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SELF-REGULATION OF THE FLOODPLAIN GEOSYSTEM – DYNAMICS WITH SATURATION

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Abstract: The modern cognitive theory is based on the recognition of the dialectic unity and struggle of opposites as the inherent property of physical objects – systems. The methodological approach proposed by us for studying the dynamics of geosystems develops this thesis. In our interpretation, the formation of all systems, including man-made ones, involves the spontaneous and latent development of other system (*satellite*) that uses the energy and substances produced by the former one. Figuratively speaking, as soon as *the producer X* of energy and matter (resource) arises, *the consumer Y* of such recourses arises as well. Despite the antagonism of *X* and *Y*, they constitute the complementary and synergetic (non-additive) entity that is inherently capable of evolution in all the variety of its forms.

Keywords: floodplain geosystem, self-regulation

Dynamics of Systems with Saturation: Basic Principles

The convergence to the dynamical equilibrium state observed in all self-organizing systems (Pozdnyakov 1988) is accompanied by the saturation processes. In terms of cybernetics, it is called the *target state* (limit saturation).

The whole experience of studying the self-organizing geosystems, including geomorphological systems, shows that they are binary structures: the formation of the system *X(t)* is accompanied by the formation of the satellite system *Y(X,t)*. The system *X* sends the energy to *Y(X,t)* and determines its spatial boundaries of development and lifetime. The dynamics of the system as the binary structure (Pozdnyakov 1988, 2007) are performed, on the one hand, due to the matter and energy coming from the environment and, on the other hand, due to their interchanging between its subsystems (Fig. 1, Annexes). Let us call the flows of matter, energy and information (*MEI*) consumed by the system *X* from the environment as the *F*-flows, while the flows that are objectively delivered to its satellite (system *Y*) as the *D*-flows. The energy in *F*-flows (“*energy for itself*”) is used for functioning and maintaining the system *X*. The amount of *MEI* accumulated in it is limited by the environmental capacity. Therefore, if the flow rate in the F-flow is constant (Q(t)=const), the quantitative characteristics of the geosystem’s dimensions M(t) of the geosystems decrease with time: ΔM(t)→ 0.

The energy in the *D*-flow is the forcedly supplied *“energy for satellite”*. Its flow rate is *q(t,M)→Max*. The formation of the satellite geosystem is an objective, inherent property of all self-organizing systems. The

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formation of the geosystem created by the *F*-flow inevitably results in the formation of the satellite geosystem and the *MEI D*-flow that supplies it with resources. Thus, the process *D* inhibits the development of the system $X(t)$ and, therefore, the system $Y(t,D)$. This means that $\Delta Y(t,D) \rightarrow 0$. At the same time, they constitute the structural-functional emergent entity and develop with saturation. The graph of such dynamics takes the form of the curve called by Verhulst as the *logistic growth curve*.

In essence, this is the law of universal action, according to which the dynamics of self–organizing systems are described by the equation:

$$dM/dt=Q(M,V,t) - q(M,t) \qquad (1)$$

where M are the output characteristics of the system taking into account the total accumulation of matter and energy developed by the systems X and Y; Q is the energy flow rate in the *F*-flow; q is the energy flow rate in the *D*-flow developed by the system Y; V is the environmental capacity; t is the time.

Floodplain Geosystem

The river floodplain is a part of the self-organizing channel geosystem, whose dynamics is performed due to the matter and energy coming from the environment and the their interchange between its subsystems. Since the floodplain is a surface periodically inundated in flood seasons, it naturally connects the channel with slopes and, therefore, one of the boundary expressions of the water stream. The floodplain dynamics is intimately connected with the channel dynamics. The channel dynamics is formed when the river channel is displaced both horizontally and vertically, i.e. $Y=Y(x,y)$, where x and y are respectively horizontal and vertical coordinates, Y is the floodplain height. At $dy/dt=0$ (non-descending channel), the river is displaced in the horizontal plane and leaves the low-level surface. The cumulative period of inundation of this surface which varies from the maximum value at the initial instant t_0 to zero in t_n. The cumulative value of the accumulated matter at the floodplain surface changes in the similar way.

