A study of natural and anthropogenic changes of soils within the Tom river valley based on GIS, remote sensing and field observations

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Abstract. This article is devoted to the study of natural and anthropogenic changes in soils within the valley of the Tom River. The study is based on field observations, remote sensing data and GIS analysis. A geodatabase and a digital elevation model of the investigated area were created. Changes in floodplain soils as a result of erosion-accumulative activity of the river are considered. The process of boggy soils formation on terraces has been studied. Anthropogenic changes in soils in the vicinity of Tomsk are revealed. The key factors of the anthropogenic modification of soils in the study area are the increased from the middle of the XX century industrial and agricultural activity such as sand and gravel extraction from the riverbed, draining, melioration and arable lands. Also important factors of the anthropogenic modification of soils are transport construction and expansion of the urban and rural areas. Now almost all soils within the Tom River valley in the vicinity of Tomsk are exposed to anthropogenic modifications to various degree. The vector of the changes is directed towards considerable desiccation due to the lowering of the groundwater level, which occurred due to the overlapping of various anthropogenic factors.

1. Introduction
The research of the natural and anthropogenic changes of landscapes and soils in big river valleys has theoretical and practical importance. In these valleys, which are often crossing different natural zones, there is an expressive specific nature of the soils structure. On the other hand, river valleys are the most populated and cultivated areas. The Tom river valley is characterized by complex soil structure, which is conditioned by its location in a transition zone from the Altay Mountain Region to the Western-Siberian Platform (figure 1). The ecosystems and soils of the valley have high rate of the natural transformations. Besides, a lot of soils have undergone serious anthropogenic modification. Intensive changes of the Tom River valley soils are observed from the middle of the Twentieth century due to the increased industrial and agricultural activity such as sand and gravel extraction from the riverbed, draining, melioration and arable lands. Also important factors of the anthropogenic modification of ecosystems and soils are transport construction and expansion of the urban and rural areas [1].

2. Areas, sources and methods of research
The area of research is situated in the Western Siberia within the Tom river valley in Tomsk Region (figure 1). The Tom River length is 827 km. The Tom River width is up to 800 m. The Tom River
joins the Ob River on 2677 km from Ob’s estuary. The average water flow is 1110 m$^3$/s, the highest flow is 13600 m$^3$/s. The catchment area is more than 62,000 km$^2$. The Tom River feeding is mainly from snow melting (up to 65%).

Figure 1. The area of research (within the green frame).

In this research we used different map sources, remote sensing data and field observations (landscape profiles, soil and geobotanical test areas). The following maps were used:
- large scale topographic maps (1:10000–1:25000) and plans;
- maps of forest survey (scale 1:50000);
- soil map of Tomsk Region (scale 1:100000);
- maps of geological survey (scale 1:200000);
- topographic plans dated 1896 (scale 1:10000);
- topographic plan of Tomsk dated 1933 (scale 1:10000);
- soil and vegetation maps of Tomsk Region dated 1928-1929.

The following remote sensing data were used:
- aerial photos dated 1944-1973 (scale 1:7000–1:30000);
- multi-spectral space satellite images from Terra (Aster) dated 2002-2006 with the spatial resolution 15 m;
- multi-spectral space satellite images from QuickBird II dated 2005-2011 with the spatial resolution 2.4 m (61 cm in panchromatic mode);
- optical images from UAV dated 2015-2016.

Field observations of soils within the valley were performed by authors during 2001–2016. They included more than 200 places (soil and geobotanical descriptions). All places were geo-referenced by GPS. The geo-referencing accuracy was 2–8 m.
In addition to complex physical geography methods, field observations and remote sensing data, we used the newest GIS-techniques, including building geodatabases, digital thematic mapping and morphometric analysis based on digital elevation models. We used software: ArcGIS 10 (ESRI Inc.), ERDAS Imagine (Intergraph Corp.), Agisoft PhotoScan (Geoscan), Easy Trace (EasyTrace Group).

The data from topographic and old thematic maps were digitized, vectorized, geo-referenced to the Gauss-Kruger cartographic projection and exported to ArcGIS Geodatabase. The table with descriptions of field observations was also added to the geodatabase. Space images were originally in digital form. Some images and aerial photos were georeferenced based on an irregular network of reference points with affine transformations in ERDAS Imagine (figure 2).

Figure 2. The aerial photo’s geometric correction with the use of ERDAS [1].

For the remote sensing data processing we used some popular methods of supervised and unsupervised classification. For example, during the creation of digital landscape and soil maps we calculated NDVI (figure 3).

