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FLOODS AND THEIR MANAGEMENT IN THE CARPATHIAN REGION OF UKRAINE

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ПАВОДКИ ТА УПРАВЛІННЯ НИМИ В КАРПАТСЬКОМУ РЕГІОНІ УКРАЇНИ

Purpose. Substantiation of the system of flood preventive measures and reduction of flood intensity.

Methodology. In our research, we used systematic, statistical and analytical methods for study of cause and effect relationships of flood forming and substantiation of anti-floods preventive measures system.

Findings. We provided characteristics of natural (precipitations, topography) and anthropogenic (reduction of forest area, decrease in water accumulation capacity of the territory) factors causing floods in the Carpathian region of Ukraine. Also, there were substantiated measures of flood prevention and management that form an integral functionally interrelated bioengineering system in the basin. This system is formed on the principles of theory of "manageable complicity" and is considered as totality of organizational and preventive (biological and engineering-technical) measures that create a new totality and provide for decrease in volume, absorption and accumulation of surface slope flow, increase in water accumulation capacity of territory, and, as a result, reduction of maximal flow module and water level in the rivers.

Originality. We substantiated the adaptive landscape principle of bioengineering system formation that provides for regulation of surface slope flow in the basins of the rivers.

Practical value. Principles of territory organization, optimization of lands structure and their spacial distribution in the river basins were developed with consideration of landscape altitude areas, while forest land improvement and engineering and hydrotechnical engineering measures can be used as methodological grounds in case of anti-flood system development in the basins of the rivers Tysa, Prut, Dnister and their tributaries.

Keywords: *floods, surface flow, basin, management, bioengineering system*

Introduction. The Carpathian region of Ukraine belongs to the areas with mountainous dissected terrain, substantial slope steepness, and plenty of rainfall (from 600 to 1700 mm per year). In this regard, there is always a potential risk of flooding, which threatens the ecological safety of the region. Floods cause considerable losses due to flooding of villages and farmland, destroying roads and service lines. Over the last 10 years losses from floods have made UAH 8 billion. In connection herewith the important task is to substantiate the system of measures preventing the flood formation and of their management.

Analysis of the recent research. Works of I. F. Kalutsky, V. S. Oliinyk, S. M. Stoiko, Ye. O. Yakovlev, L. A. Shynkaruk and other scholars are dedicated to the issue of floods in the Carpathian region of Ukraine. They consider floods to be the process that inflicts considerable material damage, has negative impact on geosystems and causes casualties. It is suggested to carry out anti-flood measures (dams, bank protection, water-storage capacities) in the river valleys and beds [1]. However, the suggested measures do not affect the formation and regulation of the slope surface runoff, which is the cause of the flood formation. Thus, the anti-flood measures taken the rivers of the Carpathian region of Ukraine by such principle did not give the expected result with regard to preventing the floods formation.

Objectives of the article. The aim of the paper is to substantiate the system of flood preventive measures and management in the Carpathian region of Ukraine.

Presentation of the main research. Floods are treated as temporary accumulation of the significant water mass with considerable potential energy on the surface, which actively influences the upper zone of the geological environment [2]. River basins in the area under study are characterized by the highest risk of floods in Ukraine and the related hazardous exogenous geodynamic processes (landslides, mudflows, destruction of river banks), flooding of large areas, and threats to people's lives. Catastrophic floods in the Carpathian region formed every 15–20 years. In Transcarpathia (basins of the Tysa, the Latorytsia, the Uzh) they were registered in 1926, 1947, 1957, 1970, 1988, and in Lviv, Ivano-Frankivsk, and Chernivtsi regions (basins of the Dniester, the Prut) – in 1911, 1927, 1941, 1955, 1969, 1980, 1988. For the last decades floods were in 1998, 2001, 2002, 2008, 2010. Floods covering only basins of certain rivers occur every 2–3 years [1–3].

These data indicate that flood formation frequency has decreased substantially. The reason for this is not only hydrometeorological situation change but also large-scale landscapes denaturalization due to significant decrease in forest area and change of their species composition and age structure.

The forestation of lowland areas has reduced to the critical level and ranges from 4–18 %, of the foothill – 24–37 %, and mountainous areas – 55–70 %. Foothill and lowland areas feature by forests of insular type, which are located non-uniformly and, as a rule, on the upper slopes and watershed divides. None of the watershed has an integrated system of forest plantations.

