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Comparing the Efficiency of River Water Quality Parameterization by Different Methods Under a Significant Human-Induced Impact

M. B. Zaslavskaya*, O. N. Erina and L. E. Efimova*****
Moscow Lomonosov State University, Moscow, 119991 Russia
**e-mail: m.zasl@mail.ru*
***e-mail: tamiblack@yandex.ru*
***e-mail: ef_river@mail.ru*

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Abstract—We examine the different approaches in assessing the water quality of water bodies located within the territories with a significant human-induced impact. The hydrological region of Norilsk was used as a test site. The data used in the analysis characterize the period between 2001 and 2003; however, they are still relevant because of a high level of human-induced impact on water bodies. For the purposes of parameterization, the water quality indices which are being most abundantly used in Russia and abroad were evaluated. Results from parameterizing the water quality, obtained by various methods and combined into an overall scheme, were used to generate the rating scale for assessing the hydro-ecological status of aquatic ecosystems. These calculations show that the method of Specific Combinatorial Water Pollution Index (SCWPI) established by the departmental standard of the Federal Service for Hydrometeorology and Environmental Monitoring of Russia (Rosgidromet) provides the most objective water quality assessment for water bodies experiencing a significant human-induced impact. Similar results also apply for water quality parameterization using the Canadian CCME WQI method, which is confirmed by the closeness of correlation between the values of these indices. According to the SCWPI method, in none of the streams was the hydro-ecological status assessed as "normal". In the sources of four rivers, it was found to be close to class 1, and their hydro-ecological status was assessed as "risk". The water in 11 measuring sections corresponds to quality class 3, or a "critical" status of the aquatic ecosystem. In 12 measuring sections corresponding mainly to the estuarine segments of the rivers and some brooks, the hydro-ecological status of the1 water bodies is characterized as "disaster", i. e. the water pertains to quality class 4 and 5. Furthermore, in none of the water bodies under study is the environmental "catastrophe" not recorded.

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Keywords: water quality, parameterization, ecological status, river runoff, pollution of water bodies, waste water.

FORMULATION OF THE PROBLEM

Water pollution can lead to hazardous changes in its chemical composition and, hence, to the deterioration of quality and consumer properties. The influence of anthropogenic load on water quality is manifested mostly in an integral form. Assessments of pollution of surface water bodies are usually made on the basis of comparing actual concentrations of chemical substances with the established standards of their maximum allowable concentration (MAC) in the water. Such an approach implies using standards which are ecologically ineffective and incompatible with the goals of ecological control over the water environment and involve invoking MACs determined in the laboratory. Furthermore, in spite of the severely criticized system of standardization, an appropriate alternative is lacking to date [1]. The methods of assessing pollution of water bodies are based on hydrological, hydrochemical and hydrobiological data obtained by using the monitoring system. With improvements in this system, the parameters monitored become complicated further, and their number increase. This situation may well lead to the fact that processing and interpretation of such a large amount of data can become highly complicated. In an effort to overcome these challenges, specialists of many countries developed classification schemes in which data obtained from monitoring a water body could be compared with standard criteria of water quality assessment. They are represented by a set of quantitative indicators characterizing the properties of water bodies under study and are used for their classification and ranking [2]. The pollution assessment of a water body includes the procedure of parameterizing the water quality characteristics:

determining and substantiating the ranges of variation of water quality parameters corresponding to an increase or decrease in safety for the population and economy as well as aquatic biocenoses. Such an interpretation of the term "parameterization" makes it possible to reconcile the procedure of parameterizing water quality characteristics with diagnostics of the occurrence of changes in ecological status of rivers [3, 4]. The beginning of efforts to standardize and normalize unfavorable impacts in the developed countries of the world is referred by many researchers to the first half of the 1970s. [5]. A large number of methods of parameterizing natural water quality have been published to date [1, 6–8]. Selection of the most representative methods is difficult due to lack of comparisons of results on the effectiveness of their use in different landscape conditions of the formation of the water chemical composition and the degree of economic development.

OBJECTS AND METHODS

In the first stage of this study, we used as the test territory the Norilsk hydrological region characterized by the duration of the series of hydrological-hydrochemical observations as well as by a broad range of spatio-temporal variability of water quality parameters. Use was made of monitoring results on surface water bodies: receivers of waste waters, obtained by the Experimental Eco-analytical Center (Transpolar Branch, Norilsk Nickel JSC) during 2001–2003.

