PREDICTION OF WATER INFLOW TO MINES USING MODIFIED TREND METHODS

Rogoż, M. and Posyłek, E.

Central Mining Institute
Katowice - Poland

ABSTRACT

In the complex hydrogeological and mining conditions found in the Upper Silesian Caol Basin the most appropriate method for predicting water inflows to coal mines is that of hydrogeological analogy. In this method the water inflow to a new mine is estimated on the basis of known inflow to an existing mine /analog-mine/. It is assumed that the differences in hydrogeological and mining conditions between these mines may be comprehended in differences in values between one or more characteristic parameters, which may be coal production, mine depth, mined area, etc. A detailed description is given of the most important parameters in hydrogeological analogy, i.e. time, mine depth, mined area and water-production coefficient, their effect on water inflow to mines is analysed and also the relationship maintaining between them. From a theoretical analysis of relations existing between development of inflows and variations of above mentioned parameters together with statistical analysis of known inflows and coal productions from all mines of the Upper Silesian Coal Basin over the last thirty years, three methods for prediction of water inflows were elaborated, i.e.:

- a method based on trend of inflow and production,
- a method based on inflow trend,
- a modified method based on water-production coefficient.

The choice of method depends on the hydrogeological and mining conditions in the mine for which the water inflow prediction is required and in the analog-mine. Right choice of analog-mine is a basic condition governing correct evaluation of predicted inflows. The reliability of the inflow prediction calculated by means of the given formulae may be estimated by calculating the confidence intervals at the assumed significance level.

INTRODUCTION

The construction of new coal mines and development of existing ones makes necessary to design properly the mine drainage installations and to secure the proper use or disposal of mining waters. These problems have important meaning as well for the protection of mining workings against water hazard, as for the utilization of underground water resources and protection of surface waters against pollution. The proper solution of these problems may be obtained only on the basis of possibly exact and reliable appreciation of the predicted quantity of water that will inflow into new or developing mine in the perspective period. Prediction of water inflow to new and developing coal mines has therefore an essential technical and economical meaning.

There are two groups of methods use for predicting the water inflows to mines. The first one is based on the deterministic approach. Here belong methods taking into account equations of fluid seepage in porous medium, from the simplest analytical ones to very sophisticated methods of mathematical modelling. The chief difficulty in the practical use of these methods is the necessity of good reconnaissance of hydrogeological conditions in the vicinity of mine in order to determine properly the boundary conditions of the model and parameters of deterministic equations. Usually the required hydrogeological data are not available.

The second group of prediction methods is based on the probabilistic approach. In these methods water inflows are considered as statistical population, which in connection with other natural and technical factors, may be multi-dimensional. Here belong numerous methods of hydrogeological analogy.

In this paper we have given a short review of various hydrogeological analogy methods most often used. We have discussed the most important factors influencing the development of water inflows to mines and on this basis we have presented three methods for prediction of water inflows to mines elaborated in the Central Mining Institute at Katowice.

OUTLINE OF HYDROGEOLOGICAL ANALOGY METHODS

These methods are based on calculating the predicted water inflows to new mines or to new panels and/or working levels of developing mines, using the known inflows to mines working in similar geological and mining conditions /analog-mines/. Usually it is assumed that the inflows to both mines are proportional to one or more parameters, like coal production, mine depth, mined area, length of galleries, time and so on.

The most known widely used is the method of water-production coefficient [4], [9], [12], in which it is assumed that the water inflow is proportional to the coal production and the water-production coefficient is calculated as a ratio of the water inflow to coal production in the analog-mine. The predicted inflow is calculated as a product of the planned coal production in new mine and the water-production coefficient.

The calculation of predicted water inflow may be made more complex by introduction of additional parameters. For instance the difference between depths of the new mine and the analog one is taken under consideration by multiplying the predicted inflow by the ratio of both depths ot its root [4], [9] .

In the geological analogy method may as well occur hydrogeological parameters like Darcy's coefficient, thickness of water bearing strata etc. The way these parameters can be taken into account is given in [6] .

More improved methods of hydrogeological analogy may be developed by using a regression analysis. On the basis of analog-mine data calculated are coefficients of the multiple regression equation of the inflow. These depends on various geological and mining parameters which are used to compare both mines. The predicted inflow is calculated by including in regression equation, parameter values related to the new mine. The regression equations may be linear or non-linear polynominals or else power products. These methods are used by Russian investigators [3], [8] and Polish ones [2], [13] .