To develop the measures for preventing the floods formation and their management, first of all, it is needed to find out the reason for the slope surface runoff emergence, which causes occurrence of floods, based on the basin and landscape approaches. The reasons must be studied for each river basin and sub-basins within it, taking into account the river basin structure and landscape altitude areas [2–5]. In the Carpathian region of Ukraine formation of slope surface runoff and floods as a result is caused by natural and anthropogenic factors.

The natural factors include:

- increased frequency of intense rainfall in large areas for a short period (250–350 mm in 2–3 days). Frequency of heavy rain occurrence has been increasing for the last 30 years, which is associated with the climate global change [2, 3];
- large river beds slopes and, as a result, high speed of water draining that promotes rapid rise of the water levels;
- dissected terrain and considerable slope steepness. In the Transcarpathian region slopes of 10° steepness occupy 47.8 % of the area, in Ivano-Frankivsk region – 28.2 %, in Chernivtsi region – 11.9 %, in Lviv region – 10.8 %. The steep slopes dominate in mountain landscapes. Under such conditions, rain and melt water flow quickly from the catchment area causing significant rise of water levels both in stream tributaries and major rivers (the Tysa, the Prut, and the Dniester).

The major anthropogenic factors are:

- destruction of the primary structure (ratio) of geosystems and reduced forest cover in the river basins. In the Carpathian region of Ukraine natural forest geosystems prevailed (over 95 %) [2], which reduced the risk (probability) of flood formation due to inherent water-regulating functions. Now the forested land area is only 2100 thousand hectares, or 36.3 % of the total area of the region. Indigenous uneven mixed stands of oak, beech, spruce and fir have been replaced with spruce monocultures and even-aged oakery, beech and spruce forests, resulting in water seepage into the soil decreasing by 5.6 % and the direct runoff increasing by 2.8 times;
- reduction of water-storage capacity of the territory (the amount of water that can be kept in a particular area) due to environmentally unsubstantiated reduction of forest area and the formation of large areas of land (arable land, hayfields, pastures, built-up land, roads), which is formed by the slope surface runoff (their area is 2988 thousand hectares, or 53.3 % of the total area of the region);
- reduction of completeness, simplification of species composition, change in the stands age structure, wood ground tractor skidding in forests. All these factors lead to the decrease in forest water-storage capacity (rainfall, which forest can hold up by stands, ground litter, and soil, as well as transfer the runoff in internal soil) and, consequently, their ability to reduce slope surface runoff and maximum spending and water levels in rivers during the flood period. Underwood (20 %) and middle-aged (50 %) stands dominate in the forests of the region under research. At the same time mature stands have the highest water-storage capacity [2, 6, 7];
- lack of measures to prevent the formation and detention (regulation) of slope surface runoff in water catchment areas.

A significant role in preventing the formation of flood is assigned to the forests. In this regard, studying the relationships between the forest cover and floods formation is topical. The performed analysis of materials of the Carpathian mudflow station indicates that the runoff module value depends on the forestation of the watershed. In case of watershed forestation of 93 % (the Zhonka river) the runoff modules are by 1.6–2.1 times less if compared to the less forested watersheds – 77 % (the Prut river) and 83 % (the Chornohirchyk river). Therefore, to reduce the risk of flood formation the forestation of river basins should not be lower than 90 % for mountain landscapes.

Based on the observation materials from the Transcarpathian water-balance station it has been also found that in the absence of forests in watersheds the maximum water flow in rivers increases by 14 %. In forested catchments (forestation of 100 %) the maximum water flow and water levels in rivers fall nearly by 3 times [7]. Water storage capacity of beech forests is 140–160 mm, that of spruce forests is 70–90 mm. In mountain landscapes water-regulating function of the forest is shown at the watershed forest cover not less than 70 % [7].

Influenced by the forest, soil infiltration capacity is increased by 2–50 times. Surface runoff on the areas covered with forest is less than 3 % of the rainfall, and can exceed 60 % in the treeless areas. The surface runoff decreases by 2–70 times, and flood peaks are reduced by 10-20 times under the influence of forest [4, 7].

