Zh.R.SHAKIRZANOVA
Y. D.GOPCHENKO
V.A.OVCHARUK
N.S.KICHUK

THE FURTHER TRAINING AND RETRAINING OF SPECIALISTS

Modelling of Land Surface Waters

Notes of Lectures

2018

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
ODESSA STATE ENVIRONMENTAL UNIVERSITY

Zh.R.SHAKIRZANOVA
Y.D.GOPCHENKO
V.A.OVCHARUK
N.S.KICHUK

Modelling of Land Surface Waters

Notes of lectures
for students of English courses for
further training and retraining of specialists
Speciality "Hydrology"

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These notes of lectures contain theoretical and methodical grounds of modern mathematical models in hydrological calculations and forecasts of rivers' water regime, methods for assessment and forecasting of water quality on the basis of standards of ecological safety of water use.

Notes of lectures are used for students of courses for further training and retraining of specialists, postgraduates, masters and students of higher education establishments with hydrometeorological bias.

CONTENTS

FOREWORD

Notes of Lectures are included in the courses for further training and retraining of specialists **"Modelling of Land Surface Waters"** that belong to the English course for further training and retraining of specialists with regard to speciality "Hydrology" aimed at use of acquired theoretical knowledge and skills in practical activities.

Purpose of courses – forming of understanding by attendees of offered modern mathematical models on calculations and forecasts of hydrological and hydrochemical characteristics of rivers, lakes and water reservoirs.

Task of courses – forming of understanding by attendees of essence of offered methods and models of hydrological calculations and long-term forecasts for land surface waters, quantitative assessment and forecasting of hydrochemical state of water bodies, acquisition by them of practical skills on application of these models under modern conditions of climate change and rivers' hydraulicity.

Main task of courses **"Modelling of Land Surface Waters"** – familiarization and practical use of modern models for rating of estimated characteristics of maximum runoff of floods and overflows, territorial long-term forecasts of hydrological characteristics of spring floods of lowland rivers, methods of assessment and forecasting of water quality based on norms of ecological safety of water use.

Notes of Lectures for further training and retraining of specialists **"Modelling of Land Surface Waters"** include three Section:

Section I. Territorial long-term forecasting of hydrological characteristics of spring floods of lowland rivers.

Section II. Engineer substantiation of estimated characteristics of maximum rivers' runoff during flooding and overflowing.

Section III. Forecasting of changes of chemical composition and quality of natural waters.

Following the training at courses **"Modelling of Land Surface Waters"** attendees must ***familiarize themselves*** with main principles of mathematical modelling for rating of estimated characteristics and long-term forecasts of rivers' runoff, assessment criteria and methods of forecasting of chemical composition of surface waters with consideration of anthropogenic changes within catchment areas and changes of global and regional climate.

Familiarization with:

- principles and methodological frameworks of creating of schemes for estimation of maximum surface runoff;
- mathematical models for territorial long-term forecasting of spring floods runoff of lowland rivers;
- modern methods of mathematical statistics and programming;
- main principles and methods of assessment of water quality in water objects;
- characteristic of chemical composition of surface waters and conditions of its forming;
- assessment criteria for possible use of mathematical model under different physical and geographical conditions and considering modern changes of hydrometeorological regime.

Programme of lecture modules

Content-related modules	Name of content-related module	Name of subject
CM-L1*	**Section I.** **Territorial long-term forecasting of hydrological characteristics of spring floods of lowland rivers**	1.1 Theoretical grounds for method of long-term forecasting of characteristics of spring floods of lowland rivers using mathematical tool of discriminative analysis. 1.2 Methodology of determination of availability of forecasting values and cartographical form of their

		representation. 1.3 Method of forecasting of dates of commencement and occurrence of maximum water discharge of spring floods.
CM-L2*	**Section II.** **Engineer substantiation of estimated characteristics of maximum rivers' runoff during flooding and overflowing**	2.1 Mathematical models of maximum runoff for rating of estimated characteristics of rivers' maximum surface runoff 2.2 Methods recommended by regulatory documents for determination of maximum rivers' runoff (SNiP 2.01.14-83, DBN-2015) 2.3 Operational models of forming of surface runoff for rating of estimated characteristics of floods and overflows Regional 2.4 Regional methods for determination of maximum runoff of Ukrainian rivers
CM-L3*	**Section III.** **Assessment of natural waters quality and forecasting the change of water chemical composition**	3.1 Forming factors and water quality criteria. 3.2 Methodological substantiation of operational forecasting of water quality indicators. 3.3 Long-term forecasting of changes of water chemical composition.

* CM – Content-related module of academic discipline (complete structural and logical section of programme of academic discipline forming particular competences); CM-L – content-related module – lecturing.

After familiarization with Sections attendees must acquire the following <u>knowledge.</u>

CM-L1:

- Main scientific provisions of method of territorial long-term forecasting of characteristics of lowland rivers' spring floods.

- Methods for establishment of probability of forecasting characteristics within several years' period.
- Cartographical forms of representation of forecasting information.
- Criteria for assessment of forecasts and adaptation of results under climate change conditions and anthropogenic influence on rivers' runoff.

CM-L2:

- Main factors of forming of runoff of rainfall floods and spring floods.
- Awareness on different types of forming of floods and overflows.
- Awareness on principles of modelling of estimated schemes of maximum runoff.
- Knowledge in the area of statistic methods and their application in practical work.

CM-L3:

- Factors that determine forming of chemical composition of river waters.
- Importance of forecasting of chemical composition of natural waters.
- Tasks and characteristic of operational forecasting of water quality values.
- Scheme of conceptual model of process of operational forecasting of water quality.
- Assessment and analysis of accuracy of operational forecasts.
- Long-term forecasting of changes of chemical composition of water and its methods.

Criteria for assessment of content-related modules

Total score of the theoretical part is equal to 30 points

Maximum score for:

CM-L1 – 10 points (written test No.1**)**

CM-L2 – 10 points (written test No.2**)**

CM-L3 – 10 points (written test No.3**)**

SECTION I
TERRITORIAL LONG-TERM FORECASTING OF HYDROLOGICAL CHARACTERISTICS OF SPRING FLOODS OF LOWLAND RIVERS

Plan of lecture

Introduction.

1.1 Theoretical grounds for method of long-term forecasting of characteristics of spring floods of lowland rivers using mathematical tool of discriminative analysis.

1.2 Methodology of determination of availability of forecasting values and cartographical form of their representation.

1.3 Means for automatic operational forecasting of maximum water discharge of spring floods.

1.4 Cartographical form of representation of forecast values of characteristics of spring floods and their availability.

1.5 Method of forecasting of dates of commencement and occurrence of maximum water discharge of spring floods.

Introduction

Continuous development of methods and models is associated with improvement of theoretical (notions about physical aspects of processes of surface runoff formation) and practical (accumulation of materials of hydrometeorological observations, availability of computer facilities) bases assisted in creating throughout the world of robust software and modelling complexes for forecasting of runoff values of river systems. This is a mathematical modelling in hydrological forecasts of both hydrograph of spring floods or rainfall floods (short-term forecasts) and volume or maximum water discharge of these phases of rivers' hydraulicity that relate to long-term forecasts.

Existing modern models for long-term forecasting of surface river runoff, in particular, for the period of spring floods first of all relate to runoff depths of middle-sized and large rivers in the basins of which regular measurements of water discharge are carried out. In such models forecasting of maximum water discharge and levels that constitute a main threat during flooding of territories is performed only for particular river stations.

Application of forecasting models for large territories, including for the rivers not examined in hydrological terms, is associated with difficulties of determination of models' empirical parameters. Such parameters should be common for those areas which appear to be similar in terms of conditions of formation of rivers' surface runoff.

In this section of the course improvement of existing fundamental scientific and methodical base takes place and a new method of premature forecasting of maximum water discharge and levels, volumes and periods of spring floods of rivers, including those not covered by hydrometeorological observations, is offered. Cartographic form of forecasting information gives an opportunity to assess scales and periods of spring flood within large territories as well as to establish probability characteristics of its occurrence within several years' period and that would ensure enhancement of safety and prevent flooding of territories provided there is extreme spring high water.

Methods of examination. A complex geographical approach for analysis of conditions of river runoff formation; theoretical analysis of hydrological processes and phenomena; statistical processing of hydrological characteristics;

geographical generalization of hydrometeorological values; discriminant analysis for determination of hydraulicity of a spring flood; numerical methods for determination of immeasurable values (rated duration of water inflow from slopes to channel network) were used.

1.1 Theoretical grounds for method of long-term forecasting of characteristics of spring floods of lowland rivers using mathematical tool of discriminative analysis

Main theoretical dependence. Theoretical provisions of method of long-term forecasts of characteristics of spring floods of lowland rivers are based on regional dependences of modular coefficients of runoff depths or maximum water discharge from aggregate water reserves in snow cover and from spring rainfalls [1-5]. These characteristics are expressed in the form of modular coefficients, that means with regard to their average several years' values. Forecasting dependences are established for rivers with regard to which there are several years' series of hydrometeorological observations in the form of (Shakirzanova, 2015)

$$k_m = f(k_P), \tag{1.1}$$

k_m - modular coefficients of:

- depths of spring runoff $k_m = Y_m / Y_0$, where Y_m and Y_0 - depths of spring runoff and their average several years' values, mm;
- maximum discharge (modules) of water of spring floods $k_m = q_m / q_0$, where q_m and q_0 – maximum modules of spring flood and their average several years' values, m^3/(s·km^2).

Modular coefficients of aggregate water reserves taking part in formation of spring floods k_P include:

- for depths of spring runoff

$$k_P = (S_m + P_1 + P_2)/(S_0 + P_{1_0} + P_{2_0});\tag{1.2}$$

- for maximum water discharge of spring floods

$$k_P = (S_m + P_1)/(S_0 + P_{1_0}),\tag{1.3}$$

S_m, P_1 and P_2 - maximum water reserve in snow cover, precipitation within the period of snow melting and decline of spring floods, mm;

S_0, P_{1_0} and P_{2_0} - their average several years' values respectively, mm.

Assignment of types of floods with regard to hydraulicity. Assignment of types of floods with regard to hydraulicity (high water, mean water and low hydraulicity) forms the base of regional dependences (1.1) for forecasting of spring runoff or maximum water discharge. For this purpose a mathematical apparatus of multidimensional statistical model – ***discriminant function,*** that takes into account a set of factors of spring floods formation, is used.

Linear discriminant function (*DF*) allows to refer an object characterized by a complex of features to one of subspaces (groups). It is recorded as follows

$$DF = a_0 x_1 + a_1 x_2 + ... + a_m x_m,\tag{1.4}$$

A (a_0, a_1, a_2, ... , a_m) - vector of coefficients of discriminant function;

$R(x_1, x_2, ..., x_m)$ – vector of factors (vector-predictor);

m - quantity of features or discriminant variables (j=1,2,...,m) characterizing the object under examination.

For m-dimensional space of features a linear discriminant function represents an equation of some separating plane with the biggest amount of cases referring to a specific group placed on its opposite sides. At this case area of separation is $DF(x_1, x_2, ..., x_m) = 0$.

Phase of recognition, i.e. forecasting of a phenomenon, consists in determination (as per selected vector-predictor) of a value of discriminant function via (1.4) and taking of an object, according to a solving rule, to one of groups into which the whole aggregate of events is split down.

Coefficient a_0 is calculated on condition that the equality $DF = 0$ determines the point of separation between two groups of events. If $DF>0$ the forecast refers an event to the first group, if $DF<0$ – to the second one.

In case of application of discriminative analysis model it is necessary to split an output selection preliminarily into classes (groups) in terms of a specific feature. As to the task set, belonging of a predicant (modular coefficients of depths of spring runoff or maximum water discharge) to a specific class is determined as per position of points on the graphs of the relation $k_m = f(k_P)$.

For lowland rivers of Ukraine the equation is as follows (Shakirzanova, 2015)

$$DF = a_0 + a_1 k_P + a_2 k_{q_1} + a_3 k_L + a_4 \theta_{02}. \tag{1.5}$$

Vector-predictor of discriminative function includes the following factors of spring floods:

k_P – aggregate water reserves at a catchment that take part in formation of spring floods in the form of (1.2) or (1.3);

$k_{q_1} = Q_1 / Q_{1_0}$ – modular coefficient of index of soils' wetness (Q_1 i Q_{1_0} – average monthly water discharge before commencement of spring floods and its average several years' value, m^3/s);

$k_L = L / L_0$ – modular coefficient of maximum depth of soil freezing during winter (L i L_0 – depth of soil freezing and its average several years' value, cm);

θ_{02} – average monthly air temperature in February, ^{o}C.

Check of adequacy of model of alternative forecast or detection of error of such forecast (error of "overlapping") is performed, for instance, as per generalized function of Mahalanobis distance or as per criterion of statistical significance of Fisher distribution that is as follows

$$F = \frac{n_1 n_2}{n_1 + n_2} \frac{n_1 + n_2 - m - 1}{n_1 + n_2 - 2} \frac{\sum_{i=1}^{n} a_i (\overline{x}_{1i} - \overline{x}_{2i})}{m}, \tag{1.6}$$

where $\overline{x}_{1i}$ i $\overline{x}_{2i}$ – average values of i discriminant variable of two aggregates;

n_1 and n_2 – quantity of objects in each group;

a_i – coefficients of discriminant function.

Difference between two groups will be statistically significant if value F exceeds critical value $F\alpha(\nu_1, \nu_2)$, where α - level of significance (one of values, for instance 0,05; 0,01; 0,001), whereas ν_1 and ν_2 – numbers of degrees of freeness determined by quantity of features m and quantity of objects in groups n_1 and n_2. In such case $\nu_1 = m$, a $\nu_2 = n_1 + n_2 - m - 1$.

With the help of a sign of discriminant equations (more or equal to zero) it is possible to differentiate floods of rivers in terms of types of hydraulicity. If discriminant function $DF1>0$ one should expect forming of spring floods to be higher than average several years' values (standards). If $DF1 \leq 0$, and $DF2 \geq 0$, spring floods will develop as per situation when runoff depths or maximum water discharge are expected to be close to the standard. If $DF1<0$ and $DF2<0$ floods will be lower than standard value.

Determination of modular coefficients of characteristics of spring floods Prepared forecasting dependences of (1.1) type may be described with polynomial equations of 3rd stage of the following type

$$k_m = b_0 + b_1 k_P + b_2 k_P{}^2 + b_3 k_P{}^3, \tag{1.7}$$

where b_0, b_1, b_2, b_3 – polynominal coefficients that are subject to determination for curves (1.1) in accordance with a sign of discriminant equations (1.5).

It should be noted that coefficients of regional equations (1.5) and (1.7) are obtained as constant ones within hydrological districts where conditions for spring floods forming are the same (Figure 1.1).

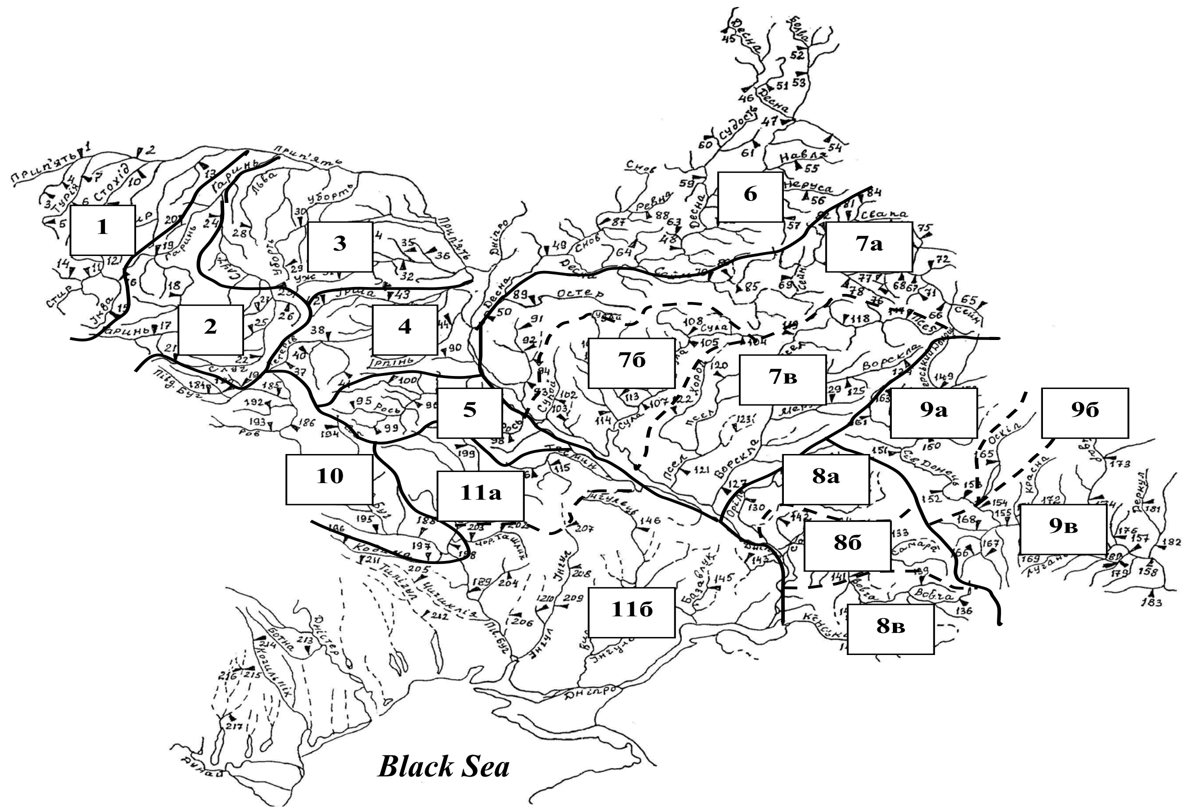

Figure 1.1 – Division into districts of plain territory of Ukraine as per parameters of forecasting methods for characteristics of rivers' spring floods

Determination of quantitative values of characteristics of spring floods. Forecast hydrological values are defined via modular coefficients obtained as per methodology k_m through the following equations:

- depths of spring runoff

$$Y_m = k_m Y_0; \quad (1.8)$$

- maximum water discharge

$$Q_m = k_m Q_0 = k_m q_0 A , \quad (1.9)$$

where Y_0 or $Q_0 (q_0)$ – average several years' values of spring runoff depths or maximum discharge (modules) of water;

A – areas of rivers' catchments, km^2.

Territorial aspects of forecasting method. Territorial forecasting (for several rivers within one hydrological district) is stipulated by calculation of average several years' runoff depths Y_0 or maximum module of spring floods q_0.

In case of availability of continuous hydrological series average several years' characteristics of spring floods are calculated for a specific river:

- depths of spring runoff

$$Y_0 = \frac{\sum_{i=1}^{n} Y_i}{n}; \quad (1.10)$$

- maximum water discharge or their modules

$$q_0 = \frac{\sum_{i=1}^{n} Q_{m_i}}{nA}, \quad (1.11)$$

where Y_i or Q_{m_i} - runoff depths or maximum water discharge of spring floods of *i* years;

n – quantity of years of observations;

A – area of river's catchment.

In case of short-time hydrological series of observations within rivers or in case of their absence average several years' values (rates) of runoff depths or maximum water discharge of spring floods (represented by maximum module q_0) are determined using regional generalizations.

Rate of maximum module of spring floods q_0 (in case of absence of runoff observations) is determined through methods that base themselves on the model of typical reduction hydrograph of floods and is calculated through equation (Gopchenko, 2005)

$$q_0 = q_0' \psi(t_p / T_0) \varepsilon_A \cdot r , \qquad (1.12)$$

where q_0 – average several years' module of maximum water discharge in a river, $m^3/(s \cdot km^2)$;

q_0' – average several years' module of maximum water discharge of slope inflow, $m^3/(s \cdot km^2)$;

$\psi(t_p / T_0)$ - function of transformation of spreading of flood's waves under the influence of channel lag;

ε_A - coefficient of channel and flood plain regulation;

r – coefficient of floods' transformation under the influence of lakes and storage reservoirs of channel type.

Average several years' module of maximum water discharge of slope inflow q_0' in (1.12) is determined within the framework of typical reduction hydrographs of spring floods (Gopchenko, 2005)

$$q_0' = 0{,}28 \frac{n+1}{n} \frac{1}{T_0} Y_0 , \qquad (1.13)$$

$(n+1)/n$ – coefficient of irregularity in time of water inflow from slopes that is accepted for basins of lowland rivers of Ukraine as equal to 8,1 (Shakirzanova, 2015);

T_0 – duration of slope inflow of snow-melt water, hours;

Y_0 – average several years' depth of flood's runoff, mm.

Average several years' depths of spring flood Y_0 for the rivers that remain uninvestigated in hydrological terms in (1.13) are determined as per schematic map of their distribution within the territory (Figure 1.2). Regional coefficients that consider influence on depths of spring flood of such factors as forestation A_f and swampiness A_{swamp} in rivers' basins (in parts of one) are introduced to their values.

Values Y_0 are determined, using a schematic map (Figure 1.2), using the equation

$$Y_0 = (Y_0)_{map} \cdot k_f k_{swamp}, \tag{1.14}$$

where $(Y_0)_{map}$ - average several years' values of depths of spring runoff taken from a schematic map for geometrical centres of rivers' catchments, mm.

Determination of influence of forestation k_f and swamps k_{swamp} on average several years' values of runoff depths is performed using the equations:

$$k_f = 1 + 0{,}070 \lg(A_f + 1); \tag{1.15}$$

$$k_{swamp} = 1 - 0{,}081 \lg(A_{swamp} + 1). \tag{1.16}$$

Values of duration of slope inflow of snow-melt waters within basins T_0 in (1.13) for the rivers that remain uninvestigated in hydrological terms are determined as per schematic map of their distribution within the territory (Figure

1.3). Regional coefficients that consider influence on duration of slope inflow of forestation and swamps are introduced to their values.

