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MODELLING OF POLLUTION TRANSPORT WITH SEDIMENT
ON THE EXAMPLE OF THE WIDAWA RIVERROBERT KASPEREK¹, MARIAN MOKWA¹, MIROSLAW WIATKOWSKI²

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Abstract: The aim of the study was to determine the contamination transport condition with sediment in the Widawa River, which inflows to the Odra River below Wrocław city. The transport simulations have been performed by means of HEC-RAS model, which was calibrated. Study and geochemical analyses indicate that pollutions are cumulated mainly in sediment of grain size, less than 0,20 mm. It was stated that the main sources of contaminations occurring in the Widawa River bottoms are: superficial run-off, municipal and industrial wastes. Sediment bed quality from the Widawa River in selected cross-sections has been analyzed. Samples of suspended load were collected and divided into eight fractions, for which the phosphorus concentration P was calculated. Deposit particles less than 0,20 mm contained most phosphorus, i.e. 73% (3,52 ppm), and particles greater than 0,20 mm about 27% (1,30 ppm) for the whole sample volume. Relationship between the phosphorus concentration P and the sediment grain size was determined. Analysis showed that the initiation of contamination-sediment suspension in the Widawa River is well described by Engelund criterion. Simulations of the migration of pollutions together with deposits in the Widawa River showed that during average flow discharge, the transport intensity of pollution was equal 2 mg/s, and sediments 6 kg/s. In the present work the water quality of the Widawa River has been also presented.

INTRODUCTION

Any material coming from denudation, erosion and deposition of industrial, agricultural and municipal contamination disposed into rivers is carried either in solid or dissolved phases [5]. Transport of solid particles and material dissolved in water stream can occur in different forms [1, 4, 17, 21]. Suspended load clusters are transported in the forms of bed, suspended and wash loads. Transport of suspended load consisting of fine particles with diameter less than 0,2 mm and usually distributed at a uniform rate results in binding the majority of chemical contaminants. Contaminants introduced into receiving water bodies, such as rivers, lakes or groundwater, mix and move with water and sediments and react with them [11, 23, 24, 26, 27, 29, 30, 32].

Bed load transport

The zone close to the bed of the river is not sampled by suspended load samplers and it is termed the unsampled zone or the zone of bed load transport. Transport in the unsampled zone includes the rolling and jumping material in the bed load, plus some portion of suspended load, and the amount of material transported in this zone can represent a significant fraction of the total load in sand-bed rivers. Bed load transport is difficult to measure, and at most gauging stations it is estimated or computed rather than measured directly. Sediments in arid zones tend to be coarse-grained, bed load generally constitutes a larger part of the total load in streams draining desert areas than those in humid areas. Grain size of bed load is larger than 1–2 mm (coarse sand, gravel and stones) [16, 21].

Suspended load transport

Suspended load refers to sediment which is supported by the upward components of turbulent currents and stays in suspension for an appreciable length of time. In the most natural rivers, sediments are mainly transported as suspended load [4, 9, 15, 17, 21, 25, 28, 31].

Generally, this sediment is formed by particles smaller than 1–2 mm as the sand, silt and clay. The suspended load transport is function of the concentration, sediment properties and of local hydraulic flow parameters.

The majority of discharged into surface water heavy metals and toxic organic compounds that are slightly soluble and not easily degradable may retain in bottom deposits [3, 8, 10, 16, 22]. Consequently, bottom deposits with high quantity of toxic substances can be a sources of contamination. Part of toxic substances present in deposits may be released into water again due to chemical and biochemical processes. These deposits affected by natural processes (erosion) or human activity (transport, dredging) may be displaced into upper water layers. Upon freshets, the contaminated deposits are transported downstream and accumulated in places where previously no contamination was observed, as well as they can be spread out in soils at river basin areas [13, 20]. Bottom deposits are considered to be essential component for water systems. Due to analysis of sediments contaminated with heavy metals, as well as toxic organic compounds, bottom deposits are very useful in quality control of water surface environment. Because of repeatedly high concentrations of toxic substances present in sediments in comparison with water, chemical analysis of sediments enables monitoring of concentration changes even at relatively low levels [7, 15]. It refers to particles transported by motion of turbulences that come from a riverbed or can be formed at the entire flow section. In majority, suspended load (grain size is between 0,1 mm and 2,0 mm) is a product of river basin denudation. According to some researchers [1, 17, 18, 20, 21], in the European rivers suspended load transport is actually limited to solid particles with diameters of 0.25–0.50 mm. Practically, the upper limit diameter of grains suspended in lowland rivers is estimated at 1.2 mm [4, 9, 10], which has been confirmed by measurements carried out for selected Polish rivers, for example the Middle and Upper Odra River [7, 15], and the Widawa River. A lower limit diameter of 0.1 mm generates great controversy.