During 1700–1940 floods were formed every 25 years. After significant wood felling carried out in the forests of the Carpathian region floods occur every 4–5 years [3]. Due to the climate change the increase in weather volatility and rainfall with intense precipitation is expected, which enhances the probability of flood formation. Flood formation is a spontaneous process that is poorly predictable and driven by the principle of uncertainty. However, the flood occurrence causality is not violated and becomes probabilistic in nature and depends primarily on rainfall. In the Carpathian region of Ukraine floods originate in mountain landscapes, which are characterized by high rainfall and significant slope steepness and are enhanced by the overlay of flood waters generated in foothill and lowland landscapes. It is therefore important to develop and implement anti-flood measures, which should be systemic (complex) and cover the entire catchment area of river basins [2].

In the Carpathian region of Ukraine an anti-flood complex has been constructed. However, it is based only on the regulation of river beds and river flow (coastal protection, protective dams) and does not ensure formation prevention and regulation of surface slope runoff in the river watersheds and improving water-storage capacity of the area. Preventing the flood formation and management are associated with considerable difficulties due to the inadequacy of the costs necessary for anti-flood measures with the society's economic capabilities. Flood management is defined as a system of interrelated measures and managerial decisions made in the river basins and aimed at preventing the formation and regulation of surface slope runoff and reduction of water levels in rivers and, as a result, at minimizing the damage from flooding. Flood management should be developed as a single system of the integrated management of a river basin [2].

The flood management system we have developed includes a set of measures that provide prevention of formation and reduction of the surface slope runoff volume, its accumulation and redistribution in time as well as works in river beds.

It involves the creation of bioengineering systems (Figure) in river basins adapted to the landscape structure based on the principles of the "controlled complexity" theory, which represent a range of institutional and protective (biological and engineering) measures that create a new integrity of the complex (mosaic) spatial structure and provide water management and increase of water-storage capacity of the area [2]. Bioengineering systems provide for:

1) identification of land categories as to their use intensity and functional (intended) purpose along with consideration of the landscape altitude areas (flood-plain, terraces above the flood-plain, slopes, etc.) and the slopes steepness;

2) counter strip organization of the area on farmland;

3) establishment of optimal structure (ratio) of land in the catchments areas (arable land: bows: forest) in mountain landscapes – 8–12 : 20–30 : 70–90; foothill – 30–40 : 25–35 : 30–40; lowland – 40–50 : 25–30 : 20–30;

4) arrangement of the system of protective foresting (runoff regulating woodland belts, planting along riverbanks, etc.);

5) construction of waterworks (runoff regulating earthworks, regulating reservoirs, water-storage tanks, etc.) on the agricultural land;

6) construction of hydro-technical utilities system of various designation in the river valleys and riverbeds (protective dams, bank protection, ponds and fluctuations in the rivers of the 1st–2nd orders; reservoirs on the rivers of the 3rd–4th orders, polders – on the river plain intervals);

7) clearing and regulation of river beds after the flood.

When designing bioengineering systems the territory arrangement being the first step for control systems design as well as optimization of the ratio and spatial location of the lands categories (lands of different designation) are particularly important. We consider the territory arrangement as a set of measures aimed at transforming the existing structure of land categories and creating "structures" close to the natural territorial complexes they were formed in. Improving the land use structure is based on the concepts of ecological and economic balance of the territory and "recovered landscape" under which lands occupied by buffer type geosystems (forest, meadow and wetland) are considered as land of "environment fund" the flood protection elements' skeleton is formed of.

The current territory arrangement is imperfect due to the artificial boundaries (borders) not coinciding with the natural ones, and agricultural land area increase has resulted in formation of large volume of runoff, which contributes to flooding. Therefore, the territory arrangement should include matching the area and land forms categories to the structure of natural territorial complexes having band structure in terms of the dissected relief. In this regard, the most rational form of the territory arrangement is a counter strip one. It provides for a differentiated approach to the size and shape of fields on agricultural lands encountering the relief conditions and linear elements location (borders of fields, woodland belts, and roads) along the outline towards the horizontals of the area. The boundaries of the selected land categories and contour strip fields are fixed on the ground by permanent elements of the area arrangement that regulate surface runoff (runoff regulating woodland belts). In case of need, additional runoff regulating elements (runoff regulating walls, buffer strips, grassed buffer strips) are designed within the strip fields. The territory arrangement and reclamation elements placement should create a differentiated system of surface runoff comprehensive regulation.

The territory arrangement also provides for the farmland classification (intense use – on the slopes up to 3°; moderately intense use – on the slopes of 3–7°; very limited use – on the slopes of over 7°). The land differentiation into classes is carried out based on the landscape maps with set out high-altitude terrains and slopes steepness maps.

