

## HYDRAULIC ASPECTS OF BORDER ODER RIVER REGULATION WORKS

WŁADYSŁAW BUCHHOLZ

West Pomeranian University of Technology, Szczecin, Poland.

**Abstract:** The paper presents hydraulic field researches (graining, velocity distributions) and calculations carried on in order to determine the possibility of reaching the border Oder river depth equal to 1.80 m at least at the highest possible warranty.

The division into regulation reaches and calculations results for particular reaches as well as the applied river training system have been presented. Also the hydraulic data (critical velocities, hydraulic slopes, warranted flows, roughness coefficients) and new types of proposed river training structures (ends of longitudinal off-bankline bunds) are given.

The paper concludes with summary and working adjustments of initiatives adopted by Polish and German sides concerning the project performance.

**Streszczenie:** Opisano badania polowe hydrauliki ruchu rumowiska oraz wyniki obliczeń, które miały określić, z możliwie największą gwarancją, możliwości osiągnięcia głębokości min. 1,80 m na granicznym odcinku Odry. Przedstawiono podział rzeki na odcinki o odmiennym systemie regulacji oraz wyniki obliczeń dla poszczególnych odcinków wraz z zastosowanym systemem regulacji. Podano także dane hydraliczne (prędkości krytyczne, spadki hydraliczne, przepływy gwarantowane, współczynniki szorstkości) oraz nowe typy budowli regulacyjnych (zakończenia tam podłużnych i opasek brzegowych). W podsumowaniu podkreślono potrzebę porozumienia ze stroną niemiecką w kwestii zaakceptowania zaproponowanych rozwiązań.

**Резюме:** Описаны местные исследования гидравлики движения наносов, а также результаты вычислений, целью которых было определение, с большей гарантией, возможностей достижения глубины минимум 1,80 м на пограничном отрезке Одера. Представлены деление реки на отрезки, характеризующиеся отличающимися системами регулирования, а также результаты расчетов для отдельных отрезков с примененной системой регулирования. Даны также гидравлические данные (критические скорости, гидравлические уклоны, гарантированные течения, коэффициенты шероховатости) и новые типы регуляционных построек (концы продольных перемычек и бережных манжет). В заключение была подчеркнута необходимость договора с немецкой стороной по вопросу одобрения предложенных решений.

### 1. INTRODUCTION

Oder River is the second largest river in Poland with drainage area of 118,611 km<sup>2</sup> and length of 847 km. Oder water-way is 745 km long and is continued to water channel 66.5 km long from Szczecin Port to Świnoujście with minimum warranted depth of 10.5 m.

Importance of Oder River is enhanced by the fact that over the length from Nysa Łużycka River at 542.4 km to Widuchowa at 704.1 km, it is the border river (the border runs also along Oder Zachodnia River over approximately 20 km length). All hydrotechnical engineering and protective actions on the border Oder River are undertaken jointly by Polish and German parties.

The most important goals among these joint actions include environmental protection for Oder River and adjacent areas and also flood control. When flood control is addressed, attention shall be drawn that for border Oder River ice jam floods could be equally dangerous as high water floods. Worth to mention is that large ice jam floods of Oder River have been reported in historical chronicles as early as in years 988, 1069, 1363, 1423, 1459, 1571, 1600 and many others. Memorable ice jam floods occurred in February and March 1947, 1971 or 1974. It could be also shown that river gauges in Bielinek and Widuchowa indicated water levels in February 1953 caused by ice jams which were higher than those during remarkable flood in July 1997.

Ice jam flood hazards for Oder River have occurred and would be always occurring, so of such importance are various actions aiming at reducing those hazards. At the same time, having in mind that the main reasons of ice jams include too little depths, attaining minimum depth of about 1.80 m (obviously at specific warranty) would improve Oder River's value as the water-way.

Further in the paper, the way of attaining this depth by modernizing the existing, however extensively depreciated river-bed regulation facilities is proposed.

## 2. METHODOLOGY OF HYDRAULIC CALCULATIONS OF REGULATION CROSS-SECTION GEOMETRY

Current status of border Oder River is far away from at least a good one. For low flow zone, average depths in cross-sections are lower than 1.20 m and in numerous points (especially along Nysa Łużycka River – Warta River section) they are even smaller. It simply makes navigation impossible, and often inhibits or hinders ice breaking actions. There are spots with limited depths along Odra River.