Therefore, the time dynamics of the floodplain is determined by the amount of the material $Q(t)$ precipitated with a thickness of m. This thickness depends on such parameters as the content of suspended particles in water, their fall velocity etc. It can be determined according to the formula (Levashov 1983):

$$m=2P\omega/wSh,$$

where P is the weight of the detrital material in a unit of water volume, w is the volume weight of particles, ω is the fall velocity of particles, S is a unit of floodplain surface area, h is the water layer thickness.

As the floodplain height approaches the limit height Y_m, which is equal to the maximum floodwater level, $\Delta Q(t) \rightarrow 0$, a $q(t) \rightarrow max$. From this, it is easy to determine the time change pattern of the floodplain height (Pozdnyakov 2007):

$$dY/dt = Q(Y,t) - q(Y, t) \qquad (2)$$

This relationship makes it possible to describe the non-monotonic time behavior of various floodplain massifs. Since the floodplain systems, as well as all geomorphological systems, are dissipative, they must go to the steady state with the course of time: $dY/dt=0$. The formation of this mode is possible in the following cases:

$Q=q=0$ and $Q=q=const.$

In the first case, the floodplain would reach the maximum floodwater level and not be inundated. This would significantly reduce the amount of matter precipitated to its surface and give rise to degradation of the system. Such a scenario is purely theoretical since only a homogeneous environment may be free of matter flows.

The second case describes the final development of the floodplain as a whole entity in specific environmental conditions and determines its dynamical equilibrium. In terms of the theory of dynamical systems, this state corresponds to the limit cycle. The real floodplain systems never reach it. However, they come infinitely close to the dynamical equilibrium, almost repeating itself and not significantly changing its main morphological and morphometric parameters. Therefore, the high floodplain demonstrates the morphological maturity when it approaches to the limit height. If the floodplain surface becomes higher than the limit height Ym for some reason, it will not be inundated any more and can be classified as a terrace, i.e. the limit cycle of the floodplain system will be destroyed, just as the system itself will do.

The relationship (2) allows one to take into account river incision, accumulation of material from slopes to the floodplain and denudation from the floodwater surface, as well as the dynamics of mobile floodplain islands and plant communities on them, as shown in (Pozdnyakov 2007).

It is known (Pozdnyakov 1988) that :

$$Y_n(t) = Y_n^0 + N_0 m$$

As the height increases, a number of floods change in time proportionally to the difference between the limit floodplain height (Y_m) and its height at a given time $Y_n(t)$:

$$\partial N/\partial t = \alpha\,[Y_m - Y_n(t)] \qquad (3)$$

where α is the factor of proportionality.

In this case, if the floodwater surface is inclined to the channel, e.g. due to accumulation of the material drifted to it from slopes, the period of floodplain inundation will be a function of not only time, but also of the coordinate x. In this case:

$$\begin{aligned} N(x,t) &= \frac{\mathrm{Y_m} - Y_n^0(x)}{m} + \\ N(x) &- \frac{Y_m - Y_n^0(x)}{m}\exp(-\alpha m t) \end{aligned} \qquad (4)$$

This formula can be used for calculating the period of floodplain inundation at a given time and any point of the floodplain surface. Obviously, if the surface slope was not disturbed by anything, it would become horizontal at a certain time. Therefore, this formula allows one to determine a rise of the floodplain height, surface of which is complicated by oxbow depressions.

The floodplain denudation is generally weak since its surface is rapidly covered with vegetation. However, the denudation becomes more intense as the height increases, especially during the period of decreasing the floodwater level, due to rain-wash and snow melting, as well as removing the material by wind.

The morphometric characteristics of the floodplain serve as the regulators of its dynamics. They have the opposite effect on input characteristics, especially on the matter inflow (amount of solid precipitation): as the sizes (height, width) increase, an increase in the matter inflow tends reaches zero. Therefore, the self-regulation in the floodplain formation, as well as in all self-organizing systems, including geosystems of abiotic environment, is based on the opposite effect of its own sizes on the input flow of the matter.