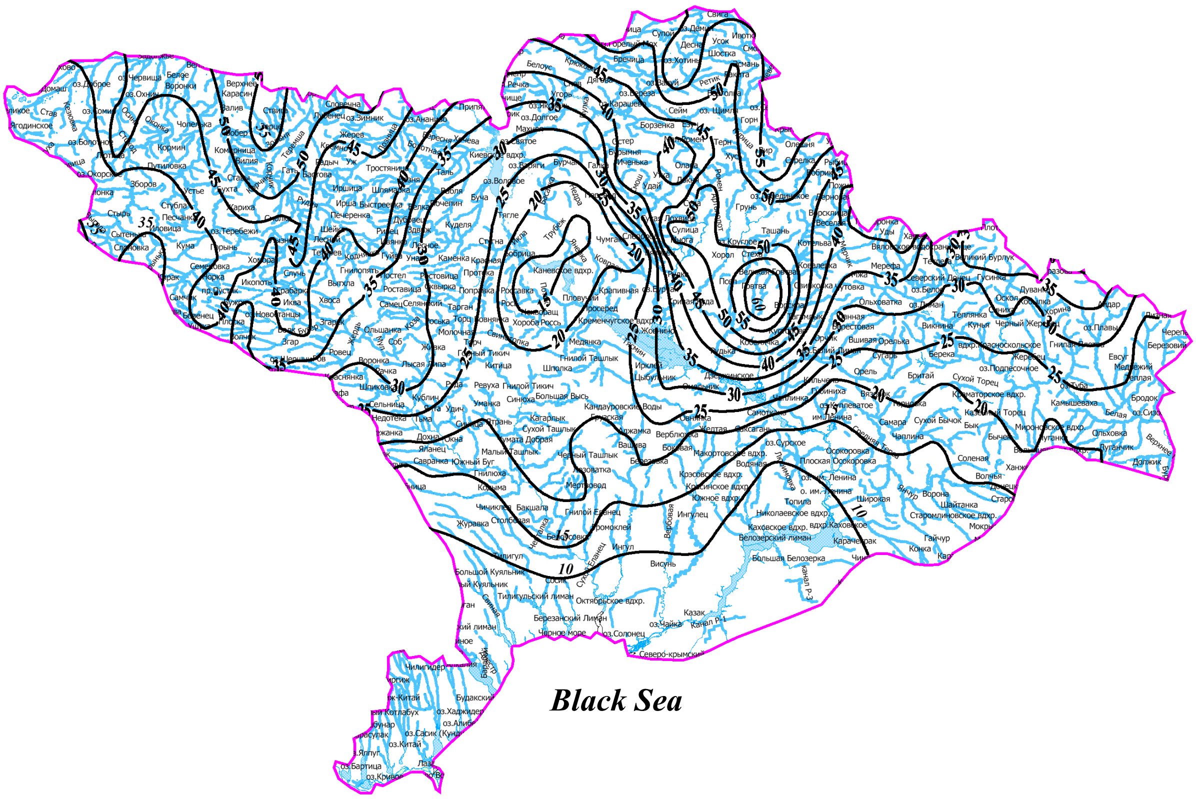

Figure 1.2 – Spatial distribution of average several years' values of depths of spring floods runoff (at A_f=0, A_{swamp}=0) in basins of rivers of plain territory of Ukraine, mm

Values T_0 are determined, using a schematic map (Figure 1.3), using the equation

$$T_0 = (T_0)_{map} \cdot k'_f k'_{swamp}, \tag{1.17}$$

$(T_0)_{map}$ - values of duration of slope water inflow taken from a schematic map for geometrical centres of rivers' catchments.

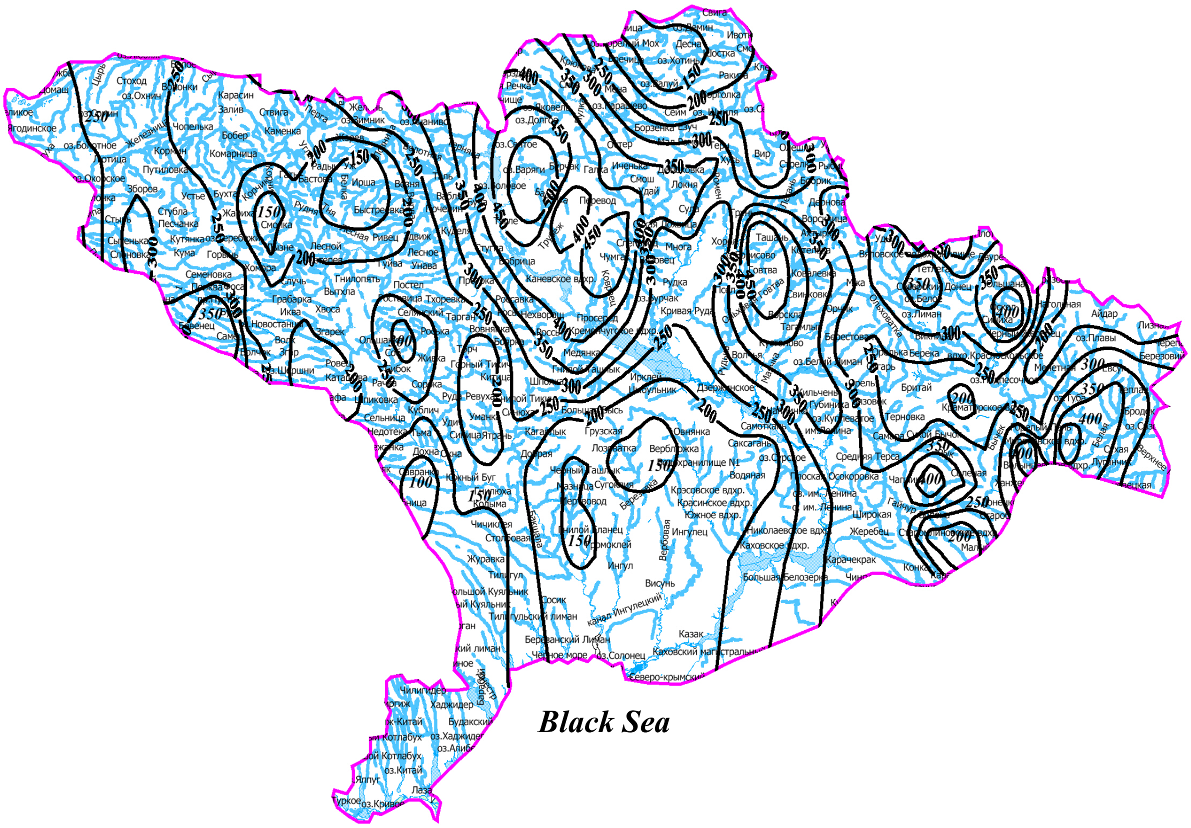

Figure 1.3 – Distribution within the territory of duration of slope inflow of snow-melt waters (at A_f =0, A_{swamp} =0) in basins of rivers of plain territory of Ukraine, hours

Values of coefficients of influence of forestation k'_f and swamps k'_{swamp} on value of duration of slope water inflow are determined through the equations:

$$k'_f = 1 + 0,37\lg(A_f + 1)\,; \quad (1.18)$$

$$k'_{swamp} = 1 + 1,23\lg(A_{swamp} + 1)\,. \quad (1.19)$$

Function of transformation of spreading of flood's waves under the influence of channel lag $\psi(t_p / T_0)$ in (1.12) is determined through the equation (Gopchenko, 2005):

- at t_p/T_0=0

$$\psi(t_p / T_0)=1.0; \tag{1.20}$$

- at 0<t_p<T_0

$$\psi(t_p / T_0) = 1 - \frac{m+1}{(n+1)(m+n+1)}\left(\frac{t_p}{T_0}\right)^n; \tag{1.21}$$

- at $t_p \geq T_0$

$$\psi(t_p / T_0) = \frac{n}{n+1}\frac{T_0}{t_p}\left[\frac{m+1}{m} - \frac{n+1}{m(m+n+1)}\left(\frac{T_0}{t_p}\right)^m\right], \tag{1.22}$$

where t_p – duration of channel lag of water, hours;

m - index of power in the equation of isochrones' curve (m=1,0);

n – index of power in the equation of curve of surface waters inflow (n=0,2).

Calculation of duration of channel lag t_p in (1.12) is performed using the relation

$$t_p = L / V_d, \tag{1.23}$$

L – hydrographical length of water course (distance from the farthest point of catchment), km, which, in case of absence of data about hydrographical length of water course, is determined as per dependences from areas of rivers' catchments A as follows

$$L = f(A); \tag{1.24}$$

V_d – speed of water lag, km/h, for determination of which the following formula is used

$$V_d = a_2 \cdot A^{\alpha_2} \cdot I^{0,33}, \tag{1.25}$$

a_2 – speed parameter that is accepted for a district of investigations as per table 1.1;

α_2 - parameter that is also determined as per table 1.1;

I – average weighted river gradient, $^o/_{oo}$, that may be determined, in case of absence of data about average weighted river gradients, depending on areas of catchments

$$I = f(A). \tag{1.26}$$

Coefficient of channel and flood plain regulation ε_A in (1.12) is determined depending on areas of catchments A, km^2

$$\varepsilon_A = e^{-0,18 \cdot \lg(A+1)}. \tag{1.27}$$

Table 1.1 – Values of parameters a_2 i α_2

Geographical zone	a_2	α_2
Woodlands	1,37	0,12
Forest and steppe zone	1,51	0,17
Steppe zone	1,19	0,14

Coefficient of transformation of maximum runoff of spring floods under the influence of lakes and storage reservoirs of channel type r in (1.12) is determined using the formula

$$r = 1/(1 + Cf'_{lake}), \qquad (1.28)$$

where f'_{lake} – average weighted lake percentage;

C – empirical coefficient that is determined by the value Y_0 as per table 1.2.

Table 1.2 – Values of coefficient C

Y_0, mm	>100	99-50	49-20	<20
C	0,2	0,25	0,35	0,40

Correction of hydrological forecasts according to present-day water regime of rivers' spring floods. In the offered method of territorial long-term forecasts basic maps and parameters of equations should be updated under the present-day changes of climate and water regime of Ukrainian rivers. With this purpose regional coefficients were introduced to the forecasting scheme in the values Y_0 and q_0 and these coefficients take into account present-day reduction of runoff depths and maximum water discharge of spring floods:

- for depths of spring floods' runoff

$$K_{Y_{2010}} = 0,97 - 0,017(\varphi^o - 50) \ ; \qquad (1.29)$$

- for maximum water discharge

$$K_{Q_{2010}} = 0,92 - 0,022(\varphi^o - 50); \qquad (1.30)$$

where φ - geographical latitude of geographical centre of gravity of river catchment, in parts of degree.

It is recommended to update such coefficients once in ten years since the trend of present-day changes may change the sign to the different one.

In such event transfer from forecast modular coefficients k_m to runoff values is performed as per the equations:

- for depths of spring floods' runoff Y_m, mm

$$Y'_m = k_Y \cdot Y_0 \cdot K_{Y_{2010}}, \tag{1.31}$$

- for maximum water discharge Q_m , m^3/s

$$Q'_m = k_{q_m} \cdot q_0 \cdot K_{Q_{2010}} \cdot A. \tag{1.32}$$

1.2 Methodology for determination of availability of forecasting values of runoff depths and maximum water discharge of spring floods

Mathematical model of territorial long-term forecasts for runoff depths and maximum water discharge of spring floods provides an opportunity to determine availability or probability of exceeding forecast values (*P* %) and this is especially important for rivers not examined in hydrological terms.

In case of availability of several years' series of runoff observations the task for determination of availability of values (*P* %) is solved via drafting of empirical curves of availability of modular coefficients of runoff depths or maximum water discharge of floods $k_m = f(P\%)$. In forecasting model k_m are determined as per forecasting dependences of the type (1.1).

For the rivers or territories that remain uninvestigated in hydrological terms determination of availability of forecasting values Y_m and Q_m may be performed through statistical processing of runoff series of observations. In such cases values of coefficients of variation of runoff depths or maximum water discharge within the part of the territory with available hydrometeorological measurements may be generalized in regional terms.

During determination of coefficients of asymmetry C_s and variation C_v and getting an average territorial value of relation C_s / C_v it is possible, in order to evaluate availability of forecasting values of runoff depths and maximum water discharge of spring floods, to use a curve of three-parametric gamma distribution of S.N. Krytskyi and M.F. Menkel (for average territorial value of C_s / C_v).

Availability of forecasting values of Y_m and Q_m is determined in the form of interval

$$P_1 < P_{Y(Q)} < P_2 \ , \qquad (1.33)$$

where P_1 and P_2 – upper and lower limits of availability determined as per tables.

At the same time, in case of absence of time series of runoff observations over river's spring floods regional equations (within plain territory of Ukraine) are used for determination of coefficients of variation:

- for depths of spring floods' runoff

$$(C_v)_Y = 1{,}62\left(\frac{Y_0}{5}\right)^{-0{,}38} ; \qquad (1.34)$$

- for maximum water discharge

$$(C_v)_Q = 1{,}90 - 0{,}22 \cdot \lg(A+1)\,. \tag{1.35}$$

1.3 Means for automatic operational forecasting of maximum water discharge of spring floods

Methodology of territorial long-term forecasting of maximum spring runoff developed at the Department of Hydrology of Land of OSENU by such authors as Gopchenko Y.D. and Shakirzanova Zh.R. (items 1.1-1.3) forms a base for creating of means for automatic operational forecasting of runoff depths and maximum water discharge of spring floods within basins of lowland rivers [1,2]. Software forecasting complexes are used for operative activities of the Hydrometeorological Centre of Ukraine (Kyiv) and the Hydrometeorological Centre of Black Sea and Sea of Azov (Odesa). They provide an opportunity to prepare (in automatic mode) forecasts of floods characteristics at basins of Ukrainian rivers as per the presented model and to determine their availability within several years' period.

Main practical stages of methodology implementation are designed in the form of computer complexes (Figure 1.4) and are presented in the form of block diagram (Figure 1.5) [6].

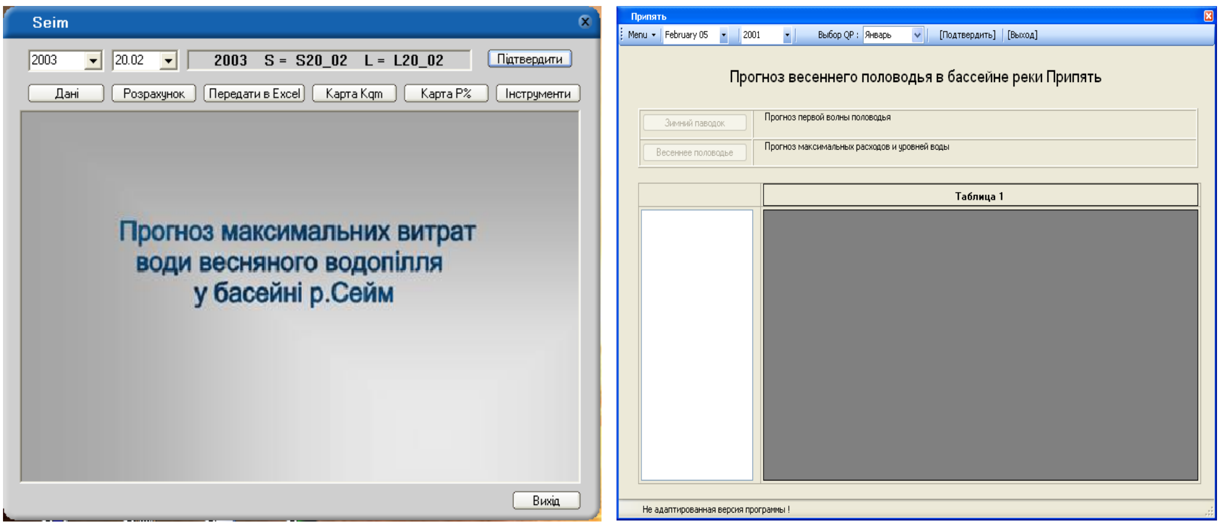

Figure 1.4 - Dialogue boxes of software complexes

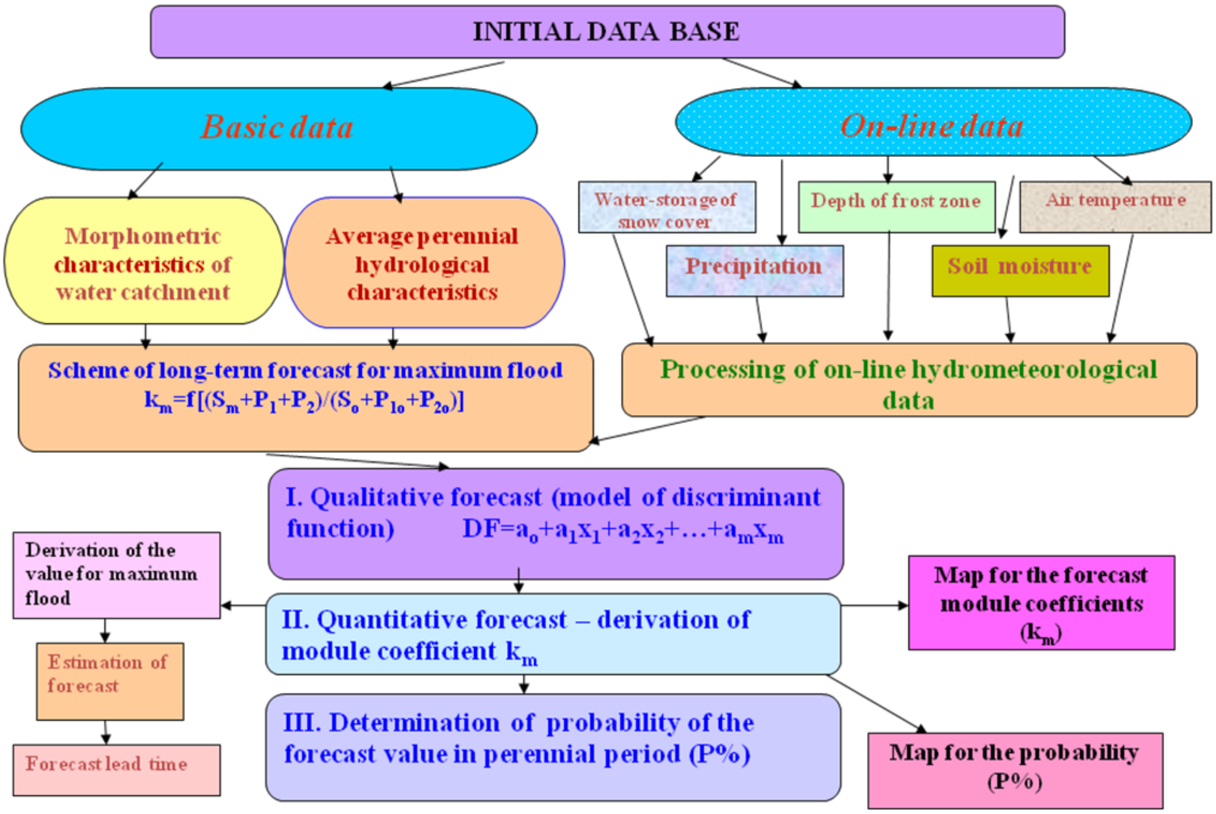

Figure 1.5 – The block scheme for the long-term forecasting of the spring flood characteristics

Procedure for forecast preparation. The following is the procedure for preparation of forecast of runoff depths and maximum water discharge of spring floods:

- creation of software base of output data: basic and operational (annual) hydrometeorological information;
- calculation of hydrometeorological factors of spring floods;
- preparation of forecast of runoff depths and maximum water discharge (levels) of spring floods;
- determination of availability of forecast values;
- cartographical representation of expected modular coefficients of

runoff depths and maximum water discharge and their availability through drafting of schematic maps using computer means;

- getting from a map of forecast values of maximum modular coefficients k_m and their availabilities P% in any hydrological posts (for center of gravity of catchments);

- evaluation of forecast values with regard to their deviation from observed values.

In case of insufficiency or absence of time series of hydrometeorological observations within rivers' basins in methodology of territorial long-term forecasts of characteristics of spring floods in order to determine them and to generalize them within a territory a cartographical technique is used. This relates to average several years' values of maximum water reserves in snow cover S_0, mm (Figure 1.6) and maximum depths of soil freezing, L_0, cm (Figure 1.7). Similar maps may be drafted every year during preparation of operative forecast of rivers' spring floods.

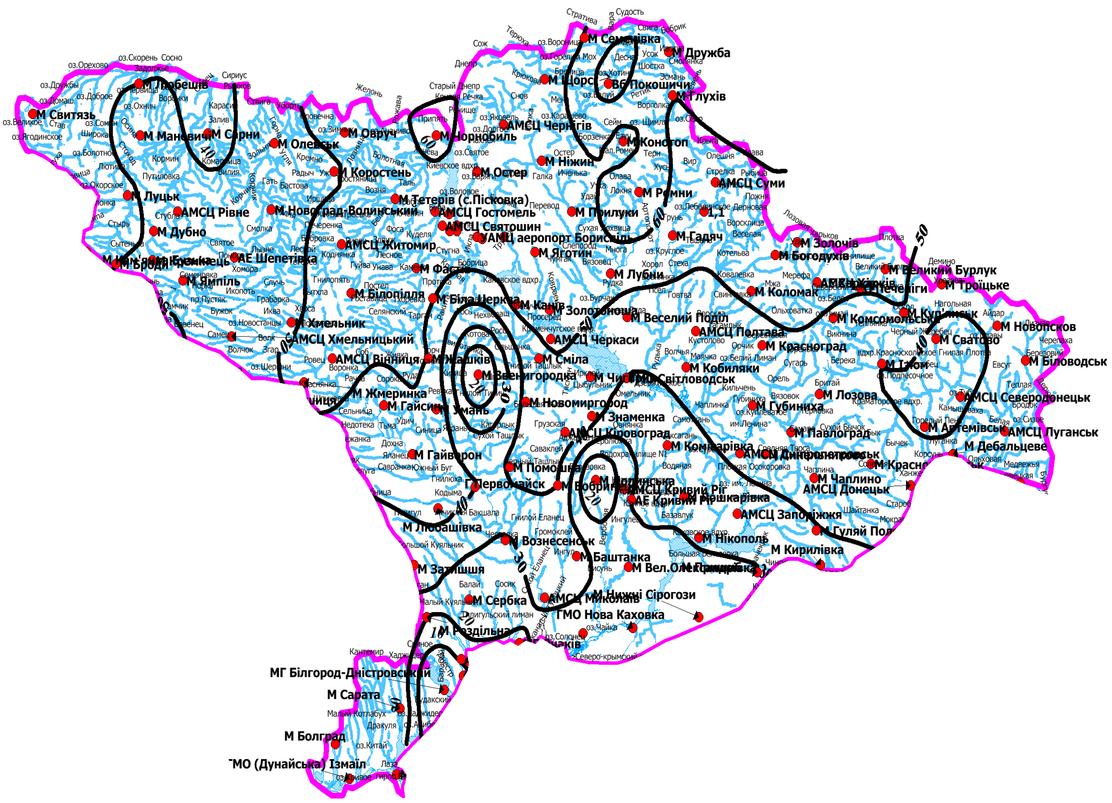

Figure 1.6 – Distribution within the territory of average several years' values of maximum water reserves in snow cover, mm

Figure 1.7 – Distribution within the territory of average several years' values maximum depths of soil freezing, cm

1.4 Cartographical form of representation of forecast values of characteristics of spring floods and their availability

A cartographical form developed through a set of instruments MapInfo appears to be a modern and visual form of forecast values representation. Expected values of maximum water discharge can't be directly represented in the form of schematic maps because there is dependence of both maximum water discharge and their modules from size of rivers' catchments.

