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Water Discharge Measuring Instruments: an up-to-date Overview

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Technological progress could not but affect the sphere of hydrometric measurements. New instruments have been implemented to add to such traditional measuring instruments as mechanical current meters or to replace them. Over the past 20 years, the number of different types measuring instruments has increased dramatically. That is why the analytical review and classification of these devices are needed to help with making appropriate management decisions in the field of streamflow monitoring and surveys. The article presents the multivariable classification of measuring instruments, based on such factors as: morphology scaling (channel width and depth), measuring conditions (open, weed or ice-covered channel), logistical factor (mobile or stationary) and required accuracy. Characteristics of each type of measuring instruments were also considered and the limitations of their applicability were described. The results presented in the paper are expected to expand the horizons of approaches used for estimation of water discharge.

Keywords – current meters, water discharge, ADCP, open channel flow measurement classification

I. Problem introduction

The classifications of instruments, used for velocity of the streamflow measuring and further calculation of water discharge, published earlier, are focused on the environmental components and sustainability [1], or on the methods of the physical essence [2], or give general ideas that allow management decision making [3]. One of the last attempts to do such an analytical work in the field of flow measurements was undertaken by Indian scientists under the leadership of Senthil Kumar J [4]. It is worth noting the huge range of the materials covered as well as in-depth development of the ultrasonic flow measurement accuracy tasks, but focused more on pipe- and artificial channel-based equipment. However, this review is not suitable enough for solving problems of instrumental equipment in the field of river (open channel measurements) hydrology and meeting the objectives, outlined in the abstract of this article.

Russian and foreign guiding normative documents in the field of hydrometeorological monitoring and surveys [5, 6] do not provide comprehensive information in a quick and easy-to-use way either. They do not describe all measuring instruments that can be used to measure velocity or any other characteristics, which can be further used for water discharge calculation. Present review is multi-criteria, and each of the above criteria is aimed at the presentation of information about the limits of applicability of a particular method or measurement instrument. In other words, the classification presented in this article can be characterized as applicability-based.

II. Classification idea

This multi-criteria classification was developed in order to answer the most challenging and reasonable questions related to the performing the hydrological surveys and monitoring, forming certain level (classifiers) of the classification:

1. Is it necessary to make measurements on-site (continuously) or to make one-time in-situ measurements as part of field work by portable devices? This is how the "Logistic classifier" (A) is formed, or the subdivision into stationary (on-site) and portable measurement instruments, which applicability is limited to use in field surveys.
2. What is the size of the stream on which the measurements are supposed to be made? The answer to this question in a view of expected depths and widths of the channel forms the second level of classification (B) "River-morphological scale".

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3. What are the hydrodynamic and associated with it conditions on the river where the measurements are supposed to be made (flow regime, the possibility of immersion of the device)? This is how the third level of grading of the classification (C) "Flow regime and hydrodynamic conditions".
4. What type of devices or methods can be used to determine water discharge, corresponding to a particular previous level of gradation? The (D) "Method or instrument type" level of the classification contains the answer to this question.
5. What is required accuracy of estimating water discharge of a river? The using of color level "expected accuracy" (E) aims to solve this problem.
6. Is it possible to use any other device in unfavorable conditions such as freeze-up channel, high turbulence or when a measuring device or a person, carrying out measurements, is not safe? You can understand this from the graphical classifier (F) "Measurement conditions".
7. Which of the instrument is the most frequently used of those given for a particular classifier? The (G) "Usage frequency" classifier is about it.

The first level (A) realized in the benchmark of this article use two different classifications – for the portable (Figure 1) and on-site instrumental solutions (Figure 2). Levels B and C are implemented directly as branches of one large classification hierarchy. Level D uses a verbal description at one level or another. Classifier E is implemented in the form of shading a block of one or another classification level in the color of the corresponding measurement accuracy. Classifier F is an additional graphic designation in a view of round sign above one or another type of measuring instrument on the right or left above. G level is a sequence of devices in a block of one level - more frequently used devices are locating higher than less used ones within a block of one level.