Rivers and reservoirs undergo natural process of silting. The most exposed to deposition areas are these where the velocity decrease occurs, such as basin areas, river

banks and reservoirs, wing dam fields, marginal lakes and dead fields, and river mouth sections (the lower part of the Widawa River). In particular, silting occurs in places just above dams where distribution of deposits is affected by dykes or dams exploitation, valley morphology and the presence of aqueous plants. Sections of tributary mouth can be also exposed to intensive silting. Flood flows are of great significance as due to their energy, coarse sediments are transported along river channels, whereas fine sediments are transported to flooded areas and places with lower flow velocities. Sediment transport is particularly intense in the phase of flood wave growth, and sedimentation is facilitated by wave falling when the water inflow and velocity decrease. However, flood with large flow intensity may cause hydraulic erosion of previously deposited wash that after activation is transported and deposited at different places. Furthermore, wash may pose significant hazards to the environment due to the presence of various toxic substances (e.g. heavy metals).

Coherent deposits depending on moisture content are in fluid, plastic or compact forms. Fluid deposits act as liquids. Plastic deposits undergo deformation upon tension but they return into their original shape. In the case of compact deposits, deformation occurs upon severe pressures and it is accompanied by cracks. The liquid limit between fluid and plastic forms (consistency) is a fundamental property of coherent soil. Mineral coherent soils with diverse grain content and organic coherent soils can be distinguished. The latter comprise fine organic wash with organic matter content ranging from 5 to 30%. Generally, fluvial wash resulted from river basin erosion consists of less than 10% of organic matter. In the case of lacustrine wash, organic matter is much higher and in fishponds it can reach even 25%.

River-carried deposits in the form of suspension may undergo sedimentation due to variable conditions of the flow regime. Sedimentation of solid particles, formation of a deposit layer on riverbed and their slopes, as well as its consolidation in function of time, is complex and depends on many factors. These factors are classified into the following four groups: hydrologic, geomorphologic, hydrodynamic and exploitative.

Soil profile (size and shape of particles, thickness of bed layer), organic matter content, presence of water dissolved salts and solid particle concentrations, play an important role. Much attention should be paid to determining size of suspended grains that show strong tendency towards agglomeration into flocules. Silt and dusty suspensions with grain size less than 0,04 mm undergo flocculation at low concentrations of water-dissolved salts. When the flocculation rate is higher, then the smaller particles and higher concentration of suspensions are observed.

Bottom deposits naturally accumulate and consolidate substances discharged into the water, including anthropogenic contamination. The composition of bottom deposits reflects the condition of the environment and it is a sensitive indicator of its contamination. Substances accumulated in bottom deposits are bound and immobilised. Due to erosion caused by floods or resulting from human activity, substances accumulated in bottom deposits can be released again into the water body and pose hazards for aquatic ecosystems and humans. The assessment of the water quality is focused on the analysis of water rather than bottom deposits. It has to be pointed out that the knowledge about biogenic compounds and speciation of metals in lacustrine bottom deposits is comprehensive, whereas more detailed information on chemical properties of fluvial wash are not available in Poland.

The main objectives of the paper are as follows:

- Study and estimation of composition of bed material and suspended load, and contaminations from the Widawa River.
- Hydraulic calculations of stream and analysis of sediment motion and suspension.
- Simulation of contamination transport with sediment.

The Widawa River characteristic

The Widawa River is the right-bank tributary of the Odra River (km 266,9) and flows through the provinces of Lower Silesia and Opole (Fig. 1, 2). Drainage area of the Widawa River in inflow cross-section to Odra is equal 1713,1 km². Agricultural and forestry management is in drainage basin. The low and middle sector of this river (km 0,0–22,0) is regulated. River flows through the city of Wrocław and it is a part of the Wrocław Hydrotechnical System

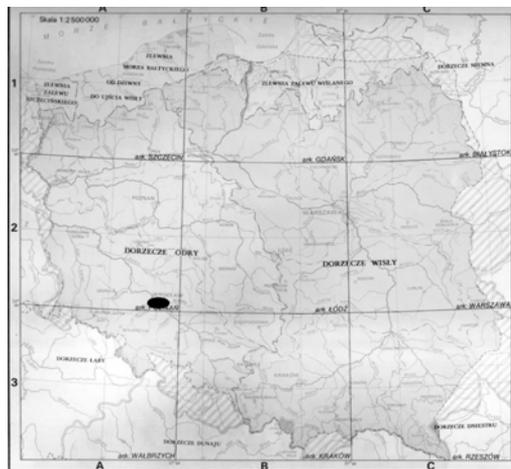


Fig. 1. The map of surface waters of Poland [3]. The black circle means the investigated sector of the River Widawa

