Обґрунтовується неможливість здійснення басейнового принципу розрахунку допустимих скидань стічних вод у водотоки у межах адміністративних областей України. Пропонується розбиття басейну річки на локальні ділянки, що спричиняє необхідність встановлення регіональних нормативів якості природної води. Викладено алгоритм розрахунку цих нормативів. Наводиться демонстраційний приклад розрахунку регіональних нормативів якості природної води за показником фосфати для басейну річки Уди

Ключові слова: стічні води, водний об'єкт, забруднююча речовина, нормативи якості, контрольний створ, допустимий скид, локальна ділянка

Обосновывается невозможность осуществления бассейнового принципа расчёта допустимых сбросов сточных вод в водотоки в границах административных областей Украины. Предлагается разбиение бассейна реки на локальные участки, что влечёт за собой необходимость установления региональных нормативов качества природной воды. Изложен алгоритм расчёта данных нормативов. Приводится демонстрационный пример расчёта региональных нормативов качества природной воды по показателю фосфаты для бассейна реки Уды

Ключевые слова: сточные воды, водный объект, загрязняющее вещество, нормативы качества, контрольный створ, допустимый сброс, локальный участок

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A METHOD OF ESTABLISHING REGIONAL STANDARDS OF SURFACE WATER QUALITY UNDER ANTHROPOGENIC LOADS

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1. Introduction

According to the Water Code of Ukraine [1], all water bodies (WBs) in Ukraine are national property of the Ukrainian people. Water resources are the basis for the existence of people, flora, and fauna. Moreover, the supply of water resources predetermines the economic development of a country and the level of social prosperity of its inhabitants. However, these resources are fairly limited and slowly replenished. Therefore, the existing realities – the increasing anthropogenic loads on all components of the natural environment, largely caused by unrestricted tangible needs of people, – make it necessary to complicate the regulations so that water resources could be used efficiently and could be protected.

The ultimate goal of water protection measures is to safeguard public health, ensure safe conditions of water use and environmental security of water facilities. The latter is aimed directly at the conservation of water bodies as an ecosystem. The object of water protection is all water bodies in the territory of Ukraine.

The most significant source of contamination of surface water is wastewater discharge (WD) from industrial, municipal and agricultural enterprises. For example, in the Ukrainian part of the Siversky Donets river basin, according to the data given in [2, 3], the WD in 2010 amounted to 1.457,24 billion m^3, including:

– normatively clean without purification – 178.2 million m^3;

– normatively clean – 618.2 million m^3;

– contaminated – 660.6 million m^3, of which 50.1 million m^3 were untreated and 610.5 million m^3 were insufficiently treated.

One of the main directions in conservation of natural resources is rationing. Thus, water-using enterprises must comply with the developed and approved standards for WD that determine the maximum permissible discharges (MPDs) of pollutants [1]. The MPD is the ultimate weight of pollutants whose discharge does not violate the established water quality standards for water bodies.

The obligation to observe the MPD is administered by Article 35 of the Water Code. The methodological basis of calculations in this case is the "Guidelines on developing and approving the MPD…" [4]. These "Guidelines…" prescribe to calculate allowable concentrations of pollutants in the WD on the basis of hydrological and hydrochemical parameters of a WB and the volume of the WD. Another criterion that is also taken into account is the category of water use – whether it is for fishery, technical use or drinking.

The problem is that a water body is a simultaneous receiver for a large number of WDs. Therefore, to calculate the MPD, it is necessary to consider all the discharges affecting the water quality of the WB in the control points. Consequently, it is essential to improve the river basin approach to the calculation of the MPD, which will ensure the prevention of a WB contamination above the established standards.

2. Literature review and problem statement

Both the pan-European and U.S. approaches to rationalising water disposal [5–8] are based on the requirement of non-exceedance of pollutants' content in the control points of a WB that are located down the stream. At the same time, the section of the watercourse from the WD point to the control point (in the so-called mixing zone) may contain exceedance as to the standard quality of natural water. The location of the control point is regulated by national legislation. In some cases, its distance from the WD point depends on the parameters of the watercourse [9, 10]. In other cases (for example, in Ukraine), it is a strictly defined distance – 500 m downstream from the WD point [4].

An essential issue in the European approach is to link the water quality standards to the existing technologies of water purification. In this case, wastewater discharge limits are imposed during two phases. The first phase allows the composition of the WD to depend on the capabilities of the available treatment technologies. If the calculated concentrations of pollutants in the control segment exceed the norm, the second stage entails tightening of the requirements to reduce the WD composition to a safe level [11, 12].