That is why, in mathematical model of territorial long-term forecasts of hydrological characteristics of spring floods within rivers, it is proposed to evaluate volumes of expected floods every year on the basis of schematic maps drafted for relative values – modular coefficients of spring floods (runoff depths or maximum water discharge k_m). Such form of representation of forecast values appears to be especially useful for the rivers that remain uninvestigated in hydrological terms.

If a forecast modular coefficient k_m<1, then maximum discharge (runoff depths) of flood will be less than a standard value, but if k_m>1, then flood exceeding a standard value is expected, and if k_m falls within the limits of one then flood will be close to a standard value.

There is another type of representation of forecasting information. It is a schematic map of probability of exceeding forecast values (runoff depths or maximum water discharge of spring floods) within several years' period (*P* %) at any part of the territory, regardless of the condition of its hydrometeorological examination.

During annual preparation of schematic maps forecasting modular coefficients k_m and their availabilities within several years' period *P*% relate to geometrical centres of catchments and are generalized in the form of isolines. For instance, at *P*=10% - expected periods of floods' occurrence will be observed once in every 10 years, with *P*=1% - once in every 100 years etc.

Examples of such schematic maps during forecasting of maximum water discharge of spring floods are presented at Figure 1.8 and 1.9.

1.5 General principles of evaluation of hydrological long-term forecasts

Evaluation of accuracy of hydrological long-term forecasts is based on the methods of mathematical statistics. For this purpose an impartial and reliable evaluation criterion allowing to compare accuracy of forecasting of any hydrological phenomena, that is tolerate error of forecast (WMO) is to be used.

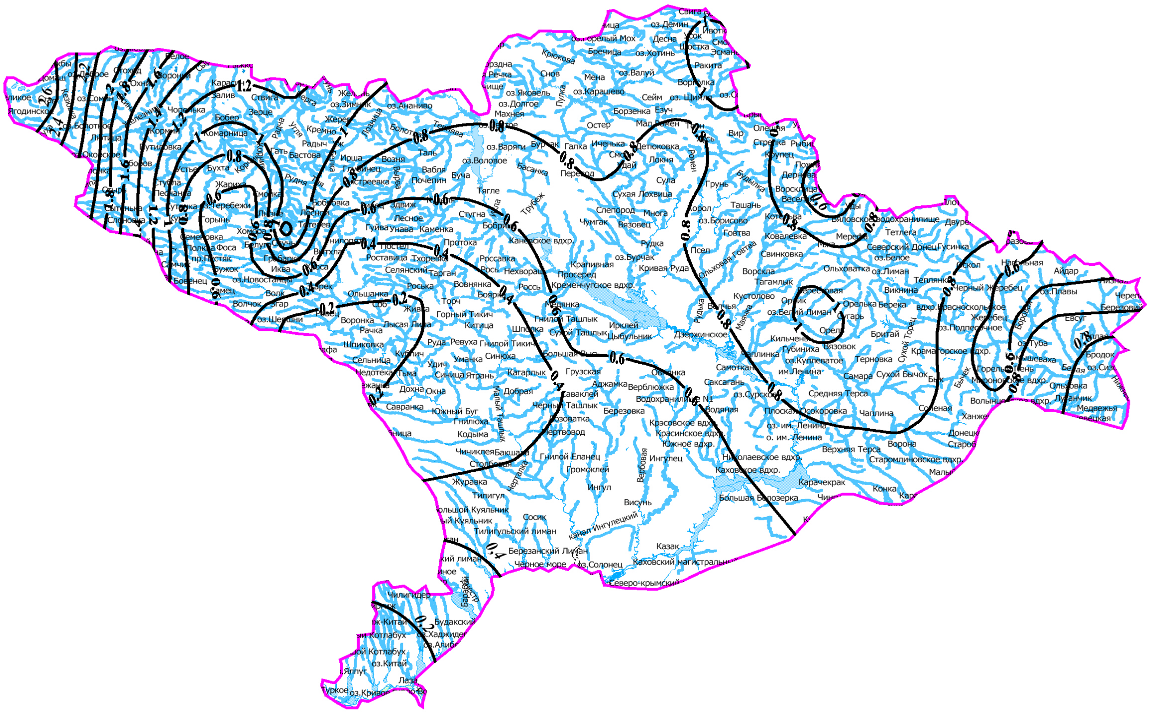

Figure 1.8 – Distribution of forecasting values of maximum modular coefficients of spring floods in 2010 within lowland rivers of Ukraine (as of the date of forecast preparation – 20th of February)

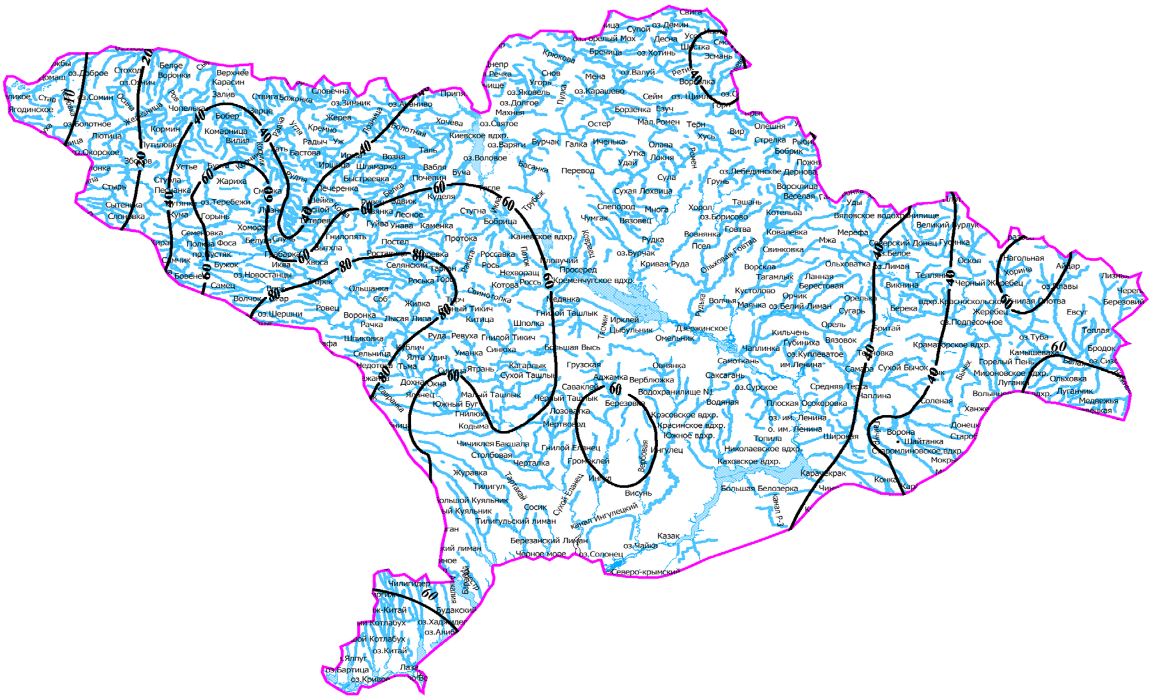

Figure 1.9 – Distribution of availabilities of forecasting values of maximum water discharge of spring floods in 2010 (P_Q%) within lowland rivers of Ukraine (as of the date of forecast preparation – 20th of February)

Tolerate error of forecast is determined depending on natural variability of forecast phenomenon. It is known that average quadratic deviation appears to be a statistical measure of variability of a random value

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}{n-1}}\,, \tag{1.36}$$

where Y_i – value of forecast parameter;

$\overline{Y}$ – average several years' value of forecast parameter;

n – quantity of terms of a series.

Tolerate error of forecast δ_{tol} is a probable deviation of forecast parameter from an average several years' value (rate) of hydrological parameter.

Determination δ_{tol} in case of long-term forecasts of water regime takes place using the formula

$$\delta_{tol} = \pm 0{,}674 \cdot \sigma\,. \tag{1.37}$$

Error of forecast δ is a difference between an actual value of parameter Y_i and an obtained forecast value Y_i'

$$\delta = Y_i - Y_i'\,. \tag{1.38}$$

A forecast is considered to be *accurate* if an absolute error value δ is less or equal to a tolerate one

$$\delta \le \delta_{tol}. \tag{1.39}$$

During evaluation of accuracy of long-term forecasts of runoff depths and maximum water discharge of spring floods for rivers, which have no time series of observations, it is reasonable to use the equations for determination of tolerate error of forecasts as follows:

- for depths of spring runoff depending on a geographical latitude of rivers' catchments (φ^{o} in portions of degrees of latitude north adjusted to grid latitude 50°)

$$\delta_{tol} = 1{,}95(\varphi^{o} - 50) + 18; \tag{1.40}$$

- for maximum water discharge of spring floods depending on sizes of rivers' catchments (A, km²)

$$\delta_{tol} = 0{,}0147 \cdot A. \tag{1.41}$$

1.6 Method of forecasting of dates of commencement and dates occurrence of maximum water discharge of spring floods

Dates for commencement and occurrence of maximum water discharge of floods within river basins are mainly determined by climatic characteristics of geographical zone and may significantly differ in different catchments depending on their sizes, forestation, marshiness and lake percentage.

Every year dates of spring floods depend on meteorological conditions of spring season. Taking into account changeable weather conditions of winter and spring seasons that are typical for present-day climate these dates may vary significantly – from very early to quite late periods of winter and spring time.

1.6.1 Methodical grounds of forecasts of dates of spring floods commencement

Commencement of spring floods is observed after dates of accumulation of maximum water reserves in snow cover within a catchment, year in year out at different dates. This period is determined by temperature conditions of spring period.

Determination of dates of floods' commencement is performed using the scheme

$$D_{com} = D_{S_m} + t_1, \tag{1.42}$$

where D_{com} – date of spring flood commencement;

D_{S_m} – date of forming of maximum water reserves in snow cover;

t_1 – duration of period from date D_{S_m} to date of flood commencement D_{com}, d.

It was established that there are dependences of duration of water retaining capacity of snow (t_1) from an average decade air temperature for the decade that was the first one after D_{S_m} (θ_1°C) in the form of

$$t_1 = f(\theta_1^o). \tag{1.43}$$

Dependences $t_1 = f(\theta_1^o)$ have a diminishing character and are described by equations of line

$$t_1 = d_1 - c_1\theta_1^o, \tag{1.44}$$

where d_1 and c_1 – empirical parameters.

Example of such dependence (1.43) is shown at Figure 1.10 for the basin of Desna river – village of Rozlioty.

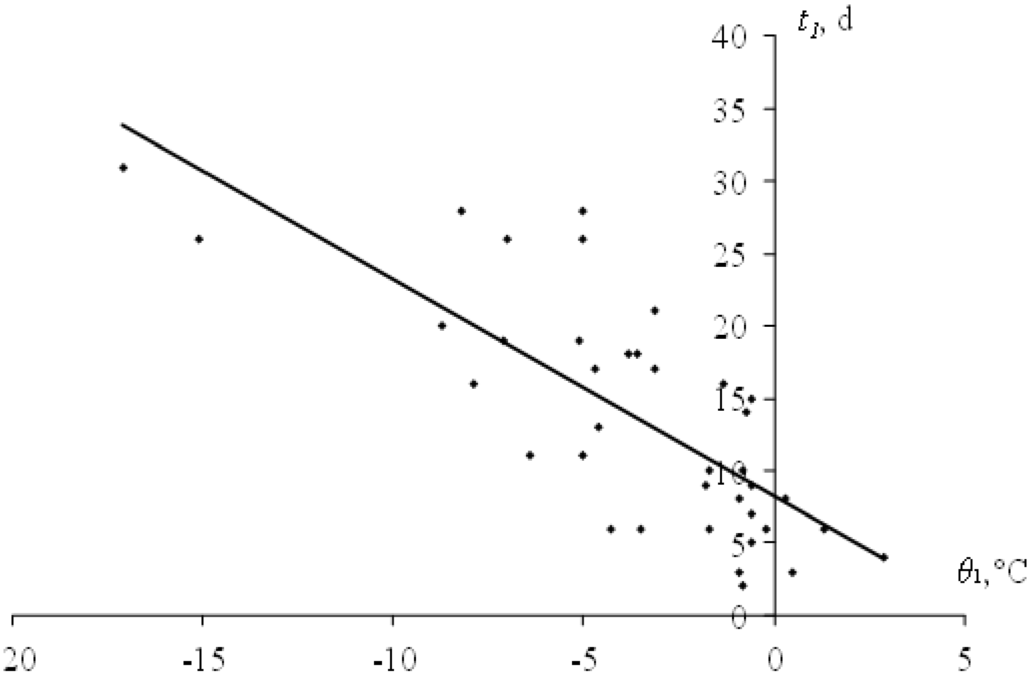

Figure 1.10 – Dependence $t_1 = f(\theta_1)$ for the basin of Desna river – village of Rozlioty, r=0,76 (air temperature recognized at Bryansk meteorological station)

Generalization of parameters d_1 and c_1 was performed via establishment of dependences of these parameters from geographical latitude of centres of catchments (φ, in parts of degrees of latitude north), adjusted to grid latitude (for example, φ=50° of latitude north), that means

$$d_1 = 0,43(\varphi^o - 50) + 7,72 \tag{1.45}$$

and

$$c_1 = 0{,}16(\varphi^o - 50) + 1{,}64\,. \qquad (1.46)$$

Therefore, according to (1.44) the following equation can be used (but only if air temperature θ_1 does not exceed 3,5 - 5,5 ºC)

$$t_1 = [0{,}43(\varphi - 50^o) + 7{,}72] - [0{,}16(\varphi - 50^o) + 1{,}64] \cdot \theta_1 \qquad (1.47)$$

Date of preparation of forecast D'_{com} as per scheme (1.42) corresponds to the date of accumulation of maximum snow reserves (D_{S_m}). Earliness of forecasts for floods commencement is determined by the parameter t_1, and that means it is equal to period from the date of forecast D_{S_m} to the date of flood commencement D_{com}.

An insignificant increase of earliness of forecast is observed with relation to lowland rivers of Ukraine D_{com} (in the form of average several years' values t_{1_0}) from North-West to East

$$t_{1_0} = 0{,}79(\varphi^o - 50) + 12{,}0 \qquad (1.48)$$

but at the average it constitutes 12 days for several years' period.

1.6.2 Methodical grounds of forecasts for dates occurrence of maximum water discharge of spring floods

Dates for occurrence of maximum water discharge of spring floods (D_{Q_m}) with relation to periods of their commencement are determined by intensity of spring melting of snow, amount and intensity of precipitation during the period of snow melting, speed of increase and accumulation of plus air temperatures etc.

Dates for occurrence of maximum water discharge of spring floods are determined as per scheme

$$D_{Q_m} = D_{com} + t_2, \tag{1.49}$$

where D_{Q_m} – date of maximum discharge of water during floods;

D_{com} – date of spring flood commencement;

t_2 – duration of raise of spring floods, this is a period from the date of flood commencement D_{com} till the date of maximum water discharge D_{Q_m}.

It was established that there are dependences of duration of discharge raise (t_2, d) from an average air temperature for the decade that was the first one after D_{com} (θ_2 °C), as follows

$$t_2 = f(\theta_2{}^o). \tag{1.50}$$

Usually dependences $t_2 = f(\theta_2{}^o)$ have a diminishing character during increase of air temperature ($\theta_2{}^o$C) and are described by the following equations

$$t_2 = d_2 - c_2\theta_2{}^o, \tag{1.51}$$

where d_2 and c_2 – parameters of equation.

Example of such dependence (1.50) is shown at Figure 1.11 for the basin of Desna river – village of Rozlioty.

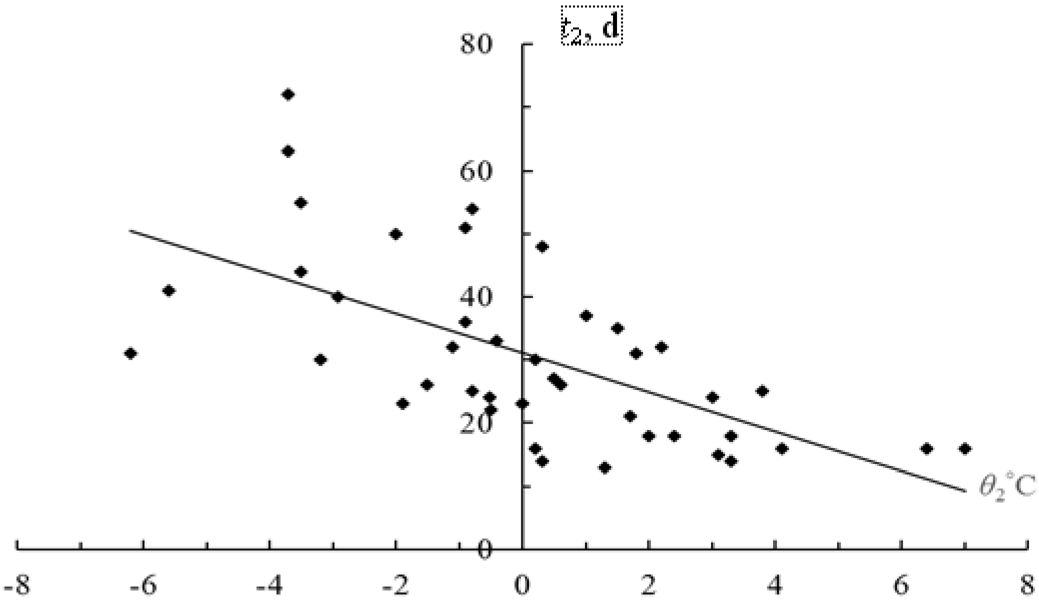

Figure 1.11 – Dependence $t_2 = f(\theta_2)$ for the basin of Desna river – village of Rozlioty, r=0,63 (air temperature was recognized at Bryansk meteorological station)

Territorial generalization of parameter d_2 was performed on the basis of establishment of its dependence on areas of rivers' catchments A (at r=0,6)

$$d_2 = 3{,}45 \cdot \exp[0{,}42 \cdot \lg(A+1)], \tag{1.52}$$

c_2 – depending on geographical latitude of centres of catchments φ, in parts of °, (at r =0,22)

$$c_2 = 1{,}75 - 0{,}12(\varphi^o - 50). \tag{1.53}$$

According to (1.51), in order to determine duration of period of flood raise t_2 the following expression was obtained (but only if air temperature is not more θ_2 than 8,0-10,0 °C)

$$t_2 = \{3{,}45 \cdot \exp[0{,}42 \cdot \lg(A+1)]\} - [1{,}75 - 0{,}12(\varphi^o - 50)] \cdot \theta_2 \ . \tag{1.54}$$

Date of forecast preparation D_{Q_m} as per scheme (1.49) is possible on actual observation date of commencement of flood (D_{com}) or on this forecast date.

Earliness of forecasts for dates of occurrence of maximum water discharge of spring floods is determined by duration of raise t_n. It was established that earliness of forecasts D_{Q_m} within basins of lowland rivers of Ukraine (at average several years' values t_{2_0}) increases together with increase of areas of catchments, since

$$(t_2)_0 = 4{,}96 \cdot \exp[0{,}32 \cdot \lg(A+1)], \tag{1.55}$$

but at the average it constitutes 15 days for range of areas of the catchments in question.

1.6.3 Establishment of availability of forecast dates for flood

Method of territorial forecasting of dates of spring flood (commencement and occurrence of maximum water discharge or levels) enables us to determine repeatedness of these dates within several years' period.

In case of availability of several years' series of observations determination of dates' availability is performed via drafting of empirical curves of availabilities of these dates (in the form of quantity of days from 31st January till the date of phenomenon occurrence) – Figure 1.12 and 1.13. Determination of probability is performed as per forecast date of flood commencement or maximum water discharge according to such curves.