New training of border Oder River requires, first of all, to determine geometrical parameters of the control river-bed.

Hydraulic calculations of geometrical parameters for regulation cross-section of border Oder River stream channel are to determine:

- regulation width at cross-section bottom –  $b$ ,
- regulation width at medium water stage level  $SSQ - B$ ,
- slope inclination –  $m$  ( $1 : m$ ),
- flow rate  $Q$  which is necessary to get desired depth  $h = 1.80$  m and percentage warranty that such flow rate occurs.

These parameters would be searched separately for each section.

It is further envisaged that a series of solutions meeting specific requirements could be reached and only when detailed analysis of the results is completed, final outcomes, methods and connection points of regulation sections with various widths expected could be proposed.

## 2.1. PRESUPPOSITIONS

The basic presupposition is the trapezoidal cross-section (theoretical) as the general and practical for the whole section of the border Oder River.

Further on, the main hydraulic assumption is that the river-bed must be in the equilibrium state for average flow. It results directly from this assumption that average vertical velocities over the full width  $b$  (bottom width of trapezoidal cross-section) must equal to limit velocity  $V_{gr}$  at average flow rate  $SSQ$ , and depths in this part of river-bed must be equal  $H = H_{gr}$ .

It is also assumed, considering here medium and low flows, that uniform motion conditions exist along the whole section of border Oder River, hence the Chézy – Manning's formula is valid to describe water motion. Such assumption is consistently made to standardize calculation process and to be able to compare results for the same methodology despite that we need to realize that Section V subjects already to non-uniform motion rules, and among the consequences for this section, the flow velocity would be reduced more than expected from calculations.

Having such assumptions, geometrical scheme of Fig. 1 is then adopted for further hydraulic calculations.

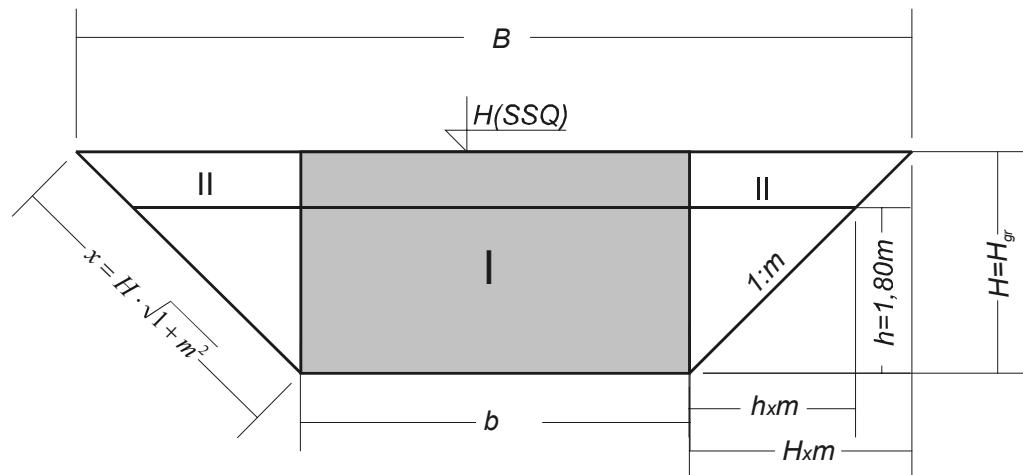


Fig. 1. Geometrical scheme of regulation cross section

Data are assumed as follows:

- flow,  $Q$ , treated as the medium flow rate  $SSQ$ ,
- depth,  $H = H_{gr}$ ,
- roughness coefficient,  $n$ ,
- water surface slope (equal to energy line slope),  $J$ ,
- depth,  $h = 1.80$  m at low flow,  $Q = ?$  (value to be found).

Values to be found:

- width on the bottom,  $b$ ,
- slope inclination,  $m$  ( $1 : m$ ),
- width,  $B$ , at medium water level,  $B = b + 2m \cdot H$ ,
- flow rate,  $Q_{\text{gwar}}$ , allowing to get the depth of 1.80 m at geometrical parameters as assumed above.