In Ukraine, in the short run, it is inappropriate to transfer to the above-described principle of calculating the MPD. The obstacle to this is, firstly, the difficult economic situation in the country, not allowing the wide use of advanced water purification technologies. Secondly, there are more extended territory dimensions compared with most European countries, and thus there are more numerous WD points that are located in large river basins. The latter circumstance requires the development of a new methodological basis of calculating the MPD, taking into account both the European experience and the economic and geographic characteristics of Ukraine.

When it concerns the valuation algorithm for the WD, the "Guidelines..." entail two possible approaches. The basic approach to calculating the MPD [4] is based on a uniform use of the assimilative capacity of the WB between water users. In this case, the calculation is carried out separately for each pollutant, taking into account the intensity of the processes of the WB self-purification as well as the specific natural (without human influence) background concentrations of the substances concerned in the WB. An alternative is to use an optimization approach [4], in which the calculation of the MPD is performed simultaneously for all the substances in accordance with their mutual transformation in the WB. The goal of the optimization problem is to minimize the total cost of purifying the WD content by all water users; the optimizable variables are the disposal ratios of the WD passing through different technological routes of water purification. Eventually, the MPD calculation is essentially reduced to the optimal control over a complex system of wastewater treatment facilities [13, 14].

According to the "Guidelines...," calculation of the permissible composition of the WD should be carried out on the basin principle. This principle assumes a simultaneous calculation of permissible concentrations in the WD for all WD points that are located within the relevant segment of the river basin.

The basin principle of calculating the MPD is fully consistent with the modern systematic approaches to managing water resources of the country, which are based on ecological and economic principles of using the basin and should ensure the restoration of the natural and ecological balance in the ecosystems and environmentally safe water use. According to the concept of water policy that is described in [15], a river basin should be managed by the Basin Council (a legislative body) and the Water Agency of the river, which is an executive authority working on a regular basis.

A current methodological problem is that the basin principle of calculating the MPD for specific estimation areas, according to [4], should be implemented in basin segments within administrative regions. In [13, 14], it is argued that such an approach can not be realized because of the large scale of the areas, and it is suggested that a river basin should be subdivided into relatively small local sites. The suggestion is that when splitting the river basin into sections it is necessary to take into account not only the borders of administrative territories but also the physical and geographical factors and the unevenness of anthropogenic impact. However, it is claimed that there is a problem with assigning natural water quality standards to each local site. Today in Ukraine there is a unified system of surface water quality standards in the form of a maximum permissible concentration (MPC) in relation only to the type of water use (a fishery, municipal water supply, technical versus drinking water use). However, regional MPCs are not specified in the water protection legislation. Thus, if a single standard is used for the whole length of the river, some of the water users will be at a disadvantage: enterprises in the upper segments of the river basin will have an opportunity to dump pollutants to a much greater extent than enterprises located downstream. This will lead to either excess pollution of the river water or to a closedown of the enterprises in the lower part of the basin.

Consequently, a disadvantage of the existing methodology of developing the MPD for substances in a WB is the lack of a mechanism of establishing regional standards of natural water quality. These standards, firstly, must not conflict with national regulations (for example, they must not exceed the maximum permissible concentration), and secondly, they must provide all enterprises in a river basin with the most uniform possibilities of wastewater disposal.

3. The aim and tasks of the study

The aim of this study is to develop an algorithm of establishing regional natural water quality standards by an example of non-conservative pollutants.

To achieve this aim, it is necessary to do the following tasks:

– to develop a mathematical solution of the problem of finding the permissible weights of pollutants released into a WB with a WD;

– to devise an algorithm for solving the problem of finding the permissible weights;

– to calculate the permissible weights on the example of the Udy river basin (Kharkiv oblast, Ukraine).

4. The methods of establishing regional standards of water quality

4. 1. The general idea of solving the problem

A possible way of solving the problem of establishing standards of natural water quality is considered in [16] with regard to location of sites. The standards of natural water quality are determined separately for each substance. The general idea of solving this problem is as follows: an enlarged scheme of the river basin is considered with regard to generalized WDs (Fig. 1), which means that all the discharges within one segment are conventionally collected into one.