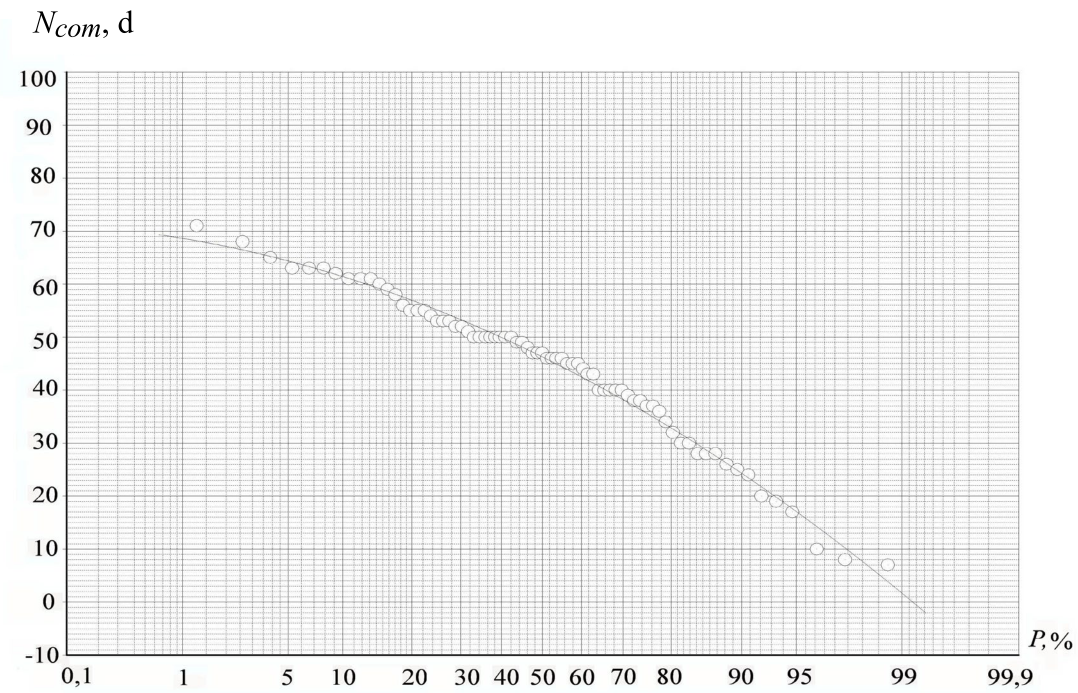

Figure 1.12 – Curve of availability of dates of spring flood commencement (in the form of quantity of days from 31st January) for Desna river – village of Rozlioty

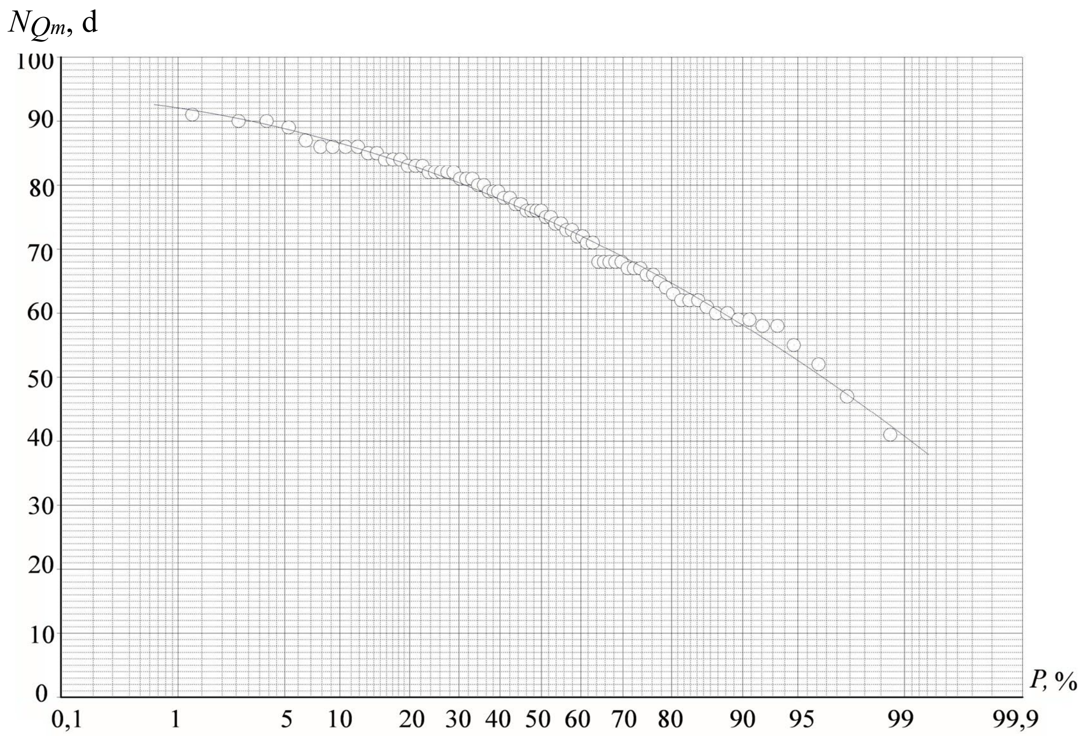

Figure 1.13 – Curve of availability of dates for occurrence of maximum water discharge (in the form of quantity of days from 31st January) for Desna river – village of Rozlioty

1.6.4 Form of representation of dates' forecasts

The form of representation of dates' forecasts as deviations of expected periods (anomalies) from average several years' dates appears to be the most widespread in hydrological practice during forecasting of periods of hydrological phenomena.

But, in terms of territorial forecasting, there is no doubt that the most demonstrative form of spatial representation for forecasting of spring floods' dates consists in use of maps of dates' territorial change.

Drafting of maps of dates of commencement and occurrence of maximum water discharge of floods is performed as of the dates of forecasting as follows: expected dates D_{com} belong to geometrical centres of gravity of catchments and draw isolines of dates' territorial change (Figure 1.14).

Forecast dates of occurrence of maximum water discharge D_{Q_m} can't be mapped because of their dependence on sizes of rivers' catchments. They are determined from (1.49) as of the date of flood commencement and as per duration of flood raise t_2.

Besides, together with maps of forecast dates of spring floods commencement a map of probability of expected dates within several years' period (P %) is also provided (Figure 1.15). This enables us to determine frequency of repeatedness of dates of commencement and occurrence of maximum water discharge (levels) of spring floods at any part of the territory, regardless of the condition of its hydrometeorological examination. For instance, at P=20% - expected periods of floods' occurrence will be observed once in every 5 years, at P=1% - once in every 100 years etc.

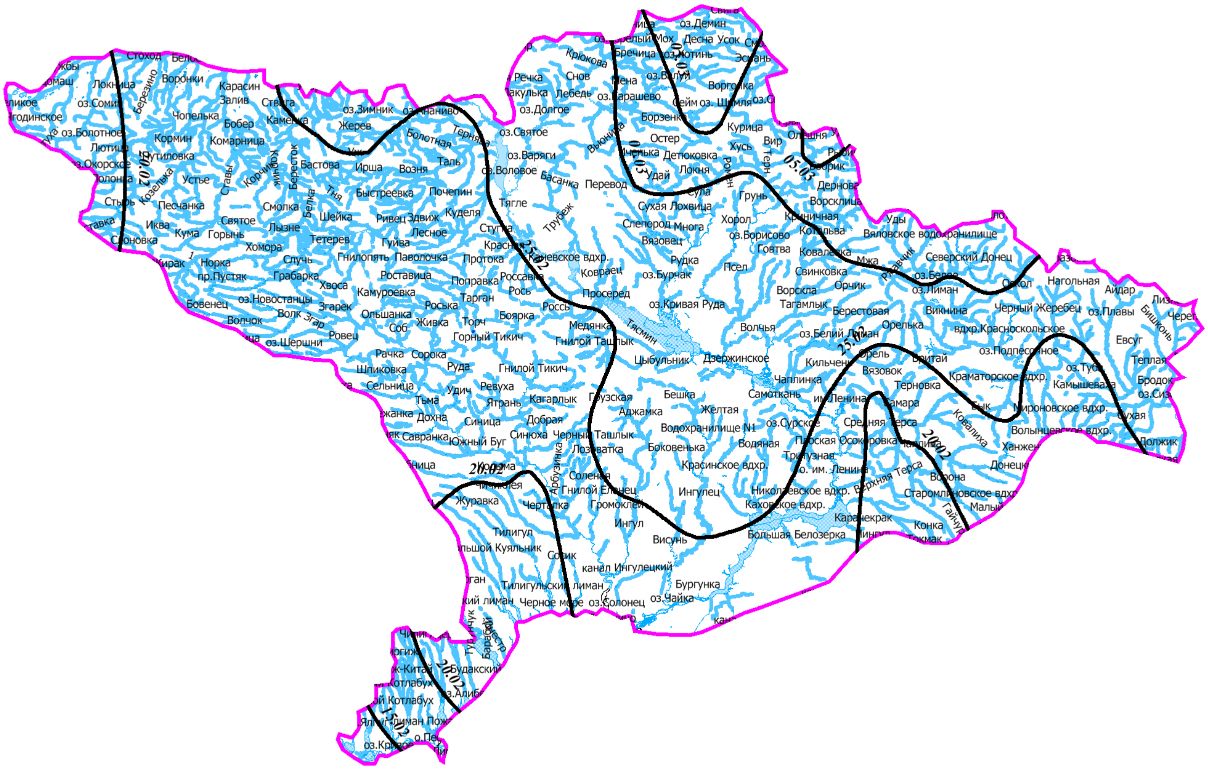

Figure 1.14 – Distribution of forecast dates of spring flood commencement in 2010 within lowland rivers of Ukraine

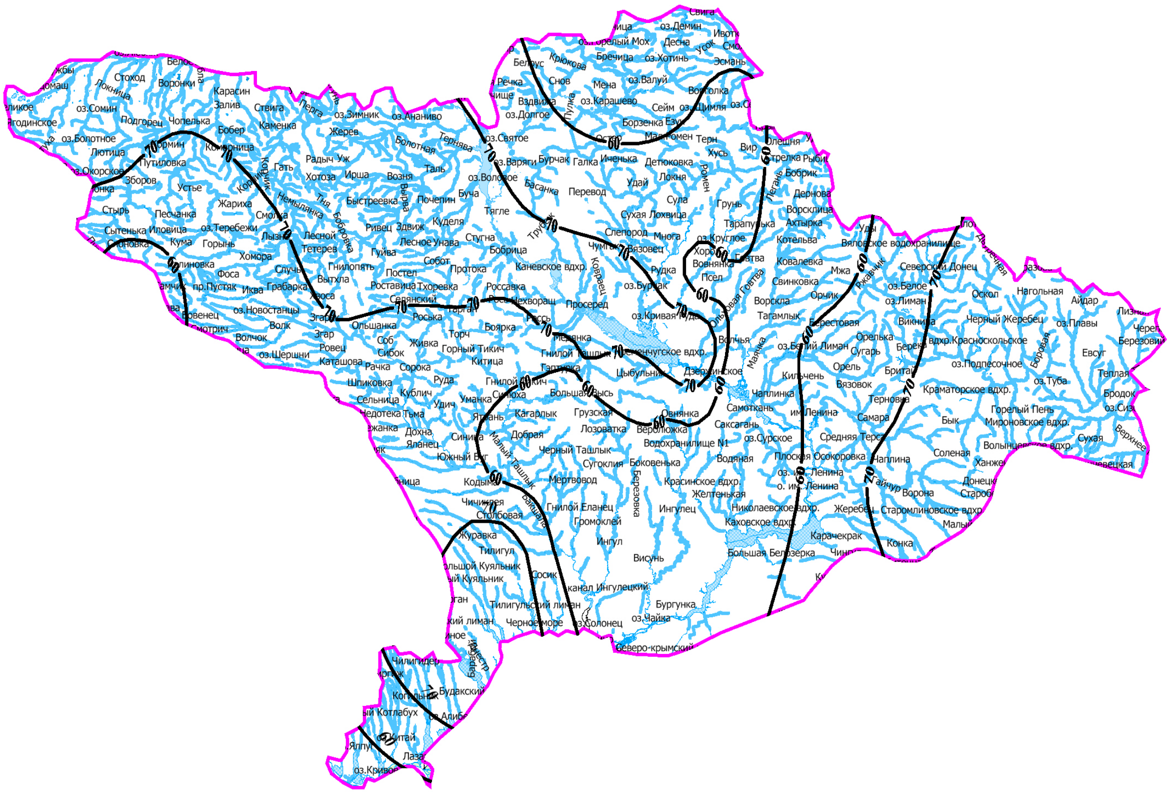

Figure 1.15 – Distribution of availabilities of forecast dates of spring flood commencement in 2010 within lowland rivers of Ukraine (*P*%)

1.6.5 Evaluation of forecasts for dates of occurrence of spring floods

Tolerate error in case of short-term forecasts for dates of occurrence of spring processes is determined depending on their earliness (table 1.3).

Table 1.3 – Value of tolerate error for dates' forecasts

Earliness of forecasts, d	1-3	4-5	6-9	10-13	14-15
Tolerate error of forecasts δ_{tol}, d	1	2	3	4	5

Evaluation of operative forecasts for dates of commencement (D'_{com}) and maximum water discharge (levels) (D'_{Q_m}) in current year is performed via calculation of error of forecast (δ, d) with reference to observation dates, as follows

$$\delta D'_{com} = D_{com} - D'_{com}, \tag{1.56}$$

$$\delta D'_{Q_m} = D_{Q_m} - D'_{Q_m}. \tag{1.57}$$

A forecast is considered to be accurate if $\delta D'_{com}$ or $\delta D'_{Q_m}$ is less or equal to tolerate δ_{tol}. Since forecast of dates of commencement and occurrence of maximum water discharge is prepared on the basis of meteorological forecast then tolerate error for forecasts of dates δ_{tol} constitutes a half of earliness of meteorological forecast in spring and is equal to 3 days.

Exercises and questions for self-checking

1. What dependence serves as a methodical ground of territorial long-term forecasting for runoff depths and maximum water discharge of spring floods in lowland rivers?
2. How to determine the type of hydraulicity in spring using long-term forecast of characteristics of spring floods for lowland rivers?
3. What is the way of determining a total amount of water forming spring floods at lowland catchment areas?
4. What parameter of soil humidity is used in vector-predictor of discriminative function?
5. How to establish availability of forecasting values of spring floods characteristics?
6. What of the following forms of representation of expected spring floods characteristics is included in the method of territorial long-term forecasts?
7. How to determine a forecasting value of runoff depth or maximum water discharge of lowland river using schematic maps of distribution of their forecasting modular coefficients?
8. What source data serve as a basis for preparation of background forecast for dates of occurrence of spring floods within lowland rivers?
9. What forms is used for representation of expected dates of spring floods commencement and dates of occurrence of maximum water discharge (levels) during spring floods?

Literature for Section I

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SECTION II
ENGINEER SUBSTANTIATION OF ESTIMATED CHARACTERISTICS OF MAXIMUM RIVERS' RUNOFF DURING FLOODS (RAIN AND SNOWMELT ORIGINS)

Plan of lecture

Introduction.

2.1 Mathematical models of maximum runoff for rating of estimated characteristics of rivers' maximum surface runoff.

2.2 Methods recommended by regulatory documents for determination of maximum rivers' runoff (SNiP 2.01.14-83, DBN-2015).

2.3 Operational models of forming of surface runoff for rating of estimated characteristics of floods and overflows Regional.

2.4 Regional methods for determination of maximum runoff of Ukrainian rivers.

Introduction

Maximum runoff of rivers is associated with high-water phases of their hydrological regime i.e. it is observed during spring floods and rainfall floods. Schematically the forming of runoff may be represented as a dual-operational system "atmospheric precipitation – slope inflow – channel runoff" (Figure 2.1).

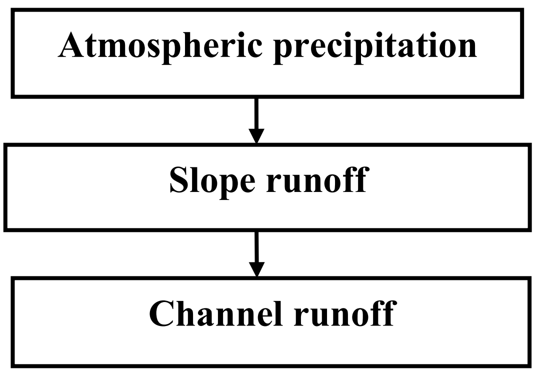


Figure 2.1 – Principal scheme of river runoff formation

Spring floods in Ukraine are stipulated by melting of season snow whereas rainfall floods are formed under the influence of rainfall precipitation. A general condition for forming of both spring and rainfall floods consists in inequality $a_t > i_t$, where a_t stands for intensity of water yield from snow (during spring floods) or rainfall precipitation (during rainfall floods), i_t – for intensity of precipitation (water yield from snow) absorption by underlying surface. Processes of snow melting are accompanied by temporary impediment of meltwater in snow cover and the time of such impediment depends on density and water retaining capacity of snow. Intensity of rainfall precipitation absorption is mainly determined by porosity of soil and its humidity. Apart from general features of slope runoff forming at the top of catchment areas there are also significant differences. In particular, meltwater absorption highly depends on soil freezing. Rainfall precipitation, before coming to underlying surface, is impeded by different layers of vegetation (wood, grass).

Research works of different authors reveal that interception does not have an essential role in formation of significant floods. From physical standpoint interception process lies in the fact that the first portions of rainfall precipitation are almost completely intercepted by leaves of vegetation in the form of separate drops or thin film. Significant part of water spray formed after drops hit the leaves just evaporates and therefore does not reach the surface of catchment areas. After complete wetting of vegetation cover rainfall precipitation reaching slopes' surface virtually is equal to the amount of precipitation, apart from the portion that evaporated from vegetation cover. Interception processes depend significantly on the wind. On the one hand the wind reduces the volume of intercepted moisture and on the other hand evaporation becomes more intense. Speaking about evaporation from the surface of wetted leaves it should be noted that it happens much more slowly than the one in clear weather. This is basically related to significantly higher relative air humidity during rainfalls.

Vegetation cover depends largely on the type of its plants. For instance, some plants intercept precipitation in the form of thin film whereas other ones intercept moisture in the form of drops. Season variations of interception are basically determined by change of foliage area.

But, when dealing with formation of rainfall floods of rare probability, excess of precipitation loss due to its interception by vegetation cover layers may be still neglected.

It should be also noted that runoff formation on slopes, apart from interception of some portion of precipitation, depends also on accumulation within depressions that are widely met throughout slopes, especially if they are used for commercial purposes. Therefore, slope runoff appears once numerous depressions are filled to their full capacity. Once rainfalls end the moisture accumulated in such depressions vanishes due to evaporation and infiltration processes. The capacity of surface detention is proportional to slopes' inclination – larger inclination causes less detention.

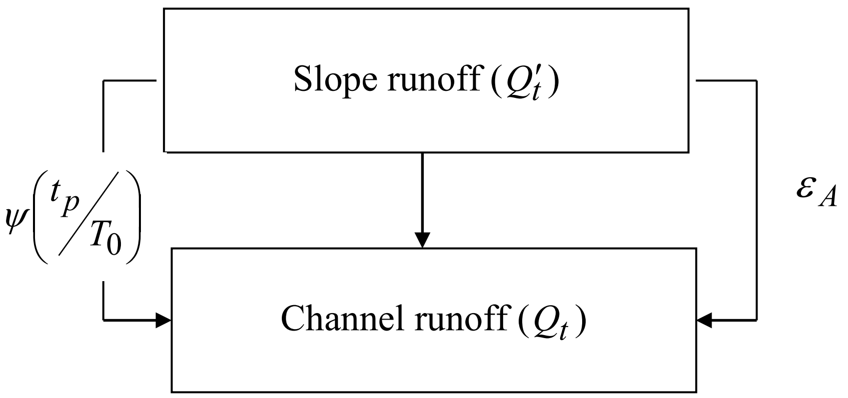
Ploughing of surface of catchment areas contributes to collapsing of natural depressions but at the same time it causes soil heaping and formation of new capacities for rainfalls' surface accumulation.

2.1 Mathematical models of maximum runoff for rating of estimated characteristics of rivers' maximum surface runoff

2.1.1 Formation of rivers' maximum runoff

Figure 2.1 demonstrates us the fact that research of rivers' maximum runoff comes down to resolution of the issues of slope inflow transformation by channel network within the operational system "slope runoff – channel runoff". Slope runoff is represented in the form of the arbitrary function t. Transfer of water in channel network is subject to hydraulic regularities. This is where slope runoff transformation during channel lag of flood and surface waves and at the expense of effects of channel and flood plain regulation is about to take place. Schematically the operator "slope runoff – channel runoff" is shown on Figure 2.2.

Transformation function $\psi\left(t_p \big/ T_0\right)$ is mainly determined by durations of channel lag $t_p = L/V_d$ and water inflow from slopes to channel network T_0. Therefore channel lag speed has an essential role in spreading of flood and surface waves V_d. It's no coincidence most of maximum runoff formulas, both calculation and forecasting ones, have the channel lag speed as their component.



$\psi\left(t_p \big/ T_0\right)$ - spreading operator influenced by channel lag;

ε_A - function of channel and flood plain regulation

Figure 2.2 – Principal scheme of channel runoff formation

Transfer of flood waves along the length of rivers has a complicated nature due to changes of channel's roughness and shape along river stations and due to the fact that waves do not appear instantly but are resulted from increase of water flows at particular sections of channels. At confluences of large tributaries transfer of flood waves gets even more complicated because of increased spreading of stream resulted from concentrated water supply. Taking into account the complexity of river network structure and the nature of lateral inflow, resolution of problems of river streams' unsteady transfer through theoretical equations appears to be near-impossible. Availability if simultaneous observations over runoff regime at several stations along the length a river would ensure generation of data on speeds of channel lag. But one should use data of relevant water flows (levels) with due diligence since delay of maximum value at the lower station does not always express the lag of flood wave. According to research of A.N. Befani (1958) application of the method of relevant levels for determination of lag time is allowed only at the areas with later inflow not exceeding 50% of transit water flow. Therefore researchers have only limited data on speeds of channel lag at their disposal. That is why hydrological literature sources have a great variety of empirical dependences based on actual data on stream velocity during flooding and overflowing with main factors taken into consideration.

2.1.2 Principal scheme of river runoff formation

There are physical and geographical, meteorological factors and hydromorphological characteristics of hydrographic network interacting during formation of river runoff. Meteorological factors determine moisture supply (in the form of rainfalls and warm water) to the surface of catchment areas. The latter are transformed in slope runoff under the influence of interception, wetting of vegetation cover and accumulation within microdepressions. Later on water keeps coming from slopes to a channel network where it is transformed into a channel runoff under the influence of channel lag and effects of channel and flood plain regulation and accumulation. Therefore, formation of rainfall floods and spring floods is a process of summation within the bounds of catchment areas of elementary volumes of slope inflow coming from different parts of such catchment areas. Such formation scheme is usually represented in the form of river system marked with isochrones of channel lag.

Isochrones are the lines of the same time of lag from them to an outlet station. There are different time intervals: a day, an hour and other periods. Figure 2.3 shows an example of such system. Water lag from the remotest point of a catchment area is called channel lag duration or channel lag time t_p. Channel lag duration is a ratio of a river's hydrographic length L to a speed of channel lag V_d. If a speed of channel lag does not change in time and along a river's length channel lag isochrones are transformed into a stationary system of lines with equal distances.

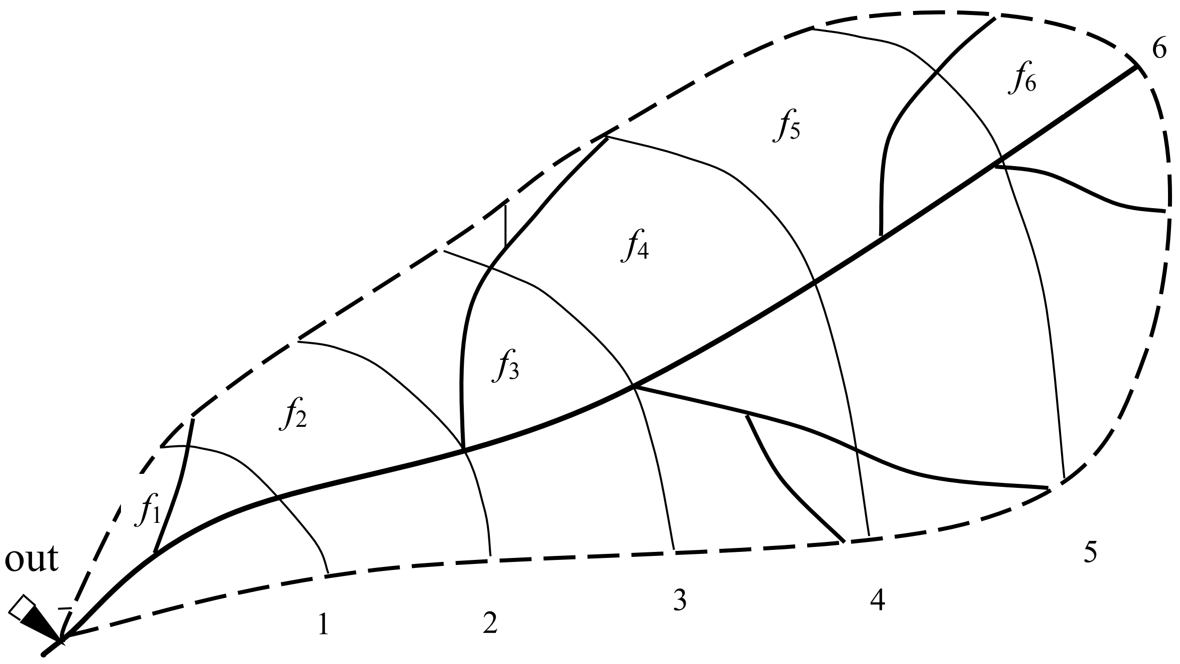


Figure 2.3 – River catchment area with system of channel isochrones

When making a scheme of isochrones let's take a time interval $\Delta t = 1$ day. Duration of flood and overflow waves lag from the remotest isochrone (the sixth one) to the outlet station is equal to $t_p = 6\Delta t$ (days).