In this case, the limit floodplain height is used as the so-called *target state*, which is to be reached by the system. The initial conditions of the matter and energy supply, as well as the environmental effects on the floodplain formation process determine the floodplain dynamics and the saturation process. However, they do not affect the attractive target of the development – the saturation limit, which is characterized in this case by the limit floodplain height.

Flood Plain Dynamics Features on Mobile Islands

Another form of the river channel relief reflecting the complex and multiple links in the “stream–channel” system are mobile islands. Formation and development of islands are caused by the combination of self-organizing processes and time-space changes in the external environment. The functioning mechanism of islands is aimed at bringing their form into conformity with the high-velocity structure of the river stream. The time evolution of mobile islands can be presented as an infinite chain of interactions between basic driving forces: high-speed stream, change in external conditions, the island’s form (external reflection of its morphogenesis) and the process of its formation. The origin for the island formation process is the structure of its functional relations. The velocity field of the channel stream instantly changes as soon as external conditions change. Changes in the high-velocity stream structure, in their turn, transform the material transfer process. It leads to the transformation of the island’s form within the action zone of the stream.

Besides, the quasi-periodicity in the location of islands along the stream can be identified in the channel areas with relatively constant external conditions (geomorphological, hydrological, geological). This fact can be explained in order to recognize the existence of self-oscillations in the stream caused by inherent properties of the stream itself (Pozdnyakov 2007; Makkaveev 1960). The relations of these properties (physical, hydrodynamic) constitute the internal structure of the stream and determine the processes responsible for location of islands in specific areas of the river channel. The expression (2) is the basic tool for analyzing the dynamics of mobile islands. Their morphology, height and structure are determined by the interaction of two processes – increase in surface height according to the equation (2) and change in its length $l(t,x)$ caused by the movement of the island as a result of washing out the upstream area $(-l(t))$ and the extension of the downstream area $(+lt))$ that occurs due to the matter accumulation. These two processes proceed continuously, but their activity depends on the hydrodynamics of the stream. In some areas of the river channel, the erosion of mobile islands is slowing down; in other areas the length of the island is shortened and its height reduced due to the rising erosion rate. In certain conditions the island can completely disappear or join the river bank

Behind any body, in this case the island (Fig. 3, Annexes), the so-called turbulent trace is formed when water flows around it (Abramovich 1960; Ginevskiy 1969). The distribution of stream velocities in this trace behind the body (island) obeys the same law as in a free turbulent jet. The zone of zero velocities and whirlpools is formed right downstream the island.

As the moving liquid captures water particles from this zone, the zone is gradually washed away and tapered out at a certain distance from the island. Thus, the zero-velocity core is formed right behind the island.

Accretion of the island occurs due to the intensive accumulation of material within the limits of the trace. When the water level falls (to the level of the low-water period), some dry land appears and the trace is formed downstream.

The length and height of the island depend on the ratio of erosion rates on its top part and accumulation of material within the trace zone. During the time interval Δt the coast line of the island is washed away and recedes at a distance $-\Delta Z$. During the same interval, height of its surface grows due to the sedimentation of detrital particles in high waters. Simultaneously, the length of the island increases by ΔZ due to the accumulation of material within the borders of the trace. The direction of the island’s movement coincides with the direction of the river’s course. Therefore, islands can move to one of the banks and join it forming floodplain massifs or be washed away.

One of the main characteristics of mobile islands is the period of their movement (T) – the time during which the island covers the distance equal to its length. It can be found as T=l/v, where l is the length of the island, v is the average erosion rate of the ledge in the upstream part of the island. The movement period depends on the hydrodynamic mode of the river. Therefore, the evolution of the island is directed towards the dynamic equilibrium corresponding to the hydrodynamic conditions.

In addition, the movement period *(T)* of the island determines the structure and age of sediments, distribution of the soil cover and vegetation along the island, as well as their age limit. The ground and wood vegetation on the island cannot be older than *T*. For example, at the average movement velocity of 5 m/year and its length of 400 m, T=80 years. During this period, the island reaches the dynamic equilibrium by its height, and the age limit of soil and trees will correspond to this period.