III. Classification Levels

A. The first "Logistic" level of classification divides instruments into stationary (on-site) and portable (in-situ). Stationary devices can operate autonomously, or have such a mode, measuring certain characteristics of the river with the subsequent continuous calculation of water discharge. This is their undoubted advantage, but, even in the time of fast technical progress, the choice of such devices is very limited, and the cost is often very high. It is also worth noting the high research intensity of maintaining the operability of such devices. This requires highly qualified staff that would be responsible for the engineering and manufacturing development, correct installation, operation and maintenance of such equipment. Most of the on-site high-accuracy devices are intrusive, while non-intrusive allow measurements only for general monitoring purposes (accounting for water resources, hydro ecological issues and etc.). Nevertheless, current tendency to transfer national observation network equipment to autonomous regime has been obvious.

Stationary devices include following instruments and methods: hydrometric units of Hydro-electric power stations HEPS (turbines and weirs), hydrometric structures (weirs, flumes); non-contact Doppler and ultrasonic radar flow meters; the slope-area method with using two precise water level gauges; on-site autonomous image velocimetry systems using high-resolution cameras and satellites; bottom submersible and river bank-side ADCP and ultrasonic devices and measuring systems; indirect methods using hydrochemical or physical parameters, stationary tracer dilution and rising bubbles facilities; tilt current meters; noise component analysis method.

Portable instruments and devices are widely spread in hydrological surveys, and actually have achieved a huge number of variations based on vastly different principles. Such devices are used for in-situ measurements, as a rule, by immersing the instrument in the water column or using image velocimetry or radar impingement, or making measurements remotely using drones, aircrafts or satellites. Almost all the devices listed as stationary have portable versions (excluding HEPS facilities). In the field conditions it is also possible to use volumetric and float methods; mechanical, electromagnetic and pressure operated current meters and moving-vessel ADCP devices.

B. "River morphological scale" level aims to classify streams to *creeks*; *minor, medium and large* rivers by morphological principle and *estuaries* by the current distribution factor (with variable backwater phenomena and complex, unique for estuarine areas structure of currents). It is important to realize that this division is not based on the traditional classification of rivers (by the catchment area), but according to the features of using certain measuring instruments and equipment related to them.

The creeks are constituted in a separate category due to the difficulty of immersing the instrument into the water column. That is why the limiting factor for them is a depth of 0.05 m (half of the sensor or propeller diameter of the vast majority of the mechanical or other types of the immersed current meters). Furthermore, it is true (especially for the creeks) that measurements are suitable for volumetric method and portable weirs and flumes.

Minor rivers are characterized by a depth of less than 1.3m - the depth of the river wading.

Medium rivers are determined by the channel width of 100 m - the maximum possible distance between the supports (armors) of hydrometric installations (meter-suspension cables, towing systems and cableways).

Large rivers include rivers where it is impossible to perform measurements from a cableway or towing system. Measurements on large rivers are associated with large labour inputs and large number of additional equipment in the case of using traditional submersible measuring instruments (cranes, balance weights, anchors, reliable floating crafts).

C. "Flow regime and morphological conditions" classifier subdivides rivers into *mountain or sub-mountain and plain*. The slope of the water surface can be considered as a classifying parameter at this level. In such a way, rivers or river sections with slopes of more than 0.2 ‰ are considered to be *semi-mountain*, more than 5 ‰ – *mountain*, less than 0.1-0.2‰ - *plain* or low-land [6]. The slope of the rivers can integrally characterize the hydraulic characteristics of the flows. There are such characteristics for mountain and semi-mountain rivers: a turbulent flow regime, the formation of whirlpools, waves, high flow rates reaching several meters per second. For the plain rivers - a quasi-stationary regime, mild turbulence, low and medium current velocities around 0.1-1 m/s, meandering are specific.

