Flow rate regime of the Western Urals' rivers

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Abstract. The flow rate is one of the most important elements of the river’s water regime. Establishing patterns in river flow rates’ changes within a year and by season is of great importance for the hydrological forecasts for spring floods, rain floods and hydrological calculations. By now, there are few publications on this area, both in Russia and abroad. The initial data were divided into 5 hydrological seasons – winter and summer low water, rise and fall of spring floods and autumn rain floods. For each season, an analysis of river flow rate over a period (1936-2013) was done. The average flow rate in rivers varied greatly depending on the water regime’s phase and the type of terrain in which the river flows. For all seasons, the amplitude of fluctuations in the flow rate on the plain rivers is less than on the mountain ones. So, in mountain rivers, flow rates vary from 0.04 to 2.42 m/s, and on flat rivers from 0.02 to 1.43 m/s. As well the pairwise and multiple correlation coefficients of flow rates for each morphometric and catchment characteristics were calculated. The highest correlation coefficients were obtained for the dependency between the average flow rate and the watershed elevation (0.30-0.75) and the watershed slope (0.42-0.76). The multiple correlation coefficients between the average flow rate and all catchment’s morphometric characteristics varied from 0.97 to 0.99. Results verification on an independent data demonstrated that the relative error was on average 2%.

1. Introduction
The study of the flow rate regime plays an important role in the study of river’s hydrological processes. The development of channel deformations, sediment transport, speed of ice drift, as well as the various pollutants transit time and the waters renewal in river systems depend on the flow rates. In addition, the rivers’ flow rate regime is important in human economic activity, e.g. in timber rafting, shipping and fishing. Studies of changes in river flow rates within a year and by season is important for the hydrological forecasts, hydrological calculations, in design and construction of hydraulic and other industrial facilities.

Currently a very few number of publications, both in Russia and abroad in studied area are present. Just some studies were found concerning the flow rates in channel deformations [1], in the maximum flow formation [2], as well as the flow rates change with depth and the flow rate regime in the areas of hydraulic structures influence [3]. No one article devoted to the river flow rates regime, their variability by season and by landscape was found. A number of Iranian authors [4] studied the longitudinal and lateral changes in the depths and rates of the Karun River. Indonesian scientists [5] were engaged in modelling the characteristics of the river flow rate on a large scale. As well as several studies about forecasting river flow rate are present [6, 7, 8].
A former study on the flow rate regime of the Western Urals’s Rivers was done by the Department of Hydrology and Water Resources Conservation of the Perm State University. In particular, in 2006 by Komlev A M [9] was published a paper on the regime of water flow rates in some rivers of the Western Urals and the Urals. Later, there were no publications for studied area. Due to the climate change there is a need to continue research with use of recent years’ data.

2. Materials and methods
The paper analyzes the flow rates for 27 stream gauging stations on 19 rivers located in different parts of the Western Urals. Data from tables "Measured water discharge" at stream gauging stations of the Western Urals and Urals, belonging to the Kama River Basin without the Vyatka and Belaya rivers for the period 1936-1975 and archived data of the measured water discharges of the Perm Center for Hydrometeorology and Environmental Monitoring for the period 1976-2013 were used.

The basic hydrographic characteristics of the rivers and their catchments (excluding the Chusovaya river according to digital topographic maps of scale 1: 200000) were taken from the results of Kalinin V G and Pyankov S V [10] (table 1).

Table 1. The basic hydrographic characteristics of the rivers and their catchments [10].

| Stream gauging station | $F$, km$^2$ | $H$, m | $S$, %o | $I$, %o |
|------------------------|------------|--------|---------|---------|
| Chusovaya River – at Kyn | 10400      | 360    | -       | -       |
| Chusovaya River – at Lyamino | 21500      | 390    | -       | -       |
| Kama River – at Gains | 27650      | 200    | 13,47   | 0,28    |
| Velva River – at Oschib | 720        | 188    | 19,38   | 0,68    |
| Kosa River – at Kosa   | 5470       | 216    | 16,76   | 0,78    |
| Lolog River – at Sergeevsky | 1550       | 190    | 18,50   | 1,52    |
| Tulva River – at Barda  | 1830       | 183    | 49,61   | 1,47    |
| Obva River – at Karagay | 4130       | 196    | 26,88   | 0,86    |