The particular kind of regression equations are trend equations in which one of independent variables is time. The trend methods are important in the matter under discussion, because the drainage processes are unstable in time. Particular attention deserves the method of trend-line elaborated by Z. Wilk [11], [12] . It consists in determining coefficients of regression equation of the inflow in relation to the product of mined area and mean depth of mining workings, input data being determined on the basis of smoothed time-series. This method is widely used in Polish coal mines. The detailed description of the method may be found in the original paper of its author [11] and in [6] .

MOST IMPORTANT PARAMETERS OF HYDROGEOLOGICAL ANALOGY

For the better understanding of the meaning of particular parameters in various kinds of hydrogeological analogy methods, we have discussed hereunder the most important ones, i.e. time, mine depth, mines area and water-production coefficient. We have tried hereby to throw some light on connections occurring between them.

Time factor

For trend equations the occurrence of time as an independent variable is characteristic. The time variable is usely introduced as an arithmetical progression. Values of remaining independent variables occurring in the trend equation are related with particular terms of time variable sequence.

Introducing the time variable into regression equation, one introduces thereby changes of drainage conditions occurring during this time. since it may be assumed that the majority of changes taking place in the mine and in surrounding rock massive is some function of time. The regression equation of inflow in relation to time is therefore resultant of regression functions of the remaining parameters changing in course of time, like mined area, mine depth, degree of dewatering the rock massive, production intensity and others.

Time may be introduced in trend equations in two ways:
1/ as an arithmetical progression, whose first term $a_1 = 0$ corresponds with the date of start of exploitation in the given mine,
2/ as whichever arithmetical progression /in particular it may be a sequence of succeeding calendar years/.

It could be thought that introduction of time variable according to the first way, it is as an absolute age of mine, enables comparisons between mines of different ages. One could therefore calculate predicted inflows to designed mine on the ground of known development of inflows to the existing one /analog-mine/ operating in similar hydrogeological conditions. Newly designed mines however, on the contrary to old ones, begin extraction at great depth. They develop at great rate and in few years they attain production of a dozen or so of thousands of tons per day. The degree of dewatering of the rock massive in a new mine is therefore uncomparable with one that took place in the old mine after the same time counted since exploitation start.

The trend equation may be a very good tool for water inflow prediction if it concerns the same mine, for which it is elaborated. In this case does not occur discordance of the development phase of inflows and the difference of the rate of mines development. The prediction may concern for instance the development of water inflows to mine in the period of planned exploitation, inflows to the new exploitation level and the like. In this case it makes no differences if the time variable is introduced in the trend equation after the first or the second way.

Depth of mine

When the depth of workings increases, two hydrogeological parameters change, namely:
1/ increases the hydrostatic pressure of water in rock massive, which causes augmentation of water inflow to mining workings,
2/ decreases the permeability of rock massive, which causes diminution of water inflows to workings.

The majority of authors assumes that the first process is dominant and that in consequence water inflows intensity when the depth of mine increases. It can be seen in the way the depth occurs in numerous formulae of hydrogeological analogy. In conditions of Upper Silesian Coal Basin this opinion does not find justification. It is observed here that water inflows to deeper levels as a rule are smaller than to less deep ones. One can suppose therefore, that prevails here the second process, i.e. increases the degree of fissure compression and decreases the intergranular permeability when depth augments.

The detailed analysis of the influence of mine depth on water inflow to mining workings, carried on in the Central Mining Institute on grounds of the abundant empirical data [6] has enable to establish an appropriate formula for the empirical coefficient ε correcting the calculated prediction of inflow when the difference between the depth of new mine H and analog-mine H_1 is important. The formula is

$$\varepsilon = \frac{H_1}{H} \qquad /1/$$

The coefficient ε can be used only when there is a substantial increase of the mine depth caused for instance by construction of a new drawing level. When the average depth of mine changes slightly in the framework of unchanged drawing levels and water inflows are predicted using trend equation, application of the coefficient ε may introduce additional errors. Changes of inflows related to changes of mine depth are in such cases taken into consideration in the trend equation itself as changes of inflows in function of time.

Production as a function of mined area increment

The measurement of mined area and its increments on mining maps is very labour-consuming. In order to simplify the data preparation we have considered the possibility of replacement in trend equations the mined area increment with coal production, which is very well registered in mines.