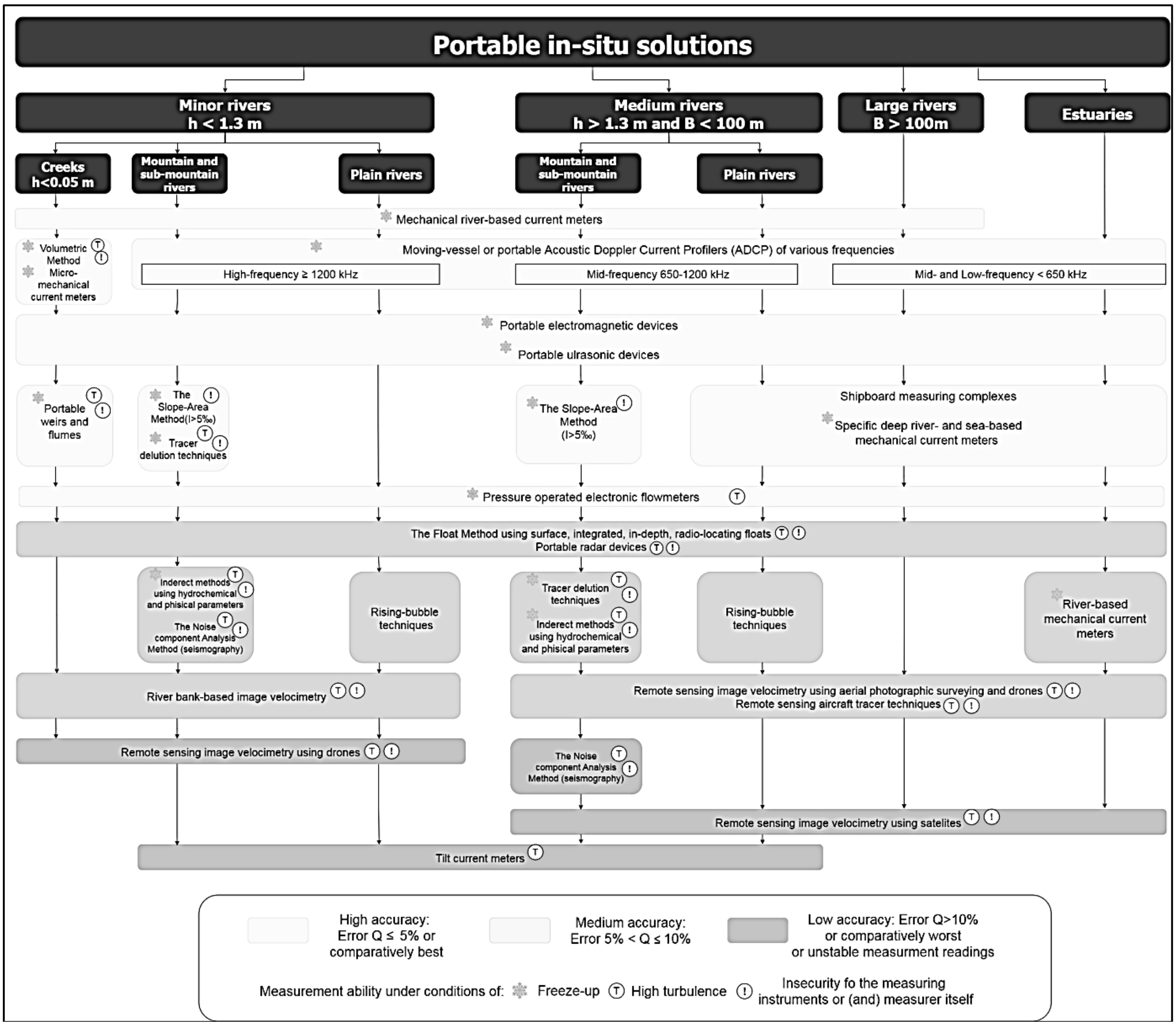

Fig. 1. Portable in-situ instruments and methods for determining water discharge classification (the best quality image can be viewed on the website of the State Hydrological Institute (SHI) [7])