Depending on the ratio between slope inflow durations T_0 and channel lag t_p there are two possible variants of channel runoff formation:

1) at $T_0 > t_p$ and 2) at $T_0 < t_p$.

Let's study each of the variants.

Channel runoff formation at the ratio $T_0 > t_p$. According to the scheme of Figure 2.3, $t_p = 6\Delta t$. To make the first condition work let's take, for example, $T_0 = 8 \cdot \Delta t$. Hydrograph of slope inflow (in modules) is represented on Figure 2.4.

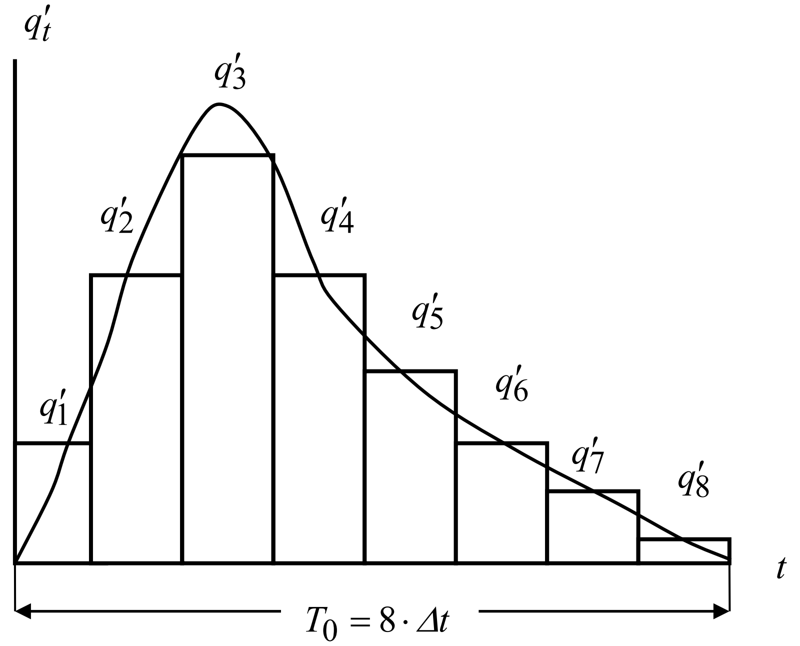


Figure 2.4 – Hydrograph of slope water inflow to channel network

Let's split it down in time into 8 parts, each of them features a time period at absciss axis Δt. Then comes averaging within Δt all ordinates of the hydrograph of slope inflow which is converted, via such procedure, from a continuous function q'_t to a discrete diagram of time distribution of inflow modules.

When taking discrete time period Δt it is understood that slope inflow q'_t enters a channel network at the beginning of an estimated unit and transfer of water volume from each inter-isochrone area takes place in the end of such unit.

For instance, at the beginning of the first estimated unit of time the whole catchment area accepts water inflow from slopes with the intensity of q'_1. In the end of the first estimated unit a transfer of inter-isochrone volumes by one isochrone would take place throughout all channels. The following water flow would pass through an outlet station

$$Q_1 = f_1 q'_1, \tag{2.1}$$

if there would be no channel and flood plain regulation within each of inter-isochrone sites. This may be characterized through the time function $\varepsilon_t \le 1{,}0$. Since channel and flood plain processes happen depending on a quantity of inter-isochrone sites ε_t would coincide in time with $t_p\,\Delta t$ and ordinates: ε_1, $\varepsilon_2, \ldots, \varepsilon_{t=t_p}$. Therefore, taking into account the effects of channel and flood plain regulation water flow Q_1 determined as per (2.1) would be overrated (1-ε_i). So at the end of the first estimated unit of time

$$Q_1 = f_1 q'_1 \varepsilon_1. \tag{2.2}$$

It should be noted that there is a relevant transfer from one site to another throughout all of above-stated parts of catchment taking place at the end of the first unit.

At the beginning of the second estimated unit catchment accepts the inflow with intensity of q'_2 with channel and flood plain regulation having the ε_2 coefficients, whereas at the end of this unit water flow constitutes

$$Q_2 = f_1 q'_2 \varepsilon_1 + f_2 q'_1 \varepsilon_2. \tag{2.3}$$

Similarly the third one and further estimated units will be as follows

$$Q_3 = f_1 q'_3 \varepsilon_1 + f_2 q'_2 \varepsilon_2 + f_3 q'_1 \varepsilon_3 ; \qquad (2.4)$$

$$Q_4 = f_1 q'_4 \varepsilon_1 + f_2 q'_3 \varepsilon_2 + f_3 q'_2 \varepsilon_3 + f_4 q'_1 \varepsilon_4 ; \qquad (2.5)$$

$$Q_5 = f_1 q'_5 \varepsilon_1 + f_2 q'_4 \varepsilon_2 + f_3 q'_3 \varepsilon_3 + f_4 q'_2 \varepsilon_4 + f_5 q'_1 \varepsilon_5 ; \qquad (2.6)$$

$$Q_6 = f_1 q'_6 \varepsilon_1 + f_2 q'_5 \varepsilon_2 + f_3 q'_4 \varepsilon_3 + f_4 q'_3 \varepsilon_4 + f_5 q'_2 \varepsilon_5 + f_6 q'_1 \varepsilon_6 . \qquad (2.7)$$

When comparing t_p and T_0 it appears obvious that at the sixth unit of time the water from watershed (the remotest isochrone of the basin) entered the outlet station through the channel. That is why water flows at the seventh unit of time, including the eight one, would be formed at the outlet gate as per the scheme

$$Q_7 = f_1 q'_7 \varepsilon_1 + f_2 q'_6 \varepsilon_2 + f_3 q'_5 \varepsilon_3 + f_4 q'_4 \varepsilon_4 + f_5 q'_3 \varepsilon_5 + f_6 q'_2 \varepsilon_6 ; \qquad (2.8)$$

$$Q_8 = f_1 q'_8 \varepsilon_1 + f_2 q'_7 \varepsilon_2 + f_3 q'_6 \varepsilon_3 + f_4 q'_5 \varepsilon_4 + f_5 q'_4 \varepsilon_5 + f_6 q'_3 \varepsilon_6 . \qquad (2.9)$$

At the beginning of the ninth unit of time water inflow from slopes to the channel network stops its movement, that is why decrease of water flow at the outlet gate takes place as per the scheme

$$Q_9 = f_2 q'_8 \varepsilon_2 + f_3 q'_7 \varepsilon 3_7 + f_4 q'_6 \varepsilon 4 + f_5 q'_5 \varepsilon_5 + f_6 q'_4 \varepsilon_6 ; \qquad (2.10)$$

$$Q_{10} = f_3 q'_8 \varepsilon_3 + f_4 q'_7 \varepsilon_4 + f_5 q'_6 \varepsilon_5 + f_6 q'_5 \varepsilon_6 ; \qquad (2.11)$$

$$Q_{11} = f_4 q'_8 \varepsilon_4 + f_5 q'_7 \varepsilon_5 + f_6 q'_6 \varepsilon_6; \tag{2.12}$$

$$Q_{12} = f_5 q'_8 \varepsilon_{58} + f_6 q'_7 \varepsilon_6; \tag{2.13}$$

$$Q_{13} = f_6 q'_8 \varepsilon_6; \tag{2.14}$$

$$Q_{14} = 0. \tag{2.15}$$

Thus, on the basis of obtained data, it is necessary to determine important characteristics of channel runoff such as: duration of flood (spring flood), time of maximum water flow and its value. It is obvious that duration of flood (spring flood) T_f is equal to

$$T_f = T_0 + t_p, \tag{2.16}$$

where

$$T_0 = T + t_{slope}, \tag{2.17}$$

$$t_{slope} = \frac{\ell_{slope}}{V_{slope}}. \tag{2.18}$$

But in fact T_{flood} would be a bit higher value at the expense of water reserves accumulated in flood plains, alluvions and banks, that is why

$$T_{flood} = T_0 + t_p + \Delta t_3, \tag{2.19}$$

where Δt_3 is a time required for response of channel and flood plain water reserves which are available during lag of flood (overflow) waves from a watershed to an outlet gate.

Regarding maximum ordinate of channel runoff it can be quite easily determined if functions f_t, q'_t and ε_t are known.

Unfortunately only two of three functions may be retrieved. They are: f_t (requires making charts of isochrones or equidistants) and q'_t (requires conduction of observations of slope runoff at runoff and water-balance stations). There are no data on channel and flood plain processes and therefore no information about concrete appearance of the function ε_t is available. But, after studying the equation of ordinates (2.3 – 2.15) of the channel hydrograph, one can expect that Q_m would be observed at the sixth, seventh and eighth units of time since equations Q_t (2.7 – 2.9) have the highest number of components. Besides, these ordinates are formed by the entire basin, not by the entire inflow which is a part of the first (for duration t_p). Graphically this thesis may be demonstrated through averaging of ordinates of curve isochrones ($f_t = f$) and flood plain regulation ($\varepsilon_t = \varepsilon$). In such case the following equation is applied:

$$Q_m = f \cdot \varepsilon \left(\sum_{t_p} q'_t \right)_m . \tag{2.20}$$

On the basis of such assumptions it is quite easy to give an objective evaluation of Q_m and the time of its emergence after drafting relevant hydrographs of slope and channel runoff (Figure 2.5)

Figure 2.5 shows us that at the symmetric hydrograph of slope inflow maximum module (water flow) is observed with some delay at terms of time with respect to duration of slope runoff rise because

$$t_{n_p} = t_{n_{slope}} + \frac{1}{2} \cdot t_p . \qquad (2.21)$$

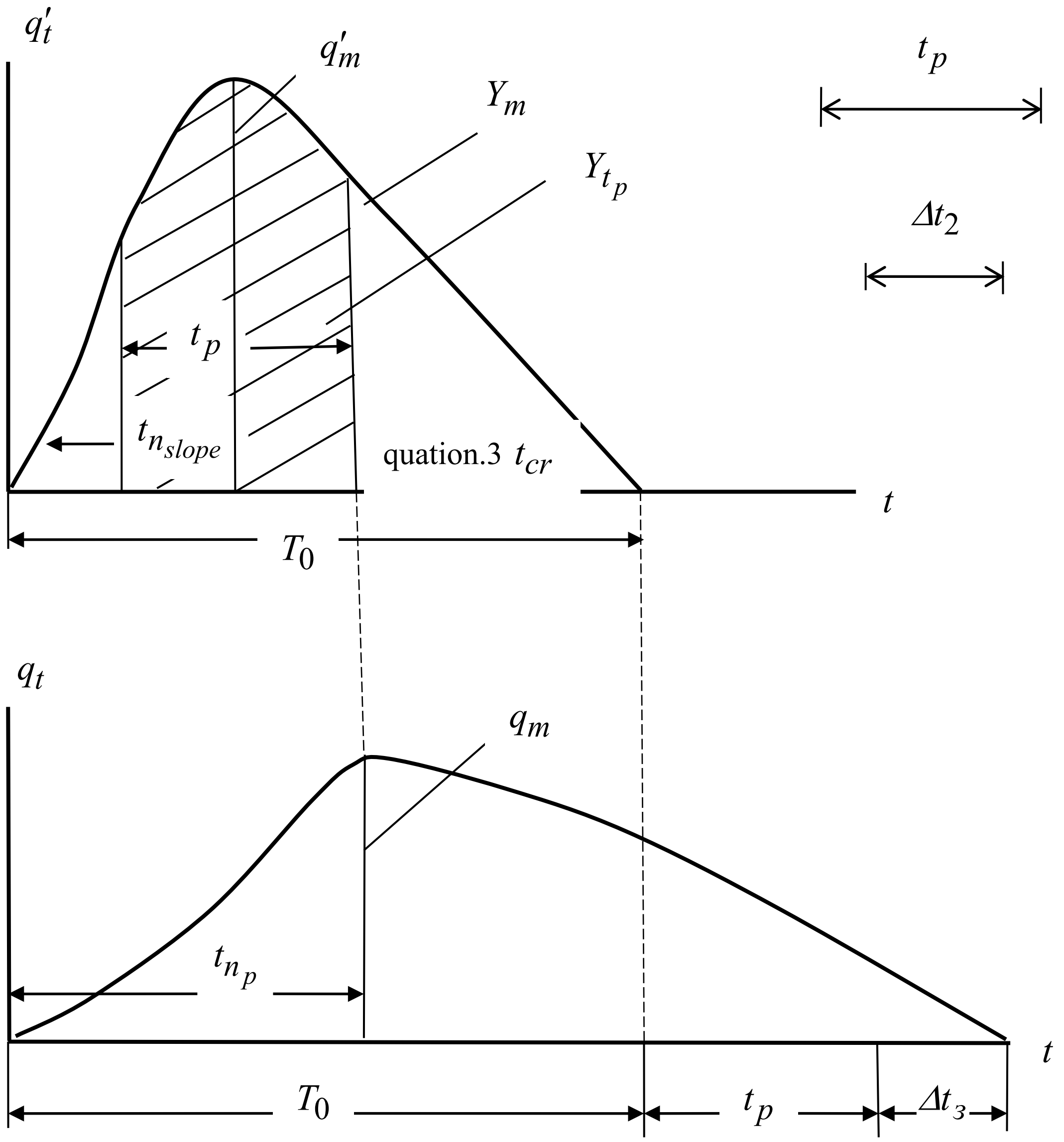


Figure 2.5 – Principal scheme of slope inflow transformation into channel slope (if $T_0 > t_p$)

In general cases the time of maximum water flow of channel runoff t_{cr} comes only when inflow layer t_p within the interval Y_{t_p} at the slope hydrograph

$$\left(\sum_{t_p} q'_t \right) = Y_{t_p} \tag{2.22}$$

would have the highest value. If we take (2.22) in our account

$$Q_m = f \cdot \varepsilon \cdot Y_{t_p}, \tag{2.23}$$

where Y_{t_p} is a current layer of slope runoff taking part in formation of maximum water flow if $t_p < T_0$.

Figure 2.5 also shows that $q'_m > q_m$. This is because the runoff layers of both slope and channel hydrographs are the same (are equal to Y_m), and durations are different, in particular $T_n > T_0$.

Therefore spreading of flood and overflow waves at the expense of duration of channel lag and the effects of channel and flood plain regulation of rivers' maximum runoff serves as the main factor of slope inflow transformation.

Formation of river runoff at the ratio $t_p > T_0$. Let's use the model of catchment area with isochrones of channel lag specified on Figure 2.5 as an initial one, i.e. $t_p = 6\Delta t$. To make the condition $t_p > T_0$ work let's take, for instance, slope inflow duration as $t_p = 4\Delta t$ (Figure 2.6).

Let's note down the system of equations for describing the channel runoff hydrograph at $t_p = 4\Delta t$ and $t_p = 6\Delta t$ in the same sequence discussed earlier:

$$Q_1 = f_1 q'_1 \varepsilon_1; \tag{2.24}$$

$$Q_2 = f_1 q'_2 \varepsilon_1 + f_2 q'_1 \varepsilon_2; \tag{2.25}$$

$$Q_3 = f_1 q'_3 \varepsilon_1 + f_2 q'_2 \varepsilon_2 + f_3 q'_1 \varepsilon_3; \tag{2.26}$$

$$Q_4 = f_1 q'_4 \varepsilon_1 + f_2 q'_3 \varepsilon_2 + f_3 q'_2 \varepsilon_3 + f_4 q'_1 \varepsilon_4. \tag{2.27}$$

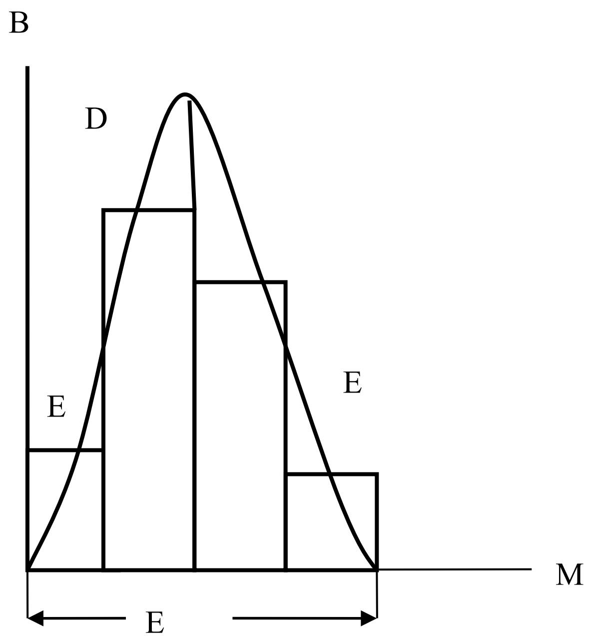


Figure 2.6 – Hydrograph of slope water inflow to channel network

At the fourth unit of time slope inflow stops its movement that is why from now on:

$$Q_5 = f_2 q'_4 \varepsilon_2 + f_3 q'_3 \varepsilon_3 + f_4 q'_2 \varepsilon_4 + f_5 q'_1 \varepsilon_5; \tag{2.28}$$

$$Q_6 = f_3 q'_4 \varepsilon_3 + f_4 q'_3 \varepsilon_4 + f_5 q'_2 \varepsilon_5 + f_6 q'_1 \varepsilon_6. \tag{2.29}$$

The sixth estimated unit is characterized by water lag from a watershed to an outlet station and that is why, starting from the seventh unit, channel runoff begins to decline:

$$Q_7 = f_4 q'_4 \varepsilon_4 + f_5 q'_3 \varepsilon_5 + f_6 q'_2 \varepsilon_6; \tag{2.30}$$

$$Q_8 = f_5 q'_4 \varepsilon_5 + f_6 q'_3 \varepsilon_6; \tag{2.31}$$

$$Q_9 = f_6 q'_4 \varepsilon_6; \tag{2.32}$$

$$Q_{10} = 0. \tag{2.33}$$

Duration of channel runoff, as in the first case, is equal to

$$T_n = T_0 + t_p + \Delta t_3.$$

It is obvious that maximum ordinate of runoff hydrograph Q_m may be expected (in case of averaging in time q'_t and ε_t) at the fourth, fifth or sixth unit of time, that is when

$$Q_m = q' \cdot \varepsilon \left(\sum_{T_0} f_t \right)_m. \tag{2.34}$$

The expression in brackets stands for an area of simultaneous formation of channel runoff (Figure 2.7). The above-stated means that, if there is a condition $t_p > T_0$, the entire slope inflow Y_m takes part in formation of maximum runoff. Such formation does not involve the entire area of catchment but only its particular part which is the highest value ($F_{act} < F$) of the estimated duration of slope inflow T_0, that is

$$F_{act} = \left(\sum_{T_0} f_t \right)_m = B'_{av} V_d \cdot T_0, \tag{2.35}$$

where B'_{av} is an average width of catchment within F_{act}.

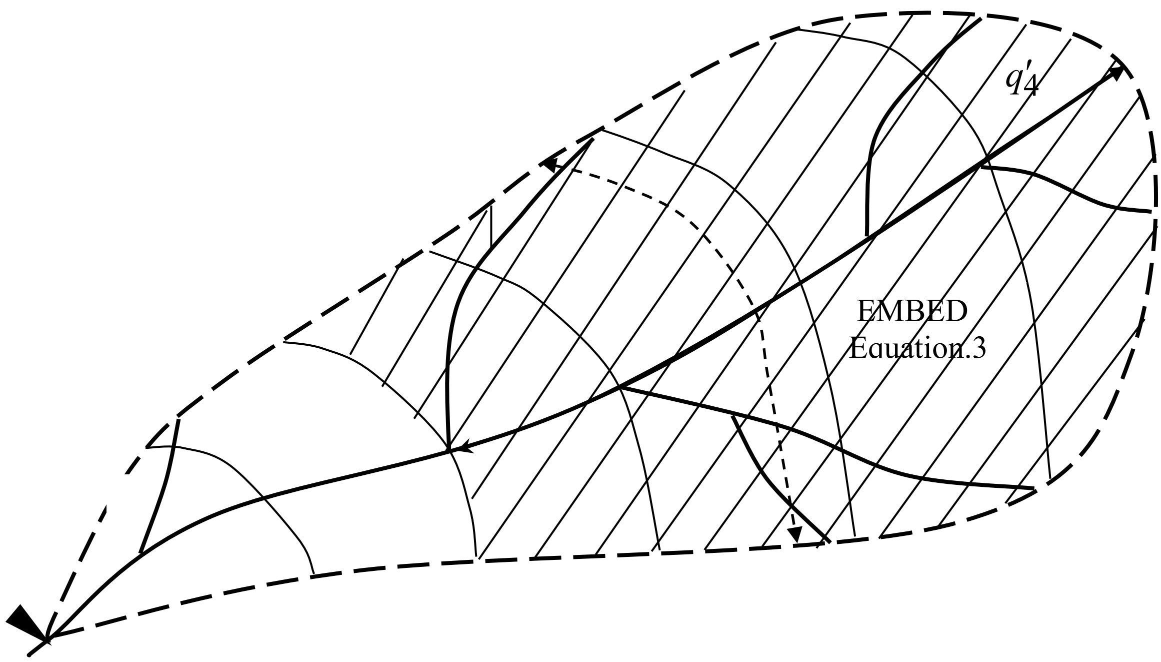


Figure 2.7 – River catchment area with system of channel isochrones

area of simultaneous formation of runoff F_{act}; $L_0 = V_d \cdot T_0$ – length of the territory forming Q_m.

Figure 2.7 demonstrates the scheme of slope inflow transformation into channel hydrograph at $t_p > T_0$.