* $F$ – catchment area, m$^2$; $H$ – watershed elevation, m; $S$ – watershed slope, %o; $I$ – channel slope, %o;

3. Results and discussions

3.1. Analysis of flow rates and channel slopes calculated data
For each hydrological season the average, minimum and maximum flow rates, and the ratio of average maximum speed to average minimum speed in each season (table 2) were calculated for 27 stream gauging stations. The ratio was calculated in order to show how much the minimum and maximum flow ratios differ from each other. As well the water surface’ average slope from the available data was calculated (table 2). All rivers were divided into plain and mountain tributaries of the Kama River and the Kama River itself in an unregulated upstream. The calculated data on the studied rivers flow rates are partially presented in table 2.

The average flow rates in rivers differ greatly in different seasons and also differ in plain (0.02-1.43 m/s) and mountain (0.04-2.43 m/s) rivers. The rivers of the plain territory are characterized by an insignificant intra-annual spread in the flow rates values, due to the rivers flow flat nature. This happens due to the fact that the some rivers catchments are swampy (Kosa River, Kondas River). It contributes to an even distribution of runoff throughout the year and low flow rates. These rivers flow rates range from 0.02 to 1.46 m/s. The plain rivers located in the southern part of the region (Babka River, Tulva River) are characterized by higher flow rates (0.03 to 2.64 m/s) than the northern and western plain rivers. The higher values of the flow rates at these stream gauging stations are caused by the steep landform and river channels straightening.
### Table 2. Flow rates and channel slopes calculated data.

