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New Approach for Estimation of Natural and Anthropogenic Components in the Recent Tendencies of Erosion Intensity and Suspended Sediment Yield Changes in River Basins

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Abstract

The offered approach is based on the establishment of the functional dependence between river water discharge (Q) and suspended sediment yield (R) $R = \lambda \times Q^m$, where λ and m are empirical coefficients, (characteristic for a given river basin) for the earliest period in a number of observations, which noticeably differs from the mean value (R) of subsequent allocated period(s). The earliest period is conventionally accepted as the "pattern" (model), with which the mean value (R) of subsequent period(s) is compared. The anthropogenic component during the subsequent period(s) is the difference between an actual suspended sediment yield and its hypothetical value, which is connected only with changes of natural (mainly, hydro-climatical) factors without any anthropogenic changes of geographical (erosive) conditions in a river basin. This hydro-climatical component is calculated by extrapolation of an early established dependence $R = \lambda \times Q^m$ for subsequent period(s). Approbation of the offered approach is made on the examples of some rivers (Zapadny Bug (Ukraine), Magdalena (Colombia), Bei-Nan (Taiwan, China), Sanchuanhe (China) and Indus (India, Pakistan, China).

Keywords: *Suspended sediment yield, Erosion, Tendency; River basin.*

1. Introduction

Among the methods of estimation of recent spatial changeability of erosion intensity the analysis of river suspended sediment yield (SSY) is one of the most objective methods, and its results are rather representative for the global scale of studying [1–7]. At the same time, SSY is not used as the absolute measure of erosion intensity in a river basin because a considerable part of sediments is not delivered to the river hydrological post and is redeposited on the way during transit (slopes, river channels and floodplains), forming the new generations of diluvium, proluvium and alluvium.

The proportion of these deposits varies, depending on the geologic, geomorphic and landscape conditions and cannot be reliably and quantitatively defined even for small river basins. Therefore, the SSY-analysis is a method for the relative assessment of erosion intensity (wider – mechanical denudation) in river basins.

SSY can also be used for characterizing the temporal variability of erosion, because, as a whole the SSY-changes for a given interval of time in any river basin, responds adequately to the changes of intensity of a given geomorphic process.

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One of the directions of study of SSY temporal variability is definition and analysis of its recent tendencies. The key problem of this analysis is assessment of the input of natural and anthropogenic components. The accounting of anthropogenic component is important for estimation of efficiency of complex actions aimed to decrease man-caused erosion and SSY, and for the normal functioning of river systems and hydraulic engineering constructions in them. The studies, known in world practice in this direction, are narrowly regional and based on other methodical approaches [8, 9].

2. Methodical approach

The analysis of tendencies of erosion intensity and SSY changes in long-term series of observations and also the partition of their natural and anthropogenic components are divided into the following stages:

1. Construction of combined diagram of the long-term series of the annual SSY and water discharge (WD) of the analyzed river.

2. Definition of the linear trend (the equation of kind R_i (or Q_i) = $\alpha \times t_i + \beta$, where R_i (or Q_i) is the theoretical (regressive) value of SSY(or WD) for the year of observations (t_i, α and β are the empirical coefficients of the equation) and the nonlinear polynomial trends of the sixth degree (the equation of kind R_i (or Q_i) = $\alpha_1 \times t_i + \alpha_2 \times t_i^2 + \alpha_3 \times t_i^3 + \alpha_4 \times t_i^4 + \alpha_5 \times t_i^5 + \alpha_6 \times t_i^6 + \beta$, where α_1,

α_2, α_3, α_4, α_5, α_6 and β are also empirical coefficients of equation) in the long-term series of observations for SSY and WD. The linear trend and its equation allow revealing a general orientation and the rates of directed changes of SSY and WD. The polynomial trend of sixth degree more nearly approaches the actual SSY (or WD)-value and it reflects not only the general orientation, but also a "plasticity" of its temporal changeability.

It allows allocating the periods in the series of SSY and WD, which considerably differ both in the mean SSY (or WD) values, and in the variability of its annual values. As a rule, application of polynomial trends with degrees higher than six does not significantly change the picture of the allocated periods. The statistical importance of the obtained regression equations (trends) – γ_{eq} – is checked by standard procedure using Fisher's *F*-criterion. Construction of the cumulative curves showing the "critical" years of erosion processes development and SSY-dynamics is also informative [7].

3. Allocation of periods (as a rule, two or three) with various mean SSY values and dynamics on the basis of visual-graphic analysis of the course of the polynomial and cumulative curves; calculation of the mean SSY(WD) values with confidence intervals (95% confidential probability), the coefficients of variation (C_v) of annual SSY and WD values, the coefficients of linear SSY determination (D), the coefficient of linear correlation (k) between annual SSY and WD values for each allocated period. The statistical importance of the specified coefficients is checked with Student's *t*-criterion and Fisher's *F*-criterion.

4. Definition of the natural and anthropogenic components in the recent tendencies of SSY-changes by the following sub-stages:

4.1. The first period (the earliest of allocated periods, T_1) is proposed as a "pattern", with reference to which the comparison of characteristics of other (later) period(s) of long-term SSY-series (T_2 and, if it is necessary, T_3) is made.

The mean characteristics and variability of the annual SSY-values of period T_1 reflect the developed natural or natural-anthropogenic conditions in river basins. These conditions have influenced the sediment transporting ability of river streams. According to N.I.Makkaveev [10], the functional equation of connection for sediment yield (R_i) has the following general form:

$$R_i = (A_{er} \times I) \times Q_i^m,$$

(1) where I is the river stream slope, Q_i is the mean WD value for the given interval of observations (for example, year), A_{er} is a complex erosion coefficient, depending on the non-uniformity of the runoff (WD), the character of the rocks comprising a river channel, the quantity and size of suspended deposits, which are delivered by tributaries, rain and melted waters and by slope geomorphic processes. The coefficients A_{er} and I can essentially vary from basin to basin. This variation depends on the local features of denudation, its geologic and geomorphic structure and geographical conditions. According to the exponent m the connection between SSY and WD values of the plain rivers is usually close to square, for the mountain rivers it is close to cubic [11].

Actually, the equation of N.I. Makkaveev (1) is a well known mathematical equation of the type: $y = \lambda \times x^m$. We can consider the complex coefficient $\lambda = a \times (A_{er} \times I)$ as conventionally constant for all periods of observations (some decades), concerning a river hydrological post (here, a is a transitive index depending on the dimensions of expression of R and Q). This convention is connected to the variability of hydro-meteorological elements from year to year (the quantity and regime of atmospheric precipitations, the degree of soil and ground freezing, the intensity of snow-melting, etc.) which can certainly affect the non-uniformity of runoff (WD), character and size of suspended deposits, composing the integrated coefficient ($A_{эр} \times I$). The coefficient $\lambda = a \times (A_{er} \times I)$ and degree m are empirically defined (with statistical importance of degree m – γ_m) by constructing the graph of exponential connection between SSY and WD for period T_1 for each river.

4.2. *Definition of natural (hydro-climatical) component.* If any anthropogenic changes of geographical conditions within a river basin (it can be primary both natural, and already agriculturally transformed landscapes) during the periods, following after period T_1 (T_2 and T_3), are absent, then an inter-annual variability of river SSY is defined, basically, by the variability of runoff in a given temporal interval in the equation (1), which was obtained for period T_1. And the integrated coefficient ($A_{er} \times I$) of period T_1 could be extrapolated for period T_2 (and/or T_3).