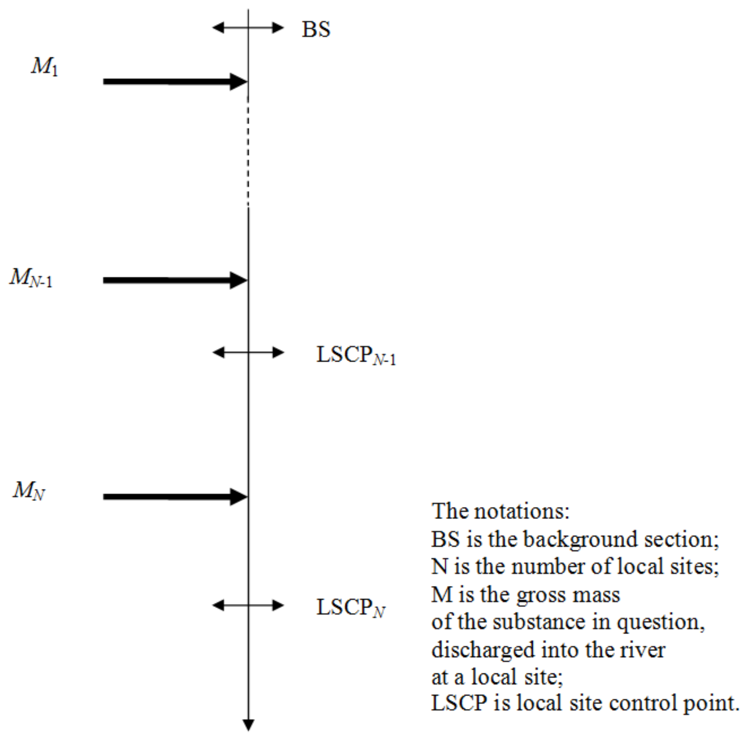

Fig. 1. A scheme of generalized wastewater discharges and local site control points

A large inflow can be taken into account as a generalized wastewater discharge; in this case, the value of M is a mass of material passing during a unit of time through an outfall point of the inflow. In the lowest position of each section, a control point is assigned to a local site (which is a local site control point, LSCP). Next, the problem is solved for finding the maximum permissible gross mass that does not lead to exceeding the maximum permissible concentration in each LSCP. It is necessary to take into account the following: if the gross mass is reduced to achieve non-exceedance of the MPC in any outfall LSCP_j (i. e., $j < N$), it automatically reduces the concentration of the substance in all LSCPs located below LSCPj. Thus, there appears a resource for increasing the load on the lower segments, which already leads to an increase in the gross mass.

The permissible gross mass must be calculated, as is customary in the wastewater discharge system rationing, on the basis of the actual condition. It is expedient to assume that the actual condition is the average value for the latest years. Moreover, it is necessary to exclude atypical periods (accidents, a temporary downtime of enterprises, deviations from the technological mode, and the like).

The eventually determined standards of river water quality are the estimated concentrations of substances in the LSCP, which correspond to the found permissible gross mass M.

4. 2. An algorithm for determining the permissible gross masses of pollutants entering the river system with wastewater

Formalization of the above-described mechanism of finding permissible gross masses and the subsequent determining of the required standards are based on the following mathematical objects:

– $\{M\}^l$ is a multitude of gross masses discharged into the river basin from the top (1st) to the 1st site inclusively;

– $\{M\}_l$ is a multitude of gross masses discharged into the river basin from the 1st site to the outfall (N-th) point inclusively;

– C_l is the calculated concentration of the substances in the LSCP_l;

– $L(\{M\}^l)$ is the procedure of reducing the gross masses $\{M\}_1$ to achieve $C_l \leq MPC$;

– $V(\{M\}_l)$ is the procedure of increasing the gross masses $\{M\}_l$ to a level that does not lead to exceeding the maximum permissible concentration in all LSCPs that are below LSCP_l.

In the terminology of functional analysis, C_j is a functional that displays the multitude of gross masses on the scale of concentrations; L and V are operators reflecting the multitude of gross masses as an equivalent set.

Concentrations in each LSCP are calculated according to the model suggested in [4].

$$c(t) = (c_0 - c_{nat}) \cdot \exp(-\beta \cdot t) + c_{nat}, \quad (1)$$

where c_0 and $c(t)$ are the substance concentrations at the initial time and at the time t, respectively; c_{nat} is the natural concentration of the substance; ß is the coefficient of the substance non-conservativeness that characterises the intensity of the self-cleaning process.