The image shows that maximum module of channel runoff ($q_m < q'_m$) is observed at the end of channel lag, i.e. $t = T_0$.

We drew your attention only to some basic conditions of formation of flood runoff, including its maximum volume, within the framework of the "slope runoff – channel runoff" operator. Scientific and methodological approaches to substantiation of basic formulas for standardization of rivers' estimated characteristics will be studied below.

2.2 Methods recommended by regulatory documents for determination of maximum rivers' runoff (SNiP 2.01.14-83, DBN-2015)

Regulatory documents contain methods and practical approaches to estimation of basic hydrological characteristics used for construction planning both in case of availability and insufficiency of hydrometric observations of appropriate duration as well as in case of non-availability of observations at points of designing.

Regulatory recommendations usually generalize experience of many years in the sphere of theoretical and practical hydrological computations gained by research institutions and design water economic organizations. Estimation characteristics related to maximum runoff of spring floods and rainfall floods include the following: maximum water flows, runoff volumes and hydrographs.

Provisions of regulatory documents are applicable to designing of river hydrotechnical facilities, railways and motorways, melioration systems, water supply systems, planning and construction of residential areas, general layouts for development of industrial and agricultural objects, implementation of flood mitigation measures.

It was emphasized in previous sections that determination of estimated hydrological characteristics, subject to availability of time series of sufficient duration, is conducted via application of analytical functions of distribution of annual excess probabilities. Periods with relative root-mean-square errors of estimated values up to 10 % are deemed to have a representative character. Insufficiency of data of hydrometeorological observations throughout long-term time series may be resolved through their prolongation using dual and multiple regression. At the same time SNiP 2.01.14-83 recommendations specify the conditions for application of methods of bringing short series' estimated characteristics to standard series' ones, in particular

$$n' \geq 10; \quad r = 0{,}7; \quad k/\sigma_k \geq 2,$$

where n' – number of consistent years of observations at an estimation point or its equivalent;

r – multiplied or dual coefficient of correlation,

k – coefficient of regression;

σ_k – root-mean-square error of coefficient of regression.

It is worthwhile to make another important remark. When speaking about maximum rainfall runoff amplitude of variations of water flows of analogue river should be reflected in parallel observations not less than 70-80 %.

The regulatory document "Guidelines for Determination of Estimated Hydrological characteristics (SN 435-72)" was prepared by the team of researchers of the State Hydrological Institute (Leningrad city). It generalizes experience of many years in the sphere of theoretical and practical hydrological computations of G.A.Alekseyev, A.N. Befani, S.N. Krytskyi, M.F. Menkel, D.L.Sokolovskyi, M.M.Chegodayev. Methods of maximum water flows estimation are considered individually for spring floods and rainfall floods. The highest of available values of waters flow which ensure operation of a facility and its components are deemed to be estimated water flows. In appropriate cases short-term fields research may be also required. Initial time series are deemed to be sufficient for determination of estimated values if they comply to requirements set for periods of observations:

– for forest-tundra and forest zones no less than - 25 years,

– for forest and steppe zone - 30 years;

– for steppe zone - 40 years;

– for dry steppe and semi-deserted zones - 50 years;

– for mountainous areas - 40 years.

If there is no or insufficient duration of time series for the catchments with areas of $F < 20000$ km^2 within the ECU and $F < 50000$ km^2 within the Asian territory of USSR estimation are to be accomplished using the formulas. Rivers are conditionally classified into 2 groups: 1 – plain rivers, 2 - mountain rivers. Rivers of 1st group are classified in their turn into those of:

a) forest and tundra zones;

b) forest steppe and steppe zones;

c) dry steppe and semi-deserted zones.

The second group includes the rivers with sharp altitude variations (more than 400 m).

Estimated maximum water flow of plain rivers is determined using the formula

$$Q_p = q_p A = \frac{k_0 \, h_p \, \mu}{(A+1)^{n_1}} \delta \, \delta_2 A, \qquad (2.36)$$

where Q_p is an estimated instant water flow with probability of P%, m^3/s;

q_p is a module of estimated maximum water flow, m^3/s·km^2;

h_p is an estimated layer of aggregate (without cutting of soil supply) of flood runoff with excess probability of P%, mm;

A is an area of catchments;

k_0 is a parameter featuring floods' friendliness;

n_1 is a degree of reduction of the ratio $\frac{q_p}{h_p}$ depending on the area of catchments;

δ is a coefficient for consideration of regulating influence of lakes and water reservoirs on maximum runoff;

δ_2 is a coefficient of reduction for consideration of influence of catchments' forestation and marshiness;

μ is a coefficient for consideration of difference of statistical parameters of runoff depths and water flows.

Values of parameters n_1 and k_0 are represented in tabular form and depend on natural zones and relief categories.

Relief category is determined using the ratio

$$\alpha = \frac{I}{I_m}, \tag{2.37}$$

where I is an average weighted fall of stream;

I_m is a typical fall

$$I_m = \frac{\Delta I}{(A+1)^{0,5}} . \tag{2.38}$$

For the plain territory of the ECU $\Delta I \approx 25{,}0$. At $\alpha > 1{,}0$ a basin would be classified in terms of relief as belonging to 1st category; at $\alpha = 1{,}0 - 0{,}5$ - as belonging to 2nd category; at $\alpha < 0{,}5$ - as belonging to 3rd category. An estimated runoff depth during flood period is determined on the basis of statistical parameters of distribution: $\overline{h}_m$, C_v and C_s. An average several years' runoff depth $\overline{h}_m$ is represented by a map. In dry areas values taken from a map are subject to corrections (greater than 1) depending on area of catchments (within a territory $A < 3000$ km^2). Variation coefficients C_v are also mapped. They are subject to corrections (greater than 1) at catchments with $A < 200$ km^2.

Estimation of maximum runoff of meltwater of mountain rivers is performed using the structural expression (2.36) at $n_1 = 0{,}15$ and k_0 specified in the table with respect to certain mountainous territories (for example, Carpathians k_0=0,0045). Average runoff depth of a flood $\overline{h}_m$ and variation coefficients C_v are represented in maps, and $C_s = 3C_v \div 4C_v$. At regional level it is proposed to apply dependences $\overline{h}_m = f(H_{av})$ and $C_v = f(H_{av})$, where H_{av} is an average altitude of catchments.

Depending on area of catchments maximum flows of rainfall floods are estimated using one of two methods: empiric reduction formula or formula of marginal intensity (table 2.1).

Table 2.1 -Limits of application of formulas of rainfall floods' maximum runoff

Natural zones	Area of catchments, A, km^2	
	formula of marginal intensity	reduction formula
A. Plain territory		
1.Tundra, forest and forest steppe zones	<50	50-30000
2. Steppe zone	<200	200-10000
3. Dry steppe zone	<200	200-1000
4. Semi-deserted zone	<200	-
B. Mountainous territories (500 m $< H_{av} <$ 2000 m)		
1. Central Asia	<200	-
2. Other regions	<200	200-10000

Reduction formula is applied as follows:

$$q_p = q_{200}\left(\frac{200}{A}\right)^{n_1} \lambda_p \delta_1 \delta_1', \qquad (2.39)$$

where q_{200} is a module of maximum water flow with excess probability

P=1% adjusted as per the area of catchment A=200 km^2 (to be determined using a map);

n_1 is a degree which was subject to zoning;

λ_p – coefficient of availability;

δ_1 is a coefficient for consideration of regulation of maximum runoff by lakes and water reservoirs;

δ_1' is a swampnesss coefficient

$$\delta_1' = 1 - 0{,}8\, lg\left(1 + 0{,}1 f_{swamp}\right); \tag{2.40}$$

f_{swamp} is a relative swampness, %.

Formula of marginal intensity looks as follows

$$q_p = A_{1\%}\, H_{1\%}\, \eta\, \delta_1\, \lambda_p, \tag{2.41}$$

where $H_{1\%}$ is a daily maximum of precipitation with the availability of P=1%, mm;

η is a coefficient of flood runoff represented in tabular form;

$A_{1\%} = 16{,}67\,\overline{\psi}(\tau)$ is a maximum runoff module (at $\delta_1 = 1{,}0$)

$$A_{1\%} = \frac{q_{1\%}}{H_{1\%}\,\eta} \quad . \tag{2.42}$$

Maximum runoff module $A_{1\%}$ is determined using a special table depending on channel's hydromorphological factor F_p and duration of slope lag t_{slope}, and

$$F_p = \frac{1000\,L}{m\,I^{1/3} F^{1/4} (\eta\, H_{1\%})^{1/4}}, \tag{2.43}$$

where m is a coefficient of channel's and flood plain's roughness.

SNiP 2.01.14-83 served as a further stage of improvement and development of regulatory base in USSR. Its basic provisions are specified in "Manual for Determination of Estimated Hydrological Characteristics". Leningrad, Hidrometeoizdat, 1984. This variant stipulates that statistic processing of time series should be conducted using the method of moments and the method of the highest likelihood. Both graphical-analytic and graphical methods are also tolerated.

An estimated maximum module of spring flood runoff with a set annual excess probability $P\%$ is determined using the structure (2.36) having some minor revisions

$$q_{p\%} = \frac{k_0\, h_{p\%}}{(A+b)^{n_1}} \mu\, \delta\, \delta_1 \delta_2 \delta_3, \tag{2.44}$$

where b is an empiric parameter which considers decrease of intensity of maximum runoff module's reduction within the territory of small catchments (changes from 1 to 10 km^2);

δ is a coefficient of lakes' and water reservoirs' influence on q_p;

δ_1 is a coefficient of reduction of maximum runoff modules at forested catchments

$$\delta_1 = a / (f_f + 1)^{n'}, \tag{2.45}$$

n' is a coefficient of reduction represented in the table with consideration of a natural zone (forest or forest steppe) and catchments' soil cover as well as with consideration of forest location within a catchment (when determining C_a);

f_f is a relative forestation of catchments, %;

$$\delta_2 = 1 - \beta \, lg\left(0{,}1 f_{swamp} + 1\right), \tag{2.46}$$

β is a coefficient of influence of certain type of marshes on a maximum module q_m;

f_{swamp} is a relative swampness, %;

δ_3 is a coefficient of maximum module reduction at ploughed catchments.

Parameter k_0 is determined for analogue rivers on the basis of the structure (2.44).

The formula (2.44) is also applied for mountain rivers though some of its parameters are adjusted for given mountainous areas only. Coefficients $\delta_1, \delta_2, \delta_3$ are excluded from the structure of basic formula as, compared to vertical zoning, they have a secondary importance at mountainous areas. Spring flood's depth h_p is estimated using the technique specified in SN 435-72. Differences include SNiP 2.01.14-83's additional parameters introduced to a map of runoff depth of the flood h_0 and covering: catchments' sizes, inclinations of slopes, lake percentage, forestation, marshiness and ploughing rates.

The only one question left unclarified is as follows: why then no corrections are introduced to a coefficient of floods' friendliness k_0?

It is proposed to estimate maximum modules of rainfall floods using analogue method

$$q_{p\%} = q_{p\%_a} \frac{\delta \, \delta_2}{\delta_a \delta_{2a}} \left(\frac{A_a}{A} \right)^{n_1}, \tag{2.47}$$

where $q_{p\%_a}$ is a maximum instant module of an analogue river's runoff;

δ, δ_a is a lake percentage coefficient of a river or an analogue river under examination;

δ_2, δ_{2a} are coefficients of reduction influence of catchments' marshiness on a maximum runoff.

The field of application of the formula (2.47) is determined by the conditions

$$k_{form} \le 1{,}5\, k_{form,a}, \tag{2.48}$$

where $k_{form}; k_{form,a}$ are coefficients of a form of catchments belonging to a river or an analogue river under examination

$$k_{form} = L / A^{0{,}56}. \tag{2.49}$$

If there is no analogue rivers $q_{p\%}$ are estimated using the reduction formula

$$q_{p\%} = q_{200} \left(\frac{200}{A} \right)^{n_1} \delta\, \delta_2 \delta_3\, \lambda_p, \tag{2.50}$$

where δ, δ_2 and δ_3 are parameters for consideration of influence of lake percentage, marshiness and ploughing rates on a maximum runoff (to be determined using the scheme of spring floods);

q_{200} is a maximum module adjusted to the area of $A = 200$ km^2 and generalized in the form of isochrones' map.

A combined runoff coefficient η for plain rivers (if there are no analogues) is estimated using the formula

$$\eta = \frac{C_2 \eta_0}{(A+1)^{n_4}} \left(\frac{I_p}{50} \right)^{m_2}, \qquad (2.51)$$

where C_2 is an empiric coefficient: it is equal to 1,2 for tundra and forest zones and 1,3 for all other zones;

η_0 and m_2 are parameters tabulated as per natural zones, types of soil and its mechanical composition;

n_4 is an exponent: it is equal to 0,07 for forest-tundra and forest zones and 0,11 for other natural zones.

Depending on types of soils η_0 for mountainous areas may be found in the table in SNiP. As reflected by the table mountainous areas of Carpathians have η_0 ranging from 0,15 to 0,80; those of the Caucasus – from 0,10 to 0,80; those at Central Asia – from 0,10 to 0,40.

2.3 Operational models of forming of surface runoff for rating of estimated characteristics of floods and overflows

Previous analysis of scientific and methodical base proves its insufficient theoretical substantiation and that is why it should be further developed and improved. Principal provisions we studied earlier lead to the conclusion that there is a potential for development of estimation methods based on the following model prerequisites. Firstly, it is more expedient to examine the "slope inflow – channel runoff" model in the form of reduction hydrographs of slope and channel (or only channel) runoff. A geometric version of such initial model is shown on Figure 2.5 (at $t_p < T_0$) and Figure 2.6 (at $t_p \geq T_0$). Secondly, the possibilities of channel isochrones' model haven't been used up yet.

In particular, at $t_p \geq T_0$

$$Q_m = \sum_{T_0} q'_t f_t \varepsilon_t ; \tag{2.52}$$

- at $t_p < T_0$

$$Q_m = \sum_{t_p} q'_t f_t \varepsilon_t . \tag{2.53}$$

Let's note that all three functions are presented in the reduction form. Area of an elementary site may be estimated as follows

$$f_t = B_t V_d \Delta t , \tag{2.54}$$

where B_t is an average width within an elementary site;

Δt is a time interval.

Taking into account (2.54) initial equations (2.52) and (2.53) will look as follows:

at $t_p < T_0$

$$Q_m = V_d \sum_{t_p} q'_t B_t \Delta t ; \tag{2.55}$$

at $t_p \geq T_0$

$$Q_m = V_d \sum_{T_0} q'_t B_t \Delta t ; \tag{2.56}$$

At $\Delta t \to 0$ (2.55) and (2.56) would be noted down in integral form, i.e.:

at $t_p < T_0$

$$Q_m = V_d \int_0^{t_p} q'_t \, B_t \, \varepsilon_t \, dt ; \tag{2.57}$$

at $t_p \geq T_0$

$$Q_m = V_d \int_0^{T_0} q_t' \, B_t \, \varepsilon_t \, dt \; . \tag{2.58}$$

Since, as already mentioned above, parametric formalization ε_t remains to be unknown, let's use the following methodical approach. At both equations let's conduct averaging of ε_t as per t_p and as per T_0 at first approximation. Then at $t_p < T_0$

$$(Q_m)' = V_d \, \bar{\varepsilon}_{t_p} \int_0^{t_p} q_t' \, B_t \; dt \, . \tag{2.59}$$

In such case the following equation is applied:

$$k_\varepsilon = \frac{Q_m}{(Q_m)'} \, , \tag{2.60}$$

which results in

$$\begin{aligned} Q_m &= k_\varepsilon (Q_m)' = V_\partial \, \bar{\varepsilon}_{t_p} k_\varepsilon \, q_m' \, B_m \int_0^{t_p} \left[1 - \left(\frac{t}{T_0} \right)^n \right] \left[1 - \left(\frac{t}{t_p} \right)^m \right] dt = \\ &= V_d \, \varepsilon_A \, q_m' \, B_m \int_0^{t_p} \left[1 - \left(\frac{t}{t_p} \right)^m - \left(\frac{t}{T_0} \right)^n + \frac{t^{n+m}}{T_0^n \, t_p^m} \right] dt = \\ &= V_d \, \varepsilon_A \, q_m' \, B_m \, t_p \frac{m}{m+1} \left[1 - \frac{m+1}{(n+1)(m+n+1)} \left(\frac{t_p}{T_0} \right)^n \right]. \end{aligned} \tag{2.61}$$

Runoff maximum module is equal to

$$q_m = \frac{Q_m}{B_{av}L} = \frac{V_d\,\varepsilon_A\,q'_m\,B_m\,t_p\,\dfrac{m}{m+1}\left[1-\dfrac{m+1}{(n+1)(m+n+1)}\left(\dfrac{t_p}{T_0}\right)^n\right]}{B_{cep}L} = \tag{2.62}$$

$$= q'_m\,\frac{B_m}{B_{av}}\,\frac{m}{m+1}\left[1-\frac{m+1}{(n+1)(m+n+1)}\left(\frac{t_p}{T_0}\right)^n\right]\varepsilon_A.$$

Ratio $\dfrac{B_m}{B_{av}}$ is equal to

$$\frac{B_m}{B_{av}} = \frac{m+1}{m}. \tag{2.63}$$

Therefore

$$q_m = q'_m\left[1-\frac{m+1}{(n+1)(m+n+1)}\left(\frac{t_p}{T_0}\right)^n\right]\varepsilon_A, \tag{2.64}$$

where $\varepsilon_A = k_\varepsilon \bar{\varepsilon}_{t_p}$ is a coefficient of channel and flood plain regulation that depends on catchments' size.

(2.64) shows us that the expression in square brackets is a decreasing function of the ratio $\dfrac{t_p}{T_0}$ and a combination of exponents n and m. Let's introduce a notation

$$\psi\left(t_p/T_0\right) = 1-\frac{m+1}{(n+1)(m+n+1)}\left(\frac{t_p}{T_0}\right)^n. \tag{2.65}$$

Then

$$q_m = q'_m \ \psi\left({t_p}/{T_0} \right) \varepsilon_A . \qquad (2.66)$$

The structure of (2.66) corresponds to the principal scheme of runoff formation specified on Figure 2.1. Maximum module of slope inflow serves as a basic parameter in the calculation formula. It can be determined once integrated through T_0, i.e.

$$Y_m = \int_0^{T_0} q'_t \, dt = q'_m \frac{n}{n+1} T_0 \ . \qquad (2.67)$$

Which results in

$$q'_m = \frac{n+1}{n} \frac{1}{T_0} Y_m , \qquad (2.68)$$

where $\frac{n+1}{n}$ is a coefficient of time nonuniformity of slope inflow.

Let's examine the variant of formation of maximum water flow Q_m provided $t_p > T_0$ using the equation (2.52). At first let's note down its simplified variant

$$(Q_m)' = V_d \ \bar{\varepsilon}_{T_0} \int_0^{T_0} q'_t \ B_t \ dt , \qquad (2.69)$$

and then an expression for transition coefficient k_ε

$$k_\varepsilon = \frac{Q_m}{(Q_m)'} \ . \qquad (2.70)$$

Based on (2.70)

$$Q_m = k_\varepsilon (Q_m)' = k_\varepsilon \, \bar{\varepsilon}_{T_0} V_d \, q'_m \, B_m \int_0^{T_0} \left[1 - \left(\frac{t}{T_0} \right)^n \right] \left[1 - \left(\frac{t}{t_p} \right)^m + \frac{t^{n+m+1}}{T_0^n \, t_p^m} \right] dt =$$

$$= V_d \; q'_m \, B_m \, T_0 \frac{n}{n+1} \left[1 - \frac{n}{(m+1)(m+n+1)} \left(\frac{T_p}{t_p} \right)^m \right]. \qquad (2.71)$$

Runoff maximum module is equal to

$$q_m = \frac{Q_m}{B_{av} L} = q'_m \frac{B_m}{B_{av}} \frac{n}{n+1} \frac{T_0}{t_p} \left[\frac{m+1}{m} - \frac{n+1}{m(m+n+1)} \left(\frac{T_0}{t_p} \right)^m \right] \varepsilon_A . \qquad (2.72)$$

Let's note down a multiplier $\frac{n}{n+1} \frac{T_0}{t_p} \left[\frac{m+1}{m} - \frac{n+1}{m(m+n+1)} \left(\frac{T_0}{t_p} \right)^m \right]$ as $\psi\left({t_p}/{T_0} \right)$ but at $t_p \geq T_0$. Therefore

$$q_m = q'_m \, \psi\left({t_p}/{T_0} \right) \varepsilon_A \, . \qquad (2.73)$$

To sum up the above-stated information let's note down calculation equations for determining $\psi\left({t_p}/{T_0} \right)$:

- at ${t_p}/{T_0} = 0$

$$\psi\left({}^{t_p}\!\big/_{T_0} \right) = 1{,}0; \qquad (2.74)$$

- at $0 < {}^{t_p}\!\big/_{T_0} < 1{,}0$

$$\psi\left({}^{t_p}\!\big/_{T_0} \right) = 1 - \frac{m+1}{(n+1)(m+n+1)} \left(\frac{t_p}{T_0} \right)^n; \qquad (2.75)$$

- at ${}^{t_p}\!\big/_{T_0} \geq 1{,}0$

$$\psi\left({}^{t_p}\!\big/_{T_0} \right) = \frac{n}{n+1} \frac{T_0}{t_p} \left[\frac{m+1}{m} - \frac{n+1}{m(m+n+1)} \left(\frac{T_0}{t_p} \right)^m \right]; \qquad (2.76)$$

- $t_p >> T_0$

$$\psi\left({}^{t_p}\!\big/_{T_0} \right) = 0. \qquad (2.77)$$

In case of catchments' area increase coefficient of channel and flood plain regulation ε_F has a decreasing character from its upper threshold value $\varepsilon_A = 1{,}0$ at $A = 0$. Forestation and swampness of catchments are considered for such parameters of calculation formula as T_0 (in structure of coefficient $\psi\left({}^{t_p}\!\big/_{T_0} \right)$) and runoff depths Y_m (in structure of maximum module of slope inflow q'_m). Circulating water bodies (lakes, water reservoirs, ponds) which directly influence regulation q_m, are considered using the coefficient r, and

$$r = 1 - f\left(\frac{\omega_{lake}}{A}\right), \tag{2.78}$$

where ω_{lake} is an area of surface of a water body;

A - is an area of catchment.