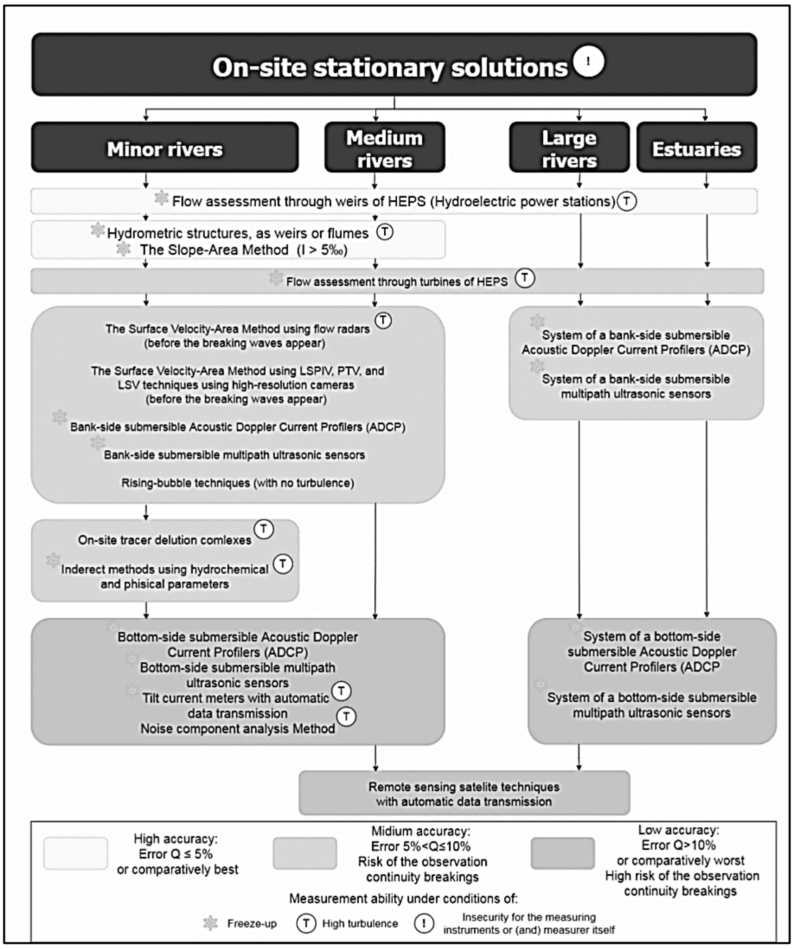

Fig. 2. On-site stationary instruments and methods for determining water discharge classification with (the best quality image can be viewed on the website of the State Hydrological Institute (SHI) [7])

D. At the "Method or instrument type" described different methods or types of the measuring instruments. Below follows the basic principles of operating of the most frequently-used particular method or type of instruments will be briefly considered (with further recommendations on which sources can be found for more detailed information).

Mechanical current meters are the most widely used instruments for measuring current velocity with further calculation of water discharge at the moment. The velocity of flow at a point is proportional to the rate of rotation of the rotor during a fixed period of time.

To date, there has been a huge range of devices manufactured by different countries of the world. In existing models there are such important tasks as: the possibility of fixing simultaneous velocity (due to the use of single-threaded screw with hermetic contact); operation on shallow depths (by reducing the rotor diameter); measurements of low velocities (due to the use of light structural materials of the rotor, increasing its sensitivity); operation under skew-jet conditions (by optimizing the component effect). Besides can be identified: optimized rotor and housing materials and recording and support equipment. According to the level of development of the principles of hydrometric instrumentation (production mechanical flow meters) countries of the world today have approximately the same level. Significant differences lie in the quality of the devices. The devices are manufactured with cup-type and propeller mechanisms [8]. The range of recorded velocities for the river mechanical current meters is from 0.04 m/s to 4-6 m/s and from 0.025 to 2-6 m/s for micro-ones. Specific deep- and sea- based mechanical current meters allow more accurate measurement of velocity when there are reverse currents and high pressure.

Despite the apparent completeness of the development of hydrometric mechanical current meters, there are *unsolved problems* as well. These include [8]:

- lack of an optimal ratio of sensitivity - component, when an increase in the sensitivity of the device would not lead to a significant deterioration component qualities and vice versa (the issue is solved by the layout of the current meter by several replaceable rotors);

- lack of consensus on the influence of the relative diameter of the propeller and its disk-area ration to somewhat different the component properties of the device;
- unsolved issue of ensuring uninterrupted operation of the device in complex conditions (frost, increased mineralization, channel weed);

Methodological aspects of mechanical current meters measurements are outlined in any of the guidelines for stream gauging, for example [9].