By presenting the gross mass as a product of the average concentration in the gross disposal of a WD and by disregarding the self-cleaning within the local site, we obtain:

$$C_l = \frac{\sum_i^l \left[(c_i - c_{nat}) \cdot \exp(-\beta \cdot t_i) + c_{nat} \right] \cdot q_i}{Q_l}, \quad (2)$$

where Q_l is a consumption volume of river water in LSCP_l; q_l is a consumption volume of the WD_i.

The operator L $(\{M\}_l)$ works as follows: for each local site, the influence coefficients are determined by the expression:

$$a_i = \exp(-\beta \cdot t_i), \quad (3)$$

where t_i is the time of water moving from the i-th LSCP to LSCP_l.

Also, based on the adopted approach in European countries, an integral coefficient of efficiency of wastewater treatment facilities is introduced into consideration as equal to

$$b_i = \sum_{l=1}^{m} \frac{(\delta_н - \delta_j)}{\delta_н}, \quad (4)$$

where m is the number of enterprises in an area; δ_j is the degree of purifying the WD due to the standards for a j-th enterprise; $\delta_н$ is the degree of purifying the WD by the best available technology.

Next, the task is to determine the masses $\tilde{M}$ that are included in the balance equation:

$$\sum_{i=1}^{l} \tilde{M}_i = Q_l \cdot MPC. \quad (5)$$

To account for the effect of influence coefficients a_i and integral coefficients b_i, the mass to be defined is calculated in the following way:

$$\tilde{M}_i = M_i \cdot (1 - k \cdot a_i b_i), \quad (6)$$

where k is an unknown coefficient to be determined.

By integrating (6) into (5), we obtain:

$$\sum_{i=1}^{l} \tilde{M}_i = \sum_{i=1}^{l} M_i \cdot (1 - k \cdot a_i b_i) = = \sum_{i=1}^{l} M_i - k \sum_{i=1}^{l} a_i b_i = Q_l \cdot MPC. \quad (7)$$

Eventually:

$$k = \frac{\sum_{i=1}^{l} M_i - Q_l \cdot MPC}{\sum_{i=1}^{l} a_i b_i}. \quad (8)$$

Thus, formulae (6) and (8) allow obtaining new values of a gross mass, which will not lead to exceeding the maximum permissible concentration in the outfall point.

With the operator $V(\{M\}^l)$, the degree of reduction of gross mass in the preliminary stage (due to the operator L) is taken into account with respect to the actual level. Therefore, it is suggested that the desired quantities should be found through the expression:

$$\tilde{M}_i = M_i \cdot (1 - k \cdot \mu_i), \quad (9)$$

where k is an unknown coefficient to be determined, $\mu_i = M_i / M_i^ф$ is the degree of the mass reduction, and $M_i^ф$ is the actual value of the gross mass.

The balance equation in this case is as follows:

$$\sum_{i=1}^{N} \tilde{M}_i = Q_N \cdot MPC. \quad (10)$$

By performing arithmetic operations similar to those described above, we obtain:

$$k = \frac{\sum_{i=1}^{N} M_i - Q_N \cdot MPC}{\sum_{i=1}^{N} a_i b_i}. \quad (11)$$

Thus, V is the operator that increases the value of the gross mass that would not exceed the initial (actual) value and will not result in exceeding the MPC in the outfall point.

4. 3. Establishment of regional water quality standards

The natural water quality standards to be determined in each $LSCP_i$ will be calculated as the concentrations of substances $\{C_i\}$, $i=1 \div N$, provided that the total discharged mass at the site will comply with the calculated values of $\{M_i\}$.

Thus, the division of a river basin into local segments is a prerequisite for the calculation of the MPD on the basin principle. This partition entails the need for setting river water quality standards at each site (which should be more rigid in comparison with the officially valid MPCs). These standards should be set taking into account the actual anthropogenic load on a WB as well as self-purification of the river water.

After the division of a river basin into local sites and the establishment of appropriate quality standards for the river water, MPDs are calculated at each site separately. Within the boundaries of a site, the calculation is performed simultaneously for all water-using enterprises by one of the methods described in the "Guidelines…" [4] (by a method that is based on a uniform use of the assimilative capacity of the watercourse or by solving the optimization problem [4]).