Using the hypothetical hydro-climatically caused annual SSY values, obtained thus, for period T_2 (and T_3) – $r_i = f(Q_i^m)$, we can calculate its mean long-term values r_{av} (T_2) or r_{av}(T_3) by equation (2). The values r_{av} (T_2) or r_{av} (T_3) are compared with mean actual SSY values of the "pattern" period T_1 – R_{av} (T_1). The difference between these mean values – Δr (T_2 or T_2), expressed by equation (3), is the *potential hydro-climatically caused change of SSY* from period T_1 to period T_2 (and/or T_3).

$$r_{av}\ (T_2 \text{ or } T_3) = [\sum r_i\ (T_2 \text{ or } T_3)]/n, \quad (2)$$

Where n is quantity of observation years in period T_2 (or T_3);

$$\Delta r\ (T_2 \text{ or } T_3) = r_{av}\ (T_2 \text{ or } T_3) - R_{av}(T_1) \quad (3)$$

The sign before Δr specifies an increase ($\Delta r > 0$) or a reduction ($\Delta r < 0$) of potential hydro-climatically caused annual SSY value during the period T_2 (and T_3) in comparison with the actual SSY-values for period T_1.

However, the natural component in the variability of erosion processes and the SSY is not limited only by hydro-climatical dynamics. A tectonic factor can have an influence as well. Its role increases with an increase of duration of observations for these processes (at least about several centuries). In the short numbers of observations (some decades) only the fast displays of this factor can interfere with inter-annual variability of SSY (especially within the small river basins): earthquakes and effusive magmatism, the influence of which is limited mainly to mountainous territories. As a rule, these displays are expressed in abnormal speeds of mechanical denudation and SSY values. So, the stationary observations of Romanian geomorphologists for consequences of the earthquake with a magnitude more than 7 points on the Richter's scale, which occurred in the Carpathians in the beginning of March, 1977, have shown that the activization of collapses, avalanches, landslips and other geomorphic processes has led to single reduction of the heights of small river basins from 0.6 to 1.8 mm [12]. The rather marked SSY values of the rivers of Ukrainian Carpathians in 1977-1978 are also, doubtlessly, the consequence of the Romanian earthquake [13].
Another bright example: after the eruption of volcano Usu (Japan) in 1977-1978 its surface and the nearby territories have been covered by friable pyroclastic rocks with a thickness of more than half a meter. The sheet and rill-gully erosion have reached the greatest intensity in 1978-1982 – up to 136 mm/year in recalculation on a general surface reduction. After 1982 the rate of erosion has been considerably decreased – up to 2–10 mm/year, and the linear erosion forms, having reached the surface of hard volcanic rock, continued to develop only at the expense of destruction of the boards [14].
Similar examples are not rare.
It is quite obvious that accounting for the tectonic component of SSY-changes is obligatory. For this purpose it is necessary to develop the special methods of assessment of influence of the factor on SSY.

4.3. *Definition of anthropogenic component.* The human activity differently influences the erosion intensity and the river SSY in various regions of the Earth. If in some regions the active human influence has come to an end in the previous centuries, then in the other regions it took place during the second half of XX century and continues to this day. Allocating the anthropogenic component, it is necessary to understand: a factor-agent of erosion and formation of river SSY is a natural process – runoff. The human activity is one of the factors, most dynamically varying in time. It creates or expands the favorable or adverse conditions for its erosion work. Hence, anthropogenic component of SSY is the quantity of deposits, which has been additionally delivered or has not been delivered by runoff into a river network above a hydrological post during period T_2 (and/or T_3) due to activization of human activity within the river basin during a given period. Human activity can be of various types: deforestation, cultivation, a change of structure of crop rotations, expansion and intensification of pastures, mining operations in the valley bottoms, grassing, expansion of afforestations, antierosive actions, creation of water reservoirs and ponds, etc.
The *anthropogenic component* in the changed SSY of period T_2 or T_3 – $\Delta A(T_{2\text{ or }3})$ – is the difference between the mean actual SSY-value for these period(s) (R_{av} (T_2) or R_{av} (T_3)) and its mean hydro-climatical (hypothetical) component (r_{av} (T_2) or r_{av} (T_3)):

$$\Delta A(T_{2\text{ or }3}) = R_{av}(T_{2\text{ or }3}) - r_{av}(T_{2\text{ or }3}) \quad (4)$$

If $\Delta A > 0$ then a human activity is directed to an increase of SSY ; if $\Delta A < 0$ then it is directed to a reduction of SSY.
A similar approach for estimating anthropogenic component of SSY, but already on a scale of all the history of economic development of river basins of the Earth, has been applied by A.P. Dedkov and V.I. Mozzherin [2, 15].

They have used the ergodic principle, which is the transformation of spatial laws into temporal ones (allocation of the three categories of river basins with different degree of transformation of natural landscapes in them).
Theoretically, it is possible to allocate the 13 probable scenarios (I–XIII) of SSY-changes in connection with trends of changes of river WD (Fig.1). These scenarios reflect the various parities between natural (hydro-climatical) and anthropogenic components in *the changed SSY* (ΔR), which can be defined as:

$$\Delta R\ (T_{2\text{ or }3}) = R_{av}\ (T_{2\text{ or }3}) - R_{av}\ (T_1), \quad (5)$$

If $\Delta R < 0$ then a reduction of SSY from period T_1 to period T_2 or T_3 is shown, while if $\Delta R > 0$ then an increase of SSY is indicated.