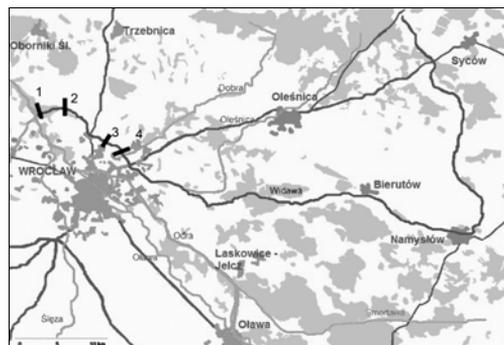


Fig. 2. The River Widawa with the measurement stations: the River Widawa mouth to the River Odra (km 0,5, No. 1), Świniary (km 5,0, No. 2), Krzyżanowice (km 12,0, No. 3) and the River Dobra mouth to the River Widawa (km 16,0, No. 4) [26]

during floods. All length of the Widawa River is 103,2 km, and main tributaries are the following streams: Studnica, Świerzna, Graniczna, Oleśnica and Dobra. The studied sector of the low Widawa River is located in Krzyżanowice station (km 12,0), where water level and flow discharge is registered. Flood discharges in the Widawa River are following: $Q_{50\%} = 27 \text{ m}^3/\text{s}$, $Q_{10\%} = 40,3 \text{ m}^3/\text{s}$, $Q_{1\%} = 83.7 \text{ m}^3/\text{s}$ and $Q_{0,3\%} = 103.0 \text{ m}^3/\text{s}$. In the main channel the water surface slope varies from 0.1‰ to 0.7‰ during the flows. Total Manning-Strickler coefficient $k_s = 1/n$ for bed of the Widawa River changes from $10 \text{ m}^{1/3}\text{s}^{-1}$ to $60 \text{ m}^{1/3}\text{s}^{-1}$, and it depends on channel characteristic, season and water depths. The low annual flow is equal $1.59 \text{ m}^3/\text{s}$ and average annual flow is $6.95 \text{ m}^3/\text{s}$. In recent years, the average temperatures of air in the Widawa River basin have been approx. 20°C (in summer period) and approx. $1,2^\circ\text{C}$ (in winter period). Precipitation has changed on average from 24 mm (in winter) to 105 mm (in summer). The water temperature oscillated at 11°C (in summer $13\text{--}19^\circ\text{C}$, in autumn and spring 4°C and 6°C respectively).

Monitoring investigations of the water surface level in Opole voivodship are conducted by WIOŚ in Opole within a period of 2010–2012 in two measuring cross-sections of the Widawa River [19]:

- above reservoir Michalice (km 70.6),
- below Ligotka (km 56.8).

Types and sources of pollutions in the Widawa River catchment

The potential sources of superficial water and deposit pollutions in the area of the Widawa River basin include the following [12]:

- Local waste dumps (surface run-off, effluents, draining by water courses and reservoirs, waste washing-out from dumps during freshets).
- Precipitation and dustfall from the atmosphere.
- Agricultural activity (fertilising, ballast admixtures in mineral fertilisers, pesticides).
- Inflow of contaminants not connected with dump storage activities (industrial districts, industrial plants, means of transport and other).

In the Widawa River catchment, there used to be or there are still operating the following facilities which may contaminate its waters: distillery and bakery in Działosze and Smogorzów; fruit-vegetable processing plant in Dziadowa Kłoda; mechanical-biological sewage treatment plants of the town Bierutów, Dobroszyce, Mirków, Stradomia Wierzchnia, Oleśnica and Namysłów; distillery in Posadowice, distillery in Bierutów, SELGRROS market in Długoleka; Wrocław sugar factory; Polar – Division Wrocław-Psie Pole and Zakrzów factories; irrigation fields in Wrocław-Rędzin and Dobrzykowice town.

EXPERIMENTAL PROCEDURES

Sediment composition

Bed material was sampled from midstream and bank zone of the sector of the Widawa River. Generally, the composition of suspended load in streams and its distribution in vertical depend from hydrological regime, hydraulic conditions, and kind of material from catchment area and river-bed. During low flow the finest fractions are usually in movement and at high flows the coarsest fractions.

The suspended load measurements (“in situ”) of the Widawa River was performed in cross-section Krzyżanowice (2004 and 2005). On the basis of these studies sediment

transport conditions, grain composition and amount of contaminants were estimated. The measurements were conducted at the low water surface levels and flows. Water depths varied from 0.45 m to 0.55 m, flow discharge was equal 1,5 m³/s and average velocity 0,8 m/s. In the investigations the bottle samplers tested in Hydraulic Laboratory of Wrocław University of Environmental and Life Sciences were used [4, 15].