4. 4. A demonstrational example calculation of regional river water quality standards in terms of phosphates

Below is a demonstrational example calculation for the Udy river basin according to the reported 2-TP (water utility) for the period from 2010 to 2014 [17]. The phosphates are chosen [18] as an exponent of contamination. This exponent is chosen, firstly, due to the fact that phosphates are one of the most significant indicators of pollution that must be normalised [19]. Secondly, phosphates in natural water are not transformed into other contaminants [20–22]; this exponent can be only subjected to self-cleaning of the river. Therefore, this exponent can be calculated with the above-described algorithm of determining the permissible gross mass. For example, the MPC of phosphates for a fishery water use is 2.15 mg/dm^3 [23].

A hydrographic scheme of the Udy river basin with a LSCP is shown in Fig. 2. The diagram contains only the rivers that are categorised as water receivers of WDs according to the specified reporting.

It should be noted that the division is conditional and is only intended to demonstrate the algorithm. The practical problem of subdividing the basin into local sites can be solved in a separate study.

Table 1 presents data on gross discharges of phosphates in the rivers of the Udy basin in relation to the local sites.

The calculation was performed under the following reference conditions [2]:

– the background water consumption of the Kha rkiv river – 0.1 m^3/s;

– the background water consumption of the Lopan river – 0.1 m^3/s;

– the background water consumption of the Udy river – 1.0 m^3/s;

– the concentration of phosphate in the background section of the river Kharkiv – 1.0 mg/dm^3;

– the concentration of phosphate in the background section of the river Lopan – 1.0 mg/dm^3;

– the concentration of phosphate in the background section of the river Udy – 2.0 mg/dm^3;

– the rate of the natural river water (for all the rivers) – 0.2 m/s;

– the non-conservative phosphate ratio – 0.03 1/day.

Table 2 shows the results of the calculation, i. e. the permissible gross masses of phosphates discharged into the Udy river basin and the phosphate concentrations in the LSCPs under the actual and allowable discharges.

By comparing the data of Tables 1, 2, it becomes obvious that the calculated allowable gross masses of phosphates are substantially less than the actual ones.