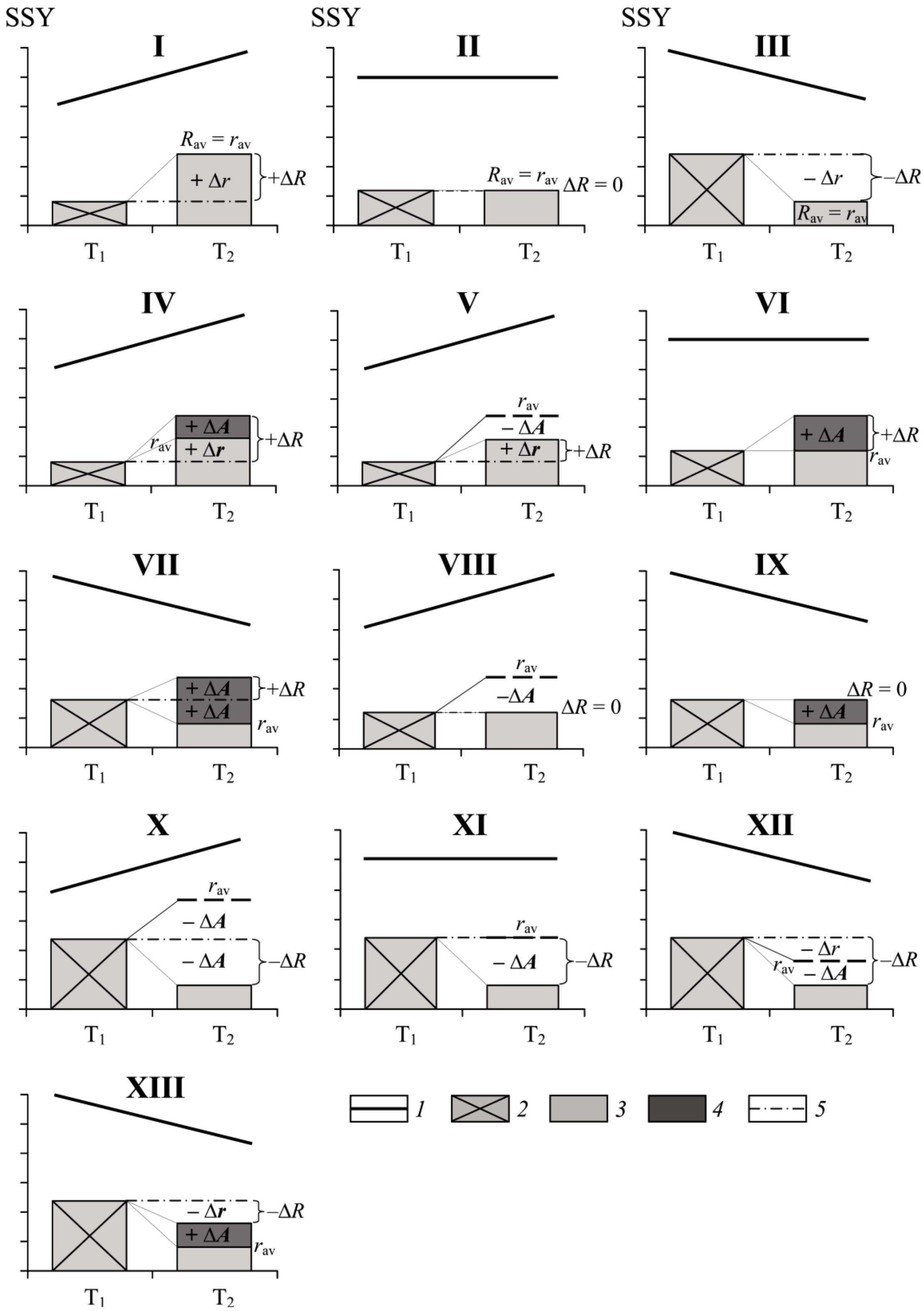

Fig. 1. The probable scenarios of suspended sediment yield (SSY) changes in connection with directed changes (trends) of river water discharge.

T_1 and T_2 – the allocated periods; 1 – a trend of river water discharge; 2 – a not dismembered mean SSY-value for period T_1; a hydro-climatical (3) and anthropogenic (additional)(4) component of mean SSY-value for period T_2, 5 – a level of not changed SSY-value for period T_2.

The scenarios I, II and III (Fig.1) are purely hydro-climatical, because river SSY-changes in them occur without the participation of the human activity: from the river basins with still not transformed natural landscapes to the river basins completely occupied with badlands where agriculture does not take place. The special cases of scenarios III and XII are a termination of SSY during the second period (where R_{av} (T_2) = 0) due to a termination of WD, connected with river degradation (mainly small rivers). It occurs due to drainage of soil and ground waters, feeding the rivers, and excessive sedimentation along the river channels. The sources of such rivers are displaced downstream, settling down at exits of deeper ground waters, poorly transformed by drainage. Such a picture is observed, for example, where men have reduced the forest areas and cultivated the lands thereby changing the ratio between the values of the surface and underground waters. It is natural that in these cases the runoff and the SSY are observed during snow melting and/or rainfalls but such rivers may cease to exist later, because from the constant water streams (actually rivers) they turn into temporary water streams.

4.4a. Definition of structure of the changed SSY (ΔR) during period T_2 or T_3: the portion of natural (hydro-climatical) component in changed SSY – ωr ($T_{2 \text{ or } 3}$); the portion of anthropogenic component – ωA ($T_{2 \text{ or } 3}$). Depending on the scenario of directed SSY-changes the calculation of specified portions is made as follows (Table.1).

If the portion of one of these components is 33–50 % it is possible to speak about its moderate influence on the changed SSY between the allocated periods, if 51–66 % – about prevailing influence, 67–90 % – about dominating influence, 91–100 % – about overwhelming influence.

4.4b. Definition of structure of the actual SSY – R_{av} ($T_{2 \text{ or } 3}$) – during the period T_2 (and/or T_3): the portion of natural (hydro-climatical) component – ∂r ($T_{2 \text{ or } 3}$); the portion of anthropogenic component – ∂A ($T_{2 \text{ or } 3}$) (Table.1).

5. The analysis of the reasons for the recent tendencies of erosion intensity and SSY changes in each river basin.

Table 1. Definition of the structure of changed (ΔR) and actual (R_{av}) suspended sediment yield.

<table>
<tr><th>Probable scenarios (see figure)</th><th>Structure of ΔR for period T_2, %</th><th>Structure of R_{av} for period T_2, %</th></tr>
<tr><td colspan="3">Hydro-climatical scenarios</td></tr>
<tr><td>I</td><td>ωr = 100
ωA = 0</td><td rowspan="3">∂r = 100
∂A = 0</td></tr>
<tr><td>II</td><td>—</td></tr>
<tr><td>III</td><td>ωr = 100
ωA = 0</td></tr>
<tr><td></td><td>Anthropogenic–hydro-climatical scenarios</td><td></td></tr>
<tr><td>IV</td><td>$\omega r = [\Delta r/\Delta R]\times 100$
$\omega A = 100 - \omega r$</td><td>$\partial r = [r_{av}/R_{av}]\times 100$
$\partial A = 100 - \partial r$</td></tr>
<tr><td>V</td><td>ωr = 100
ωA = 0</td><td>∂r = 100
∂A = 0</td></tr>
<tr><td>VI</td><td rowspan="2">ωr = 0
ωA = 100</td><td rowspan="2">$\partial r = [r_{av}/R_{av}]\times 100$
$\partial A = 100 - \partial r$</td></tr>
<tr><td>VII</td></tr>
<tr><td>VIII</td><td>—</td><td>∂r = 100
∂A = 0</td></tr>
<tr><td>IX</td><td>—</td><td>$\partial r = [r_{av}/R_{av}]\times 100$
$\partial A = 100 - \partial r$</td></tr>
<tr><td>X</td><td rowspan="2">ωr = 0
ωA = 100</td><td rowspan="3">∂r = 100
∂A = 0</td></tr>
<tr><td>XI</td></tr>
<tr><td>XII</td><td>$\omega r = [\Delta r/\Delta R]\times 100$
$\omega A = 100 - \omega r$</td></tr>
<tr><td>XIII</td><td>ωr = 100
ωA = 0</td><td>$\partial r = [r_{av}/R_{av}]\times 100$
$\partial A = 100 - \partial r$</td></tr>
</table>

3. Approbation

The long-term series of observations (with durations from 27 to 73 years) for the annual SSY and WD of five rivers from various plains and mountainous regions of the Earth with different degrees of recent dynamics of anthropogenic transformation of the natural landscapes of their basins have been used as materials for approbation of the offered approach.

3-1. The Rivers with tendencies of SSY increase

• **Zapadny Bug** (riverhead) flows within the flat western part of Ukraine. The river basin area above the hydrological post in Kamenka-Bugskaya is 2350 km^2. Some hydrological characteristics of Zapadny Bug are given in Table.2.

On the combined diagram of long-term course of the annual values of SSY and WD (Fig. 2A) the linear trends of increase from 1950 to 1987 are distinctly (γ_{eq} = 99.99 %) traced. The mean rates of such increases are, accordingly, 0.12 (l/s×km^2)/year ($Q_i = 0.12 \times t_i - 230.8$) and 0.25 t/km^2×year ($R_i = 0.26 \times t_i - 502.7$). The trends of 45% in SSY and 37% in WD have caused its long-term variability during the observation period.

The analysis of the course of the nonlinear polynomial trend of the sixth degree (Fig. 2A) and the cumulative curve (Fig. 2B) of SSY show their most considerable increase since 1971, while the increase of WD has been noted only since 1965.

It allows allocating two periods of development of erosion intensity and SSY in the basin of Zapadny Bug – 1950-1970 (period T_1) and 1971-1987 (period T_2). From T_1 to T_2 the mean long-term specific SSY (R_{av}) have been increased by 6.3 t/km^2×year (i.e. by 166%) – from 3.8±1.0 to 10.1±1.7 t/km^2×year, while the specific WD (Q_{av}) has been increased only by 54% (from 4.8±0.7 to 7.4±1.7 l/s×km^2) (Fig. 2C).

Thus, reduction of the coefficients of inter-annual variation of SSY and water discharge between the periods – accordingly, from 61 to 35% and 35 to 27%, and reduction of dependence of SSY-change on the variability of WD (coefficient of determination) – accordingly, 49 to 31% – were marked. There is the question: what is the role of increased water discharge in the noted increase of SSY in 1971-1987? The connection between the annual values of SSY (R_i) and the water discharge (Q_i) in 1950-1970 looked as: $R_i = 0.39 \times Q_i^{1.366}$ (γ_{eq} and $\gamma_m > 99.9\%$).