The analysis of abundant empirical data, gathered in mines, has shown high correlation between coal production and mined area increment. Values of correlation coefficient calculated for several mines are comprised in the majority within the range of 0.76 and 0.99. Lower values of correlation coefficient were stated only in cases of erroneous planimeter measurement of mined area increments.

Water-production coefficient as a function of coal production

The prediction of water inflows to mines with help of water production coefficient is widely used in practice by design offices and geological enterprises. The method is based on calculation of water-production coefficient being the ratio of actual water inflow in the mine to actual coal production. The coefficient expresses then the inflow related to the production unit. Sometimes instead of actual values of water inflow and production they take mean values from a period of several years. The predicted water inflow is calculated through multiplying the water-production coefficient by the planned coal production of the mine.

This method leads to important errors in estimation of predicted water inflows and therefore it is largely criticized. The detailed critical analysis of this method used in coal mines of the Upper Silesian Coal Basin gives Z. Wilk [12] . He has shown that time sequences of water inflows and coal production are correlated as well positively as negatively and values of correlation coefficient demonstrate the dependence changing from negligible to very important. The abundant statistical data collected in the Central Mining Institute, concerning the water inflows and coal production in coal mines for last thirty-years proves that the water-production coefficient generally is not a constant number for a given mine, but is a decreasing function of time and of coal production. It seems to be comprehensible by intuition if one takes under consideration the process of withdraw the static water resources from rock massive, progressing with time, and the constant increasing of production intensity in coal mines, which causes some delay of static water drainage in relation to mined area increment. This rule is not confirmed in cases of mines with inflows coming from dynamic water reserves only. There are very few such mines however.

The process of drawing out the static water reserves and of decreasing with time the hydrostatic water pressure within the depression cone, generated by the mine in water bearing rock massive, is comprehensible and confirmed by several authors [4],[11],[7]. It can be analysed quantitatively using solutions of Theis, Hantush, Boulton and others, in dependence on hydrogeological conditions, treating the mine as a "big well". The drainage of static water reserves can be also analysed with help of numerical modelling. On the other hand, the influence of exploitation rate on the value of water-production coefficient requires more detailed elucidation.

It is known from numerous observations in mines, that when the mining working exposes a water bearing stratum containing limited static water resources, the water inflow to the working is at first important and then it decreases gradualy, often till complete disappearance. Assuming that the water inflow coming from static water reserves decreases in accordance with Maillet's formula for a source [5], we have derived [6] a theoretical formula determining the dependence of water-production coefficient q_p on coal production P

$$q_p = \frac{q_p}{\alpha} \left[1 - \frac{P}{\alpha} (1 - e^{-\alpha/P})\right] \qquad /2/$$

in which q_o is the initial water inflow in the moment of opening the water-bearing stratum with working,

α is the time coefficient in Maillet's formula.

The graph of equation /2/ is shown on Fig.1. It may be proved, that function /2/ is decreasing independently on values of parameters q_o, α and P, which are always positives, considering their physical meaning.

PROPOSED METHODS FOR PREDICTION THE WATER INFLOW TO COAL MINES

There are presented hereunder three methods for prediction of the water inflow to mines, adapted to conditions of the

Upper Silesian Coal Basin, elaborated at the Central Mining Institute in Katowice. Computer program in Algol 1204 language is elaborated to enable the practical application of the methods with help of Odra 1204 computer.

Method based on trend of inflow and output

Assuming that in mines drawing static water reserves the inflow is directly proportional to coal production and inversely proportional to time, the following form of trend equation is proposed:

$$Q = A\left(\frac{P}{t}\right)^{B} \qquad /3/$$

in which Q is the water inflow to mine in thousands of cubic meters per year,
P is the coal production of mine in thousands of tons per year,
t is the calendar year,
A, B are coefficients of trend equation.

An exemplary graph of water inflows to mine computed with equation /3/, together with real inflows, is given on Fig.2.