Digital elevation model of the Tom valley was created with the use of ArcGIS 3D Analyst module (ESRI Inc.) by Delaunay triangulation [2]. As the raw data, we used the digitized isohypses (total 3 338 lines), and elevation points, including the edges of water (total 3 374 points). We also used the polygon and linear objects of the drainage system (a total of 1 310 842 lines and polygons of rivers and lakes), as well as the contours of the lakes with the known water's edge (185). The objects of the drainage system used in the calculation of DEM and polygons with known lakes water's edge were used for approximation of the flat surfaces. This allowed building triangulation irregular network (TIN), consisting of 1,042,373 triangles with a range of altitudes from 67.8 to 195 m [3]. For this, we used the TIN which is a computer database (34.7 MB) of the relief of the Tom valley (figure 4). In addition to the heights for each triangle, the TIN stores information about the angle of slopes and the exposure.

For the first time, we built the series of large-scale maps of key indicators of relief: hypsometric map, the maps of steepness and the slope exposure, allowing in-depth morphometric analysis. For this, the card obtained were converted to raster format, GRID, using a regular grid with a pitch of 10 m. As a result, the raster maps “algebra” and detailed analysis of the topography of the cells of 10x10 m became available. The analysis showed that the largest areas in the valley (26%) are occupied by the areas with altitudes of less than 80 meters. Chiefly, these areas belong to the floodplain. This indicates the predominance of the floodplain over the other elements of the relief of the Tom river valley [1].
Figure 3. The calculation of NDVI in ERDAS Imagine for the landscape mapping.

During the large-scale landscape mapping 5,147 polygons of ecosystems were created and they were divided into 112 types. The zonal statistics for map of the slopes was counted using ArcGIS Spatial Analyst module and the average slope of each ecosystem was determined. This allowed us to estimate the degree of drainage geosystems and reduce subjectivity. It was concluded that the best draining ecosystems are located in the upper part of the valley, where the average slope was 0.92° against 0.58° in ecosystems of the lower part (figure 4). On the basis of a complex spatial analysis in GIS the prevailing “neighbors” with the common borders were identified for each ecosystems. We also studied polygons position that helped in some cases (especially in the floodplain) to trace paragenetic series of ecosystems considering genetic cohesion and coupling.

Figure 4. 3D-Model of the Tom Valley – DEM based on Delaunay triangulation using ArcGIS 3D Analyst (vertical scale 10 times more than horizontal scale) [3].
3. Natural changes of soils

The causes of the natural evolution of the ecosystems and soils are usually changes of the lithogenic basis and climate [4]. The greatest natural changes in soils under conditions of almost unchanging climate are observed, in our opinion, in the floodplain and are associated with the transformation of the relief due to the deformations of the riverbed of Tom. According to R.S. Chalov [5], all channel deformations are divided into horizontal (lateral erosion) and vertical (incision or accumulation). If vertical deformations act for a time commensurate with geological periods and have a velocity of up to several centimeters per year, then the intensity of development of horizontal deformations can reach tens of meters per year. Therefore, as a major factor in the transformation of the relief of the valley and the associated natural changes of soils, we took the lateral erosion of the river. The latter is the main condition for the development of floodplains of plain rivers [6, 7]. Following the specific relief, specific modes of flood are created. The second important process is the deposition of silt in the floodplain with a regular decrease in its thickness from the channel to the slope of the valley, the third is erosion-accumulative activity in the floodplain, which leads to the formation of shafts, straits, depressions, stagnant zones, local elevations.

Natural changes of soils were studied in several key areas within the floodplain downstream from Tomsk by comparison the topographic plans dated 1896 with a modern digital landscape and soil maps created by us on the basis of topographic maps and space images from 1998-2011. The choice of key areas in the downstream part of the Tom valley is due to the much smaller influence of anthropogenic factors on changes of soils than on the areas upstream from Tomsk, which makes it possible to trace natural changes. Figures 5 and 6 show the changes of soils during 100 years at a key site in the mouth area of the Ishitan Channel. Here there is a significant shift of the riverbed of Tom River, which is manifested in the erosion of the left bank (155 m) and on the right (50 m), and therefore newly formed and transformed soils are clearly visible.

After the riverbank has emerged from the low level of the river, the process of soil formation begins on it. It processes only a thin surface crust of fresh alluvial deposits. On the surface of low shafts, which are covered with hollow water annually, a new deposit is deposited, so that they grow upward. The processes of soil formation do not have time to transform the entire thickness of the deposit, primitive stratified soils are formed. On higher shafts, flooded not annually, in years with low floods, the entire layer of sediment of the previous flood may be changed by soil formation. Sod stratified soils are formed (polygons with code 2 in figure 6).