Extrapolating this connection for the period 1971-1987 we obtain the mean long-term hydro-climatically caused (hypothetical) values of SSY – r_{av} (T_2) = 6.1 t/km^2×year (the IV scenario of SSY-change (Fig. 1)). The increase of WD could have increased the SSY – Δr (T_2) – between these periods only by 61%. The remaining 105%, hence, is more likely, the result of economic activity in the river basin. The influence of endogenic factor (the earthquakes of medium and high magnitudes, volcanic activity) is naturally excluded in this case. Due to the human activity the SSY has been additionally increased in the river basin (ΔA) by 4 t/km^2×year.

It means that the portion of hydro-climatical component (ωr) in the changed (increased) SSY of period 1971-1987 is 36.5%, whereas the anthropogenic component (ωA) – 63.5 %, i.e. the human activity (mainly, deforestation and cultivation) played the prevailing role in change of SSY of Zapadny Bug. In the many districts of western part of Ukraine the growth of gully network density and the growth of sedimentation rates within the channels of small rivers in connection with noted human activity were marked in the period 1950-1980s [16].

The following structure of the actual SSY of Zapadny Bug for the period 1971-1987 (10.1±1.7 t/km^2×year) was observed: ∂r = 60.4 % and ∂A = 39.6 %.

• **Magdalena**[*] flows in the northwest part of South America, within Colombia, running into the Caribbean Sea. The river basin area above the hydrological post in Calamar, which is located near to the river mouth, is about 250×10^3 km^2 (including the Cauca River – the largest tributary of Magdalena). The main part of its basin lies within the mountain districts (Western, Central and Eastern Cordilleras of the Colombian Andes). Some hydrological characteristics of Magdalena are shown in Table2.

On the combined diagram (Fig.3A) the linear trend of SSY-increases from 1972 to 1998 causing its general long-term variability in the given period only by 12%, is marked (γ_{eq} = 91.9 %). The mean rate of increase of the annual SSY (R_i) was 1.95×10^6 t/year ($R_i = 2.03 \times t_i - 3878.6$).

This process occurred against the WD reduction (γ_{eq} = 72.5%) with a mean intensity around 0.96×10^{9}m^3/year ($Q_i = - t_i + 2207.7$).

[*]The long-term series of observations for SSY and water discharge of this river and the subsequent approbation rivers are taken from [17].

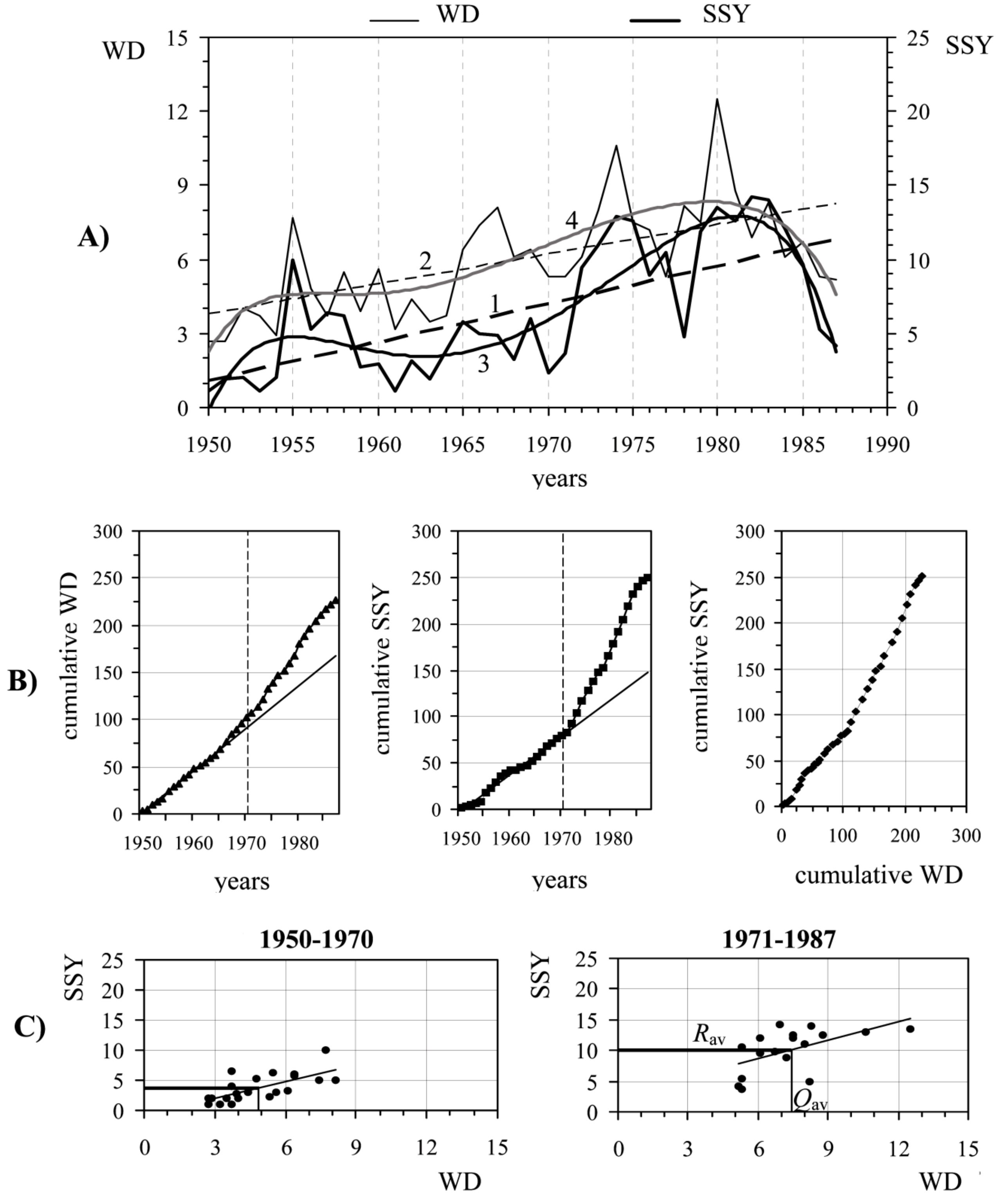

Fig. 2. The changes of annual water discharge (WD, l/s×km^2) and suspended sediment yield (SSY, t/km^2×year) (**A**), its cumulative curves (**B**) and the ratio of its periods' mean values (**C**) of River Zapadny Bug/Kamenka-Bugskaya (Ukraine) during 1950-1987. Symbols: the linear trends of the changes of annual SSY (1) and WD (2); the nonlinear polynomial trends of sixth degree of the changes of annual SSY (3) and WD (4); R_{av} (Q_{av}) – the mean long-term value of SSY (WD).

Table 2. Some hydrological characteristics of the analyzed rivers.