Coefficients of equation /3/ have been computed for all mines of Upper Silesian Coal Basin [6]. Then numerous experiments were carried on, consisting in computation the inflow values when coal production and time values were extrapolated outside intervals, for which equation coefficients have been calculated. For 75 mines under consideration in 48 ones the coefficient B is positive and variability of inflows proceeds in accordance with assumed hypothesis, i.e. inflows increase when production increase and decrease with time. Inflow values received when time and production were extrapolated are consistent with observed inflow trends in considered time intervals. In remaining mines the coefficient B is negative and inflows decrease when production increases and when production is constant, they increase with time. Changes of inflows are not in accordance with the hypothesis assumed. One should suppose that dominant are here inflows coming from dynamic water reserves as well as other factors independent on production development. In such cases equation /3/ is not adequate to alimentation conditions of the time.

Method based on inflow trend

For mines, in which inflows are independent on coal production, only time is used as analogy parameter. Following form of trend equation for such cases is proposed:

$$q = a.t^{b} \qquad /4/$$

in which a,b are coefficients of trend equation.
An exemplary graph of equation /4/ is given on Fig.3, on the background of real inflows.

Coefficients of equation /4/ are also computed for all mines of the Upper Silesian Coal Basin. It is stated, that this equation gives a proper approximation of time varying inflows and it may be applicated to calculate water inflow predictions when equation /3/ can not be used.

Modified method based on water-production coefficient

Above presented trend methods may be used only to determine the water inflow prediction in perspective period for the same mine, for which trend coefficients were computed. The water inflow prediction to a new mine being in stage of designing or under construction, meets difficulties in the way of introduction of the time variable. It was the cause that other method more suitable to such situations is elaborated.

Modification of the water-production coefficient method consists in taking under consideration the variability of the coefficient in function of coal production. On the ground of numerical experiments it is stated that the best results may be obtained using regression equation of power form

$$q_p = \;.\; P \qquad /5/$$

in which q_p is the water-production coefficient
are coefficients of the regression equation.

Predicted water inflows to a mine are calculated as a product of water-production coefficient and planned coal production

$$Q = q_p \cdot P = \quad .P^{\;+1} \qquad /6/$$

On Fig.4 is given an exemplary graph of equation /6/ in confrontation with real inflows and coal production.

Values of and coefficients have been also computed for all mines of the Upper Silesian Coal Basin [6] .

ESTIMATION OF INFLOW PREDICTION'S CREDIBILITY

Significance of the correlation connections between water inflow, coal production and time, being the prediction's basis, may be estimated with help of Student's test T given by the formula:

$$T = R\sqrt{\frac{n-2}{1-R^2}} \qquad /7/$$

in which n is the number of complet observations,
R is the correlation coefficient given by formula:

$$R = \sqrt{1 - \frac{\sum(Q - \hat{Q})^2}{\sum(Q - \bar{Q})^2}} \qquad /8/$$

in which Q are inflows measured in the mine, composing input data,
$\hat{Q}$ are inflows calculated with help of the trend or regression equation for input values of t and P,
$\bar{Q}$ is the arithmetic mean of measured inflows.

The correlation is significant if T is greater than the value of Student's t-statistic for n-2 number of degrees of freedom at the assumed significance level.

Values of correlation coefficient between water inflows and independent variables are highly differentiated. It depends probably on local hydrogeological conditions and on the kind of factors having dominant influence on the inflows variability. When trend equations /3/ and /4/ were used, for 75 analysed mines in 46 the correlation was significant at the confidence level of 0.95. The correlation between water-production coefficient and coal production was significant in 56 mines and correlation between inflow and production /equation 6/ was significant in 40 mines. Low values of correlation coefficient in trend equations /3/ and /4/ correspond with approximately horizontal line of inflows on graphs. It means that inflow values are approximately constant in time, independently on the variables P/t or t. The inflow prediction is in this case equivalent with assuming that in future water inflows will maintain at the same level as they were in the period for which equation coefficients were computed, independently on the planned coal production.

The lack of correlation between water-production coefficient and coal production does not mean the lack of correlation between water inflow and production. In such cases the use of modified method of water-production coefficient is equivalent to the classic method, in which the value of water-production coefficient is constant. The accuracy of the prediction in such cases is of course lower.

The correlation between water-production coefficient and coal production may be high also when there is no correlation between water inflow and production. It happens when inflows oscillate in proximity of a mean value, independently on the production development. In such a case the use of modified method of water-production coefficient does not introduces any additional error, but the result is the same as if the mean value of measured water inflows was accepted as a predicted value.