Incipient motion of sediment

The Shields diagram is a widely used method to determine the condition of incipient motion of sediment based on bed shear stress (Fig. 8). Points lying above the curve representing the critical condition correspond to sediment motion, and points below the curve correspond to no motion [16, 20]. Shields determined that the critical conditions are related to two dimensionless parameters: the dimensionless shear stress $\theta_{cr} = \tau_{cr}/(\rho_s - \rho)gd_i$ (also known as the Shields parameter), which does not represent the actual shear stress, and the boundary Reynolds number $Re_* = v_* d_i / \nu$. Bonnefille and Yalin [17, 21] have expressed the Shields curve in terms of the parameter θ_{cr} and dimensionless particle diameter $D_* = [(s_d - 1)gd_i^3/\nu^2]^{1/3}$, where $s_d = \rho_s/\rho$ is relative density. Shields curve can be divided into the five sections I, II, III, IV and V (Fig. 8), expressed by the following functions:

$$\begin{aligned} \text{I. } \theta_{cr} &= 0.24D_*^{-1} & 1 < D_* \leq 4 \\ \text{II. } \theta_{cr} &= 0.14D_*^{-0.64} & 4 < D_* \leq 10 \\ \text{III. } \theta_{cr} &= 0.04D_*^{-0.1} & 10 < D_* \leq 20 \\ \text{IV. } \theta_{cr} &= 0.013D_*^{0.29} & 20 < D_* \leq 150 \\ \text{V. } \theta_{cr} &= 0.055 & D_* > 150 \end{aligned}$$

where τ_{cr} – critical shear stress or critical tractive force (Nm⁻²), ρ_s – sediment density (kgm⁻³), ρ – liquid density (kgm⁻³), g – gravitational acceleration (ms⁻²), d_i – grain size (m), ν – average flow velocity (ms⁻¹), ν – kinematic viscosity (m²s⁻¹).

Initiation of suspension

Before analyzing the main hydraulic parameters which influence the suspended load, it is necessary to determine the flow conditions at which initiation of suspension will occur.

The researchers from Delft Hydraulics Laboratory [17] determined the critical flow conditions at which instantaneous upward turbulent motions of the sediment particles with jump lengths of the order of 100 particle diameters were observed. The experimental results can be represented by $v_{*cr}/w_s = 4/D_*$ for $1 < D_* \leq 10$; and $v_{*cr}/w_s = 0,4$ for $D_* \geq 10$, where v_{*cr} is critical bed-shear velocity according to Shields, and w_s is particle fall velocity of suspended sediment.

Summarizing, it is suggested that the criterion of Bagnold may define an upper limit of suspension and the criterion of Engelund a lower limit (Fig. 8) [21].

Sedimentation, transportation and erosion

In a clear, still water the particle fall velocity w_s of a solitary sand particle smaller than about 100 μm (Stokes-range) can be described by $w_s = (s_d - 1)gD_s^2/(18\nu)$, where D_s is parameter expressing the representative particle diameter of suspended sediment

particles, which may be considerably smaller than D_{50} of the bed material. For suspended sand particles in the range 100–1000 μm , the following type of equation, as proposed by Zanke, can be used $w_s = 10v/D_s \{[(1+0.01(s_d-1)gD_s^3/(18v^2))]^{0.5}-1\}$. For particles larger than about 1000 μm the particle fall velocity is calculated from $w_s = 1,1[(s_d-1)gD_s]^{0.5}$. For normal flow conditions with particles in the range 50–500 μm the reduced particle fall velocity (in a fluid-sediment mixture) can be described by a Richardson-Zaki type equation $w_{s,m} = (1-c)^4 w_s$ [4, 7, 10, 17, 21].

Hjulstrom [21] has estimated the relationship between sediment size and average flow velocity for erosion, transportation, and sedimentation for particle bigger than 0,001 mm.

The process of solid particle sedimentation is based on the quantity and the type of transported load material, its physical, chemical and rheological properties and also observations on the particles settling in the water body. Sedimentation intensity can be expressed in function of the “critical shear stress” by the Krone formula [10]:

$$D = M_d \left(1 - \frac{\tau_h}{\tau_{cr}} \right) \quad \text{for } \tau_h < \tau_{cr}$$

$$D = 0 \quad \text{for } \tau_h > \tau_{cr}$$

Where: D – sedimentation intensity [$\text{kg s}^{-1} \text{m}^{-2}$], M_d – coefficient of sedimentation intensity [$\text{kg s}^{-1} \text{m}^{-2}$], τ_h – bed shear stress [Pa], τ_{cr} – critical shear stress for initiation of solid particle sedimentation [Pa].