Hydraulic calculation can be made in two methods:

- I – without splitting the flows into two parts (rectangle and triangles),
- II – with splitting the flows.

### Method I

Assuming that Chézy-Manning's formula is consistent with general definition of the flow rate, the following is valid:

$$Q_{sr} = g_{sr} F = \frac{1}{n} J^{1/2} R_h^{2/3} F = \frac{1}{n} J^{1/2} \frac{F^{2/3}}{\chi^{2/3}} F, \quad (1)$$

where  $\chi = b + 2H\sqrt{1+m^2}$ .

Following transformations we get:

$$\frac{Q_{sr} n}{J^{1/2}} = \frac{[(b + m \cdot H) \cdot H]^{5/3}}{(b + 2H\sqrt{1+m^2})^{2/3}}, \quad (2)$$

i.e. the equation with two unknowns,  $b$ , and  $m$ .

Solutions can be found by determining the values of  $m$  and finding respective width  $b$  for each  $m$ .

For practical reasons, the values of  $m$  were assumed as follows:

$m = 3, 4, 5, \dots, 13, 14, 15$ , and calculations were made to find  $b$  for each of them.

### Method II

River channel is divided into three parts – rectangle and two triangles (Fig. 1) and assumptions are made that flow rate  $Q_1$  refers to main channel (rectangular) while flow rate  $Q_2$  refers to each triangular channel.

The sum of flow rates:  $Q_1 + 2Q_2$  should be equal to medium flow rate:

$$Q_{sr} = Q_1 + 2Q_2 \quad (3)$$

(values of  $Q_1$  and  $Q_2$  are unknown).

When further assuming the following parameters: depth  $H = H_{gr}$  and medium velocity  $V_{sr} = V_{gr}$ , then:

$$Q_1 = V_{sr} \cdot F_1 = V_{sr} \cdot b \cdot H_{gr} \quad (4)$$

or

$$Q_1 = V_{gr} \cdot b \cdot H_{gr}. \quad (5)$$

For side channel we can write:

$$Q_2 = g_{sr} F_2 = \frac{1}{n} J^{1/2} R_{h2}^{2/3} F_2, \quad (6)$$

where:

$$\left. \begin{aligned} \chi_2 &= H \sqrt{1+m^2}, \\ \text{hence: } F_2 &= \frac{mH^2}{2}, \\ R_{h2} &= \frac{F_2}{\chi_2} = \frac{mH}{2\sqrt{1+m^2}}. \end{aligned} \right\} \quad (7)$$

When relations (7) are put into (6), we get

$$\left. \begin{aligned} Q_2 &= \frac{1}{n} J^{1/2} \left( \frac{mH}{2\sqrt{1+m^2}} \right)^{2/3} \frac{mH^2}{2}, \\ 2Q_2 &= \frac{1}{n} J^{1/2} \left( \frac{mH}{2\sqrt{1+m^2}} \right)^{2/3} mH^2. \end{aligned} \right\} \quad (8)$$

When we assume that for  $m \geq 5$  is  $\sqrt{1+m^2} \approx m$ , then reduction can be made in (8) so as equation (8) is transformed to the form:

$$2Q_2 = \frac{1}{n} J^{1/2} \left( \frac{mH}{2m} \right)^{2/3} mH^2 = \frac{1}{n} J^{1/2} \left( \frac{H}{2} \right)^{2/3} mH^2. \quad (9)$$

Adding values of (8) or (9) to the value (5) we get:

$$Q_{sr} = Q_1 + 2Q_2 = g_{gr} b H_{gr} + \frac{1}{n} J^{1/2} \left( \frac{mH}{2\sqrt{1+m^2}} \right)^{2/3} mH^2. \quad (10)$$

or, after reductions:

$$Q_{sr} = Q_1 + 2Q_2 = g_{gr} b H_{gr} + \frac{1}{n} J^{1/2} \left( \frac{H}{2} \right)^{2/3} mH^2. \quad (11)$$

This calculation method allow for splitting the variables and resolving the equation. The calculations are progressed as in previous case:

- assumed are the values of  $m = 3, 4, 5, \dots, 9, 10$ ,
- value  $b$  is calculate for each assumed  $m$ .