The credibility of the inflow prediction computed by means of one of given equations may be estimated by calculating the boundaries of confidence interval at the assumed significance level. Therefore the standard deviations of the predicted value S has to be calculated with the formula /9/ derived by transformation of the formula for standard deviation of extrapolation of the linear regression equation, given by J.Gren [1]:

$$S = \exp\left\{\sqrt{\frac{1}{n-2}\left[\left(1+\frac{1}{n}\right)\sum'(\ln x)^2 + \left(\ln x_{pr} - \overline{\ln x}\right)^2\right]}\right\} \quad /9/$$

in which n is the number of complete observations:
x is the independent variable, which may be P/t, t or P
x_{pr} is value of independent variable, for which the prediction is calculated

$$\overline{\ln x} = \frac{1}{n}\sum_{i=1}^{n} \ln x_i$$

$$\sum'(\ln x)^2 = \sum_{i=1}^{n} \left(\ln x_i - \overline{\ln x}\right)^2$$

Extreme values of the confidence interval for the predicted water inflow Q, computed by one of equations /3/, /4/ or /6/ may be calculated by means of formulae

$$Q_{min} = Q \cdot S^{-t}$$

$$Q_{max} = Q \cdot S^{t} \quad /10/$$

in which t is the value of Student's statistic for n-2 number of degrees of freedom and assumed significance level.

COMPUTER PROGRAM

For practical use of the suggested methods, in the Central Mining Institute is elaborated suitable program for the Polish computer Odra 1204. The input data preparation consists in setting of a complete of three numbers, the first of which is the calendar year, the second one is the total coal production in this year in thousands of tons and the third one is the total water inflow during this year in thousands of cubic meters.

As a result of computation one receives coefficient values of equations /3/, /4/ and /5/, correlation coefficient values, Student's test value and data for prediction's credibility estimation. Furthermore one receives arrays of predicted inflow values as functions of time and coal production together with confidence intervals boundaries calculated on the confidence level 0.95.

SCOPE AND WAY OF PRACTICAL USE OF THE PROPOSED METHODS

Proposed methods for prediction of water inflows in mines can not be used automatically without critical analysis of their results made in the context of totality of hydrogeological and mining conditions of the given mine and surrounding rock massive.

The trend methods are intended for prediction of inflows to the same mine for which equation coefficients are calculated, in periods of planned coal production. The equation /3/ may be used in mines, in which B-coefficient is positive, it means the correlation between the inflow and the quotient of production and time is positive. In remaining mines changes of inflows are independent on production development, therefore the use of equation /4/ is recommended.

The modified method of water-production coefficient is intended for prediction of inflows to new mines, being under designing or construction, on the ground of known development of coal production and water inflows in the past, in another mine being in similar hydrogeological conditions /analog-mine/. The use of this method may increase credibility and accuracy of inflow prediction when in the analog-mine occurs a significant correlation between water-production coefficient and coal production as well as between water inflow and coal production.

When the inflow prediction is computed to a new extraction level in a developing or new mine, whose mean depth differs significantly from that of analog-mine, we recommend to correct the results received by means of equation /3/, /4/ or /6/, multiplying then by a coefficient determined by formula /1/.

Always when inflow prediction for a new mine is calculated, one has to keep far-reaching caution and critical judgement towards results received. One has to remember, that the coal production is only one of several factors influencing the development of water inflows to mine. Therefore the basic condition of the proper estimation of predicted water inflows to a new mine is the correct choice of the analog-mine. When the analog-mine is incorrectly chosen, even the best method can not warrant a proper prediction.

References

1. Greń, J. Statystyka matematyczna - modele i zadania. PWN, Warszawa /1978/

2. Hoffman, M., Szyszło, D. Zastosowanie metody korelacji wielorakiej do prognozowania dopływów wód do kopalni. Technika Poszukiwań, N°4 /1974/

3. Kne-rcer, W.G. Primienienija matematičeskoj statistiki dla prognozirovanija pritokov vody v šachty. Rozvedka i Ochrana Niedr, N°9 /1967/

4. Krajewski, M., Wilk, Z. Hydrogeologia kopalniana. Poradnik Górnika, Vol.I, Wyd. "Śląsk", Katowice /1971/

5. Pazdro, Z. Hydrogeologia ogólna. Wydawnictwo Geologiczne, Warszawa /1977/

6. Rogoż, M., Posyłek, E. Prognozowanie dopływów wody do kopalń zmodyfikowanymi metodami trendu i współczynnika wodoproduktcyjnego. Prace GIG, Komunikat N°711, Katowice, /1980/