Acoustic principle instruments – an Acoustic Doppler Current Profilers (ADCP) and ultrasonic devices. There are two basic types of acoustic current meters: Doppler and Travel Time. Both methods use a ceramic transducer to emit a sound into the water. Doppler instruments are more common. The ADCP works by transmitting "pings" of sound at a constant frequency into the water. As the sound waves traffic, they ricochet off particles suspended in the moving water, and reflect back to the instrument. Due to the Doppler effect, sound waves bounced back from a particle moving away from the profiler have a slightly lowered frequency when they return. Particles moving toward the instrument send back higher frequency waves. The profiler sends out difference in frequency between the waves and the waves it receives is called the Doppler shift. The instrument uses this shift to calculate how fast the particle and the water around it are moving. There are four main types of ADCP devices: portable, moving-vessel and river bank- or bottom immerse-based stationary ones.

Travel time instruments determine water velocity by at least two acoustic signals, one up stream and one downstream. By precisely measuring, the time when water have to travel from the emitter to the receiver, in both directions (the average water velocity) can be determined between the two points. By using multiple paths, the water velocity can be determined in three dimensions.

Travel time meters are generally more accurate than Doppler meters, but they are only record the velocity between the transducers. Doppler meters have the advantage that they can determine the water velocity at a considerable range, and in the case of an ADCP, at multiple ranges.

Acoustic principle-based instruments cover a wide range of measurable velocity from 0.003 m/s to 5-10 m/s in both directions of speed with the accuracy less than 10% for the computed discharge. The profiling depth depends on the frequency of the emitter: for example, high-frequency (1200kHz) ADCPs measure velocity at depths in the range from 0.1 to 7-8 m, medium-frequency (600kHz) - from 0.15-0.2 to 30-40 m, low-frequency (300 kHz or less) - from 1-2 m to 100-300 m for river device versions. In the short term, these devices can replace mechanical current meters due to low labour inputs for measuring and obtaining flow velocities throughout the water column. This process is held back mainly only by high prime cost of ADCPs and Travel Time techniques.

There are many manuals and guidelines for measuring water discharge with ADCP. It might be advised the following ones: [10] for moving vessel measurements and [11] for measurements under ice cover. For using ultrasonic devices there are no regulatory papers yet, but plenty of articles, for example, ones of Japanese researchers [12].

Electromagnetic current meters. The motion of water flowing in a river cuts the vertical component of the Earth‘s magnetic field, and an electromotive force (E_{mf}) is induced in the water, that can be measured by two electrodes. This E_{mf}, which is proportional to the average velocity in the river, is induced along each traverse filament of water, as the water cuts the line of the Earth’s vertical magnetic field. The basic system of an electromagnetic gauging station consists of a coil placed in the bed and the magnetic field, that are induced in the x direction. Since the stream flow is in the z direction, the E_{mf} will be in y direction. Faraday’s law of electromagnetic induction relates the length of a conductor moving in a magnetic field to the E_{mf} generated. The electromagnetic method can be suitable for use in rivers with weed growth, high sediment concentration, or unstable for bed conditions. This method gives a continuous record of the average velocity in the cross-section that can be combined with stage to given an on-site output of discharge [13]. But more often such devices are in portable version.

Their use is governed by the same principles as for mechanical current meters. However, it is worth noting that the measurement methodology should be a little different, but this is not reflected in any of the manuals at the moment. The point is mainly in the approach to averaging the obtained velocity values and their interpretation. Electromagnetic devices are very vulnerable to the direction of flow, therefore they often underestimate the value of the velocity, registering its vector on one or another projection [14]. But this problem is solved by a competent methodological approach (for example, it is possible to recommend taking into account the maximum from the 3-5 measured values with the holding period necessary for the certain flow regime). It is worth noting the low initial threshold of the measured flow velocities - about 1 mm/s, which distinguishes this instrument from a number of others. At the same time, the measurement accuracy is only slightly lower. The upper limit of velocity measurement is 5-10 m/s.

POEM (Pressure Operated Electronic Meter). Depth and velocity measuring instrument that uses a forward-facing pitot tube on the front of a streamlined weight, that houses velocity and depth sensors. This instrument is best suited to flooded river measurement as the POEM is not precise at water velocities <1 m/s. The average velocity for the vertical is calculated in the POEM software by integrating the depth and velocity readings. Pitot tubes, in one version or another, are also used in laboratory conditions, for measurements on minor streams and creeks [15].

An in-depth comparative study of the tools given above is described in the article [16].