Rivers (period of observations)	Hydrological characteristics			
	Mean value of WD, m^3/year	Mean specific WD, l/s×km^2	Mean value of SSY, t/year	Mean specific SSY, t/km^2×year
Zapadny Bug (1950-1987)	$444.7±51.9×10^6$	6.0±0.7	$15.5±3.3×10^3$	6.6±1.4
Magdalena (1972-1998)	$222.7±13.8×10^9$	28.0±1.7	$141±18×10^6$	564±71
Bei-Nan (1948-2002)	$3.0±0.3×10^9$	60.0±6.4	$17.95±5.30×10^6$	11330±3345
Sanchuanhe (1957-1993)	$270±35×10^6$	2.1±0.3	$21.41±6.87×10^6$	5146±1651
Indus (1931-2003)	78.71±11.42*	2.6±0.4	$110.34±24.19×10^6$	115±25

* km^3/year

The analysis of the course of the nonlinear polynomial trend of sixth degree (Fig. 3A) and cumulative curve (Fig. 3B) for SSY allows allocating the two periods in its long-term variability: 1972-1985 with R_{av} = $118.8±14.0×10^6$ t/year and Q_{av} = $227.64±19.34×10^9$ m^3/year, $R_i = 0.077×Q_i^{1.351}$ (γ_{eq} and γ_m > 99.9 %), and 1986-1998 with $R_{av} = 165.1±28.8×10^6$ t/year and Q_{av} = $217.38±19.95×10^9$ m^3/year (Fig. 3C). Between the specified periods the SSY has increased by $46.3×10^6$ t/year (or by 39 %), while the WD was reduced up to $10.26×10^9$ m^3/year (or by 4.5 %); however, the C_v of annual SSY has increased from 22.5 to 32%, while the C_v of annual WD has practically not changed. Under the specified runoff change we could expect the hydro-climatically caused mean long-term value of SSY in 1986-1998 – r_{av} – at a level of around $111.6×10^6$ t/year (i.e. $\Delta r = – 7.2×10^6$ t/year, or Δr = – 6.1 % (the VII scenario of SSY-change in Fig.1). The difference between the actual SSY of Magdalena (R_{av}) and the hydro-climatically caused SSY (r_{av}) during the given period is around $53.5×10^6$ t/year. Obviously, SSY, which increased by 39% between the periods 1972-1985 and 1986-1998 (ΔR), has been completely connected (ωA = 100%) with the changes of geographical conditions within the river basin (deforestation, agriculture, gold mining). For example, in 1950-1980s in Colombia the rate of deforestation was around $6.6\text{-}8.8×10^3$ km^2/year [18]. In the 1980-1990s the fast growth of the Colombia's population and economic utilization of the forest lands have led to destruction of around $3.5×10^6$ ha of rainforests in the valley of Magdalena [19]. Here, in the areas of forest cuttings the agriculture has a mainly extensive character (crops of corn, barley, wheat), and the soils are cultivated by primitive instruments. In the rare farm economies, specialising on cultivation of vegetables by using mechanised deep ploughing, the erosion acquires a most intensive character. The rates of soil-ground washout thus (up to 330 t/ha) exceed the natural ones by many tens and hundreds of times. The great damage for rainforests of the mountain part of Colombia, according to the publication of US Department of State [20], is caused by the cultivators of narcotic plants, because of which more than 1 million ha of such forests were lost in this country since 1985.

The following structure of the actual SSY of period 1986-1998 ($R_{av} = 165.1×10^6$ t/year) was observed: ∂r = 67.6% and ∂A = 32.4%.

• **Bei-Nan** (Taiwan, China): the river basin area is 1584 km^2. Some hydrological characteristics of Bei-Nan are given in Table 2.

On the combined diagram (Fig.4A) the linear trend of increase of SSY from 1948 to 2002, which has caused its general long-term variability in the period only by 5 %, is clearly marked (γ_{eq} = 90 %). The mean rate of annual SSY increase was around $0.275×10^6$ t/year (R_i = $0.28×t_i$ – 533.94). During the specified period the tendency of gradual reduction of river WD was marked (γ_{eq} = 88 %) with the mean intensity around $15.64×10^6$ m^3/year ($Q_i = –0.016×t_i + 35.1$).

The analysis of the course of the nonlinear polynomial trend of sixth degree (Fig. 4A) and the cumulative curve (Fig. 4B) for SSY allows allocating three periods in its long-term variability: 1948-1960, 1961-1980, 1981-2002 (Fig. 4C). According to the functional connection between the annual SSY (R_i) and WD (Q_i) ($R_i = 0.985×Q_i^{0.537}$) (γ_{eq} = 82.7 %; γ_m = 74.7 %) of the period 1948-1960, it was possible to expect the hydro-climatically caused SSY during the two subsequent allocated periods at levels not exceeding $2×10^6$ t/year. However, the actual SSY-values have surpassed these expectations more than 10 times (Table. 3). No doubt that the principal reason of the noted fact is human activity. It has removed the erosion processes in the

Bei-Nan basin in the first half of 1960s from a state of relative dynamic equilibrium. The erosion "revolt" of the period 1960-1970, which in the 1980-1990s was replaced by relaxation, has been caused by deforestation under the road construction on climatically and tectonically unstable mountain slopes here [21]. The increase of SSY/WD correlation and determination coefficients of SSY in 1961-2002 has also distinctly specified expansion in area of this basin (sheet and rill-gully erosion).

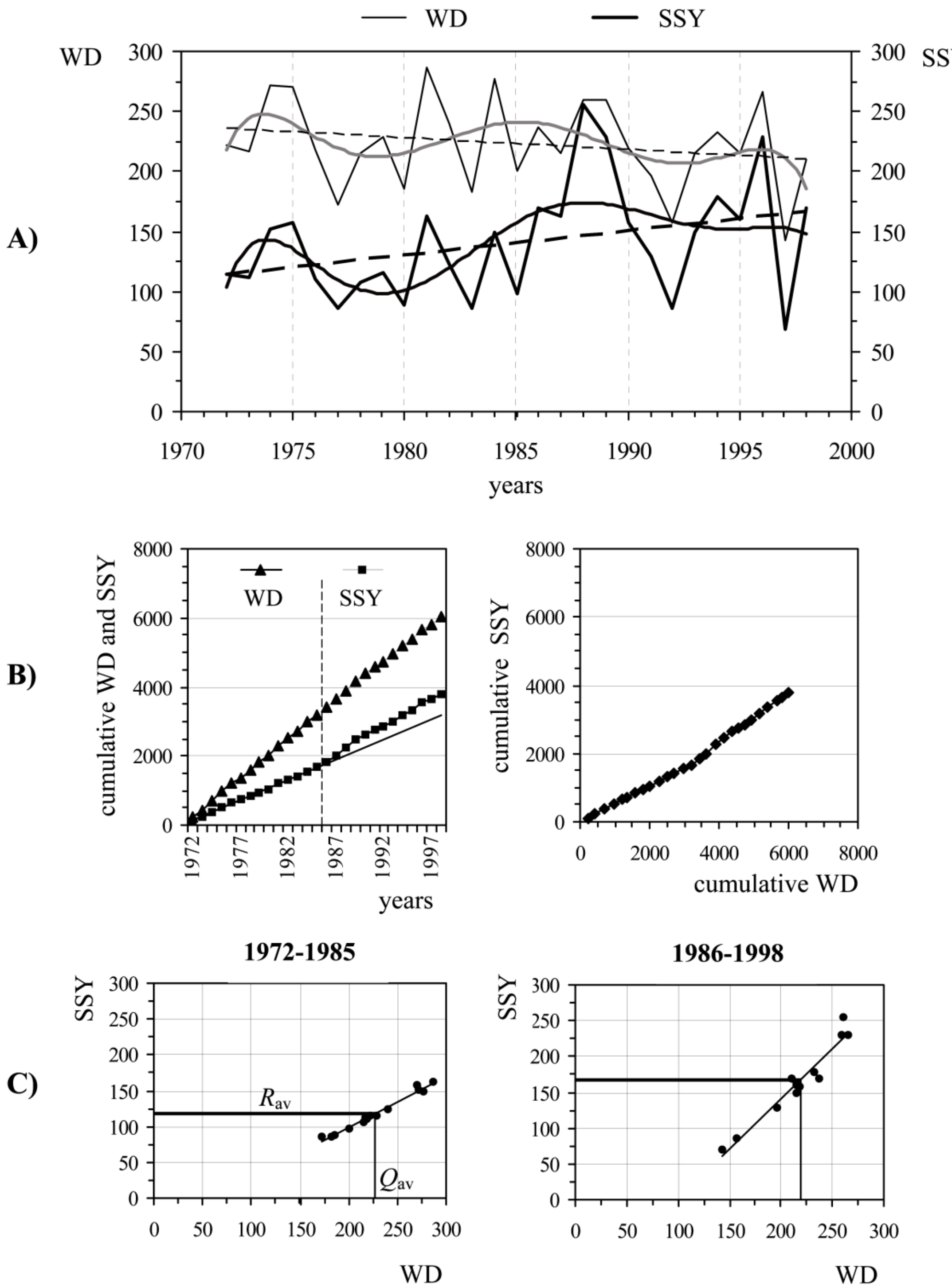

Fig. 3. The changes of annual water discharge (WD, 10^9 m^3/year) and suspended sediment yield (SSY, 10^6 t/year) (**A**), its cumulative curves (**B**) and the ratio of its periods' mean values (**C**) of River Magdalena/Calamar (Colombia) during 1972-1998 (other symbols see Fig. 2).