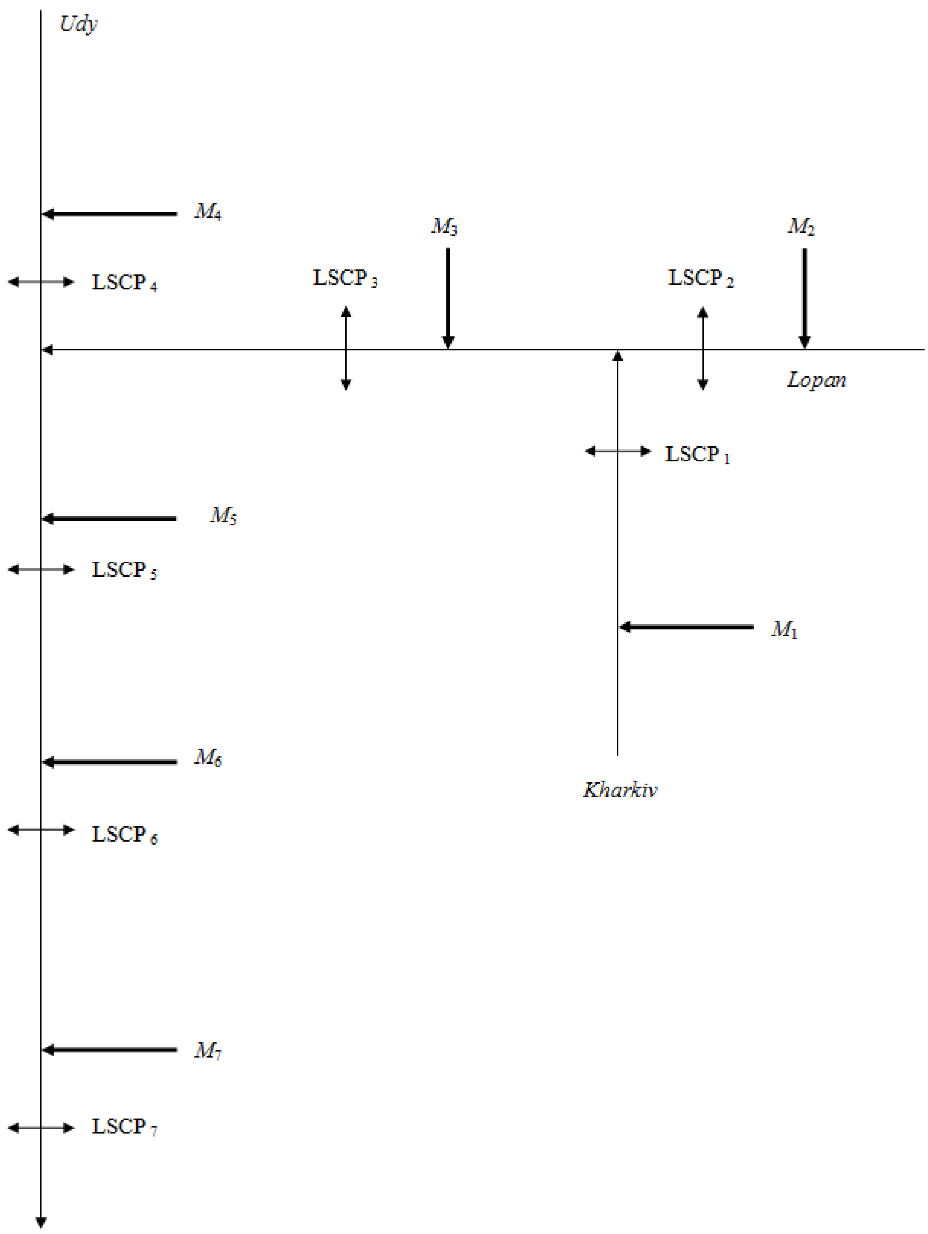

Fig. 2. A hydrographic scheme of the Udy river basin

Table 1

Data on discharge of phosphates into the Udy river

The number of a local site	The water receiving river	The distance from the LSCP to the river mouth, km	The quantity of WDs	The gross mass, kg/yr	The average concentration, mg/dm^3
1	Kharkiv	0	3	0.86	13.5
2	Lopan	21	5	1.07	3.96
3	Lopan	0	4	509.58	3.39
4	Udy	74	4	0.75	3.26
5	Udy	29	5	127.42	2.25
6	Udy	15	3	2.73	10.1
7	Udy	0	2	2.51	8.95

Table 2

The calculated concentration of phosphates in the LSCPs and the generalized discharges

The number of a local site	The concentration in the LSCP at the actual WD, mg/dm^3	The calculated permissible discharge		The regional water quality standards (concentration in the LSCP at the acceptable gross mass), mg/dm^3
		The gross mass, kg/yr	The average concentration, mg/dm^3	
1	1.78	0.14	2.15	1.01
2	1.23	0.58	2.15	1.08
3	3.32	329.20	2.19	2.15
4	1.97	0.49	2.15	1.94
5	2.40	125.72	2.22	2.15
6	2.46	1.46	5.40	2.15
7	2.43	2.48	8.85	2.13

4. 5. Analysis of the calculation results

As can be seen from Table 2, the actual wastewater discharge exceeds the standard value of the MPC in the river water in a number of LSCPs. When the permissible concentrations are considered for generalized discharges, there is no excess of the MPC in the LSCPs. The concentration data (the last column of Table 2) may be accepted as regional standards of river water quality in terms of phosphate. At the same time, in some cases, regional regulations are more than twice stricter than the MPC (2.15 mg/dm^3).

5. Discussion of the practical relevance of the developed algorithm for establishing regional standards of natural water quality

An advantage of the algorithm that has been described in the article is that the establishing of the regional standards of natural water quality allows the calculation of the MPD on the basin principle. The results of this study may be useful in improving the water protection legislation both in terms of setting standards of natural water quality and a refinement of the methodological basis of calculating the MPD.

A disadvantage of the suggested algorithm is that it can be implemented only if in a WB there are no processes of transforming some types of pollutants into other types of contaminants. Therefore, further research in this field can imply modifying the algorithm to take into account a possible transformation of pollutants in the WB water (as it happens, for example, with nitrogen group compounds [24]). Moreover, it is necessary to develop suggestions for a change in the water protection legislation in order to specify the procedure for calculating the MPD for water-using enterprises.

6. Conclusions

1. An algorithm has been developed in the study for finding regional standards of natural water quality. Its characteristic features are the division of a river basin into local sites, accounting for the degree of self-purification of water in a WB according to the considered indicators of contamination, and control over the impact of water treatment facilities of water-using enterprises.

2. The efficiency of the developed algorithm is demonstrated by the example of calculating regional standards in terms of phosphates for the Udy river basin (Ukraine). In some cases, the determined regional regulations are more than twice stricter that the conventional MPC (2.15 mg/dm^3).

Consequently, the study has showed the need to tighten natural water quality standards in the upper parts of river basins in order to optimize water use rationing.

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