For the needs of this paper both methods were used assuming that the results have to be similar (as the source equation, i.e. Ch  zy-Manning's formula is the same).

Calculations in following part of the paper were made without simplifications of the determined by relations (9)–(11).

Upon resolving the relationship  $b_i = f(m_i)$ , i.e determining the pairs of numbers  $m$  and  $b$ , the flow rates  $Q_{gwar}$  which must occur to ensure the desired minimum depth of  $h = 1.80$  m were then found for each such pair.

Transforming the formula (2), we get

$$Q_{gwar} = \frac{1}{n} J^{1/2} \frac{[(b+mh)h]^{5/3}}{(b+2h\sqrt{1+m^2})^{2/3}}, \quad (12)$$

where  $h = 1.80$  m ,

or, after simplifications:

$$Q_{gwar} = \frac{1}{n} J^{1/2} \frac{[(b+mh)h]^{5/3}}{(b+2mh)^{2/3}}. \quad (13)$$

The simplifications (13) were not used in further calculations.

Presented assumptions and formulae were further used in calculations of geometrical parameters of regulation channel cross-section, the formerly derived and assumed data having been also considered (Sections 3 through 5).

### 3. HYDROGRAPHICAL CONDITIONS OF BORDER ODER RIVER

Hydrographical conditions of border Oder River were determined from the following measurements:

- water level ordinates,
- depths in cross-sections,

Nysa Lużycka–Warta section

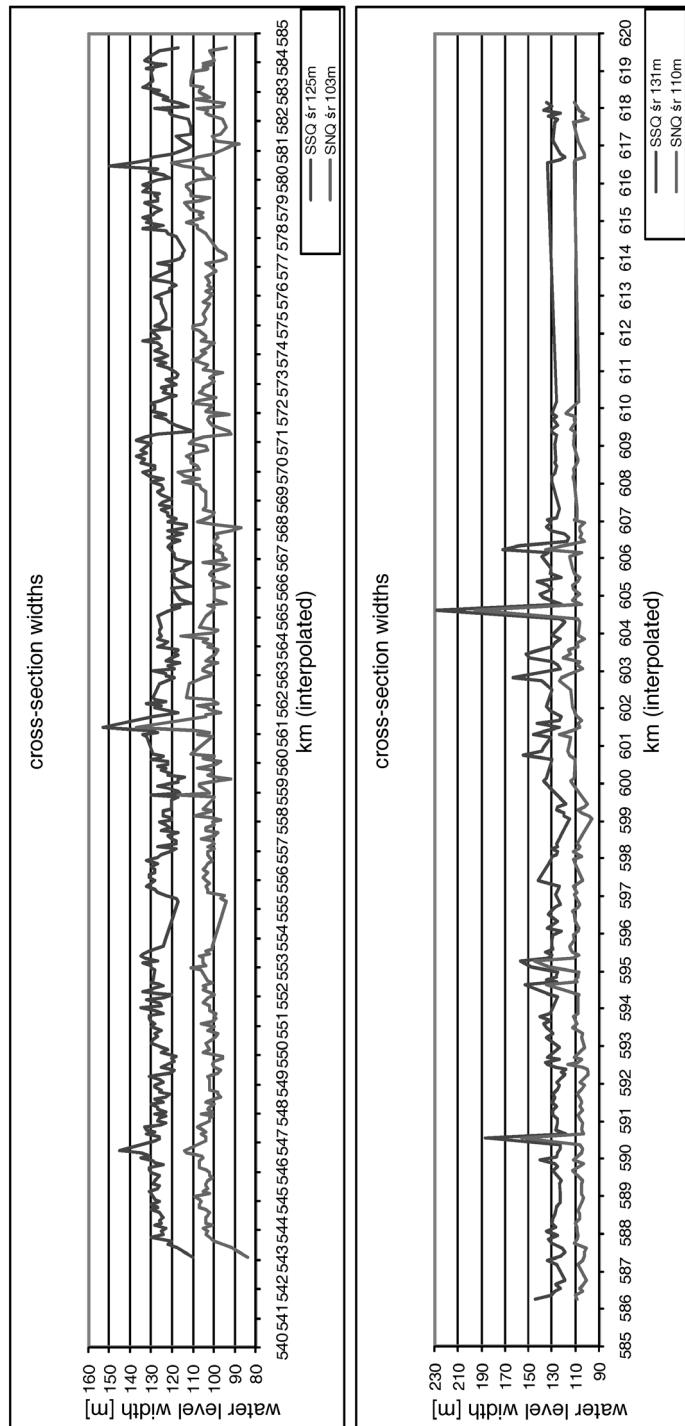


Fig. 2. Nysa Lużycka River–Warta River section

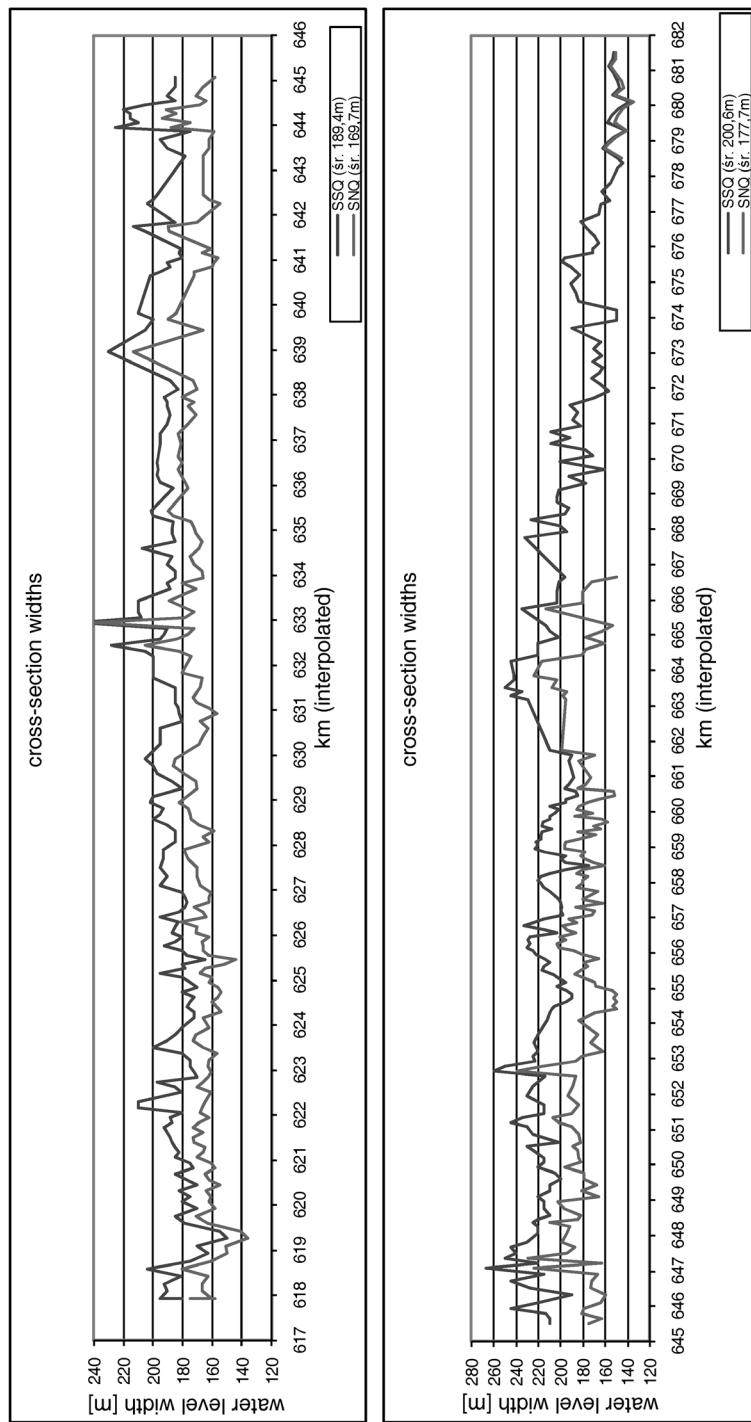


Fig. 3. Section downstream Warta River

- own control measurements of depths in selected cross-sections,
- spur-to-spur widths at the level of maximum head elevations (Figs. 2 and 3).