Sedimentation and settling of other fractions occur during water flow in rivers and aqueous reservoirs. It results in the formation of new deposit layers with a structure of stationary suspension with hardly any mechanical resistance.

Consolidation of such layers, the thickness of which after flooding can range from several centimetres to several meters, proceeds relatively fast, i.e. during a few hours. It results in a significant concentration increase vs. consolidation time. Aggregated muds and river outwash deposited deeper are usually more consolidated due to increasing load of overlaying sediment layers. At various depths of deposit layers, a gradual transition from liquid state into soft-plastic and hard-plastic states may occur. Migniot [10] distinguished four basic consolidation phases for flocculated deposits:

- phase I – sedimentation and phase separation into over-deposit water and deposit layer,
- phase II – rapid consolidation of deposit layer resulting in destruction of floccules and aggregates,
- phase III – slow consolidation of demersal layer with water filtration upward through gaps and holes,
- phase IV – slow consolidation of deposit with filtration through uniformly consolidated coherent soils.
- The assessment of wash erosion process can be carried out with reference to combined results of sedimentation and rheology investigations.
- Migniot presented a relation between critical shear stresses τ_{cr} for erosion of viscous-plastic deposits as a function of flow threshold τ_o , holding critical shear values of $\tau_o = 1.5 \text{ Pa}$ as a boundary between 2 zones: less- and more-resistant – to erosion:

- zone less-resistant – to erosion (referred to as a sheet erosion), where $\tau_{cr} = 0.317 \tau_o^{0.5}$ for $\tau_o < 1.5$ Pa,
- zone more-resistant to erosion (referred to as a mass erosion), where $\tau_{cr} = 0.256\tau_o$ for $\tau_o > 1.5$ Pa.

HEC-RAS program

HEC-RAS is a 1-dimensional integrated package of hydraulic analysis programs [6]. The system is capable of performing steady and unsteady flow water surface profile calculations. This application takes into account the influence of bridges, culverts, weirs, inline structures, lateral structures, storage areas, pump stations and sediment transport. Water surface profiles are computed from one cross section to the next by solving the energy equation. Whenever the water surface passes through critical depth, the energy equation is not considered to be applicable. Then program uses the momentum equation.

Flow $SNQ = 1.59 \text{ m}^3\text{s}^{-1}$ and $SSQ = 6.95 \text{ m}^3\text{s}^{-1}$ was introduced to the model. HEC-RAS model was calibrated on the basis of the rating curve from profile of the Widawa River sector from km 8.0 to km 14.0.

Based on the mode of transportation, total load is the sum of bed load and suspended load. There are two general approaches to the determination of total load. The first is to compute bed load and suspended load separately, and then add them together to obtain total load. The second is to determine total load function directly without dividing it into bed load and suspended load. Sediment transport for any cross-section can be computed using any of the following functions by Ackers-White, Engelund-Hansen, Laursen, Meyer-Peter and Müller, Toffaleti and Yang [21].

Modelling of total load transport with contaminates in the Widawa River was made on the low sector. Hydraulic calculations and sediment transport potential were performed in 21 cross-sections and for five flow discharges, i.e. $1.0 \text{ m}^3/\text{s}$, $1.59 \text{ m}^3/\text{s}$, $6.95 \text{ m}^3/\text{s}$, $10 \text{ m}^3/\text{s}$ and $20 \text{ m}^3/\text{s}$.

RESULTS AND DISCUSSION

Bed material and suspended sediment

Bed material from the Widawa River (Figs 2, 3, 4, 5) consists of the sands with mean size $d_{50} = 0.33\text{--}0.87$ mm (Fig. 6). The main fractions are $d = 0.1\text{--}0.25$ mm; $0.25\text{--}0.5$ mm and $0.5\text{--}1.0$ mm. The variation of the sediment bed composition on the studied river sector is small. The most is the fraction in the range of $0.25\text{--}0.5$ mm (52 %) and $0.5\text{--}1$ mm (45 %).