The territory of the Norilsk hydrological region refers to the mountain-taiga zone with patches of forest-tundra and birch-larch sparse forest. The main water bodies of the region are Lake Pyasino located at the foot of the northwestern spurs of the Putorana plateau and its tributary, the Noril'skaya river (the Talaya river in its upper reaches which receives several large tributaries: the Rybnaya, Nalednaya, Valek, Talnakh, Kharaelakh, Tomulakh, Ambarnaya, Shchuchya and other rivers. The territory of the region under consideration has a number of lakes and reservoirs which serve as water sources and receivers of effluents from the Norilsk Mining and Metallurgical Combine: Kyllakh-Kyuel', Dolgoe, Tikhoe, Podkamennoe and other lakes as well as the Kharaelakh reservoir. The chemical composition and hydrological-hydrochemical regime of the water bodies in the Norilsk hydrological region are determined by the natural characteristics of the study area as well as by the technogenic factor: the impact of waste waters from the various production facilities of the Norilsk Mining and Metallurgical Combine [9].

The main natural factors of formation of the chemical composition and hydrological-hydrochemical regime of the rivers in the study area include high hydraulicity, a high degree of flow control because of large lakes within the basin (their total area makes up 10% of the basin's total area), and a very important role of groundwater alimentation in the overall river discharge (15% for the Noril'skaya river, and 10–15% for the Shchuchya, Ambarnaya and other rivers). The beginning of hydrological studies of the water bodies within the Noril'skaya river basin dates back to 1937 and coincides with the period of construction of the city of Norilsk, and hydrochemical observations were begun only in the 1960s together with industrial development of the Norilsk and Talnakh deposits. This suggests that during the 1960s–1970s the anthropogenic sources made an important contribution to formation of the chemical composition of the natural waters in the study area which might be conventionally considered as a background. At that period, in conditions of a sever climate, excess humidity, permafrost and well-washed soil-ground, the Norilsk hydrological region developed low and moderately mineralized waters of carbonate-calcium composition, with low content of organic matter. The mineralization of the river waters during seasonal floods varied from 10 to 75 mg/dm^3, and during wintertime low-water periods from 50 to 150 mg/dm^3. An important feature in low-mineralized surface waters of the study area is an increased content of sulfate ions (up to18–25% eq). The reason for this can be the presence of ores saturated with sulfates, a widespread occurrence of karst phenomena in the presence of gypsiferous rocks, and numerous groundwater outcrops in the wintertime in the form of sources and aufeis when the river runoff is dominated by subsurface waters [9].

An important role in the total volume of river discharge is played by waste waters from the enterprises and residential sector of the mining and metallurgical combine which discharged during 2001–2003 untreated and inadequately treated waste waters from a large number of production facilities. A substantial impact on the transformation of the chemical composition of natural waters was also made by the agrotechnical transport of industrial dust containing metals, such as nickel, copper, lead, and others, as well as large amounts of sulfur dioxide (by-product in the extraction of nonferrous metals). The distribution of the volume of waste discharges for different water bodies is uneven. More than 95% of the total polluted discharges correspond to the Shchuchya, Talnakh, Ambarnaya and Novaya Nalednaya river basins. Most of pollutants in the water are represented by nitrates, iron, nickel and copper, suspended matter, sulfates, chlorides, biogenic matter, petroleum products, and synthetic surfactants (SSF), including a significant group with a critical (CP) (51–100 MAC) and extremely high (EHP) (> 100 MAC) pollution level [9].

For comparing the effectiveness of parameterization of surface water quality, out of a large number of methods developed across the globe, we selected the most widely used in Russia as well as several indices which are successfully used by monitoring services in other countries of the world.

In Russia, the index based on calculating the hydrochemical water pollution index (WPI) has been used for the longest time [10]. Water pollution classes correspond to particular ranges of variation of the value of WPI (Table 1).