7. Syrowatko, M.W. Gidrogeologija i inżyniernaja geologija pri osvojenii ugolnych mestoroždenij. Gosgortiechizdat, Moskwa, /1960/

8. Tkačuk, E.I. Prognoz šachtnych vodopritokov. Rozvedka i Ochrana Niedr N°9, /1972/

9. Turek, S. Szacowanie dopływu wody do wyrobisk górniczych dokumentowanych złóż. Poradnik Hydrogeologa, Wydawnictwa Geologiczne, Warszawa /1971/

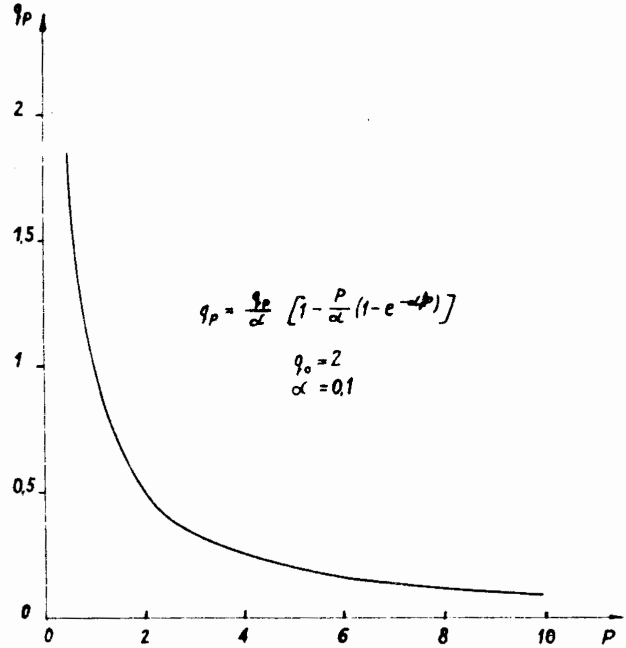
10. Wilk, Z. Zawodnienie a wielkość i głębokość kopalń we wschodniej części Górnośląskiego Zagłębia Węglowego. Wydawnictwa Geologiczne, Warszawa /1965/

11. Wilk, Z. Rozwój i zmienność zawodnienia polskich kopalń węgla kamiennego. Zeszyty Naukowe AGH, Zeszyt 9, Kraków /1967/

12. Wilk, Z. Związki między wydobyciem a dopływami wody do kopalń Górnośląskiego Zagłębia Węglowego. Zeszyty Probl. Górnictwa PAN, Zeszyt 2 /1975/

13. Wilk, Z., Szyszło, D.: Analiza porównawcza obserwowanych i prognozowanych różnymi metodami dopływów do kopalń głębinowych w Polsce. Biuletyn IG. Z badań hydrogeologicznych w Polsce. Wyd. Geol.

List of Figures



q_p
2
1,5
1
0,5
0
0
2
4
6
8
10
P
$q_p = \frac{q_0}{\alpha}\left[1 - \frac{p}{\alpha}(1 - e^{-\alpha p})\right]$
$q_0 = 2$
$\alpha = 0,1$