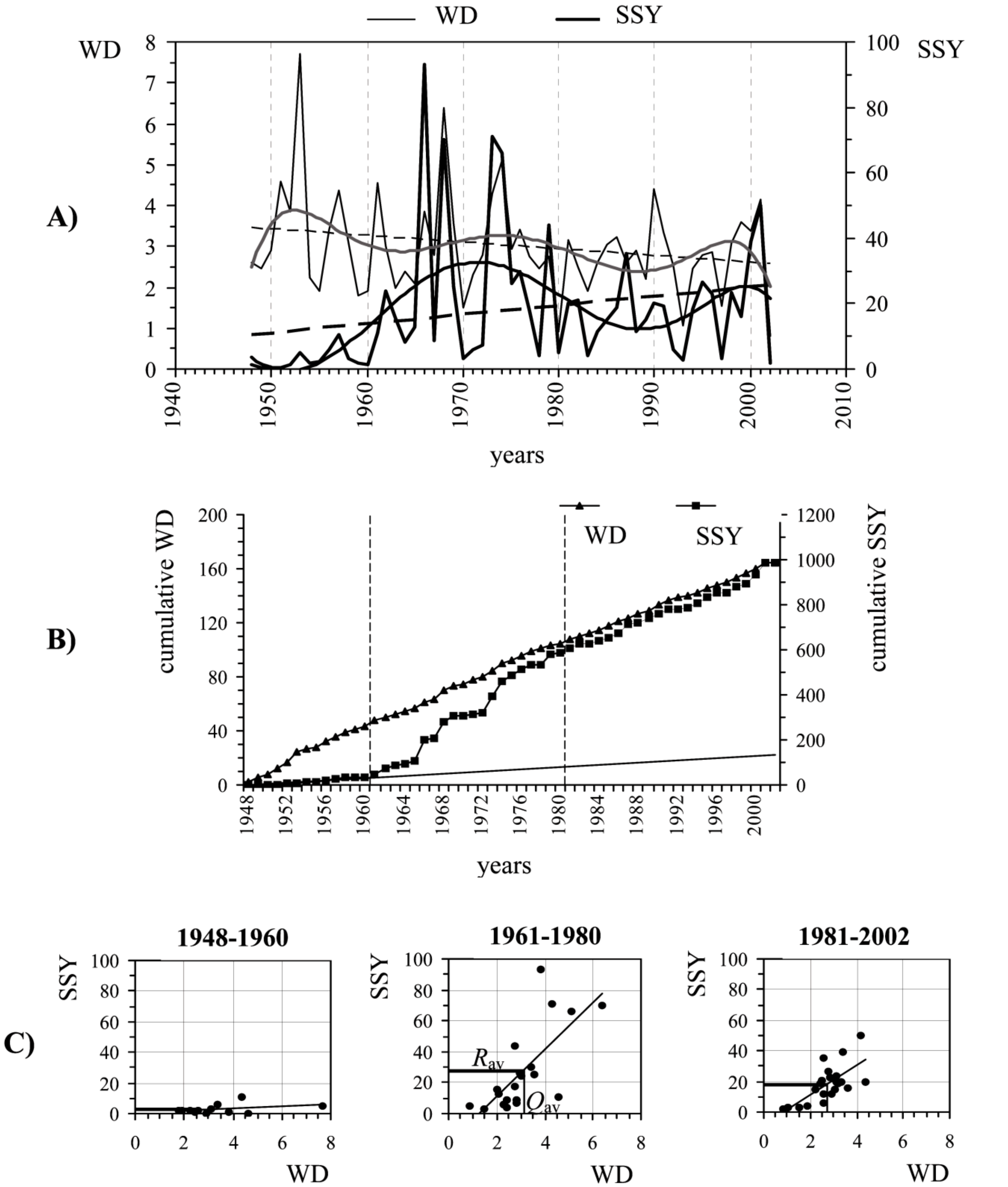

Fig. 4. The changes of annual water discharge (WD, 10^9 m^3/year) and suspended sediment yield (SSY, 10^6 t/year) (**A**), its cumulative curves (**B**) and the ratio of its periods' mean values (**C**) of River Bei-Nan (Taiwan, China) during 1948-2002 (other symbols see Fig. 2).

Table 3. The periods' characteristics of suspended sediment yield (SSY) and water discharge (WD) of River Bei-Nan in connection with its directed change during 1948-2002

The characteristics	The allocated periods		
	1948–1960	*1961–1980*	*1981–2002*
Q_{av}, $\times 10^9$ m^3/year	3.29 ± 0.88	3.09 ± 0.56	2.774 ± 0.37
ΔQ, $\times 10^9$ m^3/year (%)	—	– 0.20 (– 6%)	– 0.55 (– 16.7%)
C_v (WD), %	49	41	32
R_{av}, $\times 10^6$ t/year	2.8 ± 1.6	27.4 ± 11.8	18.3 ± 5.1
r_{av}, $\times 10^6$ t/year	—	1.77	1.65
Δr, $\times 10^6$ t/year (%)	—	– 1.03 (– 36.8%)	– 1.15(– 41.1%)
ΔR, $\times 10^6$ t/year	—	+ 24.6 (+879%)	+ 15.5 (+554%)
Scenario	—	VII	VII
C_v (SSY), %	102	98	66
ΔA, $\times 10^6$ t/year	—	+ 25.6 (+ 915%)	+ 16.7 (595%)
k, %	40	71	68
D, %	16	50	46
ωr, %	—	0	0
ωA, %	—	100	100
∂r, %	—	6.6	8.7
∂A, %	—	93.4	91.3

ΔQ – the change of WD for periods 1961–1985 and 1986–2002 in comparison with the period 1948–60

3-2. The Rivers with tendencies of SSY reduction

- **Sanchuanhe** (the Yellow River basin, Loess plateau, China): the river basin area above the hydrological post in Xiadacheng is 4161 km^2. Some hydrological characteristics of Sanchuanhe are given in Table 2.

On the combined diagram of long-term course of the annual values of SSY and WD (Fig.5A) the linear trends of its reduction from 1957 to 1993, which have caused its general long-term variability in the given period only by 24% in SSY and 23% in WD, as distinctly marked (γ_{eq} = 99.7 %).

Accordingly, the mean rates of reduction of the annual SSY (R_i) and WD (Q_i) were 0.94×10^6 t/year ($R_i = -0.965\times t_i + 1926.4$) and 4.72×10^6 m^3/year ($Q_i = -4.85\times t_i + 9835.3$).