It was found that depths of Oder increase along with river's course and they are far from satisfactory for ice breaking needs. At medium low flows (SNQ), estimated depths are about 0.95 m to 1.20 m along the section from Nysa Łużycka outlet to Warta River outlet, while downstream they are of the order 1.20 to 1.80 m. Very large variations of channel width in spur-to-spur cross-sections were also found as illustrated in Figs. 2 and 3.

If regulation was made properly and regulation structures maintained correctly, such large variations of width should not occur at all. When we compare depth variation along border Oder, it is clearly evident that the smallest depths exist for sections with large width changes. These data imply also that poor, and continuously worsening condition of regulation structures and the whole regulation system (designed in early 20<sup>th</sup> century) is in fact the reason of current problems with attaining sufficient depths to ice breaking actions and of arising and enlarging the areas being prone to ice jamming. This leads directly to continuous increase of ice jam flood hazard. This situation should be changed by implementing new regulation which rules and design must be agreed upon between Germany and Poland.

Research work and analyses allowed to divide the border Oder into five different however consistent sections;

- Section I from km 542.4 to km 584.1 (Nysa Łużycka outlet – bridge in Ślubice),
- Section II from km 584.1 to km 615.1 (railway bridge in Kostrzyń),
- Section III from km 620.0 to km 645.3 (downstream Warta River to Gozdowice),
- Section IV from km 645.3 to km 680.0 (cross-section Piasek),
- Section V from km 680.0 to km 701.8 (river gauge Widuchowa).

Furthermore, two „special” sections were distinguished:

- Oder–Warta node (km 615.1 to km 620.0),
- Widuchowa node (km 701.8 to km 707.0).

Geometrical parameters of border Oder sections are summarized in Table 1.

Table 1  
Geometrical parameters of border Oder sections

Section No.	Kilometre of water-way	Averaged drop of water level	Channel width from – to [m]	Regulation widths from – to [m]
I	542.4 ÷ 584.1	0.00028	164 to 238	95 to 130
II	584.1 ÷ 617.6	0.00026	158 to 226	95 to 140
III	617.6 ÷ 645.3	0.00017	196 to 281	150 to 210
IV	645.3 ÷ 680.0	0.00015	197 to 278	160 to 220
V	680.0 ÷ 695.0	0.00006	180 to 251	160 to 200

The sections presented could be further treated as regulation sections of border Oder.

## 4. HYDROLOGICAL/HYDRAULIC CONDITIONS

### 4.1. HYDROLOGICAL CONDITIONS

The reliable river gauges providing both water levels and flow rates for Oder section considered are:

- Ślubice water gauge located in km 584.1 ODW, gauge zero level +17.446 m above sea level acc. to Kr,
- Gozdowice water gauge located in km 645.3 ODW, gauge zero level + 3.020 m above sea level acc. to Kr.

The Ślubice water gauge is reliable instrument for Oder section from Nysa Łużycka outlet to Warta outlet, while Gozdowice water gauge – for Oder section from Warta outlet to Widuchowa.

Here assumption is made that flow rates on these two sections can be treated as constant with negligible error.

For the purposes of this paper, low to medium water levels and flow rates are used and the low warranted flow rates over multiple years at specified warranties.

These values are summarized in Table 2.

Table 2

Flow rates and characteristic water levels as observed in years 1976 to 2005

River gauge	Flow rates $Q$ [ $\text{m}^3/\text{s}$ ]		Water levels [cm]	
	SNQ	SSQ	SNW	SSW
Ślubice	138	314	131	235
Gozdowice	251	539	210	334

Table 3

Warranted flow rates  $Q_{\text{gwar}, p\%}$  from the curve of duration sums including higher ones

River gauge	duration [% days] flow rate $Q$ [ $\text{m}^3/\text{s}$ ]						
	50%	66%	75%	80%	85%	90%	95%
Ślubice	268	219	190	176	159	143	124
Gozdowice	467	383	342	314	285	258	231

### 4.2. HYDRAULIC CONDITIONS

In 2007 and 2008, field measurements on 15 different cross-sections of border Oder, 3 cross-sections per each aforementioned section, were taken. The purpose of these measurements was to get data for determining reliable diameters of bed load and

roughness coefficients for Chezy–Manning’s equation – averaged for individual sections. Following these field testing and granulometric analyses and respective calculations, the values of roughness coefficients and reliable diameters were determined as averages for individual sections.