The average total duration of floods for 15 years of observation on the Amur river around the Voroniy island (Fig. 2, Annexes) is 172 days. During this period, the warp layer of 20 cm is accumulated in the lowest areas. Hence, *m* = 0.116 cm.

The incision rate of the island in this area is so low that it can be neglected in calculations. If the island was not washed away, its surface would reach the limit height Y_{lim} = 5 m for 200 years. After 100 years, its height would reach as high as 4.93 m.

As the age of islands is determined by their movement period, the most ancient and, therefore, the highest part of the island is its head, while its tail is the lowest and youngest part. Therefore the floodplain surface on mobile islands is always inclined towards the watercourse. The limit surface height of such islands depends on their movement speed. For example, the floodplain surface on Voroniy island considered above (Fig. 2, Annexes) is inclined at 0.5° Therefore, at annual erosion of its head part by 5 m, the surface is lowered by $\text{tg } 0.5° \cdot 5 \text{ m} = 0.043$ m/year.

Thus, two oppositely directed processes are involved in the evolution of the floodplain on mobile islands.

The first one is the accumulation of warp on the floodplain surface and increase in its height, with simultaneous collection of detrital material within the borders of the trace downstream the island and increase in the length of the island (*F*-flow).

The second one is the continuous erosion of the island's head; it causes lowering the surface, restricting its height and at the same time reducing the length of the island. These two processes proceed continuously, but their activity changes depending on the hydrodynamics of the flow. In some parts of the channel, the erosion of mobile islands is slowed down; hence, the movement period *T* and, therefore, their surface height *H* and length *l* are growing. In other parts, in connection with increasing the erosion rate, not only the length of the islands is shortened but also their height decreases. Under corresponding hydrodynamic conditions, the island can completely disappear or join the bank.

In the latter case, the factor causing a decrease in the height of the island becomes zero and the floodplain surface height reaches its maximum possible value. For example, the limit height of the floodplain on the studied island Voroniy, in one of the Amur river branches, is equal to 3.7 m rather than 5 m (Fig. 2, Annexes). At this floodplain height, the thickness of the warp layer deposited on it becomes equal to the thickness by which the surface is lowered due to the erosion of the island. If the island joins some bank or stops moving (for example, the river begins to actively recede to another bank and the island goes to the zone of non-eroding velocities), the height of the floodplain on this island reaches the greatest possible value, i.e. 5 m.

The described pattern is also observed when the river is displaced to one of the banks. Then, at the opposite bank, due to intensive material accumulation in the zone of non-eroding velocities, the floodplain will increase in width, and the central parts of the floodplain will rise up to its limit height and be straightened. At the same time, as it approaches the “younger” bank, the height of the floodplain becomes lower, while its relief becomes more dissected (alternation of near-channel banks and oxbow depressions). These areas gradually rise up to the limit height as well.

This is the mechanism of increasing the height of the floodplain on the inundated massifs confined between the river bends.

When the floodplain is formed as a result of displacement of rifts, reaches and bends downstream the river, we notice, on the one hand, erosion of the inundated lands located between the channel bends, and, on the other hand, increase in its length due to the formation of shallows near the convex bank and subsequent increase of its height due to the accumulation of material during flood seasons. The height of the emerging floodplain gradually approaches a certain stable value under the given conditions. This means that the transition process is completed and the floodplain reaches the equilibrium state.

Due to the displacement of bends, each floodplain massif has its own period of existence. The limit height of the floodplain depends on the fluctuation frequency of bends and their displacement rate. For example, at the erosion rate of 0.5 m/year and the length of the floodplain massif of 200 m (distance between the bends), the period (*T*) of floodplain development will be equal to 400 years. During this period, the floodplain massif, including its detrital material, mineral composition, soil cover and vegetation, will be completely replaced by a new one. This explains the existence of floodplains of different levels. The massif of a larger size has a larger height than the same massif of a smaller size. We can observe this everywhere in the nature: the floodplains formed on small islands or on the river parts located between contiguous river bends have the smallest height. All floodplains reach their own limit height tending to become more ordered.