It was found out that the suspended load and bed material consisted of the following fractions d_i :

- bed material: $d < 0.063$ mm – 0%; $d = 0.063\text{--}0.1$ mm – 0%; $d = 0.1\text{--}0.25$ mm – 12%; $d = 0.25\text{--}0.5$ mm – 33%; $d = 0.5\text{--}1.0$ mm – 33% and $d = 1.0\text{--}2.0$ mm – 12%; $d = 2\text{--}5$ mm – 4% and $d = 5\text{--}10$ mm – 6%.
- suspended load: $d < 0.063$ mm – 11.3%; $d = 0.063\text{--}0.1$ mm – 9.1%; $d = 0.1\text{--}0.25$ mm – 56.1%; $d = 0.25\text{--}0.5$ mm – 15.9%; $d = 0.5\text{--}1.0$ mm – 5.6% and $d = 1.0\text{--}2.0$ mm – 2.0%; $d = 2\text{--}5$ mm – 0% and $d = 5\text{--}10$ mm – 0%.

Quality of water and bottoms of the Widawa River

In 2006 at station No. 1 of the Widawa River (Fig. 1) III-rd water class – satisfactory quality was noted [2, 19]. The variation analysis of the selected pollution indexes in



Fig. 3. The River Widawa, Krzyzanowice station, Spring 2012 [Photo R. Kasperek]



Fig. 4. Sand bed of the River Widawa channel, Spring 2012 [Photo R. Kasperek]

this station during period 1993–2006 indicates on insignificant fluctuations in the last years and large stabilization of the most parameters. At present the bacteriological state of the Widawa River has been improved, and the average-annual values describing eutrophication process at station No 1. have been exceeded only for phosphorus. At station No. 4, below the Dobra River mouth (km 16) these values have been exceeded for all parameters with the exception of chlorophyll “a”.

Water quality of the Widawa River in 2005 became worse and in both given points, one was noted down – the class IV – waters of the unsatisfactory quality. As far as in the point below Bierutów the following natural parameters affected the classification: the chlorophyll “a” (the class V), the smell, the colour, 5-Day Biochemical Oxygen Demand (BOD_5), the total phosphorus and the number of coli of the faecal type, this on the outlet to the Odra River river in class V was found a concentration of phosphates, and in class IV – except the colour and the number of unlucky colis – also and the total phosphorus, nitrites and nitrogen *Kjeldahla*.

The annual mean values characterizing the process of the eutrophication were exceeded in the Widawa River in both points in reference to the total phosphorus and the chlorophyll “a”. In the cross-sections of excurrent Oleśnica River and Dobra River



Fig. 5. The River Widawa channel upper of the Krzyżanowice station, Spring 2012 [Photo R. Kasperek]

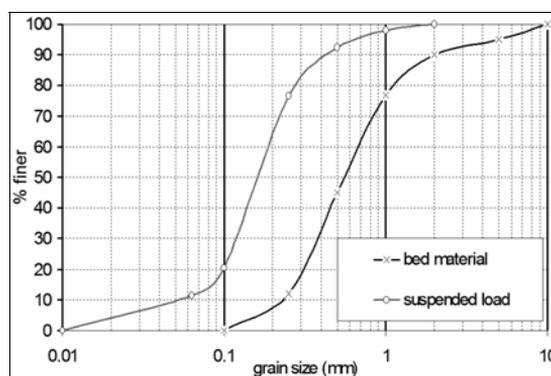


Fig. 6. Grain size distribution curve of the bed material and suspended load from the River Widawa, the Krzyżanowice station No. 3 (km 12,0)

value the annual average values were exceeded for all parameters with the exception of the chlorophyll “a”.

However, the water quality of the Widawa River in the cross-section – the bridge Krzywousty in 2007 was characterized by five parameters which exceeded the level of IV quality class of waters (BOD_5 , total nitrogen, nitrates, the total phosphorus, the number of coli of the faecal type) [14].

Because of the lack of law regulations concerning the quality of deposit criteria, in Poland the geochemical criteria are applied i.e. the classification of river deposits according to GIOŚ [11] (Tab. 1):

- I-st class: non-contaminated sediment so-called geochemical background,
- II-nd class: slightly contaminated sediment,
- III-th class: mediocre contaminated sediment,
- and IV-th class: contaminated sediment.

The quality of deposits from the Widawa River is of I–III class (Tab. 1). The highest concentrations (II–III class) of compounds were: Chromium – 103 ppm, Copper – 80 ppm, Zinc – 530 ppm, Barium – 380 ppm and Mercury – 0.5 ppm. The lowest concentrations of compounds were (I–II class): Arsenic – $6 \div 15$ ppm, Cadmium – $0,5 \div 3,1$ ppm and Lead – $5 \div 40$ ppm.