Its more advanced version is represented by the “Comprehensive classification according to the Specific Combinatorial Water Pollution Index (SCWPI)” [8, 11–14]. This method can be used to make a differentiated (for separate indicators) and comprehensive assessment of water pollution for the entire group of measured indicators. The main advantage of the method implies taking into account not only the degree of exceedance of the standard value of each water pollution indicator but also the frequency of this exceedance. This classification has been introduced in the Rosgidromet network instead of WPI.

The SCWPI-based classification of water quality makes it possible to identify five classes according to the degree of water pollution (see Table 1). Categories are singled out to achieve a large differentiation within class 3 and 4. In the case where the generic assessment point ≥ 9, a critical water [pollution index (CPI) is singled out and taken into account in the gradation of quality classes.

In addition, we used the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI, or Canadian WQI) which has the computational scheme similar to SCWPI [15]. It is used extensively worldwide in characterizing surface water quality [16–20].

The calculation is based on taking into consideration three factors: the number of components showing an exceedance of standards, and the frequency and multiplicity of their exceedance. The resulting value can vary from 100 (the most favorable status) to 0 (unfavorable). This classification involves five water quality classes (see Table 1).

The aforementioned methods of water quality parameterization taking into account the sets of hydrochemical indicators used for that purpose characterize total chemical pressure on a water body. The other group of classifications uses only those chemical and physicochemical parameters which influence the intensity of biochemical and biological processes in a water body.

One of the most powerful methods of this type (the Bavarian method) was developed in Germany by the Bavarian State Office of Water Management. The method is based on assessing the value of the chemical index of river water quality (CJ) characterizing its generalized (integral) value in the form of one number [6, 7]. Depending on the resulting value, the degree of water pollution is determined. The water quality parameterization procedure involves determining the water quality class or its intermediate variants according to the degree of water pollution. The chemical index can vary from 100 (the most favorable status) to 0 (unfavorable).

Comparison of the classifications is complicated by the employment of different sets of indicators as well as by the number of quality classes available. Thus, the CCME WQI and CJ methods use the minimum number of components (6 and 8, respectively), whereas the number of indicators taken into account in SCWPI and CCME WQI is unlimited; however, there a mandatory

Table 1. Gradations of surface water quality as identified by different classifications

Water quality class	SCWPI		WPI		CJ		Canadian WQI	
	1	2	1	2	1	2	1	2
1	1.0	Conventionally clean	≤ 0.3	Very clean	83–100	From none to light	95–100	Excellent
2	1.01–2.0	Weakly polluted	0.3–1.0	Clean	73–83	Light	80–94	Good
3	2.01–4.0:	Polluted	1.01–2.5	Moderately polluted	56–73	Moderate	65–79	Satisfactory
a	2.01–3.0	Polluted						
b	3.01–4.0	Strongly polluted						
4	4.01–11.0	Dirty	2.51–4.0	Polluted	44–56	Critical	45–64	Critical
a	4.01–6.0	Dirty						
b	6.01–8.0	Dirty						
c	8.01–10.0	Very dirty						
d	10.01–11.0	Very dirty						
5	> 11.0	Extremely dirty	4.01–6.0	Dirty	27–44	Strong	0–44	Poor
6	–		6.01-10.0	Very dirty	17–27	Very strong	–	
7	–		< 10	Exceptionally dirty	0–17	Excessive	–	

Note. 1 – value of the index, 2 – characteristic of water quality according to the value of the index. Dash – the index or characteristic is absent in a given classification.

list of 15 characteristics for the former method, and the authors of the latter method recommend that at least four key components be used.

RESULTS AND DISCUSSION

For comparing the methods of parameterizing the surface water quality in the Norilsk hydrological region, a unified scale of water quality classes was developed. The boundary values of the ranges of variation in indices of some classes were revised. As a result, six classes (Table 2) were identified in all the water quality parameterization methods, unlike their original variants consisting of five or seven classes (see Table 1). In the SCWPI classification with five classes only (without regard for the categories), an additional class was singled out, which was obtained by dividing class 4 in two, encompassing an extremely broad range of variation of the index. In this manner, categories 4c and 4d of the original classification were combined into a separate class 5, and class 5 became class 6.