Results of these research work are summarized in Table 4.

Table 4

Section No.	Water level drop $J$	Roughness coefficient $n$	Reliable diameters $d[\text{mm}]$	
			$d_{50}$	$d_p = \frac{\sum d_i p_i}{100}$
I	0.00028	0.0310	0.84	1.39
II	0.00026	0.0305	0.80	1.30
III	0.00018	0.0290	0.63	1.14
IV	0.00014	0.0260	0.67	1.15
V	0.00006	0.0230	0.68	1.10

The results obtained allowed to determine the relationship  $V_{gr} = f(H)$ , which makes it possible to find the condition for river bed load equilibrium. Graphical representation of calculations is illustrated in Fig. 4.

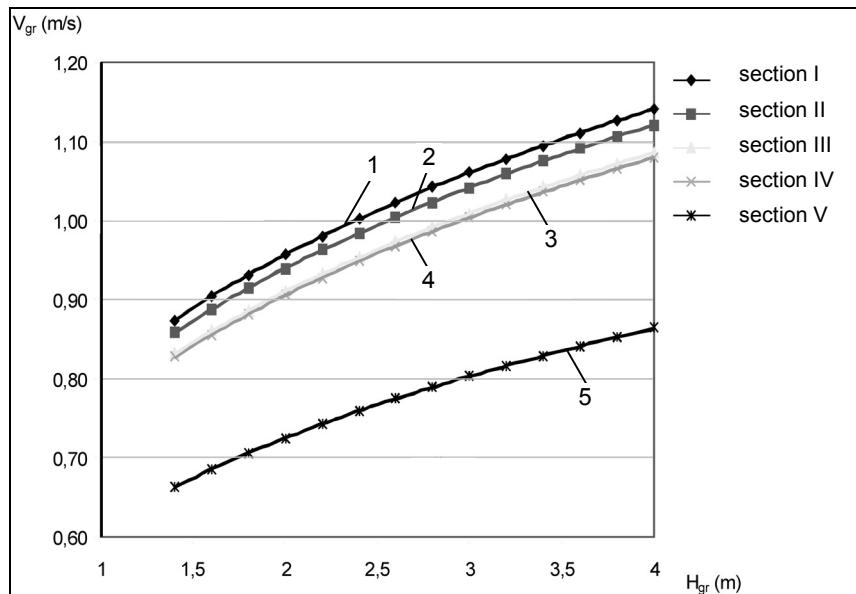
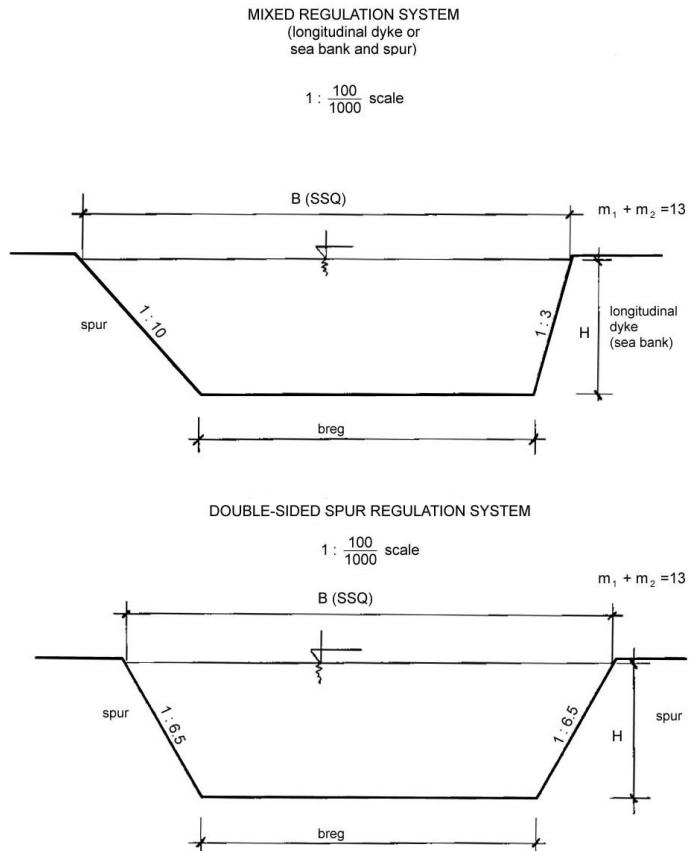