Table 1. Contamination concentration and quality classes of sediments from the River Widawa period 1999–2005

Component	Contamination concentration (ppm)	Class (Quality)
Silver Ag	0,5–1,0	II
Chromium Cr	14–103	III
Arsenic As	6–15	I–II
Copper Cu	12–80	II–III
Cadmium Cd	0,5–3,1	I–II
Nickel Ni	7–23	II
Zinc Zn	65–530	II–III
Cobalt Co	4–12	II
Lead Pb	5–40	I–II
Barium Ba	65–380	II–III
Mercury Hg	0,2–0,5	II–III

Quality of suspended load from the Widawa River

The physical and chemical analysis of suspended load sampled from the Widawa river-bed (Fig. 2, Krzyżanowice station No. 3) showed that the finest fractions $d = .,063-0,1$ mm and $d < 0.063$ mm contained the most phosphorus, respectively 1.21 mg/l and 1.49 mg/l. Least of phosphates was in the coarser sediment ($d = 1.0-2.0$ mm), i.e. 0.31 mg/l (Tab. 2, Fig. 7).

Table 2. Amount of phosphates in suspended sediment in the River Widawa

Size fraction d_i (mm)	Amount of fraction d_i (%)	Amount of phosphates P	
		mg/l	%
2,0–1,0	2,0	0,31	6,43
1,0–0,5	5,6	0,36	7,47
0,50–0,25	15,9	0,63	13,07
0,25–0,10	56,1	0,82	17,01
0,100–0,063	9,1	1,21	25,10
<0,063	11,3	1,49	30,92

The relationship between the phosphorus concentration P and the grain size d (Fig. 7) was obtained, and it can be expressed by function, where the determination coefficient $R^2 = 0.97$:

$$P = -0.335 \ln(d) + 0.3347$$

The results of the analysis of sediment movement conditions in the Widawa River are compared in Table 3. The bed materials from the Widawa River were divided into

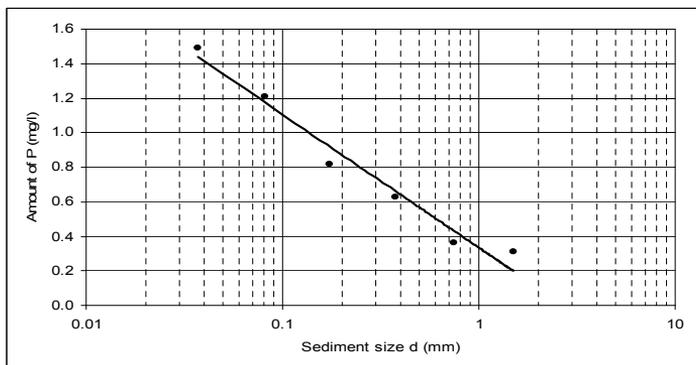


Fig. 7. Relationships between concentration P and sediment size d, the River Widawa

Table 3. Parameters describing sediment movement and suspension in the lower sector of the River Widawa by Shields, Engelund, Van Rijn and Bagnold

Grain size (mm)	D _*	by Shields			by Van Rijn		
		θ_{cr} (-)	τ_{cr} (Pa)	h_{cr} (m)	$\theta_{susp.}$ (-)	$\tau_{susp.}$ (Pa)	$h_{susp.}$ (m)
10	240	0,055	8,9	1,82	0,20	32,4	6,6
5	120	0,052	4,2	0,86	0,20	16,2	3,3
2	49	0,040	1,3	0,26	0,15	4,90	1,00
1	25	0,033	0,53	0,11	0,12	1,90	0,39
0,5	12	0,031	0,25	0,05	0,08	0,65	0,13
0,25	6	0,044	0,18	0,04	0,08	0,32	0,07
0,1	2,5	0,096	0,16	0,03	0,16	0,26	0,05
<0,063	1,6	0,15	0,15	0,03	0,20	0,20	0,04

8 fractions. The calculations of incipient motion and suspension parameters for each fraction were performed using modified Shields curve, Engelund, Van Rijn and Bagnold criteria (Fig. 8). The initiation of the finest sediment ($d < 0.063$ mm) motion by Shields starts at critical depths $h_{cr} = 3$ cm, whereas the coarser material ($d = 10$ mm) can move at $h_{cr} = 1.82$ m. Fig. 9 presents relationship of the total load transport intensity G_s and phosphorus transport intensity G_p to the discharge Q in the channel of the Widawa River.

In Table 4 the velocity results analysis of sedimentation, transportation and erosion in the Widawa River have been compared.