| №  | Stream gauging station (years) | $H$, m | Season | $v$, m/s | $I$, %<sub>0</sub> |
|----|--------------------------------|--------|--------|----------|------------------|
|    |                                |        | aver   | max      | min      | max/ min |
| 1  | Kama River – at Gains (1936-1970) | 200    |        |          |          |          |
|    |                                |        | 1      | 0.25     | 0.90     | 0.13     | 6.9     |
|    |                                |        | 2      | 0.65     | 1.18     | 0.07     | 16.9    |
|    |                                |        | 3      | 0.20     | 1.14     | 0.02     | 57.0    | 0.17    |
|    |                                |        | 4      | 0.37     | 0.68     | 0.06     | 11.3    |
|    |                                |        | 5      | 0.49     | 0.92     | 0.19     | 4.8     |
| 2  | Obva River – at Karagay (1936-2013) | 196    |        |          |          |          |
|    |                                |        | 1      | 0.18     | 1.02     | 0.05     | 20.4    |
|    |                                |        | 2      | 0.78     | 1.42     | 0.11     | 12.9    |
|    |                                |        | 3      | 0.78     | 1.31     | 0.08     | 16.4    | 0.16    |
|    |                                |        | 4      | 0.35     | 0.98     | 0.05     | 19.6    |
|    |                                |        | 5      | 0.41     | 1.14     | 0.1      | 11.4    |
|    |                                |        | 1      | 0.24     | 0.81     | 0.08     | 10.1    |
|    |                                |        | 2      | 0.77     | 1.35     | 0.12     | 11.3    |
| 3  | Kosa River – at Kosa (1938-2006) | 183    |        |          |          |          |
|    |                                |        | 3      | 0.75     | 1.17     | 0.42     | 2.8     | 0.09    |
|    |                                |        | 4      | 0.36     | 0.74     | 0.09     | 8.2     |
|    |                                |        | 5      | 0.42     | 0.86     | 0.11     | 7.8     |
|    |                                |        | 1      | 0.14     | 1.16     | 0.03     | 38.7    |
|    |                                |        | 2      | 0.47     | 0.76     | 0.05     | 15.2    |
| 4  | Velva River – at Oschib (1936-2013) | 188    |        |          |          |          |
|    |                                |        | 3      | 0.46     | 0.75     | 0.04     | 18.8    | 0.10    |
|    |                                |        | 4      | 0.18     | 0.59     | 0.03     | 19.7    |
|    |                                |        | 5      | 0.21     | 0.76     | 0.03     | 25.3    |
|    |                                |        | 1      | 0.26     | 1.06     | 0.06     | 17.7    |
|    |                                |        | 2      | 1.15     | 2.34     | 0.12     | 19.5    |
| 5  | Tulva River – at Barda (1936-2013) | 216    |        |          |          |          |
|    |                                |        | 3      | 0.90     | 2.64     | 0.16     | 16.5    | 0.56    |
|    |                                |        | 4      | 0.43     | 1.18     | 0.07     | 16.9    |
|    |                                |        | 5      | 0.48     | 1.17     | 0.08     | 14.6    |
| 6  | Vishera River – at Ryabinino (1936-1974) | 313    |        |          |          |          |
|    |                                |        | 1      | 0.30     | 0.60     | 0.20     | 3.0     |
|    |                                |        | 2      | 1.20     | 1.54     | 0.52     | 3.0     |
|    |                                |        | 3      | 1.06     | 1.42     | 0.60     | 2.4     | 0.16    |
|    |                                |        | 4      | 0.46     | 0.56     | 0.36     | 1.6     |
|    |                                |        | 5      | 0.65     | 1.03     | 0.32     | 3.2     |
|    |                                |        | 1      | 0.20     | 0.66     | 0.12     | 5.5     |
|    |                                |        | 2      | 1.22     | 1.70     | 0.28     | 6.1     |
| 7  | Kolva River – at Petrezova (1940-1974) | 270    |        |          |          |          |
|    |                                |        | 3      | 1.18     | 1.66     | 0.33     | 5.0     | 0.29    |
|    |                                |        | 4      | 0.37     | 0.95     | 0.15     | 6.3     |
|    |                                |        | 5      | 0.52     | 0.84     | 0.14     | 6.0     |
|    |                                |        | 1      | 0.30     | 0.92     | 0.10     | 9.2     |
| 8  | Chusovaya River – at Lyaminino (1956-2013) | 390    |        |          |          |          |
|    |                                |        | 3      | 1.14     | 1.14     | 0.35     | 3.3     | 0.42    |
|    |                                |        | 4      | 0.51     | 0.51     | 0.17     | 3.0     |
|    |                                |        | 5      | 0.55     | 0.55     | 0.22     | 2.5     |
|    |                                |        | 1      | 0.48     | 0.98     | 0.18     | 5.4     |
| 9  | Sylva River – at Podkamennoye (1936-1974) | 249    |        |          |          |          |
|    |                                |        | 3      | 1.27     | 1.89     | 0.44     | 4.3     |
|    |                                |        | 4      | 0.57     | 0.94     | 0.35     | 2.7     |
|    |                                |        | 5      | 0.65     | 1.29     | 0.40     | 3.2     |

* $H$ – watershed elevation, m; $v$ – flow rate, m/s; $I$ – channel slope, based on hydrometric observation data, %; 1 – winter low water; 2 – rise of spring floods; 3 – fall of spring floods; 4 – summer low water; 5 – autumn rain floods.
Mountain rivers in the eastern part of the Western Urals are characterized by a rough flow. These are such rivers as Sylva, Chusovaya, Usva, Vishera, Kutim, etc. These rivers originate on the Ural Mountains ridges and have higher flow rates than plain rivers. The flow rate varies from 0.04 to 2.42 m/s. The flow rates regime of is also different for plain and mountain rivers in different hydrological seasons.

**Plain rivers.** During the low-water period, the flow rates on the western and northern rivers vary from 0.02 to 0.98 m/s during the summer low water and from 0.03 to 1.16 m/s during the winter low water, while the maximum flow rates are from 0.56 to 1.11 m/s, and the minimum from 0.02 to 0.09 m/s. On southern rivers, the flow rate varies from 0.06 to 1.06 m/s in summer and from 0.05 to 1.01 m/s in winter. During the periods of the rise and fall of the spring flood, flow rates have maximal values 0.04-1.43 m/s for northern and western rivers, and 0.12-2.64 m/s for southern rivers.