The calculation formula (2.73) with lake percentage coefficient takes the following form

$$q_m = q'_m \, \psi\left(t_p / T_0\right) \varepsilon_A \, r \ . \tag{2.79}$$

Exercises and questions for self-checking

1. Principal scheme of river runoff formation.
2. Generalized scheme of transformation of rainfall to the channel runoff:
   a) Case if $T_0 > t_p$
   b) Case if $T_0 < t_p$.
3. Methods recommended by regulatory documents for determination of maximum rivers' runoff (SN 435-72, SNiP 2.01.14-83).
4. The using one of two methods: empiric reduction formula or formula of marginal intensity depending on area of catchments maximum flows of rainfall floods.
5. The calculating formula for maximum module of spring flood runoff in SNiP 2.01.14-83.
6. The estimating maximum modules of rainfall floods using analogue method.
7. The using the reduction formula and limit intensity for estimate rain flood maximum.
8. Operational models of forming of surface runoff for rating of estimated characteristics of floods and overflows.

9. Operational model for the formation of maximum runoff at elementary catchments:

a) Case if $t_p < T_0$

b) Case if $t_p > T_0$.

10. The equation of a slope inflow in the formulas of maximum runoff.

11. Transformation function of the runoff under the influence of the duration of the channel runoff on elementary catchment areas.

12. Estimated formula for the maximum runoff module of the operator type.

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SECTION III.

ASSESSMENT OF NATURAL WATERS QUALITY AND FORECASTING THE CHANGE OF WATER CHEMICAL COMPOSITION

Plan of lecture

Introduction

Environmental changes occurring as a result of natural fluctuations and economic activity cause significant changes of hydrological regime of rivers and water bodies of Ukraine. Therefore a systematic and constant research of both water bodies and factors affecting them is required.

Ukraine is among the countries that have limited water resources.

Among 152 countries assessed Ukraine ranks 111th in terms of inland freshwater resources per capita. The most acute water scarcity is observed in arid regions (steppe zone). In addition, over the last decades the country faces deterioration of surface waters quality which reaches a critical level in some regions. Therefore, in the present context the primary task of water management consists in providing various economic sectors with water resources of sufficient amount and conformable quality.

Monitoring the surface waters quality is performed throughout the territory of Ukraine at 164 rivers, 73 reservoirs, 41 irrigation systems. Water quality is monitored at 495 stations on the basis of 25-41 hydrochemical parameters depending on certain requirements, landscape peculiarities and man-induced impact (Figure 3.1).

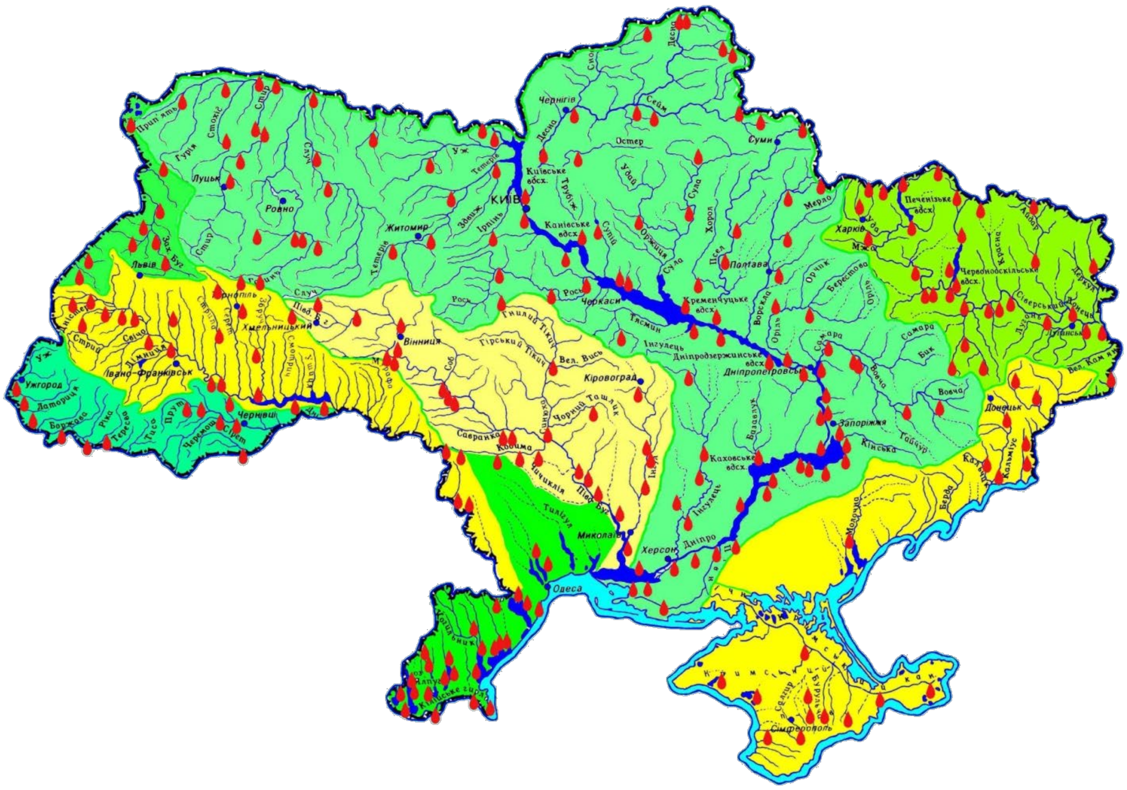

Figure 3.1 - Location of observation posts monitoring the quality of surface waters included in the system of the State Water Resources Agency

Setting a course for European integration created a powerful incentive for use of European experience on implementing the water policy in our country with its strategic directions specified in the "Water Framework Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy". The aim of the directive consists in defining and implementing a system of actions required in order to protect land surface, coastal waters and groundwater. Because of increasing man-induced impact affecting river basins, especially those of small and medium rivers of the Black Sea region, the problems of water quality assessment on the basis of hydrochemical parameters, timely analysis and forecast of hydrochemical parameters change in time and space grow more urgent.

3.1 Forming factors and water quality criteria

Chemical composition of natural waters is a complex of dissolved gases, various mineral salts and organic compounds. Almost all chemical elements known so far are dissolved in natural waters in the form of simple and complex ions, complex compounds, dissolved or gaseous molecules, stable and radioactive isotopes. V.I. Vernadskii once said that each drop of water is a microcosm reflecting the structure of the cosmos. About 90 of all stable chemical elements contained in the Earth's crust can be found in natural waters (oceans, rivers, groundwater).

Formation of chemical composition of natural waters is a process of chemical substances exchange between natural waters and other natural environments (atmosphere, rocks, soil, flora and fauna) under different physiographic conditions resulting in transfer of dissolved, gaseous, colloidal and suspended substances to natural waters.

Chemical composition of natural water determines the path covered by water in the process of its circulation. Amount of substances dissolved in such water will depend, on the one hand, on combination of the substances which were present on its way and, on the other hand, on conditions under which such interactions took place.

The factors determining formation of chemical composition of natural waters can be divided into two main groups. The first group should include direct factors having a direct impact on water (i.e. impact of substances which can enrich water with soluble compounds, or alternatively, extract the latter from it): rocks, soil, living organisms and human activity.

The second group includes indirect factors determining the conditions for interaction of substances and water: climate, relief, hydrological regime, vegetation, hydrogeological and hydrodynamic conditions etc.

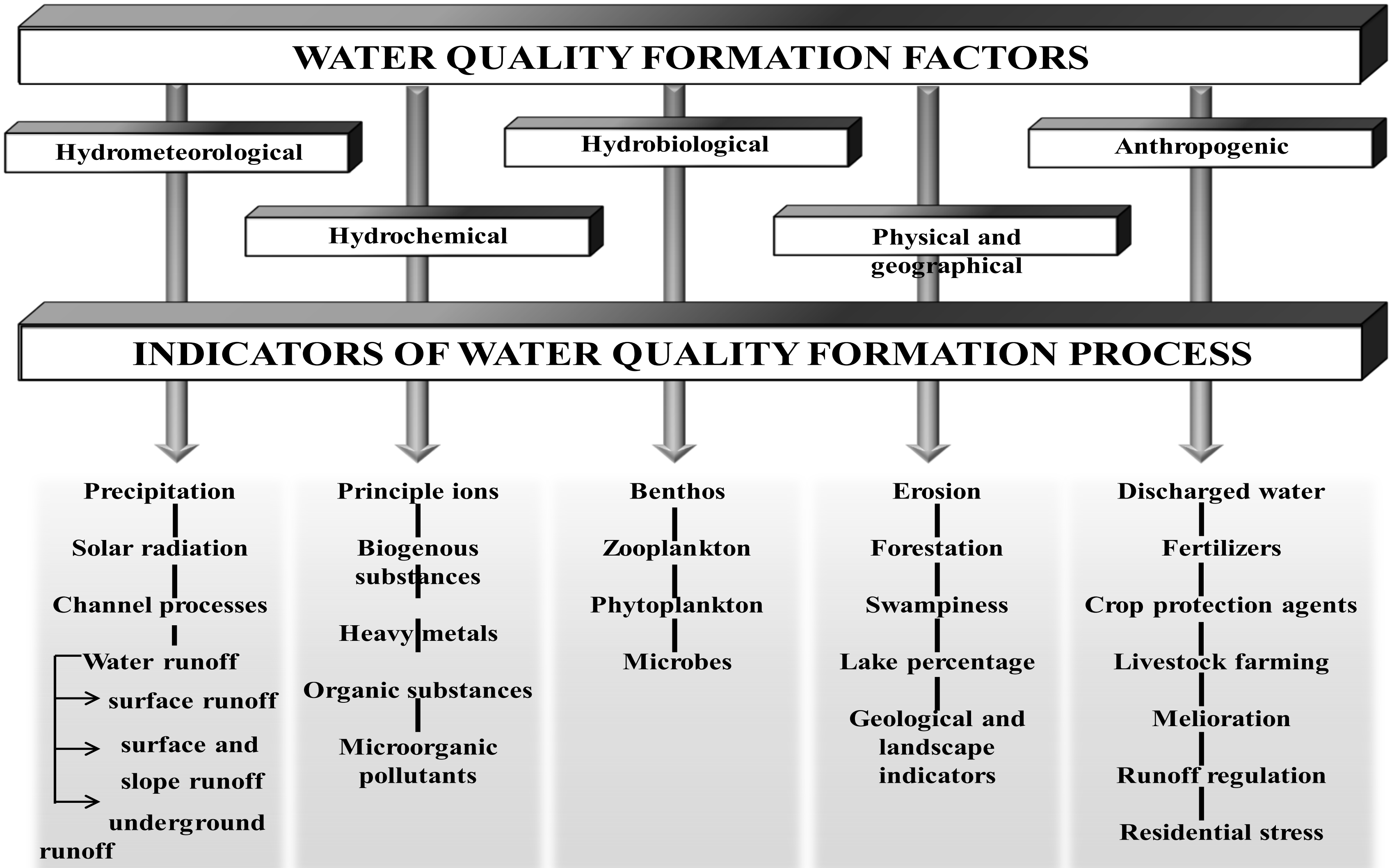

Figure 3.2 – Scheme of water quality formation

The set of factors which regulate water quality can be divided into five main blocks reflecting an internal structure and specific properties of a certain factor: hydrometeorological, hydrochemical, hydrobiological, physiographic, anthropogenic.

Figure 3.2 presents a scheme of water quality formation. The first one, hydrometeorological factor covers water runoff characteristics (surface, surface and slope, underground and solid runoff), meteorological parameters (precipitation, solar radiation, temperature conditions etc.).

Hydrochemical factor includes a range of physical and chemical processes which involve main groups of chemical substances dissolved in water (principle ions, biogenous and organic substances, microelements and specific pollutants of anthropogenic origin).

Physiographic factor includes features of a certain landscape where formation of water chemical composition of a particular water body takes place and has the following characteristics: forestation, swampiness, lake percentage, erosion.

The role and degree of impact of anthropogenic factor on general processes of water quality formation are determined by the following criteria: ploughing rates, waste waters discharge, fertilization, land reclamation, density of population, specific weight of cattle stock and other animals, extent of runoff regulation. Hydrobiological block is also an important block of water quality regulation. Its main features include zoobenthos, phytoplankton, zooplankton, microbiological indicators.

Combination of chemical substances dissolved in water provides natural waters with certain properties. Such properties of water as salinity, hardness, alkalinity, acidity, aggressiveness and corrosive power depend on content of certain substances therein.

The total effect of the above factors forms hydrochemical parameters of water in a certain water body and determines a qualitative composition of surface runoff.

Water quality criteria. Water quality is a description of water properties that determines its suitability for specific types of water use and water consumption. Water quality for a certain type of water use is determined by water quality criteria – special characteristics (indicators) the extent (concentration) of which appears to be scientifically proven and ensures a particular level of water quality according to requirements of a specific customer.

Hygienic criterion is represented by water use or water consumption limitations due to hazardous pollution or deterioration of citizens' sanitary conditions.

Reservoirs and water courses are considered to be polluted if indicators of water composition and water properties changed under direct or indirect influence of industrial activity and household use of water by the population and became partially or completely unsuitable for a certain type of water use or water consumption.

Deterioration of water quality due to change of organoleptic properties and emergence of substances which are harmful to humans, animals, birds, fish depending on a type of water use or water consumption as well as rise of water temperature changing the conditions required for normal life of aquatic organisms serve as a criterion of water pollution.

Different types of water use have their own requirements to water quality that is why each of them may have various water quality criteria.

For some water quality parameters such as dissolved oxygen, water quality criteria are set at the minimum acceptable level being sufficient for retaining biological functions of aquatic organisms.

Water quality criteria for the same indicator may differ significantly depending on the type of water use. Depending on the level of requirements to water quality water users fall into three categories:

Category 1: Water use without adherence to standards

Types of water use:

1) navigation (seamanship);

2) transport systems (timber-rafting, wastewater discharge etc.);

3) extraction of minerals (sand, gravel, natural gas, oil);

4) power generation (hydroelectric power plants, hydroelectric pumped-storage power plants).

Category 2: Water use with adherence to specific standards

Types of water use:

1) household water supply;

2) industrial production with water cooling;

3) irrigation;

4) fish farming;

5) recreation and tourism.

Category 3: Water use with background quality

Type of use: existence of ecosystems

It is very difficult to find a balance between all types of water use, especially under conditions of limited water resources. The only way is to use a multifunctional approach to water resources within particular territory, region or country.

Categories and types of water use, multifunctional approach to water resources prioritizing certain water users are the elements determining a system of measures for water quality assessment, forecasting and management.

Potable water quality criteria

These criteria include the requirements to quality of natural water bodies serving as sources of water intake and potable water supply. Raw water quality criteria normally correspond to the potable water criteria which ensure lifelong harmless consumption of such water.

When addressing the problems of potable water supply Ukrainian water management authorities refer to the following documents:

• GOST 2761-84. Sources of centralized household drinking water supply.

• SanPin 4630-88. Sanitary rules and norms for protection of surface waters against pollution.

• Rules for surface water protection (1991).

• State sanitary rules and norms of Ukraine "Drinking water, hygienic requirements to water quality of centralized household drinking water supply" as of December 23, 1996.

According to these regulatory documents the water bodies used as sources of centralized or non-centralized household potable water supply are classified as sources of the first category of water use. Categories of water use determine hygienic requirements and standards of composition and properties of water in a certain water body which should be in place if such water body is used for potable water supply.

Water quality criteria for irrigation

Irrigation is one of the main areas of agricultural water consumption. Poor water quality can affect irrigated crops and soils because of accumulation of salts in the root zone, reduction of soil permeability due to excessive impact of sodium and calcium or transfer of pathogens or contaminants posing a direct toxic threat to the plants.

Surface water, groundwater, wastewater and recycled water are normally used for agricultural irrigation purposes. The quality of irrigation water (natural water of different types circulating in an irrigation network and used for agricultural reclamation) is graded based on number of particles suspended in water (turbidity), mineralization, chemical composition, temperature. Values of solid particles should not exceed M0 '*m because once settled they could silt up an irrigation network. If there are large particles suspended in water the latter should be kept in special sedimentation basins prior to its delivery to main channels.

The optimum temperature of irrigation water should be 18-20 °C. Evaluation of salt content of irrigation water is performed based on such indicators as mineralization, concentration of certain ions or content of certain salts, general chemical composition, ratio of certain ions or their combinations, pH value.

Evaluation of irrigation water quality and its suitability for irrigation as per agronomic criteria is performed according to the requirements of the State Standard of Ukraine DSTU 2730 – 94 developed by the Institute of Soil Science and Agrochemistry of the UAAS. Such evaluation consists in determining the risk of destructive processes presence in irrigated soils, namely: soil salinization caused by a number of toxic salts; soil alkalization in terms of pH hydrogen index, ion content and toxic alkalinity; soil alkalinization in terms of the ratio of content of sodium and potassium alkaline cations to the amount of all cations.

Based on this standard irrigation water is classified into three classes of suitability for different types of soils:

1st class – suitable. Use of this water for irrigation leads to some changes of ion-salt composition of soil but these changes do not cause any significant increase of salt content, amount of exchangeable sodium and potassium and alkalinity;

2nd class – partially suitable. Use of such water leads to classified significant change of soil properties including salinization, alkalinization and subsequent decrease of soil fertility. Use of this water for irrigation is only allowed subject to constant monitoring of trends of soil processes and application of differentiated complex of agricultural melioration measures;

3rd class – unsuitable for regular irrigation. Application of preventive complex of agricultural melioration measures in this case is not justified both economically and environmentally.

Evaluation of irrigation water quality is presented in Table 3.1 with description of irrigation water classes given in Table 3.2.

Table 3.1 – Classification for evaluation of irrigation water quality

Class of water	Mineralization of water used for soil irrigation			Evaluation of water in terms of risks of specific processes development			
	With heavy-textured soils, SAC>30	With medium-textured soils, SAC of 15-30	With light-textured soils, SAC<15	Chloride salinization	Sodium alkalinization	Magnesium alkalinization	Soda formation
				CL^{-}	Ca^{2+}/ Na^{+}	Ca^{2+}/ Mg^{2+}	$(CO_3^{2-} + HCO_3^{-})$- $(Ca^{2+} + Mg^{2+})$
1	0,2 - 0,5	0,2 - 0,6	0,2 - 0,7	<2,0	>2,0	>1,0	<1,0
2	0,5 - 0,8	0,6 - 1,0	0,7 - 1,2	2,0 - 4,0	2,0 - 1,0	1,0 - 0,7	1,0 - 1,25
3	0,8 - 1,2	1,0 - 1,5	1,2 - 2,0	4,0 - 10,0	1,0 - 0,5	0,7 - 0,4	1,25 -2,5
4	>1,2	>1,5	>2,0	>10,0	<0,5	<0,4	>2,5

Table 3.2 – Description of irrigation water classes

Classes of water	Description
Class I	Irrigation water does not affect soil fertility, crop yield, quality of agricultural products, surface water and groundwater.
Class II	Irrigation water does not affect quality of agricultural products, surface water and groundwater. Lack of drainage may lead to possible salinization
Class III	Irrigation water affects soil fertility, crop yield; up to 10–25% decrease of yield of crops with low and medium salt tolerance. Lack of prior water and soil melioration will inevitably lead to development of the processes of salinization, sodium and magnesium alkalinization and soda formation. Regulation of pH index of irrigation water and calcium enrichment are required. Limitation of crops composition and introduction of special complex of melioration measures are required.
Class IV	Irrigation water affects soil fertility, crop yield; up to 25 – 50% decrease of yield of crops with low and medium salt tolerance. Water is unsuitable for use unless prior change of its composition or special research of its impact on quality of agricultural products, soil fertility and other natural factors are carried out.

3.2 Methodological substantiation of operational forecasting of water quality indicators

Forecast is a probabilistic judgement on a state of a certain object (process or phenomenon) at a given time in future and alternative ways of achieving results.

Forecasting is a process aimed at developing forecasts of change of a state of a certain object (process or phenomenon) through analysing the trends of its development in order to initiate active influence on the course of such future change.

Forecasting the chemical composition of natural waters is crucial for development of all sectors of water management complex, industry, agriculture, recreation zones, environmental measures.

In terms of earliness (according to the rates of forecast economic planning phenomena development) scientific and technical forecasts are divided into:

Operational – up to 3 months; *short-term* – up to 1 year; *medium-term* – 1–5 years, *long-term* – 5–20 years, *very-long-term forecasts* – more than 20 years.

Operational forecasting of changes of surface water chemical composition is characterized by a minor earliness of forecasts production (day, several days, month, season) and is intended for detection and forecasting of adverse state of water quality in case of hydrometeorological conditions change and emergency wastewater discharge.

Forecasts are made for specific river stations located downstream from the most dangerous sources of pollution or groups of such sources. For small and medium-sized rivers those are primarily represented by the stations with guaranteed near-complete mixing throughout the year of river water and wastewater and the closest water use station located at the site of significant impact of wastewater on river water quality. For major rivers those are represented by the water use station downstream from wastewater discharge site.

The list of substances forming the base for a forecast of water pollution level should by all means include:

a) substance (or substances) that are, compared to other substances, more likely to exceed the MPC at a control river station downstream from wastewater discharge site or to exceed the MPC in case of emergency;

b) substance (or substances) that, after creation of transformations of discharged pollutants, cause significant contamination along a certain length;

c) water-dissolved oxygen

When selecting a substance determining a length of river's contaminated area the results of systematic observations of pollutants distribution along the length of a river or the results of special reconnaissance surveys are used.

The following materials covering controlled territories should be available in order to conduct operational forecasting of river water pollution caused by wastewater:

a) maps and schematic maps of river networks;

b) list and exact location on a schematic map of hydrological posts' stations; stations of systematic hydrochemical observations and stations where water use or water consumption depend on water quality;

c) information about the average speed of water masses between posts of hydrological observations and water use posts depending on hydrometeorological conditions.

Earliness of an operational forecast depends on earliness of a forecast of hydrometeorological data (water discharge, water temperature). Concentrations of pollutants in water depend directly or indirectly on changes of water discharge and water temperature. At the time of flood anticipation, using the information on its runoff characteristics, a forecast of possible deterioration of water quality due to income through surface and slope runoff of products generated after erosion of chemical substances (fertilizers decomposition products, plant protection products, petroleum products) is performed.

The forecast is made for specific stations and river areas having a significant impact of wastewater or anticipating a flood to happen. A forecast is first of all made for the stations with near-complete mixing of river water and wastewater and also for the water use stations located within a zone of wastewater impact or within an area of flooding.

A conceptual model of operational forecasting process is presented in the form of scheme (Figure 3.3). The concept is based on logical and sequential combination of basic technological stages of forecasting process forming a cycle "problem definition – preparation of warning associated with a water pollution threat".

Forecasting is conducted based on the following phases: problem definition, current situation assessment, selection of forecasting methods, forecast calculation, preparation of warning associated with a water pollution threat.