An important arrangement measure is allocation protection zones and coastal strips along rivers and around reservoir set forth by the Water Code of Ukraine (Articles 87, 88). Strips of 25–50 m wide are to be designed within the water protection zones along riverbanks and around the reservoirs coastal protection. Forest plantations of different intended use, including those for obtaining renewable biotic fuel ("energetic forests"), should be established in the coastal protection zones.

The main purpose of engineering and hydro-technical elements being a part of bioengineering systems is to prevent formation of concentrated flows of snowmelt and rainwater on the slopes, surface runoff detention (accumulation) within the watershed in order to use local runoff water for groundwater replenishment, irrigation, and other purposes. With this in view, runoff sprays, runoff regulating drainage terraces with wide foundations, water retaining, and water guiding walls are being designed on the slopes. In the lowered terrain regulating reservoirs (ponds) are designed. They accomplish the engineering structures complex for the watershed. The regulating reservoirs are filled with surface runoff water during snowmelt and torrential rains; they are used as water accumulators to enhance the territory water storage capacity, replenishment of groundwater, river runoff regulation, and also for fish farming, irrigation and recreation.

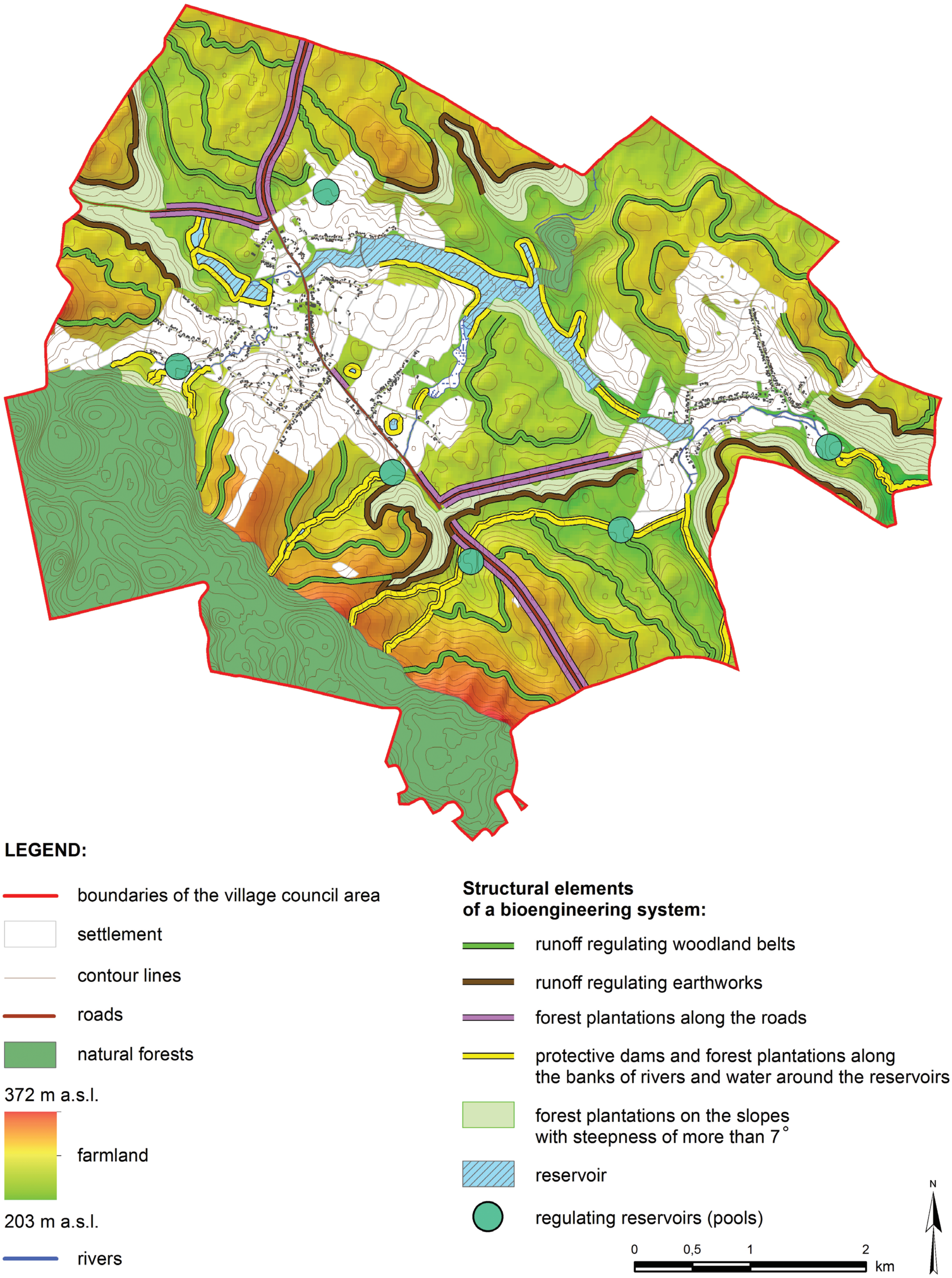

Fig. Structural elements of a bioengineering system within the village council area

The major (most important) condition to prevent the flood formation is the territory optimal forestation by increasing the forest plantations area up to the optimum level.

The feasibility of increasing the forest plantations area is sustained by the facts that:

- about 90 % of the total runoff of the Dniester, the Prut, the Tysa rivers is being formed in the Carpathian region of Ukraine; forest geosystems ensure the formation of high quality water resources and uniform distribution of water runoff over time, increase the water content of rivers in the low-flow periods;
- the likelihood of erosion and landslides emergence and development, river banks destruction will be reduced;
- resource, economic, and environmental potentials of the territory will increase;
- carbon dioxide (CO_2) deposition from the air will increase;
- a resource base for the development of new economic activity – biopower is being created based on the network of minibio-power stations operating on alternative renewable biotic fuel (biomass from "energy plantations", firewood, wood processing waste, etc.);
- aesthetic, recreational, and tourist value of the area will rise.

The prevention of floods and reduction of their intensity are ensured by dint of *forest plantations system* – the complex of forest plantations different in form and functionality created by encountering the features of terrain, soils, and surface runoff formation conditions, combined into a single unit due to the causal relationships between them.