For the autumn rain floods, the average flow rates are higher than during the winter and summer low waters, but less than during the spring floods. So, on the northern and western rivers, the flow rates range from 0.02 to 1.14 m/s, and on the southern ones from 0.03 to 2.42 m/s.

**Mountain rivers.** The mountain rivers have higher values of the flow rates in all hydrological seasons in comparison with plain rivers. During spring floods, the average flow rates vary from 0.22 to 2.42 m/s, that in 5.5 times more than the minimum flow rate and almost 2 times more than flow rate in the same season on plain rivers. The maximum values of the flow rates of 2.42 m/s were observed on Chusovaya River – at Lyamino in 1990. During the summer low water, the flow rate has lower amplitude compared to the spring flood season and varies from 0.10 to 1.55 m/s. In the winter low water, the flow rates have the lowest values in comparison with other seasons and are in the range from 0.04 to 1.56 m/s. Compared to the plain rivers, the amplitude of the flow rates variability during the winter and summer low-water periods on mountain rivers is less by 0.12 m/s. Such reduction in the flow rates variability is due to the absence of vegetation in the river bed and along the banks of mountain rivers, because the river bed in mountain rivers is stony, and not silty as in plain rivers. Therefore, in mountain rivers, both in winter and in summer low water, the channel does not change. While in plain rivers in summer the channel is covered with aquatic vegetation, which has a slowdown effect on the water flow. In winter season the vegetation is absent and the flow rates compared to the summer low water season has bigger values. In the autumn rain floods the flow rates for mountain rivers range from 0.12 to 1.55 m/s.

Analysis of the ratio of the average maximum and average minimum flow rates showed that the ratios differ greatly. At the rise of spring flood, the flow rate varied from 0.60 to 2.42 m/s, and these values exceeded the flow rate during the winter low water season from 5 to 40 times, the summer low-water period from 2 to 63 times. That difference is associated with the conditions for the flow rate regime formation in different seasons of the year.

3.2. **Dependency of flow rate on the main catchment’s and rivers’ morphometric characteristics**

The flow rate in rivers (v, m/s) is influenced by many factors: catchment area (F, m²), watershed elevation (H, m), watershed slope (S, %), as well as channel slope (I, °). As the initial data for the analysis the above-mentioned data and average flow rates for a period 1995-2013 were used. The analysis was performed for each phase of the water regime separately. The data were used since 1995 because approximately since this year the climatic changes begin in studied area [11].

For each of these parameters, pairwise and multiple correlation coefficients were calculated. The multiple correlation coefficients are allowed to assess the impact of two or more factors on the value of the flow rate in the studied rivers [12]. Stream gauging stations that lacked data on some morphometric characteristics were excluded from the analysis. As result, the highest correlation coefficients for the dependency of the average flow rate with the watershed elevation (0.30-0.75) and the watershed slope (0.42-0.76) (table 3) were obtained.

Multiple correlation coefficients for the catchment’s morphometric characteristics (catchment area, watershed elevation and watershed slope) were calculated. The analysis of multiple correlation shows that the highest coefficients (0.97-0.99) are obtained when all catchment’s morphometric
characteristics are used. The maximal coefficient was received for the spring flood season, and the minimal for the winter low water season. While the number of parameters included in the equation also increases and thus can lead to additional errors.

Among the catchment’s morphometric characteristics, the greatest influence on the flow rate has watershed slope. The next in importance is the relationship between average flow rates and watershed elevation. The catchment area has the least influence on the flow rate.

Complex analysis of different parameters takes into account the combined effect of three catchment and river characteristics on river flow rates. Calculations were made using the obtained equations for each phase of the flow rates (table 5). Using the equations obtained for each phase of the flow rates, the relative calculation errors were calculated, which was compared with the actual ones calculated over a long-term period (table 5).