Principles of Self-regulation by the Target and Current States

As opposed to living organisms having homeostatic properties and to cybernetic systems which have a special regulating device and one part performing the master control function, i.e. determining the amount of input and output matter, energy and information, in abiotic self-organizing integral structures, for example, in geomorphological systems, all these functions are performed by *F- and D-flows*. The functional diagram is shown in Fig. 4 (Annexes).

The desired values in the self-regulated geomorphodynamics processes are sizes of relief forms: height (*H*); surface area of slopes (*S*); volumes of forms (V); width of an underwater slope (B); steepness of slopes (α), which should reach specific quantitative values at the existing intensity of litho-flows when going to the limit cycle mode.

The curves representing simultaneous and interconnected changes in matter flow rates *P* and *q* in *F*-and *D*-litho-flows, respectively, depending on increase in relief sizes (*H*, *S*, and *V*), always cross each other. The crossing point between the curves shows the equality of flow rates (P=q), while its projection onto the abscissa x – the dynamically equilibrium sizes of forms, or, in terms of the self-regulation theory, *desired values*. It is clear that *H*, *S*, and *V* are directly determined by the intensity of litho-dynamic flows. Thus, *P* and *q* for the regulated values (*H*, *S*, and *V*) act as the *master control*, i.e. determine the target condition (attractor) to be reached by values *H*, *S*, and *V* when the equation $P = q$ is established.

The development of geomorphic systems is constantly under the influence of perturbation actions, which deflect the regulated values *H*, *S*, and *V* from their target values, i.e. disturb the equilibrium of the system. For geomorphic systems, such perturbation actions may be changes in weather (for example, infrequent storm downpours or short-term (as compared with geological periods) climate changes) that cause a rapid rise in the denudation rate, i.e. increase in flow rate q in D-flow. When the previous conditions are restored, the relief forms and their morphology are restored as well. If the intensity of matter flow rates in F- and D-flows is changed for a geologically significant period, they act as the master control, i.e. the relief form should be described by other morphometric and morphological parameters, or by another attractor corresponding to the changed conditions.

However, some changes in quantitative parameters that characterize the matter flow rates in F-and D-flows, undoubtedly, occur. Therefore, the morphometric parameters H, S, and V of the relief forms also vary within some limits, i.e. fluctuate. When the balance of matter flow rates ($P=q$) is achieved, the inflow of the matter and its denudation do not stop. Therefore, the equilibrium is dynamic.

The regulated parameters in the relief are the current values characterizing the sizes of its forms: height $H(t)$, area $S(t)$, volume $V(t)$, etc. If the desired values for some fixed period of time (t) are constant, the regulated values change towards the equality with their *limit values* (desired values).

In the development of floodplains, the flow rate P in F-litho-flow is presented by the detrital sediments precipitated during flood seasons. The amount of the deposited material (thickness of warp layer) decreases with time and with the growth of the floodplain's height H while the total period of inundation (N) of the floodplain, which is the function of H as well, decreases.

The flow rate q of the negative litho-flow grows or remains constant. Therefore, the equality $P=q$ will be inevitably achieved at constant environmental conditions.

Formation of the longitudinal river profile in any section of the river valley is directed at achieving the equality of forces dragging the fragments and the forces resisting the movement:

$$(V_l + \tau) - (T + C) = 0$$

At a constant incline (i) of the longitudinal profile, the dragging force (V_l) is determined by the thickness (h) of the moving water layer. As h decreases towards the river head, an increasingly higher shear thrust (τ) is required for moving fragments of the same size. The equality of these forces is possible at the increase of i, as it is observed in natural conditions when the longitudinal river profile is developing; its steepness is growing towards the river head. The incline i is growing even more when the size of fragments increases upstream, and in order to move them, the dragging force V_l must grow (whereas it decreases). Therefore, to keep the forces equal, the shear thrust τ should grow, which is spontaneously achieved at increasing i.