Fig. 4. Limit non-scouring velocities:  $V_{gr} = 0.8022H_{gr}^{0.2541}, R^2 = 1$  (curve 1),  
 $V_{gr} = 0.7877H_{gr}^{0.2544}, R^2 = 1$  (curve 2),  $V_{gr} = 0.7631H_{gr}^{0.2544}, R^2 = 1$  (curve 3),  
 $V_{gr} = 0.7599H_{gr}^{0.2532}, R^2 = 1$  (curve 4),  $V_{gr} = 0.6088H_{gr}^{0.2524}, R^2 = 1$  (curve 5)

## 5. HYDRAULIC CALCULATIONS OF THEORETICAL REGULATION CHANNEL

Earlier data, research work, methodology and calculation results from Chapter 2 above allowed to calculate parameters of regulation channel assumed to be in trapezoidal form – Fig. 5. The most advantageous parameters were attained for slope inclination 1:6.5.



	$b_{\text{reg}}$	$B$	$H$	$F$
FOR SECTION I	84.00 m	122.00m	2.95 m	303.85 m
FOR SECTION II	85.50 m	124.00 m	2.96 m	310.00 m
FOR SECTION III	140.00 m	184.00 m	4.37 m	546.00 m
FOR SECTION IV	136.00 m	181.00 m	3.45 m	547.00 m
FOR SECTION V	130.00 m	184.00 m	4.18 m	656.00 m

Fig. 5. Parameters of regulation channel in trapezoidal shape

Note! Calculations for Sections I and II can be treated as detailed and those for Sections III, IV and V as approximate ones.

The outcomes show that the depths of 1.80 m on border Oder can be attained by means of regulation at warranty of about 90% of all days of year downstream and about 85% upstream the outlet of Warta River.

## 6. CONCLUSIONS

1. Existing, too small depths of border Oder stream channel for low flow rates can be the reason of ice jamming and be an essential hindrance for fast and effective ice braking operations.

2. Easier and faster ice jamming on ever wider and wider areas, while ice braking encountered considerable difficulties, creates larger and larger hazard of ice jam floods leading to destruction or damage of river embankments and some structures in close vicinity of Oder River.

3. Worsening the condition of border Oder due to its continued shallowing results from destruction of many regulation structures and from that the old regulation system has not been adapted to actual conditions in Oder drainage area which have changed intensely (development of the area, impounding reservoirs, etc.).

4. It is possible to restore good condition of the river and to diminish the risks by modernizing the regulation system of border Oder, preferably be means of mixed system – spurs on convex banks and longitudinal dykes on concave banks. Suggestions are made to use existing structures and to build them into proposed modernized/renovated system of river regulation.

## LITERATURE

- [1] BUCHHOLZ W. et al., *Program zrównoważonego rozwoju i wykorzystania Odry*, Instytut Morski, Gdańsk 2003.
- [2] BUCHHOLZ W. et al., *Określenie parametrów koryta regulacyjnego w celu uzyskania minimalnej głębokości 180 cm na Odrze granicznej od ujścia Nysy Łużyckiej do Widuchowej poza odcinkami specjalnymi*, Katedra Budownictwa Wodnego, PS, Szczecin 2007.
- [3] BUCHHOLZ W. et al., *Opracowanie koncepcji trasy regulacyjnej na granicznym odcinku rzeki Odry od km 542,4 do km 706,0 w celu uzyskania minimalnej głębokości 1,80 m*, Katedra Budownictwa Wodnego, PS, Szczecin 2008.