The dependencies verification was done by comparing the observed flow rates with calculated flow rates (by formulas in table 4). In results the relative calculation errors ($\Delta v$) on average equal 2%. According to the table 5 the calculated flow rates ($\tilde{v}$) during the summer low water season have relative error up to 7%, during the autumn rain floods up to 9%. The least error during the periods of winter low water and spring high water seasons (up to 4%).

| Parameter | 1 | 2,3 | 4 | 5 | Season | R | Equation |
|-----------|---|-----|---|---|-------|---|----------|
| $F(x_1)$, km$^2$ | 0.57 | 0.36 | 0.28 | 0.27 | 1 | 0.96 | $y=0.00003 x_1-0.006 x_2 - 0.99$ |
| $F(x_1)$, km$^2$ | 0.57 | 0.36 | 0.28 | 0.27 | 2,3 | 0.97 | $y=0.00010 x_1-0.026 x_2 - 4.49$ |
| $H(x_2)$, m | 0.54 | 0.75 | 0.51 | 0.3 | 4 | 0.99 | $y=0.00006 x_1+0.016 x_2 - 2.65$ |
| $S(x_2)$, % | 0.42 | 0.76 | 0.75 | 0.74 | 5 | 0.99 | $y=0.00006 x_1+0.018 x_2 - 3.27$ |
| $H(x_1)$, m | 0.54 | 0.75 | 0.51 | 0.3 | 1 | 0.75 | $y=-0.008 x_1+0.01 x_2 +1.40$ |
| $I(x_2)$, % | 0.42 | 0.76 | 0.75 | 0.74 | 4 | 0.88 | $y=-0.020 x_1+0.03 x_2 +3.24$ |
| $I(x_2)$, % | 0.42 | 0.76 | 0.75 | 0.74 | 5 | 0.88 | $y=-0.007 x_1+0.02 x_2 +1.16$ |

$F(x_1)$ – pair flow rate; $F(x_2)$ – monthly total flow; $F(x_3)$ – average daily flow; $F(x_4)$ – average monthly flow; $F(x_5)$ – average seasonal flow; $H(x_1)$ – watershed elevation, m; $S(x_2)$ – watershed slope, %; $I(x_2)$ – channel slope, %; $F(x_3)$ – winter low water; $F(x_4)$ – rise and fall of spring floods; $F(x_5)$ – summer low water; $F(x_6)$ – autumn rain floods.

**Table 3.** Pairwise and multiple correlation coefficients for the flow rate dependences with catchment’s morphometric characteristics.

3.3. Complex use of the catchment’s and rivers’ morphometric characteristics

The analysis of complex use of morphometric characteristics of the rivers and catchments takes into account the combined effect of three catchment and river characteristics on river flow rates. From the catchment’s characteristics – watershed slope, watershed elevation and catchment area; from the river’s characteristics – channel slope. According to the values of these characteristics, as well as the values of the average flow rates, the coefficient of multiple correlations was calculated for each season and the regression equation was determined (table 4). Using the equations obtained for each phase of the water regime, the average flow rates were calculated, which was compared with the actual ones calculated over a long-term period (table 5).

The dependencies verification was done by comparing the observed flow rates with calculated flow rates (by formulas in table 4). In results the relative calculation errors ($\Delta v$) on average equal 2%. According to the table 5 the calculated flow rates ($\tilde{v}$) during the summer low water season have relative error up to 7%, during the autumn rain floods up to 9%. The least error during the periods of winter low water and spring high water seasons (up to 4%).
Table 4. Pairwise and multiple correlation coefficients for the flow rate dependences with catchment’s and rivers’ morphometric characteristics.

| Season | $F(x_1)$, km$^2$ | $H(x_2)$, m | $S(x_3)$, % | $I(x_4)$, % | $R$ | Equation |
|--------|-----------------|-------------|-------------|-------------|-----|----------|
| 1      | 0.57            | 0.54        | 0.42        | 0.01        | 0.99| $y=0.00003\cdot x_1+0.00009\cdot x_2+0.08\cdot x_3+0.003\cdot x_4-0.22$ |
| 2.3    | 0.36            | 0.75        | 0.76        | 0.23        | 0.99| $y=0.00010\cdot x_1+0.0160\cdot x_2+0.01\cdot x_3+0.009\cdot x_4-2.83$ |
| 4      | 0.28            | 0.51        | 0.75        | 0.17        | 0.99| $y=0.00006\cdot x_1+0.0200\cdot x_2-0.06\cdot x_3-0.005\cdot x_4+3.62$ |
| 5      | 0.27            | 0.30        | 0.74        | 0.29        | 0.99| $y=0.00006\cdot x_1+0.0200\cdot x_2-0.10\cdot x_3-0.002\cdot x_4+3.08$ |