Hydrometric structures. This type includes hydrometric flumes, weirs, hydroelectric power plants of various capacities. As a rule, the water discharge for this type of measuring facilities is determined depending on the water level (or gross head) or recalculated from the characteristics of the hydropower-plant capacity (for HEPS).

It is worth noting the high accuracy of the water discharges obtained in this way, while the main *limiting factors* in the use of structural measures are the large labour inputs during the construction of the structure (and further intrusive impact on the natural self-regulating fluvial-stream system) and the scale of the watercourse. Thus, the maximum flow capacity for hydrometric flumes and weirs does not exceed 50 m^3/s (the minimum is about 60 ml/s).

The construction of HEPS is limited by the commercial importance of its construction, while their throughput capacities can vary from 0.5 to 500 m^3/s for small HEPS, and more than 100 000 m^3/s for large ones. Modern technologies make it possible to automate the process of obtaining a water discharge, which ensures the continuity of observations, and it is an undoubted *advantage*. The practical aspects of using structural flow metering facilities are well covered in [17], methodological aspects – in [18].

Volumetric methods. The simplest way to estimate water discharge of creeks is by direct measurement of the time to fill a container of known volume. The flow is diverted into a channel or pipe which discharges into a suitable container, and the time to fill is measured by stopwatch. The time to fill must be measured accurately, especially when there is only a few seconds. The variation between several measurements taken in succession will give an indication of the accuracy of results.

If the water flow can be diverted into a pipe then it is discharged under pressure, the rate of flow can be estimated from measurements of the jet, or the water column height in the case of vertical upward dislocation. *The main limitation* of the method is a quite low range of possible measuring discharges – from vanishingly small to 50 l/s.

Dilution techniques. The basic principle of dilution gauging is to add a known quantity of a tracer to a stream and to observe its concentration in the stream at a point where it is fully mixed with the flow. The higher the flow is, the more it dilutes the tracer. Dry salt that used as the tracer must be injected at a point that favours rapid dissolution. This creates a salt solution in situ that then disperses into the flow aided by turbulence in the water column. The resulting concentration of salt is measured as electrical conductivity (at a point downstream of the injection point where it is completely mixed). The distance between the injection and measurement points is known as the mixing length (L). The dispersion pattern of conductivity over time is similar in shape to a storm hydrograph. Streamflow Q is calculated dividing the mass of salt (in grams) M by the area under the graph of concentration over time (A). The units of A are milligram-seconds per litre (equivalent to $g \cdot s/m^3$).

Dilution method-based measuring devices are available in both portable and stationary versions. Errors, with meeting all the requirements [19], for turbulent flows with active mixing should not exceed 5-10%, but due to the complexity of dilution processes and hydrodynamic factors for flows unsuitable for measurement by this method, because they can reach 200-300% [19]. In general, this approach can be recommended for mountain rivers with turbulent current and water discharge up to 5-10 m^3/s. Detailed information about the method is presented on the website [19].

Within the scope of this article, it is impossible to cover the entire range of possible water discharge determining equipment, only the main ones have been described above. For less common methods oriented towards more scientific studies, links to research will be provided below. Full information on the applicability of certain means is contained in the classification itself (Figures 1 and 2).

For the slope-area method look at [6], indirect methods using physical and hydrochemical parameters - [20], noise component analysis method [21], tilt current metering - [22], LSPIV (PIV) remote non-intrusive techniques – [23] and the rising bubble techniques – [24].

E. The classifier "Required measurement accuracy" is implemented in a graphical form in a view of shading blocks in one color or another (for more details, see the legends of Figures 1 and 2).

F. Classifier "Possible measuremnent conditions" is an additional graphic designation in round frames above one or another type of measuring instrument on the right or left above. It indicates whether unfavorable conditions as freeze-up channel, high turbulence or conditions of insecurity for the measuring instrument or measurer itself are possible. Special attention should be focused on instruments that are capable for making measurements in insecure conditions, when there is no way to enter the stream (trees carried, large debris, ice floes by the stream and other factors).

Instead of Conclusion

Due to constant technological and scientific progress, the classification presented is doomed to be updated and refined. Therefore, the developers are waiting for your remarks, additions and comments at lgpggi@yandex.ru. By joint efforts, the development of this classification will be faster, and its scientific and practical value will increase.

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