The analysis of the course of the nonlinear polynomial trend of sixth degree (Fig. 5A) and cumulative curve (Fig. 5B) for SSY shows its most considerable reduction since 1971 and less considerable since 1979. This fact allows allocating the three periods in long-term variability of erosion intensity and SSY: 1957-1970, 1971-1978 and 1979-1993 (Fig. 5C). The equation of connection between the annual SSY and WD values for the "pattern" period 1957-1970 appears to be: $R_i = 0.0003\times Q_i^{1.996}$ (γ_{eq} and γ_m > 99.9 %). If during the 1970s the SSY-reduction was exclusively the consequence of WD reduction in the river basin (although with some anthropogenic increase of SSY), then in the 1980s and in the early 1990s the human activity played more significant role in this phenomenon (Table. 4). According to W. Zhao and etc. [8], by the end of 1980s in the given river basin the bank-strengthening terraces had been constructed in an area of 267 km^2, and the territories which had suffered most from erosion activity, had been artificially covered by forests (703 km^2) or perennial grasses (46.7km^2). Besides, nine water reservoirs have been built in the valley of Sanchuanhe, accumulating the suspended sediments. Thus, about 30% of the river basin area was, anyhow, under active economical control.

The researchers from China specify that this has promoted the SSY of the river to be decreased by 36-41% since 1970. Our conclusions (Table 4) and the conclusions of colleagues from China [8], concerning the role of the anthropogenic factor, are different. This can be connected most likely, with the different approach for estimation of the influence of this factor, as well as with the specificity of the rivers within the Loess plateau, differing by the abnormally large SSY-values. The last mentioned circumstance demands the entering of further corrective amendment into the offered approach with reference to similar rivers.

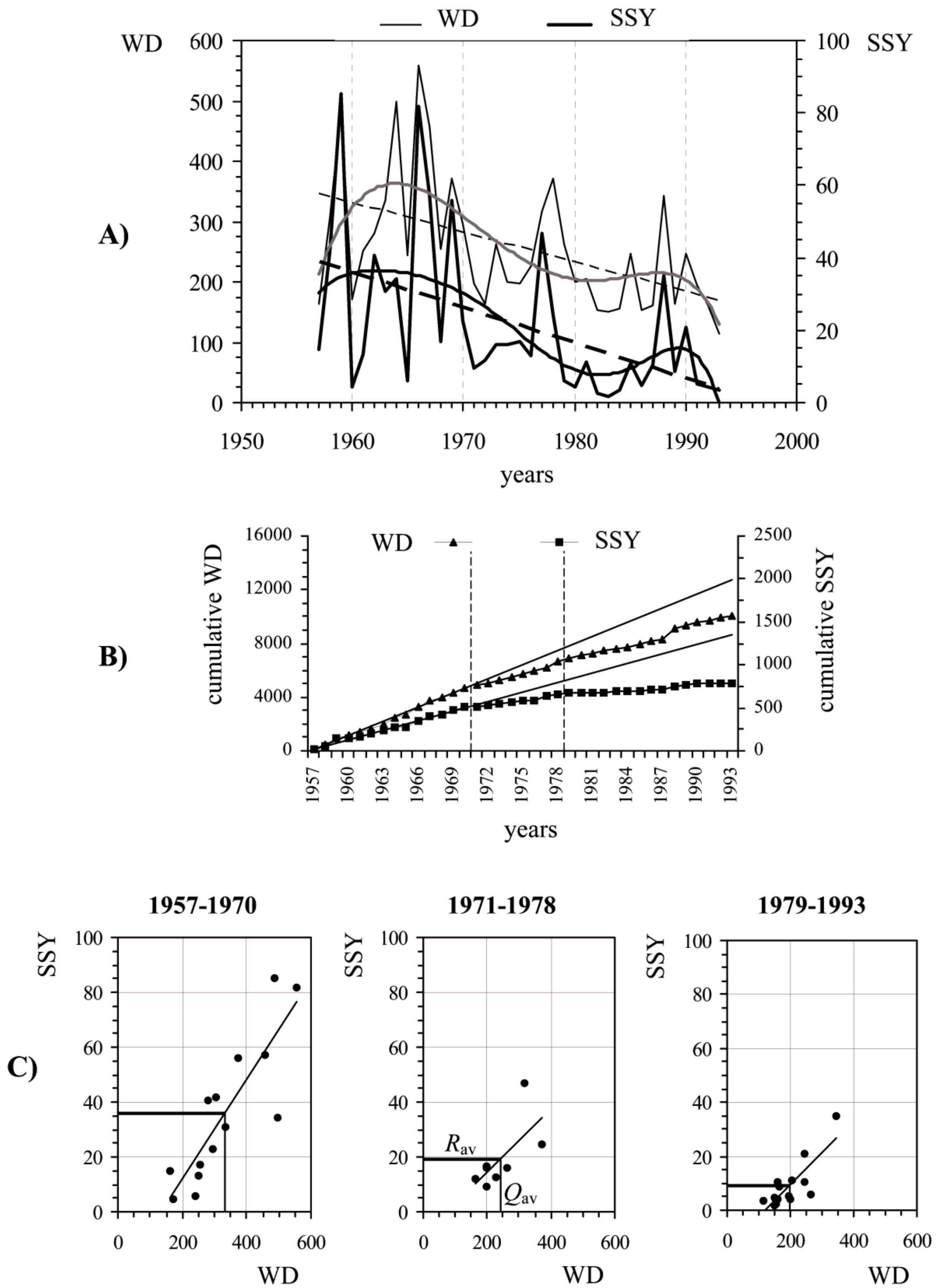

Fig. 5. The changes of annual water discharge (WD, 10^6 m^3/year) and suspended sediment yield (SSY, 10^6 t/year) (**A**), its cumulative curves (**B**) and the ratio of its periods' mean values (**C**) of River Sanchuanhe/Xiadacheng (China) during 1957-1993 (other symbols see Fig. 2).

• **Indus (**Pakistan, India, China and Afghanistan): the river basin area above the hydrological post in Kotri (Pakistan) is about 960×10^3 km^2. Some hydrological characteristics of Indus are shown in Table 2.

On the combined diagram of long-term course of the annual values of SSY and WD (Fig. 6A, B) the linear trends of its reduction from 1931 to 2003 are also distinctly marked (γ_{eq} = 99.99 %). These trends have caused its general long-term variability in the given period only by 46% in SSY and 51% in WD.

The mean rates of reduction of the annual SSY (R_i)and WD (Q_i) were, accordingly, 3.33×10^6 t/year ($R_i = -3.382\times t_i + 6762.9$) and 1.647km^3/year ($Q_i = -1.67\times t_i + 3364.3$).

The analysis of change of the annual SSY-values (Fig. 6A) shows its most considerable reduction between 1947 and 1974, which allows allocating three periods of SSY variability in this basin: 1931-1947, 1948-1974, 1975-2003 (Fig. 6C). The equation of connection between the annual SSY (R_i) and WD (Q_i) for the "pattern" period 1931-1947 looked as: $R_i = 9.811\times Q_i^{0.672}$ (γ_{eq} and γ_m > 99 %).