Under the "theory of systems", forest plantations will acquire the properties of systemic objects only when the protective effect will be observed all over the territory. Therefore, they need to be created and placed evenly over the territory, including the land of water-spreading, ravine funds, land along the water reservoirs as well as water fund lands. The systemacity requirement is subject to the arrangement and providing properties of a holistic unit to the existing and created forest plantations. It is insufficiently to allocate just a part of the river basin (even a relatively large one) for afforestation in the course of designing the forest plantations system. Territorial distribution of forest plantations should be consistent with the landscape structure elements of the basin (high-altitude areas) both horizontally (from the source to the mouth) and vertically (flood-plain, terraces above the flood-plain, slopes, watershed divides) all around the basin. The forest geosystems placement within the river basin should be differentiated based on watershed morphostructure, emphasizing the key elements where the forest vegetation performs water-regulating functions the most efficiently.

The main purpose of the forest plantation system is to prevent the formation of surface runoff and transfer it to the soil runoff to replenish groundwater reserves, while ensuring forest plantations to simultaneously perform other functions (anti-erosion, environment-forming, etc.).

The forest plantations system consists of:

- forest belts on agricultural land (runoff-regulating, afforestation, gully and ravine forest belts, hollow-strip plantations) and roadside forest belts;
- a set of forest plantations different in shape and functionality created on treeless slopes with the steepness of more than 7°, ravines and gullies, along the river banks and around reservoirs;
- the existing natural and relatively natural forests.

While substantiating the forest plantation types one should take into account the peculiarities of slope and terrace paradynamic rows since the slopes are areas the restructuring is primarily held on. The main reconstruction element on the slope land is runoff-regulating forest belts in the watershed lower levels – forest plantations of different functionality.

The system of forest plantation (forests) operations should ensure their continuous functioning and performance of water-regulating functions.

The above objective is achieved by:

- reducing clear cutting and introducing selective logging;
- forming mixed stands of different age close to natural ones;
- preserving virgin forests and old-growth stands;
- forming forests with optimal ratio between the stands age groups (young – 30 %, middle-aged – 30 %, approaching maturity – 20 %, mature and overmatured – 20 %) within the river basin.

For each river basin (sub-basin), and for the areas of village/city councils within it, it is needed to develop land management projects, which provide for the creation of bioengineering systems to prevent the formation and regulate surface slope runoff and increasing water storage capacity of the area.

