relationships may be applied to LUCIFS case studies, according to the availability of data. The gaps in the databases are generally increase with the basin size and modelling period. A general simplification of the approach with an increase in basin size and the duration of the modelling period introduces objective limitations on Global reconstruction within the LUCIFS strategy. The main limitation to global reconstructions using the LUCIFS approach are the need for application of models for use in large basins, and the reality of modelling long time periods.

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