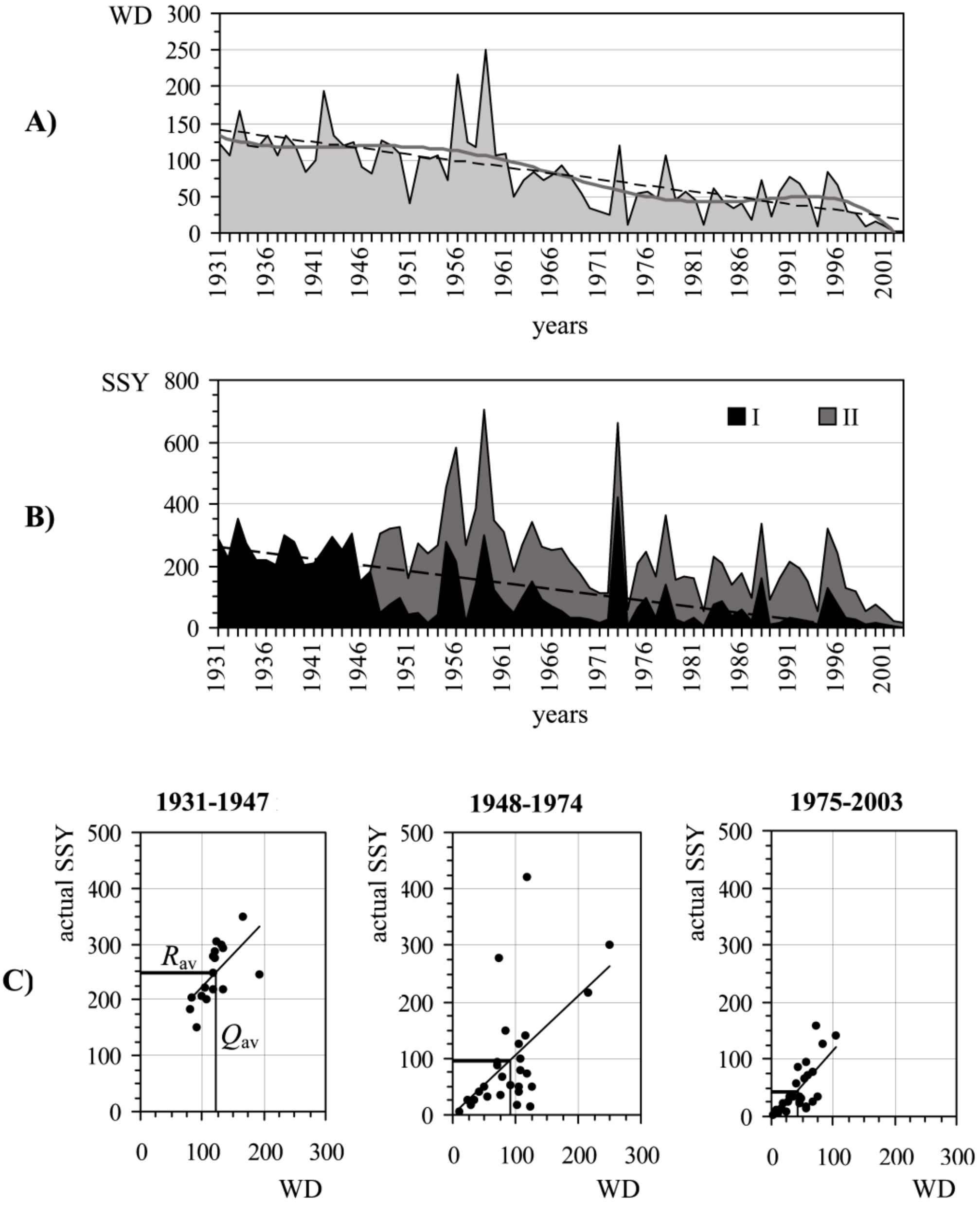

Fig. 6. The changes of annual water discharge (WD, km^3/year) (**A**) and suspended sediment yield (SSY, 10^6 t/year) (**B**) and the ratio of its periods' mean values (**C**) of River Indus/Kotri (Pakistan) during 1931-2003.
I – actual SSY, II – potential hydro-climatically caused SSY during 1948-2003 (other symbols see Fig. 2).

Table 4. The periods' characteristics of suspended sediment yield (SSY) and water discharge (WD) of River Sanchuanhe in connection with its directed change during 1957-1993

The characteristics	The allocated periods		
	1957–1970	*1971–1978*	*1979–1993*
Q_{av}, ×10^6 m^3/year	333.8 ± 64.8	242.1 ± 49.2	193.7 ± 29.9
ΔQ, ×10^6 m^3/year (%)	—	– 91.7 (– 27.5%)	– 140.1 (– 42%)
C_v (WD), %	37	29	31
R_{av}, ×10^6 t/year	36.1 ± 13.7	19.3 ± 8.3	8.8 ± 4.4
r_{av}, ×10^6 t/year	—	18.5	12.0
Δr, ×10^6 t/year (%)	—	– 17.6 (– 48.7%)	– 24.1(– 66.8%)
ΔR, ×10^6 t/year	—	– 16.8 (– 46.5%)	– 27.3 (– 75.6%)
Scenario	—	XIII	XII
C_v (SSY), %	72	62	99
ΔA, ×10^6 t/year	—	+ 0.8 (+ 2.2%)	– 3.2 (– 8.8%)
k, %	85	62	82
D, %	72	38	67
ωr, %	—	100	88.3
ωA, %	—	0	11.7
∂r, %	—	95.9	100
∂A, %	—	4.1	0

ΔQ – the change of WD for periods 1971–1978 and 1979–1993 in comparison with the period 1957–1970

The progressive reduction of SSY of the Indus in the second half of XX century in comparison with the end of first half of that century has been caused by the tendency of climatic drying in the region (a usual consequence is some reduction of basin erosion intensity) and the active utilization of the river waters for irrigation systems (a usual consequence is reduction of transporting ability of the main river and its tributaries, and strengthening of sediment accumulation in the river channels).

The construction of hydraulic engineering objects (reservoirs) has also led to the marked SSY-reduction. The human role was most notable (68%) here in the period 1948-1974 (Table. 5), though the largest water reservoirs – the traps of sediments – have been built in the Indus basin only at the end of this period (the Mangla Reservoir (1967) on the Indus and Tarbela Reservoir (1974) on the Jhelum River). Totally from 1948 to 2003 around 4.82±0.99×10^9 tons of suspended sediments have been accumulated in the river valleys of Indus basin. The effect of anthropogenic (hydraulic engineering) reduction of SSY of the Indus could be bigger, especially in 1975-2003, if not for the effects of the human activity.
According to the report published on the official site of the Government of Pakistan [22], the population of this country, where the main area of Indus basin is located, has increased from 1951 to 2001 by more than 4 times (34 to 144 million persons). The fastest rate of population growth was marked since 1970s. It has led to the growth of the cultivated areas (only from 1947 to 1975 these areas have been increased in the country by 25%) with the increased use of heavy agricultural machinery, breaking the normal water-physical characteristics of the local soils. So, from the beginning of 1950s to 1981 the number of tractors in Pakistan has increased more than 39 times [23].

The intensive basin erosion on the cultivated areas and the increase of SSY of the Indus were the consequences of this phenomenon. The forest cuttings, especially in the mountainous part of the river basin (Pakistan and India (State of Jammu and Kashmir)), have also promoted these processes

Table 5. The periods' characteristics of suspended sediment yield (SSY) and water discharge (WD) of River Indus in connection with its directed change during 1931-2003

The characteristics	The allocated periods		
	1931–1947	*1948–1974*	*1975–2003*
Q_{av}, km^3/year	120.12 ± 13.41	92.33 ± 19.9	41.76 ± 9.64
ΔQ, km^3/year (%)	—	– 27.79 (– 23.1%)	– 78.36 (– 65.2%)
C_v (WD), %	24	57	63
R_{av}, ×10^6 t/year	246.3 ± 24.7	96.0 ± 37.7	44.0 ± 15.5
r_{av}, ×10^6 t/year	—	198.2	114.0
Δr, ×10^6 t/year (%)	—	– 48.1 (– 19.5%)	– 132.3(– 53.7%)
ΔR, ×10^6 t/year	—	– 150.3 (– 61.0%)	– 202.3 (– 82.1%)
Scenario	—	XII	XII
C_v (SSY), %	21	104	97
ΔA, ×10^6 t/year	—	– 102.2 (– 41.5%)	– 70.0 (– 28.4%)
k, %	62	56	75
D, %	38	31	56
ωr, % ωA, %	— —	32 68	65.4 34.6
∂r, % ∂A, %	— —	100 0	100 0

ΔQ – the change of WD for periods 1948–1974 and 1975–2003 in comparison with the period 1931–1947

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