The formation of new floodplain ecosystems is associated with the development in the course of accumulations of sediment. When the water horizon varies from flood to low level, some parts of the riverine shallows run out from under the water and can be fixed by vegetation, so alluvial primitive stratified soils are forming (polygons with code 1 in figure 6). The highest of shallows, formed in the high water years, are not flooded in the subsequent low flood, which increases the probability of their fixation by vegetation.

Gradually forming sandy elevations are covered over sedges, and when the thickness of loamy sand is increased to 30 cm (during 5-6 years) - they are covered over young willow shrub with a thin grass [8]. This is due to the fact that in the temperate latitudes of Eurasia it is the willow that is the pioneer shrub that hardly needs soil and grows directly on the sand [9]. For a few waterless years, when high sites are not covered by water, the willow has time to firmly take root on them, so in the next high flood the flow can no longer wash away the willow bushes. In the first 7-13 years, soils of riverine shallows pass the most dynamic stage of development.

The appearance of the shrub on the surface of the shallows during the flooding causes an increase in the roughness of the bottom and, consequently, favors the accumulation of thinner material (silt, organic detritus). The latter, in turn, stimulates further development of the vegetation. The precipitated particles of sand or pebble cover the surface of the former side-forming layer of silt floodplain. On its surface, in addition to willow, many species of herbaceous plants can settle, and the riparian soils begin to develop. Subsequently, under the canopy of willow, large representatives grasses appear [10].
Figure 5. The fragment of the digitized vegetation and soil type map dated 1896.

Figure 6. The fragment of the modern soil map (red arrows show young alluvial soils, which appeared during last 100 years). Key codes: 1 - alluvial primitive stratified soils; 2 - alluvial sod stratified soils; 3 - alluvial underdeveloped sod-gley soils; 4 - alluvial sod-gley soils; 7 - alluvial sod sandy loamy soils; 8 - alluvial gley soils; 9 - alluvial underdeveloped sod soils; 46 - light gray forest soils; 101 - alluvial silty-gley soils; 108 - alluvial sod loamy soils.

With increasing thickness of the floodplain loam up to 1.5-2 m, significant changes occur. First, grasses develop, then other shrubs (usually currants) follow. Finally, the projective cover of grass reaches 50%. On the site of a former sandbank (the lower part of the right bank in figure 5), an
ecosystem of low bank with thickets of willow may develop (the polygon with code 2 in figure 6). This completes the process of converting the coastal side. A natural evolution of the gravel-pebble and sandy shoals with riverine pioneer vegetation on alluvial primitive stratified soils is directed to the low riverine thickets of willow trees with alluvial sod stratified soils.

Further development of the floodplain soils is associated with new bank formation. Parts of the rapids, first covered with water, are being gradually filled with sediments. Aqueous vegetation overgrows and becomes dominant downward, forming a natural boundary of hollows riverbed floodplain with sedge meadows on alluvial underdeveloped sod-gley soils (polygon with code 3 in figure 6). Over time, these features evolve into the central floodplain where they dominate the meadows and willow shrubs on alluvial sod-gley soils (polygon with code 4 in figure 6). In deep depressions, we observe numerous sedge meadows on alluvial gleys soils (polygon with code 8 in figure 6). The deformations of the floodplain channel may take decades, and shorten the entire development cycle to hundreds of years [9]. When the bank is at a height of 4-5 m above the water's edge, willow bushes are replaced by willow and willow-birch nettle-grass forests on alluvial underdeveloped sod soils (polygon with code 9 in figure 6, instead of shrubbery on sod stratified soils in figure 5). According to Ryazanov and Surkov [8], this process takes about 50 years. In depressions willow lasts longer. Thus, the transformation of a young sandy central floodplain takes an average of 60-70 years. After several successions of steps in the central flood plain, the forest is converted into meadow on alluvial sod-gley and gley soils (polygons with codes 108, 4, and 8 in figure 6 instead of the mixed forests on alluvial sod soil in figure 5). The process of changing from forest to meadow until now has not been studied in detail, and this issue is debatable. Apparently, this process is defined as the development of forest communities under control of external factors such as changes in the mechanical composition and thickness of alluvial deposits, the depth of the ground water, and the amount of mineralized litter.

The processes of the boggy soils formation mainly develop on slightly drained flat areas of the floodplain and terraces. In the depressions of the central floodplain of Tom River and its tributaries, lowland sedge bogs predominate. On the terraces, sedge and sphagnum bogs are widespread. The evolution of bog ecosystems and soils includes several stages with a successive change in the dynamic states of ecosystems and soils.