The first two classes as identified by the WPI technique are combined into one, because of a very narrow range of variation in the values of the index for class 1 and 2 in the original classification (≤ 0.3 and 0.3–1.0, respectively). Thus the range of WPI values for the water of class 1 in the suggested variant as 0–1, and the total number of classes decreased to six (see Table 2). For the same reason, in the Bavarian method, class 6 and 7 of the original technique were combined, as a result of which the range of values of the index for class 6 in the suggested variant of the scale varied from 0 to 27.

The Canadian technique remained unaltered. Classes of water quality parameterization were compared with the scale of Hydroecological status of water bodies in the following way: class 1 – "normal", 2 – "risk", 3 – "crisis", 4 and 5 – "disaster", and quality class 6 – "catastrophe" (see Table 2). As a result, a unified scale was obtained for parameterization of the hydroecological status of the water bodies by using different water quality classifications.

The surface water of the test water body shows a high heterogeneity in water quality assessments and, accordingly, in the ecological status of the water body when a particular parameterization method is used.

The Bavarian index (CJ) assesses the Hydroecological status of streams as the most favorable: in 17 of 27 water quality measuring sections, it refers to class 1, which corresponds to normal. Since such assessments are not confirmed by the other classifications under consideration, the Bavarian index cannot be considered effective in the case of the streams considered. This method has a fundamental shortcoming that prevents its use on water bodies with a strong degree of anthropogenic disturbance of the chemical composition, i. e. a firmly established list of indicators. This classification takes into consideration indirectly the ecosystem requirements, which makes it more suitable to diagnosing the degree of well-being of the ecological status of water bodies used for fisheries purpose. However, within river basins where a significant influence on formation of water quality comes from industries, it is necessary to take into account specific pollutants which lead to the degradation of aquatic ecosystems.

A very mixed picture emerges from the parameterization of water quality according to the values of WPI. In four measuring sections, the Hydroecological status of the water bodies is estimated

Table 2. Combined table of methods of parameterizing surface water quality and assessing the hydroecological status of water ecosystems

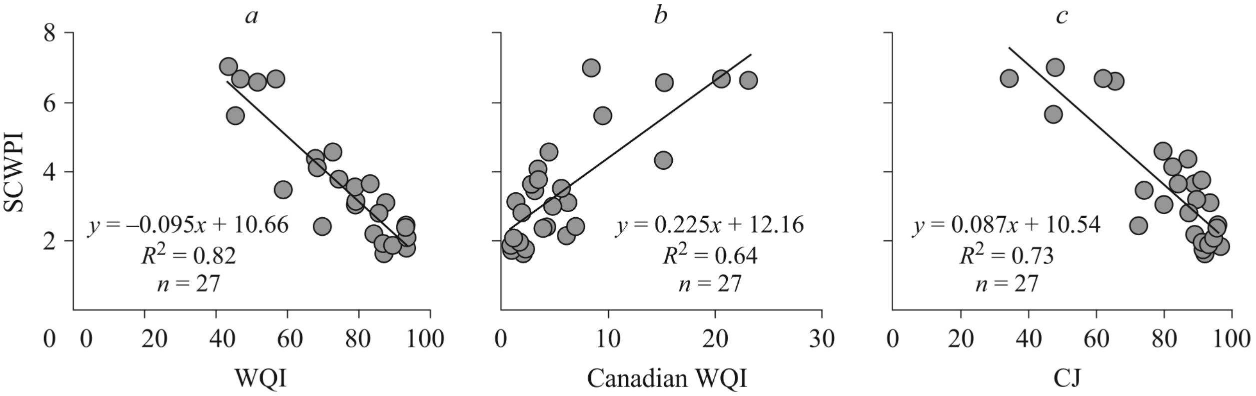
<table>
<tr><th rowspan="2" colspan="2">Parameterization method</th><th colspan="7">Water quality class</th></tr>
<tr><th colspan="2">1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th></tr>
<tr><td rowspan="2">SCWPI</td><td>Value</td><td colspan="2">1</td><td>1.01–2.0</td><td>2.01–4.0</td><td>4.01–8.0</td><td>8.01–11.0</td><td>> 11</td></tr>
<tr><td>Characteristic</td><td colspan="2">Conventionally clean</td><td>Weakly polluted</td><td>Polluted</td><td>Very polluted</td><td>Dirty</td><td>Extremely dirty</td></tr>
<tr><td rowspan="2">WPI</td><td>Value</td><td>≤ 0.3</td><td>0.3–1.0</td><td>1.01–2.5</td><td>2.51–4.0</td><td>4.01–6.0</td><td>6.01–10.0</td><td>> 10</td></tr>
<tr><td>Characteristic</td><td>Very clean</td><td>Clean</td><td>Moderately polluted</td><td>Polluted</td><td>Dirty</td><td>Very dirty</td><td>Exceptionally dirty</td></tr>
<tr><td rowspan="2">CJ</td><td>Value</td><td colspan="2">83–100</td><td>73–83</td><td>56–73</td><td>44–56</td><td>27–44</td><td>0–27</td></tr>
<tr><td>Characteristic</td><td colspan="2">From none to light</td><td>Light</td><td>Moderate</td><td>Critical</td><td>Strong</td><td>Very strong, excessive</td></tr>
<tr><td rowspan="2">Canadian WQI</td><td>Value</td><td colspan="2">95–100</td><td>80–94</td><td>65–79</td><td colspan="2">45–64</td><td>0–44</td></tr>
<tr><td>Characteristic</td><td colspan="2">Excellent</td><td>Good</td><td>Satisfactory</td><td colspan="2">Critical</td><td>Poor</td></tr>
<tr><td colspan="2">Total assessment of hydroecological status</td><td colspan="2">Normal</td><td>Risk</td><td>Crisis</td><td colspan="2">Disaster</td><td>Catastrophe</td></tr>
</table>