CONCLUSIONS

Contaminated sediment movement conditions depend on channel geometry, hydraulic regime and the structure of bed material. If at the beginning and the end of analysed river sector hydraulic regime is in steady state, and there is no inflow of other contaminants,

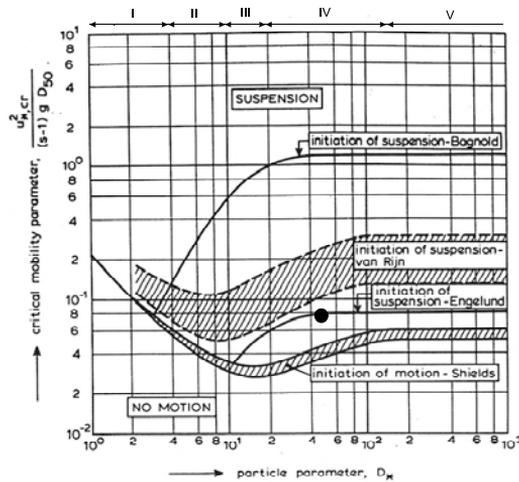


Fig. 8. Initiation of sediment motion and suspension [15]. Black point • is measurement of initiation of sediment suspension in the River Widawa channel

then system is identified. When the flow conditions varied river channel on studied sector, then the intensity of polluted sediment transport changes.

Deposits with the high amounts of toxic elements cause not only diseases and death of water species, but they are also hazardous to people and wild animals consuming fish or crustacean and molluscs. Movement of contaminated sediment during floods can cause their transport to higher water levels where organisms live. Pollutants with sediment can be transported downstream of the river and deposited at other places, where they did not occur till now, and in adjacent land ecosystems.

Pollution studies conducted on the Widawa River showed that contaminations are not only accumulated on the sediment particles less than 0.2 mm, i.e. wash load and finer suspended load. Geochemical analysis of the Widawa River deposits show that sediment fractions greater than 0.2 mm, i.e. coarser suspended load, to 2 mm, contained about 27% of phosphorus. Calculations of phosphorus amounts show that the smallest fractions ($d < 0.063$ mm) have the most contaminants, and amount of pollution diminishes together with the increase of particle size of suspended load.

Parameters describing the incipient motion of deposits and suspension of the Widawa River-bed were estimated. Initiation of the finest sediment ($d < 0.063$ mm) motion is starting at water depths $h_{cr} = .03$ m, and suspension at $h_{susp} = 0.04$ m. Coarse sediment $d = 0.2-2.0$ mm can be moved at depths $h_{cr} = 0.07-1.00$ m.

Modelling of polluted sediment transport by means of HEC-RAS model demands a wide range of input data, which have been given by authors. The measurements “in situ” and in laboratory are necessary for verification of the numerical model HEC-RAS.

The relationship between bed load transport, contamination (phosphorus) transport and flow discharge of the Widawa River was determined. During average flow discharge in the Widawa River total sediment transport is equal 6 kg/s, and phosphorus transport is about 2 mg/s.

The authors also recommend to estimate the changes of accumulated contaminants during sedimentation and consolidation suspended load and after its resuspension (after higher flow discharges, e.g. during flood).

Water quality investigations of the Widawa River showed that these waters due to the content BOD₅, total nitrogen, nitrates, phosphorus and others. are of the IV quality class. It was also found that the Widawa River is eutrophic.

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MODELOWANIE TRANSPORTU ZANIECZYSZCZEŃ WRAZ Z RUMOWISKIEM NA PRZYKŁADZIE RZEKI WIDAWY

Celem pracy było określenie warunków transportu zanieczyszczeń wraz z rumowiskiem w rzece Widawie, która wpływa do Odry poniżej miasta Wrocław. Symulacje transportu wykonano za pomocą modelu HEC-RAS, który został wykalibrowany. Badania i geochemiczne analizy wskazują, że zanieczyszczenia są gromadzone głównie w osadach o wielkości ziarna do 0,20 mm. Stwierdzono, że podstawowymi źródłami zanieczyszczeń osadów w rzece Widawie są: spływ powierzchniowy oraz miejskie i przemysłowe ścieki. Przeanalizowano jakość osadów dennych w wybranych przekrojach rzeki Widawy. Pobrano próby rumowiska unoszonego i podzielono je na osiem frakcji, dla których obliczono koncentrację fosforu P. Cząstki osadów mniejsze od 0,20 mm zawierały najwięcej fosforu tj. 73% (3,52 ppm), a ziarna większe od 0,20 mm około 27% (1,30 ppm) z całej objętości próby. Określono związek między koncentracją fosforu P a wielkością ziaren rumowiska. Z analiz wynika, że początek unoszenia osadów wraz z zanieczyszczeniami w rzece Widawie dobrze opisuje kryterium Engelunda. Symulacje przemieszczania się zanieczyszczeń wraz z rumowiskiem w rzece Widawie wykazały, że podczas średniego przepływu wody, intensywność transportu zanieczyszczeń jest równa 2 mg/s, a osadów 6 kg/s. W niniejszej pracy zaprezentowano również wyniki jakości wody z rzeki Widawy.