Fig. 1

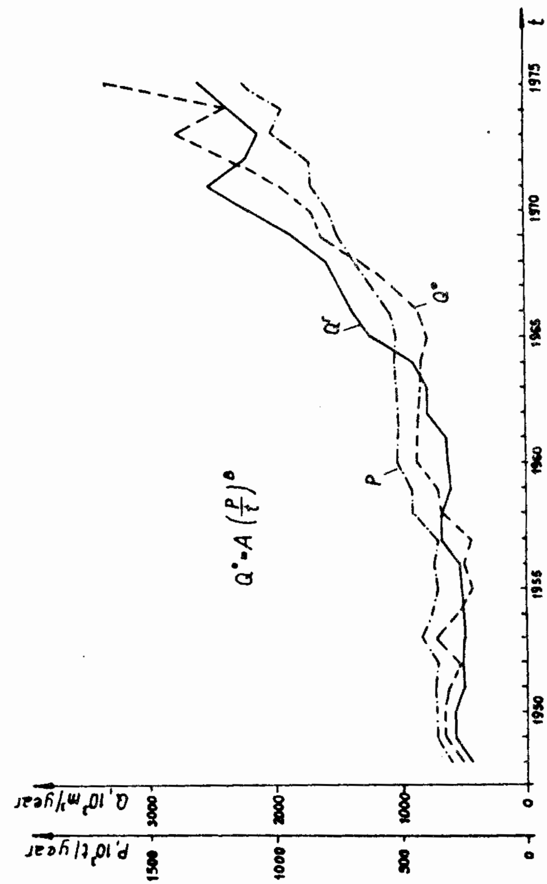

$Q^* = A\left(\frac{P}{t}\right)^a$
Q
P
Q*
Q, 10³m³/year
P, 10³t/year
0
1000
2000
3000
500
1000
1500
1950
1955
1960
1965
1970
1975
t

Fig. 2

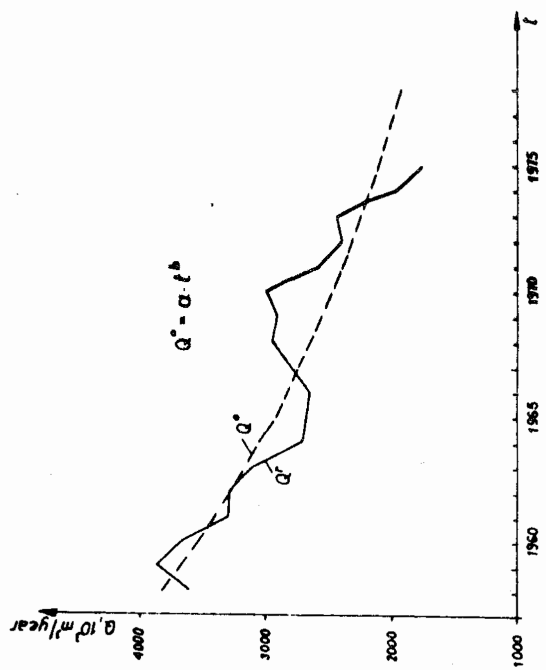


Fig.3

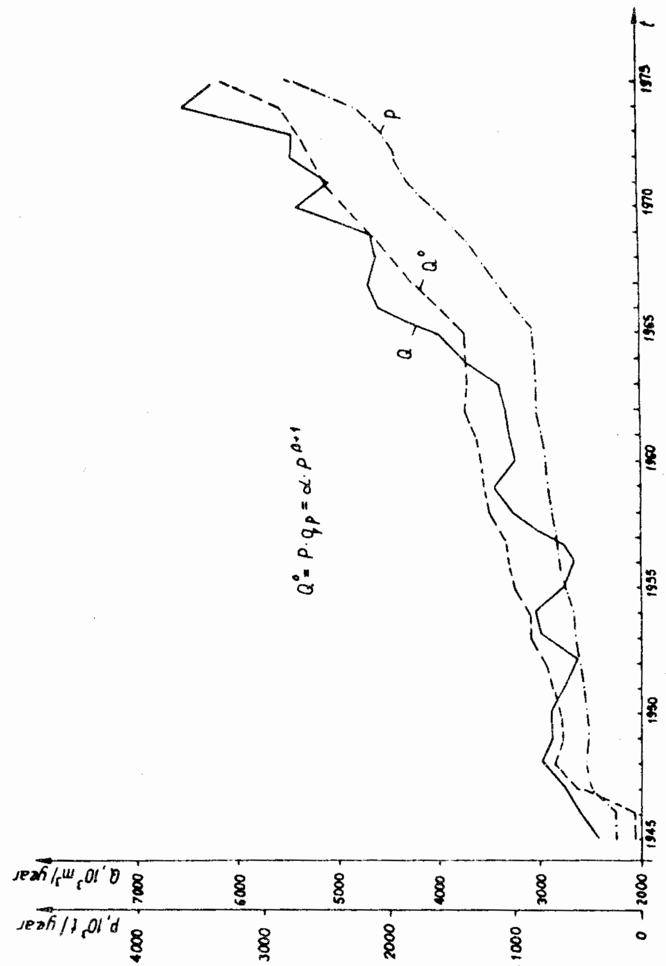

Q, 10³ m³/year
P, 10³ t/year
$Q^o = P \cdot q_P = \alpha \cdot P^{\beta+1}$
Q
Q°
P
t
1945
1950
1955
1960
1965
1970
1975
2000
3000
4000
5000
6000
7000
0
1000
2000
3000
4000

Fig 4