$r$ – pairwise correlation coefficient; $R$ – multiple correlation coefficient; $F$ – catchment area, m$^2$; $H$ – watershed elevation, m; $S$ – watershed slope, %; $I$ – channel slope, %; 1 – winter low water; 2, 3 – rise and fall of spring floods; 4 – summer low water; 5 – autumn rain floods.

Table 5. Comparison of observed and calculated flow rates.

| Stream gauging station       | $\nu$, m/s  | $\nu'$, m/s | $\Delta\nu$, % |
|-----------------------------|-------------|-------------|-----------------|
|                            | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| Obva River – at Karagay     | 0.23 | 0.99 | 0.46 | 0.48 | 0.23 | 0.97 | 0.46 | 0.48 | 0 | 2 | 0 | 0 |
| Kosa River – at Kosa        | 0.22 | 0.83 | 0.32 | 0.34 | 0.22 | 0.80 | 0.34 | 0.31 | 1 | 4 | 7 | 9 |
| Velva River – at Oschib     | 0.08 | 0.44 | 0.15 | 0.11 | 0.08 | 0.43 | 0.15 | 0.11 | 4 | 2 | 1 | 2 |
| Lolog River – at Sergeevsky| 0.17 | 0.56 | 0.19 | 0.29 | 0.17 | 0.55 | 0.19 | 0.29 | 3 | 2 | 1 | 1 |
| Tulva River – at Barda      | 0.3 | 1.28 | 0.6 | 0.72 | 0.30 | 1.27 | 0.57 | 0.76 | 1 | 1 | 5 | 5 |

$\nu$ – observed flow rates, m/s; $\nu'$ – calculated flow rates, m/s; $\Delta\nu$ – relative calculation error, %; 1 – winter low water; 2 – rise of spring floods; 3 – fall of spring floods; 4 – summer low water; 5 – autumn rain floods.

The obtained equations (table 4) can be used for estimation of the average flow rates on unexplored plain rivers with catchment areas less than 6000 km$^2$ and a watershed elevation of not more than 400 m.

4. Conclusions
Thus the maximum flow rate was observed at the rise of spring flood season and varied from 0.60 to 2.42 m/s. These flow rates exceeded the flow rate during the summer-winter low water seasons by 2-63 times. This is due to the variety of conditions for the formation of the flow rates regime in different seasons of the year. The flow rate amplitude within a year on plain rivers is less than on mountain rivers. Because the nature of the landforms and the precipitation variability. In general, flow rates for all seasons vary from 0.02 to 2.64 m/s. Firstly, such dispersion in flow rates is due to the catchment landforms nature, and secondly, the strong fluctuation in the flow rates depends on the season (minimum flow rates during the summer and winter low water season, and maximum during spring and autumn floods).

The dependences analysis of the average flow rates on the catchment’s and rivers’ morphometric characteristics showed that the watershed slope has the greatest impact on the average flow rate. The correlation coefficients between the average flow rate and this parameter are the highest (0.30-0.75).

Based on significant morphometric characteristics (watershed slope, watershed elevation, catchment area and channel slope), the multiple correlation coefficient was calculated for all seasons separately and it is equal to 0.99. Received equation made possible to use the catchment’s and rivers’ morphometric characteristics together.
Results verification on an independent data showed that the relative error is 2% for all seasons. The equations obtained can be used for estimation of the average flow rate on unexplored plain rivers with catchment areas less than 6000 km² and a watershed elevation of no more than 400 m. As well as the catchment need to be in similar climatic conditions.

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