We thoroughly examined the process of lake disappearing and the subsequent development of the transitional bog on the example of disappearance of Lake Strashnoe in the 20th century on the second terrace by comparing the different dated maps and remote sensing data (figure 7-10). In the 1930s B.G. Johannesen studied Lake Strashnoe and wrote: "The Lake Strashnoe is known to us from 1920-1921 ... The shallowing of the lake is striking ... The current state of the lake is such that it is not difficult to predict the rather rapid decrease of the existing free water space and the closure of this site with the rest of the peat bog" [11, p. 183]. In our opinion, B.G. Johansen in 1938 described the first stage of bog formation, when the bowl of the lake is filled with dying plants and the bottom level rises (figure 7). According to opinion of B.M. Mirkin et al. [12], the conditions for plant growth can improve, and in place of the floating macrophytes (duckweeds etc), high semisubmerged plants - reed, cattail and boggy horsetail - come. Gradually, the lake eventually grows and turns into a bog, on which the process of peat accumulation begins, and sedges, willow ashes, alder, and artisanal appear. Thus the lake's ecosystem with silty-gley soil in coastal line evolves into a natural complex of the lowland (eutrophic) bog with peat soil.

The layer of peat increases year by year, the roots of the plants no longer reach the soil and start to feed on the expense of peat. Mineralization of peat is slow and not completely, therefore gradually replaced by plants that are demanding food conditions, come species that are suitable for growth in conditions of limited nutrition (fluffy birch etc). New ecosystem of the mesotrophic sedge-sphagnum bog is formed (figure 9). The edges of the former Lake Strashnoye are overgrown now with a young birch and are indistinguishable from neighboring forest areas on modern space images (figure 10). The mesotrophic sedge-sphagnum bogs on the high terraces can continue to evolve to the sphagnum peat bogs under certain conditions. In this case, the further growth of the peat layer leads to an even worse
deterioration in the conditions of feeding, a complete separation of the surface of the bog from the level of mineralized groundwater occurs, and the entire bog begins to become covered with sphagnum mosses. A boggy form of pine appears, as well as cranberries and plants from the heather family (cassandra, etc).

4. Anthropogenic changes of soils

Along with the natural changes of the soils, in the last 100 years there is significant anthropogenic modification of the natural ecosystems and soils. The key factors of the anthropogenic modification of soils in the study area, in our opinion, are industrial and agricultural activities of man, as well as the expansion of residential areas and heavy transport construction. As a result of extensive mining of sand and gravel from the 1950th, the Tom River formed large pits. Such pits could be created in about 500 years during the natural cycle, since the stock of the benthic sediment is only 200 thousand. m³ [13]. Since the pit is a trap for sediment from above, an uncompensated removal of material occurs.
below the pit. This greatly enhances the erosion. Below the pit, the erosion of the river bottom occurs. The size of incision decreases downstream since the river reduces its bias and conveying capacity in line with a decrease in the inflow of bottom sediment on top. As a result, many islands are formed with pioneer vegetation on young alluvial primitive stratified soils.

For agricultural use in the study area, the network of the drainage canals and ponds was built on the site Kalmatskoe bayou-lake and the village Kislovka. The changes in the drainage system during last 50 years are shown in figures 11 and 12.

**Figure 11.** The fragment of the Tom River valley 3D-model near Tomsk. The model is draped by the aerial photo dated 1954 (red arrow – bayou-lake Kalmatskoe with silty-gley soils surrounding, green arrow – peat bog) [1].

**Figure 12.** The fragment of the Tom River valley 3D-model near Tomsk. The model is draped by the Terra (Aster) space satellite image dated 2003 (red arrow – new pond instead bayou-lake Kalmatskoe;
green arrow – the system of melioration channels and drained peat soils instead the peat bog; yellow arrow – new ponds near village Kislovka) [1].

Under the influence of the construction of waterworks, the ecosystem significantly changed. Large ponds changed the microclimate, which becomes softer. The natural forest and meadows complexes were replaced by the ecosystems, resistant to high groundwater level (willow shrubbery on sod-gley soil develop instead of mixed forests on sod soil, sedge meadows on sod-gley and gley soils develop instead of dry meadows on sod soil). Below the dam, the floodplain have dried and sod-gley soils are transforming to sod soils.