as a “catastrophe”, in a further nine sections as a “disaster”, in five as a “crisis”, in seven as a “risk”, and in only two as “normal”. However, this assessment does not also appear as objective when compared with the other classifications because of a very limited list of indicators as well because it is impossible to take into account the regional characteristics of formation of the chemical composition. Furthermore, this method neglects multiplicity and recurrence frequency of pollution, which is highly important for territories experiencing strong anthropogenic impacts.

According to the SCWPI method, in none of the streams being analyzed is the hydroecological situation estimated as “normal”. The values of the index for the water quality in four measuring sections (the sources of the Talnakh, Tomulakh, Ambarnaya and Ergalakh) are close to class 1; because of the presence of CPI, however, the water in these streams was assigned to quality class 2, and the hydroecological status was estimated as a “risk” (Table 3). Furthermore, in 11 measuring sections the water refers to quality class 3, which corresponds to a “critical” status of the aquatic ecosystem. This applies for Lakes Tikhoe and Podkamennoe, the sources of the Kharaelakh and Kupets rivers, as well as the mouths of the Yuzhnyi Ugol’nyi brook and of the Ergalakh river, and others. In 12 measuring sections, the Hydroecological status of the water bodies is characterized as a “disaster”, i. e. the water refers to quality class 4 and 5: the four measuring sections on the Shchuchya and Novaya

Table 3. Hydroecological status of water bodies of the Norilsk hydrological region assessed by the SCWPI and WQI methods