On the contrary, in the downstream direction, at $i=const$ and $d=const$ (d is size of fragments) the dragging force V_l increases proportionally to increase in thickness of the water layer thickness $u=c(hi)^{1/2}$. Hence, the rate of removing the detrital material considerably increases towards the river mouth, and the rivers run intensively, approaching their limit – the horizontal surface. This is the cause for the natural bending of the longitudinal profile. Due to the fact that the average size of detrital sediments decreases downstream, the river profile flattens out even more (the equality of forces is achieved at a very small value of i).

Tectonic movements violate the equality between the dragging forces and friction by changing i; climatic factors – by changing h, lithogenic - by erosion rate and size of detrital material. Therefore, the uniform elevation at constant water content in rivers is compensated by the rate of incision, and after any violation of the equilibrium, the process is aimed at restoring it.

The litho-flow F that initiates the formation of relief forms and the litho-flow D aimed at the process opposite to the relief formation process have their limits of action, so to say, the relief forming amplitude. For example, if denudation processes did not proceed, the relief forms established due to the elevation and incision of rivers would increase their height with some delay until the weight of the rising massif balances the force of endogenous pressure, i.e. the isostatic equilibrium is achieved. In the absence of denudation, the growth limit of a barchan or a storm wave could be determined by the height at which detrital particles of a certain size could be still brought onto it at existing velocities of wind (or water). When speaking about the land relief, the action limit of all relief forming litho-flows q is a horizontal surface tied to the sea level.

The interaction of *F*- and *D*- litho-flows forms a new, uniform limit for them which is externally expressed as an equilibrium surface of different morphological complexity. This limit exists in the reality and is observed in a current relief or in the relicts of the past, whereas the above described upper and lower limits are idealized and never exist in the nature. The upper limit could be achieved only in the absence of exogenous processes, and the lower limit - in the absence of endogenous processes.

Conclusions:

It is possible to achieve the dynamic equilibrium state, as well as to realize any other regularity or law concerning the physical world development only at constant environmental conditions during the period sufficient for the full development of the relevant process. In the reality, this necessary condition is almost impracticable. In the development of relief forms, we can observe only different degrees of approximation to this condition.

In the relief, there are not and probably cannot be any ideally equal horizontal denudation plains described by the equality $q=P=0$, since $P=0$ must be satisfied during several millions of years. Moreover, there are no mountains presented by a combination of ideally direct and equal slopes which are characterized by the continuous existence of the equation $q=P=const$.

Relief forms arise, exist and collapse, being replaced by others, as a result of continuous interaction of litho-flows. This interaction continues when the dynamic equilibrium is achieved and both components in the mass and energy balance reach their maximal values determined by specific conditions.

Thus, natural and naturally emerging systems do not have any special regulating members for determining the mismatch between the target and current states of the system. Their own sizes H act as regulators. They are connected by negative and positive associations with the supply of matter and energy in such a manner that with the increase in H the amount of energy brought into the system decreases.

Rezumat:

AUTOREGLAREA GEOSISTEMULUI DE LUNCĂ – DINAMICĂ ȘI SATURAȚIE

Teoria modernă a cunoașterii se bazează pe recunoașterea dialectică a unității și luptei contrariilor ca proprietate inerentă a obiectelor fizice – sistemele. În acest studiu este dezvoltată abordarea metodologică propusă de noi pentru studierea dinamicii geosistemelor. În opinia noastră formarea tuturor sistemelor, incluzându-le și pe cele antropice, implică dezvoltarea spontană și latentă a altui sistem (satelit) care utilizează energia și substanțele produse de primul. Figurativ vorbind, imediat ce producătorul X de energie și materie (resurse) apare, ia naștere și consumatorul Y al acestor resurse. În ciuda antagonismului dintre X și Y, ei se constituie ca o entitate complementară și sinergică (non-aditivă) care în mod inevitabil este capabilă să evolueze în toată gama de forme.