The main purpose of operational forecast consist in early prediction of value of pollutants' concentrations at a given specific station or river area at a specified time. At the same time additional tasks such as forecast of length of polluted river area, calculation of a distance to a station of complete mixing; forecast of time of polluted water masses lag from emergency discharges to control stations in case of flooding may be resolved.

A forecast interval is also established depending on the nature of forecast situation. It is allowed to set intervals from 1 day to three months when conducting an operational forecast. Parameters of expected contamination should be predicted with 1 month earliness and as soon as possible (up to 1 day) when emergency discharges occur. At the present-day stage of forecasting the problem of polluted water bodies selection is being solved.

There are two main principles of water bodies selection:

- *forced* (in case a forecast of water pollution spreading which has already occurred is required);
- *objective and searching* (a scientifically justified search of the water bodies having a potential threat of significant pollution based on a complex of criteria).

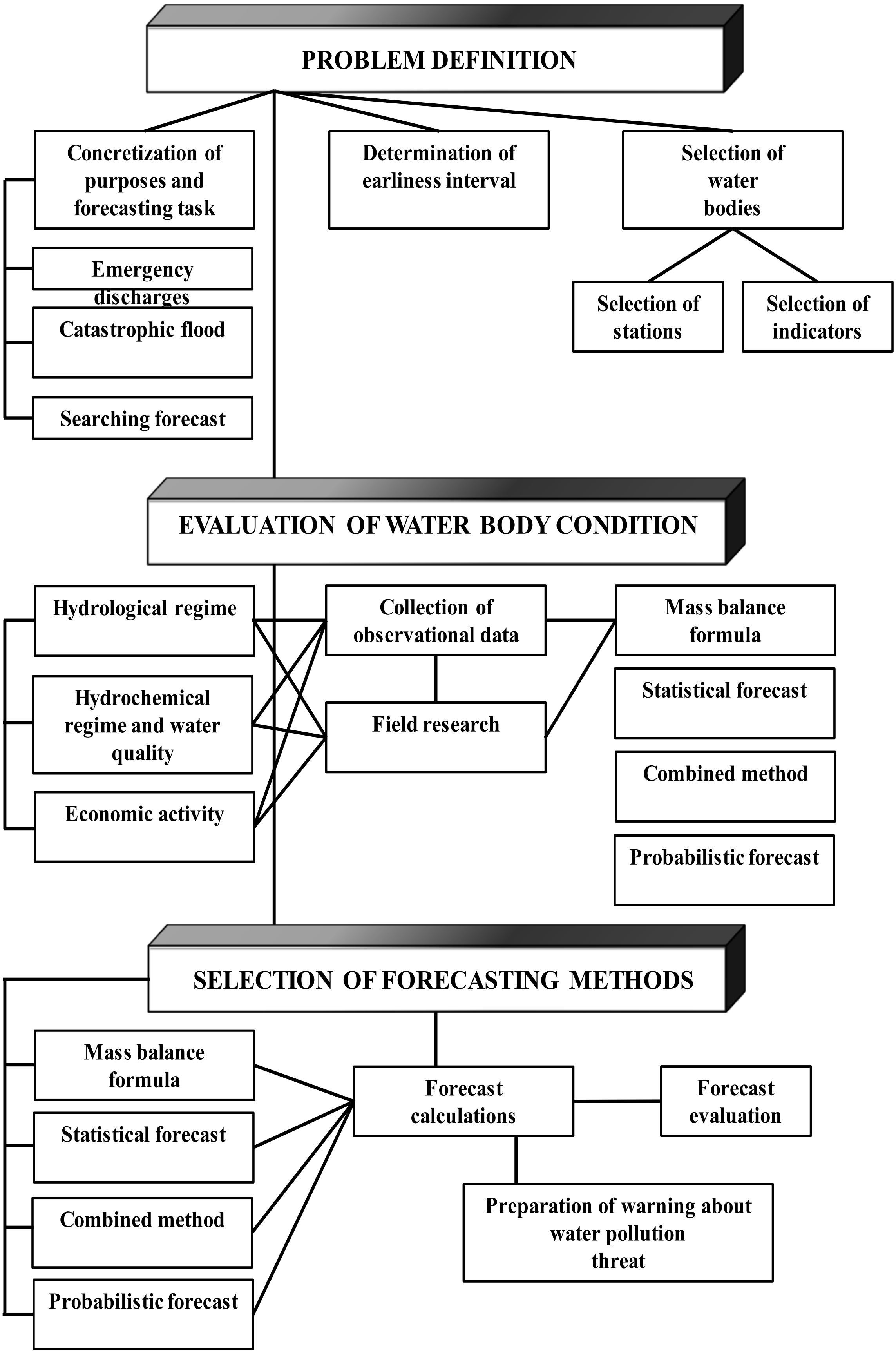

Figure 3.3 – Scheme of water quality operational forecasting

The selection is based on materials of systematic pollution observations (materials of the State Committee of Hydrometeorology and materials of the State Water Resources Agency of Ukraine).

When selecting these objects the following is to be considered:

- national economic importance of these water bodies;
- high rate of river water pollution (including periodic pollution);
- quite long-term series of hydrometeorological observations required for forecasting.

A water pollution evaluation based on a sum of ratios of concentrations $(C_1, C_2, ..., C_n)$ of substances with the same limiting harmfulness criterion (sanitary and toxicological, organoleptic, general sanitary) to respective MPCs is used to ensure quick identification of rivers with high rate of water pollution. Water is contaminated if this sum exceeds one:

$$C_1 / SRC_1 + C_2 / SRC_2 \rangle 1 . \tag{3.1}$$

Another way to perform this evaluation consists in calculating the water pollution index (WPI) using the formula:

$$WPI = \frac{1}{6} \sum_{n=1}^{6} \frac{C_n}{SRC_n} \quad , \tag{3.2}$$

where SRC_n – maximum permissible concentration of chemical component;

C_n – actual concentration of chemical component;

6 – number of ingredients.

The following table is used for determination of water pollution using WPI: 3.3.

Table 3.3 – Criteria of surface water quality evaluation using WPI

Water quality category	Text description	WPI value
I	Very clean	≤ 0,3
II	Clean	> 0,3 – 1,0
III	Moderately contaminated	> 1,0 – 2,5
IV	Contaminated	> 2,5 – 4,0
V	Muddy	> 4,0 – 6,0
VI	Very muddy	> 6,0 – 10,0
VII	Extremely muddy	> 10,0

In case water pollution evaluation requires consideration of not only level of pollution but also its stability over time a complex pollution index (CPI) should be calculated using the methods of the Hydrochemical Institute.

Once a water body for water quality forecasting is chosen selection of stations and list of indicators should be done. The network of stations of the State Committee of Hydrometeorology and the State Water Resources Agency as well as the list of indicators determined by analytical services of these institutions shuold be taken as a basis.

When preparing an operational forecast of pollution changes along the river's length 1-2 additional stations should be identified to determine background concentrations and pollutants self-purification processes. These stations are placed at a distance of 500 m above wastewater discharge location. When selecting the stations directly on a river observations at wastewater discharge locations should be also arranged in order to enable using the data on number and cyclicity of these discharges during forecasts preparation. When making operational forecasts of river water pollution the stations downstream from wastewater discharges should be used. Small rivers' stations have almost complete mixing of river water and wastewater which means that control water use stations are influenced by wastewater (floodwater).

The distance to a river station, where complete mixing of river water and wastewater takes place is calculated using the formula:

$$L_{mix} = 1{,}27\,\overline{B}/\varphi\sqrt{W/H} + \sum l_{isl}\ , \tag{3.3}$$

where L_{mix} - distance to a river station of complete mixing, m;

$\overline{B}$ - average river width, m;

φ - river tortuosity calculated using the formula:

$$\varphi = l_w/l_{sl}\ , \tag{3.4}$$

where l_{sl}, l_w - length of a river measured in a straight line and along a waterway respectively;

$\sum l_{isl}$ - total length of islands within the area of waters mixing, m;

Parameter H is calculated using the formula:

$$H = \overline{H}/\overline{B}\ , \tag{3.5}$$

where $\overline{H}$ - average river depth, m.

To calculate the parameter W the following formula is used:

$$W = M_c/g\ , \tag{3.6}$$

where M =0,7s +6,

a c - Chezy coefficient which is calculated using the formula:

$$c = \overline{V}/\sqrt{\overline{H}i}\ \ , \tag{3.7}$$

where $\overline{V}$ - average current velocity;

i - hydraulic incline.

Calculation of L_{mix} should be done twice considering river's minimum and maximum water flow.

At the second stage assessment water body condition should take place. This includes:

1) collection and evaluation of information on hydrological and hydrochemical regime of a water body including projected hydrological characteristics. They are conducted using materials of current observations of respective monitoring services.

2) collection and evaluation of data about the impact of economic activity on river water quality;

3) necessary field research to collect additional information;

4) computer processing of collected information to determine statistical parameters and correlation dependencies between hydrological regime characteristics and water quality indicators (contaminating substances).

When taking water samples a river's wastewater pollution regime should be considered. The day and time of enterprise's and sewer outlet's full capacity operation should be determined. To reduce a possible error when determining pollutants concentration arising due to spatial and temporal variability of their content, water samples averaging should be performed when taking samples in time and space. To conduct averaging of water samples taken at river's cross-section it is sufficient to take samples along three vertical lines and to produce a mixed water sample. Then the error of concentration measurement should not exceed ± 20%.

Water sampling in some observational stations should be performed with consideration of water masses lag. Time marking should start when the first water sample is taken from an upper station.

The approximate lag time between observational stations should be calculated using the formula:

$$\tau = L/\left(\overline{V} \cdot 86400\right), \tag{3.8}$$

where τ - lag time, days;

$\overline{V}$ - average river's current velocity between stations, m/s;

l - distance between observational stations.

There are three modelling methods used for forecasting:

1. preparation and application of mass balance equations based on guaranteed values of certain parameters and empirical coefficients;

2. Search and application of direct and indirect statistical relationships between pollutants concentrations and certain hydrometeorological parameters based on which forecasts with earliness of several days, one month or one season can be completed;

3. combined application of the first two modelling methods.

A mass balance equation may be applied to complete the forecasts of possible adverse changes of water chemical composition of the water courses with a given earliness:

a) when new powerful discharges of untreated or inadequately treated wastewater are commissioned;

b) when there is an obvious threat of wastewater emergency discharge;

c) during wastewater emergency discharge.

Selection of forecasting methods.

Depending on a specific forecasting situation, quality of original hydrological and hydrochemical information, availability of data about anthropogenic impact on river water one of the following methods may be applied:

- a forecast using a mass balance formula (a formula wastewater and river water mixing);

- a statistical forecast using correlation and regression dependences obtained at the previous stage of calculations;

- a combined method (combination of statistical and balance methods of forecasting);

- probabilistic (a probability of certain concentrations of pollutants with given parameters of hydrological regime is calculated).

A forecast is performed based on set parameters of its all components and according to a method chosen. After that obtained results should be analyzed and, if necessary, a warning about a water pollution threat should be prepared.

A forecast is made using a mass balance formula characterizing inflow and consumption of chemicals at a river's specific area:

$$C_{bs}Q + C_{ww}q = C_{cs}(Q + q) \ . \tag{3.9}$$

Which results in

$$C_{cs} = C_{bs}Q + C_{ww}q / Q + q \ , \tag{3.10}$$

where C_{cs}, C_{bs}, C_{ww} - concentration of substance in a river's control station, in a background station and in wastewater respectively, mg/dm^3 :

Q, q - river water flow and wastewater flow.

Different forecasting situations imply use of the formulas that consider, through application of special coefficient, peculiarities of pollutants transformation and dilution.

Statistical forecasting is performed upon availability of rather long series of systematic observations of water body pollution and its hydrological regime, significant correlation and regression relationships. It is used for forecasting the chemicals with less important anthropogenic component (main ions, mineralization) and the organic and biogenous elements, heavy metals, phenols with anthropogenic component that is comparable to natural one.

In case of major fluctuations of pollutants concentrations the following dependence is used for a background station:

$$C_{xk} - C_{bs} = f(Q) \tag{3.11}$$

and in case of significant changes of wastewater discharge regime:

$$C_{xk} - C_{bs} = f(QG), \tag{3.12}$$

where C_{xk} - concentration of substance in river water at k observational post of station x, mg/dm^3;

G - speed of substances inflow with wastewater into a river, g/s

$$G = C_{ww}q \ . \tag{3.13}$$

The following formula is used to determine an error of forecasting calculations:

$$S_{Ccs} = \sqrt{S_{qe}^2 + \sigma_{C_{bs}}^2} \ . \tag{3.14}$$

And in its turn

$$S_{qe} = \sigma_0 \sqrt{1 - r^2} \ , \tag{3.15}$$

where S_{qe} - mean quadratic error of checked calculations of substance concentration forecasts;

r - coefficient of correlation

σ_0 - mean quadratic deviation calculated using the formula:

$$\sigma_0 = \sqrt{\sum_{i}^{1}\left(C_i - \overline{C}\ \right)^2 \Big/ n-1}\ , \qquad (3.16)$$

where C_i - substance concentration of i -th value;

$\overline{C}$ - mean arithmetic value of substance concentration.

Combined forecasting method is used to improve accuracy of forecasting results and implies application of statistical methods to determine the parameters of balance formulas.

Probabilistic method belongs to statistical methods of forecasting and can be used as an alternative estimating forecasting method at the stage of preliminary evaluation of expected water quality deterioration or when application of the above recommended methods is impossible.

Once a forecast is complete an assessment of forecasting methods is carried out which includes identification of errors elimination of their causes through comparing the results of observations with the results of a forecast. A forecast is deemed to be unsatisfactory when an actual error exceeds a forecast error (with P = 95%), i.e. exceeds S_{qe}. Those forecasts which proved correct should be evaluated using a two-grade score:

good - actual error is equal or is less than S_{qe};

satisfactory - actual error exceeds S_{qe}, but is equal or is less than $S_{qe}\, t_{st}$.

A relative error of a forecast $\left(S_f\right)$, % should be calculated using the formula:

$$S_f = C_f - C_{ar} \big/ C_{ar} \cdot 100, \qquad (3.17)$$

where C_f, C_{ar} are results of such forecast and actual results respectively.

Preparation of warnings about water pollution threats

Production of operational forecasts for companies and organizations is performed with 1 month earliness interval. Notifications have a form of warnings about the threat of a dangerous or extremely dangerous river water pollution upon the occurrence of a forecast minimum water flow, a catastrophic flood or other adverse conditions. Indication of expected dangerous concentrations of pollutants, dates of their emergence and completion is also required.

3.3 Long-term forecasting of changes of water chemical composition

Modelling of both hydroecological conditions in general and even some hydrochemical and hydrobiological processes is a very difficult task due to multidimensionality of these processes and their relationships with regard to a large number of different components and factors modelled. At the same time the most difficult task is getting information about these processes which requires conduction of special expensive complex field research.

These problems become even more significant when modelling and forecasting the hydroecological processes, including hydrochemical processes associated with intensive impact of anthropogenic factors.

Forecasting of chemical substances content may be performed using a method of analogy or a calculation method. Method of analogy is a rather approximate one. It is based on an assumption that basic patterns of formation hydrochemical regime of an existing water body and a projected are the same subject to similar physical and geographical, hydrological and hydrochemical, hydrobiological conditions. Calculation method consists in quantitative separate assessment of inflow and expenditure elements of hydrochemical balance. This method can be used only for relatively conservative substances that are not considerably involved in such internal water body processes as main ions and mineralization. It is not suitable for the substances that are not actively involved in internal water body processes of biogenous and organic matter.

Long-term forecasting of surface water chemical composition change is a complicated and complex process covering a large number of individual forecasts. Its structure consists of the following stages:

1) analysis of current state of surface water quality;

2) a forecast or determination of estimated water flow (for rivers) or volume (for lakes and reservoirs);

3) a forecast of pollutants inflow into water bodies from different sectors of economy;

4) a forecast of substances concentrations in reservoirs and water courses;

5) issue of recommendations on water rational use and protection.

These stages are preceded by a stage establishing, according to forecast purpose and tasks, an earliness period, water bodies, their areas and stations, specifying forecast indicators of water quality and defining forecasting variants.

Forecast earliness period depends on the purposes of a forecast.

Earliness also affects accuracy of a forecast. The latter reduces in direct proportion to squared earliness. Such forecast has a probabilistic nature so the forecast results should be expressed in the form of upper and lower limits.

Establishing a forecast level is an equally important at the intial stage of long-term forecasting. With regard to surface water chemical composition it is determined by the nature of a forecast object (economic region, river basin, river area, station); basin scheme of long-term forecasts is the most commonly used for this purpose.

Within a river basin a forecast is produced for certain sites and stations which makes its results more specific and more relevant for practical purposes. Selection of sites and stations is based on a network which includes:

– currently the most polluted areas with concentration of ingredients and water quality indicators exceeding 10 MPC;

– sites and stations belonging to a category of slightly polluted but describing background concentrations of substances;

– sites and stations of water bodies having a great economic importance and exposed to considerable pollution;

– sites and stations near large populated locations;

– sites and stations at the edge of large river basins;

– stations used for water flow measurement and water balances determination.

Forecast indicators are selected on the basis of general and specific requirements of water users and water consumers at the time and in the future.

General forecast indicators include indicators characterizing the properties of water and substances affected mainly by physical transformation and biochemical oxidation: suspended solids, temperature, pH, mineralization, dissolved oxygen content, BOD.

Specific indicators are represented mainly by pollutants (phenols, synthetic surface-active substances, petroleum products, biogenic substances, pesticides).

Selection of forecast indicators is determined by their large concentrations in water within the areas and stations under study at the present moment, their potential inflow with wastewater and by the requirements to water users and water consumers.

The following background information is used for forecasting:

1) status of processes and relationships of individual factors in the past;

2) evaluation of possible changes related to economic issues;

3) long-term trend of economic complex development;

4) water chemical composition;

5) water management measures and rational use of water resources;

6) current and potential sources of pollution;

7) trends of wastewater treatment methods and water resources protection

measures development.

Description of current water quality.

Analysis all information characterizing the current state of surface water quality should be performed together with generalization of information based on the indicators set for a particular water body, given the water users' requirements, and statistical processing aimed at averaging output data for specific time intervals (month, year) with calculation of normative deviations and extreme concentrations. This should be done in order to find a long-term trend of water quality change at certain stations and within the entire river basin with further analysis of pollutants inflow and long-term dynamics of rivers' water content.

This information can be presented in the form of maps and tables.

Methods of long-term forecasting of chemical composition changes and surface waters quality.

To make a long-term forecast of surface water chemical composition and its quality the following two groups of methods are commonly applied:

1) methods based on the chemical mass balance formula;

2) statistical methods.

Balance methods are used for making long-term forecasts of concentration of polluting chemicals in a water body if formation of all concentration values is affected by one or more anthropogenic sources.

Statistical methods are used for long-term forecasting upon availability of several years' series of observations monitoring the content of chemicals in a particular water body.

Modern mathematical methods help to identify the trend of pollutants concentration during the present-day period and to extrapolate them for future use.

Forecasting of water quality indicators based on the balance method is carried out using the formulas (3.9, 3.10). To produce a forecast for a longer time lag one should have a forecast of pollutants for a particular water body.

Let's have a more detailed look at a process of water reservoirs' chemical composition forecasting.

A long-term forecast of water reservoir's chemical composition is prepared for its least operational level over the estimated period (year, season, calendar month).

When conducting forecasting calculations for channel reservoirs with a water exchange coefficient exceeding one it is advisory to accept the fact that river water gradually displaces the one discharged through a reservoir's dam with complete mixing with intermediate inflow water. Lag time period should be determined by the time required to fill a whole reservoir with water considering the volume of all inflow types. The following formula is used for calculations:

$$\tau = V \big/ \overline{Q}_{fw}, \tag{3.18}$$

where V - volume of water in a reservoir taken for a period in question, m^3;

$\overline{Q}_{fw}$ - average flow of water leaving a reservoir for a period in question, m^3/day.

Regardless of the time when previous period ends a lag time period should be chosen to ensure that the time when such lag period ends falls on the beginning of a period in question.

Calculation of weighted average mineralization of lagged water or concentration in it of conservative pollutants is performed using the formula:

$$C_{wam} = \frac{C_r V_r + \sum C_{in_i} V_{in_i} - C_{ice} V_{ice} + \left(C_{m.i.} V_{m.i.}\right)}{V_r + \sum V_{in_i} - V_{ice} + \left(V_{m.i.}\right)}, \tag{3.19}$$

where C_r - weighted average mineralization of water corresponding to Q_{r_i};

V_r - volume of river flow for the period in question with average flow Q_r;

C_{in_i} - average ingredient's concentration in water of i-th inflow for the period in question;

V_{in_i} - volume of flow of i-th inflow for the period in question;

$C_{ice}, C_{m.i.}$ - concentration of a considered ingredient in ice (in terms of mineralization this value is approximately 12% of mineralization of water which turned into ice, in the absence of data these parameters are not taken into account);

$V_{ice}, V_{m.i.}$ - volume of reservoir's water which turned into ice and than melted.

For the water flowing from a reservoir to a tailbay over the period taken for forecasting purposes average mineralization or average concentration of conservative substances in water should be calculated using the formula:

$$C_{cs} = \frac{100\overline{C}_m}{100 - \eta}, \tag{3.20}$$

where η - evaporated or frozen water for a lag time period τ, %

This method is also used to forecast rivers' chemical composition, pollutants inflow with industrial wastewater, water discharged from utilities systems, mine waters and surface runoff from urban areas.

Exercises and questions for self-checking

1. Which factors determine forming of chemical composition of river waters?
2. What methodological substantiation of operational forecasting of water quality values is used?

3. What is conceptual model of operational forecasting of water quality?
4. How to select the forecasting methods?
5. How to assess and analyse the accuracy of operational forecasts?
6. What are methods of long-term forecasting of changes of chemical composition and quality of surface waters?

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Навчальне видання

Шакірзанова Жаннетта Рашидівна
Гопченко Євген Дмитрович
Овчарук Валерія Анатоліївна
Кічук Наталія Сергіївна

КУРСИ ПІДВИЩЕННЯ КВАЛІФІКАЦІЇ ТА ПЕРЕПІДГОТОВКИ ФАХІВЦІВ
«МОДЕЛЮВАННЯ ПОВЕРХНЕВИХ ВОД СУШІ»

Конспект лекцій

Підп. до друку Формат Папір друк. №
Умовн. друк. Арк. Тираж Зам. №

Надруковано з готових оригіналів – макетів

Одеський державний екологічний університет
65016, Одеса, вул. Львівська, 15