In order to identify anthropogenic changes in the ecosystems and soils within the Tom River valley in the vicinity of Tomsk, a comparison was made between a digitized map of vegetation and soils dated 1929 and a modern landscape map created by us (figures 13 and 14). As a result, one can draw a conclusion about the cardinal anthropogenic transformation of natural complexes in 70 years.

The greatest changes of ecosystems and soils are observed in the floodplain. First of all, it should be noted their anthropogenic desiccation due to the lowering of the groundwater level, which occurred due to a complex overlapping factors: planting of the water level due to the extraction of gravel, the activity of the Tomsk water intake, meliorative works, deforestation, increasing of arable lands and horticultural areas. Violation of the flood regimes led to a "jump" of almost all the ecosystems one step higher in the paragenetic sequence of floodplain ecosystems.

Thus, many riverbed ecosystems have become a riparian gravel and pebble shoals, which is well visible on the site near the Lagerny Garden, where the river Tom has narrowed from 514 m to 308 m, and near the bridge (from 770 m to 180 m). Ecosystems of the riverside floodplain intensively become the category of complexes of the central floodplain. This is evidenced by the displacement of willow shrubberies to the riverbed and their replacement by meadows. High floodplain, not flooded for several decades, turns into an anthropogenic terrace. Here there is a rapid transformation of alluvial sod-gley soils to sod soils, which is confirmed by our field observations.

![Figure 13](image_url)

**Figure 13.** Map of vegetation and soils in the vicinity of Tomsk dated 1929. Red arrows – sphagnum bogs on peat soils drained now.
Figure 14. Fragment of the modern landscape map of Tom River valley.

The ecosystems and soils of the terraces were affected by the lowering of groundwater level. Many forested bogs on peat soils are modified into dried pine-birch bogs on drained peat soils (figure 13). The depths and dimensions of the Lake Peschanoe decreased, the shape of lake was transformed from round to horseshoe (figures 13, 14). Our GIS-analysis shows a reduction the area of bogged forests on sod-podzolic-gley soils more than four times - from 8.02 km² in 1929 to 1.99 km² in 2016.

As a conclusion, this work demonstrates that, at present, almost all soils within the Tom River valley in the vicinity of Tomsk are exposed to anthropogenic modifications to various degree. The vector of the changes is directed towards considerable desiccation due to the lowering of the groundwater level, which occurred due to the overlapping of various anthropogenic factors [14].

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References
[1] Khromykh V and Khromykh O 2016 Spatial structure and dynamics of Tom river floodplain landscapes based on GIS, digital elevation model and remote sensing Riparian zones: Characteristics, management practices and ecological impacts ed O S Pokrovsky (New York: Nova Science Publishers) chapter 12 pp 289–309
[2] Khromykh V V and Khromykh O V 2011 Digital Elevation Models (Tomsk: NTL) p 188
[3] Khromykh V and Khromykh O 2014 Analysis of spatial structure and dynamics of Tom valley
landscapes based on GIS, digital elevation model and remote sensing *Procedia Social and Behavioral Sciences* **120** 811–5

[4] Mamay I I 2005 *Dynamics and functioning of landscapes* (Moscow: Moscow State University Press) p 138

[5] Chalov R S 1979 *Geographical investigations of channel processes* (Moscow: Moscow State University Press) p 234

[6] Kozin V V 1979 *Paragenetic landscape analysis of river valleys* (Tyumen: Tyumen State University Press) p 86

[7] Kolesnikova O N 1988 *Structure and dynamics of the floodplain landscape on the example of floodplains southeast taiga zone of West Siberian Plain* PhD diss. (Tomsk) p 237

[8] Ryazanov P N and Surkov V V 1986 Floodplain natural territorial complexes of the downstream of Tom river and some of the trends of their change *Geography and natural resources* **1** 59–65

[9] Chernov A V 1999 River flood plains - their origin, development and optimal use *Soros Educational J.* **12** 47–54

[10] Kuminova A V 1949 *The Vegetation of Kemerovo Region* (Novosibirsk: Science) p 167

[11] Ioganzen B G, Popova M A and Yakubova A I 1951 Reservoirs of the surroundings of Tomsk *Proceedings of Tomsk University* **115** 121–90

[12] Mirkin B M, Naumova A G and Solomesh A I 2000 *The modern science of vegetation* (Moscow: Logos) p 264

[13] Kamenskov U I 1987 *Channel and floodplain processes* (Tomsk: Tomsk State University Press) p 171

[14] Khromykh O V, Khromykh V V and Khromykh V S 2015 Natural and anthropogenic dynamics of the floodplain landscapes near Tomsk *Tomsk State University J.* **400** 426–33