Istros – Museum of Braila

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Annexes:

Figure no. 1 Structure of functional relations in binary geosystems

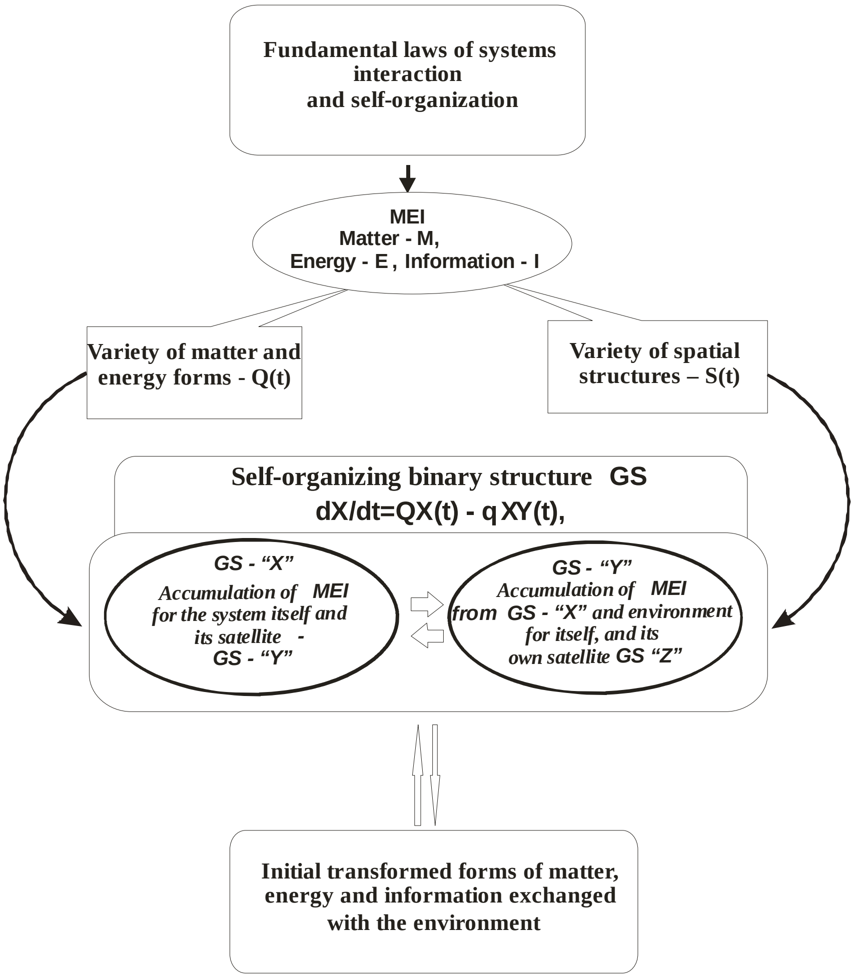

Figure no. 2 Geomorphological diagram of island moving in river channel (Voroniy island, Amur river, Far East).
I – benches with intensive washing out; *2* – sand shoal; *3* – trees vegetation; *4* – banks; *5* – depressions; *6* – water flow speed during flooding (m/s); *7* – position and numbers of profile cuts.