Water body – measuring section	SCWPI		Canadian WQI		Total assessment of hydroecological status	
	value	quality class	value	quality class	SCWPI	Canadian WQI
Lake Kyllakh-Kyuel’	3.4	4	58.4	4	Disaster	Disaster
Lake Podkamennoe	3.1	3	87.3	2	Crisis	Risk
Lake Tikhoe	2.2	3	84.2	2	Crisis	Risk
Ambarnaya river, source	1.7	2	86.7	2	Risk	Risk
Ambarnaya river, mouth	3.5	4	78.4	3	Disaster	Crisis
Burovaya river, downstream of NMZ tailing dump	3.0	3	78.7	3	Crisis	Crisis
Daldykan river, source	1.8	3	89.3	2	Crisis	Risk
Daldykan river, mouth	4.4	4	67.6	3	Disaster	Crisis
Ergalakh river, source	1.9	2	86.5	2	Risk	Risk
Ergalakh river, mouth	2.0	3	92.6	2	Crisis	Risk
Kaierkan river, 500 m upstream of waste water discharge in the city of Kaierkan	2.4	3	69.7	3	Crisis	Crisis
Kaierkan river, 500 m downstream of waste water discharge in the city of Kaierkan	5.6	5	45.0	4	Disaster	Disaster
Kupets river, source	2.4	3	93.0	2	Crisis	Risk
Kupets river, mouth	6.6	5	46.2	4	Disaster	Disaster
Novaya Nalednaya river, source	4.6	4	72.2	3	Disaster	Crisis
Novaya Nalednaya river, mouth	7.0	5	43.2	5	Disaster	Catastrophe
Talnakh river, source	1.8	2	93.0	2	Risk	Risk
Talnakh river, mouth	4.1	4	68.4	3	Disaster	Crisis
Tomulakh river, source	1.9	2	89.4	2	Risk	Risk
Tomulakh river, mouth	3.1	3	78.8	3	Crisis	Crisis
Kharaelakh river, source	2.1	3	92.9	2	Crisis	Risk
Kharaelakh river, mouth	2.4	3	92.9	2	Crisis	Risk
Shchuchya river, source (Medvezhii brook)	3.6	4	82.9	2	Disaster	Risk
Shchuchya river, source (Kaskadnyi brook)	3.8	4	74.5	3	Disaster	Crisis
Shchuchya river, source (Ugol’nyi brook)	6.6	4	51.5	4	Disaster	Disaster
Shchuchya river, source	6.7	5	56.5	4	Disaster	Disaster
Yuznyi Ugol’nyi brook, mouth	2.8	3	85.3	2	Crisis	Risk



Relationship of SCWPI with the other water quality classifications as exemplified by the water bodies in the Norilsk hydrological region.
s – SCWPI; x – Canadian WQI (*a*), WPI (*b*), CJ (*c*); R^2 – coefficient of determination characterizing the closeness of connection between indices; n – length of the series.

Nalednaya, the estuarine areas of the Ambarnaya, Daldykan, Kupets and Talnakh rivers, Lake Kyllykh-Kyuel’, and others. No ecological “catastrophe” is recorded in any one of the water bodies under consideration.

Similar results are also obtained from parameterizing the water quality for the water bodies under consideration using the Canadian technique, which is confirmed by the closeness of connection between the values of these indices ($R^2 = 0.82$) (*see figure*). In general, this method may be considered less stringent: in about half of the cases the water quality is assessed by the WQI classification better than by SCWPI (see Table 3). For instance, the Hydroecological situation in the area of the Novaya Nalednaya source, according to SCWPI, is characterized as a “disaster”, whereas only as a “crisis” according to WQI. But since the values of the indices themselves often occur on the boundary of the classes, such departures are not significant. The other measuring sections show an agreement of quality classes for the Russian and Canadian techniques.

Hence, the most effective tool for characterizing the Hydroecological status of the aquatic ecosystems in the selected test area appears to be the SCWPI technique standardized in the system of Rosgidromet as well as the Canadian WQI technique based on using identical principles.

CONCLUSIONS

The techniques of comprehensive water quality assessment from hydrochemical indicators serve as a convenient tool for comparing the pollution level of water bodies. And the differences in the number of the identified classes have seriously complicated the possibility of using estimates obtained by different methods. Therefore, by developing a unified scale, it was possible to substantially simplify the comparison of results obtained according to a particular classification.

The most important factors which must be taken into account when selecting the index to be used in obtaining objective estimates are the landscape conditions of formation of the water chemical composition and the degree of economic development of the territory.

In the parameterization of water quality for anthropogenically disturbed territories, it is crucially important to take into consideration the specific indicators of pollution, and the recurrence and multiplicity with which they exceed the established standards (MAC in Russia). Furthermore, the list of the chemical composition components taken into account in calculations and analyses must be sufficiently large for the estimate obtained to be objective. Use of ecological methods of pollution assessment, such as the Bavarian method, fails to yield objective estimates of the status of the aquatic ecosystem, which, in turn, would involve emergence of disastrous consequences caused by the absence of timely measures for the prevention of nonstandard pollution of water bodies.

Results of calculations showed that the SCWPI technique, currently used in the system of Rosgidromet, provides the most objective assessment of water quality in water bodies with significant anthropogenic impacts which compares with results obtained by other methods used in the international practice. The merit of the Canadian WQI method is the possibility of using it in cases where water quality monitoring does not encompass all SCWPI indicators necessary for a calculation.

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