Conclusions. Flood formation in the Carpathian region of Ukraine is the result of intense rainfall, complex geomorphological conditions and a significant reduction in water storage capacity of the area due to the reduction of the forested area by 2–5 times.

The anti-flood measures that exist in the region are not systemic, do not provide for preventing the development (formation) and regulation of the surface slope runoff and flood management.

Flood management strategy should be based on the basin and landscape adaptation approaches. The natural and anthropogenic factors for flood formation in river basins are rather different, thus to prevent them differentiated system of measures is to be introduced. Anti-flood measures should cover the whole catchment area and create a coherent functional bioengineered system aimed at preventing and reducing the formation volume of the surface slope runoff, increasing water storage capacity of the area, as well as adjusting the drainage water speed in the river beds by hydraulic structures (falls, water storage capacities).

Planning (design) of anti-flood measures should be carried out separately for all tributary basins of major rivers (the Tysa, the Prut, the Dniester) and their implementation should be started from the upper rivers (river basins of the 1st and 2nd orders). Land management projects will enable local authorities to monitor and take the necessary management decisions on the implementation of the necessary anti-flood measures by landowners and land users.

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Мета. Обґрунтування системи заходів попередження формування та зниження інтенсивності паводків.

Методика. При проведенні досліджень використані системний, статистичний та аналітичний методи вивчення причинно-наслідкових взаємозв'язків формування паводків й обґрунтування системи протипаводкових заходів.

Результати. Дана характеристика природних (атмосферні опади, рельєф) і антропогенних (зменшення площі лісів, зниження водоакумулюючої ємності території) факторів формування паводків у Карпатському регіоні України. Обґрунтовані заходи попередження формування паводків та управління ними, що створюють у басейні цілісну функціонально взаємопов'язану біоінженерну систему. Ця система формується на принципах теорії „керованої складності" й розглядається як сукупність організаційних і захисних (біологічних та інженерно-технічних) заходів, що створюють нову цілісність і забезпечують зменшення об'ємів, поглинання та акумуляцію поверхневого схилового стоку, підвищення водоакумулюючої ємності території та, як наслідок, зниження максимальних модулів стоку й рівнів води в річках.

Наукова новизна. Обґрунтовано ландшафтно-адаптаційний принцип формування в басейнах рік біоінженерних систем, що забезпечують регулювання поверхневого схилового стоку.

Практична значимість. Розроблені принципи організації території, оптимізації структури угідь і їх просторового розміщення в басейнах рік з урахуванням ландшафтних висотних місцевостей, а також лісоагромеліоративні та інженерно-гідротехнічні заходи можуть бути використані як методична основа при розробленні протипаводкових систем у басейнах рік Тиса, Прут, Дністер та їх приток.

Ключові слова: *паводки, поверхневий стік, біоінженерна система*

Цель. Обоснование системы мероприятий предупреждения формирования и снижения интенсивности паводков.

Методика. При проведении исследований использованы системный, статистический и аналитический методы изучения причинно-следственных взаимосвязей формирования паводков и обоснования системы противопаводковых мероприятий.

Результаты. Дана характеристика природных (атмосферные осадки, рельеф) и антропогенных (уменьшение площади лесов, снижение водоаккумулирующей емкости территории) факторов формирования паводков в Карпатском регионе Украины. Обоснованы мероприятия предупреждения формирования паводков и управления ими, которые формируют в бассейне целостную функционально взаимосвязанную биоинженерную систему. Эта система формируется на принципах теории „управляемой сложности" и рассматривается как совокупность организационных и защитных (биологических и инженерно-технических) мероприятий, которые создают новую целостность и обеспечивают уменьшение объемов, поглощение и аккумуляцию поверхностного склонового стока, повышение водоаккумулирующей емкости территории и, как следствие, снижение максимальных модулей стока и уровней воды в реках.

Научная новизна. Обоснован ландшафтно-адаптационный принцип формирования в бассейнах рек биоинженерных систем, обеспечивающих регулирование поверхностного склонового стока.

Практическая значимость. Разработанные принципы организации территории, оптимизации структуры угодий и их пространственного размещения в бассейнах рек с учетом ландшафтных высотных местностей, а также лесоагромелиоративные и инженерно-гидротехнические мероприятия могут быть использованы как методическая основа при разработке противопаводковых систем в бассейнах рек Тиса, Прут, Днестр и их притоков.

Ключевые слова: *паводки, поверхностный сток, биоинженерная система*

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