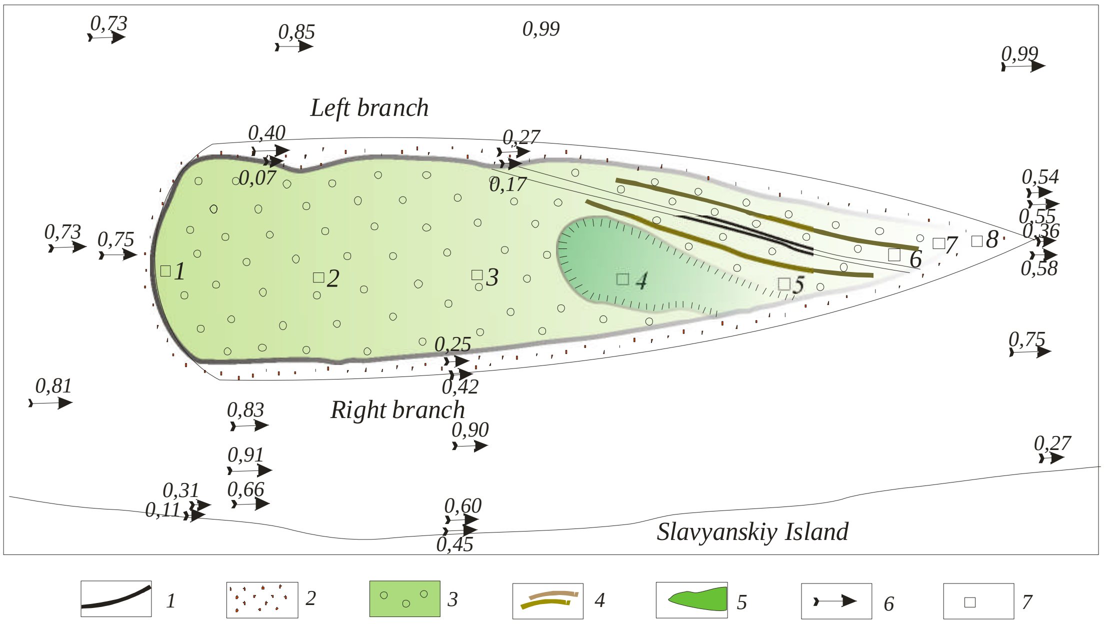

Figure no. 3 Changing of limit height changing of the moving island
a) increase of the island's floodplain height, when it is moving (curve 1, Y_{lim} = 3,7 m) and when it is stationary (curve 2, Y_{lim} = 5 m); б) floodplain limit height on the island moving at a speed 5 m/year. *M* – changing of total amount of warp with the increase of the island's floodplain; *d* – decrease of floodplain height due to erosion of the island.

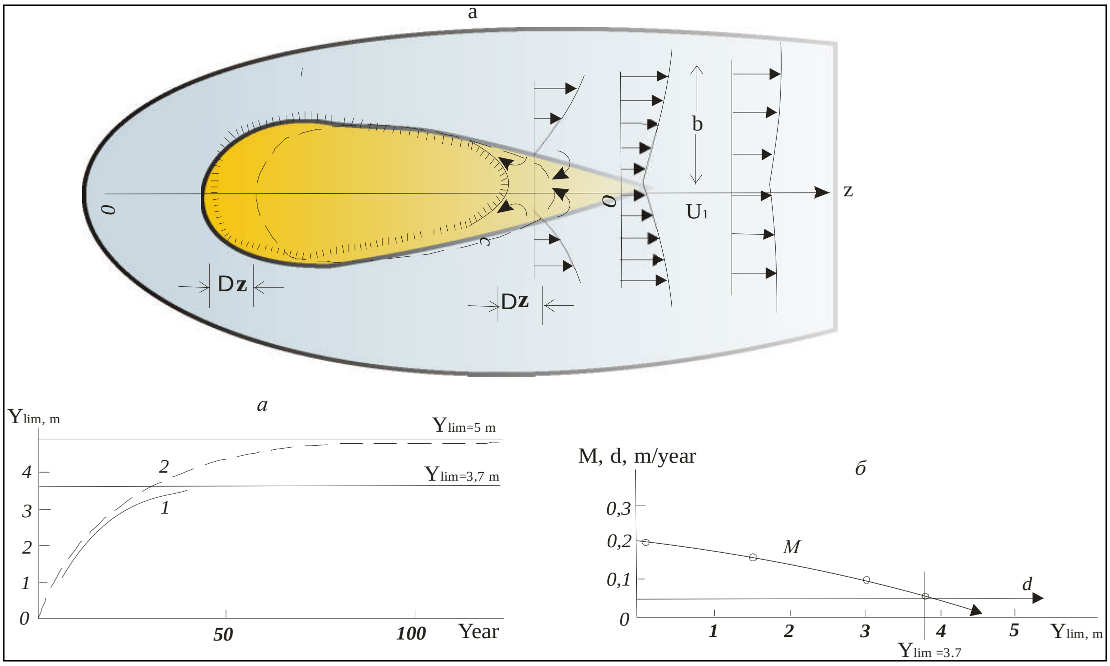

Figure no. 4 Functional diagram of geomorphosystems.
T, M, W - negentopic flows of MEI from the environment, forming F- and D-flows.